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# Highly fractionated S-type granites from the giant Dahutang tungsten deposit in Jiangnan Orogen, Southeast China: geochronology, petrogenesis and their relationship with W-mineralization

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ABSTRACT

The Dahutang deposit is a newly discovered tungsten deposit, which is within the largest ones in the world with an estimated $WO_3$ reserve of 2 million tones. W-mineralization is considered to be related with the Late Mesozoic granites in the district. However, the precise emplacement ages, sources of these granites, and their relationship with mineralization are not well understood. In this study, four mineralization-related granite bodies (G1 to G4) were identified in the Dahutang mining area, including the porphyritic-like two-mica granite (G1) (the size of its phenocrysts is from $0.2 \times 0.2$ cm$^2$ to $0.7 \times 0.3$ cm$^2$), middle- to fine-grained muscovite granite (G2), porphyritic two-mica granite (G3) (the size of its phenocrysts is from $0.3 \times 0.2$ cm$^2$ to $0.9 \times 0.6$ cm$^2$), and fine-grained two-mica granite (G4). LA-ICP-MS U–Pb dating of zircon grains from these four granite bodies yields emplacement ages of $144.0 \pm 0.6$ Ma, $133.7 \pm 0.5$ Ma, $130.3 \pm 1.1$ Ma and $130.7 \pm 1.1$ Ma, respectively. Granites contain quartz, K-feldspar and plagioclase as the principal phases, accompanied by muscovite, minor biotite and accessory minerals. Geochemically, the granites are strongly peraluminous, have high contents of alkalis, high Ga/Al ratios, enrichment in LILEs (such as Rb) and depletion in HFSEs (such as Zr, Nb, Ti). The granites formed at relatively low temperatures (679 °C to 760 °C) according to zircon saturation temperatures. Geochemical fractionation trends recorded by whole rocks and minerals permit to distinguish and model the two fractional crystallization series G1 and G2–G4. Fractional crystallization of orthoclase and albite in G1 and G4, and orthoclase and oligoclase in G2 and G3 was the principal process of magmatic differentiation that controlled Rb, Sr and Ba concentrations, whereas rare earth elements were fractionated by accessory minerals, such as apatite, zircon and monazite. The geochemical data suggest that the rocks are highly fractionated S-type granites. The granites show bulk rock $\varepsilon_{Nd}(t)$ values in the range of $-9.37$ to $-5.92$ and zircon $\varepsilon_{Hf}(t)$ values from $-8.44$ to $-2.13$, with late Mesoproterozoic $T_{DM}^{C}$ ages for both Nd and Hf isotopes. Geochemical and isotopic data suggest that these highly fractionated S-type granites G1 and G2–G4 were originated from two episodes of partial melting of different protoliths which have analogous components of metamorphosed pelitic rocks from the Neoproterozoic Shuangqiaoshan Group, which are enriched in tungsten. Extreme fractional crystallization resulted in further enrichment of tungsten in the evolved granitic magma. The new presented data together with previously published data suggest that the Dahutang granitic complex was likely to be formed during lithospheric thinning and asthenospheric upwelling process in Eastern China.



## 1. Introduction

The occurrence of tungsten mineralization is generally related to granitic intrusions of both S- and A-type granites, such as the S-type granites related with the tin–tungsten mineralization in the Khuntan Batholith, northern Thailand (Yokart et al., 2003) and the nearly contemporaneous A- and S-type granites related with tin-tungsten mineralization in the Krušné hory/Erzgebirge Mts., Central Europe (Breiter, 2012). These granites are usually enriched in tungsten, tin or molybdenum well above Clarke values and are termed as tungsten-bearing or tin-bearing granites (Hua et al., 2007; Lehmann, 1987, 1990; Mao et al., 2007; Neiva, 1984). The intrusions are commonly emplaced at shallow crustal levels and possess alkaline to peraluminous characteristics, with enrichments in volatile elements such as F, Li, and sometimes B (Fogliata et al., 2012; Xie et al., 2009; Zhao et al., 2001).

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Several models have been proposed for the role of magmatic evolution in tungsten enrichment: (i) transfer of the rare metals by a fluid to the top of a silicic magma chamber (Kovalenko and Kovalenko, 1984), (ii) extreme fractional crystallization of magma (Breiter, 2012; Gomes and Neiva, 2002; Raimbault et al., 1995), (iii) post-magmatic hydrothermal alteration processes, such as greisenization (Neiva, 2002), which promote the release of metals from biotite, hornblende and other minerals in the granite (Zhao et al., 2005). Here we present new geological, geochemical and isotopic data that shed new light on the origin of the world's largest tungsten ore deposit and related granites in the Dahutang area of the Jiangnan Orogen, Southeast China.

Southeast China is renowned for widespread magmatism and mineralization in the Late Mesozoic, and its richness in ore deposits of W, Sn, U, Nb–Ta, Cu, Pb, Zn and the REE (Hua et al., 2007; Mao et al., 2007; Sun et al., 2012). Most mineralization belts in South China are considered to be genetically and spatially associated with Late Jurassic to Early Cretaceous intrusive granites (Chen et al., 1993; Wang et al., 2012a,b; Xie et al., 2012a,b; Mao et al., 2006; Wu et al., 2012). In recent years, several Late-Yanshanian granite-related W and W–Mo deposits with ages between 143 and 137 Ma have been discovered and exploited in the transition zone between the Lower Yangtze River Valley and the Gan-Hang Belt (Mao et al., 2013; Qin et al., 2010; Song et al., 2012, 2013), with the Dahutang deposit having an estimated tungsten resource of up to 2.0 million tons of $WO_3$ and an established tungsten reserve that exceeds 1.1 million tons of $WO_3$ (Mao et al., 2013). However, little is known about the petrogenesis of the ore-related granites.

In this study, we present precise zircon U–Pb ages of four granite bodies which are spatially related to tungsten mineralization, together with geological and mineralogical chemistry and petrographic, whole rock geochemical and Nd isotopic and Hf isotopic data, in an attempt to better understand the petrogenetic processes and their relationship with mineralization as well as the tectonic evolution of the region.

## 2. Geological setting and sampling

### 2.1. Geological setting

The Southeast China includes the Yangtze Block in the northwest and Cathaysia Block in the southeast, and is surrounded by the North China Craton in the north, the Tibetan Plateau in the west, the Indochina Block in the southwest and the Philippine Sea Plate in the east. Different tectonic histories and crustal ages support a distinction between the Yangtze and Cathaysian blocks (e.g., Qiu et al., 2000; Xu et al., 2007; Zheng et al., 2006). The ca. 1500 km long ENE-trending Proterozoic Jiangnan Orogen is located along the southeastern margin of the Yangtze Block and adjacent to the Cathaysian Block (Fig. 1a). It has been widely accepted that the area of Jiangnan Orogen was outlined mainly based on the distribution of Proterozoic magmatic rocks and meta-sedimentary sequences between the two blocks (Shu and Charvet, 1996).

There are two series of metasedimentary rocks separated by an unconformity in the Jiangnan Orogen. Sedimentary rocks below the unconformity comprise the Shuangqiaoshan Group in northwestern Jiangxi Province, which are mainly pelitic and sandy metasedimentary rocks with few metavolcanic rocks (Huang et al., 2003). The Shuangqiaoshan Group is equivalent to the Tongchang Group in the northeastern Jiangxi Province and the Shangxi Group in the southern Anhui Province. Sedimentary rocks above the unconformity comprise the Dengshan Group in Jiangxi Province, equivalent to the Xiuning Formation in Anhui Province (Wang and Li, 2003), and show approximate upright, open folds (BGMRJX, 1984; Wang et al., 2007a,b). These two suits of low-grade metasedimentary rocks are considered to have been formed separately in the Meso- and Neoproterozoic (Ma et al., 1984; Zhang et al., 1984). However, recent studies have indicated that the Shuangqiaoshan Group below the unconformity was deposited during the Neoproterozoic (Gao et al., 2008, 2012; Q. Wang et al., 2007a,b, 2008). In the Dahutang area, strata of the Shuangqiaoshan Group occur in the form of a suite of thick greenschist facies turbidite metasedimentary rocks. These metasedimentary rocks can be further subdivided into four formations from oldest to youngest: Hengyong, Jilin, Anlelin and Xiushui formations (Gao et al., 2008; Liu, 1997). Locally, the Shuangqiaoshan Group consists mainly of tuffaceous sandstone, phyllite, tuff, phyllite slate and lesser spilite and quartz-keratophyre (BGMRJX, 1984; Liu, 1997).

The Dahutang area is located in the northern part of the Jiuling Mountain in the center of the Jiangnan Orogen, and surrounded by the Jiurui region of Middle-Lower Yangtze Valley Mineralization Belt in the north and the Xiangshan district of Gan-Hang Belt in the south (Fig. 1a). The Jiuling Mountain, a Neoproterozoic granitic intrusion, is the largest composite granitoid complex in south-eastern China with an outcrop area greater than 2500 $km^2$ (Zhong et al., 2005), intruded in the aforementioned basement sequences of the Shuangqiaoshan Group. The Late Mesozoic granitic rocks consist predominately of porphyritic-like two-mica granite (G1), middle- to fine-grained muscovite granite (G2), porphyritic two-mica granite (G3) and fine-grained two-mica granite (G4). These granitic rocks can be roughly divided into two stages (Fig. 2a; Cao, 2011). In the early stage, G1 granitic rocks occur as sills and dykes mostly, showing the north–south trending lengths from one hundred meters to several hundred meters and thicknesses from several meters to tens of meters, intruded in the Neoproterozoic granodiorite batholith or in the low-grade metamorphic rocks of Shuangqiaoshan Group (Figs. 1b; 2b). In the late stage, G2 G3 and G4 granitic rocks sharply cut granite G1 and Neoproterozoic granodiorite batholith as stocks, cones and pipes (Fig. 2a). Granites G2 G3 and G4 were occasionally encountered in boreholes drilled at depths of several hundreds of meters below the surface, so the geological interrelations among G2–G4 are not clear at this stage. In this area, the pegmatite with salmon-pink K-feldspar phenocrysts (the size of its phenocrysts is up to 2.5 cm × 1.2 cm) is around these granites and the tungsten-ore body at margin. Ore veins surround the crest of the Late Mesozoic granite complex, cutting G1 granitic rocks and being cut by G2 granitic rocks (Fig. 2a, b). Wolframite and scheelite are the main ore minerals in the Dahutang tungsten ore deposit. The tungsten mineralizations can occur in quartz veins, dip-dying veinlets, altered granites, greisens and cryptoexplosive breccias. Previous researchers have noted the episodic nature of the Mesozoic intrusions and their relations with the W-mineralization in the Dahutang area (Lin et al., 2006a,b).

### 2.2. Petrography

Samples for this study have been collected from drill cores and underground tunnels in the Dahutang mining area. The mineralogical and petrographic features and sampling depth of the samples are summarized in Table 1. The sample locations are briefly described as follows.

The samples of G1 (zk0-26-1 to zk0-26-3) were collected from borehole zk0-26 in the south part of the Dahutang mining area. The samples of G2 were collected from drill cores zk108 (zk108-2-1, zk108-2-2, zk108-2-4) and zk11-5 (zk11-5-25, zk11-5-27, zk11-2-12) in the north part of the Dahutang mining area and from zk11-2 in the south part of the Dahutang mining area. All the samples of G3 (zk1-4, zk1-6, zk1-9, zk1-11 and zk1-13 were collected from 726 m to 893 m in borehole zk1 in the south part of the Dahutang mining area. The samples of G1 (81#-12) and G4 (81#-23 to 81#-26) were collected from underground tunnels in the northern Dahutang mining area, the depth of these samples were less than 20 m to the surface.

The main minerals in these granites are quartz, orthoclase, muscovite, albite in G1 and G4, and oligoclase in G2 and G3. The feldspars are not zoned. The phenocrysts consist of quartz, orthoclase, albite or oligoclase. The sizes of G1 and G3 granitic phenocrysts are from 0.2 cm × 0.2 cm to 0.7 cm × 0.3 cm and 0.3 cm × 0.2 cm to 0.9 cm × 0.6 cm, respectively.