Late Permian basalts in the northwestern margin of the Emeishan Large Igneous Province: Implications for the origin of the Songpan-Ganzi terrane

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A B S T R A C T

SHRIMP zircon U-Pb ages, geochemical and Sr-Nd isotopic data are reported for two types of basalts (Type I and Type II) from a Permian volcanic-pyroclastic succession in the Tubagou section, Baoxing area along the southeastern margin of the Songpan-Ganzi terrane (SGT) in the Sichuan province of SW China. Zircons from the uppermost basaltic flows yield crystallization age of 257.3 ± 2.0 Ma, which may represent the time of culmination the basaltic eruption. Type I shows alkaline affinity with εNd(t) values of +2.4 to +2.9, and is characterized by oceanic island basalt (OIB)-type light rare earth element (LREE) and trace-element patterns. In contrast, Type II rocks are tholeiitic, and close to initial rift tholeiite (IRT)-like REE and trace element patterns, and are relatively depleted in highly incompatible elements with slightly negative Nb-Ta anomaly. The εNd(t) values of Type II are between +1.8 to +2.2. The geochemical characteristics suggest the Type I has not been significantly crustally contaminated, whereas Type II may have experienced minor crustal contamination. Clinopyroxene crystallization temperature is ~80–120°C higher than that of the normal asthenospheric mantle, implying anomalous thermal input from mantle source and a possible plume-head origin for the Tubagou lava. The geochemical and isotopic features reflecting progressive lithosphere thinning probably through plume-lithosphere interaction. The spatial and temporal coincidence between the Dashibao basalt eruption and continental rifting suggest that continental break-up and the opening of an extensional basin was probably related to the Late Permian Emeishan plume, which triggered the breakup between the SGT and the Yangtze craton.

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1. Introduction

Large igneous provinces (LIPs) are the products of anomalously high melt production rates, and thus have been linked to the arrival of a mantle plume at the base of the lithosphere (e.g., Campbell and Griffiths, 1990; Ernst et al., 2005; Saunders et al., 2005). Moreover, rising plume head–lithosphere interaction could result in continental breakup, as illustrated by the example of major LIP eruptions during the last 200 Ma (e.g., Coffin and Eldholm, 1994; Courtillot et al., 1999; Nikishin et al., 2002). However, there are exceptions with some LIPs unrelated to rupturing continental lithosphere, such as the Siberian traps and the Ontong Java plateau (Condie, 2001).

Some key lines of evidence have been proposed to support that the Emeishan Large Igneous Province (ELIP) is a mantle plume-derived LIP including high magnesian picrites, giant radiating mafic dyke swarm, and >1 km of doming of the regional lithosphere shortly before volcanism, together with the short duration of volcanism as well as geophysical signatures (e.g., Ali et al., 2010; Chen et al., 2015; Chung and Jahn, 1995; He et al., 2003a; Li et al., 2015a; Shellnutt et al., 2012; Xu et al., 2001, 2004; Zhang et al., 2006; Zhong et al., 2014). Comparable with the Siberian trap, the ELIP is traditionally thought to be not associated with continental rift or fragmentation (He et al., 2003b). However, some researchers correlated the Emeishan mantle plume with the opening of the Songpan-Ganzi extensional basin, although this inference has not been corroborated by any robust evidence (e.g., Chang, 2000; Hou et al., 1996; Song et al., 2004; Yang et al., 1994; Zi et al., 2010).

The Baoxing area in the northwestern part of the ELIP belongs to the SGT, where late Permian marine basalts (Dashibao Formation) have been recognized and considered to be likely part of the Emeishan flood basalts (Fig. 1; Song et al., 2004; Xiao and Xu, 2005; Zi et al.,

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Therefore, precise geochronologic and geochemical data and a comprehensive petrogenetic study of the petrogenesis of the Dashibao basalts can provide some key constraints on the nature of mantle sources and the relationship between the Emeishan LIP/mantle plume and the derivation of the SGT. In this paper, we present mineral chemical, bulk-rock major and trace element and Sr-Nd isotopic compositions, and a new SHRIMP zircon U-Pb age of the Dashibao basalts from the Tubagou area in the SGT. Based on these results, we attempt to:

1. track the petrogenesis of the Tubagou basalts (Dashibao Formation) and the plume–lithosphere interaction, and
2. shed new lights on the origin of the SGT.

2. Geological background

2.1. Emeishan large igneous province

The ELIP is located to the east of Tibetan plateau and the western margin of the Yangtze craton, SW China (Fig. 1). The basement of the Yangtze craton is locally composed of the Paleoproterozoic Kangding Complex comprising granulite-amphibolite facies metamorphic rocks, the Paleo-Mesoproterozoic Huili Group or its equivalents, and the Yanbian or Kunyang Groups which consist of low-grade metasedimentary rocks interbedded with felsic and mafic metavolcanic rocks. The basement is overlain by a thick sequence (~9 km) of late Neoproterozoic (~600 Ma) to Permian clastic, carbonate, and metavolcanic rocks (Sichuan BGMR, 1991).

The extensive Emeishan flood basalts are exposed over an area of \(3.0 \times 10^5 \text{ km}^2\) (Fig. 1b). The volcanic sequence has a thickness decreasing from west (~5 km) to east (several hundred meters), and contains picrite, tholeiite and andesitic basalt (e.g., Chung and Jahn, 1995; Xu et al., 2001; Zhang et al., 2006). The distribution of units belonging to the ELIP has been subsequently affected by Mesozoic and Cenozoic post-emplacement faulting (Chung and Jahn, 1995), such as the Jinshaijiang-Ailaoshan-Red river strike-slip fault (or suture zone). Recent studies suggested that basalts and mafic complexes exposed in the SGT, the Qiangtang terrain, the Simao basin, and in northern Vietnam might form an extension setting of the ELIP displaced by these faults (e.g., Fan et al., 2008; Hanski et al., 2010; Lai et al., 2012).
Recent geochronological data yield more precise constraints on the duration of eruption as 260–257 Ma with the maximum magmatic activity at ca. 260 Ma (e.g., Fan et al., 2008; Li et al., 2012, 2015b; Shellnutt et al., 2012; Xu et al., 2008; Zhong et al., 2014; Zhou et al., 2006).

2.2. Songpan-Ganzi terrane and Tubagou area

The SGT covers a long narrow triangular-shaped area of about 220,000 km², and is separated by several prominent Tethyan sutures with the major Chinese continental blocks in central-western China (Fig. 1; e.g., Zhang, 2001). The SGT is separated to the east by the Longmenshan thrust belt from the Yangtze craton, and is bounded on the north by Kunlun-Animaqing suture from the Kunlun-Qinling accretionary fold belt. To the southwest, the boundary between the SGT and the remaining part of the Tethys-Himalayan tectonic domain is thought to be located along the Jinsha suture (Fig. 1; Burchfiel et al., 1995). The SGT is almost exclusively filled by a 5–15 km thick succession of folded Triassic flysch (ca. 230–203 Ma), in addition to some pre-Triassic strata and pre-Sinian basement exposed along the eastern and southern margins (e.g., Zhou and Graham, 1996).

The Dashibao basalts are exposed within the broad Baoxing-Xiaojin-Danba-Kangding region in Sichuan province (Fig. 1b), and has a variable thickness ranging from 50 to ~500 m. The lava successions unconformably lie above the Early Permian Sandaoqiao Formation (composed chiefly of marine bioclastic limestones), and are conformably/unconformably overlain by Late Triassic marine strata (Bocigou Formation) (Fig. 2; Sichuan BGMR, 1976; Xiao and Xu, 2005). The Longmenshan Thrust Fault and the arcuate tectonic belt along the southeastern margin of the Songpan-Ganzi terrane exert a major control on the distribution of the Dashibao basalts (Fig. 1b). The Dashibao flow succession appears to have formed by multiple lava flows with some pillow basaltic lavas, implying submarine extrusions (Xiao and Xu, 2005).

2.3. Geology and petrography of the basaltic lavas

Our study area is located in the Tubagou area, north of Baoxing and the western side of Longmenshan faults, belonging to the SGT (Fig. 1b). The basalt sequence here is ~160 m thick, and is interbedded with amygdaloidal basalt and basaltic pyroclastics (Fig. 2b). Based on texture and mineral assemblages, the Tubagou basalts can be divided into two types: Type I and Type II. Type I is stratigraphically located in the lower part of the lava flow succession and is approximately 65 m thick (Fig. 2b). It is characterized by clinopyroxene phenocrysts (~15%) embedded in an interstratified or intergranular groundmass with fine grained plagioclase, pyroxene and Fe-Ti oxides (Fig. 3a, b). Type II is in the upper part of the succession, and is ~80 m thick. The phenocrysts in Type II are clinopyroxene (10–20%) and plagioclase (10–15%), where the plagioclase has been extensively altered to sericite (Fig. 3c).

The petrographic observation suggests some differences between the two types of basalts. The clinopyroxene phenocrysts in Type I are subhedral and larger ranging from 1 to 1.5 mm across (Fig. 3a). The Fe-Ti oxide contents are up to ~3% (Fig. 3b). In contrast, the clinopyroxene phenocrysts in Type II are generally subhedral to rounded and sometimes embayed and range from 0.04 to 0.3 mm across (Fig. 3c). The modal content of Fe-Ti oxides shows decrease to ~1% from bottom upward.

3. Analytical methods

Zircons were separated from Type II basalts (TBG16, Fig. 2b) using the conventional heavy liquid and magnetic separation techniques, and then handpicked under binocular microscope. Unfortunately, Type I samples do not carry adequate zircons for analysis. Zircon grains were mounted in an epoxy disc, and then polished and coated with gold film. External and internal structures were examined using transmitted
and reflected light micrographs as well as cathodoluminescence (CL) microscopy images using a Hitachi S3000-N scanning electron microscope (SEM) at the Institute of Geology, Chinese Academy of Geological Sciences (CAGS) in Beijing. Zircon dating was performed using the Sensitive High-Resolution Ion Microprobe (SHRIMP-II) at the Beijing SHRIMP Center, CAGS. Details of the analytical procedures for zircons using SHRIMP were referred to Williams (1998). The standard zircons used were SL13 (U = 238 ppm), M257 (U = 840 ppm) and TEM (206Pb/238U age = 417 Ma) (e.g., Williams, 1998). The measured 206Pb abundances were applied for common lead correction.

Mineral compositions in selected samples were analysed by a JEOL JXA-8230 Superprobe at the EMPA Laboratory of China University of Geosciences, Beijing. The operating conditions were an accelerating voltage of 15 kV and beam current of 10 nA. Detected limits in terms of weight percent oxides for the elements in these analyses are estimated as follows: SiO2, Al2O3, MgO, K2O, Na2O – 0.05 wt.%; CaO – 0.04 wt.%; and, TiO2, Cr2O3, FeO, MnO – 0.03 wt.%. All geochemical analyses were performed on selected relatively fresh samples, based on petrographic observations. Major and trace element concentrations of the rocks studied were determined at the National Research Center for Geoanalysis, CAGS, Beijing. Major element determinations were carried out by X-ray fluorescence spectroscopy using the methods of Norrish and Chappel (1977) and ferric and ferrous iron determinations were determined by a wet chemical method. The trace element abundances were measured by inductively coupled plasma-mass spectrometry (ICPMS). The analytical uncertainties of data were generally – 1% for major oxides, – 0.5% for SiO2, and 3–7% for trace elements. Major elements were measured on Siemens 303AS and 3080E spectrometers, and trace elements on VG PQ-2 Turbo and PQ-2S instruments.

Sr and Nd were separated using standard ion exchange techniques (Yang et al., 1997). Sr-Nd isotopic analyses were performed on a VG 354 mass spectrometer with 5 collectors at the Center of Modern Analysis, Nanjing University.

The precision and accuracy of analyses including data on international reference standards are given in online Supplementary Analysis, Nanjing University.

4. Results

4.1. SHRIMP zircon U-Pb age

The zircons from the basalt are generally transparent, euhedral to subhedral with lengths of long axes from 80 μm to 100 μm (Fig. 4a). The measured Th/U ratios of the zircon grains from Tubagou basalt vary from 1.94 to 3.69 (Table 1), much higher than those of metamorphic zircons (<0.2; Rubatto, 2002), and suggesting magmatic origin (e.g., Belousova et al., 2002). The measured isotopic ratios and calculated ages for samples are given in Table 1 and illustrated on concordia plots in Fig. 4b. Eleven analyses were performed on 11 grains. These grains define a concordia age of 257.3 ± 2.0 Ma, which can be considered to represent the emplacement age of the basalts.

4.2. Mineral chemistry of clinopyroxene

The electron microprobe analyses of representative clinopyroxene are listed in Supplementary Table 1. Although all analyzed clinopyroxene phenocrysts from Type I and II basalts belong to augite showing a moderate compositional range (Wo34-41En42-44Fs12-18), the TiO2 contents of Type I (0.91 to 1.19 wt.%, average 1.05 wt.%) are slightly higher than those from Type II (0.55 to 1.04 wt.%, average 0.85 wt.%). In addition, Type I has higher Na2O and slightly lower Al2O3 than Type II (Supplementary Table 1). Based on the clinopyroxene thermometer proposed by Putirka et al. (2003), the temperature of crystallization within the magma chamber can be estimated as 1406–1451°C.

4.3. Bulk-rock major and trace element composition

The major element compositions of the late Permian basalts from the Tubagou area are listed in Table 2. As noted above, the samples are variably altered in thin section (Fig. 3), and this is reflected in their LOI (loss on ignition) values. For comparison we have normalized the whole-rock raw data to anhydrous compositions by correcting for LOI, although not all LOI is caused by post-magmatic alteration. We use the normalized values for the discussions below. Type I rocks display relatively uniform SiO2 (48.78–53.20 wt.%), TiO2 (3.13–4.06 wt.%), Al2O3 (14.09–16.69 wt.%), MgO (4.66–6.39 wt.%), total FeO (FeO + 0.8998Fe2O3) (10.93–14.23 wt.%), CaO (5.90–8.97 wt.%), and Fe2O3 (0.35–0.45 wt.%). The Na2O + K2O contents are between 3.03 and 5.42 wt.%. In contrast to Type I, Type II has similar SiO2 (48.71–53.05 wt.%), Al2O3 (14.82–15.98 wt.%), MgO (4.56–7.20 wt.%) and total FeO (9.96–13.83 wt.%), but lower TiO2 (1.63–2.39 wt.%), total Na2O + K2O contents (2.64–4.75 wt%) and higher CaO (7.22–13.54 wt.%). Mg# values of Type I range from 42 to 47 whereas as most of the Mg# of Type II vary between 41 and 49, suggesting that the rocks were derived from a relatively evolved
types. The Tubagou basalts can also be classified into two types, with Type I belonging to HT type, whereas Type II classifies as LT type (Table 2). In addition, the TiO₂ concentrations seem to be associated with the modal contents of Fe-Ti oxides (Table 2; Fig. 3b, c).

On TAS diagrams (Fig. 5a), most of the Tubagou rocks fall in the subalkaline field, although the data exhibit two distinct clusters on the Nb/Y vs. Zr/Ti diagram (Fig. 5b) with Type I falling in the alkaline basalt field and Type II in the sub-alkaline series field. On the TiO₂ vs. TFeO/MgO plot (Fig. 5c), Type II samples fall along the tholeiitic line.

Trace element contents and patterns of the Tubagou basalts are shown in Table 2 and Fig. 6 respectively. Type I has higher REE contents (ΣREE=172–200 ppm) than those of Type II (ΣREE=85–132 ppm). Although both types of basalts are characterized by highly fractionated LREE/heavy REE (HREE) chondrite-normalized patterns, Type I shows more LREE-enrichment [(La/Yb)N=5.02–8.68] than Type II [(La/Yb)N=4.03–5.16]. Moreover, (Dy/Yb)N ratios of Type I range from 1.56 to 1.76 indicating a moderate HREE fractionation, whereas the samples of Type II show near-flat patterns for the HREE [(Dy/Yb)N=1.23–1.33]. However, negative Eu anomalies are slight to negligible for all the samples (δEu=0.71–0.97). Different profiles are also exhibited in the primitive mantle-normalized trace element patterns of the two types of basalt (Fig. 6b). Type I is characterized by significantly more enrichment in the most highly incompatible trace elements relative to Type II. Part of the Type I samples possesses negative Sr anomalies, whereas slightly negative Nb-Ta-Ti anomalies and prominent Sr and Pb depletion are observed in the samples from Type II (Fig. 6b). Overall, REE and trace element patterns of Type I are characterized by OIB-type, whereas the profiles of Type II are close to those of IRT, comparable to the rocks in Rio Grande rift (Thompson and Gibson, 1994).

4.4. Sr-Nd isotope ratios

The Sr-Nd isotopic compositions of the Tubagou basalts from the study area are presented in Table 3 and plotted in Fig. 7. Type I has a small range of age-corrected ⁸⁷Sr/⁸⁶Sr ratios of 0.70526 to 0.70554 and positive and uniform εNd(t) (t=257Ma) values between +2.4 and +2.9. On the other hand, εNd(t) (t=257Ma) values (+1.8 to +2.2) of Type II are slightly lower than those of Type I, and Type II displays a relatively larger variation and higher ⁸⁷Sr/⁸⁶Sr ratios, of 0.70545 to 0.70553.

On the ⁸⁷Sr/⁸⁶Sr vs. εNd(t) diagram (Fig. 7), with the exception of one sample (TBG11), the Tubagou basalts overlap the fields of the Emeishan basalts and Siberian Traps. Type I data lie within the field of OIB, whereas most of Type II display much higher ⁸⁷Sr/⁸⁶Sr ratios than OIBs. However, the Tubagou basalts apparently deviate from the high-εNd(t) and low-⁸⁷Sr/⁸⁶Sr end of several modern Indian Ocean hotspots and some Pacific ‘C-type’ hotspots (Hanan and Graham, 1996).

Table 1

<table>
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<th>Spot</th>
<th>%²⁰⁶Pb</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>²³⁵Th/²³⁸U</th>
<th>²³⁸U/²³⁵Th</th>
<th>²⁰⁶Pb/²⁰⁶Pb+²⁰⁸Pb</th>
<th>²⁰⁶Pb/²⁰⁶Pb+²⁰⁸Pb</th>
<th>± %</th>
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<td>2713</td>
<td>1.94</td>
<td>50.1</td>
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<td>1.6</td>
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<tr>
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<td>4478</td>
<td>2.87</td>
<td>56.7</td>
<td>0.05237</td>
<td>1.4</td>
<td>2.0</td>
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<td>± 3.4</td>
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<td>4478</td>
<td>2.87</td>
<td>56.7</td>
<td>0.05237</td>
<td>1.4</td>
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Fig. 4. (a) CL images of representative zircons from the Tubagou basalt (Circles indicate laser points for dating). (b) SHRIMP U-Pb zircon concordia diagram.

magma. Xu et al. (2001) used TiO₂ contents of 2.5 wt.% and Ti/Y ratio of 500 to divide the Emeishan basalts into low-Ti (LT) and high-Ti (HT) types. The Tubagou basalts can also be classified into two types, with
5. Discussion

5.1. Alteration effects on chemical compositions

As mentioned above, the samples are variously altered which reflected in their LOI values ranging from 2.36 to 5.31 wt% (Table 2). Therefore it is necessary to assess the relative mobility of elements to avoid pitfalls in the data interpretation. The mostly mobile trace elements, such as Ba and Rb, show considerably variable (Fig. 7b), largely due to an alteration effect. Thus, we focus on the immobile elements such as high field-strength elements (Ti, Zr, Y, Nb, Tl, Hf), Th and REE, especially their interelement ratios, as well as Sr-Nd isotopic data (apart from TBN11 likely due to strong alteration) used in the following discussion to evaluate the petrogenetic processes of these mafic volcanic rocks.

5.2. Volcanic series

Almost all rocks of Type II fall in the subalkaline series field on both TAS and Nb/Y vs. Zr/Ti diagrams (Fig. 5a, b), and plot near the tholeiite line on TiO2 vs. TFeO/MgO diagram (Fig. 5c). Although no olivine phenocrysts have been recognized in Type I, the samples fall into alkaline basalt field on the alteration-resistant diagram of Nb/Y vs. Zr/Ti (Fig. 5b). Thus, Type I shows geochemical affinity to the alkaline series, and this is probably the reason why no magmatic zircons were found in Type I basalts. Furthermore, the Tubagou basalts in the higher stratigraphic level show decreasing K2O + Na2O contents (Table 2; Fig. 2b), coupled with higher TiO2 and Na2O contents in the clinopyroxene phenocrysts of Type I as compared to Type II (Supplementary Table 1), which probably suggest that the Tubagou basalts transformed in composition from alkaline series to tholeitic series with time.

5.3. Crustal contamination

The (Nb/Ti)8 vs. (Th/Yb)8 diagram can be used to evaluate the involvement of crustal contamination (e.g., Pearce, 2008). Almost all the Tubagou basalts fall in the field of the Emeishan basalts from the eastern part of the ELIP, while Type I is more close to the Emeishan picrites, which suggests that the Type I has undergone negligible or no
crustal contamination (Fig. 8a). However, the data of Type II lie between the Emeishan picrites and lower crust, implying minor crustal contamination (Fig. 8a).

Isotopically, there is no correlation between $^{87}\text{Sr}/^{86}\text{Sr}(i)$ and $1/\text{Sr}$ for Type I indicating they are little affected by crustal contamination (Fig. 8b). Type II displays a general positive correction (Fig. 8b), implying that they have probably undergone minor crustal contamination. On the MgO versus $\varepsilon_{Nd}(t)$ diagram, no obvious correlations can be recognized and $\varepsilon_{Nd}(t)$ values are relatively constant with the decreasing MgO, suggesting that fractional crystallization (FC) might have exerted a dominant control on the magma process of the lavas rather than combined assimilation and fractional crystallization (AFC).

We use Sr isotopic data to simulate the energy-constrained assimilation and fractional crystallization (EC-AFC) model to evaluate the magmatic process of the Tubagou basalts. However, neither the Yangtze upper/middle crust nor the Yangtze lower crust possess the EC-AFC Sr vs. $^{87}\text{Sr}/^{86}\text{Sr}(i)$ isotope curves consistent with the observed Sr isotope data (Fig. 9), except few samples of Type II which fall near the curve of the Yangtze lower crust. Obviously, the Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}(i)$ ratios of the Yangtze craton are so high that the crustal contamination could rapidly elevate the Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}(i)$ ratios up to ~2000 ppm and ~0.712 respectively (Supplementary Table 2; Fig. 9). In contrast, the Tubagou basalts is characterized by relatively low Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}(i)$ ratios. Thus, it is unlikely that crustal contamination played a significant role in the generation of basalts.
5.4. Mantle sources of the Tubagou basalts

Given a narrow range and evolved geochemical compositions of the Tubagou basalts, it is difficult to compute the primary mantle melts and to extract information such as potential mantle temperature. Nonetheless, some inferences can be made on the thermal state in mantle source. Since primary magma could lose heat during migration from the mantle source to the magma chamber, the crystallization temperature of clinopyroxene should be considered as the lower range of the potential mantle temperature. As mentioned above, the Tubagou basalts are considered to be derived from the garnet peridotite source. Thus, we can use the 87Sr/86Sr(i) and 143Nd/144Nd(i) ratios to evaluate the degree of partial melting. The Sr-Nd isotopic data for the Tubagou basalts are shown in Table 3. The Sr-Nd isotope ratios of the Tubagou basalts are consistent with estimates for the Emeishan basalts (Wendt et al., 1999), indicating that the Tubagou basalts have a similar source to the Emeishan basalts. However, the 87Sr/86Sr(i) ratios of the Tubagou basalts are slightly lower than those of the Emeishan basalts, suggesting that the Tubagou basalts have undergone some degree of crustal contamination.

Table 3
Sr-Nd isotopic data for bulk rocks.
Concentrations of Rb, Sr, Sm and Nd were determined by isotope dilution.

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample no.</th>
<th>87Rb/86Sr(m)</th>
<th>87Sr/86Sr(m)</th>
<th>147Sm/144Nd(m)</th>
<th>147Nd/144Nd(m)</th>
<th>87Sr/86Sr(i)</th>
<th>143Nd/144Nd(i)</th>
<th>εNd(t)</th>
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<tr>
<td>Type I</td>
<td>TBG1</td>
<td>0.2675</td>
<td>0.706301</td>
<td>0.1112</td>
<td>0.512659</td>
<td>0.705323</td>
<td>0.512438</td>
<td>2.6</td>
</tr>
<tr>
<td>Type I</td>
<td>TBG2</td>
<td>0.1623</td>
<td>0.706017</td>
<td>0.1298</td>
<td>0.512647</td>
<td>0.705424</td>
<td>0.512428</td>
<td>2.4</td>
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<tr>
<td>Type I</td>
<td>TBG3</td>
<td>0.1243</td>
<td>0.705853</td>
<td>0.1408</td>
<td>0.512672</td>
<td>0.705399</td>
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<td>2.5</td>
</tr>
<tr>
<td>Type I</td>
<td>TBG4</td>
<td>0.1564</td>
<td>0.705988</td>
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<td>0.705396</td>
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<td>0.0809</td>
<td>0.705562</td>
<td>0.1315</td>
<td>0.512661</td>
<td>0.705266</td>
<td>0.512439</td>
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<tr>
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<td>0.706924</td>
<td>0.1304</td>
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<tr>
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<td>0.705847</td>
<td>0.1105</td>
<td>0.512656</td>
<td>0.705427</td>
<td>0.512426</td>
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<td>0.1346</td>
<td>0.512681</td>
<td>0.705327</td>
<td>0.512455</td>
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<td>0.512637</td>
<td>0.705885</td>
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<tr>
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<td>0.1334</td>
<td>0.512629</td>
<td>0.705468</td>
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<td>1.9</td>
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<td>Type II</td>
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<td>0.706657</td>
<td>0.1416</td>
<td>0.512643</td>
<td>0.706198</td>
<td>0.512405</td>
<td>1.9</td>
</tr>
</tbody>
</table>

5.4. Mantle sources of the Tubagou basalts

Given a narrow range and evolved geochemical compositions of the Tubagou basalts, it is difficult to compute the primary mantle melts and to extract information such as potential mantle temperature. Nonetheless, some inferences can be made on the thermal state in mantle source. Since primary magma could lose heat during migration from the mantle source to the magma chamber, the crystallization temperature of clinopyroxene should be considered as the lower range of the potential mantle temperature. As mentioned above, the Tubagou basalts yield a temperature range of 1406–1451°C for the clinopyroxene crystallization. Compared with normal asthenospheric mantle, this temperature range is ~80–120°C higher (McKenzie and Bickle, 1988). Therefore, the higher estimated potential mantle temperatures, together with OIB-type geochemical characteristics and the contemporaneous eruption with the Emeishan basalts, suggest a mantle plume origin for the Tubagou basalts.

As indicated in Table 2, total Na2O+K2O contents of the lava sequence show upward decrease. Likewise, in the Kenya and Oslo rifts, the magma alkalinity also displays a decrease with the ascending asthenospheric mantle (Baker, 1987; White and McKenzie, 1989). Experimental results indicate that the melts derived from the garnet peridotite (>30 kbar) have low Al2O3 contents (Herzberg, 1995). Type I contains 14.32 wt.% Al2O3 in average, which is lower than that of Type II (14.62 wt.% in average, Table 2). Thus, the melting depth of Type II is shallower than Type I.

Ample geochemical and geophysical data (e.g., Langmuir et al., 1992; Niu and Batiza, 1991) demonstrate that the melting depth has a strong control over partial melting degree of lavas (e.g., DePaolo and Daley, 2000; Elam, 1992). On Nb/Yb vs. Th/Yb diagram (Fig. 10a), the degree of partial melting from Type I to Type II remarkably increases, which is consistent with the case of the southern Main Ethiopian Rift (Rooney, 2010). (Tb/Yb)P vs. (Yb/Sm)P plots (Fig. 10b) can be used to quantitatively estimate the nature of mantle source and the extent of melting (McKenzie and O’Nions, 1991). Type I data lie closer to a melt path for garnet peridotite than to one for spinel peridotite. With the assumptions used to construct Fig. 10b, the data are consistent with a 70–85% contribution through melting in the presence of garnet, and with only small amounts of partial melting (5–6%). In contrast, Type II data plot near the spinel–garnet transition field with 40–55% contribution from melting in the garnet peridotite source, but the melt fraction is elevated to 7–9%.

The Types I and II show some contrast, particularly in the chondrite-normalized REE and primitive mantle normalized trace element patterns (Fig. 6). Partial melting and the accumulation or fractionation of most silicate phases is unlikely to significantly affect the incompatible element ratios with similar distribution coefficients (Wang et al., 2004). Type I and Type II rocks display similar Nb/Ti, Nb/La and Zr/Nb ratios and Nd isotopic compositions (Tables 2, 3; Fig. 7), and thus preclude the possibility that they originated from two different mantle sources. Types I and II rocks show identical ranges of Mg# and exhibit a scattered trend rather than a continuous magma evolution trend on the Harker diagrams (not shown). Moreover, it has been confirmed that crustal contamination does not play a significant role in the generation of the Tubagou basalts. Consequently, the geochemical discrepancies between the Type I and II cannot be attributed to fractional crystallization and crustal contamination, and suggest variable degree partial melting of the same mantle source at different depths. Lower degree of partial melting produced Type I lava under the thick lithosphere, whereas Type II resulted from higher degree of partial melting at shallower depth. We consider this feature to reflect the process of lithospheric thinning during plume–lithosphere interaction. In addition, the parental magma of Type I experienced minor crustal contamination, which lead to relatively higher 87Sr/86Sr(i) ratios and weakly negative Nb-Ta anomalies.

Generally, the TiO2 contents of continental flood basalts span a large range, and Shellnutt and Jahn (2011) emphasized that the variation in TiO2 (HT and LT) probably resulted from the same source but with different degrees of partial melting. On the other hand, some studies have proposed that fractional crystallization, especially those of Fe-Ti oxides, is the key factor that controls the Ti abundance and Ti/Y ratios.
due to the different Fe-Ti oxides/melt partition coefficients of Ti and Y (Hou et al., 2011; Zhang et al., 2006). As described above, TiO₂ contents of the Tubagou basalts vary with the modal content of Fe-Ti oxides (Fig. 3b, c, Table 2), suggesting that fractionation of Fe-Ti oxides exerted significant impact on the Ti abundance in the lavas. Thus, the TiO₂ content in the Tubagou basalts was mainly controlled by the degree of partial melting, together with the accumulation of Fe-Ti oxides.

Shellnutt et al. (2015) recognized Neoproterozoic inherited zircons within Emeishan magmatic rocks and proposed that some Emeishan basalts was derived from melting of Neoproterozoic underplated mafic rocks during the injection of high temperature picritic magmas. As far as we are aware, there is no late-Permian picrites in the Baoxing area probably because the studied area is located in the periphery of the ELIP, whereas picrites are usually the early melting products in the central domain of LIPs (e.g., Campbell and Griffiths, 1990). As noted above, U-Pb dating did not yield any old inherited zircons (Table 1). Recalculation of initial Nd isotopic ratios of the Neoproterozoic Suxiong basalts to corresponding age of 260 Ma (Li et al., 2002) show εNd(t = 260 Ma) values between -4.4 and +0.7 which are lower than those of the Tubagou basalts [εNd(t) = +1.8 to +2.9], indicating that the parental magma of the Tubagou basalts might not have formed through the melting of the Neoproterozoic mafic underplated rocks. Moreover, experimental petrology suggests that the product of partial melting of basalt is generally intermediate–felsic rocks rather than basic rocks, unless complete melting occurs (e.g., Bonin, 2007; Clemens et al., 1986). In summary, the generation of the Tubagou basalts is inconsistent with the model of melting of underplated rocks.

5.5. Insight into duration of the Dashibao basalts and tectonic evolution of SGT

The SHRIMP U-Pb zircon dating of the Tubagou basalt shows a mean age of 257.3 ± 2.0 Ma (Fig. 4; Table 1). Since this sample is collected from the uppermost part of the Tubagou lava succession (Fig. 2b), we interpret this age as the approximate estimate of the termination age of the Dashibao basalts, whereas the SHRIMP U-Pb zircon age (BX-18b, 263 ± 2.0 Ma) from the lowermost Yaoji Dashibao basalts (Fig. 1b, Zi et al., 2010), might represent initial eruption age of the Dashibao basalts. Thus, the eruption of the Dashibao volcanism can be constrained at ~263 to ~257 Ma, and match well the peak stage of the Emeishan magmatic activity (e.g., Shellnutt, 2014), which indicates close genetic link between the Tubagou basalts (Dashibao Formation) and the Emeishan flood basalts (e.g., Song et al., 2004; Xiao and Xu, 2005; Zi et al., 2010). If this true, it is important to evaluate the role of ELIP event in the evolution of the SGT.

Biastratigraphic, lithological, geochronological, and geochemical studies provide some evidence for the affinity between the SGT and the Yangtze craton. Pre-Neoproterozoic basement with Yangtze affinity has been recognized within and around the SGT (e.g., Chang, 2000; Sichuan BGMR, 1991; Yang et al., 1994). Archean to Paleoproterozoic Yangtze-type basement was discovered along the southeastern margin of the SGT, which suggest the SGT and Yangtze craton share a common Precambrian basement (Fig. 11; Chang, 2000). Biostratigraphic and sedimentologic investigations suggest that late Mesoproterozoic to Paleozoic strata and its fauna–flora in the SGT are comparable to those in the Yangtze craton, and they are considered to have been contiguous until the Permian (e.g., Chang, 2000; Yin and Harrison, 2000; Weislogel, 2008; Fig. 11).

The rift setting characterized by lithosphere stretching has been suggested by the sedimentary environment as reflected in the regional stratigraphic sequence (Zhang et al., 2012). Seismo-megaturbidite has been recognized at the base of the Sandaqiao Formation in the Baoxing area and is composed of coarse bioclastic limestone. This special tectonostratigraphic unit is considered to be formed in submarine collapse slope facies generated by local synsedimentary normal faults, which likely reflect a mantle plume (Emeishan) induced rift and depression movement (Fig. 11; e.g., Chang, 2000; Zhao et al., 2012).

The U-Pb detrital zircons from the Triassic turbidite of the SGT (Weislogel et al., 2006) show major age populations that imply the detrital zircon (ca. 280–250 Ma) provenance as rhodacitic volcanic rocks from felsic igneous Guadalupian-Lopingian (270–250 Ma) strata in the Longmen Shan, possibly associated with rifting of the Songpan-Ganzi basin (e.g., Chen and Yang, 2003). In terms of δ¹³C in the Upper Neoproterozoic carbonate sequences (Doushantuo and Dengying Formation), the Danba area in the SGT and the classical sections (Yichang) of the Yangtze craton have similar variation and are.

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**Fig. 8.** Crustal contamination discrimination diagrams for the Tubagou basalts. (a) (Nb/Th)P vs. (Th/Yb)P. Data source: Primitive mantle (PM), N-type mid-ocean ridge basalts (N-MORB) and OIB, Sun and McDonough (1989); Emeishan picrites, Zhang et al. (2006); Emeishan basalts, Qj and Zhou (2008), Lai et al. (2012); the Yangtze upper ridge basalts (N-MORB) and OIB, Sun and McDonough (1989); Emeishan picrites, Zhang et al. (2006).
comparable, which suggest that they share a common Precambrian basement (Fig. 11; Huang and Buick, 2002 and references therein).

Plume–lithosphere interaction not only causes extensive flood basalt magmatism (CFB/LIP) but may also initiate rifting and continent break-up (e.g., Courtillot et al., 1999), such as Ethiopian/Yemen traps (Courtillot et al., 1987), Deccan LIP (Malod et al., 1997), and Karoo–Ferrar LIP (Duncan et al., 1997) and so on. However, the scales of extensional activities and whether the rifts occur in the CFBs depend greatly on the stress state of the lithosphere, and rift structures tend to follow the trend of pre-existing weaknesses (e.g., Dunbar and Sawyer, 1989; Ziegler and Cloetingh, 2004). Either in the late Neoproterozoic or the early Paleozoic, intra-continental rifts were active along the northwestern margin of the Yangtze craton, and gave rise to tectonic weaknesses (Li et al., 2003; Ling et al., 2003; X.C. Wang et al., 2008).

Based on the geochemical characteristics, combined with the above evidence, the petrogenesis of the Tubagou basalts as well as the evolution of the SGT can be outlined as follows. In the Late Permian (~263 Ma), the arrival of the Emeishan mantle plume at the base of the lithosphere resulted in extensive eruption of flood basalts along the western margin of the Yangtze craton. Like other areas in the periphery of the ELIP, the Dashibao basalts with alkaline affinity (Type I), under a thick lithospheric lip, was produced by low degree of partial melting of a rising mantle plume within the garnet peridotite stability region. The pre-existing weak zones aided in plume–lithosphere interaction and lithospheric thinning. At ca. 257 Ma, with mantle plume upwelling, the tholeiitic LT Dashibao basalts (Type II) were generated by higher degree of partial melting in the spinel–garnet transition field. Meanwhile, the continuous plume-lithosphere interaction resulted in the opening of an intracontinental rift basin, and the SGT was
ultimately split off from the Yangtze craton (Chang, 2000; Chen and Yang, 2003; Song et al., 2004).

6. Conclusions

(1) Two Types basalts have been identified in the Tubagou region in SW China. SHRIMP U-Pb ages reveal that the basalts formed at 257.3 ± 2.0 Ma, mean these basalts were formed coevally with the Emeishan magmatism. In addition, the Tubagou basalts are geochemically similar to the Emeishan basalts, and marked by high clinopyroxene crystallization temperature (1406–1451°C), suggesting the role of the Emeishan mantle plume.

(2) The Tubagou basalts experienced no or minor crustal contamination. Type I has alkaline series affinity and typical OIB-type geochemical characteristics. In contrast, Type II belongs to the tholeiite series and shows geochemical affinity to IRT.

(3) Type I was formed through low degrees of partial melting in the deep mantle source (garnet peridotite region), whereas Type II was most likely generated by higher degrees of partial melting at shallower depths (garnet–spinel transition region). The variations in mantle sources indicate lithosphere thinning during plume-lithosphere interaction, which is responsible for the opening of an extentional basin and the breakup of the SGT from the Yangtze craton.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2016.03.021.

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References


