CHINESE JOURNAL OF GEOCHEMISTRY Vol. 26 No. 2 2007

DOI: 10.1007/s11631-007-0207-3

Signatures of the source for the Emeishan flood basalts in the Ertan area: Pb isotope evidence

YAN Zaifei (严再飞)[1,2*], HUANG Zhilong (黄智龙)[1], XU Cheng (许成)[1], CHEN Mi (陈觅)[1,2], and ZHANG Zhenliang (张振亮)[1,2]

[1] *State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China*

[2] *Graduate School, Chinese Academy of Sciences, Beijing 100039, China*

* *Corresponding author, E-mail: zaifeiyan78@hotmail.com*

Received April 18, 2006; accepted May 10, 2006

Abstract The Emeishan flood basalts can be divided into high-Ti (HT) basalt (Ti/Y>500) and low-Ti (LT) basalt (Ti/Y<500). Sr, Nd isotopic characteristics of the lavas indicate that the LT- and the HT-type magmas originated from distinct mantle sources and parental magmas. The LT-type magma was derived from a shallower lithospheric mantle, whereas the HT-type magma was derived from a deeper mantle source that may be possibly a mantle plume. However, few studies on the Emeishan flood basalts involved their Pb isotopes, especially the Ertan basalts. In this paper, the authors investigated basalt samples from the Ertan area in terms of Pb isotopes, in order to constrain the source of the Emeishan flood basalts. The ratios of $^{206}Pb/^{204}Pb$ (18.31–18.41), $^{207}Pb/^{204}Pb$ (15.55–15.56) and $^{208}Pb/^{204}Pb$ (38.81–38.94) are significantly higher than those of the depleted mantle, just lying between EM I and EM II. This indicates that the Emeishan HT basalts (in the Ertan area) are the result of mixing of EMI end-member and EMII end-member.

Key words LT and HT basalts; Ertan basalts; geochemistry; Pb isotope; enriched mantle

Continental flood basalt (CFB) province, as one of the large igneous provinces (LIPs), features the eruption of magmas in large volume in short time, and temporal coincidence with oceanic expansion or continental breakup (Courtillot et al., 1999). Some researchers found that CFB and mantle plume are correlative (Richard et al., 1989; Campbell and Griffiths, 1990). However, Mesozoic Tertiary basalts differ significantly in isotope and trace element characteristics from oceanic basalts derived from convecting upper mantle. It is considered that the differences mentioned above resulted from crustal contamination (Arndt et al., 1993; Wooden et al., 1993), or different sources gave rise to such differences (Mantovani and Hawkesworth, 1990). According to Ellam and Cox (1991), the lithospheric mantle played an important role, except for deeper mantle-derived materials, in continental volcanism. Even some researchers thought that the sources of some CFB were located in the lithospheric mantle (Hawkesworth et al., 1990; Pegram, 1990; Hooper and Hawkesworth, 1993). Study on Palaeogene basalts from the Faroe Island suggested that the low Ti-type basalts would have resulted from melting of the depleted mantle in response to high-degree melting, whereas the high-Ti type basalts were of deep mantle-derivation (Holm et al., 2001).

Eight major continental flood basalts provinces have been produced over the last 300 Ma (Courtillot et al., 1999), the Emeishan trap is one of the provinces. The Emeishan flood basalt (EFB) province is located in Sichuan Province, Yunnan Province and Guizhou Province and has been recognized recently. EFB from different areas or different types of EFB in the same area tend to display a diversity of geochemical features (Xu Yigang et al., 2001; Xiao Long et al., 2004). For example, the Binchuan low-Ti (LT) basalts were derived from the sub-continental lithospheric mantle (SCLM); the high-Ti (HT) basalts are OIB-like (Xiao Long et al., 2004). In addition, the activity of the Emeishan LIP contributed to the formation of the Huize Pb-Zn ore deposit (Zhang Zhenliang et al., 2005). However, little research has been conducted on EFBs from the Ertan area where rocks, petrographically from basic to acid, are recognized. Thus, study on EFB, especially on their Pb isotopes, from the Ertan area is helpful to constrain the origin of EFB. In this paper, we will present new geochemical parameters for the EFB and discuss the petrogenesis of the rocks as well.

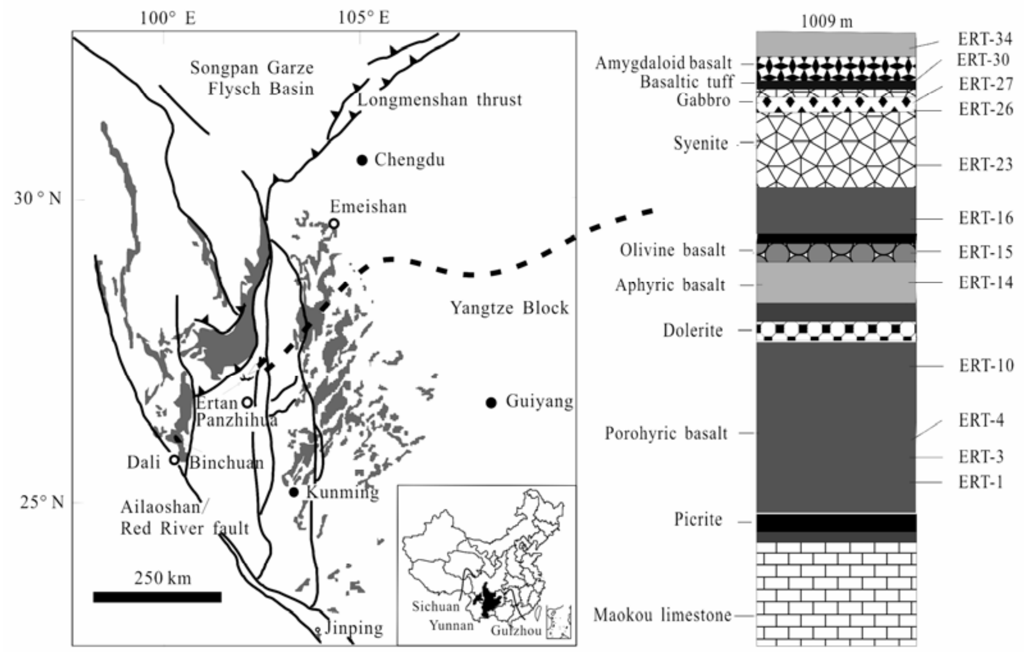

Fig. 1. The sketch map of the Emeishan flood basalt province and adjacent regions (Modified after Jason et al., 2005; Xu Yigang et al., 2001; Wang Yunliang et al., 1993).

1 Geological background and petrography

The Emeishan large igneous province (ELIP) is located at the western margin of the Yangtze Craton, SW China (Fig. 1). The EFB are exposed in a rhombic province covering an area of ~250000 km^2 with thickness ranging from several hundred meters up to 5 kilometers within Yunnan, Sichuan and Guizhou provinces (Chung Sunlin and Jahn, 1995; Xu Yigang and Chung Sunlin, 2001) and the evolved lavas erupted at the Permian-Triassic boundary (Chung Sunlin et al., 1998). The lava succession in the western sector of the ELIP is thicker than in the eastern sector. The average thickness of ELIP is about 700 m and the total volcanic volume is 0.3×10^6 km^3 (Xu Yigang and Chung Sunlin, 2001). Many geologists have placed their focus on ELIP since the Emeishan plume was recognized.

The EFB are continental flood basalts associated with intraplate rifting. The products of Late Permian volcanism include nephelitic basalt, alkalic basalt and other unsaturated-SiO$_2$ rocks (forepart), tholeiite and alkalic basalt (metaphase), orthophyre, trachyte and rhyolite (final phase). In regard to their mineral composition the EFB contain plagioclase, clinopyroxene, glasses, minor magnetite and ilmenite (Wang Yunliang et al., 1993). The Ertan area is located in the center of the Panxi rift valley, the basalts, in this area, are dominated by olivine basalt, aphyric basalt, porphyric basalt and amygdaloid basalt. Moreover, dykes, such as syenite, gabbro, dolerite and basaltic volcanic tuff, as hypabyssal intrusives, are inserted by bimodal volcanic rocks. In the Ertan basalts, olivine phenocrysts account for about 0–5%; plagioclase phenocrysts, about 10%–30%; clinopyroxene phenocrysts, about 5%–15%; groundmass in the basalts is mainly made up of plagioclase (20%–45%), clinopyroxene (15%–30%), basaltic glass (15%–25%), Ti-Fe oxides (5%–15%) and magnetite (3%–7%).

2 Sampling and analytical method

Samples studied in this paper were collected from basalts in the Ertan area of southern Sichuan Province during a geological reconnaissance (Fig. 1). Unfortunately, systematic sampling of the volcanic succession with a stratigraphic height control was not possible owing to the poor exposure and severe weathering/alteration of the lava flows. This prevents us from making a detail geochemical assessment of the temporal evolution of these rocks. These samples include 26 basalt samples, 6 gabbro samples, 3 syenite samples and 2 basaltic volcanic tuff samples.

About 100–150 mg whole rock powder was completely decomposed in a mixture of HF-HNO$_3$ for Pb isotopic analysis. Pb was separated on Teflon$^®$ columns containing ~80 μL AG1-X8, 100–200 mesh and employing HBr-HCl wash and elution procedure. Procedural blank was <50 pg for Pb. For the measurements of isotopic composition, Pb was loaded with a mixture of Si-gel and H$_3$PO$_4$ onto a single-Re

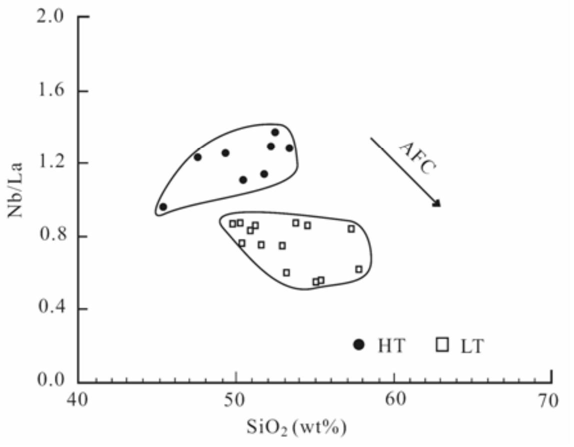

Fig. 2. The plots of of Nb/La vs. SiO_2. Data of Nb/La and SiO_2 are from Xiao Long et al. (2004).

filament and measured at 1300℃. Pb standard NBS 981 was used to determine thermal fractionation and measured isotopic ratios of samples were corrected with a value of 0.1% per atomic mass unit. Isotopic ratios were measured on a Finnigan MAT-262 thermal ionization mass spectrometer (TIMS) in the Laboratory for Radiogenic Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Raw data obtained were calculated using the Isoplot program (Ludwig, 2001), giving $2\sigma_m$ error. Technique details on chemical separation and measurement are described in Chen et al. (2000, 2002). Results are seen in Table 1.

3 Geochemistry of the rocks

According to some researchers (Xu Yigang et al., 2001; Xu Yigang and Chung Sunlin, 2001; Peate and Ole, 2003; Xiao Long et al., 2004), the basalts can be classified as the high-Ti (HT) basalts and low-Ti (LT) basalts in terms of the concentrations of TiO_2 and the ratios of Ti/Y in the rocks; namely, high-Ti (HT) basalts with >2% TiO_2 and >500 Ti/Y, and low-Ti (LT) basalts with <2% TiO_2 and <500 Ti/Y. The rocks with different TiO_2 concentrations or Ti/Y ratios possess different geochemical characteristics in LIP.

3.1 Low-Ti basalts

The Emeishan low-Ti lavas exhibit low Ti/Y (<500), $Fe_2O_3^*$ (<12%), Nb/La (0.6–1.4), $\varepsilon_{Nd}(t)$ (-4.8–1.4) and relatively high SiO_2 (48%–53%) and Mg# (0.52–0.64) (Xu Yigang et al., 2001). Some researchers (e.g. Xiao Long et al., 2004) subdivided the LT lavas into LT_1 and LT_2. In addition, the controversy on crustal contamination for EFB is still under way. Recent research indicates that the parental magma for the LT basalts was derived from a shallow sub-continental lithospheric mantle (Xiao Long et al., 2004). Negative correlation is displayed between Nb/La and SiO_2, which indicates that the evolved lavas have undergone assimilation and fractional crystallization (Fig. 2). The plots of $\varepsilon_{Nd}(t)$ vs. $(^{87}Sr/^{86}Sr)_i$ for EFB also indicate the LT basalts were contaminated (Fig. 3). In diagram 4A, the LT basalts show a positive correlation between the initial Sr isotope ratio $(^{87}Sr/^{86}Sr)_i$ and SiO_2, which reflects probably that the lavas had been contaminated by the crust or continental lithospheric mantle; whereas a negative correlation is shown between the Sr isotope initial ratio $(^{87}Sr/^{86}Sr)_i$ and Mg# (Fig. 4B), which resulted from the materials with high $^{87}Sr/^{86}Sr$ ratios (e.g. the upper crust). This indicates that the LT magmas were derived from a shallower lithospheric mantle.

3.2 High-Ti basalts

The Emeishan high-Ti basalts exhibit high Ti/Y (>500). The lavas are subdivided into HT_1, HT_2 and HT_3, in terms of the concentrations of TiO_2, the ratios of Nb/La and $\varepsilon_{Nd}(t)$ (Xu Yigang et al., 2001). The HT_1

Table 1. The Pb isotopic composition of the Emeishan flood basalts

Sample	$^{206}Pb/^{204}Pb$	2SE(M)(%)	$^{207}Pb/^{204}Pb$	2SE(M)(%)	$^{208}Pb/^{204}Pb$	2SE(M)(%)
		Ertan basalt				
ERT-3	18.3104	0.007	15.5472	0.007	38.9457	0.009
ERT-15	18.4104	0.017	15.5457	0.017	38.8423	0.017
ERT-22	18.3584	0.006	15.5580	0.007	38.8189	0.007
ERT-31	18.3815	0.008	15.5516	0.008	38.8239	0.008
		Ethiopian basalt (HT2)				
E38	18.86	…	15.55	…	38.81	…
E33	18.94	…	15.55	…	38.65	…
E35	18.87	…	15.53	…	38.67	…
E40	18.95	…	15.56	…	38.91	…
E266	18.85	…	15.53	…	38.76	…

Note: 2SE(M) is the error. Isotopic ratios were measured on a Finnigan MAT-262 thermal ionization mass spectrometer (TIMS) at the Laboratory for Radiogenic Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Ethiopian basalts are from Raphaël et al. (1999).

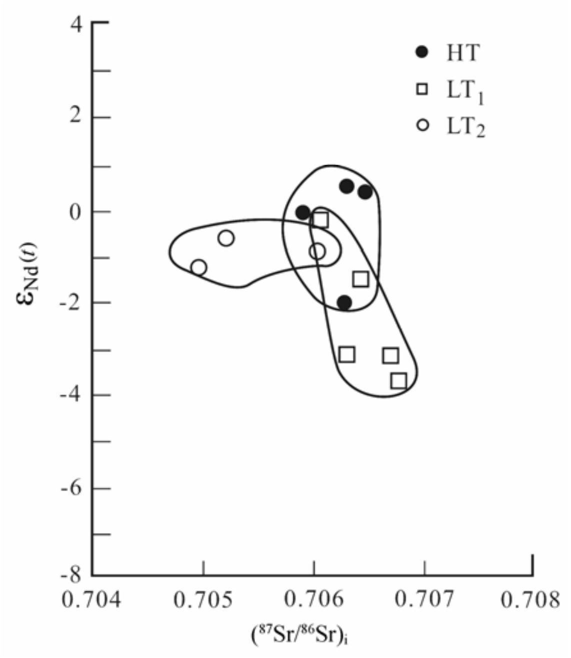

Fig. 3. The plots of $\varepsilon_{Nd(t)}$ vs. $(^{87}Sr/^{86}Sr)_i$. Data of $\varepsilon_{Nd}(t)$ and $^{87}Sr/^{86}Sr$ are from Xiao Long et al. (2004).

lavas display significantly high TiO_2 (3.65%–4.70%), Fe_2O_3* (12.7%–16.4%), Nb/La (0.75–1.1), coupled with higher $\varepsilon_{Nd}(t)$ (1.1–4.8) and lower SiO_2 (45%–51%); the HT_2 lavas are compositionally similar to the HT_1 lavas but show conspicuous depletions in U and Th. The HT_3 type has higher Mg# (51–61) than the HT_1 and HT_2 lavas.

The lack of correlation between $(^{87}Sr/^{86}Sr)_i$ and SiO_2 for the HT_2 and HT_3 basalts indicates that the rocks have not undergone assimilation or assimilation and fractional crystallization (AFC) (Fig. 4A); slight positive correlation for the HT_1 basalt indicates the evolved lavas occurred in the intermediate zone between the HT lavas and the LT lavas (Fig. 4A, B). This indicates the HT magmas were derived from a deeper mantle source that may be probably a mantle plume.

3.3 Ertan basalts

Few studies on the Ertan basalts have been conducted, especially isotopic research. TiO_2>2.1wt% in the rocks (YAN Zaifei, unpublished), with the characteristics of HT basalts; Mg# (58–84) in the rocks is higher than that of other basalts in ELIP (31–64) (Xu Yigang et al., 2001). The $^{87}Sr/^{86}Sr$ ratios (>0.706) for the Ertan basalts are high and $\varepsilon_{Nd}(t)$ (< 0) values are low (YAN Zaifei, unpublished), which reflects the features of crustal materials and continental lithosphere. This resulted probably from assimilation of the upper crust and continental lithosphere, or the parental magmas of the Ertan basalts were derived directly from the continental lithospheric mantle. However, the patterns of incompatible trace elements for the Ertan basalts are OIB-like (Fig. 5). This indicates that the parental magmas of the Ertan basalts were derived from an asthenospheric mantle and the magmas were

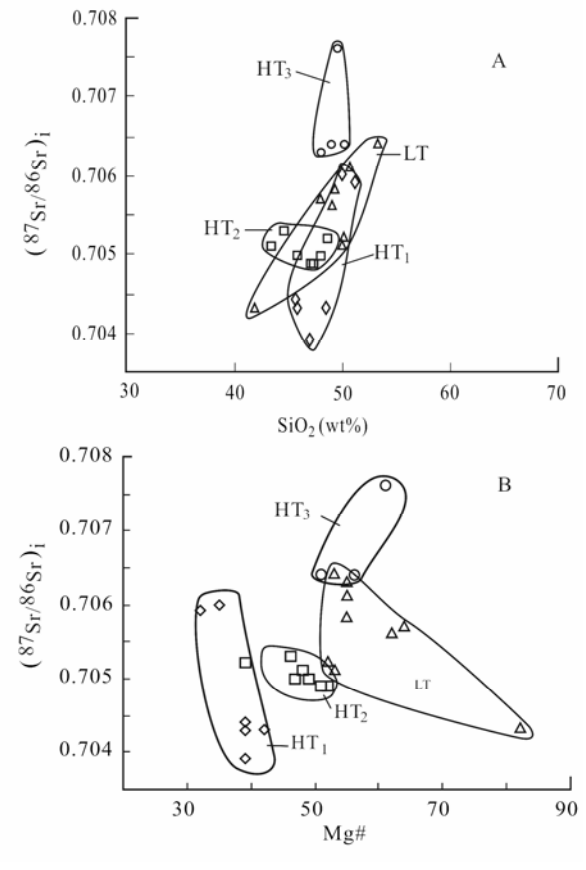

Fig. 4. The plots $(^{87}Sr/^{86}Sr)_i$ vs. SiO_2 and $(^{87}Sr/^{86}Sr)_i$ vs. Mg#. Data of Sr isotope, Mg# and SiO_2 (wt%) are from Xu Yigang et al. (2001).

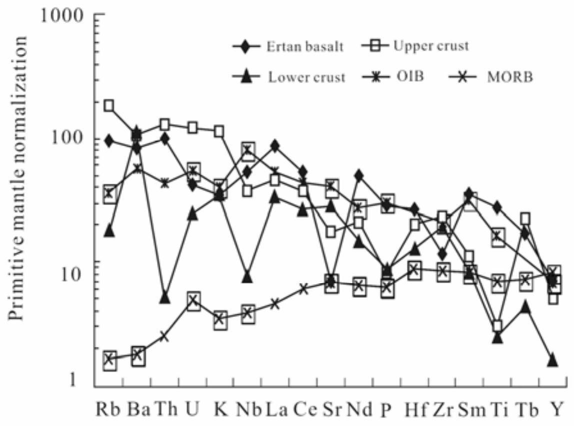

Fig. 5. The patterns of the Emeishan flood basalts from the Ertan area. The Ertan basalts are from unpublished data (average, *n* =26). The upper crust is from Taylor et al. (1984); the lower crust is from Weaver and Tarney (1984); MORB is from Saunders and Tarney (1984) and Sun (1980); OIB is from Sun (1980).

contaminated in conduit systems over time as a successive eruption by upper crustal materials and continental lithosphere.

4 Pb isotopes

Extensive research on CFB has been conducted, mostly focusing on Pb isotopes (e.g. Marques et al., 1999; Raphaël et al., 1999; Trua et al., 1999; Rogers et al., 2000). According to Marques et al. (1999), the Brazilian Paraná flood basalts can be subdivided into the LT-type basalts and HT-type basalts. These basalts in southern Paraná and northern Paraná display different Pb isotopic characteristics, respectively. The initial Pb ratios of southern basalts are variable: $(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=18.20$, $(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=17.45$; $(^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=15.61$, $(^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=15.50$; $(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=38.32$, $(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=37.89$; whereas northern basalts have significantly similar initial Pb isotopic ratios: $(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=17.78$; $(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=17.65$; $(^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=17.53$; $(^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=15.52$; $(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=38.12$; $(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=38.05$. In terms of the ratios, Marques et al. (1999) thought both southern basalts and northern basalts were derived from different lithospheric mantle components, plumes provided only heat for melting of the lithosphere, but no materials. The magmas of the LT and HT basalts in northern Paraná were derived from homogeneous components; the magmas of the LT and HT basalts in southern Paraná resulted from mixing of different components. The Ethiopian CFB were also subdivided into the LT-type basalts and the HT-type basalts (Raphaël et al., 1999). The rocks have: $(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=18.04$–$18.71$; $(^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=15.48$–$15.54$; $(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{LT}=37.55$–$38.05$; $(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=18.51$–$18.95$; $(^{207}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=15.51$–$15.57$; $(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{HT}=38.12$–$38.91$. The Pb isotopic values of the HT basalts are significantly similar to those of the Ertan basalts (Table 1). According to Raphaël et al. (1999), the parental magmas of the LT and HT basalts in the Ethiopian LIP were all derived from the asthenospheric mantle. However, the incompatible trace elements in the LT basalts display the signature of evolved lithosphere, such as depletions in Nb and Ta; the HT basalts are significantly similar to OIB. This probably resulted from the geological process in which plume brought large amounts of crustal materials upwards. Therefore, Pb isotope is a powerful tool to trace the source of basaltic magmas, even if other geochemical parameters are interfered (e.g. major elements and trace elements).

However, few studies on EFB have involved Pb isotopes (e.g. Xu Yigang et al., 2001; Xiao Long et al., 2004; Chung Sunlin and Jahn, 1995; Wang Yunliang et al., 2001; Jason et al., 2005; Zhang Zhaochong and Wang Fusheng, 2003), especially the Ertan basalts. So, we think Pb isotopic studies on the Ertan basalts will be useful as a powerful proof to constrain the source of EFB. Data concerned are presented in Table 1, the ratios of $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ (18.31–18.41) for the Ertan basalts are significantly higher than those of the depleted mantle (17.2–17.7) and EMI (17.6–17.7), conspicuous lower than those of HIMU (>20.8); the ratios of $^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$ (15.55–15.56) are relatively high as compared with those of EMI (15.46–15.49) and depleted mantle (~15.4); the ratios of $^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$ (38.81–38.94) are significantly higher than those of the depleted mantle (37.2–37.4) and higher than those of EMI (38.0–38.2). These values of the Ertan basalts are significantly similar to the Pb ratios of the Ethiopian CFB (Table 1). The plots based on the ratios show that Pb isotope values for the Emeishan HT basalts (Ertan area) vary between EMI and EMII and are similar to those of Ethiopian CFB (Fig. 6). The petrogenesis of mantle plume for the latter has been proved (e.g. Raphaël et al., 1999; Trua et al., 1999). This indicates that the Emeishan HT basalts from the Ertan area resulted from mixing of EM I end-member and EM II end-member from an enriched mantle. However, Zhang Zhaochong and Wang Fusheng (2003) thought the source of EFB involves EMI, EMII and DMM, probably resultant from the LT lavas because the HT lavas were derived from a deeper mantle whereas the LT lavas from a shallower lithospheric mantle.

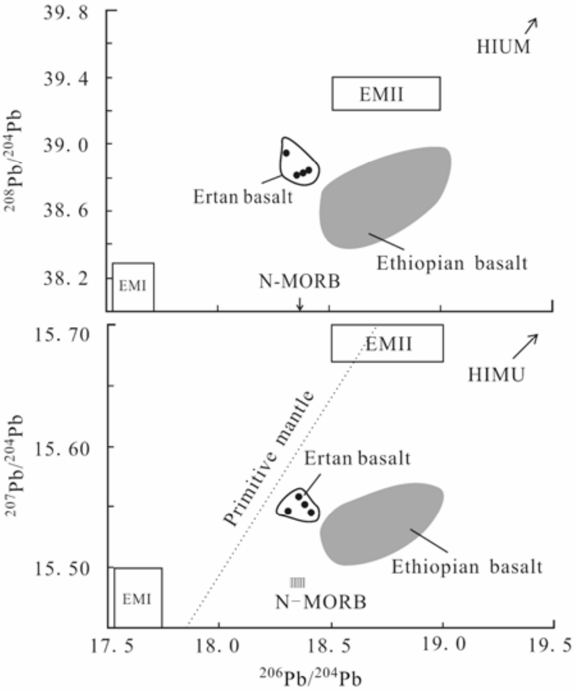

Fig. 6. The plots of $^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$ vs. $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ and $^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$ vs. $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$. Data of N-MORB, EMI, EMII and HIMU are from Zindler and Hart (1986) and Hart (1988); those of the primitive mantle from Hofmann (1997).

5 Conclusions

The Emeishan LT basalts and HT basalts display different geochemical characteristics, respectively. The LT basalts are characterized by low Ti/Y (<500), Fe_2O_3* (<12%), Nb/La (0.6–1.4), $\varepsilon_{Nd}(t)$ (-4.8–1.4) and relatively high SiO_2 (48%–53%) and Mg# (0.52–0.64). The HT basalts have high Ti/Y ratios (>500) and the rocks are subdivided into HT_1, HT_2 and HT_3. The HT1 lavas are significantly high in TiO_2 (3.65%–4.70%), Fe_2O_3* (12.7%–16.4%), Nb/La (0.75–1.1), coupled with higher $\varepsilon_{Nd}(t)$ (1.1–4.8) and lower SiO_2 (45%–51%). The HT_2 basalts are compositionally similar to the HT_1 basalts but show conspicuous depletions in U and Th. The HT_3-type basalts have higher Mg# (51–61) than the HT_1 and HT_2 basalts.

The LT basalts were derived from a shallower lithospheric mantle and have undergone assimilation and fractional crystallization (AFC). The HT basalts erupting as mantle plume were derived from a deeper mantle.

The concentrations of TiO_2 in the Ertan basalts are >2.1%, consistent with those of the HT basalts. The patterns of incompatible trace elements for the Ertan basalts are OIB-like. This reflects the signature of asthenospheric mantle for the lavas. In the rocks, $^{206}Pb/^{204}Pb$ (18.31–18.41), $^{207}Pb/^{204}Pb$ (15.55–15.56), and $^{208}Pb/^{204}Pb$ (38.81–38.94) are higher than those of the depleted mantle and EMI. Pb isotopic ratios for EFB from the Ertan area vary between EMI and EMII and are similar to those of the Ethiopian CFB. This indicates the Emeishan HT flood basalts (the Ertan area) are the mixture of EMI and EMII end-members.

Acknowledgements The authors wish to thank Dr. Chu Zhuying from the Laboratory for Radiogenic Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, for his help. This research project was granted by the National Natural Science Foundation of China (Nos. 40372048 and 40573036).

References

Arndt N.T., Czamanske G.K., Wooden J.L., and Fedorenko V.A. (1993) Mantle and crustal contributions to continental flood volcanism [J]. *Tectonophysics*. **223**, 39–52.

Campbell I.H. and Griffiths R.W. (1990) Implications of mantle plume structure for the evolution of flood basalts [J]. *Earth Planet. Sci. Lett.* **99**, 79–93.

Chen F., Hegner E., and Todt W. (2000) Zircon ages, Nd isotopic and chemical compositions of orthogenesis from the Black Forest, Germany: Evidence for a Cambrian magmatic arc [J]. *International Journal of Earth Sciences*. **88**, 791–802.

Chen F., Siebel W., Satir M., Terzioglu N., and Saka K. (2002) Geochronology of the Karadere basement (NW Turkey) and implications for the geological evolution of the Istanbul zone [J]. *International Journal of Earth Sciences*. **91**, 469–481.

Chung Sunlin and Jahn B.M. (1995) Plume-lithosphere interaction in generation of the Emeishan flood basalts at the Permian-Triassic boundary [J]. *Geology*. **23**, 889–892.

Chung Sunlin, Jahn B.M., Wu G.Y., Lo C.H., and Cong B.L. (1998) The Emeishan flood basalt in SW China: A mantle plume initiation model and its connection with continental break-up and mass extinction at the Permian-Triassic boundary. In *Mantle Dynamics and Plate Interaction in East Asia* (eds. M.F.J. Flower et al.) [C]. AGU Geodyn. Ser., AGU, Washington, D.C., **27**, 47–58.

Courtillot V., Jaupart C., Manighettiv I., Tapponnier P., and Besse J. (1999) On causal links between flood basalts and continental breakup [J]. *Earth Planet. Sci. Lett*. **166**, 177–195.

Ellam R.M. and Cox K.G. (1991) An interpretation of Karoo picrite basalts in terms of interaction between asthenospheric magmas and the mantle lithosphere [J]. *Earth Planet. Sci. Lett*. **105**, 330–342.

Hart S.A. (1988) Heterogeneous mantle domains: signatures, genesis and mixing chronologies [J]. *Earth Planet. Sci. Lett*. **90**: 273–296.

Hawkesworth C.J., Kempton P.D., Rogers N.W., Ellam R.M., and Van Calsteren P.W. (1990) Continental mantle lithosphere and shallow level enrichment processes in the Earth's mantle [J]. *Earth Planet. Sci. Lett*. **96**, 256–268.

Hofmann A.W. (1997) Mantle geochemistry: The message from oceanic volcanism [J]. *Nature*. **385**, 219–229.

Holm P.M., Niels H., and Regin W. (2001) Geochemical and Pb-Sr-Nd isotopic evidence for separate hot depleted and Iceland plume mantle sources for the Paleogene basalts of the Faroe Islands [J]. *Chem. Geo*. **178**, 95–125.

Hooper P.R. and Hawkesworth C.J. (1993) Isotopic and geochemical constraints on the origin and evolution of the Columbia River Basalt [J]. *J. Petrol*. **34**, 1203–1246.

Jason R.A., Gary M.T., Zhou Meifu, and Song Xieyan (2005) Emeishan large igneous province, SW China [J]. *Lithos*. **79**, 475–489.

Ludwig K.R. (2001) *Isoplot/Ex, rev. 2.49: A Geochronological Toolkit for Microsoft Excel* [C]. Berkeley Geochronological Center, Special Publication, **1**, 58.

Mantovani M.S.M. and Hawkesworth C.J. (1990) An inversion approach to assimilation and fractional crystallization processes [J]. *Contrib. Mineral. Petrol*. **104**, 289–302.

Marques L.S., Dupré B., and Piccirillo E.M. (1999) Mantle source compositions of the Paraná Magmatic Province (southern Brazil): Evidence from trace element and Sr-Nd-Pb isotope geochemistry [J]. *J. Geodynamics*. **28**, 439–458.

Peate D.W. and Ole S. (2003) Pb isotope evidence for contributions from different Iceland mantle components to Palaeogene East Greenland flood basalts [J]. *Lithos*. **67**, 39–52.

Pegram W.J. (1990) Development of the continental lithospheric mantle as reflected in the chemistry of the Mesozoic Appalacbhian tholeiites [J]. *Earth Planet. Sci. Lett*. **97**, 316–331.

Raphaël P., Catherine D., Christian C., Gezahegn Y., and Bernard M. (1999) Isotopic and trace element signatures of Ethiopian flood basalts: Evidence for plume-lithosphere interactions [J]. *Geochimica. Cosmochimica. Acta*. **63**, 2263–2279.

Richard M.A., Duncan R.A., and Courtilor V.E. (1989) Flood basalts and hot-spot tracks: Plume heads and tails [J]. *Science*. **246**, 103–107.

Rogers N., Macdonald R., Fitton J.G., George R., Smith M., and Barreiro B. (2000) Two mantle plumes beneath the East African rift system: Sr, Nd and Pb isotope evidence from Kenya Rift basalts [J]. *Earth Planet. Sci. Lett*. **176**, 387–400.

Saunders A.D. and Tarney J. (1984) Geochemical characteristics of basaltic volcanism within back-arc basins. In *Marginal Basin Geology* (eds. B.P. Kokelaar and M.F. Howells) [M]. pp.59–76. Spec. Publ. Geol. Soc. London.

Sun S.S. (1980) Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs [C]. *Phil. Trans. R. Soc. Lond*. **A297**, 409–445.

Taylor P.N., Jones N.W., and Moorbath S. (1984) Isotopic assessment of relative contributions from crust and mantle sources to magma genesis of Precambrian granitoid rocks [C]. *Phil. Trans. R. Soc. Lond*. **A310**, 605–625.

Trua T., Deniel C., and Mazzuoli R. (1999) Crustal control in the genesis of Plio-Quaternary bimodal magmatism of the main Ethiopian rift (MER): Geochemical and isotopic (Sr, Nd, Pb) evidence [J]. *Chem. Geol*. **155**, 201–231.

Wang Yunliang, Li Juchu, Zhou Rongsheng, Wang Wangzhang, Tong Chunhan, and Xiong Shunhua (1993) *Principle on Trace Element Geochemistry of Igneous Rocks and Its Applications and Demonstration of the Petrogenesis of Emeishan Basalts* [M]. Chengdu University of Science and Technology Press, Chengdu (in Chinese).

Wang Yunliang, Zhang Chengjiang, and Xiu Shumin (2001) Th/Hf-Ta/Hf indentification of tectonics setting of basalts [J]. *Acta Petrologica Sinica*. **17**, 413–421 (in Chinese with English abstract).

Weaver B.L. and Tarney J. (1984) Empirical approach to estimating the composition of the continental crust [J]. *Nature*. **310**, 575.

Wooden J.L., Czamanske G.K., Fedorenko A.V., Arndt N.T., Chauvel C., Bouse R.M., King B-S. W., Knight R.J., and Siems D.F. (1993) Isotopic and trace element constraints on mantle and crustal contributions to Siberian continental flood basalts, Noril'sk area, Siberia [J]. *Geochim. Cosmochim. Acta*. **57**, 3677–3704.

Xiao Long, Xu Yigang, Mei Houjun, Zheng Yunfu, He Bin, and Franco Pirajno (2004) Distinct mantle sources of low-Ti and high-Ti basalts from the western Emeishan large igneous province, SW China: Implications for plume-lithosphere interaction [J]. *Earth Planet. Sci. Lett*. **228**, 525–546.

Xu Yigang, Chung Sunlin, Jahn Borming, and Wu Genyao (2001) Petrologic and geochemical constraints on the petrogenesis of Permian-Triassic Emeishan flood basalts in southwestern China [J]. *Lithos*. **58**, 145–168.

Xu Yigang and Chung Sunlin (2001) The Emeishan large igneous province: Evidence for mantle plume activity and melting condition [J]. *Geochimica*. **30**, 1–9 (in Chinese with English abstract).

Zhang Zhaochong and Wang Fusheng (2003) Sr, Nd and Pb isotopic characteristics of Emeishan basalt province and discussion on their source region [J]. *Earth Science—Journal of China University of Geosciences*. **28**, 431–439 (in Chinese with English abstract).

Zhang Zhenliang, Huang Zhilong, Guan Tao, Yan Zaifei, and Gao Derong (2005) Study on the multi-sources of ore-forming materials and ore-forming fluids in the Huize lead-zinc ore deposit [J]. *Chinese Journal of Geochemistry*. **24**, 243–252.

Zindler A. and Hart S.A. (1986) Chemical geodynamics [J]. *Ann. Rev. Earth Planet. Sci*. **14**, 493–71.