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MORB-type rocks from the Paleo-Tethyan Mian-Lueyang northern ophiolite in the Qinling Mountains, central China: implications for the source of the low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ mantle component in the Indian Ocean

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Abstract

Samples from a basalt and gabbro section of the Paleo-Tethyan (~350 Ma) Mian-Lue northern ophiolites (MLNO) in the Qinling Mountains of central China display sub-parallel and relatively smooth incompatible trace element-depleted patterns and have high $\epsilon_{\text{Nd}(350 \text{ Ma})}$ (8.1–11.3) and low $^{206}\text{Pb}/^{204}\text{Pb}_{(350 \text{ Ma})}$ (16.90–17.25). The MLNO basalts and gabbros are compositionally similar to normal mid-ocean ridge basalts (MORB), particularly to those from the Carlsberg Ridge and Indian Ocean Ridge Triple Junction. The basalts and gabbros also have high $\Delta 7/4$ and $\Delta 8/4$ isotopic values characteristic of the Dupal isotopic anomaly in the southern hemisphere. Although the MLNO is presently in the northern hemisphere, it was previously located within the southerly location of the Indian Ocean based on paleomagnetic data. Thus, assuming that the low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of the MLNO basalts and gabbros is not due to seawater alteration or continental contamination, the unique isotopic signature of both the Paleo-Tethyan oceanic igneous crust and the modern Indian MORB may have come from a very similar, if not identical mantle reservoir. This indicates that a portion of the modern Indian MORB mantle isotopic domain could have been in existence for at least ~350 Ma. We propose that the low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic character of the MLNO basalts and gabbros as well as similar Indian MORB originated either from a low μ sub-domain of the depleted asthenospheric mantle in the southern hemisphere or due to contamination of the depleted asthenosphere by deep-rooted plumes carrying a low $^{206}\text{Pb}/^{204}\text{Pb}$ mantle component. In contrast, the origin of the more common Indian MORB with low $^{206}\text{Pb}/^{204}\text{Pb}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ is most probably associated with the delamination of the Gondwanan continental lithosphere during formation of the Indian Ocean. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The isotopic signature of mid-ocean ridge basalts (MORB) from the Indian Ocean is different from that of MORB from the Pacific and North Atlantic oceans. Indian MORB is characterized by lower $^{206}\text{Pb}/^{204}\text{Pb}$ and higher $^{87}\text{Sr}/^{86}\text{Sr}$ for a given $^{143}\text{Nd}/^{144}\text{Nd}$ than the latter [1–7]. Indian MORB also tend to have high $^{207}\text{Pb}/^{204}\text{Pb}$ and especially $^{208}\text{Pb}/^{204}\text{Pb}$ for a given $^{206}\text{Pb}/^{204}\text{Pb}$. The Sr, Nd and Pb isotopic characteristic of Indian MORB, and all igneous rocks in general, is a product of billions of years of evolution of their source material because of the long half-lives of the parent isotopes of ^{87}Sr , ^{143}Nd , ^{206}Pb , ^{207}Pb , and ^{208}Pb . Thus constraining the origin of the Indian MORB-type isotopic signature potentially could lead to a better understanding of the evolution and dynamics of the Earth mantle.

Two general classes of hypotheses have been proposed to explain the origin and history of the distinct isotopic signature, particularly the low $^{206}\text{Pb}/^{204}\text{Pb}$, of Indian MORB [3–10]. The first one is that its source components are a fairly young mantle end-member created during the processes of breakup of the Gondwana continent to form the Indian Ocean (e.g., [5,6]). Mahoney et al. [6] show that although the Indian MORB-type isotopic signature has been present in the Indian basin for at least 140 Myr, it is not present in all samples of old western Indian MORB. Thus Mahoney et al. [6] suggest that the origin of the low $^{206}\text{Pb}/^{204}\text{Pb}$ components mainly responsible for the Indian Ocean mantle isotopic domain may not greatly pre-date the opening of the Indian Ocean spreading centers. The second hypothesis posits that the Indian MORB-type isotopic signature comes from a regional asthenospheric mantle containing plume materials that upwelled from the lower mantle (e.g., [7–10]). For example, Weis and Frey [7] infer that the Kerguelen plume (~ 118 Ma) is the source of the relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ for given $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of some of the Indian MORB. However, they also favor a significant

role of recycled continental lithosphere as the long-term source component for some of the older (~ 110 – 155 Ma), low $^{206}\text{Pb}/^{204}\text{Pb}$ Indian MORB.

Results of previous investigations show that the distinct isotopic signature of Indian MORB is as old as the Indian ocean crust because the basalts investigated were mostly taken from the Indian ocean basin itself. These results do not prove or disprove the existence of the Indian MORB-type isotopic signature prior to ~ 155 Ma. Thus it appears that one of the keys to a better understanding of the history and origin of the low $^{206}\text{Pb}/^{204}\text{Pb}$ component in the Indian sub-oceanic mantle depends on the age of the component.

Similar to the formation of the Indian Ocean, the now-vanished Tethys Oceans were formed during the previous break-ups of Gondwana in the southern hemisphere. The Paleo-Tethys was formed earlier during the Late Paleozoic [11] and the Neo-Tethys was formed later from the Triassic to Cretaceous [12]. Fragments of the Tethyan oceanic crust are believed to be preserved as ophiolites along the Tethyan Suture Zone (Fig. 1). It is also believed that parts of the Tethys Oceans occupied much the same region as the present Indian Ocean (Fig. 2) [6,13,14]. Thus there is a possibility that both Tethyan and Indian oceanic crusts were generated from a very similar, if not the same asthenospheric mantle source. If this is true then it is possible to trace the temporal evolution of the Indian MORB-type isotopic signature by investigating Tethyan ophiolites. For example, a recent study of two Neo-Tethyan ophiolites by Mahoney et al. [6] shows that the 110 Ma Yarlungzangbu ophiolite in Tibet possesses an Indian MORB-type isotopic signature but the older 150 Ma Masirah ophiolite shares both Indian and Pacific–North Atlantic isotopic signatures. However, data for the older Paleo-Tethyan ophiolites are very few and it is unknown if their igneous rocks carry the isotopic signature of modern Indian MORB.

In this paper, we present trace element and Nd, Pb, as well as a couple of Sr isotopic compositions of the basalts and gabbros from a section of a

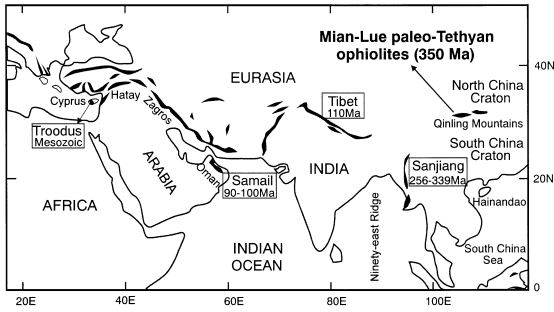


Fig. 1. Map showing the distribution of the Tethyan ophiolites (in black) and location of the Paleo-Tethyan Mian-Lue northern ophiolite (MLNO). Ages of some of the ophiolites mentioned in the text are also shown. The original figure is after [12].

Paleo-Tethyan (~350 Ma) ophiolite from the Qinling orogenic belt, central China [15]. Preliminary data show that these Tethyan oceanic rocks have a normal MORB-type trace element composition and a Dupal anomaly-like isotopic characteristics [15,16]. Here we provide a more complete trace element and isotopic data set and show that the variably altered paleo-Tethyan basalts and gabbros are compositionally very similar to those modern MORB from the Indian Ocean with low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$. Assuming that the Nd and Pb isotopic signature of the Paleo-Tethyan samples more or less reflect that of their mantle source, we then present possible mantle source components of the Paleo-Tethyan basalts and gabbros and the implications of these models for the origin of the Indian MORB-type isotopic signature.

2. Geologic setting

The Qinling orogenic belt in central China is located between the North China (or Sino-Korean) and Yangtze (or South China) continental cratons (Fig. 1). It links the Dabie Orogenic Belt in the east and the Qilian–Kunlun Orogenic belt in the west, forming a mountain range that extends for more than 1000 km from east to west. A belt of ophiolitic and tectonic melange occurs in the southern foothills of the Qinling Mountains and extends for about 160 km from east to west

[17]. Different ophiolitic blocks are present in the northern area of the melange belt, in the Mian and Lueyang counties, and these have been termed the Mian-Lue northern ophiolites (MLNO) [16–18]. The MLNO blocks and enclosing rocks underwent strong deformation and low greenschist facies metamorphism but clear lithologic contacts between them can still be recognized. Moreover, a typical ophiolitic sequence starting from an ultramafic layer consisting of serpentinized harzburgite, a gabbroic layer including metacumulate gabbro and gabbroic dikes, and a volcanic layer composed of meta-tholeiites occurs along a south to north profile of the Hunshuiguan–Zhuangke ophiolitic block. Siliceous sedimentary rocks of possible deep water origin and with Early Carboniferous radiolarian fauna (e.g., *Albaillella* sp.; *Latentifistula* cf. *ruetae*; *Entactinia variospina*) have also been discovered close to Hunshuiguan–Zhuangke ophiolitic block [19]. The age of these fossils implies that the MLNO was formed at about 350 Ma [15,17,19]. Although some ophiolitic blocks within the MLNO have different possible types and origins, preliminary geochemical data suggest that the mafic rocks from Hunshuiguan–Zhuangke ophiolitic block have a normal MORB-type elemental composition which originated from a depleted asthenospheric mantle [15,16]. They were most

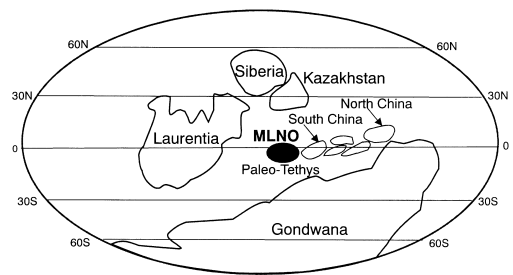


Fig. 2. Projected locations of the MLNO and Paleo-Tethys at ~350 Ma based on paleomagnetic data from the Qinling Mountains [20] and relative positions of the South China (Yangtze) and North China (Sino-Korean) blocks. Continental reconstruction for late Devonian is after [13]. Location of the MLNO is determined by the authors on this diagram. South China = Yangtze continental block; North China = Sino-Korean continental block. The figure is modified after [13].

probably formed during seafloor spreading in an oceanic or back-arc basin environment.

The fragments of the now extinct Paleo-Tethys oceanic crust that comprise the MLNO blocks were located near the equator between the Gondwanan and Eurasian continents during the Carboniferous period (~ 350 Ma) based on paleomagnetic data from Qinling and South China [20,21]. A reconstruction of paleo-continent by Metcalfe [13] also places the MLNO in the same general location (Fig. 2). The genera and species of radiolarian fauna found in the MLNO are the same as those in the Sanjiang, southwest China [19], including the Shuanggou ophiolite (339 Ma) and the Tongchangjie ophiolite (~ 250 – 350 Ma) [11]. The Mian-Lueyang extinct ocean was probably an eastward branch whereas that of the Sanjiang was a southwestward branch of the Paleo-Tethys Ocean.

3. Analytical procedure

Data presented here are from mafic volcanic rocks and gabbros that were collected from a section of the Hunshuiguan–Zhuangke block of the MLNO (henceforth called the MLNO basalts and gabbros). In addition to low greenschist facies metamorphism, some of the samples show slight calcareous alteration. Nevertheless, original textures of the volcanic rocks (e.g., porphyritic) and minerals of all rocks (e.g., plagioclase and clinopyroxene) are still preserved in all samples analyzed.

To constrain the effects of seawater alteration and metamorphism on the samples, plagioclase was separated from three gabbros that were also analyzed for whole rock composition (samples 021, 022 and 023) and from two additional gabbros (YP9 and YP11). All plagioclase separates were analyzed for Pb, Sr and Nd isotopic compositions by thermal ionization mass spectrometry (TIMS) at the Scripps Institution of Oceanography (SIO) using the analytical procedure described by Cheng et al. [22] and Janney and Castillo [23]. Concentrations of U, Th, Pb, Sm, and Nd in almost all plagioclases were analyzed using a Finnigan Element 2 high resolution inductively

coupled mass spectrometry (ICP-MS) also at SIO using a procedure similar to that described by Janney and Castillo [23] and Gieβmann and Greb [24]. Prior to isotopic and concentration analyses, the plagioclase separates were leached in ultrapure 2.25 N HCl in an ultrasonic bath for about 2 hours to remove secondary carbonates.

Seven rock samples of the least altered MLNO basalts and gabbros were chosen for analysis. The samples were first soaked in 5% HCl for 2 h in order to leach out secondary carbonate minerals and then powdered in an agate mill. The powders were analyzed for their Pb and Nd isotopic compositions by TIMS and trace element concentrations by ICP-MS at the Isotope Laboratory of Guangzhou Institute of Geochemistry, China. Samples were analyzed using a Perkin Elmer Elan 6000 ICP-MS using the procedure described by Li [25]. The analytical procedure for TIMS is described in detail by Li and McCulloch [26]. Analytical uncertainties and fractionation corrections used at both the Isotope Laboratory and SIO are listed as notes under appropriate tables.

4. Results

The results of trace element and Nd, Pb and Sr isotope analyses are listed in Tables 1 and 2, respectively. All the MLNO basalts and gabbros generally have relatively smooth and similar trace element patterns (Fig. 3a,b). They are depleted in highly incompatible trace elements except for some mobile elements (e.g., Rb, Ba, Sr), the concentrations of which are easily influenced by seawater alteration (see below). The only exception is sample 024, which shows a slightly irregular trace element pattern and most probably is also a result of alteration. All samples are depleted in light rare earth elements and the degree of depletion shows small variation, i.e., $\text{La/Yb}_{(N)}$ only varies from 0.22 to 0.44 (Table 1 and Fig. 3a). This incompatible trace element-depleted pattern is consistent with the published tholeiitic major element composition of the MLNO basalts and gabbros [16]. In summary, the trace element data show that the MLNO basalts and gabbros are more similar to

Table 1
Trace element composition of MLNO basalts and gabbros

Sample #	021	022	023	024	025	026	028	W-2	
Sample type	G	B	G	G	B	B	B	Meas.	Recom.
La	1.33	1.38	1.22	0.96	1.32	1.71	1.66	11.11	10
Ce	4.81	4.84	4.46	3.47	4.51	6.03	5.84	23.75	23.5
Pr	0.97	0.96	0.88	0.7	0.85	1.16	1.14	3.06	3.2
Nd	5.73	5.71	5.24	4.29	4.87	6.73	6.5	13.08	14
Sm	2.34	2.3	2.11	2	1.78	2.68	2.44	3.25	3.4
Eu	0.87	1.02	0.81	0.73	0.64	1.04	0.8	1.13	1.15
Gd	3.63	3.65	3.14	3.79	2.92	4.09	3.71	3.86	3.6
Tb	0.63	0.63	0.5	0.69	0.55	0.71	0.7	0.6	0.63
Dy	4.4	4.3	3.2	4.96	3.93	4.81	4.73	3.75	3.8
Ho	0.97	0.95	0.66	1.11	0.9	1.04	1.09	0.78	0.84
Er	2.94	2.85	2.07	3.31	2.68	3.09	2.95	2.15	2.4
Tm	0.44	0.43	0.31	0.49	0.39	0.46	0.46	0.31	
Yb	2.95	2.91	2.04	3.15	2.58	3.09	2.96	2.01	2.08
Lu	0.43	0.43	0.3	0.45	0.38	0.44	0.45	0.3	0.32
Cr	77	128	153	67	251	177	122	103	93
Ni	56	55	58	183	90	69	70	75	70
Co	46	47	55	57	50	53	34	51	44
Sc	46	46	49	46	47	52	34	36	35
V	338	336	361	342	300	443	276	295	262
Cu	40	45	35	187	9	98	68	107	103
Pb	4.76	1.87	2.90	0.39	0.27	3.21	1.91	7.9	7.6
Zn	218	155	108	180	120	134	63	92	77
Rb	6	0.38	2	50	14	5	54	22	20
Ba	57	17	20	526	124	60	367	181	173
Sr	120	172	167	25	86	279	93	227	195
Ta	0.05	0.06	0.05	0.08	0.05	0.07	0.06	0.51	0.5
Nb	0.7	0.9	0.6	1.1	0.7	1	0.8	8.5	7.8
Zr	63.1	64.6	55.1	70.5	53.1	75.5	70.7	88	95
Hf	1.75	1.76	1.48	1.92	1.44	2.03	1.87	2.1	2.4
Y	27	27	20	31	25	29	31	21	23
Th	0.05	0.05	0.04	0.05	0.04	0.08	0.04	2.23	2.2
U	0.03	0.04	0.02	0.04	0.02	0.03	0.03	0.53	0.48
Ti	6384	6471	5682	7188	5635	7464	7591	6594	6355
P	480	369	466	476	450	362	362	553	572

G, gabbro; B, basalt. All elements except U, Th and Pb were analyzed by ICP-MS in the Isotopic Laboratory of the Guangzhou Institute of Geochemistry, China. Recommended values for standard W-2 are from Govindaraju [49].

normal MORB than any other modern oceanic rock type, although in general, they are more depleted than most normal MORB (Fig. 3a,b).

The MLNO basalts and gabbros have high measured Nd isotopic ratios ($^{143}\text{Nd}/^{144}\text{Nd}_{\text{meas.}}$ up to 0.513417). Their $\epsilon_{\text{Nd}(350 \text{ Ma})}$ range from 8.1 to 11.3, indicating that these rocks were derived from a mantle source that is depleted in incompatible trace elements for a long period of time (billions of years), similar to that of normal MORB (Figs. 3 and 4). The samples have low present-day $^{206}\text{Pb}/^{204}\text{Pb}$ isotope ratios (16.949–

17.603), and in the oceanic environment, these combined Nd and Pb isotopic ratios are almost exclusively observed in Indian MORB. The samples have low measured U and Th concentrations, consistent with the long time-integrated incompatible trace element-depleted pattern of the source. However, they have on average high and variable Pb concentrations giving variable $^{238}\text{U}/^{204}\text{Pb}$ and $^{232}\text{Th}/^{204}\text{Pb}$ values (0.38–6.36 and 0.53–9.46, respectively). The samples also have high $\Delta 7/4$ and $\Delta 8/4$ values (the vertical deviation of the $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ values from $\text{NHRL}_{(350 \text{ Ma})}$

Table 2
Lead, Nd and Sr isotopic composition of whole rocks and plagioclase separates from MLNO

Sample #	Sample type	U (ppm)	Th (ppm)	Pb (ppm)	$\frac{^{238}\text{U}}{^{204}\text{Pb}}$	$\frac{^{232}\text{Th}}{^{204}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ (meas'd)	$\frac{^{207}\text{Pb}}{^{204}\text{Pb}}$ (meas'd)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ (meas'd)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ (350 Ma)	$\frac{^{207}\text{Pb}}{^{204}\text{Pb}}$ (350 Ma)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ (350 Ma)	Sm (ppm)	Nd (ppm)	$\frac{^{147}\text{Sm}}{^{144}\text{Nd}}$	$\frac{^{143}\text{Nd}}{^{144}\text{Nd}}$ (meas'd)	ϵ_{Nd} (350 Ma)	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ (meas'd)
021	gabbro	0.03	0.04	4.76	0.38	0.53	17.121	15.481	36.881	17.100	15.480	36.872	2.42	6.03	0.2485	0.513217	9.1	0.70583
021-pl	plagioclase	0.05	0.06	1.97	1.54	1.91	17.087	15.549	37.086	17.001	15.544	37.053	0.26	0.64	0.2531	0.513362	11.8	0.70905
022	gabbro	0.04	0.05	1.87	1.31	1.69	17.213	15.520	37.051	17.140	15.516	37.021	2.30	5.71	0.2450	0.513178	8.3	
022-pl	plagioclase	0.03	0.02	1.89	0.99	0.68	17.596	15.589	37.623	17.541	15.586	37.611	1.07	3.63	0.1793	0.513208	11.9	0.70945
023	gabbro	0.02	0.04	2.90	0.42	0.86	17.042	15.463	36.715	17.019	15.462	36.700	2.11	5.24	0.2444	0.513305	10.9	0.70671
023-pl	plagioclase	0.001	0.003	0.22	0.28	0.86	17.212	15.527	37.145	17.196	15.526	37.130	0.16	0.40	0.2433	0.513227	9.4	0.70929
024	basalt	0.04	0.05	0.39	6.36	8.22	17.603	15.587	37.565	17.248	15.568	37.422	2.00	4.29	0.2836	0.513417	11.3	
025	gabbro	0.02	0.04	0.27	4.58	9.46	17.455	15.574	37.457	17.200	15.560	37.292	1.78	4.87	0.2224	0.513225	10.3	
026	basalt	0.03	0.08	3.21	0.57	1.56	16.949	15.457	36.694	16.917	15.455	36.667	2.68	6.73	0.2425	0.513194	8.8	
028	basalt	0.03	0.04	1.91	0.96	1.33	17.257	15.532	37.140	17.203	15.529	37.117	2.44	6.50	0.2285	0.513130	8.1	
YP11-pl	plagioclase	0.001	0.006	0.25	0.24	1.51	17.193	15.485	37.004	17.179	15.484	36.978	0.19	0.41	0.2819	0.513337	9.8	0.70780
YP9-pl	plagioclase			0.46			17.231	15.485	36.964							0.513667		0.71025
SIO							16.903	15.447	36.561							0.511868		
Isotope Lab							16.934	15.486	36.673							0.511860		

Pb, Sr and Nd isotopic compositions of the plagioclases and Sr isotopic ratios of the rocks were analyzed by TIMS at SIO. Trace element concentrations of the separates and U, Th and Pb of the rocks were measured by high resolution ICP-MS also at SIO. Analytical uncertainty for $^{87}\text{Sr}/^{86}\text{Sr}$ measurements is 0.000018. Sr isotopic ratios were fractionation corrected to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and are reported relative to $^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$ for NBS 987. Analytical uncertainty for the $^{143}\text{Nd}/^{144}\text{Nd}$ measurements is ± 0.000014 . Nd isotopic ratios were measured in oxide form, fractionation corrected to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72225$ ($^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$), and are reported relative to $^{143}\text{Nd}/^{144}\text{Nd} = 0.511860$ for the La Jolla Standard. Pb isotopic ratios were measured by static multi-collection and were corrected for fractionation using replicate analyses of standard NBS 981 and normalized to the values of Todt et al. [51]. Analytical uncertainties are about 0.005 for $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ and 0.01 for $^{208}\text{Pb}/^{204}\text{Pb}$. Sm and Nd concentrations of the rock samples were analyzed by ICP-MS in the Isotope Laboratory of the Guangzhou Institute of Geochemistry, China (data are the same as in Table 1). Pb and Nd isotopic compositions of the rocks were analyzed by TIMS also at the Isotope Lab. Nd isotopic ratios were measured in metal form and fractionation corrected to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Analytical uncertainty for $^{143}\text{Nd}/^{144}\text{Nd}$ measurement is ± 0.00002 . Pb isotopic ratios were corrected for fractionation using replicate analyses of the standard NBS 981 and normalized to the values of Todt et al. [51]; analytical uncertainty is better than 0.10/00 per amu. Age-corrected Pb isotopic ratios and $\epsilon_{\text{Nd}(t)}$ were calculated using $t = 350$ Ma.

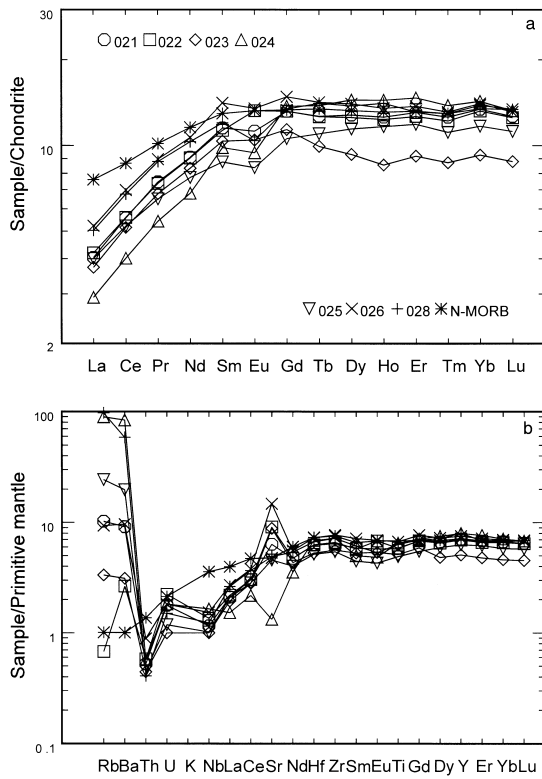


Fig. 3. Normalized (a) rare earth element and (b) incompatible trace element concentration patterns for the MLNO basalts and gabbros. Normalizing values from [50].

[8]), which were calculated using age-corrected Pb isotope ratios (Table 2). These high $\Delta 7/4$ and $\Delta 8/4$ values are typical Dupal isotopic signature of Indian MORB and ocean island basalts in the southern hemisphere [8,27].

Most of the MLNO basalts and gabbros plot within the estimated 350 Ma field for Indian MORB in the $\epsilon_{Nd(350\text{ Ma})}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}_{(350\text{ Ma})}$ diagrams (Fig. 4b); only one sample plots near the field for Pacific–North Atlantic MORB. One sample, however, plots in neither field. Most of the MLNO data also plot within the estimated 350 Ma field for Indian MORB in the Pb isotope diagrams (Fig. 5a,b), although in general the former show a larger range in age-corrected $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ at comparable $^{206}\text{Pb}/^{204}\text{Pb}$ than the latter. Two samples have relatively higher $^{207}\text{Pb}/^{204}\text{Pb}$ than the estimated 350 Ma Indian MORB field. Weis and Frey [7] concluded that

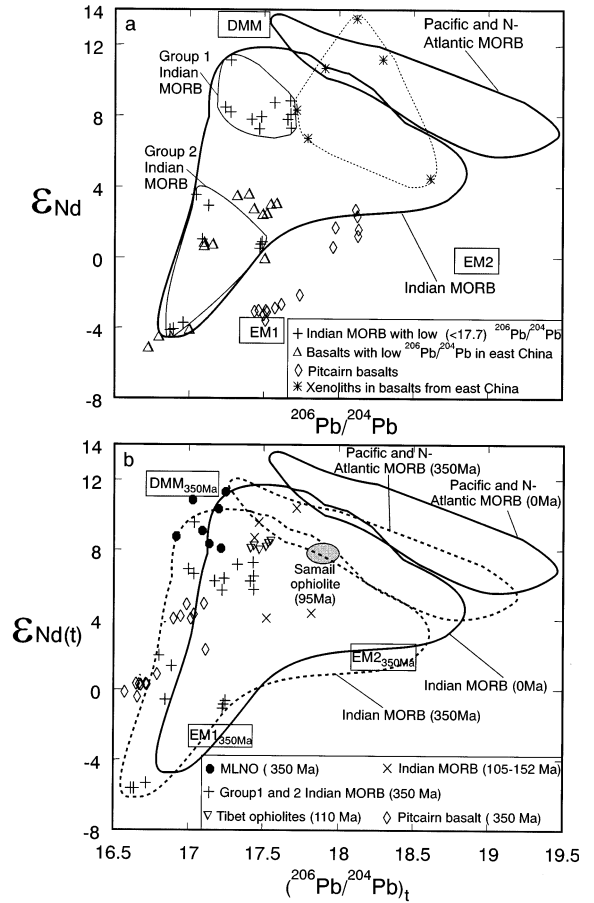


Fig. 4. $^{206}\text{Pb}/^{204}\text{Pb}$ vs. ϵ_{Nd} diagrams for the MLNO basalts and gabbros. (a) $^{206}\text{Pb}/^{204}\text{Pb}_{(\text{meas.})}$ vs. $\epsilon_{Nd(\text{present})}$. (b) $^{206}\text{Pb}/^{204}\text{Pb}_{(350\text{ Ma})}$ vs. $\epsilon_{Nd(350\text{ Ma})}$. Indian MORB with low $^{206}\text{Pb}/^{204}\text{Pb}$ (<17.7) are divided into two groups; group 1 has high $^{143}\text{Nd}/^{144}\text{Nd}$ and low $^{206}\text{Pb}/^{204}\text{Pb}$ and group 2 has low $^{143}\text{Nd}/^{144}\text{Nd}$ and low $^{206}\text{Pb}/^{204}\text{Pb}$. Some of these Indian MORB with low $^{206}\text{Pb}/^{204}\text{Pb}$ (from [1–3,5]) are shown for reference. Also shown for reference are basalts with low $^{206}\text{Pb}/^{204}\text{Pb}$ and mantle xenoliths from eastern China [39,52,53], Tibetan ophiolite [6,29], Samail ophiolite [28,30], and Pitcairn basalts [54]. Present-day Indian and Pacific–North Atlantic MORB fields are from [6,55]. MORB fields at 350 Ma are constructed by assuming that the upper mantle source of MORB has an average $^{147}\text{Sm}/^{144}\text{Nd}$ of 0.24 and $^{238}\text{U}/^{204}\text{Pb}$ of 4.67 [42]. Proposed mantle end-members DMM=depleted MORB mantle, EM1=enriched mantle type 1, and EM2=enriched mantle type 2 values are from [27,56]. DMM, EM1, and EM2 values at 350 Ma are calculated using proposed $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{238}\text{U}/^{204}\text{Pb}$ values for these end-members from [42,56–58].

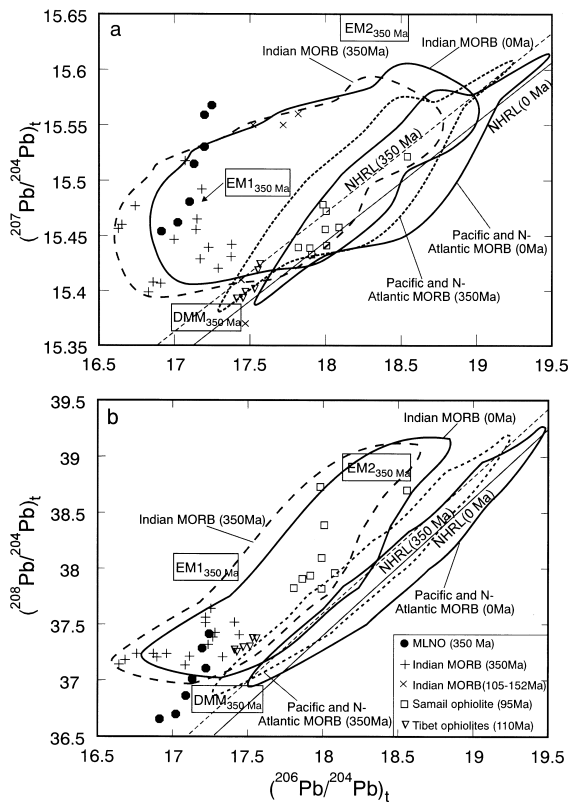


Fig. 5. Age-corrected Pb–Pb isotope ratio diagrams for the MLNO basalts and gabbros. (a) $^{206}\text{Pb}/^{204}\text{Pb}_{(350\text{ Ma})}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}_{(350\text{ Ma})}$. (b) $^{206}\text{Pb}/^{204}\text{Pb}_{(350\text{ Ma})}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}_{(350\text{ Ma})}$. Neo-Tethyan Tibet [6,28] and Samail [27,29] ophiolites at 350 Ma are shown for reference. MORB fields at 350 Ma are constructed by assuming an average $\mu=5.0$ and $\kappa=2.3$ in the mantle source of MORB [42]. $\text{NHRL}_{(350\text{ Ma})}$ is calculated by assuming that the reference line has mean $\mu=9.07$ and $\kappa=23.9$ values similar to MORB [59]. Sources of the $\text{DMM}_{(350\text{ Ma})}$, $\text{EM1}_{(350\text{ Ma})}$, and $\text{EM2}_{(350\text{ Ma})}$ and other data are as in Fig. 4.

several old Indian MORB with unusually high $^{207}\text{Pb}/^{204}\text{Pb}$ may contain small amounts of sediment which were not removed by acid leaching. It is possible that our samples, emplaced on continent, may also contain a small amount of sediment. Three samples have relatively lower $^{208}\text{Pb}/^{204}\text{Pb}$ at comparable $^{206}\text{Pb}/^{204}\text{Pb}$ than the 350 Ma Indian MORB field. It is possible that our samples were derived from a mantle reservoir with relatively low Th/Pb, as indeed shown by our analytical results.

The plagioclase separates have low Sm and Nd

concentrations. These have very high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios and almost all give higher $\epsilon_{\text{Nd}(350\text{ Ma})}$ than bulk rock values (Table 2). These results indicate that the mantle source of the rocks was indeed highly depleted in incompatible trace elements. Moreover, all mineral separates have low Pb isotopic ratios that are also within the range of the whole rock values. As a whole, the Nd and Pb isotopic ratios of plagioclase separates are consistent with the whole rock Nd and Pb isotope data, indicating that the analytical results in the two isotope laboratories are directly comparable and that the measured whole rock Nd and Pb isotopic values truly represent an incompatible element-depleted source material.

The plagioclase separates have high and variable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in contrast with their fairly homogeneous Nd and Pb isotope values. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of two of the host rocks are also high and variable. These results strongly indicate that the Sr isotopic composition of the MLNO basalts and gabbros had been altered by seawater. This inference is corroborated by results of previous studies that showed that Sr isotopic ratios of oceanic rocks are easily affected by seawater alteration (e.g., [28]). What can be inferred from the plagioclase separate and host gabbro Sr isotopic data is that their variable and high ratios most probably resulted from seawater alteration. Thus, we do not use the Sr isotopic data in the following discussion.

5. Discussion

The results of this study *at face value* show that MLNO basalts and gabbros occupy the low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ end of the MORB array (Figs. 4 and 5). As mentioned earlier, MORB with low $^{206}\text{Pb}/^{204}\text{Pb}$ mainly occur in the Indian Ocean basin and it is widely believed that the presence of low $^{206}\text{Pb}/^{204}\text{Pb}$ components in the Indian sub-oceanic mantle is mainly responsible for this distinct isotopic signature. In detail, however, Indian MORB with low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios are quite variable in their isotopic composition. For example, Mahoney et al. [5] noted that MORB from the 39–41°S segment of

the Southwest Indian Ridge are different from those from the Carlsberg Ridge. The latter have higher $^{143}\text{Nd}/^{144}\text{Nd}$ values than the former although both have the same unusually low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. A similar compositional variation is also found in old Indian MORB: a few basalts at DSDP Site 260 have relative low $^{143}\text{Nd}/^{144}\text{Nd}$ and low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios but some basalts at DSDP Sites 765 and 261 have relatively high $^{143}\text{Nd}/^{144}\text{Nd}$ and low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios [7]. Thus, Indian MORB with low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (<17.7) can actually be divided into two main groups: those with high $^{143}\text{Nd}/^{144}\text{Nd}$ ($\epsilon_{\text{Nd}(t)} > 6$) and those with low $^{143}\text{Nd}/^{144}\text{Nd}$ ($\epsilon_{\text{Nd}(t)} < 6$) values (see also [4]). The first group mainly occurs in the Indian Ocean Ridge Triple Junction, Carlsberg Ridge and DSDP Sites 765 and 261 whereas the latter occurs in the Southwest Indian Ridge between 39 and 41°S latitude and DSDP Site 260.

It is also mentioned earlier that the Neo-Tethyan (110 Ma) Yarlungzangbu ophiolite in Tibet has a low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ signature [6,29] similar to some Indian MORB (Fig. 4b). The Neo-Tethyan (~ 95 Ma) Samail ophiolite also shows MORB-type signature [28,30], and to a limited extent approaches that of Indian MORB. These Neo-Tethyan data combined with our Paleo-Tethyan results suggest that the Tethyan asthenospheric mantle domain contained a component with low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios similar to the modern Indian sub-oceanic mantle. Consequently, data reveal that the low $^{206}\text{Pb}/^{204}\text{Pb}$ isotopic signature of Indian MORB is a long-lived feature and already existed for at least 350 Ma. And since the Tethyan Oceans occupied more or less the present Indian Ocean region in the past, either the low $^{206}\text{Pb}/^{204}\text{Pb}$ with high $^{143}\text{Nd}/^{144}\text{Nd}$ component in the modern Indian sub-oceanic mantle domain is inherited from that of the Tethyan asthenospheric mantle or a similar process (or processes) forming the component has been in operation for a long time.

A majority of the investigations of Indian MORB focus mainly on the source of the more common low $^{206}\text{Pb}/^{204}\text{Pb}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ component in the Indian sub-oceanic mantle (e.g., [2–7]). These studies propose the introduc-

tion of delaminated lithospheric mantle beneath the Indian Ocean following the breakup of Gondwana. Several workers also suggest a similar explanation for the presence of Indian MORB-like (i.e., low $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$) signature in MORB from the Atlantic (e.g., [31,32]). Moreover, detailed isotopic work done on lavas along the western Pacific margin suggests a similar scenario, delamination of the Eurasian continental lithosphere, to explain the presence of Indian MORB-like signature in marginal basin lavas (e.g., [33]). Thus, although the distinct, low $^{206}\text{Pb}/^{204}\text{Pb}$ signature of Indian MORB is commonly associated with the delamination of Gondwanan continental lithosphere, this proposal is only for the origin of the low $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ group. One of the main results of our study is the confirmation of the existence of low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ group of Indian MORB [4]. The major question that remains is: what is the source of this isotopic signature?

5.1. Seawater alteration and/or continental contamination of depleted oceanic lavas?

Our results may not allow us to effectively identify the source or sources of the low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ group of Indian MORB because the Pb isotope signature of the MLNO basalts and gabbros could have been due to alteration and/or contamination. Previous studies have shown that only severe seawater alteration can affect the $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of oceanic rocks because seawater is exceedingly low in Nd (4×10^{-6} ppm), and such alteration decreases, rather than increases, the $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of altered rocks (e.g., [22,28]). Indeed, the high measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of both the plagioclase separates and bulk rocks indicate that seawater alteration effects on the Nd isotopic systematics are minimal and that the original source of the Paleo-Tethyan igneous crust is the depleted upper mantle.

That the Pb isotopic composition of the MLNO basalts and gabbros has been affected by seawater alteration is highly suspected as the Pb elemental concentrations of the MLNO basalts and gabbros are relatively high and variable.

However, it must be noted that similar to Nd isotopic ratios, Pb isotopic ratios of oceanic rocks are generally not affected by seawater alteration because, like Nd, the Pb content of seawater is low (2×10^{-6} ppm). More important, seawater alteration tends to increase the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of oceanic rocks because almost all seawater analyzed to date has a high $^{206}\text{Pb}/^{204}\text{Pb}$ ratio. Seawater alteration also increases the U content of submarine lavas, and hence, if alteration occurs early in the history of the rock, the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of the altered rock is increased (e.g., [34,35]). The fact that both the plagioclase separates and bulk rocks have low Pb isotopic ratios (Table 2) strongly suggests that the Pb isotopic composition of the samples was not much affected by seawater alteration (see [6] for more detailed discussion).

It is thus more likely that the Pb isotopic composition of the samples had been contaminated during obduction of the MLNO blocks onto the continent. A number of studies have recognized that crustal-scale fluid advection systems can redistribute soluble Pb in continental orogenic settings, but without affecting the Nd and Sr isotope systematics (e.g., [36]). Some mafic rocks with low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios may also originate directly from the continental lithospheric mantle [31,37]. Currently available data, however, show that basement rocks in the western end of the South Qinling orogenic belt (e.g., metabasalts and sedimentary rocks of the Proterozoic Bikou Group) have high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (17.618–19.375, with most rocks higher than 18.0, Xu, unpublished data), whereas those basement rocks in the eastern end are only as low as 17.450 [38]. In fact, the MLNO basalts and gabbros have one of the lowest $^{206}\text{Pb}/^{204}\text{Pb}$ values (as low as 16.949) among the samples taken so far from the entire Qinling Mountains. Thus, if the Pb isotopic systematics of the MLNO basalts and gabbros resulted from mixing between continental crust material and a depleted mantle source, then the depleted mantle had to have an even lower $^{206}\text{Pb}/^{204}\text{Pb}$ ratio than that of the MLNO basalts and gabbros.

Pb isotopic data for ultramafic xenoliths from eastern China are also inconsistent with the no-

tion that the MLNO basalts and gabbros were derived from a continental lithospheric mantle. These samples possess relatively high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (17.697–18.816) and variable ϵ_{Nd} values (4.5–13.5) [39], suggesting that the MLNO basalts and gabbros could not have been partial melts of the lithospheric mantle represented by the ultramafic xenoliths. Together with the Pb isotope data for the basement rocks in the Qinling region, there is not enough evidence to prove that a source component with $^{206}\text{Pb}/^{204}\text{Pb}$ ratio lower than that of the MLNO basalts and gabbros is present in the continental crust or sub-continental lithospheric mantle in the region.

In summary, it is possible that the similarity in Nd and Pb isotopic signature between the MLNO basalts and gabbros and some Indian MORB is purely coincidental as the Pb isotopic composition of the MLNO samples may be due to continental contamination. However, a combination of factors suggests that the Nd and Pb isotopic composition of the MLNO basalts and gabbros more or less reflects that of their Paleo-Tethyan mantle source. These factors are: (1) alteration-resistant behavior of most of the bulk trace elements and of the Nd isotope systematics in both the whole rocks and plagioclase separates, indicating long-term (billions of years) incompatible trace element depletion (e.g., low Nd/Sm ratio) of their source, (2) unradiogenic Pb isotopic ratios of both plagioclase separates and bulk rocks confirming the long-term depletion of the source (i.e., low U/Pb and Th/Pb ratios), (3) absence of basement rocks and ultramafic xenoliths in the western Qinling region with low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, and (4) paleotectonic reconstruction which places the MLNO in the general location of the modern Indian Ocean. Based on these results, we tentatively conclude that the relatively high and variable Pb elemental concentrations of the MLNO basalts and gabbros are due to either a mantle source component with low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratio similar to that of modern Indian MORB but with higher Pb abundance, or more likely, due to redistribution of elemental Pb from other parts of the local oceanic crust into the MLNO basalts and gabbros during seafloor hydrothermal processes ~ 350 Ma. We

then argue that the Pb isotopic (although not the elemental) signature of the MLNO basalts and gabbros may not have been severely affected by seawater alteration and/or continental contamination. Below we offer three possible models to explain the origin of the Nd and Pb signature of the MLNO basalts and gabbros. Note that even if our assumption is incorrect, the alternative models we present are still viable explanations for the genesis of the low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ group of Indian MORB.

5.2. Continental lithosphere source

In this model, the Pb isotopic composition of the MLNO basalts and gabbros is inherited from the upper mantle containing fragments of delaminated continental lithosphere with low $^{206}\text{Pb}/^{204}\text{Pb}$ and unusually high $^{143}\text{Nd}/^{144}\text{Nd}$ values. The process of producing this isotopic signature is similar to the proposed mechanism to produce the low $^{206}\text{Pb}/^{204}\text{Pb}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ group of Indian MORB mentioned above. During continental break-up to form ocean basins, pieces of the continental lithospheric mantle are delaminated and are passively embedded in the asthenospheric sub-oceanic mantle. The modified asthenospheric mantle becomes the source of the MLNO basalts and gabbros. This is a general delamination process and is not temporally and areally restricted to the formation of the Paleo-Tethyan Ocean. For both this and the contamination model, however, we are not aware of any continental igneous rocks and mantle xenoliths in the Qinling region that could represent the appropriate low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ end-member mantle component for the MLNO basalts and gabbros. Hence, although this model is theoretically possible, it is not supported by available data.

5.3. Mantle plume source

A low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ plume component mixes with the depleted asthenosphere mantle reservoir to produce the MLNO basalts and gabbros. The problem with this hypothesis is whether there is any low $^{206}\text{Pb}/^{204}\text{Pb}$ plume component. Weis and Frey [7] and Mahoney et

al. [5] argue that mantle plumes do not contain anomalously low $^{206}\text{Pb}/^{204}\text{Pb}$ component because both modern and ancient hotspot lavas in the Indian Ocean do not have low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. Peate et al. [37] also suggest that basalts with low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio from the Walvis Ridge, which was originally thought to be a typical plume construct [8,40], are derived from a shallow lithospheric mantle.

Although most mantle plumes in the Indian Ocean generally do not have a low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio, a few plume samples show this low lead isotopic feature. For example, a couple of plume-related basalts from the 38–82 Ma old section of the Ninety east Ridge and some 115 Ma old Kerguelen lavas have relatively low age-corrected $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (~ 17.60 and 17.50 , respectively) [7,41]. Moreover, some of the hotspot lavas from the Pitcairn Islands in south central Pacific have low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (Fig. 4a,b). Finally, some mantle plumes are grossly heterogeneous in space and/or time, and thus some of their intrinsic composition may have substantially lower $^{206}\text{Pb}/^{204}\text{Pb}$ than yet measured [5]. Thus some mantle plumes may carry a low $^{206}\text{Pb}/^{204}\text{Pb}$ component so that this second model cannot be completely ruled out.

5.4. A depleted upper mantle source

The low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ source of the MLNO basalts and gabbros is an uncontaminated sub-domain of the depleted upper mantle source of MORB. This idea is not new as Dosso et al. [4] have previously suggested the presence of such a low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ component (i.e., their SEIR 1 end-member) in the Indian sub-oceanic mantle. Basically, the component is a pocket of the depleted (e.g., low U/Pb, high Sm/Nd) upper mantle that has been shielded from the flux of Pb from mantle plumes that gives the vast majority of modern MORB a high time-integrated $^{206}\text{Pb}/^{204}\text{Pb}$ ratio [42]. The original depleted upper mantle actually has a μ value much lower than the bulk earth value estimated to be 8 ± 2 , consistent with its overall incompatible element-depleted character, but an open system evolution has been affecting

the U–Pb isotope systematics of this reservoir [42]. The history and origin of the low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ mantle component is therefore as old as the depleted upper mantle reservoir, which it is a part of. Here we favor this third hypothesis.

A possible explanation of why a sub-domain of the low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ depleted upper mantle only occurs in the Indian (and most likely in the Tethyan and possibly in the South Atlantic) Ocean is that unlike in the Pacific and North Atlantic Ocean, spreading is extremely slow in portions of the Indian Ocean spreading ridge system and the nearby African plate has been relatively stable since at least the opening of the Indian Ocean basin (e.g., [43]). The combined effects of slow upper mantle upwelling and presence of a nearby stable and thick continental lithosphere favor less upper mantle circulation beneath portions of the Indian Ocean. In contrast, faster seafloor spreading particularly along the Pacific ridges promotes relatively more rapid stirring of the asthenosphere as well as more advanced mixing and fractionation of MORB magmas inside crustal magma chambers.

5.5. The tectonic setting of the MLNO

Despite differences in explaining the source of the low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio, all three models call for the involvement of the depleted upper mantle. It is therefore important to discuss the possible tectonic setting of the MLNO, which is a part of the Paleo-Tethyan ophiolite complex. Two main models are proposed for ophiolite genesis: a MORB model and supra-subduction zone (SSZ) model [44,45]. It is currently recognized that SSZ ophiolites constitute a large proportion of the ophiolitic record. Those that formed in a mature back-arc spreading environment, however, are difficult to distinguish from MORB-type ophiolites [45]. For example, studies have shown that basalts from some regions in the Mariana back-arc basin do not contain any arc component and have elemental and isotopic compositions very similar to MORB (e.g., [46,47]). Gribble et al. [47] suggest that the Mariana back-arc spreading center requires an upwelling asthenospheric mantle regime

similar to that beneath the mid-ocean ridge environment. Hence basalts accreted along a back-arc basin seafloor spreading center can also be derived from a depleted asthenosphere. Although it is very difficult to constrain with certainty whether the MLNO basalts and gabbros were formed along a mid-ocean ridge or a mature back-arc spreading environment, a few available data suggest that their source most probably was a portion of the depleted sub-oceanic mantle. In addition to the absence of distinct, relative depletion in high field strength elements which is a characteristic feature of SSZ lavas, the MLNO basalts and gabbros have high Nb/U ratios (average value of ~ 30). These values are similar to the high Nb/U ratios of lavas derived from the depleted sub-oceanic mantle and are distinct from the low Nb/U lavas formed in continental and convergent margin settings (e.g., [48]). Finally, although this argument could be construed as somewhat circular, the occurrence of Indian MORB with low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios suggests that it is indeed possible to have such a depleted mantle component in an oceanic environment.

6. Summary and conclusions

The variably altered and slightly metamorphosed basalts and gabbros of the Paleo-Tethyan (~ 350 Ma) Mian-Lueyang northern ophiolite have low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, similar to some Indian Ocean MORB. Our new data reinforce the presence of such a low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ group of Indian MORB. The results also highlight the difficulty in interpreting previous and future geochemical data for Tethyan and other ophiolitic complexes because of post-magmatic chemical alteration or modification. In the present study, the largest uncertainty is with the Pb isotopic composition as the samples have low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and high and variable Pb elemental concentrations, features that are commonly associated with continental contamination. The low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of plagioclase separates and available Pb and Nd isotopic data for the country rocks and ultramafic

xenoliths in the Mian-Lueyang region, however, argue against severe continental contamination. In addition, the degree of consistency of available plate tectonic data which place the MLNO crust in the vicinity of the modern Indian Ocean indicate to us that the Nd and Pb isotopic similarity between MLNO samples and some of the Indian MORB is not simply coincidental. We thus argue that although the composition of the MLNO samples is somewhat altered, there is a possibility that their Nd as well as Pb ratios closely reflect those of their mantle source. Assuming that this is the case, the source of the MLNO basalts and gabbros could be the depleted asthenospheric source of normal MORB that was shielded from the open system evolution that has increased the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of the bulk of modern MORB source. Alternatively, the source of the MLNO basalts and gabbros is a depleted MORB mantle containing a component from deep-rooted mantle plumes. Thus, the distinct isotopic signature of the Indian Ocean mantle domain, particularly its low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ ratio, may have already been in existence prior to the creation of the Indian Ocean.

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