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A lower crust origin of some flood basalts of the Emeishan large igneous province, SW China

J. Gregory Shellnutt [a,*], Tadashi Usuki [b], Allen K. Kennedy [c], Han-Yi Chiu [a]

[a] National Taiwan Normal University, Department of Earth Sciences, 88 Tingzhou Road, Section 4, Taipei 11677, Taiwan
[b] Academia Sinica, Institute of Earth Sciences, 128 Academia Road, Section 2, Taipei 11529, Taiwan
[c] Curtin University, Department of Applied Physics, Kent Street, Bentley, Western Australia 6102, Australia

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ABSTRACT

High seismic velocity layers within the lower crust (i.e. ~40 km) of the Yangtze Block are interpreted as mafic underplated rocks derived from the Late Permian Emeishan mantle plume. However, the region experienced a previous magmatic event during the Neoproterozoic (~800 Ma) that produced the Kangdian basalts and associated mafic intrusions and therefore the lower crust seismic velocity layers may represent a mixture of two different magmatic episodes. The identification of inherited Neoproterozoic (i.e. ~750 to ~850 Ma) zircons within Emeishan magmatic rocks indicates either assimilation of older material during emplacement or that the rocks could be derived from a mafic Neoproterozoic precursor. Equilibrium partial melt modeling of Neoproterozoic Kangdian basalts can produce compositions similar to Emeishan basalt at a pressure of 1.2 GPa (i.e. ≈40 km depth). It is suggested that the injection of high temperature picritic magmas into the lower crust of the Yangtze Block could be sufficient to induce high degrees of melting of the lower crust and produce magmas that are similar in composition to some Emeishan mafic rocks and/or produce melts that could contaminate 'pristine' Emieshan magmas.

1. Introduction

Melting of mafic lower crust is an important process for the genesis of some mafic to silicic magmas (Green, 1971; Kitchen, 1985; Defant and Drummond, 1990; Rapp and Watson, 1995; Stein and Goldstein, 1996; Gao et al., 2004; Pertermann and Hirschmann, 2003; Hirschmann et al., 2003; Smithies et al., 2011). The injection of high temperature magmas into the crust can provide the necessary heat to induce melting of lower crustal lithologies (Green, 1971; Huppert and Sparks, 1988; Annen and Sparks, 2002; Annen et al., 2006). The composition of the magmas produced by partial melting of the lower crust is related to the initial composition of the rocks that are melting but is also related to the amount of melting which in turn is related to the duration of heating (Clemens and Vielzeuf, 1987; Annen and Sparks, 2002; Annen et al., 2006; Smithies et al., 2011).

Regions of voluminous (i.e. 10^5 km^3), contemporaneous and spatially contiguous basic to ultrabasic rocks within the crust are known as mafic large igneous provinces (LIP) and testify to high thermal regimes that transfer melts from the mantle to the crust (Ernst and Buchan, 2003; Campbell, 2005; Saunders, 2005; Bryan and Ernst, 2008). Moreover, some volcanic and plutonic rocks spatially and temporally associated with LIPs are identified as being derived from crustal sources indicating that crustal melting was contemporaneous with mantle melting (Meyer et al., 2009; Shellnutt et al., 2011a, 2012a). The Late Permian Emeishan flood basalts of SW China are the most common rock-type of the Emeishan large igneous province (ELIP). The ELIP is considered to be one of the best examples of a mantle plume-derived large igneous province because there is evidence of pre-volcanic uplift, presence of ultramafic volcanic rocks (i.e. picrites), and a short eruption duration of flood basalts (He et al., 2003; Hanski et al., 2004; Ali et al., 2005; Campbell, 2005, 2007; Shellnutt et al., 2012b; Shellnutt, 2014). One of the most intriguing interpretations of the ELIP mantle plume model is the identification of high seismic velocity layers within the lower crust of the Yangtze Block beneath the region considered to be the epicenter of magmatism. The same region is thought to have thicker average crust than other regions of the western Yangtze Block (Xu et al., 2004; Xu and He, 2007; Chen et al., 2010). Xu et al. (2004) interpreted the deep (i.e. >100 km) high seismic velocity layers to be the fossilized Emeishan mantle plume head whereas the lower crust (i.e. 40–60 km) high velocity layers are considered to be the underplated

* Corresponding author. Tel.: +886 2 7734 6386; fax: +886 2 2933 3315.
E-mail address: jgshelln@ntnu.edu.tw (J.G. Shellnutt).

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mafic and ultramafic rocks that fed the surface flows and shallow crustal intrusions.

The high seismic velocity layers in the lower crust may not solely represent underplated Emeishan rocks. The western margin of the Yangtze Block was the site of either long-lived subduction-related magmatism or mantle plume-related magmatism during the Neoproterozoic (Li et al., 1999; Zhou et al., 2002a,b; Zhao and Zhou, 2007). The Neoproterozoic (∼800 Ma) Kangdian basalts are located at the western boundary of the Yangtze Block within the Kangdian rift and are found within the same geographic area as the Emeishan basalts. The basalts and associated mafic dykes and plutonic rocks are described by Li et al. (2002) as being compositionally similar to continental flood basalts from Ethiopia and/or alkali basalts of Hawaii. In the case of the Kangdian basalts, they are interpreted to be derived from an OIB-like mantle plume source associated with the break-up of Rodina whereas similarly aged granitic rocks and younger (i.e. ∼750 Ma) gabbros in the same region are interpreted to be derived within an active continental margin setting (Li et al., 2002, 2005, 2006; Zhou et al., 2002a,b, 2004; Lin et al., 2007; Zhao and Zhou, 2007; Zhao et al., 2008; Wang et al., 2009, 2010). Regardless of how the Kangdian or other Neoproterozoic rocks formed (i.e. subduction zone setting vs. mantle plume), it is possible that magmas accumulated in the lower crust of the Yangtze Block and thus the crustal seismic layers may not be completely attributed to the ELIP. In fact, the seismic layers could represent a mixture of mafic and ultramafic rocks from both the Kangdian event and the Emeishan event.

In this paper we report the results of *in situ* zircon U/Pb dating and Hf isotopes of inherited Neoproterozoic zircons from Late Permian granitic rocks of the ELIP. We discuss the origins of the inherited zircons and evaluate the possibility that some ELIP-related magmatic rocks, including the flood basalts, may be derived by partial melting of mafic rocks at lower crustal depth (i.e. 1.2 GPa).

2. Geological background

The Late Permian ELIP is located in southwestern China on the western edge of the Yangtze Block near the boundary with the Early Triassic Songpan-Ganze terrane (Fig. 1a). The distribution of ELIP rocks was affected by faulting associated with the accretion of the Songpan-Ganze terrane and later during the Paleogene collision of India and Eurasia. ELIP rocks cover an area of at least 0.3×10^6 km^2 including the Song Da zone of northern Vietnam that was translated ∼600 km along the Ailao Shan-Red River shear zone during the Oligocene (Chung and Jahn, 1995; Chung et al., 1997). The ELIP is subdivided into three structural zones (i.e. inner, intermediate and outer) based on crustal thickness estimates using seismic profiling (Fig. 1a and b). The inner zone of the ELIP is interpreted to have the thickest crust followed by progressively thinner crust within the outer zone (Xu et al., 2004). The volcanic succession ranges from a maximum thickness of ∼5 km in the inner zone to <1 km at the margin of the outer zone. The volcanic rocks consist mostly of flood basalts but there are picrites found amongst the lower flows of the inner zone whereas basaltic andesites and silicic volcanic rocks are common within the upper flows throughout the ELIP. The flood basalts are compositionally divided into 'high-Ti' and 'low-Ti' groups that are interpreted to reflect different petrological origins. The 'high-Ti' (i.e. TiO_2 > 2.5 wt%) basalts are considered to be derived by low degrees (<8%) of partial melting of a mantle plume source within a rift setting whereas the formation of the 'low-Ti' basalts (i.e. TiO_2 < 2.5 wt%) is debated. The 'Low-Ti' basalts may be derived from the sub-continental lithospheric mantle (SCLM), or by crustal contamination of picritic magmas, or melting of the same source as the high-Ti basalts but merely represent higher degrees (i.e. 10–15%) of partial melting (Xu et al., 2001; Song et al., 2001, 2004, 2008a,b; Hanski et al., 2004; Xiao et al., 2004; Hou et al., 2006; Wang et al., 2007, 2011; Fan et al., 2008; Zhou et al., 2008; Shellnutt and Jahn, 2011). The inner zone, chiefly the area between Panzhihua and Xichang (i.e. Panxi region), contains many giant orthomagmatic Fe–Ti–V oxide deposits whereas Ni–Cu-(PGE) and PGE deposits occur within the inner zone and outer zone (Shellnutt, 2014). During the Late Permian the Yangtze Block was located at equatorial latitudes off eastern Pangaea and the ELIP volcanic rocks erupted on top of middle Permian limestones or directly on to Precambrian cratonic rocks.

The granitic plutons of this study are located in the Song Da zone of northern Vietnam and the Panzhihua area in Sichuan (Fig. 2). The Song Da zone is on the SW side of the Ailao Shan-Red River (ASRR) fault and consists of the Phan Si Pan uplift, Tu Le basin and Song Da belt (Fig. 2). The Song Da zone rocks from the Phan Si Pan uplift and Tu Le basin and are considered to be correlative with the inner zone of the ELIP (Usuki et al., 2015). The area is crosscut by the left-lateral ASRR shear zone that extends for over 1000 km from SE Tibet to the South China Sea (Tapponnier et al., 1990; Leloup et al., 1995; Chung et al., 1997). The Phan Si Pan uplift consists mainly of Phanerozoic alkaline and sub-alkaline granitoids with some Precambrian igneous and meta-igneous rocks whereas the Song Da belt consists of picrite, flood basalt, rhyolitic rocks and Mesozoic sedimentary rocks (Lan et al., 2001; Nam et al., 2003; Hanski et al., 2004; Wang et al., 2007; Anh et al., 2011). The volcanic rocks of the Song Da belt rest on early Permian limestone and are unconformably overlain by Triassic limestone and coal-bearing shale (Anh et al., 2011). The Tu Le basin consists of alkaline rhyolite and trachyte.

Two granitic plutons from the Panzhihua area of the ELIP were selected for this study (Fig. 3). The peraluminous Yingpanliangzi pluton is located within the city of Panzhihua just south of the Jinsha River and intrudes Neoproterozoic (i.e. ∼800 Ma) granitic gneisses and Sinian (i.e. ∼600 Ma, depositional age) limestone that was deposited on top of the gneisses and subsequently metamorphosed to marble (Shellnutt et al., 2011a; Ganino et al., 2013). The outcrop is along a dirt road revealing fresh, albeit sporadic outcrops that contain ellipsoidal microgranular enclaves that are more mafic than the host rock. The pluton is known to be younger than ∼600 Ma because dykes emanating from the main exposure are observed cutting the Denying (∼600 Ma) marble. The sample (GS03-065) dated for this study is located at 26°33′36″ N, 101°42′53″ E. The peralkaline Panzhihua granite is located (i.e. 26°34′29″ N, 101°37′38″ E) to the west of the Yingpanliangzi pluton and intruded Emeishan flood basalt. The Panzhihua granite is interpreted to be petrogenetically related to the Panzhihua layered gabbroic intrusion that hosts a world-class Fe–Ti–V oxide deposit (Shellnutt and Jahn, 2010).

3. Methods

Zircon grains were separated using conventional heavy liquid and magnetic techniques, mounted in epoxy, polished, coated with gold, and photographed in transmitted and reflected light to identify grains for analysis. U/Pb isotopic ratios of zircons from sample GS03-065 (i.e. peraluminous granite) and GS03-010 (i.e. peralkaline granite) were measured using the SHRIMP II at Curtin University of Technology in Perth, Western Australia and Chinese Academy of Geological Sciences, Beijing, China, respectively. The measured isotopic ratios were reduced off-line using standard techniques (Claoue-Long et al., 1995) and the U/Pb ages were normalized to a value of 564 Ma determined by conventional U–Pb analysis of zircon standards CZ3 (GS03-065) and TEMORA-1