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Notes

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ABSTRACT

The Emeishan flood volcanism that erupted at Permian-Triassic boundary time produced a large igneous province of at least 2.5 × 10^5 km^2 in the western margin of the Yangtze craton, southwestern China. The volcanic successions, suggested to have resulted from a starting mantle plume, comprise thick piles of basaltic flows and subordinate picrites and pyroclastics. The picrites, which have high magnesian contents (MgO ≃ 20–16 wt%), variable degrees of light rare earth element enrichment [$(Ce/Yb)_N$ ≃ 4–25] and heterogeneous isotope ratios [$\varepsilon_{Nd}(T)$ ≃ +4 to −4], are proposed to have been generated by mixing between the dominant plume-derived magmas and small amounts of lamproitic liquids from the continental lithospheric mantle.

INTRODUCTION

Large igneous provinces (LIPs; Coffin and Eldholm, 1994), characterized by voluminous volcanic sequences erupted in a short period of time, are believed to be linked genetically with mantle plume activities (Richards et al., 1989; Campbell and Griffiths, 1990). Examples of LIPs include continental flood basalt provinces and oceanic plateaus. Continental flood basalts commonly have trace element and radiogenic isotope compositions that are outside the range of plume sources defined by oceanic island basalts. In cases where crustal contamination can be excluded, many studies suggest that the lithospheric mantle plays a significant role, in addition to plume materials from the deep mantle, in continental flood volcanism (e.g., Ellam and Cox, 1991; Saunders et al., 1992). However, arguments against an important lithospheric mantle contribution (McKenzie and Bickle, 1988; Arndt and Christensen, 1992) have also been advocated.

The relation between the composition of mantle melts, degree of partial melting, and temperature of mantle sources has been much discussed (cf. McKenzie and Bickle, 1988). Generally, in areas where a hot mantle plume rises, as occurs in many LIPs, the degree of melting would be greater and the parental melt can be picritic. Such high-magnesian liquids could not only provide constraints on defining geochemical characteristics of the plume source region (Campbell and Griffiths, 1990), but could also be used to evaluate the role of plume-lithosphere interaction (Ellam et al., 1992; Saunders et al., 1992).

In this paper we report new geochemical and Sr-Nd isotope data of picrites from the Emeishan flood basalt province, an important LIP in southwestern China not yet well recognized by the international geological community. These high-Mg rocks show heterogeneous enrichment in the incompatible trace elements, similar to those observed in the Nuanetsi picrites of the Karoo province (South Africa) (Ellam and Cox, 1991). We use these data to demonstrate that the lithospheric mantle has played a key role in the generation of Emeishan picritic magmas, which are believed to be parental to the voluminous basaltic rocks related to a mantle plume activity.

BACKGROUND

In China, the Emeishan basalt is generally referred to the Permian-Triassic massive volcanic successions in the western margin of the Yangtze craton. These volcanic rocks unconformably overlie early Late Permian carbonate formations (i.e., the Maokou Limestone) and are covered by Triassic sedimentary sequences. They crop out dis-

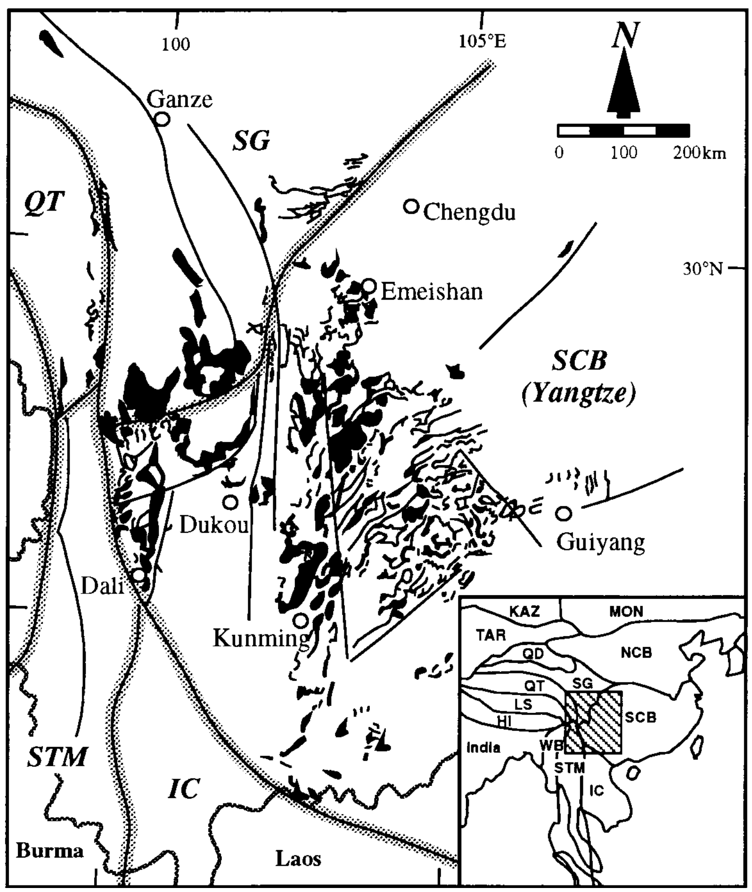

Figure 1. Generalized map showing outcrops of Emeishan flood basalts (black areas) as well as contemporaneous massive basalts (also in black) emplaced in Songpan-Ganze and Qiangtang terranes. Lines mark boundaries of and inset illustrates distribution of major terranes in China and adjacent regions (Huang et al., 1992). HI = Himalaya; IC = Indochina; KAZ = Kazakhstan; LS = Lhasa; MON = Mongolia; NCB = North China block; QD = Qaidam; QT = Qiangtang; SCB = South China block; SG = Songpan-Ganze accretionary complex; STM = Shan-Thai-Malay; TAR = Tarim; WB = West Burma.

TABLE 1. CHEMICAL AND ISOTOPIC COMPOSITIONS OF EMEISHAN PICRITES

	EM-55	EM-56	EM-57	EM-58	EM-70	EM-79	EM-83
Major elements (wt%)							
SiO_2	45.02	44.23	45.30	45.32	45.18	43.90	44.28
TiO_2	2.77	2.46	2.61	2.60	2.14	1.32	1.77
Al_2O_3	7.82	7.42	7.66	7.62	6.41	7.73	9.25
Fe_2O_3*	13.64	13.25	13.64	13.51	12.21	13.75	12.78
MnO	0.19	0.18	0.19	0.18	0.16	0.20	0.17
MgO	16.56	18.51	17.79	17.83	19.78	19.19	15.98
CaO	8.88	7.98	8.59	8.50	9.04	10.30	9.71
Na_2O	1.38	1.07	1.50	1.27	1.05	0.79	1.21
K_2O	0.90	0.97	0.84	0.97	0.12	0.74	0.44
P_2O_5	0.23	0.22	0.22	0.22	0.24	0.09	0.15
L.O.I.	2.40	2.71	1.56	1.87	2.49	0.49	2.67
Mg number*	72.8	75.5	74.2	74.4	78.1	75.4	73.3
Trace elements (ppm)							
Rb	19	22	17	18	2	21	12
Ba	336	927	279	459	45	113	172
Th	3.9	2.8	3.3	3.1	5.3	0.7	1.7
U	0.7	0.5	0.7	0.6	1.1	0.2	0.3
Nb	28	22	27	27	34	9	14
Ta	1.9	1.2	1.7	1.6	1.9	0.6	0.6
Sr	429	367	454	444	229	231	148
Zr	168	151	161	162	181	72	112
Hf	4.4	4.3	4.4	4.2	4.9	2.1	2.6
Y	22	21	21	21	15	13	21
V	302	241	286	284	226	258	309
Ga	16	15	15	16	13	13	15
Cu	141	117	126	135	103	145	197
Zn	100	94	100	100	74	110	95
Sc	28	n.d.	26	27	n.d.	n.d.	n.d.
Co	69	77	74	73	73	82	72
Ni	713	901	795	784	1004	794	828
Cr	1344	1457	1534	1436	1906	1590	1717
La	31.1	25.7	27.6	26.9	42.0	8.4	15.3
Ce	64.2	55.2	58.3	56.6	87.5	19.2	32.3
Nd	32.2	28.22†	30.36†	30.33†	41.11†	11.53†	19.43†
Sm	6.93	5.698†	6.202†	6.223†	7.356†	2.819†	4.369†
Eu	1.98	1.75	1.89	1.86	1.74	0.85	1.25
Tb	0.87	0.76	0.81	0.79	0.90	0.51	0.57
Yb	1.62	1.30	1.60	1.53	0.98	1.40	1.50
Lu	0.21	0.20	0.17	0.19	0.13	0.13	0.20
Isotope ratios							
$^{87}Sr/^{86}Sr$	0.70497	0.70501	0.70480	0.70488	0.70647	0.70586	0.70541
I_{Sr} (250 Ma)	0.70451	0.70439	0.70441	0.70446	0.70638	0.70492	0.70458
$^{143}Nd/^{144}Nd$	0.51260	0.51261	0.51259	0.51267	0.51229	0.51276	0.51268
ε_{Nd} (250 Ma)	1.4	1.7	1.5	2.8	-4.0	4.0	2.8

Note: Elemental determinations, except where marked, were made by XRF at Université de Rennes and by INAA at National Taiwan University. The analytical uncertainties are generally better than 5% for the XRF and 5-15% for the INAA. Isotope measurements were made by a Finnigan MAT262 at Université de Rennes. The two standard errors are less than 0.00001 for both Sr and Nd isotope ratios, which are reported relative to $^{87}Sr/^{86}Sr = 0.71020$ for NBS987 and $^{143}Nd/^{144}Nd = 0.511860$ for La Jolla, respectively. n.d. = not determined.

* Total iron as Fe_2O_3; Mg number = molecular proportion of MgO/(MgO+FeO), calculated by assuming FeO = 0.9 x total FeO.

† Concentrations determined by isotope dilution at Université de Rennes.

persed in a rhomb-shaped province of ~500 × 500 km^2 (Fig. 1) via block faulting probably active since the Early Jurassic, a process that also exposed the associated intrusive rocks in many localities. The thickness of the entire volcanic sequence varies from ~5 km in the west to a few hundred metres in the east. It consists mainly of basaltic lavas and subordinate amounts of picrites and pyroclastic rocks. In addition, thick flows and tuffs of trachyte and rhyolite composition form an important member in the upper sequence (Huang, 1986; Chung and Jahn, 1993). These acidic eruptions are suggested to have produced the Permian-Triassic boundary clay and ash beds widespread in South China (Chung et al., 1995); zircons from the ash beds have been dated by the sensitive high mass-resolution ion microprobe (SHRIMP) ion probe method, which yielded a magmatic age of 251.2 ± 3.4 Ma (Claoué-Long et al., 1991). All of the massive volcanic successions may have been emplaced in a short time period, similar to the Siberian Traps at ~250 Ma (Campbell et al., 1992), a time coincident with a major extinction event. We (Chung and Jahn, 1993) therefore proposed that the Emeishan flood basalt province resulted from a starting mantle plume (Campbell and Griffiths, 1990) in Permian-Triassic time, when the South China block was drifting near the equator (Huang et al., 1992).

EMEISHAN PICRITES

In the Emeishan province, mafic volcanic rocks show a wide range of major element abundances ($SiO_2 \simeq$ 43–56 wt%; MgO $\simeq$ 4–11 wt%) and various degrees of enrichment in the incompatible trace elements (Huang, 1986). Most basalts are evolved, with MgO < 7 wt%, and are believed to be differentiated from picritic parental magmas. The picrites studied in this paper were collected in two locations near the Dukou area (Fig. 1), where the volcanic sequence is 1–2 km thick. Samples of the first location (EM-55 to EM-58) are from different levels of a 50-m-thick flow; those of the second location (EM-70, EM-79, and EM-83) are from three separate thin flows intercalated with basaltic lavas. As shown in Table 1, all these rocks have high magnesian (MgO $\simeq$ 20–16 wt%) and low aluminum ($Al_2O_3 \simeq$ 6.4–9.3 wt%) and calcium (CaO $\simeq$ 8.0–10.3 wt%) contents. They are marked by variable degrees of enrichment in the very incompatible trace elements, a characteristic shared with the associated basalts. In addition, the increase of light rare earth element (REE) enrichment [$La_N \simeq$ 12–60, $(Ce/Yb)_N \simeq$ 4–25; normalized to primitive-mantle values of Sun and McDonough, 1989] is coupled with a decrease of heavy REE abundances ($Yb_N \simeq$ 3–2) and a slight Nb-Ta depletion [e.g., $(Nb/La)_N \simeq$ 1.03–0.78]. Some mobile elements, such as Rb, Ba, and K, however, may have been affected by secondary alteration processes. For example, sample EM-70 displays unusually low abundances of these elements but is highly enriched in the light REEs and other very incompatible elements.

The initial ε_{Nd} values and $^{87}Sr/^{86}Sr$ ratios of the picrites, i.e., $\varepsilon_{Nd}(T)$ and $(^{87}Sr/^{86}Sr)_i$, calculated for 250 Ma, range from +4 to −4 and 0.7044 to 0.7064, respectively (Table 1). They plot inside the field defined by Emeishan basalts, a field that is grossly comparable to oceanic island basalts (Fig. 2A). The Emeishan field is more restricted than fields for the Siberian Traps (Wooden et al., 1993) and other continental flood basalts worldwide. We prefer to use only $\varepsilon_{Nd}(T)$ values rather than a combination with $(^{87}Sr/^{86}Sr)_i$

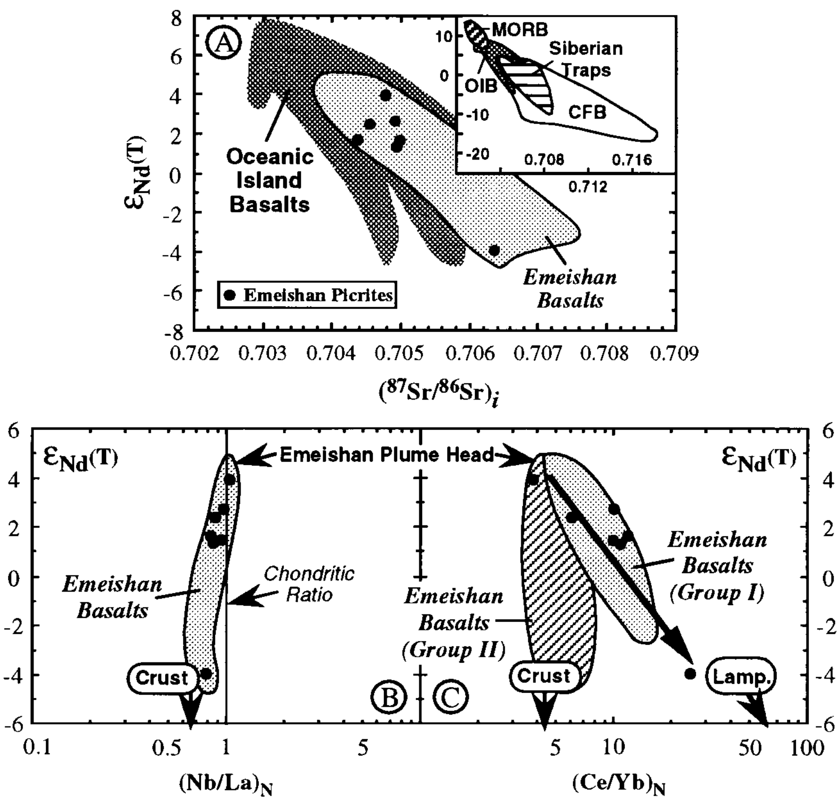

Figure 2. Plots of ε_{Nd}(T) vs. (A) $(^{87}Sr/^{86}Sr)_i$, (B) $(Nb/La)_N$, and (C) $(Ce/Yb)_N$ for Emeishan picrites. In A, fields for Emeishan basalts, oceanic island basalts (OIB), Siberian basalts, and continental flood basalts (CFB) worldwide (inset; Wooden et al., 1993) are compared (MORB = mid-ocean ridge basalt). B and C: Both suggested contaminants of Emeishan basalts, i.e., upper continental crust (Taylor and McLennan, 1985) and olivine lamproites (Jaques et al., 1989), have ε_{Nd} values that would be far below lower margin of diagram, as indicated by arrows. Note that two subgroups of basalts can be distinguished, and picrites are in group I trend, marked by distinctly elevated Ce/Yb ratios.

ratios in our petrogenetic discussion, because the latter might have been more or less shifted by secondary alteration. For the following reasons all these picrites are regarded as primary mantle melts. (1) Some samples (e.g., EM-70 and EM-83) have fine-grained textures, with euhedral, isolated, simple olivine phenocrysts; no large olivine crystals are observed. In other samples, with large olivine crystals (EM-55 and EM-56), the rather homogeneous core compositions (Fo_{87}–Fo_{91}) argue for their chemical equilibrium with the whole-rock Mg numbers (72.8–78.1; Table 1), according to the Mg-Fe exchange coefficient between olivine and melt (Roeder and Emslie, 1970). (2) There is a good correlation between isotope ratios and trace element systematics for the picrites, as shown in the ε_{Nd}(T) vs. $(Ce/Yb)_N$ plot (Fig. 2C). The picrite with the least light-REE enrichment (EM-79) shows the highest ε_{Nd}(T) value and does not display Nb-Ta depletion. By contrast, the one with the greatest light-REE enrichment (EM-70) has the lowest ε_{Nd}(T) value and a negative Nb-Ta anomaly (Fig. 2B). This is more likely caused by binary magma mixing than by olivine accumulation (see discussion below).

DISCUSSION

The Emeishan basalts can be divided into two subgroups, each with specific elemental and isotopic features. As shown, the group I basalts reveal a covariance in plots of ε_{Nd}(T) vs. $(Ce/Yb)_N$, whereas Ce/Yb ratios are nearly constant for the group II basalts within the ε_{Nd}(T) range of +5 to −5 (Fig. 2C). This separation indicates that there must have been at least two distinct processes involved in the basalt generation. In both cases, the primary plume-derived melts can be represented by the least enriched picrite sample EM-79, the geochemical characteristics of which are comparable to those of some picrites from the Siberian Traps (Wooden et al., 1993) and the high-Mg Icelandic basalts (Elliott et al., 1991). We consider its ε_{Nd}(T) value of +4 to be indicative of the average isotope composition for the Emeishan plume head. This is supported by the associated basalts with similar elemental characteristics, which show coherent isotope ratios of ε_{Nd}(T) from +4 to +5 (Fig. 2). This coherency may be interpreted as a result of compositional mixing of partial melts from the plume head, which, following the dynamic mantle plume model of Campbell and Griffiths (1990), is made up of the deep plume source and overlying mantle materials entrained during its ascent.

Considering the upper continental crust to be a potential contaminant (Fig. 2C), the group II Emeishan basalts can be explained as products of combined crystal fractionation and crustal assimilation processes from the parental magmas. However, this explanation fails to satisfy the requirement of the group I basalts and picrites, which need a mixing component with low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ratios, strong enrichment in the light REEs and other very incompatible elements, and a mild Nb-Ta depletion as well (Fig. 2). The broad similarity of elemental patterns between the enriched Emeishan picrites and olivine lamproites from Western Australia (Fig. 3) implies that the component may be a lamproitic melt derived from a continental lithospheric mantle source (Nelson et al., 1986; Jaques et al., 1989). Lamproitic rocks commonly have high Mg numbers and very low abundances of Al_2O_3, CaO, Y, and heavy REEs, characteristics also revealed by the picrite samples (Table 1). Consequently, we propose that the Emeishan picrites were formed by mixing of two end members: these are (1) the large amount of liquid caused by decompression melting of the plume head, and (2) the small-volume lamproitic melt derived from the lithospheric mantle. If Western Australian olivine lamproites are taken to represent the latter, the most enriched Emeishan picrite can be generated by a 9:1 mixing of the two proposed components. The incorporation of ~10% lamproitic melt accounts for not only the drastic enrichment of the very incompatible elements but also the minor Nb-Ta depletion (Fig. 3).

Our model may encounter some difficulties in regard to melting of the mantle lithosphere beneath continents, as argued by Arndt and Christensen (1992), because the lithospheric mantle is generally considered to be refractory and cold, ~300 °C below its melting point at a given depth. However, this can be circumvented if the continental lithospheric mantle source region has undergone hydrous metasomatism. Metasomatized mantle peridotites may accommodate small amounts of water, which would significantly lower their solidus temperature and probably induce dehydration melting (Gallagher and Hawkesworth, 1992). We

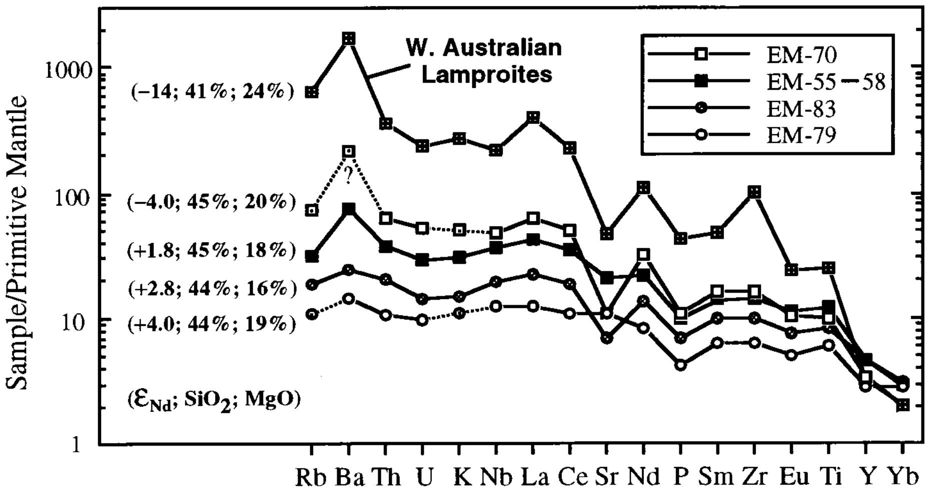

Figure 3. Primitive-mantle normalized diagram for Emeishan picrites and olivine lamproites from Western Australia (Jaques et al., 1989). Average composition of samples EM-55–EM-58 from one single flow is plotted. For reference, $\varepsilon_{Nd}(T)$ values and SiO_2 and MgO contents are also given. Alteration is suggested to have resulted in change of concentrations of mobile elements, such as loss of Rb and K in sample EM-70. However, it may also cause addition of Rb and K because of formation of secondary micas in EM-79. In both cases, Rb and K abundances are simply illustrated by extrapolation (Rb) and interpolation (K). Ba spike of sample EM-70 is hypothesized by mimicking that of samples EM-55–EM-58. Normalizing values of primitive mantle are from Sun and McDonough (1989).

believe that the lower part of the metasomatized lithospheric mantle, if thermally reactivated, can be a suitable source for the generation of lamproitic melts, which in turn may serve as a contaminant to the plume-derived magmas (Ellam and Cox, 1991; Saunders et al., 1992).

CONCLUSIONS

The Emeishan basalt province is considered to have resulted from a starting mantle plume at the time of the Permian-Triassic boundary. The geochemical and isotopic evidence provided by the picrites studied supports the idea that the lithospheric mantle can play an important role in continental flood volcanism. The Karoo picrites are thought to have been produced by a similar process, i.e., plume-derived magmas mixed by lamproitic melts of lithospheric mantle origin in even greater (up to 50%) proportions (Ellam et al., 1992). Nevertheless, alternative models are necessary to reconcile the wide range of geochemical data for other continental LIPs (cf. Saunders et al., 1992). Future studies of different rock types in the Emeishan province, particularly the alkalic rocks emplaced before the massive basalt eruptions (Huang, 1986), should better demonstrate the complexity of plume-lithosphere interaction in continental flood magmatism.

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