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The genetic relationship between the large Guanfang W deposit and granitic intrusions, in Yunnan Province, southwest China: Evidence from U–Pb and Re–Os geochronology and Pb and Sr isotopic characteristics

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A B S T R A C T

The recently discovered Guanfang large W deposit, in Yunnan Province, southwest China, is located in the Diandongnan thrust-nappe fold belt in the western part of the Cathaysia Block. The orebodies occur at the contacts between the Suozuodi granite and Middle Cambrian marbles. LA-ICP-MS zircon U—Pb dating of the ore-bearing Suozuodi granite yields a crystallization age of 91.6 ± 1.0 Ma (MSWD = 0.56). An isochron age of 91.6 ± 1.3 Ma (MSWD = 0.24) was obtained by Re—Os dationg of five molybdenite samples separated from sulfide-bearing ores. Scheelite at the Guanfang deposit is characterized by broad rangs of Pb isotopic ratios ($^{207}Pb/^{204}Pb$ = 15.568 to 15.735, $^{206}Pb/^{204}Pb$ = 17.912 to 18.390, $^{208}Pb/^{204}Pb$ = 38.491 to 38.730) and high initial $^{87}Sr/^{86}Sr$ ratios (Isr = 0.7118 to 0.7140), which consistent with the isotopic characteristics of the Suozuodi granite. Pb and Sr isotopic results indicate that the ore-forming materials were derived from a crustal source, without addition of mantle materials. The Guanfang tungsten deposit was formed in a *syn*-collision tectonic setting during the late stage of the Yanshanian tectonism.

1. Introduction

Southeastern Yunnan metallogenic belt, in southwest China, is known for hosting W, Sn, and Ag—Pb—Zn resources such as Gejiu, Bozhushan and Dulong ore fields (Fig. 1b). Many of these deposits show intimate temporal and spatial relationships with late Mesozoic *syn*-collisional granites (Gejiu, Bozhushan and Dulong granite pluton; Fig. 1b). These highly differentiated granitic rocks (with differentiation index > 85) are characterized by high silica ($SiO_2 \geq 65\%$), alkali ($K_2O + Na_2O > 8\%$), and volatile (H_2O and CO_2) contents and enriched in the ore-forming elements such as W, Sn, Ag, Zn, Pb (Cheng et al., 2010; Xie et al., 2009; Yunnan Geological and Minerals Bureau, 1990; Zhang and Chen, 1997; Zhang and Zhang, 2011).

The Bozhushan ore field in the Southeastern Yunnan metallogenic belt consists of two large deposits (Guanfang W, 10 Mt. at 0.5% W; the Bainiuchang Ag—Pb—Zn—Sn (W) deposits, 6470 t at 95 g/t Ag, 172 Mt. at 2.46% Zn; 109 Mt. at 1.56% Pb, 8.6 Mt. at 0.12% Sn), and several small deposits and occurrence (e.g. Changputang W—Sn, Xiachang Ag, Laojunshan and Malutang W deposits; Yunnan Geological and Minerals Bureau, 1990; Zhang, 2007; Zhang and Zhang, 2011; Fig. 1C). Due to the lack of systematic geological study, the relationship between granitic magmatism and W-polymetalic mineralization of the Bozhushan ore field is still ambiguous. A comprehensive knowledge of the genetic relationship between the granitic magmatism and W—Sn mineralization will provide important insights on the ore-forming mechanism and its geodynamic background, and practical guilds to mineral exploration.

In this study, systematic zircon U—Pb and molybdenite Re—Os geochronological and Sr and Pb isotopic studies are carried out on the newly discovered Guanfang tungsten deposit (Zhang and Zhang, 2011). This study provides (1) precise geochronological results to constrain the genetic correlation between granitic magmatism and W mineralization; (2) Sr and Pb isotopic constraints on sources ore-forming metals, and (3) constrains on the geodynamic background of W—Sn mineralization.

2. Regional geology

The Bozhushan intermediate–felsic complex is located in the Diandongnan thrust–nappe fold belt (DTFB) in southeast Cathaysia Block (Fig. 1b, c). Paleozoic and Triassic sedimentary rocks are widely

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exposed in the Bozhushan area (Fig. 1c; Zhang and Zhang, 2011). The Cambrian sandstone and marble are widely distributed in the southern part of the area, and intruded by the Bozhushan complex. This lithological unit hosts most of the W-polymetalic orebodies (Zhang and Zhang, 2011). The Ordovician, Devonian and Permian strata outcropping in the north are mainly marine carbonates with intercalated sandstone, whereas the Triassic rocks comprise marble, terrigenous clastic rocks and siltstones.

NE-trending folds and series of NE-, NW- and EW-trending faults are developed in this area, and the Cretaceous Bozhushan complex was intruded at the intersections between NW-trending fractures and NE-trending folds. (Fig. 1c). Previous Rb—Sr geochronoligical study shows that the Bozhushan complex can be divided into seven units that were intruded during two stages (Fig. 1c; Xie et al., 2009; Zhang and Chen, 1997). Lithological units of the first stage (104–97 Ma), include the Suozuodi, Yangyushu and Dashan units, which are medium–grained biotite monzogranites composed mainly of plagioclase (30–40%), orthoclase (15–25%), perthite (10–20%), quartz (30–40%), and minor biotite (5–10%), with medium–grained and inequigranular textures. Orthoclase grains are hypidiomorphic–idiomorphic with sizes of 2–8 mm and display Carlsbad twinning. Plagioclase grains are also hypidiomorphic–idiomorphic, 0.5–4 mm in size, and display polysynthetic twinning. Quartz grains are irregularly shaped and 1–4 mm in size. Biotite grains are yellowish to dark brown in color with grain, sizes of 0.2–1.2 mm. Some biotite grains were replaced by chlorite. Accessory minerals include magnetite, tourmaline, and zircon. SiO_2 and total alkaline contents are 64.8%–72.0% (average 68.7%) and 5.5%–8.2% (average 6.9%), respectively (Table 1). The rocks display positive Rb, U, Th, and LREE anomalies and medium–strongly negative Eu anomalies ($\delta Eu = 0.37–0.55$; Table 1; Fig. 2a, b). Most rocks fall into the peraluminous (average A/CNK = 1.14) and S-type granite categories (Fig. 3a) and were generated in a *syn*-collisional setting (Fig. 3b).

The second stage (79–48 Ma) includes fine-grained K-feldspar-bearing granites of the Leidazhan, Fenshuiling, Bozhupo, and Dashan units. The granites are composed of plagioclase (10%), orthoclase (15%), perthite (10%), quartz (60%), and biotite (2%), and have porphyroblastic textures. Phenocrysts are quartz and orthoclase showing Carlsbad twinning. Plagioclase displays polysynthetic twinning. Quartz grains have allotriomorphic granular textures and are 0–2 mm in size. Accessory minerals include magnetite and tourmaline. The granites are characterized by high SiO_2 (75.9%–76.9%) and total alkaline (7.6%–8.8%) contents (Table 1), and mostly classified as metaluminous and A-type granites (Xie et al., 2009). These rocks are enriched in Nb, Ta, and Y, and are strongly depleted in Sr, Ba, and Eu ($\delta Eu = 0.06–0.11$; Table 1; Fig. 2a, b). Granites of the second stage were formed in an extensional setting (Xie et al., 2009; Zhang and Chen, 1997) (Table 1; Fig. 3b).

3. Ore geology

The Middle Cambrian Dayakou and Tianpeng Formations are exposed in the Guanfang mine area (Figs. 4–6), and are the host rocks of the orebodies. The Dayakou Formation is composed of marble and the Tianpeng Formation consists of sandstone, marble, and limestone. These sedimentary rocks were intruded by the medium-grained biotite monzonite granite of the Suozuodi Unit (Fig. 7; Zhang and Zhang, 2011), which covers an area of ~5 km^2. The medium-grained Suozuodi granite is composed mainly of plagioclase (35%), K-feldspar (30%), quartz (20%), biotite (15%), and accessory minerals (magnetite, apatite, and zircon). K-feldspar and plagioclase grains are both hypidiomorphic–idiomorphic and 2–5 mm in size. Quartz grains are irregularly shaped and 1–4 mm in size. Biotite grains are yellowish to dark with 0.8–3.0 mm in size. Previous study (Zhang and Zhang, 2011) shows that the granites in the mining area are peraluminous and classified as S-type (Table 1; Fig. 3a), characterized by strong positive Th and U anomalies and negative Eu, Ba, Sr, and Nb anomalies (Table 1; Fig. 2a, b). The granites are interpreted as crustally derived in a continental collision setting (Fig. 3b). The concentration of W in the granite is 23.7 times higher than the average granite in China (Zhang and Zhang, 2011).

Marble in the Guanfang Deposit is altered to skarn. Tungsten is hosted mainly in calcic skarn that occur in the contact zone between granite and marble and consist of hedenbergite, grossularite, and minor tremolite and epidote (Fig. 8a, c, d, f;). Minor magnesian skarn minerals such as monticellite (Fig. 8b) were formed in the altered Dayakou formation that contains intercalated dolomitic limestone. Orebodies are mainly hosted in the internal contact zone between granite and marble (Fig. 6). The W orebodies are typically stratiform or lenticular (Fig. 5), dipping southeast with dip angles of 30°–40°. They are generally several meters to tens of meters wide, and extending 100–500 m along strick. The main ore minerals include scheelite, minor pentlandite, pyrrhotite, galena, sphalerite, and chalcopyrite (Fig. 8e, g, h), and gangue minerals are mainly garnet, diopside, phlogopite, epidote, and tremolite (Fig. 8a–f). Scheelite and accompanying sulfides are mostly irregular and granular in shape, with a few being hypidiomorphic–idiomorphic granular. Disseminated and massive mineralization are common in this deposit.

Based on crosscutting and replacement relationships three stages of mineralization and alteration are recognized: The prograde skarn (Period 1) associated with anhydrous skarn minerals; retrograde skarn (Period 2) associated with scheelite–molybdenite mineralization, and a late quarz–sulfide (Period 3) that can be further subdivided into early and late sulfide stages.

The following replacement relationships are observed in thin sections: (1) It is commonly observed in the wall rocks that the earlier skarn stage (Period 1) diopside was replaced by grossular (Fig. 8c, d). (2) Earlier diopside, grossular, and accompanying scheelite was replaced by late skarn stage (Period 2) tremolite (Fig. 8a) that is closely related to W mineralization; (3) Diopside, grossular and scheelite was replaced by *syn*-ore epidote (Fig. 8f); (4) Forsterite (Fig. 8b) is widespread in the distal areas of the diopside–tremolite alteration zone, 10–100 m away from the granite body. Forsterite shows no replacement relationship with scheelite.

The prograde skarn (Period 1) is characterized by the precipitation of large amounts of calc-silicate minerals such as diopside and garnet (Fig. 8a,c). The retrograde skarn (Period 2) is characterized by the precipitation of hydrous silicate minerals such as tremolite and epidote (Fig. 8e), and large amounts of scheelite, molybdenite, and magnetite (Figs. 8e, h, 9b), with scheelite coexisting with molybdenite. Period 2 was important for scheelite formation. Period 3 was characterized by the formation of minerals such as chalcopyrite, pentlandite, and sphalerite. It included an early sulfide stage that was mostly associated with the formation of chalcopyrite and pentlandite that replaced calc-silicate minerals (Fig. 8g) and chalcopyrite replacing magnetite (Fig. 8h). Sphalerite replaced chalcopyrite in the late stage sulfide period (Fig. 8h).

4. Samples and analytical methods

Granite samples were collected from the Suozhudi biotite monzonite granite (sample ZK8–234) in the NO-8 drillhole (Fig. 4) for U—Pb isotopic dating and analyses of major and trace elements.

Zircon grains were sperated by the Hebei Langfang Keda Service Company for analysis. The detailed selection process was as follows. Colorless and transparent zircon grains with fine crystal shapes and no fluid inclusions were hand-picked under a binocular microscope, embedded in epoxy resin, and then polished to expose the central surface of the zircons before being analyzed by cathode luminescence and LA–ICP–MS. The LA–ICP–MS zircon U—Pb analyses were performed at the State Key Laboratory of Continental Dynamics at Northwest University, Xi'an, China, using a Perk Elmer/SC IEX GONGS mass spectrograph coupled with an Elan6100DRC dynamic reaction pool quadrupole (ICP–MS). The analyses were carried out with a beam diameter of 25 μm, a repetition rate of 5 Hz, and energy of 10–20 J/cm^2. Each analysis