Chemostratigraphy of Flood Basalts in the Garzê-Litang Region and Zongza Block: Implications for Western Extension of the Emeishan Large Igneous Province, SW China

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Abstract The Late Permian Emeishan Large Igneous Province (ELIP) is commonly regarded as being located in the western part of the Yangtze craton, SW China, with an asymmetrical shape and a small area. This area, however, is just a maximum estimation because some parts of the ELIP were not recognized or dismembered and destroyed during the Triassic to Cenozoic tectonism. In this paper, the chemostratigraphical data of the Zongza block, the Garzê-Litang belt and the Songpan-Garzê block suggest that the Late Permian basalts in these areas have remarkable similarities to the ELIP basalts in petrography and geochemistry. Flood basalts in the Sanjiangkou area are composed of the lower part of the low-Ti (LT) tholeiite and the upper part of the high-Ti (HT) tholeiite, which is the same as the flood basalts on the western margin of the Yangtze craton. Flood basalts in the Zongza and Songpan-Garzê areas, which are far from the Yangtze craton, consist of HT tholeiite only. This is the same as the flood basalts within the Yangtze craton. Therefore we argue that these contemporary basalts all originated from the Emeishan mantle plume, and the ELIP could have a significant westward extension with an outcropped area of over 500,000 km^2. This new scenario shows that the LT tholeiite occurs on the western margin of the Yangtze craton, while the HT tholeiite overlying the LT basalts occupies the whole area of the ELIP.

Key words: Emeishan large igneous province, flood basalts, chemostratigraphy, Yangtze craton, Garzê-Litang, Zongza block

1 Introduction

The Emeishan flood basalts in SW China, one of the oldest large Phanerozoic igneous provinces (LIPs), are interpreted as resulting from the impact of mantle plumes at the lithospheric base (Chung and Jahn, 1995; Chung et al., 1998; Song et al., 2001; Xu et al., 2001). Although the plume model is consistent with the petrologic and geochemical signatures of the basalts (Xu et al., 2001; Xu and Chung, 2001) and is supported by crustal doming uplift immediately preceding the eruption of the Emeishan basalts (He et al., 2003), the viability of this model is doubted by some geologists in view of the relatively small surface exposure of the basaltic lavas (~250,000 km^2) in comparison with 1,000,000 km^2 for normal LIPs (Coffin and Eldholm, 1994), and the relatively few volcanic cycles in some localities (Thomposon et al., 2001). However, both petrologic and sedimentological studies suggest that the center of the postulated mantle plume that generated the Emeishan flood basalts (Emeishan Large Igneous Province, ELIP in short) was located in western Yunnan, i.e., the western part of the ELIP (Chung and Jahn, 1995; Xu and Chung, 2001; He et al., 2003; Xiao et al., 2003a). The distribution of plume-derived basalts is expected to be more or less symmetrically distributed around the impact site of the plume (Campbell and Griffiths, 1990). In this sense the asymmetric distribution of the Emeishan basalts implies that its western sectors may have remained unrecognized (e.g. basalts of the Gangdagai Formation in the Zongza block and the Garzê-Litang belt, and basalts of the Dashibao Formation in the Songpan-Garzê block) due to complex deformation and poor exposure of strata, or because they were truncated during the Mesozoic and Cenozoic tectonic movements (e.g. Jinping basalts, Chung et al., 1998; Xiao et al., 2003b; Xiao et al., 2003c). Pearce and Mei (1985) proposed that the basalts on the Songpan-Garzê block is contemporary with the Emeishan basalts. Previous studies (Mo et al., 1993; Chung et al., 1995) suggested that the Zongza micro-block was a part of the Yangtze craton and was rifted away from theis craton in the Late Permian. This implies that the volcanism of the Emeishan mantle plume could have generated voluminous basalts and some of them are exposed in the Zongza micro-block.

This idea can be tested through sedimentary stratigraphic comparison and chemostratigraphic comparison of lava successions in the Zongza block, Garzê-Litang belt and Songpan-Garzê block and in the Yangtze craton. For this purpose, the volcanic successions at Binchuan (typical Emeishan flood basalts), Zhongdian and Sanjiangkou (Gangdagai Formation) in Yunnan Province and at Baoxing (Dashibao Formation) in Sichuan Province (Fig. 1) have been systematically sampled at different stratigraphic levels, or cited from newly available mapping data. The Binchuan section was chosen because previous studies have revealed a considerable compositional diversity of the lavas and because it represents the major rock associations of the ELIP (Xu et al., 2001; Xiao et al., 2003a; Xiao et al., 2003b), thus ensuring the suitability of applying the chemostratigraphic approach to relating tectonically different sectors. This paper presents new geochemical and chemo-stratigraphic data for the Gangdagai and Dashibao basalts from other three major terrains. Our purpose is to attempt to reconstruct the ELIP and better understand its rock types and their spatial distribution. It will be shown that the Gangdagai and Dashibao basalts can be genetically correlated well with those from Binchuan in terms of comparison of their stratigraphic variation, rock types and their chemostratigraphy, although precise chronology study and comparison are required but hard to be obtained. The identification of the Emeishan basalts to the west of the previously defined boundary implies a significantly large exposure area for the former ELIP, and thus the diameter of the head of the ELIP was reappraised.

2 Geologic Setting

The previously defined ELIP is located in the western part of the Yangtze craton, SW China (Fig. 1). Its western boundary is commonly considered as the Longmenshan-Aialoshan fault along the margin of the Yangtze craton. The massive volcanic successions lie uncomfortably on the late Middle Permian Maokou formation and were overlain by the early Late Permian Longtan formation. The preserved ELIP is exposed in a rhombic province of ~250,000 km^2 within Yunnan, Sichuan and Guizhou provinces (Fig. 1). The current western boundary of the Yangtze craton is the Longmenshan-Ailaoshan suture and some parts of the ELIP were dismembered by the sinistral movement of the Ailaoshan-Red River shear zone, or subducted during the closing of the Ailao Shan Ocean (Paleo-Tethys) in the Late Triassic (Chung et al., 1997; Xiao et al., 2003c). The massive volcanic succession has a pronounced variation in lava thickness from west to east

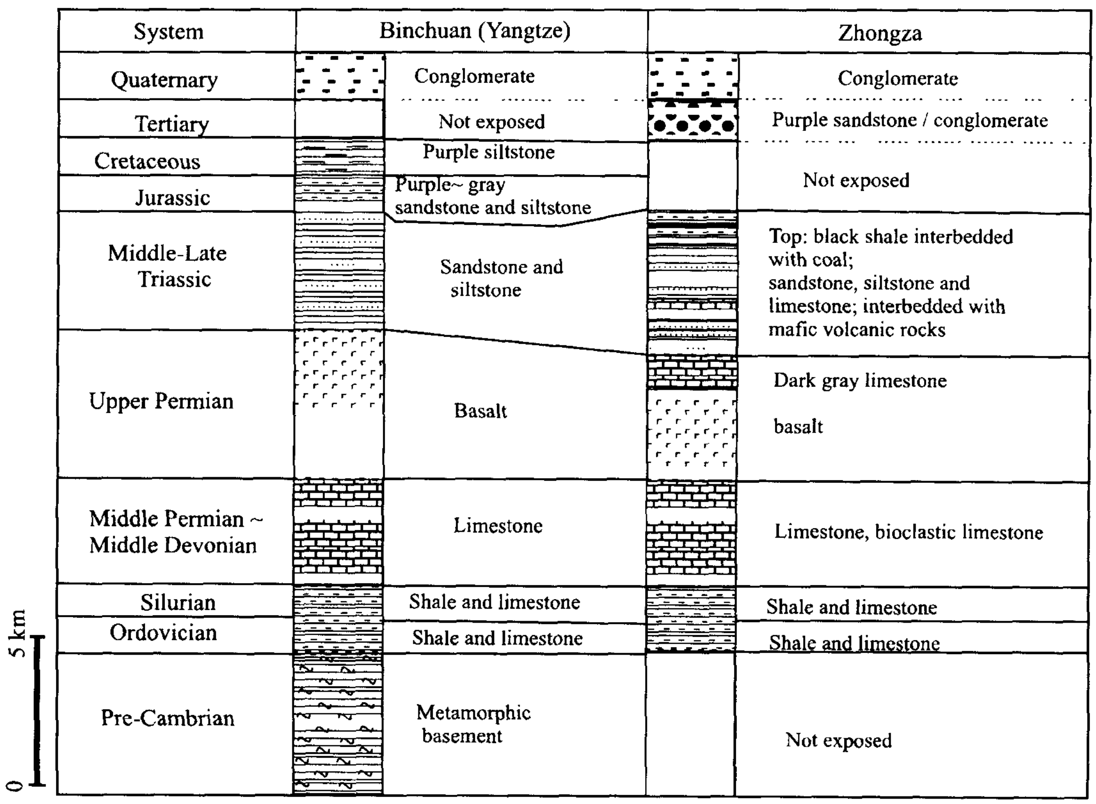

Fig. 1. Stratigraphy comparison of the Yangtze craton and the Zongza block.

(Lin, 1985) and a remarkable diversity of rock types including the lower low-Ti basalts and upper high-Ti basalts, minor basaltic andesite, rhyolite-trachyte, alkaline basalts and basaltic pyroclastics based on individual case studies (Song et al., 2001; Thompson et al., 2001; Xu et al., 2001; Xiao et al., 2003a). Stratigraphically comparable Permian basalts in the Zongza block, the Garzê-Litang belt and the Songpan-Garzê block that are usually inter-bedded with submarine sediments and located in different tectonic sectors, were poorly studied and are considered to have an origin different from that of the Emeishan continental flood basalts. These were named the Gangdagai Formation in Yunnan Province (some in western Sichuan Province) and the Dashibao Formation in Sichuan Province. They have thicknesses ranging from over 4,000 meters (Sanjiangkou) to a few hundred metres (~600m, Zhongdian) and also have LT and/or HT rock associations comparable with the Emeishan basalts (He et al., unpublished).

3 Sedimentary Stratigraphic Comparison of the Yangtze Craton and the Zongza Micro-block

Figure 1 shows sedimentary stratigraphy columns of the Yangtze craton (Binchuan) and Zongza micro-block. It is clearly that the Binchuan represented the Yangtze craton shows comparable sedimentary stratigraphy with the Zongza micro-block in the pre-Late Permian. In the early Late Permian, both of them have basalts dominated volcanism but there were more submarine sedimentary deposits in the Zongza area, showing a continental-margin or shallow-sea environment. This is supported by the interpretation that the Zongza micro-block was initially a part of the Yangtze craton, and was separated from the western margin of the Yangtze craton during the Late Permian (Mo et al., 1993; Chung et al., 1995). The rifting event of the Garzê-Litang belt is temporally consistent with the Emeishan volcanism (Chung et al., 1995). Post-Permian sedimentary stratigraphy in Binchuan and Zongza are quite different, suggesting distinct sedimentary environments and tectonic settings. This shows that the Zongza micro-block began to separate from the Yangtze craton in the late Late Permian.

At a large scale, the Permian stratigraphy also shows contemporary volcanism in the post-Middle Permian period. As shown in Table 1, independent mapping results (Yunnan, 1990; Sichuan, 1991) suggest that extensive mafic volcanism started after the Maokou and before the Longtan period.

4 Chemostratigraphic Comparison of Late Permian Basalts in the Zongza, Garzê-Litang, Songpan-Garzê and Binchuan Areas

Six representative volcanic successions located on either side of the Longmenshan fault zone were chosen for comparison (Fig. 2). Classification of rock types was done mainly based on the scheme for classifying the Emeishan continental flood basalt tholeiites as high-Ti (HT, TiO_2>2.5%; Ti/Y>500) and low-Ti (LT, TiO_2<2.5%; Ti/Y<500) groups (Xu et al., 2001), with the LT group being further subdivided into LT1 and LT2 subgroups according to their $Mg^{\#}$ ($Mg^{\#}$=100 Mg/(Mg+Fe^{2+})), Th/Nb, Sm/Yb and a few other geochemical parameters (Xiao et al., 2003a). In Fig. 2, one representative section is shown for each tectonic division. In the figure, the Binchuan, Sanjiangkou, Baoxing and Zhongdian sections are illustrated, which belong to the Yangtze craton, the Garzê-Litang belt, the Songpan-Garzê block and the Zongza block respectively. As the thickest lava succession in the ELIP, the Binchuan section serves as a reference for comparison with other basalt members and has been well studied by Xu et al. (2001) and Xiao et al.

Table 1 Stratigraphical comparison of the Permian in Sichuan, Yunnan and Guizhou provinces (after Sichuan, 1991)

<table>
<tr><th rowspan="2">System</th><th rowspan="2">Formation</th><th colspan="5">Sichuan</th><th rowspan="2">Yunnan</th><th rowspan="2">Guizhou</th></tr>
<tr><th>Eastern Sichuan</th><th colspan="4">Western Sichuan</th></tr>
<tr><td rowspan="3">Upper Permian</td><td>Changxing</td><td>Changxing limestone</td><td rowspan="3">Gangdagai</td><td rowspan="2">Clastic rock group</td><td rowspan="3">Dashibao</td><td rowspan="2">Clastic rock group</td><td>Changxing lime-stone</td><td>Changxing lime-stone</td></tr>
<tr><td rowspan="2">Longtan</td><td>Longtan limestone</td><td>Longtan limestone</td><td>Longtan limestone</td></tr>
<tr><td>Emeishan basalts</td><td>Flood basalts</td><td>Flood basalts</td><td>Emeishan basalts</td><td>Emeishan basalts</td></tr>
<tr><td rowspan="2">Middle Permian</td><td>Maokou</td><td>Maokou limestone</td><td colspan="2" rowspan="2">Binfeng limestone</td><td colspan="2" rowspan="3">Maowu limestone and sandstone</td><td>Maokou limestone</td><td>Maokou limestone</td></tr>
<tr><td>Qixia</td><td>Qixia limestone</td><td>Qixia limestone</td><td>Qixia limestone</td></tr>
<tr><td>Lower Permian</td><td>Liangshan</td><td>Liangshan sandstone</td><td colspan="2">Dongdahe sandstone</td><td>Liangshan sand-stone</td><td>Liangshan sand-stone</td></tr>
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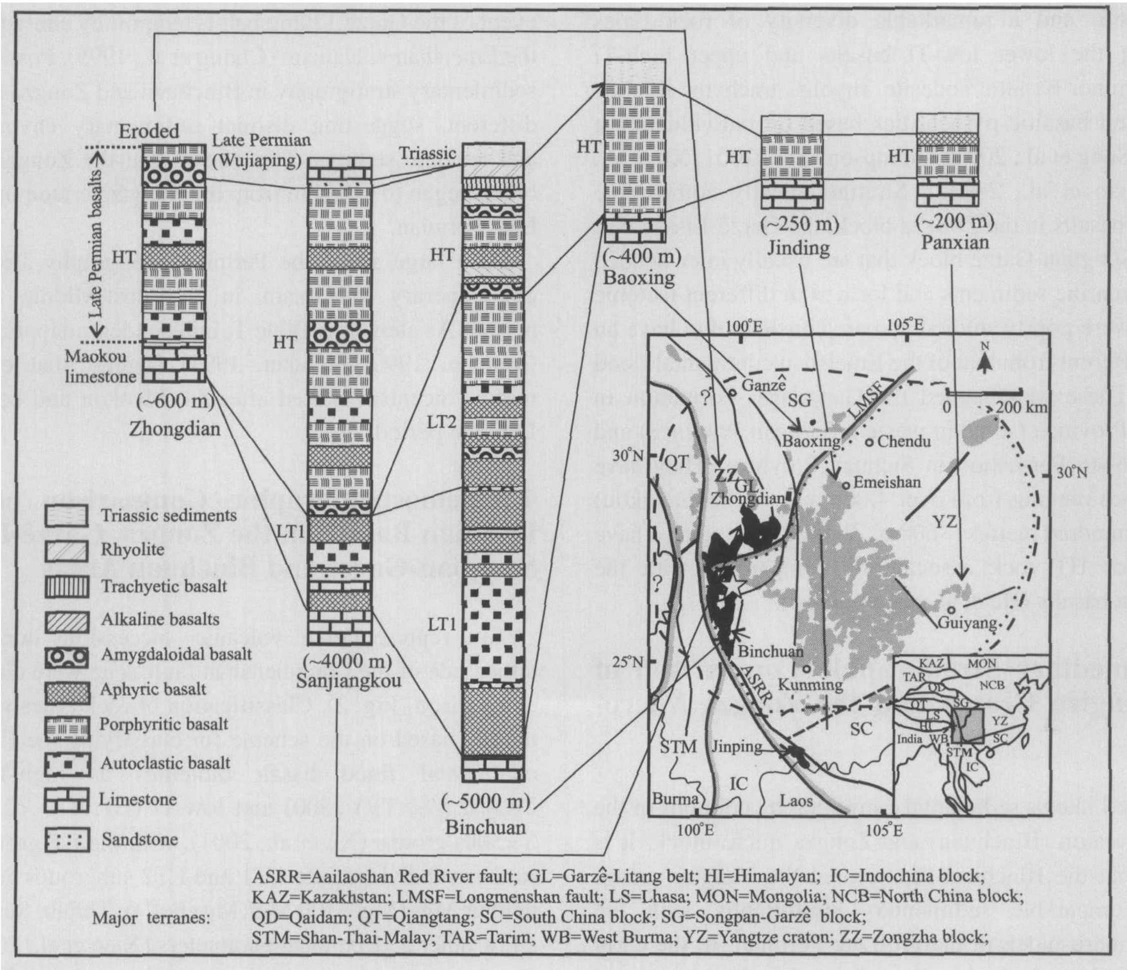

Fig. 2. Geological sketch map showing the area of the ELIP (modified after Xiao et al., 2003c) and its representative volcanic stratigraphies. Light gray areas in inset geological map are outcrops of the HT Emeishan flood basalts. The inset illustrates the major tectonic units in eastern Asia (modified after Chung et al., 1998). Dark gray areas are outcrops of LT and HT basalts. Dotted lines show previous defined area of ELIP. Dashed line shows the area of the ELIP defined by this study. Typical sections from different terrains are chosen for comparison. LT and HT represent low-Ti and high-Ti tholeiite respectively, for an explanation see text. Data from Binchuan are from Xiao et al. (2003a), data of Sanjiangkou from He et al. (unpublished), and data from Baoxing from Xu et al. (unpublished).

(2003b). The same classification scheme was applied to other sections to unravel the petrologic and compositional diversity of the basalts. The thickness and rock types of each chosen volcanic succession display significant variations, and remarkable and characteristic trends. Significantly, sections along the margin of the Yangtze craton show similar rock associations as the LT basalts in the lower parts (also see the Jinping section, Xiao et al., 2003c) and HT basalts in the upper parts (comparable with the Binchuan section), while outer sections only have HT basalts (Fig. 1). Since their lithological characteristics were well described by many researchers (e.g. Xu et al., 2001; Xiao et al., 2003a; Xiao et al., 2003b; He et al., unpublished; Xu et al., unpublished) and summarized in Fig. 1, and the HT and LT basalts on the Yangtze craton have similar geochemical characteristics, this section will focus on chemostratigraphic comparison between the Binchuan section and other three representative sections away from the Yangtze craton. In general, when the same classification scheme is applied to all sections, the LT1 basalts have higher $Mg^{\#}$ (67–51) than the LT2 basalts ($Mg^{\#}$ = 54–48) (Fig. 3). A more evolved nature is found for the HT basalts where $Mg^{\#}$ varies between 53 and 44 (Fig. 3a). Distinction between the LT1 and LT2 lavas is also clear in the plot of Th/Nb versus Ti/Y, which highlights the high contents of highly incompatible elements in the LT1 lavas (Fig. 3b). Differences between these three groups are also easily recognized in their REE (rare earth element) patterns and multiple element spidergrams (Fig. 4). Among the three groups, the HT magmas show the highest light REE concentration with $(La/Yb)_N$ ranging between 11 and 17. In the primitive-mantle normalized spider-diagrams, the HT lavas are characterized by depletion of Rb and Ba relative to Th and by a marked negative Sr anomaly (Fig. 4a), which

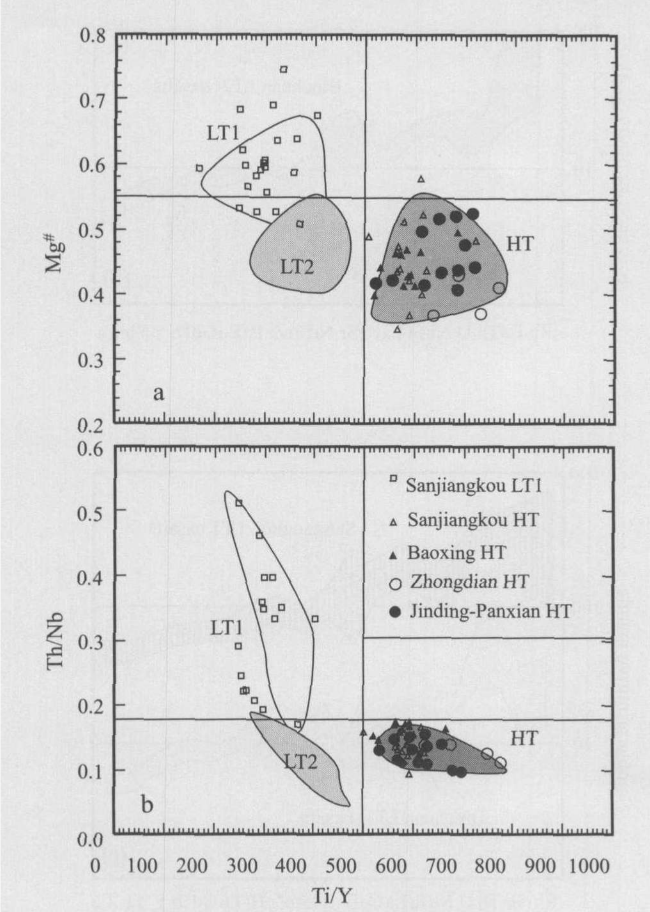

Fig. 3. Diagrams showing variations of $Mg^{\#}$ and Th/Nb against Ti/Y for volcanic rocks from the ELIP. The Ti/Y ratios are applied to classifying rock types as LT (Ti/Y<500), while Th/Nb and $Mg^{\#}$ subdivide LT into LT1 and LT2 tholeiite groups. Data sources are the same as in Fig. 1.

can be considered as a proxy of a Eu anomaly and signifying plagioclase fractionation. No significant negative Nb anomaly is noted in the samples from this group. Much lower contents of light REE are observed in LT lavas. Specifically, the LT2 basalts show lower light REE contents ($(La/Yb)_N$ = 3–4) than the LT1 basalts ($(La/Yb)_N$ = 6–8) (Xiao et al., 2003c). Weak negative Eu anomalies are noted in the LT1 lavas but not observed in the LT2 samples (Fig. 4b, c). A significant difference between the LT1 and LT2 basalts is evident even in the primitive-mantle normalized spider-diagrams (Fig. 4). The LT1 basalts show pronounced negative Nb and Ta anomalies and, however, no such anomalies are associated with the LT2 basalts, although variable, positive Sr anomalies are present in some LT2 lavas, in contrast to the weak to pronounced negative Sr anomalies in the LT1 samples.

In summary, the basalts from the Zongza block, the Garzê-Litang belt and the Songpan-Garzê block show similar rock associations with, and display similar geochemical characteristics to the typical Emeishan basalts of the Binchuan area except that there are no LT2 basalts in these three terrains. It is proposed that they were originally associated with the Emeishan mantle plume and represent the westward extension of the ELIP.

5 Spatial and Temporal Variations of Rock Types

As presented above, the chemo-stratigraphy of flood basalts from different terrains also provides valuable data to construct volcanic rock type variations both spatially and temporally. The well-documented rock types on the Yangtze craton are LT (LT1+LT2)+HT basalts on the western margin, and HT basalts within the craton (Xiao et al., 2003c). The chemostratigraphy presented in this paper reveals that the LT1+HT rock associations occur in the Garzê-Litang belt, and are connected to the Yangtze craton margin, and the HT basalt associations occur in the Zongza and Songpan-Garzê blocks. The thickest basalt stratum located at or close to the center of the ELIP interbedded with submarine sediments may be a response to crustal extension, rifting and the strongest and long-lived volcanism. This is also supported by small volumes of LT basalts prior to massive Late Permian flood basalts that were found at Sanjiangkou, namely the Tuxinmoyan Formation. These might represent initial volcanism associated with the rising mantle plume. Therefore, temporally, the LT basalts with high $Mg^{\#}$ and low REE contents erupted prior to the HT basalts that have low $Mg^{\#}$, high REE and LILE contents, suggesting that the interaction between the mantle plume and the lithosphere produced all three types of magmas.

6 Constraints on Westward Extension of the ELIP and the Scale of Plume Head

The close affinity among the Gangdagai Formation, the Dashibao Formation basalts and the Emeishan basalts also yields important implications for the western boundary of the ELIP. Paleomagnetic studies and plate reconstruction suggest that in the Permian the western Yangtze craton was a passive continental margin (Huang et al., 1992; Yin and Nie, 1996). To the west was the paleo-Tethys ocean (Zhong, 1998), whereas to its northwest was the Garzê-Litang Ocean that might be related to the starting Emeishan mantle plume (Chung and Jahn, 1995). It is therefore considered possible that the basalts in the west sector of the ELIP were erupted into the paleo-Tethys ocean and that it may have marked the initial western boundary of the ELIP. This part of the ELIP was probably an oceanic plateau. The Gangdagai Formation basalts in the Zongza block allow us

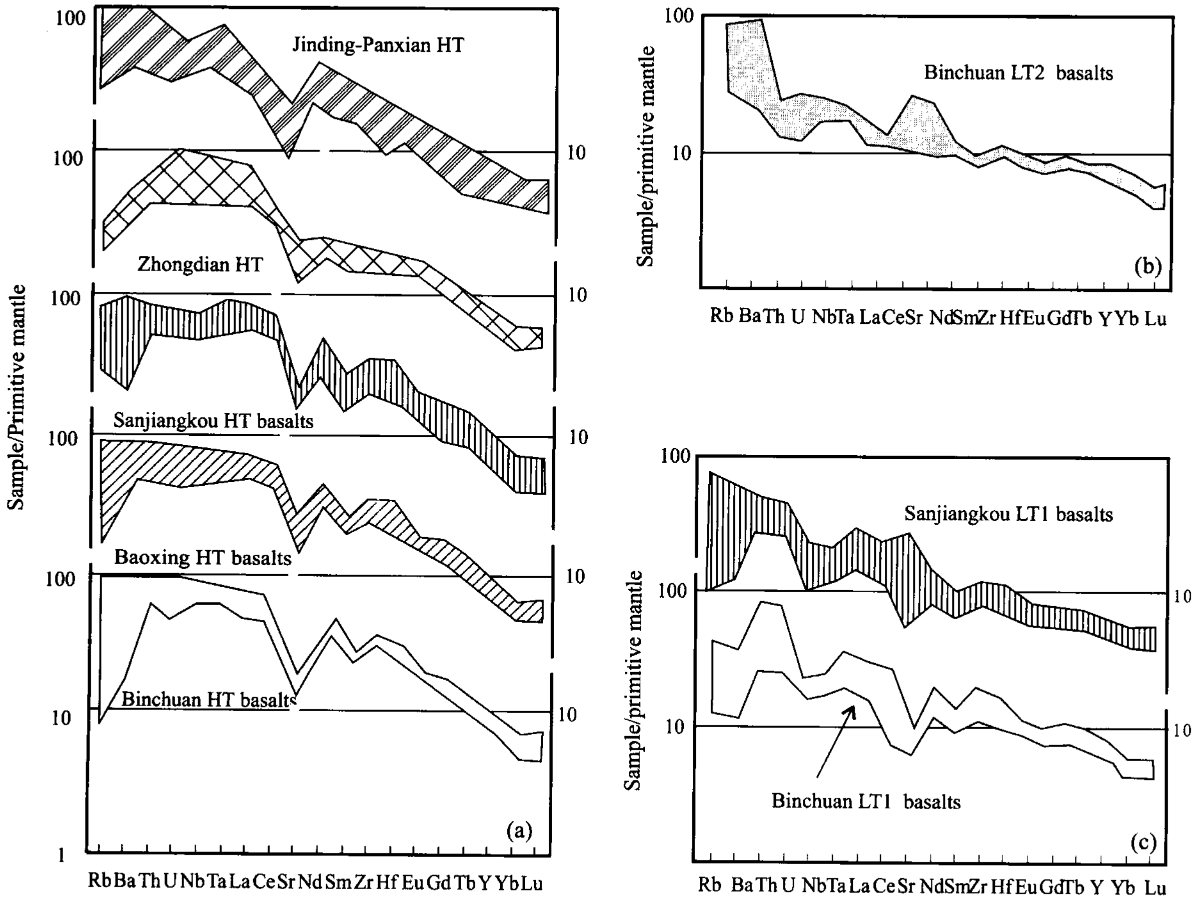

Fig. 4. Primitive mantle-normalized trace element concentrations in the Emeishan volcanic rocks for HT basalts (a) LT2 basalts (b) and LT1 basalts (c). Data sources are the same as in Fig. 1. The normalizing values are from Sun and McDonough (1989).

to make a preliminary estimation about the westward extent of the ELIP, although the reconstruction of the ELIP is difficult since the closure of paleo-Tethys must have dramatically dismembered and destroyed the western sector of the former Emeishan province. The Garzê-Litang Ocean was estimated to have a width about 500 km (Mo et al., 1993) at the Late Permian and it had closed by the late Triassic. The distance from Lijiang to Zongza is ~100 km. These newly identified flood basalts suggest that the former ELIP might have had large-scale westward extension, about 600 km west of Lijiang. Considering the previously defined ELIP on the Yangtze craton has a diameter of ~600 km and given the estimation of width of the Garzê-Litang ocean may not precise, we understated that the reconstructed ELIP now has a radius of over 400 km and an area over 500,000 km^2. Thus the diameter of the Emeishan plume head can be estimated to be over 800 km according to Campbell and Griffiths (1990).

7 Conclusions

The Late Permian flood basalts of the Gangdagai and Dashibao Formations in the Zongza block, the Garzê-Litang belt and the Songpan-Garzê block are contemporary and have close affinities with typical Emeishan flood basalts at Binchuan and are attributed to the western part of the ELIP, which is subsequently extended to the west with a revised area of about 500,000 km^2. The diameter of the Emeishan plume head is estimated to be over 800 km.

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