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Origin of Permian basalts and clastic rocks in Napo, Southwest China: Implications for the erosion and eruption of the Emeishan large igneous province

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ABSTRACT

The Linghao Formation is composed of interbedded clastic and basaltic rocks in the Napo region of Youjiang Basin, Southwest China. The basalts are geochemically divided into low-Ti and high-Ti groups. Relative to the high-Ti group, the low-Ti group exhibits lower Ti/Y ratios, higher ratios of Th/Nb and Th/La, more significant negative Nb–Ta anomalies and lower $\varepsilon_{Nd}(t)$ values (−7.26 to +0.29). The high-Ti group is characterized by primitive mantle normalized OIB-like incompatible element patterns. These geochemical signatures are also comparable to those of the Emeishan high-Ti and low-Ti basalts in Southwest China, respectively, and support a view that both of the low-Ti and high-Ti basalts at Napo are part of the Emeishan large igneous province (ELIP). The geochemical features imply that the high-Ti basalts could have been generated by low degree of melting of the garnet peridotite, whereas the low-Ti basalts may be derived from an EMII-like source. All clastic rocks exhibit no Nb–Ta anomalies on primitive mantle normalized elemental diagrams. Detrital zircons from clastic rocks yield U–Pb ages of ~260 Ma and have a geochemical affinity to within-plate-type magmas, implying a sedimentary source dominated by the ELIP. Most clastic rocks from the upper part of the Linghao Formation show higher TiO_2 contents and lower ratios of Al_2O_3/TiO_2, Th/Sc, and Zr/Sc than those from the lower part. The former were related to the Emeishan high-Ti basaltic rocks, whereas the latter may have mixed felsic source compositions. In terms of chemostatigraphic correlation, we propose that the eruption of the ELIP may be more complex than previously thought and a prolonged and punctuated history of ELIP formation may exist in the Youjiang Basin.

1. Introduction

The Emeishan large igneous province (ELIP) in Southwest China and northern Vietnam (Fig. 1) consists of voluminous high-Ti and low-Ti basalts, picrites, mafic/ultramafic to felsic intrusions, as well as trachytes and rhyolites (Shellnutt and Wang, 2014; Shellnutt and Zhou, 2007; Song et al., 2001; Wang et al., 2007; Xiao et al., 2004; Xu et al., 2001, 2010; Zhang et al., 2006; Zhou et al., 2005, 2006; Zi et al., 2010). The ELIP is likely to have formed near the Guadalupian–Loping boundary (~260 Ma) (He et al., 2007, 2010a; Xu et al., 2008; Zhong et al., 2014; Zhou et al., 2002a) with a short eruption duration (<2 Ma) (Ali et al., 2002, 2005, 2010; He et al., 2007; Shellnutt et al., 2012; Zheng et al., 2010) and so may be the cause of the end-Guadalupian mass extinction (Courtillot et al., 1999; He et al., 2007; Wignall et al., 2009; Zhou et al., 2002a).

Most previous knowledge about the ELIP mainly derives from studies on magmatic rocks that support a mantle plume-induced mechanism for the formation of this large igneous province (Chung and Jahn, 1995; He et al., 2010b; Lai et al., 2012; Song et al., 2008; Xiao et al., 2004; Xu et al., 2001; Zhou et al., 2006; Zi et al., 2010). Only a few studies have discussed the ELIP based on the sedimentology (Ali et al., 2010; He et al., 2003) and the geochemistry of related sediments (He et al., 2007, 2010a). The stratigraphic thinning of the Middle Permian Maokou Formation (limestone) underneath the Emeishan flood basalts likely resulted from regional uplift (He et al., 2003). The uplifted area was broken into three zones on the basis of the amount of inferred erosion (Fig. 1): Inner zone with pre-volcanic uplift of 300 to >1000 mand Intermediate and Outer zones with minimal uplift (Ali et al., 2010; He et al., 2003; Ukstins Peate and Bryan, 2008). This was interpreted to be an independent supporting evidence for the mantle plume-initiation model for the ELIP (Ali et al., 2010; He et al., 2003). However, recent studies have demonstrated that the thickness variations in the Maokou Formation (limestone) are due to structural thinning from faulting and do not

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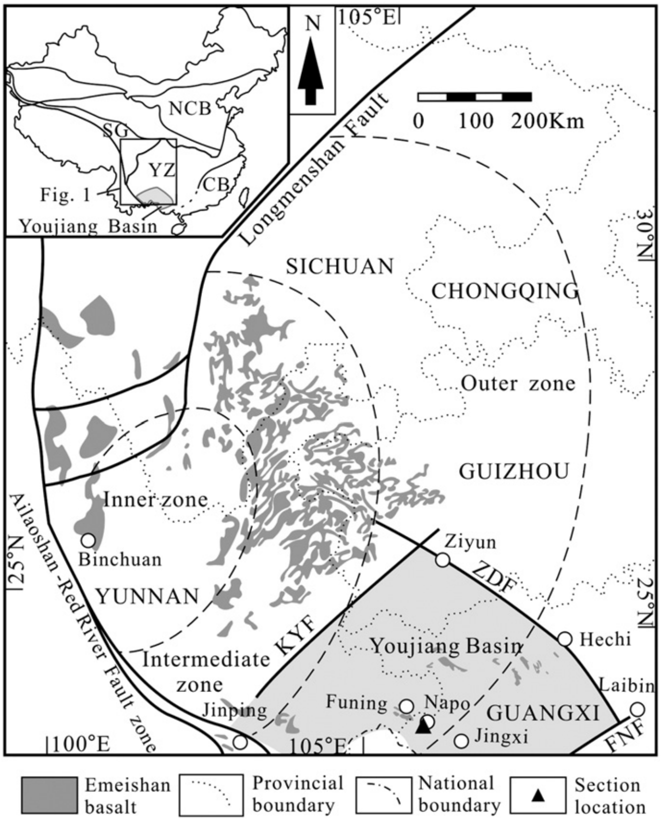

Fig. 1. (a) Schematic map showing the distribution of the Emeishan basalts and the section location (modified from Xu et al. (2001) and Fan et al. (2008)). Dashed lines separate the inner, intermediate and outer zones defined by He et al. (2003). YZ, Yangtze Block; CB, Cathaysian Block; SG, Songpan–Ganzi; NCB, North China Block; KYF, Kaiyuan–Yinyi Fault; ZDF, Ziyun–Danchi Fault; PNF, Pinhxiang–Nanning Fault.

support kilometer-scale plume-related domal uplift prior to Emeishan eruptions (Sun et al., 2010).

The subcircular uplift, called the 'Chuandian old land', existed in the inner zone of the ELIP after the main period of the Emeishan volcanism (He et al., 2007). The Upper Permian Xuanwei Formation (terrestrial clastic rocks) and Longtan Formation (marine clastic rocks), found exclusively around the Chuandian old land, overlie the Emeishan basalts in the eastern ELIP (He et al., 2007). The geochemistry of clastic rocks from the Xuanwei Formation and the Guadalupian–Loping boundary at Chaotian indicates that these clastic rocks were derived from erosional deposits of the ELIP (He et al., 2007, 2010a).

He et al. (2007, 2010a) proposed a model in which the uppermost silicic members in the center of the ELIP were eroded first, and the "felsic" materials were transported and deposited in the eastern ELIP, forming the lowermost part of the Xuanwei Formation and mudstones from the Guadalupian–Loping boundary at Chaotian. Further erosion uncovered the mafic part of the ELIP, and this eroded "mafic" material was deposited over the sediments derived from the felsic flows (He et al., 2010a). The initial deposition of the Upper Permian clastic rocks suggests that the Emeishan volcanism may have terminated and experienced massive erosion.

In this paper, we present whole-rock and zircon geochemistry, zircon U–Pb geochronological and Sr–Nd isotope studies on clastic rocks and basalts of the Upper Permian Linghao Formation at Napo, in the Youjiang Basin, Southwest China. The Linghao Formation clastic rocks and basalts at Napo were formed in a submarine environment, and this volcano–sedimentary sequence will provide new information on the erosion and eruption of the ELIP.

2. Geological background and sampled stratigraphy

The ELIP covers an area of ~250,000 km^2 near the western margin of the Yangtze Block (Fig. 1; Chung and Jahn, 1995; Xu et al., 2001; Ali et al., 2005). The Ailaoshan–Red River strike–slip fault and the Longmenshan fault are traditionally thought to be the southwestern and northwestern boundaries of the province. However, some basalts and mafic complexes exposed in the Songpan–Ganzi Terrane and in northern Vietnam could constitute an extension of the ELIP (Anh et al., 2011; Hanski et al., 2010; Wang et al., 2007; Xiao et al., 2003; Zi et al., 2010). The exposure of the Emeishan basalts is mainly focused in the center of the province (Inner and Intermediate zones) and is relatively poor in the Outer zone (Fig. 1). However, the basalts from the western Guangxi Province and the mafic intrusive rocks and andesitic basalts at Funing in the southeastern Yunnan Province (southeastern ELIP, corresponding to the Outer zone), which have an age and geochemistry comparable to those of the Emeishan basalts, have been interpreted to be part of the ELIP (Fan et al., 2008; Lai et al., 2012; Zhou et al., 2006). The western/central part of the province has the thickest volcanic succession, which may reach 5 km in thickness and is characterized by low-Ti basalts overlain by high-Ti basalts (Xiao et al., 2004; Xu et al., 2001). However, the Outer zone consists of high-Ti basalts, and the thickness of the basalts is less than 100 m (Xu et al., 2001). The Emeishan basalts are covered by clastic rocks belonging to the Upper Permian in the east and the Upper Triassic in the central part (He et al., 2003).

The Youjiang Basin (also termed the Nanpanjiang Basin) is a Late Paleozoic marine basin facing south to the eastern Paleo-Tethys Ocean. The initiation of this basin is associated with Early-Middle Devonian transgression during the opening of the Paleo-Tethys Ocean along the Jinshajiang–Ailaoshan zone (Du et al., 2013; Guo et al., 2004; Huang et al., 2013a). The marine sedimentation in this basin ended with the Indosinian collisional orogenic event along the southern margin of South China in the Middle-Late Triassic (Lehrmann et al., 2014; Yang et al., 2012a, 2012b). During the Late Permian, a complex platform and basinal succession developed in the Youjiang Basin (Du et al., 2013). The basinal deposits are mainly bedded cherts and volcanogenic turbidites that enclose carbonate breccias and bioclastic limestones (Shaiwa and Linghao formations) (Gao et al., 2005; Lehrmann et al., 2005; Yang et al., 2012a).

The Napo area is located in the southwest of the Youjiang Basin and the sampled section is situated in western Napo County (Fig. 2). The Linghao Formation occurs within a sequence composed of Devonian to Middle Permian and Lower-Middle Triassic volcano–sedimentary successions (Fig. 2). The Linghao Formation is mostly composed of basalts and clastic rocks, intercalated by some white thin-bedded chert in the lower part and by some thick-bedded conglomerate limestone in the topmost part (Yang et al., 2014). The volcano–sedimentary succession of the Linghao Formation at Napo is approximately 630-m in thickness (Yang et al., 2014), which has been shown in our section to be about 430-m in thickness (Fig. 3).

The basalts in the lowest part of the Linghao Formation at Napo show pillow structures (Fig. 4a), suggesting a submarine environment. An ~8 m-wide gap at the contact between breccias of the underlying Sidazhai Formation and pillow basalts of the Linghao Formation was obscured by soil and vegetation. Given the highly faulted nature of this area (Fig. 2), a fault is inferred between the breccias of the Sidazhai Formation and pillow basalts of the Linghao Formation. The breccias (~1.5 m thick) in the lower part of the Linghao Formation are composed of angular limestone and black chert clasts of 1–5 cm in size and lenticular, discontinuous and interbedded within yellow, thin-bedded mudstones (Fig. 3). The sandstones in the lower part of the Linghao Formation are gray, thin-to-medium bedded and display parallel bedding. The upper part consists of fine-grained massive basalts intercalated with dark gray, thin-to-medium-bedded mudstone and sandstone. Radiolarian fossils were observed in mudstones from the upper part of