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Petrogenesis of the Middle Jurassic Yinshan volcanic-intrusive complex, SE China: Implications for tectonic evolution and Cu-Au mineralization

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ABSTRACT

Volcanic–subvolcanic rocks and associated Cu-Au deposits in Yinshan are located in the eastern part of the Neoproterozoic Jiangnan orogenic belt between the Yangtze and Cathaysia blocks, constituting a large metallogenic district in southeastern China. This paper presents new laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) zircon U–Pb dating, element and Sr-Nd-Hf isotopic data for Yinshan igneous rocks in the Dexing region. Our results show that the Yinshan igneous rocks were produced during the Middle Jurassic (ca. 176–166 Ma). Geochemically, the Yinshan igneous rocks are characterized by calc-alkaline and show some adakitic affinities with high Sr contents (up to 903 ppm), Sr/Y (up to 93.2) and La_N/Yb_N ratios (12.4 to 65.1) and low Y (2.53 to 15.8 ppm) and Yb contents (0.22 to 1.39 ppm). The absence of a negative Eu anomaly, extreme depletion in Y and Yb, relatively low MgO contents (0.2 to 2.9 wt.%), and relatively high $^{207}Pb/^{204}Pb$ ratio (15.555–15.575), indicate that Yinshan igneous rocks were likely derived from the partial melting of thickened lower continental crust. In addition, the Yinshan igneous rocks show similar element characteristics to arc-derived igneous rocks with bulk Earth-like ε_{Nd} (t) values (−1.1 to +1.8) and initial $^{87}Sr/^{86}Sr$ (0.7036–0.7090), relatively depleted ε_{Hf} (t) values (−1.5 to +5.8), and Hf model ages of 0.8–1.2 Ga. However, there is no arc-related evidence in the study area in the Middle Jurassic, which indicates that these arc-related elemental and isotopic compositions are possibly inherited from Meso- to Neo-Proterozoic juvenile continental crust formed by the Neoproterozoic oceanic crust subduction along the Jiangnan Orogen. The geodynamic environment responsible for the development of the Middle Jurassic Yinshan igneous rocks is probably a localized intra-continental extensional environment along the NE Jiangxi Deep Fault, as a tectonic response to far-field stress at the margins of South China Plate during the early stage of the paleo-Pacific plate subduction. Regarding the Cu-Au mineralization, we infer that Cu-Au were released from subducted oceanic slab and reserved in the juvenile crust during Neoproterozoic subduction along the eastern Jiangnan Orogen. Partial melting of Cu-Au rich Neoproterozoic juvenile crust during the Middle Jurassic time in the Yinshan area caused the formation of adakitic rocks and large-scale Cu-Au deposits. Our model provides a new insight into genesis of adakitic rocks and related Cu-Au deposits in a non-arc setting.

1. Introduction

Southeast (SE) China is characterized by the widespread development of Mesozoic igneous rocks (Fig. 1a). These rocks have drawn great attention in the last decades because of their tectonic significance and related large-scale mineralization (Chen and Jahn, 1998; Jahn, 1974; Li and Li, 2007; Wang et al., 2006b, 2011; Zhou and Li, 2000; Zhou et al., 2012). Two important Cu-Au metallogenic districts, including Dexing district in the eastern Jiangnan Orogen and the middle-lower reaches of the Yangtze River valley Metallogenic Belts (YRMB) (Fig. 1a), have been observed in SE China (Chang et al., 1991; Gu et al., 2007; Ling et al., 2009; Pan and Dong, 1999; Xie et al., 2009; Zhai et al., 1996; Zhu et al., 1983). Most of Cu-Au mineralization related (CAMR) porphyries in these two areas share geochemical affinities with adakites, with high LREE concentrations, high Sr/Y and La/Yb ratios, and low HREE (e.g., Y, Yb) concentrations (Ling et al., 2011; Liu et al., 2010; Sun et al., 2011; Wang et al., 2006b; Xu et al., 2002; Zhang et al., 2001; Zhou et al., 2012). These CAMR adakitic rocks were thought to have formed by partial melting of delaminated lower continental crust in the intra-continental extensional regime in SE China (Wang et al., 2006a, 2006b, 2007a; Xu et al., 2002). Moreover, this model emphasized the contributions of mantle materials to the CAMR adakitic rocks, and especially to Cu-Au mineralization (Wang et al., 2006a, 2006b, 2007a; Xu et al., 2002).

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Alternatively, models have been suggested to explain the genesis of Mesozoic CAMR adakitic rocks in SE China. A ridge subduction model was proposed to explain the relationship between Mesozoic magmatic rocks and ore deposits in the YRMB (Ling et al., 2009; Sun et al., 2010). This model is supported by the drifting history of the Pacific and Izanagi Plates (Sun et al., 2007), the evident geochemical characteristics of adakites (Ling et al., 2011; Liu et al., 2010), the distribution of rock association of adakites and A-type granites (Li et al., 2011; Ling et al., 2009), and the higher concentrations of Cu and Au in slab melts than continental crust and primitive mantle melts (Sun et al., 2010, 2011). This model was also used to explain the genesis of Dexing CAMR porphyries (Wang et al., 2011). A different model proposed that Dexing CAMR porphyries were emplaced in a continental arc setting and mainly derived by melting of the subducted sediments. This model was based on their isotopic compositions, which are distinctly different both from the Pacific MORB and from the Yangtze lower crust, but analogous to the subducting sediments in the West Pacific trenches (Zhou et al., 2012). These two new models for the CAMR adakitic rocks in SE China emphasized the direct influence of oceanic-continental subduction to the formation of adakitic rocks and associated Cu-Au deposits (Ling et al., 2009; Liu et al., 2010; Sun et al., 2010, 2011; Zhou et al., 2012). However, no definite Mesozoic basaltic arc magmatism has been found in the intra-continental area of SE China to support the petrogenesis of CAMR adakitic rocks in the geodynamic setting.

In this study, we selected the Yinshan igneous rocks that are adjacent to the world class Dexing porphyry Cu-Au deposits in order to carry out detailed LA-ICP-MS zircon U–Pb geochronology as well as major and trace element and Sr-Nd-Hf isotope analyses. This study investigates the petrogenesis of the intra-continental adakitic rocks and related Cu-Au mineralization in SE China.

2. Geological setting

The South China Block consists of the Yangtze Block in the north and the Cathaysia Block in the south (Fig. 1b). The NEE-SSW Neoproterozoic Jiangnan Orogen extends ~1500 km along the southeastern margin of the Yangtze Block (Fig. 1b). This orogen may represent the Neoproterozoic subduction and convergence between the Yangtze and Cathaysia Blocks (Wang et al., 2006c, 2007b, 2008; Zhou et al., 2009), on the basis of the presence of 1.1–0.97 Ga ophiolites (Chen et al., 1991; Li et al., 1997), ca. 866 Ma high-pressure blueschists (Shu and Charvet, 1996), ca. 870–800 Ma post-collision magmatism with arc signatures, and the foreland basin sedimentation (Wang et al., 2006c; Zheng et al., 2008; Zhou et al., 2009). Neoproterozoic to Triassic (800–200 Ma) sequences unconformably overlie the Proterozoic metamorphic basement in the Yangtze Block (Shu and Charvet, 1996). It is commonly accepted that South China underwent one compressional event in the Triassic (Li et al., 2003), which probably occurred in response to the collision between the Indochina and South China Blocks (Carter et al., 2001; Lepvrier et al., 2004), or between the South China and North China Blocks (Li et al., 1993; Ratschbacher et al., 2003). The northwestward subduction of the paleo-Pacific plate beneath the South China Block probably took place in the Early Jurassic (He et al., 2010; Jahn, 1974; Maruyama et al., 1997; Zhou and Li, 2000; Zhou et al., 2006). The widespread Early Yanshanian magmatism association of A-type granite, syenite, gabbro and bimodal volcanic rocks (Chen et al., 2002; He et al., 2010; Li et al., 2007b; Wang et al., 2006b) likely developed in an intra-continental rift-related environment in response to far-field stress at plate margins resulting from the initial paleo-Pacific plate subduction (He et al., 2010; Zhou and Li, 2000; Zhou et al., 2006).

The eastern Jiangnan Orogen lies in the eastern part of the Yangtze Block, to the north of the Jiangshan-Shaoxing fault zone, and is transected by the NE Jiangxi Deep Fault in the southeastern part (Fig. 1b). Ophiolitic melanges (ca. 1000 Ma) are distributed along the NE Jiangxi Deep Fault, representing a subordinate Neoproterozoic suture zone between the Yangtze Block and an oceanic island arc (Chen et al., 1991; Li et al., 1997; Wang et al., 2008). The Shuangxiwu Group (ca. 970 Ma) and Tieshajie Formation (ca. 902 Ma) consist of altered basaltic and andesitic rocks formed during Neoproterozoic arc magmatism (Li et al., 2009; Zhang et al., 2009a) (Fig. 1b). Mesozoic igneous rocks and associated mineralization also occur in the Dexing region (Inset of Fig. 1c), for example Dexing adakitic porphyry (SHRIMP U–Pb zircon age of 171 ± 3 Ma) (Wang et al., 2006b) with Cu-Au mineralization (molybdenite Re-Os age of 172.3 ± 2.3 Ma) (Zhou et al., 2012).

The Yinshan Cu-Au deposits occur 50 km NW of the Jiangshan-Shaoxing fault zone (Fig. 1c), and are controlled by Yinshan volcanic crater, which consists of the Xishan rhyolitic to dacitic volcanic rocks and Xishan andesite porphyry in the western part and the accompanied sub-volcanic from rhyolitic to dacitic rocks in the eastern part (JGEB Jiangxi Geological Exploration Bureau, 1996). Yinshan deposit share similarities with Dexing porphyry deposits (e.g., tectonic setting, zircon U–Pb ages, geochemical characteristics of CAMR rocks, large-scale Cu-Au mineralization, and intensively hydrothermal alterations) (Du and Chen, 1987; JGEB Jiangxi Geological Exploration Bureau, 1996; Li et al., 2007a; Mao et al., 2011; Zhang et al., 2007), indicating that Yinshan deposits may belong to a porphyry copper deposit system similar to Dexing porphyry deposits (Du and Chen, 1987; JGEB Jiangxi Geological Exploration Bureau, 1996; Mao et al., 2011; Zhang et al., 2007). However, the occurrence of epithermal Pb-Zn-Ag mineralization in the distal zone (JGEB Jiangxi Geological Exploration Bureau, 1996; Wang et al., 2010), lacking of potassic alteration in depth (JGEB Jiangxi Geological Exploration Bureau, 1996), and absence of widespread boiling fluid inclusions (Zhang et al., 2007), indicate the Yinshan deposits might not be a porphyry ore deposit but a transition deposit from the porphyry- to the epithermal-style. Copper reserves in the Dexing region are estimated to be over 10 million metric tons, and the Yinshan deposit contains 0.62 million tons of Cu, and 2.1 million ounces of Au. The wall rocks of the related Cu-Au deposits are epizonal metamorphic rocks (e.g. marine volcaniclastic rocks with spilite-keratophyre, tuff, quartz-keratophyre, and slates) of the Neoproterozoic Shuangqiaoshan Group. The Yinshan igneous rocks are characterized by extensive alterations (e.g., beresitization, carbonation) similar to typical porphyry Cu-Au deposits worldwide.

3. Petrography

The volcanic and intrusive rocks in the area of the Yinshan deposit can be divided into three cycles (Fig. 1c) based on stratigraphic and cutting relations. The first cycle is characterized by occurrence of ca. 450 m thick rhyolitic lava (ca. 0.8 km^2) in the Xishan district, accompanied by intrusive stocks of quartz porphyry (ca. 0.02–0.04 km^2) at the Jiuqu and Beishan districts. The second cycle is characterized by the formation of ca. 700 m thick dacitic volcanic rocks in the Xishan district, which intruded the first cycle of the rhyolitic volcanic rocks. In the Jiuqu district, this cycle is characterized by ~E–W dacitic porphyry dyke (ca. 0.09 km^2), which are mostly 50–70 m wide and 1200 m long. The last cycle is indicated by the small intrusive stock of andesite porphyry (<0.01 km^2) intruding the former two cycles of igneous rocks at Xishan area (Fig. 1c) (JGEB Jiangxi Geological Exploration Bureau, 1996).

Xishan rhyolite, which developed during the first cycle, exhibits porphyritic textures, and mainly consists of quartz (3–15%), alkaline feldspar (10–15%), plagioclase (2–5%) and biotite (1–2%). Alkaline feldspar is found as phenocrysts or interstitial crystals among lath-shaped microlites. As intrusions formed in the first cycle, Beishan and Jiuqu quartz porphyries are gray and porphyritic with quartz (28–35%), alkaline feldspar (10–20%), plagioclase (3–5%), biotite (1–3%) and occasionally hornblende (~1%) (Fig. 2a). Quartz is common and is found as rounded grains with a typical grain size of 0.3 to 5 mm. The matrix displays a fine microcrystalline texture, consisting of alkaline feldspar, quartz, and plagioclase. Accessory minerals include apatite, zircon, and magnetite. Jiuqu dacite porphyry, emplaced during the second cycle, displays porphyritic texture, and consist of plagioclase (15–20%), quartz (2–10%), alkaline feldspar (3–10%)