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Origin of two differentiation trends in the Emeishan flood basalts

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Abstract **Both the Bowen and Fenner differentiation trends have been recognized in the Emeishan flood basalts. While the Longzhoushan lavas in Panxi paleorift evolved on a trend of silica enrichment (Bowen trend), the lavas from Guizhou evolved along the Fenner trend leading to the magmas with high Fe_2O_3 (23%) and low SiO_2 (44%) contents. This provides evidence for the existence of Fe-rich and Si-poor magmas in nature. Such contrasting differentiation trends, marked by different timing of crystallization of Fe-Ti oxides, are correlated with the extent of crustal contamination of the magmas. Limited crustal contamination in the Guizhou lavas is coupled with the low oxygen fugacity which delayed the onset of magnetite crystallization. In contrast, significant involvement of crustal components in the Longzhoushan lavas increased f_{O_2} which in turn triggered early crystallization of magnetite. The close spatial association between the Longzhoushan lavas and the synchronous V-Fe-Ti deposit-bearing layered intrusions suggests a potential relationship between them.**

Keywords: basalts, differentiation, crustal contamination, Fe-rich magma, Emeishan large igneous province.

Tholeiitic magma could evolve to either silica-rich and iron-poor rhyolitic products (the Bowen trend)[1] or iron-rich and silica-poor products (the Fenner trend)[2]. The difference between the two trends is controlled by the onset of magnetite fractionation, which is in turn controlled by oxygen fugacity[3]. Increasing f_{O_2} will stabilize the magnetite field in basaltic systems, causing marked Si enrichment and Fe depletion in residual liquid[3,4]. In contrast, low oxygen fugacity delays the onset of magnetite crystallization leading to prolonged Fe-enrichment in magma[5]. In the natural system, the Bowen differentiation is common in many large igneous provinces (LIP)[6], whereas the Fenner trend and Fe-rich magma (FeO_{total} > 20 wt%) are rather rare. One of type examples of the Fenner trend is the differentiation of the Skaergaard intrusion which included extreme iron enrichment (FeO_{total} >20 wt%) but no silica enrichment ($SiO_2 \approx 45$ wt%) until the very late stages of magma evolution[7,8]. However, the classic interpretation of Wager (1960)[7] has been questioned by Hunter and Sparks (1987)[6] who argued that iron enrichment versus silica depletion trend appears to be difficult to correlate with the low SiO_2 contents (44%—46%) in the crystallization products of the gabbroic assemblage. They questioned the existence of high Fe-rich, Si-poor basalts in nature and suggested that the Skaergaard magma evolved on a trend of pronounced silica enrichment similar to that observed among volcanic suites in Iceland.

Much discussion and subsequent works have been stimulated on the differentiation of the Skaergaard intrusion and on the evolution of tholeiitic magmas in general[4,5,9—12]. So far, most of highly Fe-enriched compositions containing up to 18—19 wt% FeO_{Tot} are indirectly inferred from cumulated layers or documented in basaltic glasses at divergent plate margin[12]. The volcanic equivalent of these Fe-rich and Si-poor magmas is very rare in the continental volcanic terrains[6]. Here, we report the Fenner and Bowen trends observed in the late Permian Emeishan flood basalts, SW China. The coexistence of the two trends in the same continental LIP is not common. In particular, some tholeiitic basalts from Guizhou have total Fe_2O_3 content as high as 23% and SiO_2 as low as 44%, confirming the existence of Fe-rich and Si-poor magmas in nature. Comparison of X_{Mt} in magnetite and identification of crustal components in magma suites highlight the role of oxygen fugacity and crustal contamination in the differentiation of tholeiitic magmas. Ubiquitous crustal contamination in the continental flood basalts explains the scarcity of the Fe-rich and Si-poor magmas in the continental setting. Finally, implication of the spatial relationship between differentiation trends in erupted magmas and V-Fe-Ti deposit-bearing layered intrusions in the Emeishan basaltic province is discussed.

1 Geological setting and samples

The Emeishan basalts are widely spread in Yunnan, Sichuan and Guizhou provinces, covering an area of over 250000 km^2. It is a pertinent LIP in China[13]. Stratigraphic studies and limited Ar-Ar dating results of the basaltic lavas and associated intrusives show that the Emeishan basalts were emplaced during the late Permian. No radiometric data about eruption duration and eruption rate are available. However, the lack of thick sedimentary piles or paleosols within the volcanic sections and magnetostratigraphic studies suggest a short eruption period of the entire sequence. It has been argued on the basis of REE inversion on the mafic basalts and nature of primary magmas that the Emeishan traps was formed by a mantle plume head[13—15].

Significant variation in thickness of volcanic successions has been noted in the Emeishan LIP. For instance, the thickness varies from over 5000 m in the west (i.e. Binchuan, Yunnan Province) to several hundred meters in the east (i.e. in Guizhou Province). Over 150 samples forming the objective of this study were collected from Longzhoushan (26°5′N/102°0′E) in Sichuan and Duge (26°4′N/104°7′E), Xianglushan (26°5′N/104°2′E) and Zhijin (26°5′N/105°7′E) in Guizhou (Fig. 1). The Longzhoushan volcanic sequence is located within the Panxi palaeo-rift system, and is temporally and spatially associated with the V-Ti-Fe ore deposit-bearing mafic-ultramafic intrusions in rift zone[16]. The latter three sections are located in the east part of the Emeishan LIP. Representative of the samples is ensured by systematic sampling of lava flows with control of different stratigraphic heights (Fig. 1). Major element compositions were determined using the Philips PW1400 X-ray fluorescence spectrometer at Taiwan University, on glass discs. Bulk-rock trace element data were obtained by the inductively coupled plasma-mass spectrometry at Guangzhou Institute of Geochemistry, the Chinese Academy of Sciences. Mineral

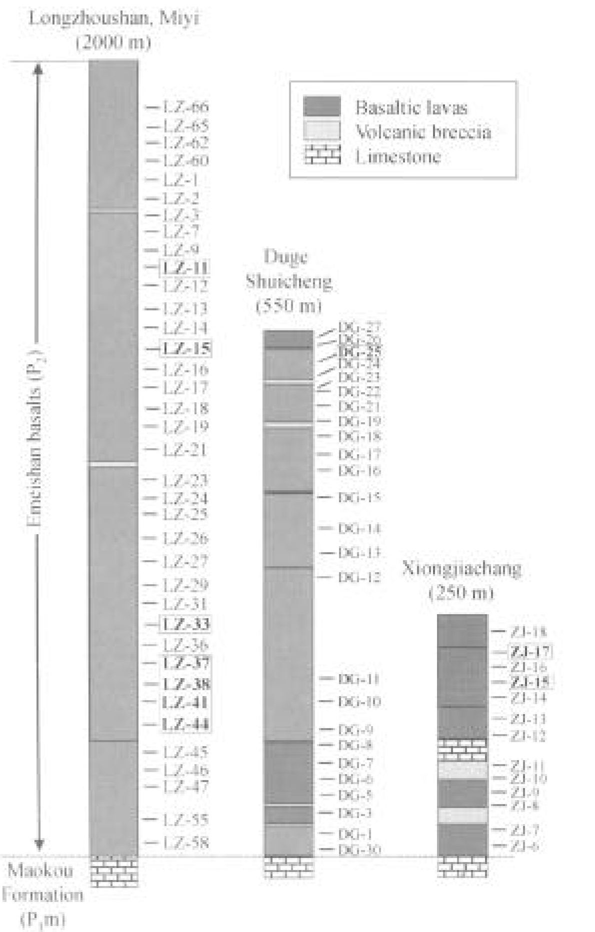

Fig. 1. Diagram showing composite stratigraphic columns at Longzhoushan (Sichuan Province) and Duge and Xiongjiachang (Guizhou Province) and relative stratigraphic locations of studied samples in the volcanic sections. Strongly differentiated, high Fe-Ti samples (outlined with box) are located at the upper part of lava sequence in Guizhou Province, but occur in the middle part of lava section at Longzhoushan.

chemistry was determined using a JOEL Superprobe at Nanjing University equipped with a four-wavelength dispersive electron microanalyzer. Representative analyses are listed in Table 1.

2 Differentiation trends

Samples from Longzhoushan and Guizhou display significantly different trends of the late stage of magma differentiation (Fig. 2). Fe and Ti contents in the Longzhoushan lavas remain roughly constant when MgO varies between 6%—11%, then increase rapidly when MgO decreases from 6% to 4% (Fig. 2(a)). The Fe_2O_3 and TiO_2 contents decrease, SiO_2 increase rapidly toward the felsic rocks (Fig. 2(b)). This fractionation trend (i.e. Bowen trend) is similar to those observed in worldwide continental volcanic regions, and can be attributed to a variable amount of crystallization of olivine, clinopyroxene, plagioclase and Fe-Ti oxides. The inferred fractionating assemblage (olivine → clinopyroxene+plagioclase → Fe-Ti oxides + apatite) with decreasing temperature is consistent with experimental results[4]. The most differentiated lavas occur in the middle part of lava section at Longzhoushan and are sandwiched by less differentiated lavas.

Unlike the fractionation trend observed at Longzhoushan, the TiO_2 content in the Guizhou lavas increases rapidly when MgO decreases from 6% to 4%, and continues to increase but at a lower rate when MgO is low (Fig. 2(a)). This differentiation trend (i.e. Fenner trend) results in the formation of magmas extremely rich in Fe_2O_3 (23%) and TiO_2 (5%), but poor in SiO_2 (44%) (Table 1, Fig. 2). It is noted that these strongly differentiated, high Fe-Ti samples are located at the upper part of lava sequence (Fig. 1) and contain no phenocrysts of Fe-Ti oxides. Therefore, the high Fe-Ti contents cannot be attributed to accumulation of Fe-Ti oxides, but more likely reflect the compositions of liquidus magmas at final fractionation stage. Such a liquid is compositionally similar to that proposed for the Skaergaard intrusion[5].

3 Cause of compositional divergence

As shown in Fig. 2, the differentiation trends at MgO > 4% are essentially similar for the two lava suites in the Emeishan basalts and the compositional divergence occurs at MgO of ~4%. Titanomagnetite and ilmenite become liquidus phases in the Longzhoushan lavas at MgO of ~4%, leading to the Fe-Ti depletion and Si enrichment in residual melts. These minerals, however, do not appear as liquidus phases in the Guizhou lavas throughout the entire course of fractionation, because of the general absence of magnetite and ilmenite phenocrysts in these lavas. Thus, the compositional divergence observed in the Emeishan basalts is likely related to the timing of onset of Fe-Ti oxide fractionation. A number of experiments have demonstrated the influence of oxygen fugacity on the behavior of Fe-Ti oxides during the magma differentiation[3,4]. The contrasting oxygen fugacity is thus expected for the

Table 1 Representative major (%) and trace element (μg/g) analyses of the Emeishan flood basalts

	Longzhoushan				Guizhou			
	LZ-50	LZ-66	LZ-17	LZ-11	ZJ-7	ZJ-15	DG-18	DG-25
SiO_2	47.66	49.56	51.42	60.54	49.69	47.19	49.72	44.48
TiO_2	3.63	4.01	1.32	0.46	4.31	5.23	2.03	4.94
Al_2O_3	9.63	14.45	19.26	21.21	13.39	16.49	14.24	14.25
$(Fe_2O_3)_T$	12.53	13.98	9.76	5.53	15.17	20.78	13.25	23.39
MnO	0.17	0.18	0.18	0.09	0.19	0.10	0.19	0.24
MgO	10.81	4.86	1.98	0.26	4.62	2.48	6.04	2.47
CaO	12.59	9.27	4.73	1.21	8.73	3.14	11.76	3.66
Na_2O	1.24	2.27	7.60	7.26	2.15	4.05	2.26	5.85
K_2O	1.43	1.05	3.09	3.32	1.42	0.02	0.31	0.19
P_2O_5	0.31	0.37	0.64	0.11	0.45	0.52	0.20	0.53
LOI	2.11	0.66	0.41	1.06	0.95	4.90	1.48	2.33
Mg#	0.63	0.41	0.29	0.09	0.38	0.19	0.48	0.17
X_{Mt}	0.45	0.98	0.92	0.87	0.21	0.19	0.19	0.60
Rb	36.5	34.8	91.9	72.3	34.61	0.81	10.30	7.01
Ba	529.1	474.0	846.7	940.9	542.3	229.2	306.2	156.0
Sr	473.0	655.5	708.5	219.0	554.5	184.9	352.4	294.0
Y	23.7	33.6	24.6	29.2	39.5	40.2	28.0	29.6
Zr	292.4	318.9	214.0	395.9	335.7	364.6	142.4	286.3
Hf	8.42	8.80	4.41	8.57	9.28	10.27	3.27	6.15
Nb	41.5	35.1	51.9	71.7	38.16	42.75	14.41	29.55
Ta	2.89	2.45	2.63	3.81	2.62	3.13	0.85	2.01
Th	5.60	6.47	9.53	17.46	6.89	7.71	2.82	5.50
U	1.31	1.68	2.01	3.26	1.77	1.81	0.78	0.65
La	36.9	43.3	35.9	43.2	43.59	45.09	16.98	36.65
Ce	87.0	95.7	66.1	74.7	97.17	105.89	37.24	78.16
Pr	12.4	12.9	7.5	8.0	13.43	14.89	4.85	9.58
Nd	54.28	54.19	27.32	26.23	57.37	63.93	20.70	39.16
Sm	9.96	10.36	4.81	4.46	11.53	12.66	4.50	7.91
Eu	2.93	3.07	1.47	1.02	3.40	3.70	1.43	2.45
Gd	7.24	9.12	4.54	4.01	10.41	11.08	4.82	7.21
Tb	1.07	1.31	0.70	0.69	1.48	1.54	0.76	1.06
Dy	5.30	6.92	4.12	4.33	8.15	8.25	4.57	5.41
Ho	0.91	1.28	0.81	0.91	1.47	1.50	0.89	0.95
Er	2.33	3.37	2.23	2.78	3.91	4.08	2.58	2.45
Tm	0.32	0.48	0.36	0.48	0.56	0.57	0.38	0.34
Yb	1.85	2.71	2.17	3.07	3.24	3.25	2.33	1.95
Lu	0.26	0.39	0.33	0.46	0.45	0.47	0.36	0.29

magma suites from Longzhoushan and Guizhou.

To test this inference, X_{Mt} in magnetite from two lava suites are compared in Fig. 3(a), because X_{Mt} is positively related to oxygen fugacity[4]. The variation in X_{Mt} for the Longzhoushan lavas is somewhat correlated with the differentiation extent (Fig. 3(a)). X_{Mt} gradually increases from 0.50 with the differentiation degree and reaches the maximum (0.99) at MgO = 4%. It then decreases slightly in the very evolved lavas. The maximum f_{O_2} is coeval with magnetite as liquidus phase along the liquid line of ascent, typical of tholeiitic basalts[17]. Such an evolution in oxygen fugacity during fractionation can be explained by variation in fractionating mineral assemblages. Olivine and pyroxene are mainly involved in the early stage of magma fractionation. Because Fe occurs predominantly as Fe^{2+} in these minerals, the residual melts after the crystallization of olivine and pyroxene become enriched in Fe^{3+}. Consequently, the oxygen fugacity increases gradually with crystal fractionation until Fe-Ti oxides become liquidus phases. The oxygen fugacity in the strongly fractionated lavas will decrease as the fractionation of Fe-Ti oxides lowers Fe^{3+} contents in residual magmas.

The evolution of oxygen fugacity in the Guizhou lavas is slightly different from that observed at Longzhoushan (Fig. 3(a)). X_{Mt} in the Guizhou lavas is lower than in the Longzhoushan lavas, suggesting a lower f_{O_2} for the former. The relatively low oxygen fugacity in the Guizhou lavas may have significantly delayed the magnetite crystallization, thereby driving the residual melts towards the extreme Fe-enrichment. It is also noted that, although the oxygen fugacity in the Guizhou lavas reaches the maximum at MgO=4%, it remains roughly unchanged for the lavas with MgO less than 4%. This may be due to the absence of fractionation of Fe-Ti oxides in the late evolution stage of the Guizhou lavas.

It is interesting to note that the contrasting oxygen fugacity in the lavas from Longzhoushan and Guizhou

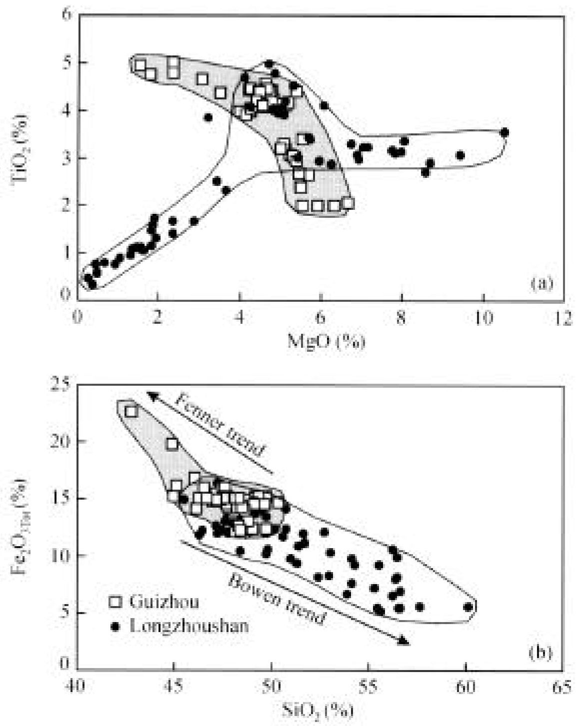

Fig. 2. (a) TiO_2 versus MgO and (b) Fe_2O_3 versus SiO_2 plots for the Emeishan basalts. Open and filled symbols represent samples from Guizhou and Longzhoushan, respectively.

correlates with the extent of crustal contamination of magmas. Most lavas from Guizhou have a Th/Ta ratio around the primitive mantle ratio (2.3; Fig. 3(b)), consistent with the closed-system fractional crystallization of primitive mantle-derived melts. In contrast, the Longzhoushan lavas display variable Th/Ta ratios ranging from 2.3 to 6.7 (Fig. 3(b)). The high Th/Ta ratio in the Longzhoushan lavas may be related to involvement of crustal components in magma genesis. Crustal components may be derived either from the lithospheric mantle[19] or from the continental crust[20]. Crustal components can be introduced into the mantle through subduction and delamination processes. Due to their low melting point, these components can act as contaminants of plume-derived magmas[19]. However, the negative correlation between SiO_2 and Nb/La for the Longzhoushan lavas (Fig. 3(c)) suggests that the assimilation-fractionation-crystallization processes[20] are likely responsible for the high Th/Ta ratio in the Longzhoushan lavas. The continental crust of the Yangtze Craton has Th/Ta as high as 13[21] and is thus the potential contaminant. The crustal contamination model is also supported by recently acquired Os isotopic data (Xu, J. F. et al., unpublished data).

Although the difference in oxygen fugacity in magmas may be that of the source region, the higher oxygen fugacity in crustally contaminated samples than in uncontaminated lavas strongly indicates the ultimate role of crustal contamination in controlling differentiation trend of continental flood basalts. The scarcity of the Fe-rich and Si-poor magmas in continental setting is ascribed in part to the high density of such magmas[22]. Alternatively, this may be due to the ubiquitous crustal contamination in continental flood basalts[23]. Oxygen fugacity increases during crustal assimilation processes, triggering early crystallization of magnetite. Additional support for this suggestion is provided by the observation that reported Fe-rich differentiated liquids are largely found at the divergent plate margin where crust is thin or absent[21].

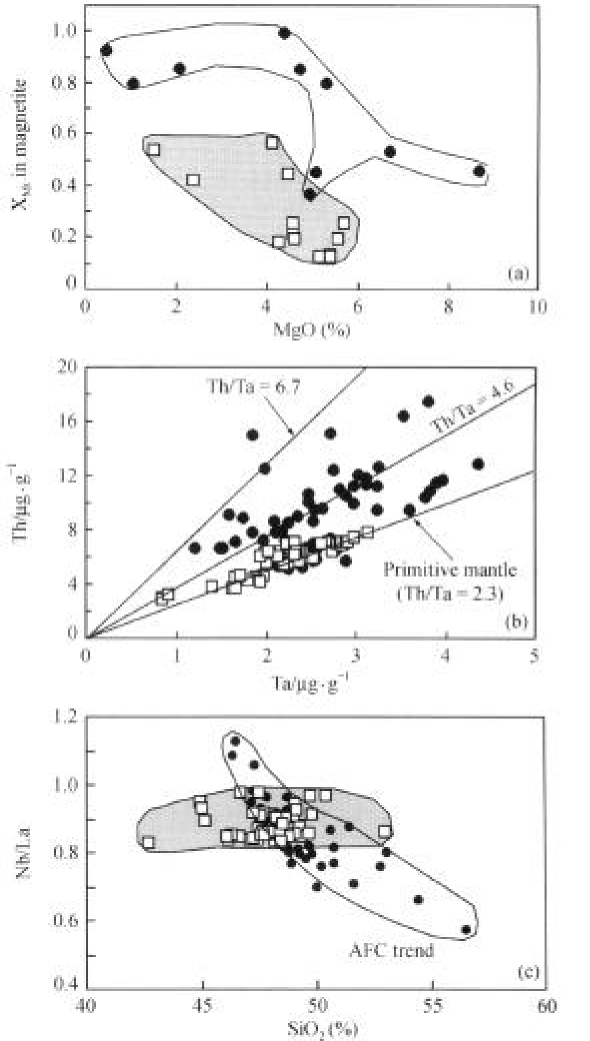

Fig. 3. (a) X_{Mt} in magnetite against MgO content; (b) Ta versus Th; (c) Nb/La against SiO_2 in the Emeishan basalts. Same symbols as in Fig. 2. Th/Ta ratio of primitive mantle is after Sun and McDonough (1989)[18]. The negative correlation in (c) defined by the Longzhoushan lavas is consistent with the AFC style of contamination[20]. Symbols as in Fig. 2.

4 Implications and conclusions

The differentiation trends in the Emeishan basalts show a strong provincial affinity with the Bowen trend occurring in the Panxi paleorift zone and the Fenner trend in the eastern part of the Emeishan LIP. A huge volume of V-Fe-Ti deposits in layered intrusions has been explored at Panzhihua and Hongge which are located proximal to Longzhoushan. In contrast, no Fe-Ti deposit-bearing layered intrusions have been documented to date in the eastern Emeishan LIP. Such a spatial association between magma differentiation trends and mineral deposits has important bearing on the genesis of V-Ti-Fe ores and exploration of similar mineral resources in the region. Recent zircon U-Pb dating shows that the layers at Panzhihua and Xinjie were emplaced at 256—258 Ma[24], consistent with the eruption age of the Emeishan flood basalts constrained on the basis of biostratigraphic studies. This suggests that at least some layered intrusions are roughly synchronous with the Emeishan basalts. Consequently, the fractionation processes involved in the erupted basalts may reflect those of unerupted magmas in depth. In the Panxi paleorift zone, the peculiar lithospheric structure allowed the mantle plume to rise to a very high level. As a consequence, temperature in the crust dramatically increased. Under this circumstance, crustal components were locally mobilized and participated in the evolution of plume-derived magmas. Crustal contamination resulted in the increase of oxygen fugacity, triggering early crystallization of magnetite. Continuous magma replenishment and prolonged fractionation processes ultimately resulted in the formation of giant Fe-Ti ore deposits. If this interpretation is correct, it implies that extreme iron enrichment in tholeiites may not be necessary for the generation of Fe-Ti deposits. Supporting evidence for this argument can be found in the Guizhou lavas. The low oxygen fugacity delayed the appearance of Fe-Ti oxides as liquidus phases in the Guizhou lavas leading to the formation of Fe-rich and Si-poor magmas. This can explain the general absence of large Fe-Ti deposits in Guizhou Province. Some evolved magmas have high Fe_2O_3 (23%) and low SiO_2 (44%) contents, highlighting the existence of Fe-rich and Si-poor magmas in nature. However, such magmas are volumetrically insignificant, probably because the low oxygen fugacity cannot be maintained for a long period in the continental setting.

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