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Petrology and geochemistry of Permian mafic–ultramafic intrusions in the Emeishan large igneous province, SW China: Insight into the ore potential

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ABSTRACT

Mafic–ultramafic layered intrusions constitute important components in the western part of the Emeishan large igneous province (LIP) in SW China. Here we present zircon U–Pb geochronology, geochemistry and Sr–Nd isotopic data from four representative barren mafic–ultramafic intrusions in Wupodan (WPD), Shangyi (SY), Louyi (LY) and Xiayi (XY). All these four intrusions were emplaced during the Late Permian, coeval with the formation of Emeishan flood basalts and associated mineralized intrusions. All rocks from the four intrusions exhibit mineralogical homogeneity, in the absence of any associated intermediate-felsic plutons. Chondrite-normalized REE patterns of LY, SY and WPD intrusions exhibit moderately fractionated patterns with $(La/Yb)_N$ of 3.55–5.12, whereas the XY intrusion shows pronounced LREE enrichment with $(La/Yb)_N$ of 11.61–12.94. Samples from the four intrusions lack any significant Eu anomalies, and have low $\varepsilon_{Nd}(t)$ values of −3.0 to −1.9 and variable initial $^{87}Sr/^{86}Sr$ ratios of 0.7057–0.7074, overlapping with the field defined by Permian Emeishan basalts and the related mineralized mafic–ultramafic intrusions. Clinopyroxenes from the SY, WPD and LY intrusions show relatively high equilibrium temperatures ranging from ~1300 °C to ~1400 °C, which can be regarded as a signature of plume-related origin. Although the clinopyroxenes from the XY intrusion exhibit a relatively lower equilibrium temperature (~1200 °C), the geochemical signature resembling OIB suggests a plume-related origin. Thus, these intrusions appear to be part of the Emeishan LIP. These features, combined with moderate to pronounced depletion of HFSE (e.g. Nb, Ta and Ti) and enrichment of LILE (e.g. Rb, Ba, K), correlate the LY, SY and WPD intrusions to the interaction between mantle plume and subcontinental lithospheric mantle that had been previously modified by subduction-related materials. In contrast, the XY intrusion was derived from the plume source contaminated by subcontinental lithospheric mantle. We also attempt a comparison between the unmineralized and mineralized intrusions in terms of their parental magmas, crystallization history, nature of the mantle source, degrees of partial melting of source and the extent of crustal contamination. Some geochemical criteria that may be useful in discriminating between mineralized and unmineralized mafic–ultramafic intrusions are summarized, and insights into the ore potential of the four barren intrusions are addressed.
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1. Introduction

The Emeishan large igneous province (LIP) in SW China incorporates several world-class Fe–Ti–V oxide deposits, interspersed with numerous Cu–Ni–(PGE) sulfide deposits, although it is relatively small in volume (~0.3×10^6 km^3, Ali et al., 2005). These deposits are hosted by mafic–ultramafic intrusions, underlying the lava pile, and are mainly exposed in the central part of the Emeishan LIP. Based on previous studies, the mineralized mafic–ultramafic intrusions can be classified into two types (Fig. 1): (1) small ultramafic subvolcanic sills that host magmatic Cu–Ni–(PGE) sulfide-bearing ores (e.g., Limahe, Baimazhai, Yangliuping, Jinbaoshan and Zhubu; Song et al., 2003; Tao et al., 2007, 2008; Wang and Zhou, 2006); and (2) large mafic layered intrusions that host giant Fe–Ti–V oxide deposits (e.g., Panzhihua, Baima, and Taihe; Shellnutt et al., 2009a; Zhou et al., 2005 and references therein; Ganino et al., 2013; Howarth and Prevec, 2013; Pang et al., 2013). In addition to the two major types, a transitional type (e.g., Xinjie and Hongge) hosting both Fe–Ti–V oxide and Cu–Ni–(PGE) sulfide deposits at different stratigraphic levels have also been recognized (Dong et al., 2013; Zhang et al., 2009a; Zhong et al., 2002, 2004), similar to those in the Bushveld Complex in South Africa (Eales and Cawthorn, 1996; Kruger, 2005; Lee, 1996). Although numerous investigations on the petrologic and geochemical features of the ore-bearing intrusions have been carried out (Ganino et al., 2008; Pang et al., 2008b; Song et al., 2003; Tao et al., 2007, 2008; Wang and Zhou, 2006; Zhang et al.,

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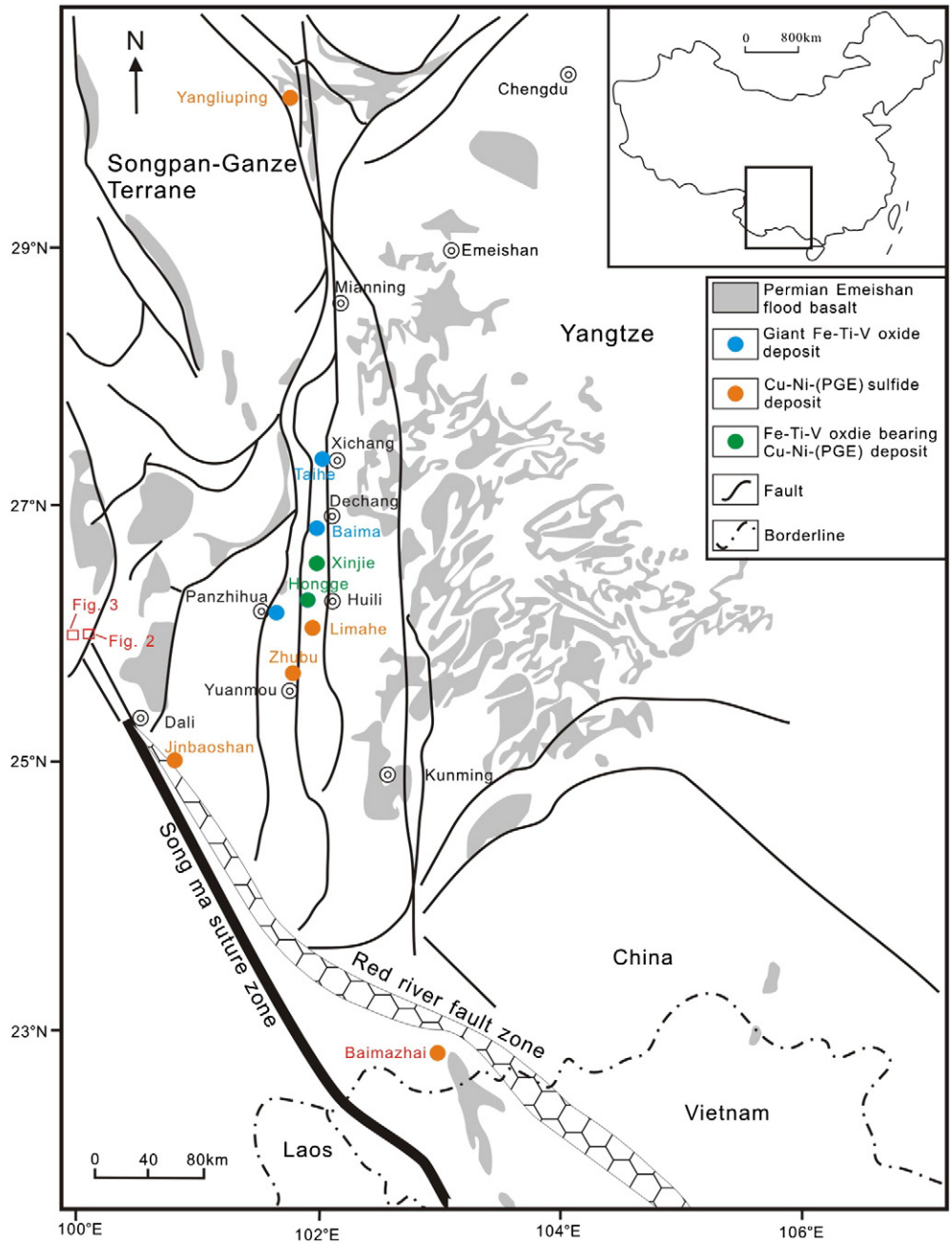

Fig. 1. Sketch map showing the distribution of the Emeishan flood basalt and related main types of deposits. Modified after Song et al. (2009a).

2009b; Zhou et al., 2005), the signatures of mineralization have not been clearly identified, especially the mechanism by which millions of tonnes of metallic elements were concentrated to form massive oxide or sulfide deposits remain poorly understood.

In addition to the mineralized intrusions, many contemporary barren mafic–ultramafic intrusions have also been recognized in the Emeishan LIP recently. These barren intrusions show geochemical signatures similar with those of the mineralized counterparts. These intrusives therefore raise a number of interesting questions such as the processes governing the formation of the mineralized and barren intrusions and the exploration potential of the latter type. In order to address these problems, we selected four representative barren mafic–ultramafic intrusions (Xiayi, Louyi, Shangyi, and Wupodan) for detailed petrological, geochronological and geochemical studies, and we attempt to discuss the petrogenetic aspects and present a comparison between the mineralized and barren intrusions with a view to understand the key factors governing mineralization of Fe–Ti–V oxide and Cu–Ni–(PGE) sulfide ores within this large igneous province.

2. Geological setting

2.1. Regional geology

The Emeishan LIP, exposed in southwestern China and northern Vietnam, covers an area of >2.5 × 10^5 km^2 (Fig. 1; Ali et al., 2005; Chung and Jahn, 1995; Hanski et al., 2004; Zhang et al., 2009a), and is composed dominantly of flood basalts and numerous associated intrusions compositionally ranging from mafic/ultramafic to felsic. The Emeishan LIP has been widely considered to be the product of mantle

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