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**Origin and evolution of ore-forming fluids, and genesis of the
Duhuangling and Jiusangou gold deposits in eastern Yanbian,
northeast China**

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Abstract

The Duhuangling and Jiusangou gold deposits are located east of the Yanbian area, NE China. We present the results of systematic studies of the ore geology, fluid inclusion (FI) features, and isotopic geochemistry of the two gold deposits. Four mineralization stages have been defined in each gold deposit: pyrite + sericite + quartz (stage I), quartz + pyrite $\pm$ chalcopyrite $\pm$ arsenopyrite (stage II), quartz + native gold + polymetallic sulfide (stage III), and quartz–calcite (stage IV). FIs from the two gold deposits are similar and contain five types: pure vapor phase (V-type), vapor-rich phase (RV-type), liquid-rich phase (RL-type), daughter mineral-bearing polyphase (S-type), and pure liquid phase (L-type) FIs. Stage I FIs homogenize at temperatures of 350–450 °C, yielding salinities of 5.40–48.67 wt.%. FIs from both stages II and III samples homogenize at 160–350 °C, yielding salinities of 5.71–39.75 wt.%. FIs in pyrite from the stage II have $^3\text{He}/^4\text{He}$ ratios of 0.0069–0.0148 Ra and $^{40}\text{Ar}/^{36}\text{Ar}$ ratios of 1302–4433, demonstrating that ore-forming fluids of the two gold deposits were derived from the crust. The δD values of the two gold deposits range from -107‰ to -92‰ , with $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values of 4.3‰ to 9.0‰, indicating that the ore-forming fluids were mainly magmatic water in origin. Lead isotope data suggest that the ore-forming materials were originated from deep crust. Integrated data indicate that both Duhuangling and Jiusangou gold deposits are medium- to high-temperature, hydrothermal gold deposits.

Keyword: Ore-forming fluids; genesis of gold deposit; Yanbian; northeast China

Introduction

Since the early 20th century, economic geologists have recognized epithermal deposits as being important sources of gold (Lindgren 1922). Research and exploration over the past 20 years have led to the discovery of 11 gold-rich porphyry copper deposits and 14 epithermal gold deposits in the circum-Pacific region, which together contain >200 t (>7 million oz) of gold (Sillitoe 1997; Jiang et al. 2004). These discoveries have led to a great number of significant researches into the formation of epithermal deposits (e.g., Hedenquist et al. 1994, 1996; Sillitoe 1997; Cooke et al. 2000; Mao et al. 2003; Deyell et al. 2005; Rye 2005; Jiang et al. 2013).

The Yanbian area, located in the continental margin of eastern China, is part of the West Pacific porphyry–epithermal gold–copper metallogenic belt and hosts a great number of ore systems. Since the discovery of the first epithermal gold deposit at Wufeng in the 1930s (Rui et al. 1995), seven other epithermal gold deposits, two gold-rich porphyry copper deposits, and lots of epithermal gold occurrences have been identified in this region, including Jiusangou and Duhuangling (Fig. 1b). In recent years, several researches have been working on the ore geology, fluid geology and chronology of the two gold deposits (Fig. 1b; e.g., Han et al. 2013; Chai et al. 2014), but the genesis and genetic models of these two deposits are still in dispute. Some researchers suggested that the ore-forming fluids of the Duhuangling gold deposit probably belong to a low- to medium-temperature hydrothermal system (Zhou et al. 2007; Huai et al. 2007). However, others suggested that was a super-shallow to

shallow magmatic–hydrothermal system (Yin et al. 2010) and that the Duhuangling gold deposit was high-sulfidation epithermal (Han et al. 2013). On the other hand, the Jiusangou gold deposit was suggested to be hydrothermal, related to volcanic (Rui et al. 1995) or high-sulfidation epithermal (Men 2011; Han et al. 2013; Chai et al. 2014). Thus, mechanisms and processes responsible for ore genesis in both deposits remain controversial.

In this study, we focus on the geology, fluid inclusions, and isotope geochemistry of the Duhuangling and Jiusangou gold deposits. We discuss the ore genesis, and evolution of the ore-forming fluids. Our data and results suggest that the geneses of the two gold deposits are medium- to high-temperature, hydrothermal gold deposits, which is transitional between high-sulfidation epithermal gold deposit and gold-rich porphyry copper deposit.

1. Geological background

The Yanbian area is located in eastern Jilin Province. Tectonically, the area is within the east of the Xing'an–Mongolian orogenic belt (XMOB), and adjacent to the North China Craton to the south, the Jiamusi Massif to the north, and the Khanka to the northeast (Fig. 1a). The region has a complex tectono-magmatic history, which was a result of influences by a series of events involving evolution of the Paleo–Asian Ocean, construction of the XMOB, and subsequent subduction of the Paleo–Pacific Plate (Sun et al. 2006). The Yanbian area is dominated by Late Paleozoic marine volcano–sedimentary sequence, Mesozoic volcanic–sedimentary rocks as well as

granitic complex. Both the NE–SW and NW–NE trending faults are dominant with secondary fault systems trending NNE–SSW, N–S, and E–W (Fig. 1b; Sun et al. 2006). The area contains numerous gold-rich porphyry copper deposits and epithermal gold deposits (Fig. 1b). Magmatic events associated with this mineralization include emplacements of the Early Cretaceous granitic magmas, and volcanic and subvolcanic events at 125–95 Ma (Han et al. 2013; Sun et al. 2013a). The two gold deposits hosted in granitic, volcanic, and subvolcanic units, and distributed in an N–S trending fault along the eastern margin of the Wangqing volcanic basin, are the objects of this study (Fig. 1b).

2. Ore deposit geology

3.1 Duhuangling gold deposit

The Duhuangling gold deposit is located on the eastern side of the volcanic basin, 15 km northwest of Xiaoxinancha, which is a gold-rich porphyry copper deposit. Intrusions associated with the Duhuangling gold deposit are Early Cretaceous quartz diorite (118.1 ± 2.2 Ma), granodioritic porphyry (110.1 ± 1.1 Ma), biotite granodiorite (115.9 ± 3.3 Ma), diorite, and subandesite (Fig 1c; Han et al. 2013; Chai et al. 2014). Several E–W trending faults that control orebodies are developed in the mine. In addition, there are numerous E–W, NEE–SWW, N–S, and NW–SE trending secondary faults.

Nineteen orebodies have been identified, including altered rock-type orebody and crypto-explosive breccia-type orebody, all of which are hosted in the quartz diorite.

The gold deposit occurs as altered rock (2[#] and 3[#]; Fig. 1c) and crypto-explosive breccia (1[#]; Fig. 1c). The orebody 1[#] is the biggest one and is associated with breccia pipe, which exceed 50.0 m in length and 224.0 m in depth, trends NNE–SSW and dips at 70–75°, with an average thickness of 11.0 m. The gold-bearing breccia has an average Au grade of 3.0 g/t. The orebodies 2[#] and 3[#] are both characterized by gold-bearing sulfide quartz veinlet and crosscut altered granodiorite porphyry. The orebodies are parallel, trends 330–350° and dips at 65–80°, with Au grade of 3.8–9.4 g/t. At surface, six small orebodies have been identified which are 40.0–100.0 m long and 0.5–12.0 m wide. These reserves contain 9.7 t of potential gold-bearing resources (unpublished Duhuangling census report, 2004).

The ores are characterized by euhedral- to subhedral-granular, metasomatic, and cataclastic textures (Fig. 2f, g), and by massive, brecciated, veinlet-disseminated, and geode structures (Fig. 2a, b, c, i). The sulfide minerals are mostly pyrite and chalcopyrite, with minor pyrrhotite, chalcocite, sphalerite, and galena. Gangue minerals are mainly quartz and sericite, with minor calcite, chlorite, epidote, and clay mineral. Native gold comprises >90% of gold minerals, and occurs within intergranular spaces of pyrite (Fig. 2f).

Alteration in the Duhuangling gold deposit includes sericitization, kaolinization, silicification, carbonatization, propylitization, and K-feldspathization (Fig. 2a, e, d). Silicification and sericitization are closely related to mineralization.

Four stages of mineralization have been identified in the Duhuangling gold deposit. Stage I (quartz–sericite–pyrite) consists of milky quartz (Q₁), sericite, and yellowish

pyrite (Fig. 2b, e), and is the early mineralization stage, free of gold. Stage II (quartz–chalcopyrite–pyrite) consists of gray quartz (Q₂) and golden subhedral- to anhedral-granular pyrite, with minor chalcopyrite, sphalerite, and gold mineral (Fig. 2a, c). Stage III (quartz–polymetallic sulfide) consists of quartz (Q₃), pyrite, chalcocite, galena, chalcopyrite, sphalerite, and native gold (Fig. 2h). Stage II and stage III are the main Au deposition stages. Stage IV (quartz–calcite) is characterized by carbonatization. Calcite-quartz (Q₄) veins crosscut all the three early stages (Fig. 2i).

3.2 Jiusangou gold deposit

The Jiusangou gold deposit is located 5 km northwest of the Duhuangling deposit (Fig. 1b) at the intersection of the NNE–SSW (Fuxing) and NW–SE (Jincang) faults. The geological units are represented by continental volcanic sequences of the Upper Cretaceous Jingouling Group and Late Yanshanian diorite, diorite porphyrite (109.3 ± 2.1 Ma), quartz diorite, and granite porphyry intrusions (Chai et al. 2012). The E–W and N–S trending faults, which controlled the orebodies, are developed. The host rocks are composed of diorite porphyry, fine-grained diorite, and granite porphyry (Fig. 1d).

At surface, seven altered rock-type orebodies have been identified, and these orebodies have a thickness of 4.7–6.2 m, with Au grades of 1.9–9.0 g/t. The biggest orebody (1[#]) is 130.0 m long and 40.0 m wide, trends 330–30° and dips at 0–20°, with an average Au grade of 5.4 g/t. Another large orebody (2[#]) is slightly smaller than 1[#], which is 120.0 m long and 55.0 m wide, trends 210–245° and dips at 0–27°, with a

higher average Au grade of 6.3 g/t. Liu et al (1999) suggested that it contains at least 5.0 t of gold. Gold occurs in fissures within pyrite and arsenopyrite (Fig. 2f).

The ores generally exhibit euhedral- to subhedral-granular, metasomatic, or peritectic textures (Fig. 3g, h, i), and have disseminated and cystic structures (Fig. 3c, e, f). The ore minerals are dominated by pyrite and arsenopyrite (Fig. 3h, i) with minor amounts of chalcopyrite (Fig. 3g), tennantite, galena, sphalerite, native gold, and electrum. Gangue minerals are illite, quartz, calcite, tourmaline, and sericite. Alteration includes silicification, kaolinization, pyritization, and sericitization, with minor carbonatization, K-feldspathization, and chloritization (Fig. 3a, e, f). Silicification and sericitization are closely related to mineralization.

Four mineralization stages are distinguished. Stage I (disseminated quartz–pyrite–sericite) consists of pyrite and quartz, free of gold. It is the early mineralization stage (Fig. 3b). K-feldspathization (Fig. 3a) is replaced by silicification and sericitization. Stage II quartz (Q₂) is gray and characterized by disseminated and massive arsenopyrite (Fig. 3c), and silicification and pyritization. Products of this stage comprise veins, altered rock ores, and minor brecciated rock ores. Stage III (sulfide–quartz) is characterized by numerous veins that contain pyrite, quartz, and native gold, with or without galena and chalcopyrite. Stage III veinlets cut through stage II minerals (Fig. 3e). Sulfides mainly occur as euhedral–subhedral pyrite and chalcopyrite veins (Fig. 3e). This stage is confined to the quartz-vein ores, which also exhibit kaolinization and minor chloritization. Stage IV (calcite) is characterized by carbonate alteration. Veinlets of this stage occur within the vein ores and altered zones.

Two types of veinlets are identified: calcite–quartz (Fig. 3e) and pyrite–quartz; its veins are normally <3 cm in width.

4. Fluid inclusions (FIs)

4.1. Sample and analytical methods

Samples were collected from underground mine workings at depths of 200 m, 250 m, and 300 m within the Duhuangling gold deposit, and from depths of 230 m and 280 m within the Jiusangou gold deposit. These comprised milky-white quartz, pyrite–quartz, sulfide-bearing quartz, and calcite–quartz veins (Figs 2, 3). FI microthermometry was performed using a THMS600 heating–freezing stage (Linkam, Tadworth, United Kingdom) at the Geological Fluid Lab of Earth Sciences, Jilin University, China. Analyses involved determining the homogenization temperatures of FIs within quartz that were trapped during different stages of mineralization. In total, 194 FIs were analyzed using the procedures and parameters outlined in Zhang et al. (2013). The obtained temperatures were used to measure in-situ gas compositions from representative two-phase and polyphase FIs using a LABHR–VIS LabRAM HR800 Raman spectrometer at the Analytical Laboratory of Beijing Research Institute of Uranium Geology, China. Analyses using the approaches outlined in Burke (2001) and Zhang (2013).

4.2. Petrographic characteristics of fluid inclusions

Microscope-based petrographic observations indicated that quartz-hosted FIs from

the Duhuangling and Jiusangou gold deposits were generally similar, containing pure vapor phase (V-type), vapor–liquid two-phase (W-type), daughter mineral-bearing polyphase (S-type), and pure liquid (L-type) FIs (Fig. 4). Minor pure CO₂ (PC-type) inclusions were also observed in the mineralization stage of the Duhuangling gold deposit, but carbonic-aqueous (CO₂–H₂O–NaCl; C-type) inclusions did not exist during freezing and heating. Thus, we focused on the S-type, W-type, L-type, and V-type FIs in this study. FIs observed from both gold deposits had similar features, which were described in detail as follows.

(1) V-type: V-type FIs represented ~10% of the total early-stage FI populations in each gold deposit (Fig. 4a, i). These FIs usually coexisted with W-type and S-type FIs. They ranged from 8–10 µm and presented elliptical or round shapes. However, minor irregular shape FIs were also observed.

(2) W-type: W-type FIs were common in samples and could be divided into vapor-rich FIs (RV-type; V/L >50%) and liquid-rich FIs (RL-type; V/L <50%). W-type FIs were common in samples, forming nearly 70% of the total population in each deposit. The RV-type FIs (6–14 µm) were recognized mainly in mineralization stage I in both gold deposits. It was also observed in minor proportions in mineralization stage II in the Jiusangou gold deposit. The RL-type FIs were observed in all mineralization stages in both gold deposits, and had total size ranges of 4–24 µm (clustered at 8–14 µm). Both the RV- and RL-types FIs were isolated or were associated with S-type FIs (Fig. 4c, d). Overall, FIs from the Duhuangling gold deposit were slightly larger than those from Jiusangou.

(3) S-type: S-type FIs were mainly observed in stages I, II, and III, and ranged from 6–28 μm (clustered in 8–16 μm). These FIs were isolated or were in association with W-type FIs. FIs from the Jiusangou gold deposit were slightly larger than those from Duhuangling. S-type FIs from Jiusangou contained several kind daughter minerals. Halite (Fig. 4e, f, j) and sylvite (Fig. 4h, k) were common. In addition, transparent minerals observed in S-type FIs are probable anhydrite (Fig. 4h) and barite (Fig. 4g), respectively, and an opaque mineral might be chalcopyrite (Fig. 4h). However, daughter minerals from Duhuangling samples contained halite and sylvite. A transparent mineral might be sulfate (Fig. 4l).

(4) L-type: L-type FIs were only observed in the late mineralization stage in each deposit. They were rare, making up only 5% of the inclusion population (by volume) and were 6–10 μm in size.

4.3. Microthermometry, salinity, and density

The microthermometric data obtained from the Jiusangou and Duhuangling gold deposits were summarized in Table 1 and Fig. 5. Calculation of salinity for the water–salt liquid system followed the methods described by Hall (1988) and Bischoff (1991), and the salinity of S-type FIs was estimated by the final halite melting temperature (Sterner et al. 1988).

4.3.1. Duhuangling gold deposit

Stage I quartz contained V-type, RV-type, RL-type, and S-type FIs. The analyzed RV-type and RL-type FIs had final ice-melting temperatures ($T_{\text{m-ice}}$) of $-10.8\text{ }^{\circ}\text{C}$ to

−4.0 °C, and −13.2 °C, respectively, corresponding to salinities of 6.44–14.84 wt.% and 17.19 wt.% (NaCl equivalent). These FIs homogenized at temperatures in the ranges of 330.0–379.0 °C and 325.5–404.5 °C, respectively, with the RL-type FIs homogenizing with the disappear of vapor phase and the RV-type FIs homogenizing into the vapor phase. These inclusions yielded densities of 0.66–0.83 g/cm³. Homogenization temperatures for the S-type FIs were between 335.0 °C and 420.0 °C, and the melting temperature of halite ($T_{m\text{-halite}}$) ranged from 265.4 °C to 411.0 °C. Halite dissolved earlier than the vapor, although a few other daughter minerals did not dissolve. Their salinities were 35.68–48.67 wt.% (NaCl equivalent) and their calculated densities were 1.03–1.08 g/cm³.

Stage II quartz contained RL-type and S-type FIs, with rare RV-type FIs. The RL-type FIs had final $T_{m\text{-ice}}$ of −15.1 °C to −5.5 °C, corresponding to salinities of 8.54–18.88 wt.% (NaCl equivalent). They homogenized to the liquid phase at temperatures of 246.6 °C and 345.8 °C, corresponding to densities of 0.78–0.96 g/cm³. $T_{m\text{-halite}}$ ranged from 189.0 °C to 325.0 °C, and salinities of 31.34–40.19 wt.% (NaCl equivalent) were obtained when halite was homogenized to liquid. The majority of halites dissolved at a higher temperature than vapors. Homogenization temperatures for the S-type FIs were from 260.0 °C to 325.0 °C, and their calculated densities were between 1.08 g/cm³ and 1.10 g/cm³.

Stage III quartz contained abundant RL-type FIs with rare halite-bearing S-type FIs. The RL-type FIs yielded final $T_{m\text{-ice}}$ of −15.0 to −0.9 °C, and salinities of 1.56–18.79 wt.% (NaCl equivalent). These FIs were homogenized to the liquid phase

at temperatures (T_{h-hot}) of 160.6–252.1 °C, and had calculated densities of 0.85–0.98 g/cm³. Only one S-type FI from stage III sample was analyzed, producing $T_{m-halite}$ of 210.0 °C and yielding a salinity of 32.39 wt.% (NaCl equivalent). The halite dissolved at a higher temperature than vapors and homogenized to liquid at 210.0 °C.

L-type and RL-type FIs were observed in stage IV samples. The final T_{m-ice} of the RL-type FIs ranged from –3.5 °C to –3.3 °C, and their salinities were in the range of 5.40–5.70 wt. % (NaCl equivalent). They were homogenized to liquid at 92.7–154.0 °C and their calculated densities ranged from 0.96 g/cm³ to 1.00 g/cm³.

4.3.2. Jiusangou gold deposit

Stage I quartz contained V-type, RL-type, and S-type FIs, with rare RV-type FIs. The RL-type FIs had T_{m-ice} between –17.2 °C and –10.8 °C, and calculated salinities of 14.84–20.59 wt.% (NaCl equivalent). These FIs homogenized into the liquid phase at 343.8 °C–468.5 °C, and the densities were estimated of 0.75 g/cm³ to 0.81 g/cm³. $T_{m-halite}$ ranged from 179.0 °C to 236.4 °C, and halite homogenized to liquid, with salinities in the range of 30.88–33.85 wt.% (NaCl equivalent). The S-type FIs had homogenization temperatures from 433.2 °C to 454.0 °C, yielding densities of 0.90–0.93 g/cm³. The RV-type FIs had homogenization temperatures of 390.0 °C–470.0 °C, but it was hard to measure T_{m-ice} as their small sizes.

Stage II quartz was composed of RL-type and S-type FIs, with rare RV-type FIs. The RL-type FIs had final T_{m-ice} values of –18.6 °C to –13.5 °C, corresponding to salinities of 17.47–21.65 wt.% (NaCl equivalent). The homogenization temperatures to the liquid phase ranged from 249.0 °C to 340.6 °C, which yielded salinities of

0.93–0.99 g/cm³. $T_{m\text{-halite}}$ ranged from 215.0 °C to 352.6 °C, with the majority of halite dissolving at a higher temperature than vapors. However, a few did not dissolve. These data corresponded to densities of 32.65–42.65 wt.% (NaCl equivalent). The homogenization temperatures were from 289.0 °C to 328.0 °C for the S-type FIs, and their calculated densities ranged from 1.05 g/cm³ to 1.09 g/cm³.

Stage III quartz contained RL-type FIs, with minor S-type FIs. The RL-type FIs yielded a final $T_{m\text{-ice}}$ of –6.7 °C to –0.3 °C and salinities of 0.52–10.11 wt.% (NaCl equivalent). These FIs had $T_{h\text{-hot}}$ of 168.8–266.8 °C, yielding densities of 0.83–0.89 g/cm³. Their $T_{m\text{-halite}}$ ranged from 173.4 °C to 261.2 °C, and halite homogenized to liquid. In addition, only one halite dissolved at a lower temperature than vapors and others yielded salinities of 30.63–35.40 wt.% (NaCl equivalent). The S-type FIs had homogenization temperatures between 195.0 °C and 241.7 °C, and had calculated densities of 1.10–1.17 g/cm³.

Due to their small sizes, only L-type and RL-type FIs were observed in stage IV samples. All the RL-type FIs homogenized at temperatures <150 °C.

4.4. Ore-forming pressure and depth

Ore-forming pressures were calculated from the equation:

$$P_I = P_0 \times T_I/T_0, \quad (1)$$

where $P_0 = 219 + 2620 \times S$ and $T_0 = 374 + 920 \times S$. P_0 is the initial pressure, S is salinity, P_I is the ore-forming pressures, T_I is the measured temperature, and T_0 is the initial temperature (Shao 1990). We used a pressure gradient of 26.5 MPa/km (Hu

2003) to estimate depth of both gold deposits. Using equation (1), FIs from the Duhuangling gold deposit yielded pressures of 13.07–75.82 MPa and depths of 0.49–2.86 km. Mineralization stages I, II, and III were calculated to be associated with pressures (and depths) of 32.59–75.82 MPa (1.23–2.86 km), 26.08–55.38 MPa (0.98–2.10 km), and 14.61–30.74 MPa (0.54–1.16 km), respectively. By contrast, FIs of the Jiusangou gold deposit yielded pressures and depths of 14.37–73.25 MPa and 0.54–2.76 km, respectively. The first three mineralization stages were calculated to be associated with pressures (and depths) of 40.93–73.25 MPa (1.54–2.76 km), 33.74–61.49 MPa (1.27–2.32 km), and 14.37–42.80 MPa (0.54–1.61 km), respectively. It suggested that metallogenesis occurred at depths generally less than 1.5 km. Thus, both gold deposits were classified to be hypabyssal.

4.5. Laser Raman spectroscopy

Laser Raman spectroscopy reveals that the Duhuangling and Jiusangou gold deposits have similar gas compositions. Early-stage V-type FIs were mainly CO₂ (Fig. 7b) with traces of N₂ (Fig. 7a), and W-type FIs were mainly H₂O with minor CO₂ (Fig. 7f). In the main mineralization stage, W-type FIs were mainly H₂O (Fig. 7e) with minor CO₂, and trace amounts of CH₄ and N₂ (Fig. 7c).

5. Isotopic characteristics of FIs

5.1. Hydrogen–oxygen isotopic compositions

5.1.1. Samples and analytical methods

The main mineralization stage samples for hydrogen and oxygen isotope analyses were collected from 250 m and 300 m depth within the Duhuangling gold deposit. Analyses were performed on a MAT 252 gas mass spectrometer at the Stable Isotope Geochemistry Lab, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, using the analytical approaches outlined by Chen (2008). Values of $\delta^{18}\text{O}$ in quartz and δD in FIs were calibrated according to Vienna Standard Mean Ocean Water (V-SMOW) standards, with analytical precisions of $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 2.0\text{‰}$ for δD . The results of analyses on samples and standards are presented in Table 2, along with similar sample data reported in previous studies.

5.1.2. Results

Samples from the Duhuangling gold deposit have values of $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ in quartz of 4.3–5.1‰, and values of $\delta\text{D}_{\text{V-SMOW}}$ for FIs of -104‰ to -107‰ . By contrast, samples from the Jiusangou gold deposit have values of $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ in quartz of 7.3‰ and 9.0‰, and values of $\delta\text{D}_{\text{V-SMOW}}$ for FIs of -92‰ and -104‰ (Table 2). All of these results are similar to typical values for magmatic fluids ($\delta^{18}\text{O}_{\text{H}_2\text{O}} = 5.5\text{--}9.5\text{‰}$ and $\delta\text{D}_{\text{V-SMOW}} = -40\text{‰}$ to -80‰ ; Sheppard 1986). These data plotted in the lower part of magmatic water on an H–O isotope diagram (Fig. 8), which suggests that the ore-forming fluids consist predominantly of magmatic water with minor meteoric water.

5.2. Noble gas isotopes

5.2.1. Samples and analytical methods

Subhedral–anhedral stage II pyrite samples were collected from depths of 300 m

within the Duhuangling gold deposit and 280 m within the Jiusangou gold deposit. Samples selected for crushing and analysis lacked multistage FIs, according to the recommendations of Hu et al. (1998) and Burenaed et al. (1999, 2016). In addition, a series of 1–2 g aliquots of 100% purity were created from FI-hosting minerals that had similar structures and isotropic optical properties, and were used to represent the specific stages of mineralization present within each deposit. Four single pyrite samples were selected for analysis (Table 3) using a VG5400 mass spectrometer (MS-III) in the Geochemistry Laboratory of the Faculty of Science, Tokyo University, Japan. Gases were captured by crushing samples and were subsequently cooled for noble gas separation by using the techniques outlined in Nagao et al. (1996) and Sumino et al. (2001). Analytical precision was better than 5% (1σ).

5.2.2. Results

The results of isotopic analysis were given in Table 3. Values for ^4He , ^{20}Ne , ^{40}Ar , ^{84}Kr , and ^{132}Xe plot along a normal distribution on a variation diagram (Fig. 9a), indicating that the analyzed FIs did not lose noble gases after being trapped. In addition, these inclusions had $^3\text{He}/^4\text{He}$ (R) values of 0.007–0.015 Ra, where Ra is the atmospheric value of 1.4×10^{-6} . The typical crustal He signature (R value) was 0.01–0.05 Ra (Tolstikhin 1978; O’Nions and Oxburgh 1988). In addition, these inclusions had $F(^4\text{He})$ values between 17,561 and 125,131, indicating an abundance of atmospheric He within this section of the crust during mineralization. The $F(^4\text{He})$ values of sulfide samples from the Duhuangling and Jiusangou gold deposits were more than 15,000 times that of the atmosphere (Table 3), indicating a concentration of

^4He that was >15,000 times greater than that present in the atmosphere. In addition, the amount of air-saturated water ($F(^4\text{He}) = 0.18\text{--}0.28$) within these samples was >45,000 times that of the atmospheric value, indicating that these samples contained negligible atmospheric He and that none was added to the inclusions after entrapment.

Samples from both deposits had $F(^{84}\text{Kr})$ and $F(^{132}\text{Xe})$ values of 1.26–1.53 and 3.51–5.78, respectively, which indicated that elemental fractionation did not occur after entrapment. This result was supported by correlation between the FXe and FKr values [$F_x = (X/^{36}\text{Ar})_{\text{sample}}/(X/^{36}\text{Ar})_{\text{air}}$, where $(^{132}\text{Xe}/^{36}\text{Ar})_{\text{air}} = 0.75 \times 10^{-3}$ and $(^{84}\text{Kr}/^{36}\text{Ar})_{\text{air}} = 0.0207$], although the fractionation factors in this system were somewhat lower at $\text{FKr} < 4$ and $\text{FXe} < 16$ (Kendrick et al. 2001).

Samples from both deposits had similar $^3\text{He}/^4\text{He}$, $^{20}\text{Ne}/^{22}\text{Ne}$, $^{21}\text{Ne}/^{22}\text{Ne}$, $^{38}\text{Ar}/^{36}\text{Ar}$, and $^{40}\text{Ar}/^{36}\text{Ar}$ ratios (Table 3). The measured $^3\text{He}/^4\text{He}$ ratios 0.0096–0.0206 were significantly lower than those expected for the upper mantle ($^3\text{He}/^4\text{He} = 6\text{--}9 \text{ Ra}$) and the atmosphere ($^3\text{He}/^4\text{He} = 1 \text{ Ra}$; Allegre et al. 1987; Patterson et al. 1994; Sun et al. 2006), but were close to those of fluids in continental crust (Stuart et al. 1995). The measured $^{20}\text{Ne}/^{22}\text{Ne}$ (9.817–9.960) and $^{21}\text{Ne}/^{22}\text{Ne}$ (0.0290–0.0295) ratios in both deposits were similar to the atmospheric values of $^{20}\text{Ne}/^{22}\text{Ne}$ (9.800) and $^{21}\text{Ne}/^{22}\text{Ne}$ (0.0290), but were somewhat different from the values expected for mantle-derived fluids ($^{20}\text{Ne}/^{22}\text{Ne} = 9.8\text{--}13.2$ and $^{21}\text{Ne}/^{22}\text{Ne} = 0.580\text{--}0.680$). In addition, measured $^{38}\text{Ar}/^{36}\text{Ar}$ ratios 0.18962–0.19270 were consistent with those expected for air-saturated water (0.188), although the measured $^{40}\text{Ar}/^{36}\text{Ar}$ ratios 1302.4–4433.6

from both gold deposits were slightly higher than those expected for air-saturated water (295.5, Burnard et al, 1999; Sun et al, 2006) and fluids in continental crust. However, they were significantly lower than that for the mantle ($>40,000$; Fig. 9b).

All of these data plotted along crustal, cosmogenic Ne, and nuclear fission evolution lines on a $^{21}\text{Ne}/^{22}\text{Ne}$ – $^{20}\text{Ne}/^{22}\text{Ne}$ diagram (Fig. 9b). These samples also plotted to the right of the cut-off line in the field defining the lower crust on a $^3\text{He}/^4\text{He}$ – ^4He diagram, indicating that the FIs contained higher levels of radiogenic ^4He than that typically found in crust fluids (Fig. 10a; Gautheron et al. 2005). They also plotted within the crust fluid field, albeit with enriched ^{40}Ar values, in a $^3\text{He}/^4\text{He}$ – $^{40}\text{Ar}/^{36}\text{Ar}$ diagram (Fig. 10b), suggesting that the ore-forming fluids of the two gold deposits derived from the crust.

5.3. Lead isotopic compositions

5.3.1. Samples and analytical procedures

The separation and analytical techniques used to determine lead isotopic compositions in this study were similar to those used during the noble gas isotopic analysis described above, using a MAT-261 mass spectrometer housed at the Analytical Laboratory of Beijing Research Institute of Uranium Geology, Beijing, China. Two-sigma variations were 0.05%, 0.09%, and 0.30% for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$, respectively. The analytical precision of the lead isotope was better than $\pm 0.09\%$. All results were given in Table 4.

5.3.2. Results

The measured $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios in pyrite from the Duhuangling gold deposit were 18.3072–18.3244, 15.5208–15.5328, and 38.1055–38.1419, respectively, whereas those from pyrite in the Jiusangou gold deposit were 18.2955–18.3513, 15.5322–15.5441, and 38.1325–38.1715, respectively (Table 4). When plotted on the $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{208}\text{Pb}/^{204}\text{Pb}$ diagrams, data points for these lead isotope compositions fell in the lower-crustal source region field along the orogenic evolution line (Fig. 11a, b). It implied that the ore-forming materials might have originated from deep-seated resources related to a lower crust.

6. Discussion

6.1. Origin of ore-forming fluids

A number of recent systematic investigations have been performed on the origin of ore-forming fluids in epithermal gold deposits associated with felsic magmatism (e.g., Hedenquist 1987, 1996; Corbett 2002; Carrillo et al. 2003; Sillitoe 2010). Epithermal gold deposit is commonly closely associated with porphyry deposit in space and in time, and they shares similar ore-forming fluid characteristics. Many geologists suggested that ore-forming fluids in both cases had the same origin, or else that the ore-forming fluids of the epithermal gold deposit was evolved from porphyry deposit system (Eaton et al. 1993; Corbett 2002). The Duhuangling and Jiusangou gold deposits, together with the Xiaoxinancha gold-rich porphyry copper deposit, are all located in the same metallogenic belt in the Yanbian area (Han et al. 2013), and have

similar ore geology features (Table 5), fluid inclusion features, ages of metallogeny, and stable isotope signatures. Nonetheless, origin of the fluids that formed the Duhuangling and Jiusangou gold deposits is uncertain: they could have been products of the immiscibility of deep-seated gold-bearing fluids; they could represent ore-forming fluids that had evolved from the Xiaoxinancha gold-rich porphyry copper deposit; or alternatively they may have been exsolved during unrelated magmatism.

The measured homogenization temperatures of FIs entrapped during the early stage of the Duhuangling and Jiusangou ore formation are essentially similar to those from the Xiaoxinancha deposit reported by Men (2011). In addition, quartz samples from main stages of the two gold deposits, together with that quartz from early stage of the Jiusangou gold deposit, have similar H–O isotopic compositions to those from Xiaoxinancha (Fig. 8). These evidences indicate that it is impossible that the ore-forming fluids of the Duhuangling and Jiusangou gold deposits evolved from that of Xiaoxinancha. Homologous fluids should have formed only from ore-bearing fluid immiscibility prior to unloading of its metallogenic elements.

The $^3\text{He}/^4\text{He}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ ratios of FIs from the Xiaoxinancha deposit are 0.08–4.45 Ra, and 306–430, which indicates that the initial ore-forming fluids were produced by partial melting of crust material containing a mantle component (Sun et al. 2008). However, the ore-forming fluids of the Jiusangou and Duhuangling gold deposits are riched in radioactive ^{21}Ne , ^4He , and ^{40}Ar , all of which are typical components of crust fluids (Figs. 9, 10). In addition, these samples plotted in the crust region on the $^3\text{He}/^4\text{He}$ – $^4\text{He}/^{20}\text{Ne}$ diagram, which was close to granitic source,

additional evidences of derivation from crust or granite-related magmatic fluids (Fig. 12).

The Jiusangou and Duhuangling gold deposits and the Xiaoxinancha gold-rich porphyry copper deposit are in the same metallogenic belt, having similar metallogenetic ages, fluid inclusions, and H–O isotopes showing a feature of magmatic water. However, the ore-forming fluids of the two gold deposits do not contain mantle component and are derived from an exsolution process of crustal magmatic water, with enrichments of ^{40}Ar , ^{36}Xe , and ^4He (Candela 1997; Harris et al. 2004). Thus, we suggest that the ore-forming fluids of the two gold deposits are magmatic water derived from crust.

6.2. Ore-forming fluid evolution

Four mineralization stages have been classified in the Duhuangling and Jiusangou gold deposits. Quartz crystals from the early-stage contain RV-, RL-, and S-type FIs. The FIs in early-stage samples indicated that the initial ore-forming fluids are high-temperature (mainly 350–470°C) and high salinity (15–50 wt.%; Fig. 6), which are similar to those of porphyry deposit (Hedenquist et al. 1994; Sillitoe 1997, 2010; Li et al. 2006). These features indicate that the initial ore-forming fluid belongs to a $\text{H}_2\text{O}\text{--}\text{NaCl} \pm \text{CO}_2$ system. Subsequently, the fluids evolved into low- to medium-temperature (160–350 °C), with various salinities during main stages, showing a heterogeneous thermal condition (Shepherd et al., 1985). FI data plotted on a homogenization temperature versus salinity diagram (Fig. 6) show that the early

stage fluids are medium- to high-salinity, and that low-salinity and high-salinity FIs coexisted during the main stages. Furthermore, the coexistence within the same sample of RL and RV type FIs show a similar range of homogenization temperatures and opposite modes of homogenization (i.e., $V \rightarrow L$ vs. $L \rightarrow V$). This indicates that these ore-forming fluids are immiscible in the main stages, which is an important mechanism resulting in ore-metal deposition of hydrothermal system (Roedder 1984; Shepherd et al. 1985; Davidson 2001; Hagemann and Lüders, 2003). Laser Raman spectroscopy data reveal that the ore-forming fluids of the two deposits contained CO_2 and minor small-size pure CO_2 (PC-type) FIs were observed in the mineralization stage of the Duhungling gold deposit. However, there was no independent CO_2 phase in these FI samples during freezing and heating, indicating that the CO_2 content was rare. Thus, the ore-forming fluids should belong to a $\text{NaCl-H}_2\text{O}$ system. The C-type FIs may be trapped during fluid immiscibility in the main mineralization stage at low- to medium-temperature (160–350 °C). FIs trapped during the last mineralization stages have low salinities (<6.0 wt.%) and temperatures (<150 °C), indicating that the ore-forming fluids experienced cooling and diluting.

6.3. Ore genesis

Previous studies have proposed a variety of processes responsible for genesis of the Duhuangling gold deposit including: (1) low- to medium-temperature hydrothermally altered rock type (Huai et al. 2007; Zhou et al. 2007), (2) shallow to super-shallow magmatic–hydrothermal type (Yin et al. 2010), and (3) high-sulfidation epithermal

type (Han et al. 2013; Chai et al. 2014). Additionally, the Jiusangou deposit has been reported to be either a volcanic hydrothermal or epithermal type (Rui et al. 1995) or a high-sulfidation epithermal type (Men 2011; Han et al. 2013), although it is now generally accepted that both deposits are high-sulfidation epithermal gold types related to volcanic–subvolcanic magmatism. However, these various processes, which are based on the characteristics of ore deposit geology, do not provide satisfactory explanations of the nature of the deposit.

The ore geology features of the Duhuangling and Jiusangou gold deposits also indicate that the mineralization occur within Early Cretaceous granitic complex, comprising of quartz diorite and granodiorite in both mines, with additional granodiorite porphyry in Duhuangling, and diorite porphyry and diorite in Jiusangou. Both deposits are associated with subvolcanic rocks and their main orebody types are altered rock and crypto-explosive breccias. Moreover, ore minerals are pyrite and arsenopyrite, with minor chalcopyrite, sphalerite, and native gold and alteration consisted of sericitization, silicification, and kaolinization (Table 5). All of these ore geology characteristics are similar to typical high-sulfidation epithermal gold deposits associated with volcanic–subvolcanic magmatism described worldwide (Hedenquist and Lowenstern 1994; Arribas et al. 1995; Ruggieri et al. 1997).

However, features of the FIs present in both deposits suggest that the two gold deposits are characteristic of both high-sulfidation epithermal gold deposit and porphyry deposit. FI homogenization temperatures from the stages II and III were 160–350 °C and 170–340 °C, with salinities of 1.56–41.95 wt.% and 0.52–40.19 wt.%

(NaCl equivalent), respectively. Calculated depths of ore formation are less than 1.5 km. H–O isotopic composition of the ore-forming fluids is also similar to those of porphyry deposit (Fig. 8). Nonetheless, the crypto-explosive breccia orebody associated with K-feldspathization and carbonatization is a typical feature of porphyry deposit (Table 5). In high-sulfidation deposits, the ore is typically closely associated with, or lies within, the zone of most acidic alteration (White and Hedenquist 1995). Integrating all data, we conclude that both gold deposits are a transitional type between a high-sulfidation epithermal gold deposit and a gold-rich porphyry deposit. Thus, we consider both as medium- to high-temperature, hydrothermal gold deposits.

6.4 A metallogenic model

The Yanbian area contains abundant gold-rich porphyry copper and epithermal gold–copper or gold deposits (Sun et al. 2006). The area is located in the eastern part of the XMOB, and is highly predicted an excellent metallogenic background and condition for epithermal gold deposit (Han et al. 2013; Sun et al. 2013b). As the two most significant gold mineralizing events that both gold deposits are a transitional type between a high-sulfidation epithermal gold deposit and a gold-rich porphyry deposit in this region.

We propose a new metallogenic model for the genesis of the two gold deposits. A partial melting of lower crust occur in an active continental margin setting relate to the subduction of the Paleo-Pacific Plate in early Cretaceous (110-105 Ma, Chai et al. 2014), forming felsic magmas (Chai et al. 2014), which filled lower crust magmatic

chambers. Then crystallization and differentiation of this magma formed the quartz diorite, granodiorite porphyry, and granite porphyry phases that then fluid immiscibility generated the early stage high-temperature and high-salinity ore-forming fluids. The fluids from deep source migrated upwards along the shear zone and faults, with rapid decreasing of temperature and pressure. The fluids experienced fluid immiscibility again. The heterogeneous fluids caused large amounts of sulfide precipitation with gold, resulting in altered rock-type orebody. Then rapid decreasing pressure formed crypto-explosive breccia-type orebody at a shallow level.

In addition, a close temporal–spatial relationship between epithermal gold–copper and gold-rich porphyry copper deposits was revealed (Corbett 2002; Heinrich 2003). We propose that a gold-rich porphyry copper orebodies may be existed at deep levels, and the data presented here may be useful in future exploration targeting.

7. Conclusions

1. Isotope geochemistry of samples from the Duhuangling and Jiusangou gold deposits suggest that the ore-forming fluids of two gold deposits are magmatic water derived from crust.
2. Their geological characteristics, fluid inclusion data, and isotope data indicate that both deposits are medium- to high-temperature, hydrothermal gold deposits.
3. The early stages of mineralization occurred because of strong fluid immiscibility prior to these fluids having metasomatically interacted with the host rocks to deposit gold and other ore minerals. This interpretation agrees with the penetration of

hydrothermal fluids into the host rocks, which formed crypto-explosive breccia-type orebodies, altered rock-type orebodies, and gold-bearing sulfide–quartz veinlets.

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Figure legends

Fig.1 Geotectonic division in NE China, after Shao and Tang (1995) (a), geological map of the Yanbian area showing the locations of gold and copper deposits, modified after Meng et al. (2001) (b) and geological map (c: Duhuangling gold deposit, d: Jiusangou gold deposit)

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Gold-bearing altered rock type ore. f, Pyrite cataclastic texture, hair-like sphalerite, and native gold. g, anhedral chalcopyrite and sphalerite. h, Quartz–sulfide vein. I, anhedral chalcopyrite and sphalerite.

Abbreviation: Py = pyrite, Q₁₋₄ = quartz in different stages, Ccp = chalcopyrite, Au = nature gold, Sp = Sphalerite.

Si = silicification, Ser = sericitization, Kf = K-feldspathization, Kao = kaolinization.

Fig.3. Photographs showing the ore geology of the Jiusangou gold deposit.

a, K-feldspathization and silicification. b, Early stage milky quartz (Q₁) and yellow–white pyrite. c, Quartz–sulfide ore. d, Quartz–sulfide vein. e, Quartz and carbonatization veinlets. f, K-feldspathization and kaolinization. g, Chalcopyrite replacement pyrite. h, Euhedral–subhedral arsenopyrite and anhedral pyrite. i, Euhedral arsenopyrite within euhedral pyrite.

Abbreviation: Py = pyrite, Q₁₋₄ = quartz in different stages, Ccp = chalcopyrite, Apy = arsenopyrite.

Car = carbonatization, Si = silicification, Kf = K-feldspathization, Kao = kaolinization.

Fig.4. Photomicrographs of fluid inclusions from the Duhuangling and Jiusangou gold deposits. V = vapor phase, S = sylvite, H = halite, Anh = anhydrite, Brt = barite, Ccp = chalcopyrite, Mag = magnetite

Fig.5 Homogenization temperature (Th) histogram of fluid inclusions in different stages from the Duhuangling and Jiusangou gold deposits

Fig.6. Plots of homogenization temperature (Th) vs salinity of fluid inclusions from the Duhuangling and Jiusangou gold deposits

Fig.7. Laser Raman spectra of fluid inclusions from the Duhuangling gold deposit.

Fig.8. $\delta\text{O}-\delta\text{D}$ plots of the ore fluids for Duhuangling and Jiusangou deposits.
(According to Hedenquist and Lowenstern 1994)

Fig.9. Noble gas composition of fluid inclusions in the ore minerals (a) and $^{21}\text{Ne}/^{22}\text{Ne}$ — $^{20}\text{Ne}/^{22}\text{Ne}$ diagrams (b)

Fig.10. ^4He — $^3\text{He}/^4\text{He}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ — $^3\text{He}/^4\text{He}$ diagrams for fluid inclusions (After Gautheron et al. 2005 and Ballentine et al. 2002)

Fig.11. Lead isotope ratios diagram of the ore minerals in the Duhuangling and Jiusangou gold deposits (After Zartman and Doe 1981)

Fig.12. $^3\text{He}/^4\text{He}$ — $^4\text{He}/^{20}\text{Ne}$ diagram (After Allegre et al. 1987; O’Nions 1994)

Table 1 Microthermometric data of fluid inclusions from the Duhuangling and Jiusangou gold deposits

Deposit	Stage	Type	Size (μm)	Proportion%	T _{m-ice} (°C)	T _{m-halite} (°C)	T _{h-hot} (°C)	Salinity (wt%)	Density (g/cm ³)	Pressure (MPa)
Duhuangling	I ₁	RV	6~14	55-90	-10.8~-4.0	--	330.0~379.0	6.44~14.84	0.66~0.83	55.04~75.82
		RL	8~24	8~30	-13.2	--	325.5~404.5	17.19	0.86	40.94
		S	8~14	10~25	--	265.4~411.0	335.0~420.0	35.68~48.67	1.03~1.08	32.59~39.28
	II ₁	RV	6~10	50-60	--	--	321.8~327.9	--	--	--
		RL	4~12	5-45	-15.1~-5.5	--	246.6~348.5	8.54~18.88	0.78~0.96	26.08~33.19
		S	6~16	10-20	--	189.0~325.0	260.0~325.0	31.34~40.19	1.08~1.10	40.83~55.58
	III ₁	RL	4~14	8-30	-15.0~-0.9	--	160.6~252.1	1.56~18.79	0.85~0.98	14.61~30.74
		S	16	5-10	--	210.0	210.0	32.39	1.15	33.36
	IV ₁	RL	4~10	10-25	-3.5~-3.3	--	92.7~154.0	5.40~5.70	0.96~1.00	<13.07
	Jiusangou	I ₂	RV	3~5	55-70	--	--	390.0~470.0	--	--
RL			4~20	5-45	-17.2~-10.8	--	343.8~468.5	14.84~20.59	0.75~0.81	40.93~60.04
S			20~28	30-50	--	179.0~236.4	433.2~454.0	30.88~33.85	0.90~0.93	60.30~73.25
II ₂		RL	6~14	5-35	-18.6~-13.5	--	249.0~340.6	17.47~21.65	0.93~0.99	33.74~48.62
		S	8~18	5-25	--	215.0~352.6	289.0~328.0	32.65~42.65	1.05~1.09	47.78~61.49
III ₂		RL	4~20	5-40	-6.7~-0.3	--	168.8~267.8	0.52~10.11	0.83~0.89	14.37~27.75
		S	6~8	15-20	--	173.4~261.2	195.0~241.7	30.63~35.40	1.10~1.17	30.37~42.80
IV ₂		RL	4	25	--	--	<150.0	--	--	--

Table 2 Hydrogen and oxygen isotope analysis of fluid inclusions results

Sample	Deposit	Sample description	Mineral	δD_{V-SMOW}	$\delta^{18}O$	Homogenization temperature	$\delta^{18}O_{H_2O}$	Data sources
Dhl-9	Duhuangling	Pyrite quartz vein	quartz	-104	9.6	350°C	4.3	
Dhl-N5		Pyrite quartz vein	quartz	-107	10.2	350°C	4.9	
Dhl-N6		Pyrite quartz vein	quartz	-104	10.4	350°C	5.1	
JSG-1	Jiusangou	Pyrite	quartz	-92	15.2	320°C	9.0	Zhao et al., 2008
JSG-2		phyllic	quartz	-104	13.5	320°C	7.3	
XNC-N24-1	Xiaoxinancha	Quartz vein	quartz	-100	7.0	350°C	1.7	Men, 2011
XNC-N24-2		Calcite vein	calcite	-130	14.3	100°C	-2.8	
I-580-6A-1		Quartz vein	quartz	-82	5.9	400°C	1.9	
I-580-6A-2		Calcite vein	calcite	-92	0.9	170°C	-10.4	
XNC-I-1		Granite	quartz	-110	8.9	500°C	6.6	
XNC-1		Granite	quartz	-109	8.8	500°C	6.6	
XNC-2		Granite	quartz	-106	8.8	500°C	6.5	

Clayton formula: $1000 \ln \alpha = \delta^{18}O_{\text{mineral}} - \delta^{18}O_{H_2O} = 3.38 \times 10^6 T^{-2} - 3.4$, The mineral measured $\delta^{18}O$ is quartz, T represent for absolute temperature

Table 3. The noble gas isotope data for the Jiusangou and Duhuangling gold deposits.

Sample	Mineral	Mass g	³ He 10 ⁻¹⁵ cc/g	⁴ He 10 ⁻⁹ cc/g	³ He/ ⁴ He 10 ⁻⁶	²⁰ Ne	²¹ Ne	²² Ne	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne
						10 ⁻⁹ cc/g				
Jsg-1	Pyrite	0.3116	34±10	1677±168	0.0206±0.0057	0.419±0.042	0.00131±0.00014	0.0425±0.0043	9.870±0.112	0.0309±0.0013
Jsg-2	Pyrite	0.3206	40±15	3067±307	0.0132±0.0047	0.350±0.035	0.00115±0.00013	0.0359±0.0036	9.734±0.080	0.0320±0.0015
Dhl-1	Pyrite	0.3190	116±42	12032±1203	0.0096±0.0034	0.405±0.041	0.00168±0.00018	0.0413±0.0042	9.811±0.088	0.0406±0.0014
Dhl-2	Pyrite	0.3266	166±99	14970±1497	0.0111±0.0065	0.951±0.096	0.00330±0.00035	0.0966±0.0097	9.849±0.069	0.0342±0.0011

Continued from Table 3

Sample	³⁶ Ar	³⁸ Ar	⁴⁰ Ar	³⁸ Ar/ ³⁶ Ar	⁴⁰ Ar/ ³⁶ Ar	⁸⁴ Kr	¹³² Xe	F ⁴ He	F ⁸⁴ Kr	F ¹³² Xe
						10 ⁻¹² cc/g				
Jsg-1	0.577±0.060	0.110 ±0.011	752±79	0.19011±0.00075	1302.4 ±14.2	15.1 ±1.6	1.52 ±0.17	17561	1.26	3.51
Jsg-2	0.561 ±0.058	0.106 ±0.011	1115±117	0.18962±0.00097	1990.0 ±22.0	17.8 ±1.9	2.43 ±0.26	33033	1.53	5.78
Dhl-1	0.581 ±0.060	0.112 ±0.012	2577±271	0.19270±0.00130	4433.6 ±67.3	17.2 ±1.8	2.52 ±0.27	125131	1.43	5.78
Dhl-2	1.245 ±0.127	0.237 ±0.024	3128±319	0.19011±0.00101	2511.6 ±16.6	32.6 ±3.4	3.48 ±0.36	72653	1.26	3.73

³He_{DM}/³He_m=[(1-(³He/⁴He)_c)/(³He/⁴He)_m]/(1-(³He/⁴He)_c/(³He/⁴He)_{DM})]×100; ²⁰Ne_{DM}/²⁰Ne_m=[(1-(³He/⁴He)_{air})/(³He/⁴He)_m]/(1-(³He/⁴He)_{air}/(³He/⁴He)_{DM})]×100; Ar%=[(⁴⁰Ar/³⁶Ar)_m-295.5]/(⁴⁰Ar/³⁶Ar)_m×100; FX=(X/³⁶Ar)_m/(X/³⁶Ar)_{air}; DM- mantle; m= The measured values; c- Crustal fluids;air- atmosphere; According to Gautheron, et al. 2002 and Buikin, et al. 2005

Table 4 Lead isotope composition of the ore minerals in the Duhuangling and jiusangou glod deposits

Deposit	Sample	Sample description	Mineral	$^{206}\text{Pb}/^{204}\text{Pb}$	2σ	$^{207}\text{Pb}/^{204}\text{Pb}$	2σ	$^{208}\text{Pb}/^{204}\text{Pb}$	2σ
Jiusangou	JSG1	Pyrite altered rocks	pyrite	18.2955	20	15.5322	17	38.1325	41
	JSG 2		pyrite	18.3513	15	15.5441	12	38.1715	30
Duhuangling	DHL1	Disseminated pyrite altered rocks	pyrite	18.3244	7	15.5328	8	38.1419	19
	DHL 2		pyrite	18.3072	8	15.5208	7	38.1055	18

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Table 5 Geological and fluid inclusions features from the research area and typical deposits

Deposit	Jiusangou deposit	Duhuangling deposit	Xiaoxinancha deposit	High-sulfidation epithermal gold deposit	Gold-rich porphyry copper deposit
Host rock	Diorite porphyrite, diorite, and granite porphyry	Quartz diorite	Granite complex	Typically calc-alkalic andesite, dacite, and rhyodacite; commonly porphyry	Calc-alkaline or high-K calc-alkaline; commonly porphyritic intrusions
Orebody type	Altered rock-type	Altered rock-type and crypto-explosive breccia-type	Veinlet-disseminated, sulphide-quartz vein	Altered rock-type	Veinlet-disseminated type
Ore structure	Disseminated and cystic	Massive, brecciated, veinlet-disseminated, and geode structures	Main vein, disseminated	Main disseminated, also present brecciated, vein	Main disseminated and veinlet, minor brecciated
Ore mineral	Main pyrite and arsenopyrite, minor chalcopyrite, tennantite, galena, sphalerite, native gold, and electrum	Main pyrite and chalcopyrite, with minor pyrrhotite, chalcocite, sphalerite, galena, and native gold	Pyrite, pyrrhotite, chalcopyrite, arsenopyrite, bornite, molybdenum, sphalerite, galena, native gold	Pyrite, chalcopyrite, tennantite, bismuthinite, native gold, sphalerite, galena	Pyrite, chalcopyrite, Pyrite, chalcopyrite, magnetite
Gangue mineral	Quartz, illite, calcite, tourmaline and sericite	Main quartz and sericite and minor calcite, chlorite, epidote, and clay mineral are also present	Quartz, calcite, sericite, chlorite, biotite	Quartz, alunite, barite, kaolinite, pyrophyllite	Quartz, sericite, K-feldspar
Alteration	Silicification, kaolinization, pyritization, and sericitization, with minor carbonatization, K-feldspathization, and chloritization	Sericitization, kaolinization, silicification, carbonatization, propylitization and K-feldspathization	K-feldspathization, biotitization, chloritization, sericitization, silicification, minor silicification	Silicification, alunitization and kaolinization	K-feldspathization, Sericitization, mudding, propylitization
Fluid characteristic	170-470℃, salinities from 1.56 to 48.67 wt. %	160-420℃, salinities from 0.52 to 42.65 wt. %	470-190℃, salinities from 9.45 to 20.15 wt. %	200-300℃; salinities from 1 to 24 wt. %	300-700℃, salinities > 30 wt. %
ore-forming fluids origin	Main magmatic water	Main magmatic water	Mantle-derived magmatic fluids.	Dominantly meteoric water with significant magmatic components	Dominantly magmatic water with minor atmospheric water
Geotectonic setting	Subduction -related continental margin	Subduction -related continental margin	Subduction -related continental margin	Subduction -related continental margin or island-arc	Subduction -related continental margin or island-arc
Reference	This paper; Chai et al. 2013	This paper; Chai et al. 2013	Men 2011; Sun et al. 2008	Sillitoe 1997; White and Hedenquist 1995	Sillitoe 1997, 2010; Li et al. 2006

Fig.1 Geotectonic division in NE China, after Shao and Tang (1995) (a), geological map of the Yanbian area showing the locations of gold and copper deposits, modified after Meng et al. (2001) (b) and geological map (c: Duhuangling gold deposit, d: Jiusangou gold deposit)

209x219mm (300 x 300 DPI)

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179x138mm (300 x 300 DPI)

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181x134mm (300 x 300 DPI)

Fig.5 Homogenization temperature(Th) histogram of fluid inclusions in different stages from the Duhuangling and Jiusangou gold deposits

137x210mm (300 x 300 DPI)

Fig.6. Plots of homogenization temperature (T_h) vs salinity of fluid inclusions from the Duhuangling and Jiusangou gold deposits

93x68mm (300 x 300 DPI)

Fig.7. Laser Raman spectra of fluid inclusions of the Duhuangling gold deposit.

153x76mm (300 x 300 DPI)

Fig.8. δO - δD plots of the ore fluids for Duhuangling and Jiusangou deposits. (According to Hedenquist and Lowenstern 1994)

130x82mm (300 x 300 DPI)

Fig.9. Noble gas composition of fluid inclusions in the ore minerals (a) and $^{21}\text{Ne}/^{22}\text{Ne}$ — $^{20}\text{Ne}/^{22}\text{Ne}$ diagrams (b)

192x78mm (300 x 300 DPI)

Fig.10. ^4He — $^3\text{He}/^4\text{He}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ — $^3\text{He}/^4\text{He}$ diagrams for fluid inclusions (After Gautheron et al. 2005 and Ballentine et al. 2002)

196x80mm (300 x 300 DPI)

Fig.11. Lead isotope ratios diagram of the ore minerals in the Duhuangling and Jiusangou gold deposits (After Zartman and Doe 1981)

167x58mm (300 x 300 DPI)

Fig.12. $^3\text{He}/^4\text{He}$ — $^4\text{He}/^{20}\text{Ne}$ diagram (After Allegre et al. 1987; O’Nions 1994)

155x95mm (300 x 300 DPI)