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Multiple magma evolution and ore-forming processes of the Hongge layered intrusion, SW China: Insights from Sr–Nd isotopes, trace elements and platinum-group elements

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ABSTRACT

The Hongge layered intrusion (259 Ma), which is located in the inner zone of the Emeishan large igneous province (ELIP), is one of the most typical Fe–Ti–V ore deposits in the Pan–Xi area. Mafic–ultramafic layered intrusions of the ELIP have attracted a lot of attention lately because these intrusions host world class Fe–Ti–V oxide deposits plus interesting Cu–Ni–(PGE) mineralization which may have economic potential. This paper, reports new whole-rock major and trace element compositions, PGE abundances and Sr–Nd isotopic data for selected cumulate rocks and basalts. We use these data to investigate the nature of parental magmas and the controls on its evolution from the source mantle en route to the surface involving the Hongge ore-bearing intrusion. Two abrupt changes in Mt/Ilm and trace element ratios such as Ba/Th with depths in the Hongge layered intrusion indicate that this intrusion formed by at least two pluses of relatively primitive magma. The whole rock Sr–Nd isotopic data of basaltic and intrusive rocks plot in the region of Emeishan low-Ti basalts and the compositions of residual liquid (at ~1260 °C and 1155 °C) calculated by MELTS are similar to our actual high-Ti (BFQ-2) and low-Ti (BC-1) basltic samples, indicate they are co-magmatic rather than derivation from a distinct source. Total PGE abundances in the Hongge samples are extremely low, ranging from 0.5 to 10 ppb. Sulfide-bearing rocks in the Hongge intrusion and the nearby coeval Banfangqing and Baicao basalts have similar mantle-like Pd/Pt ratios (2–6) and extremely high Cu/Pd ratios (3×10^4 to 4×10^5), indicating that sulfide segregation took place at depth prior to emplacement at Hongge and eruption in this region. Sulfide saturation in the Hongge magma may have resulted from such crustal contamination event. Crystallization of silicate minerals under the anhydrous magma, magma hydration plus Fe–Ti enrichments in the parental magma are three critical factors for the formation of Fe–Ti oxide ore layers in the Hongge intrusion.

1. Introduction

Layered intrusions can provide valuable insights into understanding the genesis and evolution processes of mafic–ultramafic magma and the ore-forming processes associated with the formation of Cr, Fe–Ti–(V), and platinum group element (PGE) deposits, because they record the evolution history of magma associated with LIPs and passive continental margin (e.g. Wager and Brown, 1968; Irvine, 1975; Keays et al., 1999; Cabri, 2002). The ~260 Ma Emeishan large igneous province (ELIP) is one of the best exposed LIPs and hosts two types of temporally and spatially associated intrusions within it; these are: a. Fe–Ti–V oxide deposits in mafic–ultramafic layered intrusions, including the Panzhihua, Hongge, Taihe and Baima intrusions (Zhong et al., 2002, 2005; Zhou et al., 2005, 2008; Pang et al., 2008b); and b. Ni–Cu–(PGE) sulfide deposits in other mafic–ultramafic bodies, including the Limahe, Jinbaoshan, Baimazhai and Yangliuping intrusions (Song et al., 2003; Wang et al., 2006; Tao et al., 2007, 2008).

The Hongge intrusion in the Panzhihua–Xichang (Pan–Xi) area hosts the largest magmatic Fe–Ti–V oxide deposit in this region. It contains about 4572 Mt of oxide ores with 27 wt.% FeO, 10.6 wt.% TiO_2, and 0.24 wt.% V_2O_3 and presences of 0.5–3.5% disseminated sulfides (Yao et al., 1993; PXGT, 1987). Two main models including that fractional crystallization (Shellnutt et al., 2009, 2011, 2013; Shellnutt and Jahn, 2010) and liquid immiscibility (Zhou et al., 2005; Liu et al., 2014a, 2014b) were suggested as the main mechanisms for the Fe–Ti oxide ores in the Panxi district. Additionally, Ganino et al. (2008) proposed that the reaction between the mafic magma and the footwall limestone elevated

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the oxygen fugacity which results in early crystallization of Fe–Ti oxide and the formation of the Fe–Ti oxide ore layers in the Lower Zone of the Panzhihua intrusion. In addition, Bai et al. (2012a) has suggested that the Fe–Ti oxide ore layers in the Hongge intrusion were formed by injection of multiple pulse of Fe–Ti-rich magma and accumulation of titanomagnetite in a dynamic system. However, the precise mechanisms which concentrate million tons of Fe, Ti and V metals in this region are still debated and enigmatic.

PGE (Platinum-group elements) commonly are highly siderophile elements and their behavior can provide valuable information on the petrogenesis of mantle-derived igneous rocks and their source. The processes such as magma-rock interaction, sulfur saturation and sulfide segregation can be traced by PGE due to their high sensibility (Barnes et al., 1985; Keays, 1995; Lorand et al., 2008). The PGE content (total PGE: 0.09–63.5 ppb) in the Fe–Ti oxide layers of the Hongge intrusion appear to be very low (Bai et al., 2012b), which inspire us to use the low PGE concentrations to explore the nature of the mantle source and the sulfide saturation processes for the Hongge intrusion.

In this paper, we focus on the sulfide-enriched rocks, the Fe–Ti oxide ores and the associated basalts in the Hongge layered intrusion. New whole-rock major, trace element, PGE and Sr–Nd isotopic data of selected cumulate and basaltic rocks are reported to investigate the characteristic of parental magmas and to provide a better understanding of the evolution of the parental magma from the source mantle en route to the surface, more importantly, the critical factors required to constrain the formation of Fe–Ti ores within the Hongge layered intrusion.

2. Geological background

The Emeishan large igneous province (ELIP) is located between the western Yangtze Block and the eastern Tibetan Plateau and composed of massive flood basalts, numerous mafic–ultramafic layered intrusions, granites, syenites and other alkaline intrusions (Chung and Jahn, 1995; Fig. 1). The ELIP has attracted much attention because it contains numerous world-class V–Ti iron oxide deposits and is contemporaneous with the end-Guadalupian (~260 Ma) mass extinction (Shellnutt, 2014). The Emeishan continental flood basalts (ECFB), overlying the middle late Permian limestone of the Maokou formation, are exposed in the western Yangtze block with an area of approximately 5×10^5 km^2 (Xiao et al., 2004a,b). The basaltic sequence ranges in thickness from several hundred meters in the east to over 5 km in the west (Xu et al., 2001). The Emeishan basalts in the central ELIP include upper high-Ti (HT) basalts ($TiO_2 > 2.5$ wt.%, Ti/Y > 500) and lower low-Ti (LT) basalts ($TiO_2 < 2.5$ wt.%, Ti/Yb < 500), which are considered to have been derived from distinct mantle sources (He et al., 2010; Xiao et al., 2004a; Xu et al., 2001) or formed by fractional crystallization of different mineral phase from a common parental magma (c.f. Hao et al., 2004; Zhang, 2009; Dong and Zhang, 2009; Shellnutt and Jahn, 2011). Sporadic picrites associated with the high-Ti basalts were recorded from several localities (Chung and Jahn, 1995; Zhang et al., 2006). The recent study of Kamenetsky et al. (2012) indicated that the picrite lavas from thick stratigraphic successions at Binchuan and Yongsheng represent the low-Ti and high-Ti end-members of continental flood basalt magmatism, respectively. The high-Ti flood basalts have similar trace element and Sr–Nd isotope characteristic comparable with the OIB and are considered to be associated with a mantle plume (Song et al., 2001; Zhou et al., 2002, 2006).

In the central ELIP, numerous mafic–ultramafic layered intrusions containing Fe–Ti oxide deposits and Cu–Ni–(PGE) sulfide mineralization are exposed in the Pan–Xi area that has been controlled by a series of N–S-trending faults. These intrusions are distributed along the 200-km-long rift belt, including the Hongge (259 ± 1.3 Ma, Zhong and Zhu, 2006), and Xinjie (259 ± 3 Ma, Zhou et al., 2002) mafic–ultramafic intrusions and the Panzhihua (261 ± Ma, Shellnutt et al., 2011), Baima (261 ± 2 Ma, Shellnutt et al., 2009) and Taihe (262 ± 3 Ma, Guo et al., 2004) mafic intrusions. The relatively small sill-like intrusive bodies located in the central ELIP (e.g., Limahe, Tao et al., 2009) and outer zone of ELIP (Baimazhai, Wang et al., 2006; Yangliuping, Song et al., 2003) host Cu–Ni–(PGE) sulfide mineralization.

3. Geology and petrography of the Hongge layered intrusion

The 15 km-long, 3–5 km-wide, 1.2 km-thick and NNE-striking elongated lopolith Hongge Fe–Ti–V oxide ore deposit which crops out over an area of about 60 km^2 is located to the northeast of Panzhihua city (Fig. 1). The Hongge intrusion intersects the dolomitic limestones of the Sinian Dengying Formation and granitic gneisses of the Neoproterozoic Kangding Complex. The Dengying Formation is composed of dolomitic limestone, which is metamorphosed to marble in place adjacent to the layered intrusion. The west and north contact zones of the intrusion were intruded by the late Permian alkaline granites and alkaline syenites (Fig. 1; Zhang et al., 1999). The Hongge intrusion was surrounded and cut by ~255.2 ± 3.6 Ma later Permian granite and syenite (Xu et al., 2008). Part of the intrusion at the northeast corner is overlain by ~180 m-thick basaltic sequence of the ECFB (Fig. 1c). Based on the cumulus minerals and lithologic textures (Figs. 2 and 3; Zhong et al., 2002), the strongly differentiated Hongge intrusion was divided into three lithologic zones from the base to the top: the lower olivine clinopyroxenite zone (LOZ), the middle clinopyroxenite zone (MCZ) and the upper gabbro zone (UGZ). The LOZ and MCZ are characterized by the appearance and disappearance of olivine whereas the UGZ is defined by the appearance of abundant euhedral apatite. The massive Fe–Ti oxide bodies mainly occur in the upper part of the LOZ and the lower part of the MCZ (Zhong et al., 2002) as layers with different thickness contacts with the intrusion.

The thickness of LOZ is about 340 m. It is composed of medium- to fine-grained rocks containing cumulus olivine, magnetite and ilmenite and minor chromite, and intercumulus clinopyroxene and hornblende within its lower part. The Fe–Ti oxide minerals occur as inclusions in the cumulus phases clearly indicate they precipitated early than silicate minerals (primocrysts) including olivine and clinopyroxene. Fine-grained magnetite and ilmenite mainly occur in the interstitial spaces between olivine and clinopyroxene. The MCZ comprises lherzolite and olivine clinopyroxene at the bottom and clinopyroxenite at the top, which contains cumulus plagioclase. The MCZ has more interstitial magnetite and ilmenite than the LOZ. Minor amounts of Cr-spinel and olivine locate in the rocks beneath the massive Fe–Ti oxide layers. The abundance of plagioclase increases progressively from the base to the top in the MCZ and UGZ. Some clinopyroxene crystals in the base of the MCZ contain exsolved Fe–Ti oxides. The MCZ contains the largest and richest economic Fe–Ti–V oxide layers. Also, platinum-group element-rich horizons were documented in the lower parts of the LOZ and the MCZ, which are below a thick magnetite horizon. The average total PGE concentration in the PGE-enriched horizon within the LOZ and the MCZ is 0.354 ppm and 0.533 ppm, respectively (Liang et al., 1998). Pyrrhotite is the major sulfide mineral, accounting for ~90% of the sulfide assemblages. Sperrylite, vincentite and laurite are the most common platinum-group minerals (PGM) within the intrusion (Liang et al., 1998). The 527- to 1346-m-thick UGZ is composed of plagioclase, clinopyroxene, with minor olivine in its base.