Hydrothermal alteration, mineralization and structural geology of the Zijinshan high sulfidation Au-Cu deposit, Fujian Province, South East China

Jing Chen[1, 2], David R. Cooke[1, 2], José Piquer[3], David Selley[1], Lejun Zhang[1, 2], Noel C. White[1,4]

1 – Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Tasmania, Australia

2 – Transforming the Mining Value Chain (TMVC), ARC Industrial Transformation Research Hub, University of Tasmania, Hobart, Tasmania, Australia

3 – Instituto de Ciencias de la Tierra, Universidad Austral de Chile, Edificio Pugín, Av. Eduardo Morales Miranda, Valdivia, Chile

4 – Ore Deposits and Exploration Centre (ODEC), Hefei University of Technology, Hefei, China

Abstract

Zijinshan is a world class Au-Cu district located in southwest Fujian Province, southeast China. It contains a diverse array of ore deposits hosted by the Zijinshan granite complex and surrounding volcano-sedimentary rocks. Associated deposits include high sulfidation epithermal gold-copper, intermediate sulfidation epithermal polymetallic silver-base metal, and porphyry molybdenum-copper deposits. The Zijinshan high-sulfidation Au-Cu deposit is located in the middle of the Zijinshan district, and ore zones are hosted in, below, and adjacent to the Zijinshan lithocap. The host rocks are part of a Jurassic granite complex emplaced between 165 and 157 Ma. $^{40}Ar/^{39}Ar$ age spectra of hydrothermal alunite indicate that hydrothermal activity at Zijinshan occurred at 102.86 ± 0.61 to 101.19 ± 0.60 Ma and was associated with dacite porphyry dikes that intruded at 104.8 ± 0.9 Ma.

Hydrothermal activity produced pervasive silicic and advanced argillic alteration assemblages which are zoned from a central, massive quartz alteration domain, outward to massive quartz – dickite, disseminated quartz – alunite ± dickite and disseminated quartz – muscovite – dickite zones. Copper sulfides occur in hydrothermally-cemented breccias, veins, and minor disseminations in granite; copper minerals include covellite, digenite and minor enargite. Oxide Au ores are associated with strongly weathered silicic alteration in the upper parts of the deposit.

A set of sub-vertical NE-striking faults were active prior to mineralization at Zijinshan. During mineralization, a NW-striking fault system controlled the emplacement of veins, breccias and dacite dikes. Kinematic indicators show that most of the NW-striking faults were active as normal oblique faults during mineralization. Post-mineralization ENE-striking dextral strike slip faults are associated with minor conjugate NNW-striking faults.

The pre-mineralization structures at Zijinshan likely formed during NW-directed compression. Syn-mineralization structures formed under subvertical contraction and subhorizontal NNE-plunging extension. Post-mineralization structures developed in a strike-slip regime defined by a NW-oriented axis of compression and NE-trending axis of extension. Changes in the styles of pre- and syn- mineralization structures are related to fluctuations in the regional stress regime. The transition from compression to extension was fundamental to mineralization. Post-mineralization faults are related to transient local variations in stress regimes at deposit-scale.

Introduction

The Zijinshan mineral district, southwest Fujian Province, South East China, is currently China's largest gold mining district, with a total resource over 4 Mt Cu (avg. 0.35 %), 400 t Au (avg. 0.32 g/t), 6400 t Ag (avg. 70 g/t) and 0.07 Mt Mo (avg. 0.036%; Zhang, 2013; Zhong et al., 2017a and b; Table 1). The Zijinshan Au-Cu deposit is located in the middle of the Zijinshan district. It contains 305 t Au and 2.3 Mt Cu, and it has had a sustained annual production of 13.5 t Au and 10,000 t Cu since 2006 (Zijin Mining internal report, 2015). Zijinshan was the first documented high sulfidation epithermal deposit in mainland China (So et al., 1998).

Structural, hydrothermal and lithological factors can significantly affect permeability and may control the geometry of epithermal orebodies (Sillitoe, 1993; Simmons et al., 2005). At Zijinshan, high sulfidation mineralization is hosted by a relatively homogenous intrusive protolith (Jurassic granite) and minor subvolcanic intrusions (Cretaceous dacite) that have been cut by fault-related tectonic-hydrothermal breccias. Zijinshan is a useful case study for investigating structural controls on fluid flow in a high sulfidation environment, with the presence of widespread granitic host rocks, simplifying the assessment of protolith effects.

This paper provides a detailed analysis of the structural geology, alteration and mineralization of the Zijinshan Au-Cu deposit. We focus on the structural framework and hydrothermal evolution of the Zijinshan high sulfidation epithermal Au-Cu deposit, including the structural controls on breccias and veins. The spatial and geometric relations between individual veins, breccias and dikes are documented. We identify the major structures that were active during ore formation to interpret the deformation history during mineralization and regional tectonism. Our findings have implications for the Mesozoic geodynamic evolution of SE China, and provide insights into how changes in the local and regional stress regimes influenced epithermal and porphyry-style mineralization.

Mining and exploration history

The Zijinshan district has a long mining history, extending from the Song Dynasty (AD. 1040), with over 100 ancient mine tunnels known in the district. Modern exploration started in the 1960s with prospecting in the surrounding rivers and streams. From the 1960s to 1980s, several local geological surveys conducted exploration in the region, including stream sediment geochemistry, soil geochemistry and geological mapping, self-potential and heavy mineral surveys. Detailed stream sediment sampling and 1:25000 scale mapping, combined with channel sampling of the ancient mine tunnels delineated a 13 km^2 gold anomaly. Gold orebodies were defined in 1985 after 9000 m of trenching, 2600 m of tunnelling and 4200 m of diamond drilling.

Regional geology of the South China Block

The South China Block is composed of the ca. 2.5 - 1.8 Ga Yangtze Craton and the ca. 1.8 - 1.4 Ga Cathaysia Block (Li et al., 1997; Li et al., 2009; Fig. 1). The Yangtze Craton consists of Archean and Paleoproterozoic plutonic and metamorphic rocks. The Cathaysia Block has Neoproterozoic and minor Paleoproterozoic outcrops (Zheng, 2003). The Yangtze Craton and the Cathaysia Block collided during the Jinning Orogeny (1.0 - 0.85 Ga), as part of the assembly of Rodinia (Fig. 1; Zhou and Zhu, 1993; Li et al., 1999; Pirajno and Bagas, 2002).

During the breakup of the Rodinia Supercontinent, the South China Block underwent continental rifting from around 830 Ma to 740 Ma, possibly caused by a mantle plume (Li et al., 1999; Zheng et al., 2008). A second collision between the Yangtze Craton and Cathaysia Block occurred during the Kwangsian Orogeny (420 - 400 Ma), which caused intense deformation and associated volcanism and plutonism, and this generated a regional angular unconformity between Silurian and middle Devonian strata (Shu et al., 2008; Wang et al., 2011). During the Triassic, the Indosinian Orogeny resulted in the closure of an arm of the Paleo-Tethys ocean. The Qinling-Dabie orogenic belt formed in the Late Triassic on the boundary between the North China and South China Blocks (Li, 1994; Xue et al., 1996; Sun et al., 2002).

A major Mesozoic tectono-thermal event, the Yanshanian Orogeny, began at 190 Ma and terminated at 90 Ma (Zhou et al., 2002). It marks the change from Tethyan to Pacific tectonism in SE China and resulted in a broad NNE- to NE-trending magmatic belt on the SE continental margin (Pirajno and Bagas, 2002). The South China Fold Belt is a product of Yanshanian deformation and magmatism (Ren, 1991; Pirajno and Bagas, 2002, and references therein). The Coastal Volcanic Belt defines the southeastern margin of the South China Fold Belt and is bounded by the Zhenghe-Dapu Fault (Fig. 1). The Coastal Volcanic Belt is dominant by calc-alkaline intrusions and volcanic rocks in a belt that extends for approximately 1,200 km (Pirajno and Bagas, 2002, and references therein). Middle Cretaceous porphyry Cu and epithermal Cu-Au deposits and Late Cretaceous granite-related Sn deposits in South China are clustered along the Coastal Volcanic Belt (Mao et al., 2013). These ore deposits, including Zijinshan, were localized along regional faults and in fault-bounded volcanic basins (Hua et al., 2005; Mao et al., 2008). The Zijinshan district is located on the western boundary of the Coastal Volcanic Belt (Fig. 1).

Yanshanian magmatic activity can be divided into the Early Yanshanian (190 – 140 Ma) and Late Yanshanian (140 – 90 Ma). The Early Yanshanian period (190 – 140 Ma) began with rift-type interplate magmatism and volcanism (190 – 180 Ma) in the E-trending Nanling Range (Fig. 1). The granitoids include calc-alkaline I-type granites and minor A-type granites, and gabbro-diorites (Zhou et al., 2006; Xu et al., 2009). Bimodal volcanism produced basalts and rhyolites with similar thicknesses and abundances (Zhou et al., 2006).

Crustal thickening, crust-mantle interaction and remobilization of Cathaysia Block commenced around 170 Ma, forming a 1,200-km wide NNE- trending fold-thrust fault system (Zhou and Li, 2000). This event is interpreted to be related to the low angle subduction of the Paleo-Pacific plate beneath the south-eastern margin of Eurasia (Zhou and Li, 2000; Xu et al., 2009). The Early Yanshanian period is interpreted by some to mark the ending of the Tethyan regime and the beginning of paleo-Pacific tectonism (Zhou et al., 2002; Mao et al., 2013). However, an alternative view is that South China was in a post-orogenic setting following the Indosinian Orogeny in the Early Yanshanian period, with lithospheric extension resulting in local crustal thinning and widespread emplacement of crustally-derived granites (Hua et al., 2005).

Methodology

Detailed mapping was undertaken in the Zijinshan open pit at 1:200 scale using a modified Anaconda-style methodology (Einaudi, 1997). Color codes are used to distinguish rock types, alteration, veins, mineralization and limonites in the field. The key aspect of the Anaconda-style mapping is to project data onto a horizontal plane (Einaudi, 1997). The baseline for mapping is a hypothetical line at the chest height along a drift or trench wall. The measured baseline serves to separate the map sheets into two areas: the air side and the rock side. Lithotypes and contacts, breccias, veins, faults, disseminated sulfides and other structures are plotted on the rock side on the base map. Background alteration (e.g., quartz, dickite, alunite, kaolinite alteration) of the host rocks and vein halos are plotted on the air side (Einaudi, 1997). Oxidation products of ore minerals are plotted on a second overlay. After mapping of all the field stations on the Zijinshan benches, a composite Anaconda bench map was prepared. The plan map of the open pit has been composed based on all of the bench maps (fact maps), and on interpretations between benches.

Alteration mapping was undertaken with the assistance of field-based short wavelength infrared spectroscopy (SWIR) analyses for identification of micas, clays and other hydrous alteration minerals. SWIR analyses were conducted on-site using Zijin Mining Company's PNIRS spectrometer. SWIR analyses combined with visible and near-infrared (VNIR) analyses for identifying hypogene and supergene minerals (hematite, goethite and jarosite) using Terraspec ASD were conducted at CODES, University of Tasmania. The PNIRS spectrometer passed quality control in 2007 and the results have been calibrated with Terraspec by polyethylene and pyrophyllite standards provided by Nanjing Institute of Geology and Mineral Resources (Xiu et al., 2007). Data compiled from outside our mapping area was modified after the map from Zijin Mining internal report (2015).

Our deposit-scale structural study of the Zijinshan deposit, including kinematic and dynamic analysis, measurement of strikes and dips of individual faults at each structural station (Appendix 1). Offsets of each fault were determined by the displacement of markers such as hydrothermal veins and breccias. Senses of movements of faults were recorded using kinematic indicators, including slickenfibers, deformed breccia clasts, and veins. A total of 135 fault planes were measured, of which 54 (40%) yielded reliable kinematic information (Appendix 1). The district-scale structural study of the Zijinshan district by Piquer et al. (2017) was undertaken synchronous with our deposit-scale study.

The dominant fault plane orientation statistics were analysed using Stereonet™ software (Allmendinger et al., 2011). Because most of the kinematic indicators used are defined by hydrothermal minerals, and by displacement of the syn-mineralization breccias and veins, these data were used to evaluate the tectonic stress regimes prevailing during and after mineralization. The kinematics of fault-slip data were analysed for the various lithotypes using FaultKin™ software (Allmendinger, 2002), which was used to calculate the orientation of the pressure and tension axes for different fault groups.

Dynamic analysis of the structural evolution of the Zijinshan deposit was calculated using the Multiple Inverse Method (Yamaji, 2000). The orientations of paleo-stress tensors were identified from the inversion of fault-slip data. This method can separate stresses from heterogeneous fault-slip data without prior information on the stresses, and does not require subdivision of the faults according to the stresses (Yamaji, 2000). Four parameters were used to identify the stress state: three for the direction of the stress axes, and one for the shape of the stress ellipsoid. The shape of the stress ellipsoid (Ø) is indicated by $Ø = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$. The k-element makes k subsets from the set of N fault-slip data. The optimal choice by simulation is based on k = 4 or 5. For most datasets, k = 5 is recommended, or k = 4 if the dataset is particularly large (> 122; Yamaji et al., 2011). All possible stresses were identified and visualized as clusters on stereonets. The reliability of each stress calculated is shown by the density of the cluster. The numbers of solutions and the corresponding frequency follow the Pareto distribution in the statistics, so that a small numbers of grid points have most of the solutions but quite a few points have few or no solutions (Yamaji, 2000). Subsets with unreasonable combinations of data are discarded. Geological fault-slip data are tested using the compatibility criterion of stress states and data, which is judged with misfit threshold d_T = 20°, which is defined as the angle between the observed and theoretical slip direction on a fault plane under a given stress state (Yamaji, 2000). If the misfit angle is greater than this, the fault datum is said to be incompatible or unexplained by the stress state used to calculate the misfit angle. If any stress state cannot explain all the k data in a subset, the subset is said to be incompatible with the stress state and these subsets are then discarded (Yamaji, 2000).

Geology of the Zijinshan district

The Zijinshan district is located on the southeast margin of the South China Fold Belt, west of the Coastal Volcanic Belt (Fig. 1). It is situated on the northern margin of the NW-trending Shanghang volcanic basin, a 25 km-long, 8 km-wide rhombic-shaped basin that formed during the Mesozoic (Feng, 1993; Fig. 2A). The Shanghang basin is interpreted to be a strike slip pull-apart basin bounded by the major Shanghang-Yunxiao fault on its southwest side (Wang and Lin, 1998; Lin and Chen, 2011; Fig. 2A).

Proterozoic and Paleozoic metasedimentary rocks of the Zijinshan district have been folded, forming the NE-trending Xuanhe anticlinorium (Fig. 2B). The core of the anticlinorium exposes Neoproterozoic metamorphic rocks that are overlain by Late Paleozoic clastic sedimentary rocks and Early Cretaceous Shimaoshan volcanic rocks (Figs. 2B and 3).

Granitoids in the Zijinshan district were emplaced during the Yanshanian period. The Early Yanshanian Zijinshan granite complex intruded the core of the Xuanhe anticlinorium. It contains three phases: Jingmei granite (165 ± 1 Ma), Wulongsi biotite granite (164 ± 1 Ma) and Jinlongqiao granite (157 ± 1 Ma; Fig. 2B; Jiang et al., 2013). During the Late Jurassic, the Caixi monzogranite (150 ± 3 Ma) intruded the Zijinshan granite complex on the northeastern side of the district (Fig. 2B; Zhao et al., 2007).

Late Yanshanian volcanism and magmatism is temporally and genetically related to porphyry and high sulfidation epithermal mineralization in the Zijinshan district (Tables 1 and 2). The oldest Cretaceous intrusion is the NE-trending Sifang granodiorite stock (107.8 ± 1.2 Ma), which intruded the Caixi monzogranite (Fig. 3; Mao et al., 2002). The Luoboling granodiorite porphyry (106.9 ± 0.4 Ma) intruded the southern margin of the Sifang granodiorite stock. Dacite porphyry and dacite dikes (104.8 ± 0.9 Ma) intruded the Zijinshan granite complex in the center of the district (Table 2). Dacitic dikes also intruded the Luoboling granodiorite porphyry, as observed in drill cores from Luoboling. The Jintonghu monzonite dikes (96.1 ± 1.7 Ma – 94.9 ± 1.6 Ma) and Nanshanping alkaline syenite and monzonite dikes (99.5 ± 1.2 Ma – 92.7 ± 1.0 Ma) intruded the northern side of the Luoboling granodiorite. These dikes are weakly altered and unrelated to mineralization; they are classified as post-mineralization intrusions (Li and Jiang, 2014; Li et al., 2015).

The Zijinshan district contains the Zijinshan high sulfidation epithermal Au-Cu deposit (102.86 ± 0.61 Ma – 101.19 ± 0.60 Ma; alunite Ar-Ar dating, Pan et al., submitted), the Luoboling porphyry Cu-Mo deposit (104.6 ± 1.0 Ma; molybdenite Re-Os dating, Zhong et al., 2014), the Yueyang (also known as Bitian) intermediate-sulfidation epithermal Ag-Cu-Au deposit (91.47 ± 0.39 Ma; adularia Ar-Ar dating, Liu and Hua, 2005), the Wuziqilong high sulfidation epithermal Cu deposit (102.5 ± 1.5 Ma; sericite Ar-Ar dating, Zhang et al., 2003), and the Longjiangting intermediate sulfidation Cu, the Xinan porphyry Cu-Mo and the

Dajigang high sulfidation Au-Cu prospects (Fig. 2B). Characteristics of the porphyry and epithermal deposits and their related intrusive rocks are summarized in Table 1.

Geology of Zijinshan Au-Cu deposit

The Zijinshan Au-Cu deposit is located in the center of the Zijinshan district (Fig. 2B). It is hosted by the Zijinshan granite complex. The Wulongsi biotite granite is the principal host rock for the Au-Cu orebodies (Figs. 4 and 5A). The biotite granite is elongate in a NE-SW orientation, and it occupies the middle of the Zijinshan granite complex, with a surface area of approximately 12.5 km^2 (Fig. 4A). The Jinlongqiao granite (Fig. 5B) crops out over an area of 2.6 km^2 in the northwestern part of the Zijinshan granite complex (Fig. 4A), occurring as small stocks with sharp or faulted contacts with the Wulongsi biotite granite. The Zijinshan deposit contains 575 Mt of Au ore (avg. 0.53 g/t) in the supergene profile and 646 Mt hypogene ore with 0.63 % Cu, 0.07 g/t Au and 3.7 g/t Ag (Zhang, 2013).

The Early Cretaceous Sifang granodiorite intruded the Zijinshan granite complex in the northeastern part of the mine area. Late Cretaceous dacite dikes intruded the Zijinshan granite in the south (Fig. 4A). The dikes are 3 - 200 cm wide, with average widths of 30 - 50 cm, commonly NW-trending and moderately dipping to the NE and SW (Figs. 4A). The dacite porphyries are gray to gray-white, locally weathered yellow to red (Figs. 5C and 5D).

Alteration

Previous studies of Zijinshan identified three types of alteration: silicic, quartz – alunite – dickite and “sericite” (So et al., 1998; Zhong et al., 2018). With the benefit of the open pit exposures and detailed SWIR analyses, the current study has generated mineralogical and alteration data in three dimensions, allowing for the delineation of the laterally extensive domains of silicic and advanced argillic alteration that define the Zijinshan lithocap.

In the pit, zones of intense silicic alteration grade laterally outward into zoned advanced argillic alteration made by quartz – dickite and quartz – alunite, and to muscovite alteration (Fig. 4B). Minor kaolinite and patchy pyrophyllite define the peripheral alteration zone (Fig. 4B).

Silicic zone: Pervasive silicic alteration produced irregular bodies of massive and vuggy quartz. These domains mostly occur in the center of the present-day open pit, and they are spatially associated with matrix-rich breccia bodies (Fig. 4B). Massive quartz has a broader spatial distribution than vuggy quartz. Quartz has replaced feldspars and filled open spaces in the massive quartz alteration zone. Clasts and matrix in polymict breccias in the center of the deposit have been completely replaced by quartz. The contact between vuggy quartz and massive quartz zones are transitional, whereas contacts between the silicic zones and surrounding advanced argillic and argillic zones are sharp.

There is a strong protolith control on the style of silicic alteration at Zijinshan (Figs. 6A and 6B). Vuggy quartz alteration dominantly occurs in dacite porphyry dikes. Vuggy quartz alteration is texturally distinctive, with the vuggy texture produced by acid leaching of feldspar phenocrysts (Stoffregen, 1987; Fig. 6). Vuggy quartz-altered rocks contain quartz, pyrite and minor rutile. In minor cases, rosettes of covellite and coarse-grained pyrite have filled vugs. In the silicic zone, equigranular granite is commonly altered to massive quartz.

A discrete zone of vuggy quartz with vugs filled by dickite occurs adjacent to the vuggy quartz, massive quartz and quartz – dickite alteration zones, with transitional contacts (Figs. 4B and 6C). The vuggy quartz with dickite zone is the smallest alteration zone, with dimensions less than 200 m by 200 m in plan, and a vertical extent of 150 m.

Advanced argillic zone: A large area of advanced argillic alteration, which is characterized by dickite, alunite, pyrophyllite and hypogene kaolinite, surrounds the silicic alteration zone (Fig. 4B). Quartz – dickite alteration occurs adjacent to silicic zones at Zijinshan (Fig. 4B). It is the most widespread alteration type exposed in the Zijinshan open pit, extending from 1000 m a.s.l. to 200 m a.s.l. Dickite has replaced feldspars in the granite wall rocks (Fig. 6D). Intense dickite alteration in some dacite and granite has obscured the primary textures and changed the host rock colors from gray to white. The abundance of dacite dikes may have been underestimated by previous workers due to the pervasive, intense dickite alteration. Dickite is the dominant cement in some hydrothermally-cemented breccias.

Alunite alteration is typically pervasive and complex. Alunite at Zijinshan is commonly coarse-grained, 0.5 - 1.0 mm in diameter, and pink or yellow colored (Figs. 4B and 6E). Intense alunite alteration halos surround hydrothermally-cemented breccias and veins (Fig. 4B). Fine-grained intergrowths of alunite – quartz ± dickite replace feldspar phenocrysts, and occur as disseminations in the altered groundmass of dacitic dikes. Fine-grained mixtures of alunite and quartz also define halos around 1 to 5 cm-wide quartz – pyrite – covellite ± digenite and quartz – alunite – covellite – digenite veins. Alunite that formed coeval with copper mineralization occurs as coarse-grained clusters and rosettes intergrown with digenite – covellite in breccia cement and in syn-brecciation sheeted quartz – alunite – covellite – digenite veins.

The alunite – pyrophyllite alteration zone has a patchy distribution in deeper parts of the deposit (Fig. 4B). The pyrophyllite has corroded margins and has been replaced by alunite (Fig. 6F). Pyrophyllite is intergrown with dickite in the dickite-cemented breccias. The breccia cements are fine grained (0.2 – 0.5 mm), with intergrown dickite and pyrophyllite forming a porcellanous textures.

Muscovite alteration zone: This alteration zone is characterized by strong muscovite and weak dickite alteration, and occurs in marginal and deep parts of the deposit (Fig. 4B). The altered rocks are pale yellow to pale green, and consist of quartz, muscovite, dickite and pyrite, with minor rutile. The primary texture of the host rock is typically preserved, with plagioclase and feldspar phenocrysts replaced by aggregates of fine-grained quartz and muscovite (Fig. 6G). Fine-grained muscovite aggregates have been corroded by dickite at these margins, whereas coarse-grained muscovite in quartz – pyrite veins are associated with the muscovite – dickite alteration assemblages.

Supergene kaolinite alteration: Kaolinite alteration is restricted to the upper part of the deposit (~ 800 m a.s.l), defining a blanket that overlies and overprinted the silicic, quartz – alunite and quartz – dickite alteration zones. Kaolinite is abundant locally in pockets within the advanced argillic altered rocks, typically associated with dickite (Fig. 6H). The spatial distribution and the SWIR spectral characteristics of poorly-crystalized kaolinite indicate that kaolinite is probably supergene.

Mineralization

There are three principal styles of mineralization at Zijinshan: veins, breccias and disseminations. This section describes ore and gangue minerals that occur as infill in both breccias and veins (Figs. 7, 8 and 9) during four main paragenetic stages of hydrothermal activity, based on the crosscutting relationships.

Stage 1 is characterized by veins with fine-grained (< 1 mm), euhedral pyrite intergrown with quartz and muscovite. Stage 1 veins typically occur in moderately quartz – muscovite – pyrite altered wall rocks (Fig. 7A), varying from planar to tension gash veins and ranging from 0.5 to 20 cm wide (typically 0.5 - 4 cm). They either have 1 - 2 cm wide quartz alteration halos or lack obvious halos (Fig. 7A). Quartz occurs as dressy linings, and crystals grew symmetrically from the margins of stage 1 veins, with pyrite occurring in vein centers (Fig. 7A). Coarse-grained euhedral pyrite has filled cavities in the altered granite adjacent to stage 1 veins together with quartz. Muscovite varies from microcrystalline aggregates to coarse, euhedral platy crystals (up to 1 mm), intergrown with dogtooth quartz crystals. Most stage 1 quartz – pyrite veins are hosted by granite, and associated with abundant sub-euhedral to euhedral disseminated pyrite grains (0.5 - 2 mm). Stage 1 pyrite veins are consistently crosscut by stage 2 and stage 3 copper sulfide veins (Fig. 7) and hydrothermally-cemented breccias. No visible copper minerals were identified either in hand samples or petrographically in stage 1 veins.

Stage 2 veins commonly occur at depth (below 700 m a.s.l.) and in the center of the deposit. Stage 2 is the earliest stage of hypogene copper mineralization. This stage produced discrete quartz – enargite veins (up to 15 cm wide) associated with patchy disseminated pyrophyllite alteration in the host granite. Enargite is commonly well-crystalized, occurring as euhedral, slender (0.05 - 2mm) crystals in the margins of stage 2 veins. Some enargite crystals have been crosscut by stage 3 covellite – digenite veins. Minor fine-grained bornite (< 0.1 mm) formed in stage 2 (Fig. 7B). Chalcopyrite is very rare, only occurring as inclusions (0.02 - 0.1 mm) in enargite and pyrite, whereas relict pyrite is preserved in the center of some stage 2 enargite grains (Fig. 7E). Stage 2 contributed minor amounts (6.5 - 10%) of the total hypogene copper resource (Zijin unpublished metallurgy report, 2001).

Stage 3 is the most widespread and economically important phase of mineralization at Zijinshan. Stage 3 is characterized by abundant quartz, covellite, digenite and abundant to minor pyrite (Fig. 7C). Stage 3 veins vary from 1 mm to 40 cm width (typically 1 to 10 cm), and occur as sheeted veins, conjugate sets, isolated veins and wispy discontinuous veins.

Individual stage 3 veins typically have a sequence of sulfide deposition that begins with pyrite, followed by digenite, then covellite (Fig. 7). Pyrite and digenite are typically anhedral, fine-grained (1 - 50 μm) and contains inclusions of enargite. Covellite is commonly coarse-grained (up to 1 cm) and has been deformed in veins and breccias adjacent to faults. Stage 3 veins locally contain chalcocite and wittichenite.

Stage 3 veins have mutually crosscutting relationships with the covellite – digenite cemented breccias, both of which crosscut stage 1 and 2 veins (Fig. 7D). Truncated stage 2 veins occur in clasts within covellite – digenite-cemented breccias. Stage 3 veins and breccias occur in the center and northern domain of the deposit and are exposed over a wide vertical interval (-200 m to 1000 m a.s.l.). This stage contributed over 70% of the overall copper resource (Zijin unpublished metallurgy report, 2001).

Stage 4 veins are dominated by dickite and alunite and locally contain minor covellite and digenite. Dickite and alunite formed discrete veins in the granite and dacite. Many stage 4 dickite veins occur in the fault zones, whereas stage 4 alunite veins have been deformed adjacent to fault zones (within 20 - 200 cm of the fault). Stage 4 veins have locally re-opened stage 3 covellite – digenite veins (Fig. 7C), infilling the center of the veins, and stage 3 pyrite – covellite – digenite assemblages have been preserved on the vein margins (Fig. 7C).

Supergene mineralization and alteration

Weathering has produced intense supergene alteration and oxide gold mineralization (above 750 m a.s.l), which contains ~305 t gold (average 0.53 g/t). Pervasive hematite, supergene kaolinite, patchy goethite and jarosite are the typical supergene minerals (Fig. 8). Some oxide Au is concentrated with earthy hematite in the weathered silicic alteration zone – these ores are the current focus of mining at Zijinshan (Fig. 7I; So et al., 1998; Zhang, 2013). Hypogene sulfides and sulfosalts have been commonly oxidized to variable extents, filling the fractures in the altered rocks, containing rare secondary copper minerals, including chalcanthite, malachite, scorodite and chenevixite.

Supergene weathering improves the metallurgy of high sulfidation ores by liberating refractory gold from sulfides during sulfide oxidation and by reducing rock density with clay alteration (Sillitoe, 2005). These effects increased the gold grade from sub-economic in hypogene ores (average Au grade of 0.07 g/t) to economic grades averaging 0.53 g/t in the supergene profile (Zijin unpublished metallurgy report, 2001). Copper grades in the hypogene ore average 0.63%, but have been reduced to 0.018% in the oxide ores as a result of leaching (Zijin unpublished metallurgy report, 2001).

Gold occurs in Zijinshan hypogene ores predominantly in the crystal lattice of enargite, digenite, covellite and rarely in pyrite (Zijin unpublished metallurgy report, 2001). Small gold grains have been detected as inclusions in supergene hematite in some quartz veins by LA-ICP-MS (Chen, 2019). Gold may have been released from the hypogene sulfides by physical disaggregation and chemical dissolution (Bowell, 1992; Stoffregen, 1986). Dissolution and reprecipitation of the gold appear to have been important for supergene mineralization at Zijinshan.

Breccias

In order of abundance, breccia subfacies at Zijinshan include hydrothermally-cemented breccia, cement and matrix-bearing breccia and matrix-rich breccia (Table 3, Figs. 4A and 9).

Domains of matrix-rich breccia have been distinguished from cement-rich breccia, and from breccias with roughly equal amounts of cement and matrix in hydrothermal breccia complexes using the methods of Davies et al. (2008b). The abundance and distribution of these hydrothermal cement and matrix have implications for breccia formation and grade distribution.

In the northern part of Zijinshan deposit (Fig. 4A), hydrothermally-cemented breccias occur as sub-parallel breccia veins (average 20 to 40 cm wide) that strike NW and dip less than 45° NE. The hydrothermally-cemented breccias vary from monomict, granite clast-rich breccias to polymictic breccias with granite, dacite porphyry and quartz vein clasts (Fig. 9). The hydrothermally-cemented breccias are divided into three subfacies based on the dominant mineralogy: quartz – pyrite, alunite, and covellite – digenite (Fig. 9). Clasts are commonly quartz – alunite – dickite altered. The hydrothermally-cemented breccias contain 0.15 % to > 0.5% copper.

Matrix-rich breccias crop out in the southern part of the deposit as 0.2 - 2 m wide dikes that strike NW and dip moderately NE (Fig. 4A). The matrix-rich breccias are polymict and contain clasts of granite, dacite porphyry, quartz veins and massive quartz – pyrite altered rocks (Fig. 9). The matrix is interpreted to have been derived from abrasion and comminution of the host granite and dacite, and have been intensely quartz-altered. Copper grades in the matrix-rich breccias are typically < 0.15%. The matrix-rich breccias and hydrothermally-cemented breccias are localized in southeast and northeast of the mine, respectively.

Cement and matrix-bearing breccias are rare, typically occurring in the center of the deposit (Fig. 4). Subfacies of these breccias have been defined by the dominant cement minerals: sulfide-cemented and dickite-cemented (Fig. 9). Copper grades are variable from < 0.15 % to 0.5 %, depending on the cement composition.

Structural geology

A series of pre-, syn- and post-mineralization fault sets crosscut the Zijinshan deposit. The structural history has been determined from field observations of crosscutting and overprinting relationships, principally among faults, veins and breccias (Figs. 10 and 11). Faults have been assigned to groups according to their relative timing (Fig. 4A; Tables 4, 5 and 6). There are systematic variations in dominant structural orientations between each group. In cases where timing relationships were lacking, faults have been assigned to groups based on similarities in orientation, location, and kinematic indicators of displacement.

This paper follows the fault nomenclature of So et al. (1998), which has been used in many unpublished Zijin Mining Company reports (e.g., Zijinshan Au-Cu deposit annual reserve report, 2001, 2008, 2009). Their scheme uses two digits to describe each fault (Tables 4, 5 and 6). The NE-striking faults are termed F1-X (X = 1, 2, 3…). The NW-striking faults are termed F2-X. The ENE-striking and NNW-striking are termed F3-X and F4-X, respectively. Faults mapped in the current study that were not previously identified have been named as follows: North F1-X and West F2-X faults (Fig. 4A).

Pre-mineralization faults

Pre-mineralization faults at Zijinshan include a set of discontinuous NE-striking faults that dip steeply (70 - 85°) SE or NW (Table 4, Fig. 4A). These faults were reactivated and offset during magmatism and later mineralization, making their geometries relatively difficult to characterize.

The major pre-mineralization structures at Zijinshan are the F1-4, North F1-5, F1-5, F1-6 and F1-7 faults (Fig. 12, Table 4). These faults form arcuate shapes in plan view and have been disrupted and offset by later dacite intrusions and hydrothermal breccias (Fig. 12). The angle of dip of F1-4 to F1-7 faults varies from steep (70°) to sub-vertical (85°). The dip direction of the F1-4 fault is SE, whereas other pre-mineralization faults dip NW (Fig. 4). F1-4 has some indicators of reverse movement (Piquer et al., 2017). No kinematic information for F1-5 to F1-7 faults was obtained in this study.

At the regional scale, the NE-trending faults are parallel to the axes of the Xuanhe anticlinorium (Fig. 2). From NW to SE, faults change dips from SE to NW (Zijin mining internal report, 2015; Piquer et al., 2017; this study). The NE-trending faults have complex movement histories, and may have formed before the Xuanhe anticlinorium (Lin and Chen, 2011). The NE-trending faults were reactived as steeply dipping reverse faults, which deformed the Paleozoic metasedimentary rocks and plunge to the NW (Tao and Xu, 1992; Lin and Chen, 2011), and they are related to the fold hinge of the Xuanhe anticlinorium.

Syn-mineralization faults

Syn-mineralization faults are: (1) spatially related to hypogene copper mineralization; (2) cemented by copper minerals or have a damage zone that contains copper-mineralized veins; (3) have mutually crosscutting relationships with mineralized breccias and veins; or (4) have facilitated intrusions or mineralized dacitic dikes.

They have offsets ranging from centimeters to several meters (Table 5), and based on the dominant fault movements, dip angles and overall relationships, they are divided into four groups: Group A – NW-striking normal faults; Group B – NW-striking normal-sinistral strike slip faults; Group C – NW-striking sinistral strike slip faults; Group D – NW-striking reverse-sinistral strike slip faults. Crosscutting relationships include that normal fault movements predated sinistral strike-slip displacement (Fig. 10).

Group A (northwest-striking normal faults): The major normal faults are the F2-15, North F2-15 and F2-16 faults (Table 5). They strike 300 - 320°, and dip shallowly to moderately (30 - 55°) to the NE. These faults are typically less than 500 m long and 1 m wide where exposed in the pit. The faults are continuous on the west side of the pit, but typically splay into several arcuate or subsidiary faults to the east (Fig. 4A), and dickite and alunite fibers indicate the normal movement of group A faults. Dacite intrusions and hydrothermal breccia veins are localized by group A faults (Fig. 13).

Group B (northwest-striking normal-sinistral strike slip faults): Syn-mineralization normal-sinistral strike-slip faults at Zijinshan include the F2-10 and F2-12 faults (Table 5). They strike 295 - 325° and moderately to steeply (45 - 75°) NE-dipping. The faults consist of tectonic breccias and cataclasite, dickite and minor alunite mineral fibers, and deformed clasts in breccias indicate the normal-sinistral strike slip movement of the group B faults. Dacite porphyry dikes have intruded along some fault planes. The most distinctive feature of group B faults is that the offsets are greater and the fault planes are wider than group A faults (Fig. 13). This may be due to sinistral strike slip movement reactivating the pre-existing, weak, normal group A fault planes, increasing the size of the damage zones.

Group C (northwest-striking sinistral strike slip faults): This group of faults has restricted occurrences in the open pit. F2-13 is the only continuous NW-trending sinistral strike slip fault observed. It is 310 m long, with continuous exposures from the 652 m to 784 m benches (Fig. 4A). The F2-13 fault consists of a 1.5 m wide tectonic breccia and gouge zone. Group C faults dip moderately to steeply (50° - 80°) to the NE (Table 4). Dickite mineral fibers indicate that group C faults are sinistral strike slip faults. Group C faults are steeper (50° - 80°) than both group A faults (30° - 55°) and group B faults (45° - 75°), and the fault planes are smoother and more planar than those of group A and B faults (Fig. 13).

Group D (northwest striking reverse-sinistral strike slip faults): The group D faults are restricted to a few locations between group A, B and C faults, including the F2-11 and F2-14 faults (Fig. 4A). Fault F2-11 disrupted a 80 cm-wide dacite porphyry dike that intruded along a group A fault. Group D faults strike NW (280° - 330 °) and dip moderately (35° - 75°) to the NE (Table 4). Dickite and alunite mineral fibers indicate the reverse-sinistral strike slip movement of the group D faults (Fig. 10). Elongated clast in breccia veins are consistent with reverse faults that have been reactive by sinistral movement along the margins of the alunite and breccia veins.

Post-mineralization faults

Post-mineralization faults form a set of ENE-trending and conjugate NNW-trending structures that disrupted or crosscut the mineralized breccias, veins and early stage faults. Most of these faults are ENE-trending dextral strike slip faults that dip steeply NW (F3-1, F3-2, F3-3, North F3-4, F3-4, F3-5). The conjugate F4-1 and F4-2 faults are NNW-trending sinistral strike slip faults that dip steeply to the SW (Fig. 4A). Senses of movement on the post-mineralization faults have been recorded by hematite, jarosite and minor goethite mineral fibers. The characteristics of the post-mineralization faults are summarized in Table 6.

Structural analyses and evolution of the Zijinshan deposit

Kinematic and dynamic analyses have been conducted based on our new structural data (Appendix 1). Each group of faults has been analyzed, and the dominant stress regimes in pre-, syn- and post-mineralization stages have been determined.

Previous studies of the Zijinshan district concluded that NE-striking reverse faults formed before mineralization and controlled the geometry of the early Jurassic granite intrusions (Tao and Xu, 1992; Zhang et al., 2003; Piquer et al., 2017). These studies concluded that the F1-4 fault extended from Zijinshan deposit to the north, and controlled the location of the Wuziqilong Cu deposit and Luoboling porphyry Cu-Mo deposit (Fig. 2). They found evidence for reverse movement on the F1-4 fault at both Wuziqilong and Luoboling. However, in our study, we found little evidence for reverse movement on any of the NE-trending faults at Zijinshan. This may be due to multiple fault reactivations obscuring evidence for early reverse movements. It is possible that compression predated mineralization by a considerable time and this could explain why there is so little evidence of the reverse sense of movement on NE-trending faults.

A total of 29 syn-mineralization faults with reliable kinematic indicators have been mapped and characterized, enough to calculate paleo-stress tensors using the Multiple Inverse Method (Yamaji et al., 2011). Results of the kinematic and dynamic analysis are shown in Figure 14. The average principal stress directions indicate extension, with subvertical shortening and a stretching to the NNE (Fig. 14). A minor secondary cluster of NW-trending σ_3 may be explained by most of these groups of faults having stress ratios close to 0 (violet and blue colors in Fig. 14), indicating that σ_2 and σ_3 have similar magnitudes, preventing effective distinction between the intermediate (σ_2) and minimum (σ_3) principal stresses. The results show that mineralization occurred in a period of overall stress relaxation with subvertical shortening and NNE-SSW extension prevailing.

Reliable kinematic indicators could be measured on 25 post-mineralization faults. They yielded consistent results with regard to the calculation of paleo-stress tensors. The lower plunge of σ_1 for the post-mineralization faults compared to the syn-mineralization ones, suggests that they form in a strike-slip regime, with NW-oriented σ_1 and NE-oriented σ_3 (Fig. 15). This is consistent with observations of Piquer et al. (2017) that a secondary strike slip stress regime was regional regionally active in a short span of time at Luoboling and Dajigang deposits. Our study has revealed that two distinct stress regimes (extension and strike slip) prevailed at Zijinshan in different time periods (i.e. during and after mineralization). The strike-slip regime disrupted some of the syn-mineralization dacite intrusions, hydrothermal breccias and orebodies and marked the end of high sulfidation hydrothermal activity.

Discussion

Stress regimes and relationships with tectonic settings

Prior to mineralization, the Zijinshan host rocks were subjected to NW-directed compression and were deformed in the Xuanhe anticlinorium and associated pre-mineralization faults. This compressional regime is interpreted to be related to NW-directed subduction of the Paleo-Pacific plate beneath the Eurasian continent after the Late Jurassic that affected the entire southeastern margin of the South China Block (Zhou and Li, 2000; Mao et al., 2013). It is possible that multiple tectonic events from the Late Jurassic to Early Cretaceous (Li et al., 2014), caused movements on the pre-mineralization faults.

NW-trending structures were active during the Early Cretaceous, producing a series of NW-trending pull-part volcanic basins and continental-scale NW- to WNW-trending normal-oblique faults in southeast China, including the Shanghang volcanic basin and Shanghang-Yunxiao fault (Fig. 2). The NW-trending Shanghang-Yunxiao basement fault was reactivated as a normal-oblique basin-bounding fault during formation of the Shanghang basin during the Early Cretaceous (Wang and Lin, 1998; Lin and Chen, 2011). These regional-scale structures provided the broad structural framework of the Zijinshan district (Piquer et al., 2017). The NW-trending faults at Zijinshan, especially the NW-trending normal and normal-sinistral faults, were inherited from the regional NW-striking basement and basin-bounding structures

(Fig. 2). High sulfidation style mineralization and related alteration at Zijinshan occurred at 102.86 ± 0.61 Ma to 101.19 ± 0.60 Ma (Pan et al., submitted) under NNE-SSW extension. This extension event at Zijinshan district has been temporally constrained by multiple magmatic and hydrothermal events from 113 Ma to 95 Ma (Table 7; Fig. 16). The extensional setting affected the entire southeastern margin of the South China Block during the Early Cretaceous, and it is interpreted to be related to steepening of the subduction of Paleo-Pacific slab (Zhou et al., 2006; Piquer et al., 2017). The alternative interpretation is the extensional environment was produced by changes in the rate of the convergence (i.e. plate motions and/or deformations) across the Paleo-Pacific boundary (Li et al., 2014).

After mineralization, the region evolved from an extensional to a strike slip deformation regime, associated with NW-directed compression and NE-directed extension. This stress regime produced a series of ENE-striking dextral strike slip faults and conjugate NNW-trending sinistral strike slip faults. As noted from the regional structural geology study, an extensional regime prevailed throughout the district (Piquer et al., 2017). There are no ENE-trending strike slip structures in the Zijinshan district (Fig. 2; Piquer et al., 2017) or indeed at the regional-scale in southeastern China. The post-mineralization strike-slip regime at Zijinshan therefore probably does not reflect the broader tectonic regime but instead is related to transient changes in the stress state at the deposit-scale.

Timing of fault activation

Table 7 summarizes key features, movement histories, and the inferred stress regime for each paragenetic stage at Zijinshan. The relative timing of fault activation has been estimated from field observations of crosscutting relationships between faults, intrusions, volcanic rocks, and orebodies (Fig. 16).

Based on limited available data, the pre-mineralization NE-trending faults are interpreted to have formed contemporaneous with the Xuanhe anticlinorium during the Indosinian period (Zhang et al., 2003). They controlled the emplacement of the Jurassic granite complex (So et al., 1998; Piquer et al., 2017) but also disrupted the host granite (Fig. 4A), indicating that they remained active after Late Jurassic magmatism ceased. Only a few NE-trending faults are preserved in the district, and there are no indications of NE-trending faults in the 113 ~ 110 Ma Cretaceous Shimaoshan Group volcanic-sedimentary rocks (Piquer et al., 2017; Tables 2 and 7; Fig. 16), implying that they were not active during and after mineralization.

A syn-mineralization NW-trending fault system developed at Zijinshan and Luoboling (Piquer et al., 2017; This study). NW-trending faults crosscut the northeast edge of the Luoboling porphyry granodiorite and truncated porphyry Cu- Mo mineralization, implying that reactivation occurred after mineralization at Luoboling (i.e., after 104.6±1.0 Ma; Table 2; Lai and Qi, 2014; Zhong et al., 2014; Li and Jiang, 2017). NW-trending faults controlled the emplacement of the dacite porphyry dikes (104.8 ± 0.9 Ma; Pan et al., submitted), hydrothermal breccias, and mineralized veins at Zijinshan (Fig. 4A). High sulfidation style mineralization and related alteration at Zijinshan occurred at 102.86 ± 0.61 Ma to 101.19 ± 0.60 Ma (Pan et al., submitted). The Jintonghu monzonite is elongated NW and is inferred to have been controlled by NW-trending normal faults in the Zijinshan district (Li et al., 2016). Jintonghu is the youngest intrusion (96.1 ± 1.7 Ma – 94.9 ± 1.6 Ma; Table 2), providing an upper time limit for the activation of the NW-trending faults in the district. The NW-trending faults thus may be still have been active until 95 Ma (Fig. 16).

The period of post-mineralization strike-slip faulting was probably short-lived in the Zijinshan district, because strike-slip fault displacements have not been observed at Yueyang (91.47 ± 0.39 Ma; Liu and Hua, 2005). There is no evidence of magmatism – hydrothermal activity related to the post-mineralization strike slip faults.

Permeability controls on mineralization

Structural controls on high sulfidation epithermal deposits have been documented previously from Hope Brook Mine, Canada (Dube et al., 1998), Peak Hill, Australia (Masterman et al., 2002), La Grande, Chile (Masterman et al., 2004, 2005) and Yanacocha, Peru (Turner, 1997; Longo, 2000; Teal and Benavides, 2010). At Zijinshan, mapping of the main structural elements has provided a first order understanding of the controls on the subsequent emplacement of intrusions, mineralized breccias and veins. The syn-mineralization faults formed under an extensional setting and were the most important conduits for fluid flow through the Zijinshan granite. They imply that extensional tectonism was fundamental to mineralization at Zijinshan.

Many high sulfidation epithermal deposits, such as Yanacocha, Peru (Turner, 1999; Longo et al., 2010); Lepanto, Philippines (Chang et al., 2011) and Tantahuatay, Peru (Gustafson et al., 2004) are hosted in coherent andesitic to dacitic volcanic sequences. The Zijinshan deposit is hosted predominantly by a Jurassic granite complex (Fig. 4). Intact granites have intrinsically lower permeability ($k = 10^{-9} - 10^{-5}$ D; Brace, 1980) compared to volcanic rocks. The permeability of andesitic to dacitic volcanic rocks is typically between 10^{-3} to 10^{1} D (Wright et al., 2009). Andesitic to dacitic pyroclastic rocks have slightly higher permeability ($k = 10^{-2}$ to 10^{2} D; Wright et al., 2009). The intrinsically lower permeability of the host rock at Zijinshan compared to other HS deposits (e.g., Yanacocha, Lepanto and Tantahuatay) significantly affected the alteration distribution and geometry of Zijinshan's orebodies. Silicic alteration at Yanacocha produced shallow-dipping, tabular bodies (100 – 200 m thick) that are conformable with the volcanic stratigraphy. There are also structurally controlled subvertical silicic bodies that crosscut the volcanic stratigraphy (Longo et al. 2010). At Yanacocha, the intrinsic high permeability of the host volcanic rocks facilitated extensive hydrothermal fluid flow along both the volcanic stratigraphy and feeder faults (Longo et al. 2010). High grade gold ores at Yanacocha occur in the steeply-dipping faults, whereas lower grades occur within the tabular silicic alteration zones (Longo et al., 2010).

The HS Lepanto Cu-Au deposit, Philippines is another location where permeable stratigraphy played an important role in controlling the geometry of the orebodies. Over 70% of the enargite-Au ores at Lepanto occur in the stratabound alteration zones above the unconformity between the permeable Imbanguila dacite and underlying related impermeable basement (Chang et al., 2010). Massive sulfide ores at Tantahuatay, Peru is an example of stratabound high sulfidation mineralization in permeable andesitic volcanic rocks (Gustafson et al., 2004).

The volcanic-hosted examples outlined above contrast markedly with Zijinshan, where granite-hosted HS ore is hosted by moderately dipping, sheeted veins and breccias localized by NW-trending faults (Fig. 4A). Tectonic-hydrothermal brecciation along the syn-mineralization faults at Zijinshan significantly increased the permeability of granites by at least two or three orders of magnitude, and possibly by up to five or six orders of magnitude (e.g., Brace, 1980; Morrow et al., 2001). The damage zones associated with regional faults and subsidiary fractures provided the permeability architecture essential for vein and breccia formation, focusing high grade Cu-Au mineralization. Repeated reactivation of NW-trending faults during ore-formation occurred coincident with episodic release of fluids from an underlying magma, and/or when regional stresses triggered fault slip, further enhancing the permeability of the host rocks and facilitating hydrothermal fluid flow along brecciated fault zones. Although crystalline granite rocks are not the ideal host rocks for high sulfidation ores, Zijinshan demonstrated that extensional faulting can facilitate significant HS mineralization and alteration in previously impermeable plutons and stocks.

Exploration implications

Some high sulfidation ore deposits overlie and are interpreted to be genetically related to porphyry deposits (e.g., Lepanto-Far Southeast, Philippines; Arribas et al., 1995; Hedenquist et al., 1998; Chang et al., 2011; Rosario, Chile, Masterman et al., 2004, 2005; Tumpangpitu, Indonesia, Harrison et al., 2018). At Zijinshan and in the deepest part of the present-day pit, muscovite - dickite and alunite - pyrophyllite alteration assemblages are exposed beneath silicic alteration zones. This alteration zonation pattern is consistent with the transition from high sulfidation to porphyry environments as documented elsewhere (e.g., Hedenquist et al., 1998; Sillitoe, 1999; Gustafson et al., 2004; Masterman et al., 2005).

Since the moderately dipping NW-trending faults were the most important pathways for fluid flow at Zijinshan, exploration for a potential porphyry source should focus on the deeper parts of this fault system. On-going drilling work by Zijin Mining company is extending the domains of structural-controlled high sulfidation orebodies at depth to the NE. The Luoboling porphyry Cu-Mo deposit is located 2 km northeast of Zijinshan (Fig. 2) at elevations 500 m below the Zijinshan deposit with the Luoboling porphyry intrusion cropping out at surface (Fig. 2). There is no evidence of rotation or tilting between Zijinshan and Luoboling. Furthermore, the syn-mineralization normal-oblique faults between Zijinshan and Luoboling have recorded only minor displacements (on the order of centimetres to meters). It is therefore unlikely Luoboling was uplifted significantly after mineralization at Zijinshan to produce the current spatial relationships. We therefore conclude that the Luoboling porphyry is exposed at elevations too high for it to be the fluid source for the Zijinshan high sulfidation epithermal Au-Cu deposit. Given that the mineralized structures dip moderately (~ 45°) to the NE, the most likely direction to a porphyry-style orebody would be to the NE of the Zijinshan deposit, underneath the Zijinshan lithocap. The gap in drilling between the two mineralized centers (Zijinshan and Luoboling) need to be filled to test this hypothesis.

Conclusions

The Zijinshan high-sulfidation Au-Cu deposit is located in the middle of the Zijinshan district. Hypogene copper ore zones are intimately associated with extensive silicic and advanced argillic alterations. Spatially, silicic alteration occurs in the center of the deposit, passing outwards to quartz – dickite and quartz – alunite alteration domains. Four hypogene paragenetic stages have been identified. Stage 1 is characterized by quartz – muscovite veins with muscovite halos. Stage 2 quartz – enargite veins are associated with pyrophyllite alteration. Stage 3 covellite – digenite – pyrite veins have distinctive alunite or dickite vein halos. Stage 4 alunite and dickite veins locally contain minor covellite – digenite.

Structural mapping undertaken at Zijinshan open pit has defined pre-, syn- and post-mineralization fault sets, based on their styles, timing and crosscutting relationships. Pre-mineralization faults are NE-striking and dip steeply to the SE or NW. Syn-mineralization faults are NW-trending and dip moderately to the NE. Post-mineralization faulting produced a set of ENE-trending dextral strike-slip faults and conjugate NNW-trending sinistral strike-slip faults.

Prior to mineralization, the Zijinshan host rocks were subjected to NW-directed compression, and were deformed in the Xuanhe anticlinorium, producing pre-mineralization faults. This compressional regime is interpreted to be related to the NW-directed Paleo-Pacific slab subduction in the Jurassic. High sulfidation state mineralization and related alteration at Zijinshan occurred under NNE-SSW extension, associated with NW-trending normal-oblique faults. The extensional setting prevailed throughout the southeastern part of the South China Block during the early Cretaceous and could be related to steepening of the slab during Paleo-Pacific subduction. Post- mineralization, Zijinshan evolved to a strike-slip regime, with NW-directed compression and NE-directed extension. This local stress regime appears to have only affected Zijinshan, as there is no evidence for NE-trending strike-slip faults in the broader district.

The syn-mineralization faults were the most important conduits for fluid flow during mineralization. Extensional faulting significantly enhanced the permeability of the host rocks of Zijinshan, facilitated hydrothermal fluid flow, leading to the formation of the giant high sulfidation gold-copper deposit. Based on our structural data, we exclude the possibility that the Luoboling granodiorite porphyry is the source of mineralizing fluids for Zijinshan. The exploration target of the fluid source is at depth towards the NE, underneath the Zijinshan lithocap.

Acknowledgments

We acknowledge the financial, logistical and technical support of Zijin Mining Group Co., Ltd., and thank Kaihui Yang and Jinping Qi for their support for this project. We thank Xiaocan Wei and Shan Yu, plus many other Zijin staff, including Jing Li, Jinzhang Zhang, Wencan Zeng, Xuefeng Feng and Jiaojiao Jiang for their help on site and during field work. The senior author was the recipient of an SEG student grant, which is gratefully acknowledged. Thanks to the China Scholarship Council for providing living allowance, and to University of Tasmania for tuition fees for the senior author. We thank our research colleagues of CODES and the TMVC research hub for discussion, advice and encouragement.

We give special thanks to Stuart F. Simmons, Anthony A. Longo, Julie Rowland and Pete Hollings for their valuable and constructive comments that greatly improved the quality of the manuscript.

References

Allmendinger, R., 2002, Stereonet v. 1.1.6 and FaultKin v. 1.2.2, Department of Geological Sciences, Cornell University, Ithaca (shareware software,. geo. cornell. edu/pub/rwa).

Allmendinger, R.W., Cardozo, N., and Fisher, D.M., 2011, Structural geology algorithms: Vectors and tensors, Cambridge University Press, 289 p.

Arribas, A., Hedenquist, J.W., Itaya, T., Okada, T., Concepción, R.A., and Garcia, J.S., 1995, Contemporaneous formation of adjacent porphyry and epithermal Cu-Au deposits over 300 ka in northern Luzon, Philippines: Geology, v. 23, p. 337-340.

Bowell, R., 1992, Supergene gold mineralogy at Ashanti, Ghana: implications for the supergene behaviour of gold: Mineralogical Magazine London, v. 56, p. 545-545.

Brace, W., 1980, Permeability of crystalline and argillaceous rocks: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1980, p. 241-251.

Chang, Z.S., Hedenquist, J.W., White, N.C., Cooke, D.R., Roach, M., Deyell, C.L., Garcia, J., Gemmell, J.B., McKnight, S., and Cuison, A.L., 2011, Exploration tools for linked porphyry and epithermal deposits: Example from the Mankayan intrusion-centered Cu-Au district, Luzon, Philippines: Economic Geology, v. 106, p. 1365-1398.

Chen, J., Chen, Y.J., Zhong, J., Sun, Y., Li, J., and Qi, J.P., 2011, Fluid inclusion study of the Wuziqilong Cu deposit in the Zijinshan district, Fujian Province: Acta Petrologica Sinica, v. 27, p. 1425-1438.

Chen, J., Chen, Y.J., Zhong, J., Sun, Y., Qi, J.P., and Li, J., 2015a, Geological and ore-fluid characteristics of Longjiangting Cu deposit in Zijinshan Orefield, Fujian Province, and their genetic implications: Mineral Deposits, v. 34, p. 98-118.

Chen, J., Cooke, D.R., Zhang, L.J., White, N.C., Chen, H.Y., and Qi, J.P., 2015b, Hydrothermal alteration, mineralization and breccias at the Zijinshan high sulfidation Cu-Au deposit, Fujian Province, China: Society for Geology Applied to Mineral Deposits Conference 2015, p. 267-270.

Chen, J., 2019, Hydrothermal and structural evolution of the Zijinshan high sulfidation Au-Cu deposit, Fujian Province, China, Ph.D. thesis, Hobart, Tasmania, Australia, University of Tasmania, p 362.

Davies, A.G.S., Cooke, D.R., Gemmell, J.B., and Simpson, K.A., 2008a, Diatreme breccias at the Kelian gold mine, Kalimantan, Indonesia: Precursors to epithermal gold mineralization: Economic Geology, v. 103, p. 689-716.

Davies, A.G.S., Cooke, D.R., and Gemmell, J.B., 2008b, Hydrothermal breccias and veins at the Kelian gold mine, Kalimantan, Indonesia: Genesis of a large epithermal gold deposit: Economic Geology, v. 103, p. 717-757.

Dube, B., Dunning, G.R., and Lauziere, K., 1998, Geology of the Hope Brook Mine, Newfoundland, Canada; a preserved late Proterozoic high-sulfidation epithermal gold deposit and its implications for exploration: Economic Geology, v. 93, p. 405-436.

Einaudi, M., 1997, Mapping altered and mineralized rocks; an introduction to the "Anaconda method": Stanford University, Califonia, 22 p.

Feng, Z.Z., 1993, Mesozoic volcanism and tectonic environments in Fujian: Regional Geology of China, v. 4, p. 311-316.

Gustafson, L. B., Vidal, C., Pinto, R., and Noble, D., 2004, Porphyry-epithermal transition, Cajamarca region, northern Peru: Society of Economic Geologists Special Publication, v. 11, p. 279-299.

Harrison, R.L., Maryono, A., Norris, M.S., Rohrlach, B.D., Cooke, D.R., Thompson, J.M., Creaser, R.A., and Thiede, D.S., 2018, Geochronology of the Tumpangpitu porphyry

Au-Cu-Mo and high-sulfidation epithermal Au-Ag-Cu deposit: Evidence for pre-and postmineralization diatremes in the Tujuh Bukit district, Southeast Java, Indonesia: Economic Geology, v. 113, p. 163-192.
Hedenquist, J.W., Arribas, A., and Reynolds, T.J., 1998, Evolution of an intrusion-centered hydrothermal system; Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines: Economic Geology, v. 93, p. 373-404.
Hua, R.M., Chen, P.R., Zhang, W.L., and Lu, J.J., 2005, Three major metallogenic events in Mesozoic in South China: Mineral Deposits, v. 24, p. 99-107.
Jiang, S.H., Liang, Q.L., Bagas, L., Wang, S.H., Nie, F.J., and Liu, Y.F., 2013, Geodynamic setting of the Zijinshan porphyry-epithermal Cu-Au-Mo-Ag ore system, SW Fujian Province, China: Constrains from the geochronology and geochemistry of the igneous rocks: Ore Geology Reviews, v. 53, p. 287-305.
Lai, X.D., and Qi, J.P., 2014, The regularity of structural controls on ore mineralization in the Luoboling porphyry Cu-Mo deposit, Shanghang, Fujian: Acta Geologica Sinica, v. 88, p. 1904-1916.
Li, B., and Jiang, S.Y., 2014, Geochronology and geochemistry of Cretaceous Nanshanping alkaline rocks from the Zijinshan district in Fujian Province, South China: Implications for crust-mantle interaction and lithospheric extension: Journal of Asian Earth Sciences, v. 93, p. 253-274.
Li, B., Jiang, S.Y., Lu, A.H., Zhao, H.X., Yang, T.L., and Hou, M.L., 2016, Zircon U-Pb dating, geochemical and Sr-Nd-Hf isotopic characteristics of the Jintonghu monzonitic rocks in western Fujian Province, South China: Implication for Cretaceous crust–mantle interactions and lithospheric extension: Lithos, v. 260, p. 413-428.
Li, B., and Jiang, S.Y., 2017, Genesis of the giant Zijinshan epithermal Cu-Au and Luoboling porphyry Cu-Mo deposits in the Zijinshan ore district, Fujian Province, SE China: A multi-isotope and trace element investigation: Ore Geology Reviews, v. 88, p. 753-767.
Li, J.H., Wang, G.P., Zheng, T.F., and Liang, S.J, 1995, Study on the multiple classification and correlation of the strata in Fujian Province: Geology of Fujian, v. 4, p. 203-256.
Li, J.H., Zhang, Y.Q., Dong, S.W., and Johnston, S.T., 2014, Cretaceous tectonic evolution of South China: A preliminary synthesis: Earth-Science Reviews, v. 134, p. 98-136.
Li, X.H., Zhao, J.X., McCulloch, M.T., Zhou, G.Q., and Xing, F.M., 1997, Geochemical and Sm-Nd isotopic study of Neoproterozoic ophiolites from southeastern China: Petrogenesis and tectonic implications: Precambrian Research, v. 81, p. 129-144.
Li, X.H., Li, W.X., Li, Z.X., Lo, C.H., Wang, J., Ye, M.F., and Yang, Y.H., 2009, Amalgamation between the Yangtze and Cathaysia Blocks in South China: Constraints from SHRIMP U-Pb zircon ages, geochemistry and Nd-Hf isotopes of the Shuangxiwu volcanic rocks: Precambrian Research, v. 174, p. 117-128.
Li, Z.X., 1994, Collision between the North and South China blocks: A crustal-detachment model for suturing in the region east of the Tanlu fault: Geology, v. 22, p. 739-742.
Li, Z.X., Li, X.H., Kinny, P.D., and Wang, J., 1999, The breakup of Rodinia: Did it start with a mantle plume beneath South China?: Earth and Planetary Science Letters, v. 173, p. 171-181.
Lin, D.Y., and Chen, Z.H., 2011, Relationship between Shanghang pull-apart basin in Fujian and Zijinshan copper-gold deposit mineralization: Journal of Xian University of Science and Technology, v. 31, p. 438-442.
Liu, X.D., and Hua, R.M., 2005, $^{40}Ar/^{39}Ar$ dating of adularia from the Bitian gold-silver-copper deposit, Fujian Province: Geological Review, v. 51, p. 151-155.
Longo, A. A., 2000, The San Jose-Carachugo-Chaquicocha gold trend, Yanacocha District, northern Peru: Geology and ore deposits, p. 201-220.
Longo, A. A., Dilles, J. H., Grunder, A. L., and Duncan, R., 2010, Evolution of calc-alkaline volcanism and associated hydrothermal gold deposits at Yanacocha, Peru: Economic Geology, v. 105, p. 1191-1241.

Mao, J.R., Tao, K.Y., Lee, C.Y., Xie, F.G., and Xu, N.Z., 2002, Geochronology and geochemical characteristics in late Mesozoic Sifang pluton, southwestern Fujian, and their significance: Acta Petrologica Sinica, v. 18, p. 449-458.

Mao, J.W., Xie, G.Q., Guo, C.L., Yuan, S.D., Cheng, Y.B., and Chen, Y.C., 2008, Spatial-temporal distribution of Mesozoic ore deposits in South China and their metallogenic settings: Geological Journal of China Universities, v. 14, p. 510-526.

Mao, J.W., Cheng, Y.B.,Chen M.H., and Pirajno, F., 2013, Major types and time-space distribution of Mesozoic ore deposits in South China and their geodynamic settings: Mineralium Deposita, v. 48, p. 267-294.

Masterman, G.J., White, N.C., Wilson, C.J.L., and Pape, D., 2002, High-sulfidation gold deposits in ancient volcanic terranes: Insights from the mid-Paleozoic Peak Hill deposit: NSW: Society of Economic Geologists Newsletter, v. 51, p. 1, 10-16.

Masterman, G.J., Cooke, D.R., Berry, R.F., Clark, A.H., Archibald, D.A., Mathur, R., Walshe, J.L., and Duran, M., 2004, $^{40}Ar/^{39}Ar$ and Re-Os geochronology of porphyry copper-molybdenum deposits and related copper-silver veins in the Collahuasi District, northern Chile: Economic Geology, v. 99, p. 673-690.

Masterman, G.J., Cooke, D.R., Berry, R.F., Walshe, J.L., Lee, A.W., and Clark, A.H., 2005, Fluid chemistry, structural setting, and emplacement history of the Rosario Cu-Mo porphyry and Cu-Ag-Au epithermal veins, Collahuasi district, northern Chile: Economic Geology, v. 100, p. 835-862.

Morrow, C., Moore, D. E., and Lockner, D., 2001, Permeability reduction in granite under hydrothermal conditions: Journal of Geophysical Research, v. 106, p. 30551-30560.

Pan J.Y., Ni, P., Chi, Z., Wang, W.B., Zeng, W.C., and Xue, K., 2019, Alunite $^{40}Ar/^{39}Ar$ and zircon U-Pb constraints on the magmatic-hydrothermal history of the Zijinshan high-sulfidation epithermal Cu-Au deposit and the adjacent Luoboling porphyry Cu-Mo deposit, South China: Implication for their genetic association: Economic Geology, submitted.

Piquer J, Cooke, D.R., Chen J., and Zhang, L.J., 2017, Syn-extensional emplacement of porphyry Cu-Mo and epithermal mineralization: The Zijinshan district, SE China: Economic Geology, v. 112, p. 1055-1074.

Pirajno, F., and Bagas, L., 2002, Gold and silver metallogeny of the South China Fold Belt: A consequence of multiple mineralizing events?: Ore Geology Reviews, v. 20, p. 109-126.

Ren, J.S., 1991, The basic characteristics of the tectonic evolution of the continental lithosphere in China: Regional Geology of China, v. 4, p. 289-293.

Shu, L.S., Yu, J.H., Jia, D., Wang, B., Shen, W.Z., and Zhang, Y.Q, 2008, Early Paleozoic orogenic belt in the eastern segment of South China: Geological Bulletin of China, v. 27, p. 1581-1593.

Sillitoe, R.H., 1993, Giant and bonanza gold deposits in the epithermal environment: Assessment of potential generic factors: Society of Economic Geologists Special Publication, v. 2, p. 125-156.

Sillitoe, R.H., 1995, Exploration of porphyry copper lithocaps: Proceedings of Pacific Rim Congress, 1995, p. 527-532.

Sillitoe, R.H., 1999, Styles of high-sulphidation gold, silver and copper mineralisation in porphyry and epithermal environments: Proceedings of the Australasian Institute of Mining and Metallurgy, 2000, p. 19-34.Sillitoe, R.H., 2005, Supergene oxidized and enriched porphyry copper and related deposits: Economic Geology, v. 100, p. 723-768.

Sillitoe, R.H., 2005, Supergene oxidized and enriched porphyry copper and related deposits: Economic Geology, v. 100, p. 723-768.

Sillitoe, R.H., 2010, Porphyry copper systems: Economic Geology, v. 105, p. 3-41.

Simmons, S.F., White, N.C., and John, D.A., 2005, Geological characteristics of epithermal precious and base metal deposits: Economic Geology 100th anniversary volume, v. 29, p. 485-522.

So, C.S., Zhang, D.Q., Yun, S.T., and Li, D.X., 1998, Alteration-mineralization zoning and fluid inclusions of the high sulfidation epithermal Cu-Au mineralization at Zijinshan, Fujian Province, China: Economic Geology, v. 93, p. 961-980.

Stoffregen, R., 1986, Observations on the behaviour of gold during supergene oxidation at Summitville, Colorado, USA, and implications for electrum stability in the weathering environment: Applied Geochemistry, v. 1, p. 549-558.

Stoffregen, R.E., 1987, Genesis of acid-sulfate alteration and Au-Cu-Ag mineralization at Summitville, Colorado: Economic Geology, v. 82, p. 1575-1591.

Sun, W.D., Li, S.G., Chen, Y.D., and Li, Y.J., 2002, Timing of synorogenic granitoids in the South Qinling, central China: Constraints on the evolution of the Qinling-Dabie orogenic belt: The Journal of Geology, v. 110, p. 457-468.

Tao, J.H., and Xu, C.L., 1992, Discussion on the rock- and ore-controlling structures of the Zijinshan copper-gold deposit in Shanghang County, Fujian Province: Geology of Fujian, v. 3, p. 186-203.

Teal, L.B. and Benavides, A., 2010, History and geologic overview of the Yanacocha mining district, Cajamarca, Peru: Economic Geology, p. 1173–1190.

Turner, S.J., 1997, The Yanacocha epithermal gold deposits, northern Peru: High-sulfidation mineralization in a flow dome setting. Ph.D. Thesis, Colorado School of Mines, 682 p.

Turner, S.J., 1999, Settings and styles of high-sulfidation gold deposits in the Cajamarca region, northern Peru: PacRim '99, Bali, Indonesia, October 10–13, Australian Institute of Mining and Metallurgy, Proceedings, p. 461–468.

Wang, S.X., and Lin, D.Y., 1998, Preliminary reserch on evolution of crack activity and rift-basin in the west-middle region of Fujian Province: Fujian Seismology, v. 14, p. 37-39.

Wang, Y.J., Zhang, A.M., Fan, W.M., Zhao, G.,C.W. Zhang, G., Zhang, Y.Z., Zhang, F.F., and Li, S.Z., 2011, Kwangsian crustal anatexis within the eastern South China Block: Geochemical, zircon U-Pb geochronological and Hf isotopic fingerprints from the gneissoid granites of Wugong and Wuyi-Yunkai Domains: Lithos, v. 127, p. 239-260.

Wright, H.M., Cashman, K.V., Gottesfeld, E.H., and Roberts, J.J., 2009, Pore structure of volcanic clasts: measurements of permeability and electrical conductivity: Earth and Planetary Science Letters, v. 280, p. 93-104.

Xiao, A.F., Li, D.P., and Liu, X.M., 2012, LA-ICP-MS zircon U-Pb dating for the volcanic rocks of the Lower Formation of the Shimaoshan Group and evolution of the Cretaceous magmatism in the Zijinshan Cu-Au orefield, Fujian Province: Geotectonica et Metallogenia, v. 4, p. 613-623.

Xiu, L.C., Zheng, Z.Z., Yu, Z.K., Huang, J.J., Yin, L., Wang, M.J., Zhang, Q.N., Huang, B., Chen, C.X., Xiu, T.J., and Lu, S., 2007, Mineral analysis technology application with near infrared spectroscopy in identifying alteration mineral: Acta Geologica Sinica, v. 81, p. 1584-1590.

Xu, X.B., Zhang, Y.Q., Jia, D., Shu, L.S., and Wang, R.R., 2009, Early Mesozoic geotectonic processes in south China: Geology in China, v. 36, p. 573-593.

Xu, C., Chen, H.Y., Huang, W.T., Qi, J.P., Duan, G., Zhang, L.J., Wu, C., Zhang, S., and Zhong, W.B., 2017, Mesozoic multiphase magmatism at the Xinan Cu-Mo ore deposit (Zijinshan Orefield): Geodynamic setting and metallogenic implications: Ore Geology Reviews, v. 88, p. 768-790.

Xue, F., Lerch, M.F., Kröner, A., and Reischmann, T., 1996, Tectonic evolution of the East Qinling Mountains, China, in the Palaeozoic: A review and new tectonic model: Tectonophysics, v. 253, p. 271-284.

Yamaji, A., 2000, The multiple inverse method: A new technique to separate stresses from heterogeneous fault-slip data: Journal of Structural Geology, v. 22, p. 441-452.

Yamaji, A., Sato, K., and Otsubo,M., 2011, Multiple Inverse Method software package (http://www.kueps.kyoto-u.ac.jp/~web-bs/tsg/software/mim/man_e.pdf), 37 p.

Zhang, D.Q., She, H.Q., Li, D.X., and Feng, C.Y., 2003, The porphyry-epithermal metallogenic system in the Zijinshan region, Fujian Province: Acta Geologica Sinica (Chinese edition), v. 77, p. 253-261.

Zhang, J.Z., 2013, Geology, exploration model and practice of Zijinshan ore concentrated area: Mineral Deposits, v. 32, p. 757-766.

Zhao, X.L., Mao, J.R., Chen, R., Xu, N.Z., Zeng, Q.T., and Ye, H.M., 2007, Zircon SHRIMP age and geochemical characteristics of the Caixi pluton in southwestern Fujian Province: Acta Petrologica et Mineralogica, v. 26, p. 223-231.

Zheng, Y.F., 2003, Neoproterozoic magmatic activity and global change: Chinese Science Bulletin, v. 48, p. 1639-1656.

Zheng, Y.F., Gong, B., Zhao, Z.F., Wu, Y.B., and Chen, F.K., 2008, Zircon U-Pb age and O isotope evidence for Neoproterozoic low-^{18}O magmatism during supercontinental rifting in South China: Implications for the snowball Earth event: American Journal of Science, v. 308, p. 484-516.

Zhong, J., 2014, Temporal and spatial evolution of the Zijinshan porphyry-epithermal magmatic and mineralization system, Fujian Province, Ph.D. thesis, Beijing, China, Peking University, 191 p.

Zhong, J., Chen, Y.J., Pirajno, F., Chen, J., Li, J., Qi, J.P., and Li, N., 2014, Geology, geochronology, fluid inclusion and H-O isotope geochemistry of the Luoboling porphyry Cu-Mo deposit, Zijinshan orefield, Fujian Province, China: Ore Geology Reviews, v. 57, p. 61-77.

Zhong, J., Chen, Y.J., and Pirajno, F., 2017a, Geology, geochemistry and tectonic settings of the molybdenum deposits in South China: A review: Ore Geology Reviews, v. 81, p. 829-855.

Zhong, J., Chen, Y.J., Qi, J.P., Chen, J., Dai, M.C., and Li, J., 2017b, Geology, fluid inclusion and stable isotope study of the Yueyang Ag-Au-Cu deposit, Zijinshan orefield, Fujian Province, China: Ore Geology Reviews, v. 86, p. 254-270.

Zhong, J., Chen, Y.J., Chen, J., Qi, J.P., and Dai, M.C., 2018, Geology and fluid inclusion geochemistry of the Zijinshan high-sulfidation epithermal Cu-Au deposit, Fujian Province, SE China: Implication for deep exploration targeting: Journal of Geochemical Exploration, v. 184, p. 49-65.

Zhou, T.H., Goldfarb, R.J., and Phillips, N.G., 2002, Tectonics and distribution of gold deposits in China–an overview: Mineralium Deposita, v. 37, p. 249-282.

Zhou, X.M., and Zhu, Y.H., 1993, Late Proterozoic colisional orogen and geosuture in southeastern China: Petrological evidence: Chinese Journal of Geochemistry, v. 12, p. 239-251.

Zhou, X.M., and Li, W.X., 2000, Origin of Late Mesozoic igneous rocks in Southeastern China: Implications for lithosphere subduction and underplating of mafic magmas: Tectonophysics, v. 326, p. 269-287.

Zhou, X.M., Sun, T., Shen, W.Z., Shu, L.S., and Niu, Y.L., 2006, Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: A response to tectonic evolution: Episodes, v. 29, p. 26-33.

FIGURE CAPTIONS

Fig. 1. A) Simplified tectonic map of China showing the major tectonic units (after Ren, 1991); B) Schematic geological map of the South China Block, showing distribution of the Yanshanian volcanic and intrusive rocks. Geology taken from the 1: 200,000 scale geological map of China compiled by Ren et al. (1991). The Jiangshan-Shaoxing suture zone separates the Yangtze Craton from the Cathaysia Block. The Lishui-Dapu fault zone separates the Coastal Volcanic Belt from the Cathaysia Block interior. The triangle symbol indicates the Zijinshan district.

Fig. 2. A) Regional structure framework of the Zijinshan district (after Jiang et al., 2013). The star and square mark the location of the Zijinshan district at the northern margin of

Shanghang Basin. The Yueyang-Gushibei and Tiziling faults bounded the Shanghang basin, which are both normal sinistral strike-slip faults, belonging to the Shanghang-Yunxiao fault system; B) Sketch geological map of the Zijinshan district (after Zhong et al., 2014, Piquer et al., 2017). Mineralization ages of the deposits are shown on the map (references in Table 2). The rectangle marks the location of the Zijinshan high sulfidation deposit.

Fig. 3. Summary stratigraphic column of the Zijinshan district, based on Li et al. (1995).

Fig. 4. A) Sketch geological map of the Zijinshan Au-Cu deposit (pit surface November 2014) based on detailed Anaconda-style mapping and structural geology study by the senior author. B) Alteration map of the Zijinshan deposit showing the distribution of alteration zones (pit surface November 2014) based on detailed field mapping and SWIR analyses of surface samples. Sample locations are shown on the map with black dots.

Fig. 5. Igneous rocks of the Zijinshan Au-Cu deposit. A) Wulongsi biotite granite is medium- to fine-grained (0.4 - 3 mm), equigranular, with microcline (35%), plagioclase (25%), quartz (25%), muscovite (5%), and biotite (5%), and accessory zircon, apatite, titanite and allanite. This sample has weak dickite alteration (440151.5 mN, 2786779.8 mE, 44.5 m a.s.l.); B) Jinlongqiao granite is fine grained (0.2 - 2 mm) and equigranular, with K-feldspar (40%), plagioclase (20%), quartz (30%), and muscovite (5%) and accessory zircon, apatite, titanite and allanite (439265.76 mN, 2786845.6 mE,155 m a.s.l.). C) Dacite porphyry has 0.3 - 3 mm diameter phenocrysts that consist of euhedral plagioclase (10 - 20%), hornblende (4 - 10%), biotite (2%), K-feldspar (1 - 5%), and quartz (1 - 5%). The groundmass is dominant by plagioclase, defining a pilotaxitic texture (< 0.5 mm). Hornblende phenocrysts have been altered to biotite. The yellow-brown color is due to jarosite staining (440103 mE; 2786750 mN, 174.97m b.s.l.); D) Weakly porphyritic dacite with rare plagioclase phenocrysts. The yellow coloring is due to jarosite staining (440645 mE, 2786664 mN, bench 760 m) Abbreviations: Bi - biotite; Kf - K-feldspar; Ms - muscovite; Pl - plagioclase; Qz - quartz.

Fig. 6. Hydrothermal alteration assemblages and associated textures at Zijinshan. A) Granite with massive quartz alteration. K-feldspar and plagioclase have been replaced by quartz. The original granite texture can still be recognized (440431 mE, 2786706 mN, bench 652 m); B) Granite with vuggy quartz texture. K-feldspar and plagioclase have been preferentially leached, leaving the distinctive vuggy texture (440627 mE, 2786531 mN, bench 760 m). C) Well-crystallized dickite filled vugs of the host granite (440533 mE 2786584 mN, bench 700 m). D) Quartz - dickite altered granite. Dickite replaces feldspar, obscuring the granitic texture (DZK 305, 440151.5 mE, 2786779.8 mN, 296 m a.s.l.). E) Altered granite with abundant alunite and minor pyrite. The primary granite textures are not apparent due to the intense alteration that gives the rock its pink color (440946 mE, 2787235 mN, bench 808 m). F) Alunite – pyrophyllite – pyrite altered granite. Pyrophyllite replaced plagioclase, leaving white colored altered grains. Pinkish alunite pinched into white pyrophyllite grains. Minor pyrite filled the rims and fractures of the pyrophyllite grains (ZK12-13, 440676.9 mE, 2787648.4 mN, 627.1 m a.s.l.). G) Dickite - muscovite altered granite. Fine-grained dickite and muscovite replaced the K-feldspar and plagioclase as compact aggregates (DZK701, 440072.0 mE, 2786847.5 mN, 333.3 m a.s.l.). H) Kaolinite and dickite filled cavities in advanced argillic altered granite (440704 mE, 2786673 mN, bench 784 m). Abbreviations: Aln - alunite; Cv - covellite; Dic - dickite; Hem - hematite; Kln - Kaolinite; Ms - muscovite; Py - pyrite; Pyro - pyrophyllite.

Fig. 7 Mineralization and veins characteristics. A) Stage 1 quartz – pyrite veins. The veins contain abundant pyrite, minor quartz and have muscovite alteration halos. No open space is preserved in these veins. Thick pyrite veins have thin pyrite vein branches (440151.5 mE, 2786779.8 mN, 311 m a.s.l.). B) Thick quartz – enargite vein. Slender crystals of enargite formed at the margins of the vein with quartz filled in the center (440603 mE, 2786792 mN, bench 700 m). C) Stage 4 alunite vein has re-opened stage 3 covellite – digenite – pyrite vein. Stage 3 covellite – digenite - pyrite vein has a quartz – alunite alteration halo (440677 mE, 2787648 mN, 213 m a.s.l.). D) Stage 3 quartz – covellite – digenite – pyrite veins with thin quartz – alunite halos. Stage 3 veins crosscut stage 1 quartz – pyrite vein with quartz halos. These veins are hosted in dickite – alunite altered granite (440734 mE, 2786982 mN, bench 724 m). E) Photomicrograph (reflected light) of stage 2 enargite vein. Enargite vein contains minor bornite inclusions. Pyrite has been replaced by later enargite (436419 mE, 2785575 mN, 96 m a.s.l.). F) Photomicrographs (reflected light) of stage 3 alunite – covellite – enargite grains. Alunite has deformed tabular crystals. Covellite replaced enargite and filled spaces between alunite grains (440668 mE, 2786389 mN, bench 784 m). G) Photomicrograph of alunite vein, showing tabular alunite crystals intergrown with quartz (XPL; 440215 mE, 2789534 mN). H) Gold ore with vuggy texture. Hematite is the dominant supergene mineral. The gold grade of this sample is 0.4 g/t based on whole rock geochemical analyses (ICP-MS, ACME Lab, Vancouver, Canada; 440617 mE, 2786420 mN, bench 760 m). Abbreviations: Aln - alunite; Bn - Bornite; Cv - covellite; Dg - Digenite; Dic - dickite; Hem - hematite; Kln - Kaolinite; Ms - muscovite; Py - pyrite; Pyro -pyrophyllite; Qz - quartz.

Fig. 8 Summary of ore and gangue minerals present in each of the five stages, based on the observed crosscutting relationships of veins and breccias. Line thickness represents relative mineral abundances. Dashed lines indicated sporadic deposition.

Fig. 9 Examples of different breccia facies at Zijinshan. A) Quartz - pyrite cemented breccia (CM1). The dusty gray color is due to the presence of fine-grained disseminated pyrite intergrown with quartz. Quartz - dickite altered granite clasts. This sample contains 1 - 4% matrix (440899 mE, 2787042 mN, bench 784 m). B) Alunite-cemented breccia (CM2). Abundant alunite-cemented monomict granite clasts (440619 mE, 2786421 mN, bench 760 m). C) Outcrop-scale view of monomict granite-clast covellite-cemented breccia (CM3). Rosettes of coarse grained covellite and digenite cement rotated-granite clasts (440530 mE, 2786519 mN, bench 700 m). D) Matrix-rich breccia (MX). Polymictic granite and dacite clasts with 50% sand-sized matrix. Clasts and matrix are both intensely quartz-altered (440837 mE, 2787220 mN, bench 760 m). E) Covellite-cemented and matrix-bearing breccia (CMX1). Polymict granite, quartz-pyrite clusters clasts, covellite and pyrite as cement with 20% mud to sand-sized matrix (440934 mE, 2787059 mN, bench 796 m). F) Dickite-cemented and matrix-bearing breccia (CMX2). Polymictic granite and quartz clasts, with 20% mud to sand-sized matrix (440704 mE, 2786777 mN, bench 760 m). Abbreviations same as Fig. 7.

Fig. 10 Examples of slickenfibers as movement indicators of faults. Arrows shown on the figures indicate movements of the missing block, which indicate the sense of movement of the faults. A. Dickite fibers in the footwall of a normal fault (440133.2 mE, 2786584.0 mN, bench 604 m). B. Alunite fibers in the footwall of a reverse-sinistral strike-slip fault (440475.0 mE, 2786786.7 mN, bench 652 m). C. Horizontal mineral fibers have overprinted oblique fibers, indicating that sinistral strike slip movement postdated normal movement. They are syn-mineralization faults, because the mineral fibers are dickite and muscovite (440558.7 mE, 2786559.5 mN, bench 724 m). D. Goethite fibers in the south block of a dextral strike-slip fault (440570.3 mE, 2786638.7 mN, bench 724 m).

Fig. 11 Displacement of markers indicating offset of faults in the Zijinshan open pit. Arrows indicate the relative movement of the faults. A. Offset of a matrix-rich breccia dike provides evidence of normal fault movement (440556.5 mE, 2786548.1 mN, bench 724 m). B. Deformed clasts in matrix-rich breccia are consistent with breccia formation in a contractional jog of a syn-brecciation normal fault (440532.8 mE, 2786633.0 mN, bench 700 m). C. The displacement of a quartz – pyrite – covellite – digenite-cemented breccia vein indicates post-brecciation dextral fault movement (440494.9 mE, 2786810.7 mN, bench 652 m). D. Displacement of a quartz – pyrite – covellite – digenite cemented breccia indicates post-brecciation reverse-dextral fault movement (440543.2 mE, 2786933.0 mN, bench 652 m).

Fig. 12 Field exposures of pre-mineralization faults. A) F1-4 fault plane filled by tectonic breccia on bench 820 m (441015.0 mE, 2787088.8 mN); B) North F1-5 fault exposed on bench 796 m. The pre-mineralization fault plane has been disrupted by an intensively dickite-altered dacite porphyry dike (440759.2 mE, 2786716.0 mN).

Fig. 13 Field exposures and characteristics of syn-mineralization faults. A) Syn-mineralization normal fault F2-15 on bench 652 m, hydrothermally-cemented breccia along the fault plane (440494.9 mE, 2786810.7 mN); B) Close-up view of the granite and dacite porphyry contact, parallel to syn-mineralization normal fault North F2-15. The granite is intensely quartz altered. The feldspar phenocrysts of the dacite porphyry have been altered to dickite; C) The syn-mineralization normal-sinistral strike slip F2-12 fault on bench 652 m; mineral fibers are overprinted by hematite (440431.2 mE, 2786674.8 mN); D) Reverse-oblique movement reactivated on margin of a hydrothermally-cemented breccia vein (details in Fig. 10B). The breccia vein and the sheeted quartz – alunite – covellite – digenite vein formed on pre-existing NW-striking normal faults and were offset and reactivated by later reverse-oblique movement. The mineral fibers indicating reverse sinistral strike slip movement are dickite and alunite. This indicates reverse oblique movement contemporary with mineralization, but later than syn-mineralization normal oblique movements (440475.0 mE, 2786786.7 mN, bench 652 m).

Fig. 14 Stereoplots and principal stress direction plots for the syn-mineralization faults at Zijinshan. All stereoplots are lower-hemisphere, equal-area projections. A) Rose diagram of all syn-mineralization faults grouped by senses of movement. Dominant strike sets (270 - 300°, 300 - 320°, and 320 - 340°) are highlighted, although the dominant orientation of each group varies slightly with location in the open pit. B) Stereoplot showing fault planes (great circles) with slip vectors (points). C) and D) Stress states significant for faultslip data are visualized as clusters on the paired stereograms; principal orientations of the stresses are denoted by lower-hemisphere, equal-area projection. The paired stereograms show the orientations of the stresses detected by the Multiple Inverse Method. Clusters of the symbols with similar colors and similar attitudes on the stereograms represent significant stresses for a given set of fault-slip data. Principal stresses are the maximum (σ_1) and minimum stresses (σ_3) on a particular fault plane. In this case, the major principal stress (σ_1) is sub-vertical oriented and the minor principal stress (σ_3) is NNE-oriented. During syn-mineralization faulting, this indicated a NNE-SSW direction of extension.

Fig. 15 Principal stress direction plots for the post-mineralization faults at Zijinshan deposit. Same plots and legend as in Fig. 14. The major principal stress (σ_1) is NW-oriented and the minor principal stress (σ_3) is NE-oriented. During post-mineralization faulting, this indicated a strike-slip regime, with NW-SE compression and NE-SW extension.

Fig. 16 A summary time chart displaying the ages and time spans including the key information of magmatism and hydrothermal events based on the published geochronology work at Zijinshan district (Table 2). Timing of fault activation (Table 7) have constrained each structural stage of Zijinshan deposit, corresponding to regional or local stress regime.