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Mantle source, magma differentiation and sulfide saturation of the ∼637 Ma Zhouan mafic–ultramafic intrusion in the northern margin of the Yangtze Block, Central China

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ABSTRACT

The sill-like Zhouan mafic–ultramafic intrusion in the northern margin of the Yangtze Block formed at 637 ± 4 Ma and consists of a lherzolite unit and an olivine gabbronorite unit, with a marginal zone between the lower margin of the olivine gabbronorite unit and the underlying country rocks composed of marble and schist of the Meso- to Neoproterozoic Zhujiashan Formation.

Rocks from the lherzolite unit have 41.4–44.0 wt.% SiO_2 and 29.0–38.4 wt.% MgO and contain olivine with Fo values ranging from 80 to 85 mole%, indicating crystallization from a moderately evolved magma. They commonly have <0.1 wt.% S and low, variable PGE (2–40 ppb) and display flat primitive mantle-normalized chalcophile element patterns with relatively low Cu/Pd ratios (3900–427,415), indicating derivation possibly from S-undersaturated magmas. Rocks from the olivine gabbronorite unit contain 44.0–47.1 wt.% SiO_2 and 22.5–28.9 wt.% MgO and contain olivine with relatively low Fo values (67–68 mole%), indicating crystallization from a more evolved magma. They contain 0.03–0.9 wt.% S and <15 ppb PGE and have Cu/Pd ratios (462,500–10,915,500) much higher than those for the rocks from the lherzolite unit. Rocks from the olivine gabbronorite unit show relatively steep, trough-like patterns depleted in PGE relative to Ni and Cu, indicating that they formed from sulfide-saturated magmas. Rocks from the marginal zone have relatively high SiO_2 (45.1–53.1 wt.%) and low MgO (7.4–19.6 wt.%) and have chemical composition varying between the olivine gabbronorite and the country rocks. They contain 0.57 wt.% S and <10 ppb PGE, with high Cu/Pd ratios (404,300) and chalcophile element patterns similar to the olivine gabbronorite unit. Rocks from the lherzolite unit have $(Th/Yb)_{PM}$ ratios (3.7–9.1) much lower than the upper crust (28.2) and the country rocks (41.3), indicating small degrees of crustal contamination. Their $\varepsilon Nd(t)$ (−4.4 to +1.1) and $\gamma Os(t)$ (8–36) values indicate an EMI mantle source. Primary magma was PGE-poor because sulfide retained in the mantle source due to small degrees of partial melting of the enriched mantle source.

We propose that moderately evolved magmas may have reached sulfide saturation due to fractionation of olivine in a deep-seated staging magma chamber, forming an olivine-laden crystal mush with minor sulfide droplets in the lower part and more evolved, PGE-depleted magmas in the upper part of the chamber. The evolved, PGE-depleted magmas were forced out of the staging chamber and entered the shallow magma chamber to form the olivine gabbronorite unit. The lherzolite unit formed from the emplacement of the olivine-laden crystal mush into the same chamber. Because of paucity of extensive crustal contamination, only minor amounts of sulfide segregation occurred in the olivine gabbronorite unit and the marginal zone. The Zhouan intrusion thus may not be a good target for economic Ni–Cu sulfide deposit.

1. Introduction

The nature of mantle source has been documented to be important in the generation of mafic intrusions associated with Ni–Cu–(PGE) sulfide deposits (Naldrett, 2004, 2010). Magmatic Ni–Cu–(PGE) sulfide deposits commonly formed from mafic

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magmas via high degrees of partial melting of a depleted mantle source, or the convecting mantle via adiabatic melting of mantle plume (Maier and Groves, 2011), such as the Noril'sk deposit in the Siberia Trap, Russia (Lightfoot et al., 1990), komatiite-related Kambalda deposit in Australia (Lesher and Arndt, 1995) and Ni–Cu–(PGE) sulfide deposits in the Emeishan large igneous province (ELIP) in SW China (Zhou et al., 2008; Wang et al., 2011). Ni–Cu–(PGE) sulfide deposits formed from magmas derived from an enriched mantle source are rare because low degrees of partial melting of the enriched mantle source usually result in sulfide retained in the mantle (Keays, 1995; Bennett et al., 2000). For example, high-Ti mafic intrusions of the ELIP which were derived from small degrees of partial melting of an enriched mantle source are usually barren in sulfide (Wang et al., 2007, 2011). It is possible that Ni–Cu–(PGE) deposits, especially PGE deposits, form from magmas derived from sub-continental lithospheric mantle (SCLM) via two-stages of melting (Hamlyn and Keays, 1986) or metasomatized SCLM incorporated with convecting mantle-derived magmas (Barnes et al., 2010), such as the recurrent nature of PGE–Ni–Cu mineralization events on the Karelia craton (Maier and Groves, 2011). However, the ore potentials of mineral deposits from the metasomatized SCLM or enriched mantle source may need to be evaluated individually.

Fractionation, extent of crustal contamination and magma mixing are important processes for the formation of magmatic sulfide deposits (Irvine, 1975; Brugmann et al., 1993; Naldrett, 2004) and understanding these processes is crucial for evaluating the ore potentials of mafic–ultramafic intrusions. Chalcophile elements, Ni, Cu and PGE, are sensitive to sulfide saturation in magmas because they are strongly partitioned into sulfide melts (Bezman et al., 1994; Fleet et al., 1996). They are useful for the discrimination of the magma fractionation that was involved in the generation of mafic–ultramafic intrusions (Barnes et al., 1985; Keays, 1995; Crocket, 2002; Crocket and Paul, 2004). Sr–Nd and Re–Os isotopes can be used for characterizing the nature of mantle source, and are sensitive monitors of crustal contamination of mantle-derived magmas (Walker et al., 1994; Shirey and Walker, 1998; Lambert et al., 1999, 2000; Choi et al., 2006). The combination of lithophile and chalcophile elements and Re–Os isotopes is thus powerful for investigating the role of fractionation of silicate and sulfide and crustal contamination in magmas.

In the northern margin of the Yangtze Block there are a number of Neoproterozoic (~635 Ma) mafic–ultramafic intrusions in the Suizao area (Fig. 1). Among these intrusions, the sill-like Zhouan intrusion (637 ± 4 Ma, Wang et al., 2012) is the only one that hosts Ni–PGE sulfide mineralization (Wang et al., 2006a). The Zhouan intrusion consists mainly of a lherzolite unit and an olivine gabbronorite unit. However, the Ni and PGE mineralization of the intrusion may not be economically important. Factors that control sulfide saturation in the formation of the Zhouan intrusion need to be evaluated. In this paper, we present new major, trace and chalcophile elements and Re–Os and Sr–Nd isotopes for the Zhouan intrusion. We demonstrate that the parental magma of the Zhouan intrusion was derived from an EMI mantle source and the two rock units formed from the same parental magma and were emplaced into the same magma chamber. This work has general significance for evaluating magmatic processes related to Ni–Cu–(PGE) sulfide mineralization associated with metasomatized SCLM.

2. Geological background

The Yangtze Block is separated from the Qinling–Dabie–Sulu orogenic belt to the north and the Tibetan Plateau to the west. The Yangtze and Cathaysia Blocks were amalgamated along the Jiangnan folded belt to form the South China Block at Neoproterozoic (Chen et al., 1991; Zhao et al., 2011) (inset in Yan et al., 2011; Fig. 1).

The Yangtze Block has a Precambrian basement overlain by a sedimentary sequence (Yan et al., 2003). The basement consists mainly of Mesoproterozoic arenaceous–argillaceous sedimentary strata which had metamorphosed to low-grade greenschist facies (Gao et al., 1999), and an Archean terrane composed of the ~3.2 Ga TTG gneiss of the Kongling Formation (Gao et al., 1999; Jiao et al., 2009). The thick sedimentary sequence (>9 km) of the late Mesoproterozoic to upper Jurassic strata is composed of glacial deposits and clastic, carbonate and meta-volcanic rocks (Yan et al., 2003).

Neoproterozoic igneous rocks include voluminous ~825–635 Ma mafic–ultramafic intrusions in the western margin of the Yangtze Block (Zhou et al., 2002a; Zhao et al., 2008), and those in the Hannan, Huangling and Suizao areas in the northern margin of the Yangtze Block (Fig. 1).

820–780 Ma mafic–ultramafic intrusions in the Hannan area (Fig. 1) include the sulfide-mineralized Wangjiangshan layered intrusion (819 ± 10 Ma, Zhou et al., 2002b), Beiba intrusion (814 ± 9 Ma, Zhao and Zhou, 2009a), Fe–Ti oxide-mineralized Bijigou layered intrusion (782 ± 10 Ma, Zhou et al., 2002b), and Luojiaba intrusion (746 ± 4 Ma, Zhao and Zhou, 2009a). They intrude the Paleoproterozoic Houhe Formation composed of trondhjemitic gneiss, amphibolite and migmatite, Meso- to Neoproterozoic Hudiya Formation of metasedimentary-volcanic rocks (Zhao and Zhou, 2008) and Neoproterozoic Xixiang Formation of volcanic rocks (Gao et al., 1990). There is a diabase–gabbro dyke swarm (806 ± 4 Ma, Zhang et al., 2008) in the Huangling area, possibly formed due to oceanic slab subduction beneath the northern margin of the Yangtze Block (Zhao et al., 2010).

~635 Ma mafic–ultramafic intrusions in the Suizao area include the Changling (638 ± 10 Ma, Hong et al., 2009), Zhouan (637 ± 4 Ma, Wang et al., 2012), Shoushan (636 ± 11 Ma, Hong et al., 2009), Duchongshan (632 ± 6 Ma, Xue et al., 2011) and Bashan intrusions (631 ± 11 Ma, Hong et al., 2009). These intrusions intrude the Meso- to Neoproterozoic Zhujiashan and Neoproterozoic Suixian Formations. The Zhujiashan Formation consists of interlayered marble and schist. The Suixian Formation consists of a metamorphosed bimodal volcanic suite with interlayers of metasedimentary rocks in the lower part, metasedimentary rocks with rhyolitic pyroclastic rocks and metamorphosed intermedium to mafic lavas in the middle part, and metasedimentary rocks with metamorphosed trachyandensite and alkali rhyolites in the upper part (Xue et al., 2011). The 632 ± 1 Ma Yaolinghe Formation in the Wudang area (Fig. 1) is nearly coeval to the mafic–ultramafic intrusions in the Suizao area and is composed of a bimodal basalt–rhyolite suite formed in a continental rift setting (Zhang et al., 1999; Cai et al., 2007; Xia et al., 2008).

The Zhouan intrusion was discovered because of aeromagnetic anomalies in 1970s. The intrusion intrudes the Meso- to Neoproterozoic Zhujiashan Formation, which is overlain by ~30 to 120-m thick Cenozoic sedimentary rocks. On a plan view at 220 m depth, the intrusion appears to be a sill-like body about 2450 m long, and 700 m wide in the west part and 1500 m wide in the east part (Fig. 2a). It extends downward about 300–400 m in the cross-section according to drilling reports (Fig. 2b).

The Zhouan intrusion consists of a lherzolite unit and an olivine gabbronorite unit. A thin marginal zone is recognized between the olivine gabbronorite and the country rocks of the Zhujiashan Formation in the lowermost margin of the intrusion. In the cross-section, the lherzolite unit is overlain by the Zhujiashan Formation, the olivine gabbronorite unit is overlain by the lherzolite unit and underlain by the marginal zone, and the