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Platinum-group elemental chemistry of the Baima and Taihe Fe–Ti oxide bearing gabbroic intrusions of the Emeishan large igneous province, SW China

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ABSTRACT

Nickel-, copper-, and platinum group element (PGE)-enriched sulphide mineralization in large igneous provinces has attracted numerous PGE studies. However, the distribution and behavior of PGEs as well as the history of sulphide saturation are less clear in oxide-dominated mineralization. Platinum group elements of oxide-bearing layered mafic intrusions from the Emeishan large igneous province are examined in this study. Samples collected from the Baima and Taihe oxide-bearing layered gabbroic intrusions reveal contrasting results. The samples from Baima gabbroic rocks have low total PGE abundances ($\Sigma PGE < 4$ ppb) whereas the Taihe gabbroic rocks, on average, have more than double the concentration but are variable ranging from $\Sigma PGE < 2$ ppb to $\Sigma PGE \sim 300$ ppb. The Baima gabbro is platinum-subgroup PGE (PPGE = Rh, Pt and Pd) enriched and iridium-subgroup PGE (IPGE = Os, Ir and Ru) depleted, with a distinct positive Ru anomaly on a primitive mantle normalized multi-element plot. The Taihe gabbros are also PPGE enriched but with negative Ru and Pd anomalies on a primitive mantle normalized multi-element plot. The PGE concentrations of Baima rocks are indicative of fractionation of a relatively evolved, mafic, S-undersaturated parental magma that was affected by earlier sulphide segregation. In contrast, the Taihe rocks record evidence of both S-saturated and S-undersaturated conditions and that the parental magma was likely emplaced very close to S-saturation. Comparisons of the platinum group element contents in the Emeishan flood basalts and the Emeishan oxide-bearing intrusions suggest that the PGE budget in a magma is not controlled by magma series (high-Ti vs. low-Ti), but very much by crustal contamination. The unlikelihood of substantial crustal contamination in the Taihe magma allowed the magma to remain S-undersaturated for a longer duration. PGE and sulphide mineralization was not identified in the Taihe intrusion but the presence of one PGE-enriched sample ($Pt + Pd = \sim 300$ ppb) suggests that the parental magma likely did not experience sulphide segregation and is a potential target for further prospecting.

1. Introduction

The Late Permian Emeishan large igneous province (ELIP) of SW China is host to magmatic Ni–Cu–(PGE) sulphide and Fe–Ti–V oxide deposits which contain economic to subeconomic concentrations of metals (Zhou et al., 2008). The formation of a given deposit-type (i.e. sulphide vs. oxide) is thought to be related to the type of parental magma (i.e. high-Ti basalt vs. low-Ti basalt) and the subsequent processes (i.e. fractional crystallization and sulfur segregation) which allowed for metal enrichment (Zhong et al., 2002, 2003, 2004; Song et al., 2003, 2008; Wang et al., 2006, 2007, 2010; Zhou et al., 2008; Shellnutt et al., 2011; Shellnutt and Wang, 2014). There are at least five (e.g. Baima, Hongge, Panzhihua, Taihe and Xinjie) mafic-ultramafic intrusions located within the central part of the inner zone of the ELIP which contain significant oxide and to a lesser extent sulphide deposits. The Panzhihua, Baima and Taihe deposits are hosted within evolved layered gabbroic intrusions which are primarily oxide-rich whereas the Hongge and Xinjie deposits are hosted within layered mafic-ultramafic intrusions which are sulphide and oxide-rich.

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The enrichment of metals within the Panzhihua, Baima and Taihe oxide-bearing intrusions is debated and is thought to be due to a number of factors including: 1) Fe-rich picritic parental magmas (Zhang et al., 2009; Hou et al., 2012), 2) silicate liquid immiscibility (Zhou et al., 2005, 2013), 3) assimilation of carbonate rocks (Ganino et al., 2008) or 4) fractional crystallization (Shellnutt et al., 2009, 2011; Shellnutt and Jahn, 2010). As a consequence of their oxide-rich nature, the Panzhihua, Baima and Taihe intrusions have not been considered to be primary targets for platinum group element prospecting. However, Maier et al. (2003) documented PGE-rich horizons within the oxide-rich Stella intrusion of South Africa and suggested that some oxide-rich deposits may indeed contain economic concentrations of PGEs. As well, in other mafic–ultramafic intrusions, such as the Lac des Iles Intrusive Complex, Canada, migration of deuteric fluids has been considered as an important process contributing to PGE, particularly Pd, mineralization within the intrusion. Furthermore, the behavior of PGEs provides valuable insight for the effects of crystal fractionation of sulphides and silicate minerals within a magma system. Chalcophile elements, such as the PGEs, Ni and Cu, have extremely high sulphide–silicate partition coefficients, of which those for the PGEs are at least an order of magnitude higher than for Ni or Cu, making the chalcophile elements useful proxies for sulphide fractionation in the parental magma (Keays, 1995; Maier and Barnes, 1999; Maier et al., 2003; Crocket and Paul, 2004; Lightfoot and Keays, 2005). For instance, a magma undergone sulphide fractionation is expected to be highly depleted in PGEs relative to Ni and Cu, thus high in Cu/Pd and Ni/Ir.

In order to understand the behavior of sulfur and to determine the likely S-conditions of their parental magmas in the Baima and Taihe magmatic systems, we present platinum group element analyses of these rocks. We also compare our new results with previously published work from the other PGE-bearing cumulate rocks (i.e. Xinjie, Hongge) of the ELIP in order to determine if there are similarities between the two different types of magmatic oxide deposits in the Panxi region.

2. General geology

The Emeishan large igneous province (ELIP) covers an area of 0.3×10^6 km^2 within southwestern China and northern Vietnam and consists of flood basalts, spatially associated felsic plutons and layered mafic–ultramafic intrusions, some of which host giant Fe–Ti–V oxide or Ni–Cu sulphide deposits (Fig. 1a; Chung and Jahn, 1995; Ali et al., 2005; Wang et al., 2007; Zhou et al., 2008; Shellnutt, 2014). The ELIP is located along the western edge of the Proterozoic Yangtze Block near the boundary with the Early Triassic Songpan-Ganze terrane and was subsequently dismembered during the Mesozoic and Cenozoic by post-emplacement faulting associated with the collision of the North China Block and South China Block and the Indo-Eurasian collision (Chung and Jahn, 1995; Liu et al., 2006). The volcanic succession includes picrites, basaltic andesites, rhyolites, trachytes and basalts which range in composition from tholeiitic to transitional (Xu et al., 2001; Xiao et al., 2004; Wang et al., 2007; Fan et al., 2008; Shellnutt and Jahn, 2011). The basalts form the most voluminous rock type and range in thickness from 1.0 to 5.0 km in the western part and 0.2 to 2.6 km in the eastern part. A mantle-plume model is ascribed to explain the geological features of the ELIP such as the extensive flood basalts, ultramafic lavas, short eruptive duration (260–257 Ma), structural doming and lower crustal seismic velocity layers and is considered to have contributed to the decline in biota during the end-Guadeloupian mass extinction (Xu et al., 2004; Ali et al., 2005; He et al., 2007; Shellnutt et al., 2012; Shellnutt, 2014). Although ELIP magmatism was short lived, Emeishan-related underplated mafic rocks probably served as a source for mafic and felsic magmas after emplacement (Xu et al., 2008; Shellnutt et al., 2008, 2012).

The Panxi region, between the cities of Panzhihua and Xi Chang, of southern Sichuan province is an important area within the ELIP because plutonic and hypabyssal rocks are exposed including mafic–ultramafic intrusions which host substantial orthomagmatic Fe–Ti–V oxide deposits. The Panzhihua, Baima and Taihe gabbros are chemically evolved and spatially associated with peralkaline granitic rocks whereas the Hongge and Xinjie intrusions are predominantly ultramafic suggesting there are petrogenetic differences between the two types of intrusions (Shellnutt and Zhou, 2007; Zhang et al., 2009; Tao et al., 2010; Shellnutt et al., 2011; Shellnutt and Wang, 2014).

The Baima igneous complex (BIC) is located in the central part of the Panxi region (Fig. 1c), ~100 km northeast of Panzhihua, and consists of gabbroic and syenitic units (Chen, 1990; Yang et al., 1997; Shellnutt et al., 2009). The layered gabbroic unit lies to the east of the syenitic unit and is dipping ~25° to the west and contains cumulus olivine, clinopyroxene and plagioclase with interstitial oxide minerals (Shellnutt and Pang, 2012). The U/Pb zircon ages of the two units are within error of ~260 Ma and cover an area of similar size, but their respective volumes are unknown (Shellnutt et al., 2009). Samples were collected at surface exposures across the northern portion of the intrusion (Fig. 1c). The syenitic unit is structurally above the gabbroic unit and contains abundant ellipsoidal mafic enclaves varying in size from a few centimeters to tens of centimeters in length (Shellnutt et al., 2010).

The Taihe layered gabbroic intrusion is located to the west of the city of Xi Chang and is currently being mined for Fe–Ti–V oxide minerals (Fig. 1d). Samples were collected at two localities and the rocks have similar textures and mineralogy as the Baima rocks (Shellnutt et al., 2011). The first group of samples (GS04-159 to -165) was collected from the central portion of the open pit whereas the second group of samples (GS04-170 to -173) was collected ~100 m to the east. To the east of the gabbroic intrusion is the Taihe peralkaline granite which is exposed in a series of quarries in the surrounding highland. The peralkaline granite and layered gabbro have U/Pb zircon ages of ~260 Ma and the entire complex is fault bound with basalts (Xu et al., 2008). Similar to the Baima peralkaline syenites, the granitic pluton contains numerous microgranular enclaves (Shellnutt et al., 2010).

3. Petrography

3.1. Baima gabbros

The Baima layered gabbro consists of four main lithological zones, with increasing stratigraphic height: the lower cumulate zone, oxide ore zone, olivine gabbro zone and upper gabbro zone (Chen, 1990; Shellnutt and Pang, 2012). The gabbros consist of variable proportions of coarse grained cumulate olivine, plagioclase, clinopyroxene and interstitial Fe–Ti oxide minerals with minor amounts of sulphide minerals, Fe–Mg spinel and apatite. The olivine is typically rounded and ranges in size from a few millimeters (~5 mm) to <0.1 mm. It decreases in abundance from ~30% in the lower cumulate zone to <5% in the upper gabbro zone whereas the pyroxene makes up a larger portion of the mode toward the upper parts of the complex. The plagioclase is commonly tabular, euhedral to anhedral in shape and ranges in size from ~5 mm to <0.1 mm and has alteration rims of brown hornblende or biotite when in contact with oxide minerals. The clinopyroxene appears similar in size and shape to the plagioclase crystals and is pleochroic with extensive ilmenite exsolution lamellae. The oxide minerals are primarily made of an interstitial network surrounding the silicate minerals. The magnetite displays extensive oxidation exsolution lamellae of