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Letter

Al-in-olivine thermometry evidence for the mantle plume origin of the Emeishan large igneous province

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ABSTRACT

The Emeishan large igneous province (ELIP) is renowned for its world-class Ni–Cu-(PGE) deposits and its link with the Capitanian mass extinction. The ELIP is generally thought to be associated with a deep mantle plume; however, evidence for such a model has been challenged through geology, geophysics and geochemistry. In many large igneous province settings, olivine-melt equilibrium thermometry has been used to argue for or against the existence of plumes. However, this method involves large uncertainties such as assumptions regarding melt compositions and crystallisation pressures. The Al-in-olivine thermometer avoids these uncertainties and is used here to estimate the temperatures of picrites in the ELIP. The calculated maximum temperature (1440 °C) is significantly (~250 °C) higher than the Al-in-olivine temperature estimated for the average MORB, thus providing compelling evidence for the existence of thermal mantle plumes in the ELIP.

1. Introduction

The origin of large igneous provinces (LIPs) remains a matter of intense debate (Anderson, 2005), with many researchers favouring the involvement of deep mantle plumes (Campbell, 2007). Alternative models to explain within-plate magmatism without invoking a mantle plume include high water content (Xia et al., 2016), anomalously fertile mantle (subducted eclogitic crustal lithologies stored in the mantle) (Sobolev et al., 2007), continental lithospheric delamination (Tanton and Hager, 2000), edge-driven mantle convection (King and Anderson, 1998), meteorite impact (Jones, 2005) and slab break off (Keskin, 2003). Due to the lack of independently unambiguous evidence, however, the existence of hot mantle plumes has been extensively debated over the years (Campbell, 2007; Foulger et al., 2015; Lustrino and Anderson, 2015; Sobolev et al., 2016).

Estimates of the crystallisation temperatures of Mg-rich magmas are critical for our understanding of the thermal state of the mantle and testing the mantle plume model (Campbell, 2001; Herzberg, 2011; Herzberg and Asimow, 2015; Zhang et al., 2006). The olivine-melt equilibrium-based thermometer was conventionally thought to be one of the most precise methods available until recently (Herzberg et al., 2007; Herzberg and O'hara, 2002; Putirka et al., 2007). However, olivine thermometry requires determination of a primary magma composition that is equilibrated with olivine in the mantle source (or maximum forsterite content of olivine phenocrysts observed) and an appropriate olivine-liquid Fe-Mg exchange reaction coefficient ($KD^{Ol/liq}_{Fe/Mg}$). These parameters may lead to ambiguous results (Coogan et al., 2014) if using the same data with slightly different assumptions to calculate the primary melt compositions (e.g., Falloon et al., 2007; Putirka et al., 2007).

The Al-in-olivine thermometer (Wan et al., 2008) is based on the temperature dependence of the partitioning of Al between coexisting forsterite-rich olivine and chromium spinel. It has the advantage of being largely independent of crystallisation pressure, oxygen fugacity, melt composition (e.g., volatiles such as H_2O and CO_2) and source lithology (e.g., pyroxenite) (Coogan et al., 2014; Wan et al., 2008). However, it is not recommended for olivine-spinel pairs that are outside the calibration ranges of the experiments (Coogan et al., 2014; Wan et al., 2008). Furthermore, as a trivalent cation, Al diffuses much more slowly in the olivine lattice than Mg and Fe (Spandler and O'Neill, 2010). Hence, the initial crystallisation information may be preserved through the Al content, even when Fe and Mg have been reset. Olivine and Cr-spinel are usually the earliest minerals crystallised from the most primitive magmas (Wan et al., 2008), so the Al-in-olivine thermometer enables us to make an accurate estimation of the maximum temperature of the primitive magmas (Coogan et al., 2014).

The Late Permian (~260 Ma) Emeishan large igneous province (ELIP) in southwest China (Fig. 1) contains a series of world-class Ni–Cu–(PGE) sulphide deposits and Fe–Ti–V oxide deposits. The ELIP is also synchronous with several major geologic events such as the Capitanian mass extinction event, an ocean super-anoxic event, a major C and Sr isotope excursion, the Illawara geomagnetic reversal, sea-level drop and climate cooling during the Late Permian (Shellnutt, 2014; Wignall et al., 2009; Yang et al., 2015), which indicates a possible relationship between

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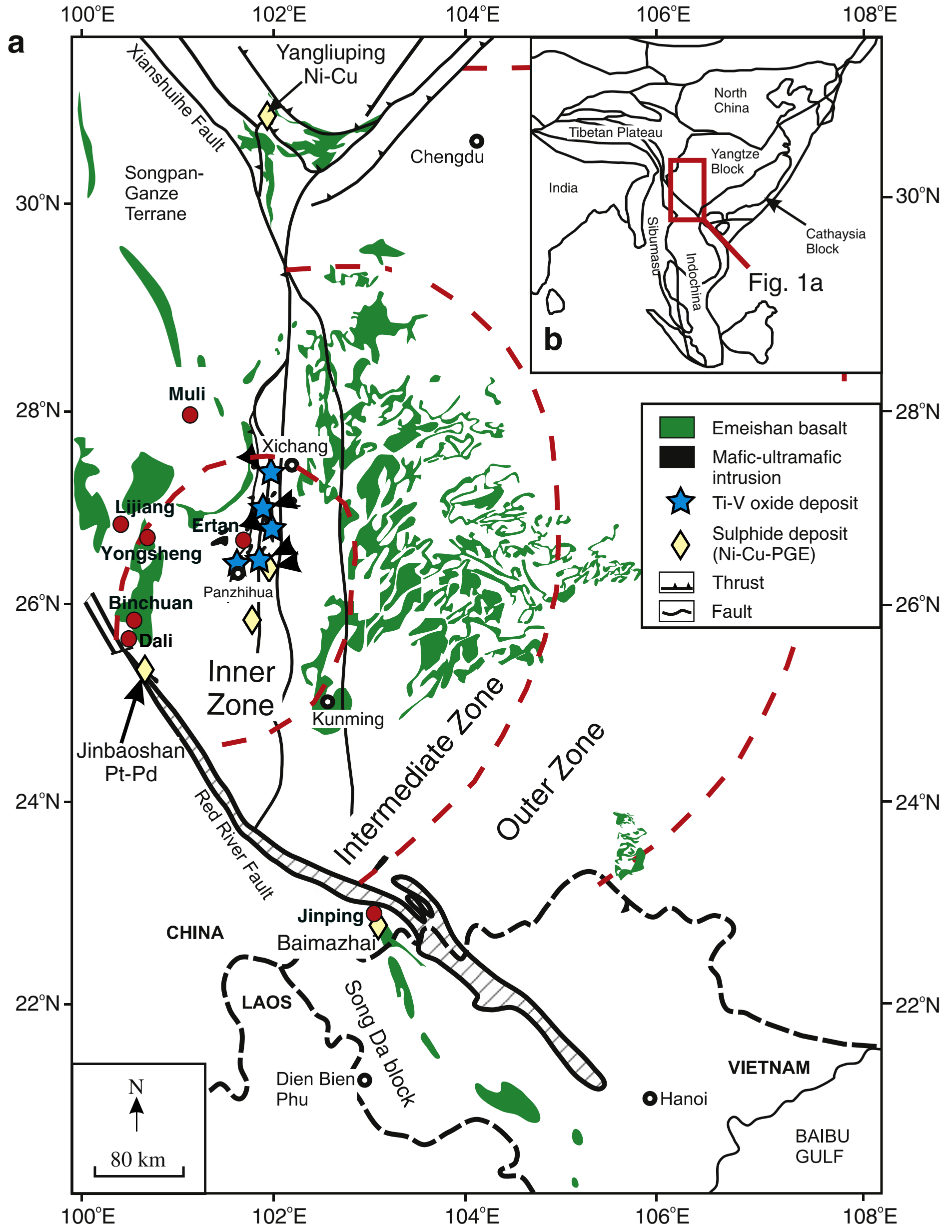

Fig. 1. (a) Distribution of the Emeishan large igneous province showing the concentric zones (dashed red lines), volcanic and intrusive rocks, and Ti–V oxide and Ni–Cu-PGE sulphide deposits (Shellnutt, 2014). Red circles show locations of picrites from Yongsheng, Binchuan and Dali that were reported in Kamenetsky et al. (2012) and used in this study. (b) Major tectonic divisions of China. Modified after Shellnutt (2014).

them. Understanding the origin of the ELIP is therefore of critical importance. The ELIP is generally thought to be a mantle plume-derived LIP (Chung and Jahn, 1995; He et al., 2003; Li et al., 2015; Xu et al., 2001, 2004; Zhang et al., 2006, 2008, 2009); however, such a hot mantle plume model has been challenged recently (He et al., 2014; Jerram et al., 2016; Kamenetsky et al., 2012; Peate and Bryan, 2008; Shellnutt, 2014; Shellnutt et al., 2010; Sun et al., 2010). For example, Peate and Bryan (2008) suggested that the geological evidence for dynamic pre-volcanic uplift as predicted by plume models is lacking. Based on receiver function analysis, He et al. (2014) proposed that delamination of the lower crust to the mantle transition zone could have generated the basalts in the ELIP, so the mantle plume model is unnecessary. Geochemically, Kamenetsky et al. (2012) suggested that the picrites originated from the sub-continental lithospheric mantle that is composed of variable proportions of garnet pyroxenite and peridotite rather than a deep-seated mantle plume source or asthenospheric source. As a result, an accurate estimate of the crystallisation temperatures of the most primitive magmas is critical for properly understanding whether the ELIP originated from an anomalously hot source region. Here, we address this issue using the Al-in-olivine thermometer for the ELIP picrites.

2. Geological setting

The ELIP is located at the western edge of the Yangtze craton in SW China, which is composed of a large continental flood basalt province of an area at least 0.3×10^6 km^2 in SW China and northern Vietnam (Song Da zone) (Fig. 1) (Shellnutt, 2014; Xu et al., 2004). The wedge-shaped distribution of ELIP volcanic rocks is interpreted to be related to Mesozoic and Cenozoic faulting that is associated with the development of the Songpan-Ganze terrane and India-Eurasia collision (Chung and Jahn, 1995). It consists of mafic and ultramafic volcanic rocks and contemporaneous felsic plutons and layered mafic–ultramafic intrusions, some of which host giant Fe–Ti–V oxide and Ni-Cu-PGE sulphide deposits (Shellnutt, 2014). The ELIP is generally subdivided into three