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Origin and evolution of ore fluid, and gold-deposition processes at the giant Taishang gold deposit, Jiaodong Peninsula, eastern China

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ABSTRACT

The Early Cretaceous Taishang gold deposit is the largest deposit in the Linglong goldfield, Jiaodong Peninsula, with a pre-mining endowment of 326 t of gold. It is hosted in the 165–150 Ma Linglong biotite granite and controlled by the NEE- to NE-trending Potouqing Fault near the northern end of the regional Zhaoping Fault system. Hydrothermal alteration is well developed in the footwall of the Potouqing Fault and is characterized by a narrow zone of sericitization, followed by a wider zone of silicification, and an even wider zone of potassic alteration. The main orebodies (No. I orebody) comprise disseminated and stockwork-veinlet systems, although about 5% of the resources are in larger quartz veins (No. II orebody). Four stages have been identified for both styles of mineralization, on the basis of cross-cutting relationships and mineralogical and textural characteristics: pyrite–quartz–sericite (stage 1), quartz–pyrite (stage 2), quartz–pyrite–base-metal-sulfide (stage 3) and quartz–carbonate (stage 4). Gold was mainly deposited in stages 2 and 3, with minor amounts in stage 1.

Petrographical, microthermometric, and laser Raman spectroscopic studies on fluid-inclusion assemblages in quartz and calcite from the four stages reveal three types of primary fluid inclusions: type 1 H_2O-rich aqueous-carbonic, type 2 CO_2-rich aqueous-carbonic, and rare type 3 carbonic inclusions. Stage 1 quartz primary inclusions are only type 1 inclusions, with an estimated composition of 88% H_2O, 10% CO_2, 4.5 wt.% NaCl equiv., and 0.5% CH_4, with trapping at ~336 °C and ~1.7 kbars. The gold-rich stages 2 and 3 from both orebodies typically contain primary fluid-inclusion assemblages with both type 1 and 2 inclusions, which show similar phase-transition temperatures and were trapped between 246° and 294 °C. The stage 4 quartz and calcite contain only primary type 1 inclusions, which are estimated to have a composition of 93% H_2O, 6.0% CO_2, 3.6 wt.% NaCl equiv., and trace amount of CH_4, and were trapped at temperatures of >236 °C.

The $\delta^{34}S$ values of hydrothermal pyrite from the four stages have a narrow range from 4.5‰ to 8.0‰, and are within the ranges for whole-rock sulfides from the Archean Jiaodong Group, and magmatic pyrite from Mesozoic granitoid and intermediate-basic dikes. The $\delta^{18}O$ values of hydrothermal quartz range mainly from 10.9 to 12.5‰ and remain constant for all four stages; calculated fluid $\delta^{18}O$ values are 1.3–10.0‰. The δD_{water} values calculated from hydrothermal sericite range from −60 to −45‰. Considering the fluid inclusion compositions, $\delta^{18}O$ and δD compositions of ore-forming fluids, and regional geological events, the most likely ultimate potential fluid and metal reservoirs would be the Paleo-Pacific oceanic slab and its overlying sediments, which were thrust below the high-grade metamorphic rocks of the Jiaodong Peninsula.

The initial ore-forming fluids were medium-high temperature, CO_2-rich, and low salinity H_2O–CO_2–NaCl ± CH_4 homogeneous fluids. Over the duration of the hydrothermal system, the fluid remained fairly consistent in P–T–X, although becoming slightly more water-rich during final post-ore activity. Fluid immiscibility occurred during stages 2 and 3 ore deposition at pressures that fluctuated strongly from 1700 to 580 bars during hydrofracturing. The $(HS)_2^-$ ion was the most probable gold-transporting complex at Taishang. Wall-rock sulfidation and episodic pressure drops, with associated fluid unmixing and other chemical changes, were the two main mechanisms of ore deposition.

1. Introduction

The Jiaodong gold deposits, currently the most important gold resources (with Au reserves of >4000 t) in the leading gold-producing country globally (with Au production of ~452 t in 2014), have been

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historically distinguished into two types: (1) the Jiaojia-type gold deposits, occurring as disseminated- and stockwork-style mineralization hosted in alteration zones along major regional-scale faults; and (2) the Linglong-type gold deposits, occurring as massive auriferous quartz veins hosted in subsidiary second- or third-order faults (Qiu et al., 2002; Deng et al., 2003; Li et al., 2015). The two styles of gold deposits are believed to be formed by markedly different mineralization mechanism (Wen et al., 2015): the former is possibly a consequence of extensive water–rock interaction, and the latter resulted from fluid immiscibility. However, the two ore styles are frequently gradational and thus usually are present within a single deposit. The similar fault controls, alteration assemblages, mineral paragenesis, element concentrations, ore-fluid chemistry and ore-forming ages, reveal that they formed in broadly uniform hydrothermal fluid and physicochemical conditions throughout the whole Jiaodong Peninsula (Yang et al., 2014a), despite the fluid and metal sources of them remain problematic (Goldfarb and Santosh, 2014). The vast majority of Jiaodong gold deposits are hosted by the late Mesozoic granitoids, and so the possibility that ores may form from felsic–intermediate magmas fluids has been discussed for many years (Fan et al., 2003; Yang et al., 2007, 2008, 2009; Wang et al., 2010; Guo et al., 2014). Nevertheless, the ore-fluid P–T–X conditions of most deposits show that fluids are also consistent with those typical of a metamorphic source (Wang et al., 2015).

In the Linglong goldfield, one of the oldest gold-mining districts in Jiaodong and with a documented mining history as early as the Tang dynasty, both gold exploration and exploitation had historically focused only on the Linglong-type gold deposits (Song et al., 2014). The Linglong goldfield, therefore, was considered to not be prospective for the Jiaojia-type gold deposits, prior to the discovery of the Taishang gold deposit (Li and Yang, 1993) in 1966 by the No. 6 Geological Team of Shandong Bureau of Geology and Mineral Resources. Detailed investigation and exploration was carried out at the deposit from 1966 to 1992 and the gold mining operation started in 1976 (Li et al., 2007). To date, the Taishang gold deposit is the largest gold deposit in the Linglong goldfield and the second largest gold deposit in China, with a proven premining gold reserve of 326 t gold at a grade of 2.82 g/t Au. The distinctive geological environment, structural setting, and metallogenic features provide an excellent opportunity to study in detail the gold-depositional processes for the disseminated style of ores in the Linglong goldfield. This will be helpful in determining whether there are notable differences in fluid P–T–X from the well-studied Linglong-type ores, and may contribute to the development of a metallogenic model for the Jiaodong gold deposits.

There are a number of previous studies of the Taishang gold deposit, including those focused on deposit geology (Li et al., 2013a), ore-controlling structures (Cui, 2008), hydrothermal alteration (Zhao et al., 2008), and pyrite trace-element geochemistry (Chen et al., 2014). However, there is only one published paper focused on the fluid inclusions of the Taishang gold deposit. Although temperature (220–300 °C), salinity (5.5–9.0 eq. wt.% NaCl), density (0.76–0.92 g/cm^3), and CO_2-bearing fluid inclusions in the ores were recorded (Zhou and Li, 1991), the paragenetic stages of the quartz and related generations of fluid inclusions were not described. Thus the interpretation of the data from Zhou and Li (1991) is constrained by the lack of evidence for the paragenesis of the examined minerals. Furthermore, studies on the origin and evolution of the ore fluid designed to constrain gold-depositional processes have so far not been conducted, in part reflecting the lack of any stable isotope studies of the Taishang deposit.

A scientific understanding of the fluid inclusions and stable isotope geochemistry of the Taishang deposit was designed to help understand the distinctive Jiaojia-type of mineralization in the Linglong Goldfield, and thus target additional large tonnage gold ores in the extensive late Mesozoic granitoids of the Jiaodong area. This paper, therefore, documents four types of fluid inclusions and two fluid-inclusion assemblages corresponding to four mineralization stages. Combined with microthermometry, Laser Raman spectroscopy and stable isotope analysis, the origin and evolution of ore-forming fluids in the Taishang gold deposit will be discussed, in order to reveal the P–T–X conditions and mechanism of gold deposition.

2. Regional geology

2.1. Tectonic and metallogenic setting

The Jiaodong Peninsula is underlain by two Precambrian tectonic units, the Jiaobei Terrane in the northwest and the Sulu Terrane in the southeast, which were sutured along the NE-trending Wulian–Qingdao–Yantai Fault (WQYF) during continental collision in the Triassic to Early Jurassic (Fig. 1). The Jiaobei Terrane comprises the Jiaobei Uplift in the north and the Jiaolai Basin in the south. The former, dominated by Precambrian metamorphic basement and supracrustal rocks cut by Mesozoic intrusions, has most of the large gold deposits and hosts more than 90% of the proven gold resources (~3600 t Au; Yang et al., 2014a) in the Jiaodong gold province (Fig. 1).

The ca. 2.9–2.5 Ga tonalite–trondhjemite–granodiorite (TTG) gneisses in the Qixia and Zhaoyuan districts (Deng et al., 2011; Wan et al., 2012) are the oldest rocks in the region. They form the basement to the metamorphosed metasedimentary and metavolcanic rocks of the JIaodong Group (Jahn et al., 2008). Both the TTG gneisses and Jiaodong Group were subsequently folded and underwent amphibolite-facies metamorphism at ca. 2.5 Ga (Geng et al., 2012). They were intruded by ca. 2.2–2.0 Ga mafic–ultramafic rocks and A-type quartz monzonites (Zhou et al., 2008), which were overlain by the protoliths to the paragneiss, schist, calc-silicate rocks, marble, and minor mafic granulite and amphibolite of the Paleoproterozoic Fenzishan and Jingshan Group (Dong et al., 2010; Liu et al., 2013b; Li et al., 2013b). An important continent–continent collision at ca. 1.9 Ga is recorded by metamorphism and deformation of rocks of the Jingshan and Fenzishan Groups (Tam et al., 2011, 2012; Liu et al., 2012). The Neoproterozoic sedimentary rock cover in the Penglai and adjacent areas (Penglai Group; Chu et al., 2011), consists mainly of marble, slate, and quartzite (Faure et al., 2004).

Mesozoic granitoids in the Jiaobei uplift have been traditionally divided into the Linglong, Guojialing, and Aishan Suites (Zhang et al., 2010; Yang et al., 2012), with the former two suites being significant hosts for gold mineralization (Fig. 1). The 165–150 Ma Linglong Suite consists of garnet-, biotite-, amphibole-, and muscovite-bearing granite (Jiang et al., 2012; Yang et al., 2012), which was intruded into rocks of the Jiaobei terrane at depths of 25–30 km (Zhang et al., 2010; Jiang et al., 2012). This indicates that the prominent crustal thickening in the Jiaodong region occurred at the end of the Middle Jurassic (Yang et al., 2006). The 132–123 Ma Guojialing-type granodiorite suite (Yang and Zhou, 2001; Liu et al., 2014), with intrusions emplaced into both the Late Jurassic granites and the Precambrian basement at depths of 5–13 km (Yang et al., 2014b), is composed of porphyritic quartz monzonite, granodiorite, and monzogranite with large K-feldspar phenocrysts (Hou et al., 2007; Zhang et al., 2010). The latest Early Cretaceous Aishan granitoids, mostly composed of monzogranites and syenogranites of I-type affinity with local alkali-feldspar granite of A-type affinity (Yang et al., 2014a), were emplaced at ca. 118–110 Ma (Goss et al., 2010).

The gold deposits of the Jiaobei Uplift are controlled by the NE- to NNE-trending faults, which bound and cut the Late Jurassic Linglong granitoids (Deng et al., 2006, 2008). From west to east, they include the Sanshandao, Jiaojia, Zhaoping, and Qixia faults, with a spacing of about 15–30 km. Accordingly, there are four gold belts, given the same names as the faults in this district (Fig. 1). These extensional faults are argued to be subsidiary faults to the regional Tan–Lu fault system. They have been active since the Late Jurassic and are thought to have accommodated two main stages of deformation during the late Mesozoic. The first stage is characterized by ductile–brittle normal faulting with sinistral shear movement (Faure et al., 2012; Goldfarb and Santosh, 2014; Yang et al., 2014a). This was followed by reactivation, expressed by