Original Article

Fluid Inclusions and C–H–O–S–Pb Isotopes: Implications for the Genesis of the Zhuanshanzi Gold Deposit on the Northern Margin of the North China Craton

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Abstract

The Zhuanshanzi gold deposit lies in the eastern section of the Xingmeng orogenic belt and the northern section of the Chifeng-Chaoyang gold belt. The gold veins are strictly controlled by a NW-oriented shear fault zone. Quartz veins and altered tectonic rock-type gold veins are the main vein types. The deposits can be divided into four mineralization stages, and the second and third metallogenic stages are the main metallogenic stages. In this paper, based on the detailed field geological surveys, an analysis of the orebody and ore characteristics, microtemperature measurement of fluid inclusions, the Laser Raman spectrum of the inclusions, determination of C–H–O–S–Pb isotopic geochemical characteristics, and so on were carried out to explore the origin of the ore-forming fluids, ore-forming materials, and the genesis of the deposits.

The results show that the fluid inclusions can be divided into four types: type I – gas–liquid two-phase inclusions; type II – gas-rich inclusions; type III – liquid inclusions; and type IV – CO2-containing three-phase inclusions. However, they are dominated by type Ib – gas liquid inclusions and type IV – three-phase inclusions containing CO2. The gas compositions are mainly H2O and CO2, indicating that the metallogenic system is a CO2–H2O–NaCl system. The homogenization temperature of the ore-forming fluid evolved from a middle temperature to a low temperature, and the temperature of the fluid was further reduced due to meteoric water mixing during the late stage, as well as a lack of CO2 components, and eventually evolved into a simple NaCl–H2O hydrothermal system. C–H–O–S–Pb isotope research proved that the ore-forming fluids are mainly magmatic water during the early stage, with abundant meteoric water mixed in during the late stage. Ore-forming materials originated mostly from hypomagma and were possibly influenced by the surrounding rocks, suggesting that the ore-forming materials were mainly magmatic hydrothermal deposits, with a small amount of crustal component. The fluid immiscibility and the CO2 and CH4 gases in the fluids played an active and important role in the precipitation and enrichment of Au during different metallogenic stages. The deposit is considered a magmatic hydrothermal deposit of middle–low temperature.

Keywords: C–H–O–S–Pb isotope, metallogenic period and stage, microthermometry and laser Raman, ore-forming fluid, Zhuanshanzi gold deposit.
1. Introduction

The Zhuanshanzi gold deposit is located in Inner Mongolia, approximately 50 km east of Chifeng city and in the Aohanqi territory. The geographical coordinates are E: 119°35', N: 42°18' (Fig. 1). It is composed of the Zhuanshanzi, Liangbanshan, and Luofengmao mining areas. Presently, hundreds of gold veins have been found. The total amount of gold metal has been verified and controlled by 18 t, with an average grade of 10 g t⁻¹. The Chifeng-Chaoyang gold mineralization zone is an important gold ore concentration region in the Yan Liao metallogenic belt of the northern margin of the North China Craton (NCC). There are more than 10 large- and medium-sized gold deposits, including Jinchanggougou, Erdaogou, Zhuanshanzi, Honghuagou, Lotus Hill, Anjiayingzi, and so on, as well as hundreds of gold occurrences. The aforementioned gold deposits are mostly located at the edge of the platform to the south of the Chifeng-Kaiyuan deep fracture and mainly occur in the Archean metamorphic rocks. Only the Zhuanshanzi gold deposit developed in the Xingmeng orogenic belt, and its surrounding rock is different from that of the other gold deposits.

Our predecessors have completed considerable research on the Zhuanshanzi gold deposit and its surrounding region, such as the geological characteristics of the deposit (Xu, 1995; Yin et al., 1997; Yao, 2008; Wang et al., 2016), geochemistry of the rock (Sun et al., 2016), mineralogical characteristics (Yin, 2002; Yin, 2003), the metallogenic tectonic environment (Sun, 2013; Wang, 2014), metallogenic prediction (Liu & Jin, 1991; Zhang et al., 1998; Li & Yang, 2000), and metallogenic chronology (Wei, 2001; Wang, 2014; Sun et al., 2016). However, studies on the genetic types of the gold deposits and their ore-forming materials are relatively scarce. Wang et al. (1994) proposed a Zhuanshanzi gold deposit formation model, where the gold deposit formed from basal magma remelting caused by ore-bearing hydrothermal intrusions. Wang et al. (1994) proposed a metallogenic model of the Zhuanshanzi gold deposit, which was believed to have formed by basement magma remelting, causing an ore-bearing hydrothermal invasion. Wei (2001) further expanded the metallogenic model and suggested that the uplifting effect of the Zhuanshanzi granitic rock was related to the long-range effect of the subduction of the ancient Pacific plate. Yin and Yan (2007) considered that it belongs to a medium-temperature superhydrothermal deposit according to the characteristics of the ore-forming fluid, and its mineralization may be related to the Shaoguoyingzi rock. Sun (2013) suggested that there is a connection between gold mineralization and the Zhuanshanzi granodiorite in space and time and that it is a shallow-type orogenic gold deposit. Wang et al. (2016) studied its isotopic geochemical characteristics and believed that the deposit was a typical intrusion-related gold deposit.

As a typical gold deposit of medium size in the orogenic belt, the Zhuanshanzi gold deposit has a long mining history, but its degree of geological study is obviously low, restricted to a certain extent to the metallogenic theory of the metallogenic belt. Mineral exploration and regional metallogenesis rules are very unfavorable. In view of this, we have carried out detailed field geological investigation work, orebody and ore characteristic analysis, fluid inclusion microscopic temperature measurement and laser Raman spectroscopy, C-H-O-S-Pb isotopic geochemical characteristic analysis, etc. It is of great scientific significance to determine the nature of the ore-forming fluids, the source of the ore-forming fluids and ore-forming materials, and the genesis mechanism of the deposits.

2. Regional geological setting

The Zhuanshanzi gold deposit lies on the northern margin of the NCC, in the eastern part of the Xingmeng orogenic belt (Fig. 1a), north of the Chifeng-Kaiyuan translithospheric fracture of Inner Mongolia, and on the south side of the Inner Mongolia Variscan fold system (Fig. 1b).

The Archean Wulashan Formation gneiss complexes (AR3Wgr) and metamorphic supracrustal rock (AR3Wmsrt), the Paleozoic Late Carboniferous Jiujuzi group (Cjj) sandstone and slate, the Mesozoic Early Jurassic Beipiao (J2b) shale and sandstone, and the early Cretaceous Yixian Formation (K1y) volcanic rocks are the main strata of the region. In particular, Mesozoic Early Cretaceous Yixian Formation (K1y) volcanic rocks are widely distributed, as well as Quaternary deposits. Regional magmatic activities mainly occurred during the Paleozoic and Mesozoic, and the late Paleozoic granitoids of a mainly porphyritic biotite granite batholith are widely distributed in the southern part of this area, which formed during the late Hercynian (Zhang, 1990). The Mesozoic granitoid complexes developed from the Triassic to the early Cretaceous, including diorite, granodiorite, granite, and granite porphyry, which were produced with small rock mass, rock
Fig. 1 Sketch showing the location of the regional tectonics (a), the geological map of the Chifeng-Chaoyang region (b), and the geological map of the Zhuanshanzi deposit (c). (1) Quaternary; (2) Jurassic; (3) Permian; (4) Archean metamorphic rocks; (5) Cretaceous granite porphyry; (6) Cretaceous fine-grained granite; (7) Permian – Triassic diorite; (8) felsophyre; (9) geological boundary; (10) gold vein; (11) faults; and (12) gold deposit.

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3. Deposit geology

3.1 Mining area geology

The main exposed stratum in the Zhuanshanzi gold deposit is the lower Permian system Qingfengshan Formation, a set of moderately acidic volcanic–volcaniclastic rocks, and the Suolun Formation, a set of marine carbonate–clastic rocks. Marble is relatively favorable for mineralization, and mineralization is better, but the slate is poorly mineralized, while the mineralization of the diorite and granite porphyry is weaker. The late Hercynian diorite and Yanshan granitoids are the two main types of intrusive rocks in the mining area (Fig. 1c). Studies show that the two intrusive rocks are closely related to gold mineralization (Liu & Jin, 1991; Yan et al., 1997; at the same time, many scholars believe that the Dachengzi granite and the Luofengmao rock in Yanshanian are closely related (Liu & Jin, 1991; Yan et al., 1997; at the same time, many scholars believe that the Dachengzi granite and the Luofengmao rock in Yanshanian are closely related to gold mineralization (Wang & Zhang, 1995; Xu, 1995; Wang, 2014). The industrial value of the orebody mostly occurs east of the Heishui-Lianhuashan fault.

There are more than 80 veins clustered, banded, or of equidistant distribution in the Zhuanshanzi gold deposit (Fig. 1c), and quartz veins and alteration tectonic rock-type gold veins are the main vein types of the gold deposit, along with second calcite veins. Veins are strictly controlled by the NW shear fault zone. Approximately 100 gold-bearing fracture zones are distributed on the north side of the fault, which is the 27 # vein. The industrial orebodies are generally in ore cracks at the scale of the lens body or the lentil body output, and continuity is poor. There are seven veins (Table 1) with a length of more than 1000 m of the 89 veins of the NW-veins of the gold deposit, with an average length of 1557 m. The remainder are usually 20–580 m in length, with an average length of 193 m.

The main metal minerals are pyrite, galena, chalcopyrite, sphalerite, etc., and the main gangue minerals are quartz and calcite. The ore structure is relatively simple, and the more common ore structures are veins or thin veins (Fig. 2a, b), massive, plaque, stripes, combs, and crystal caves (Fig. 2c). The common ore structure has a xenomorphic granular texture, which is composed of sulfide minerals with particle sizes of 0.5–1 mm or less, without orientation. Second, it is a self-shaped, semi-self-shaped coarse- or medium-granular structure (Fig. 2d, e, i), a cataclastic structure (Fig. 2f), a solid-solution separation structure (Fig. 2h), a metasomatic grid structure (Fig. 2g), and a symbiotic edge structure (Fig. 2h).

3.2 Mineralization period and characteristics of mineralization alteration

According to the geological characteristics of the deposit and mineral assemblage and the characteristics of the ore structure, the Zhuanshanzi gold deposit can be divided into four mineralization stages (Fig. 3). The first stage is quartz + a small amount of pyrite, milky quartz. The first generation of quartz was filled and metasomatized along the host structure’s fissures, with visibly coarse-grained cubes of pyrite distributed in the quartz veins (Fig. 2d), and there is a very small amount of gold mineralization. An industrial orebody did not form during this stage. In the second stage, quartz + pyrite (Fig. 2e, f), pyrite was filled and metasomatized along fracture zones and fissures in the milky quartz in the milky white quartz veins or formed in veins in the top and bottom walls of the structural cracks, or formed with veinlets disseminated in the tectonic rock. A small amount of galena appeared, in symbiosis with pyrite. This was an important metallogenic stage of the deposit. In the third stage, quartz + polymetallic sulfide (Fig. 2g, h), quartz and a large amount of pyrite, galena, sphalerite, and chalcopyrite appeared in the ore veins, which was the main metallogenic stage. The fourth stage, quartz + calcite + pyrite (Fig. 2i), consisted of independent calcite veins or quartz calcite veins including a small amount of quartz. At this stage, a large number of coarse-grain-shaped pyrites can be seen along with a small amount of galena and sphalerite. The alteration of the surrounding rock related to the mineralization is mainly silicification, sericitolite, and chloritization.
4. Sample characteristics and analytical methods

4.1 Samples and test methods of the fluid inclusion microtemperature and the Laser Raman spectrum

Eight samples of different ore veins and different metallogenic stages were selected for study fluid inclusions from the 4#, 5#, 72#, and 28# orebodies, with sample numbers 72 # -1, 72 # -2, 28 # -1, 28 # -2, ZSZ4-1, ZSZ4-2, ZSZ5-1, and ZSZ5-2. Doubly polished sections were prepared for fluid inclusion optical examination, microthermometrics, and Laser Raman microprobe analysis. Fluid inclusion microtemperature work was completed in the Division of Geology and Mineral Resources, Beijing Research Institute of Uranium Geology (BRIUG), and the Research Institute of Petroleum Exploration and Development, China. Heating and cooling experiments were carried out using a Linkam THMS 600 programmable heating-cooling stage. Before the test, 25% CO2–H2O, pure H2O, and pure CO2 (−56.6/C) inclusions (international standard) were used for systematic correction. The reproducibility of measurements was ±0.2°C below +30°C and ±2°C above 100°C. Most measurements were carried out at a heating rate of 0.2–0.4°C min⁻¹. The heating rate for measurements was reduced to 0.1–0.2°C min⁻¹. Based on the cooling point, the salinity of two-phase inclusions of water solution was calculated using the Bodnar (1993) formula. The inclusions are CO2 three-phase inclusions. Based on the vanishing temperature of the clathrate compound, the method developed by Shepherd et al. (1985) was used to calculate it.

Laser Raman spectroscopy was carried out in the Division of Geology and Mineral Resources, BRIUG, and the Research Institute of Petroleum Exploration and Development, China. The instrument used was a LabRAM HR800 micro-confocal laser Raman spectrometer manufactured by the Renishaw Company in the United Kingdom, and its working parameters were as follows: a Yal crystal, frequency-doubling, solid-state laser was used for the light source; the scanning range was 100–4300 cm⁻¹; the wavelength was 532 nm; the laser power was 20 mW; the laser beam spot was approximately 1 μm; and the spectral resolution was 0.14 cm⁻¹.

4.2 Hydrogen and oxygen isotope samples and test methods

Hydrogen and oxygen isotopic analysis of the quartz samples of different metallogenic stages was carried out. Pure quartz was selected and crushed to approximately
40 mesh powder for preparation. The test work was performed at the Institute of Geology, Chinese Academy of Geological Sciences. H₂O extracted from the primary fluid inclusions using the thermal burst method was reacted with Zn to extract H. The burst temperature was 550°C. The conventional BrF₅ method was used for oxygen isotope analysis, and δ¹⁸O was determined using a MAT 253 mass spectrometer. The precision of hydrogen and oxygen isotope analyses was ±0.2‰, respectively. δ¹⁸O_H₂O is calculated from the equilibrium fractionation equation of δ¹⁸O_H₂O = δ¹⁸O_{quartz} − 3.38 × 10⁶ T⁻² + 3.40 (Clayton et al., 1972) when the equilibrium temperature is between 200 and 500°C. The equilibrium temperature T is the average of the uniform temperature.

4.3 Carbon oxygen isotope samples and test methods

Five samples for carbon–oxygen isotope testing were taken from the 28 # calcite veins, and pure calcite was picked and crushed to 40 mesh powder for preparation. At 25°C, calcite reacts with phosphoric acid to release CO₂. The δ¹³C_V-PDB and δ¹⁸O_SMOW values of the calcite samples were measured directly from the CO₂. The test work was completed at the Second Institute of Oceanography & Key Lab of Submarine Geosciences, State Oceanic Administration.

4.4 Sulfur isotope samples and test methods

S isotope testing of eight pyrite samples of different gold-forming stages was carried out. First, the ore samples were crushed to 40–80 mesh, and pyrites were selected under a double eyepiece. The purity was greater than 95%, and the pyrites were crushed to 200 mesh. The S isotope analysis was carried out at the Division of Geology and Mineral Resources, BRIUG. The oxidant of the preparation samples was Cu₂O and was measured using a MAT-251 mass spectrometer.
Fluid inclusions and isotope geochemistry

using V-CDT (Vienna standard-troilite in Canyon Diablo meteorite) international standards. The analysis accuracy was better than 0.2‰ (Chu et al., 2007).

5. Results

5.1 Petrographic characteristics of fluid inclusions

Most fluid inclusions are primary, and the inclusions are in a variety of shapes, including long stripe, oval, nearly round, polygonal, or irregular shapes. The particle sizes of these inclusions mainly range from 5 to 15 μm, but several articles can be up to 40 μm. According to the phase of the inclusions, they can be divided into four types:

- Type I gas–liquid two-phase inclusions were composed of a brine solution and bubbled at room temperature. According to the gas–liquid ratio, they can be further divided into type Ia and type Ib. The gas–liquid ratio of type Ia is 8–25% (Fig. 4a, j), and the gas–liquid ratio of type Ib is 25–40% (Fig. 4b, e, h, i, j). The inclusion shape is generally nearly round, oval, or size ranging from 5 to 15 μm. In the fluid inclusions during the cooling process, the liquid-phase H2O solidifies into ice. During the heating process, the solid-phase (ice) H2O gradually melts to liquid, and with the rise in temperature, it can completely homogenize to gas. Gas–liquid two-phase fluid inclusions can be found in the four stages of the ore, especially type Ib inclusions, which are the most common type of inclusion.

- Type II gas-rich fluid inclusions were mainly composed of a bubble and liquid phase at room temperature. The gas–liquid ratio is generally more than 50%, with the most concentrated from 60 to 80%. The size of the inclusions is generally 6–12 μm, and the shapes are generally oval, subround, etc. They were scattered in the quartz or occurred in groups with other inclusions (Fig. 4c–f). In the fluid inclusions during the cooling process, the H2O liquid phase solidified into ice. During the heating process, the solid phase (ice) H2O gradually melts to liquid, and with a rise in temperature, it can completely homogenize to gas. Inclusions of this type developed in the first to third metallogenic stages.

- Type III single-liquid fluid inclusions were the majority of inclusions of a single phase at room temperature. They can be divided into type IIIa and type IIIb according to the different components. Type IIIa are pure CO2 inclusions with a size of approximately 3–8 μm (Fig. 4b–e), with visible gas-phase CO2 bubbles during the process of cooling and a gas–liquid ratio concentrated from 45 to 60%. During the heating process, the gas-phase CO2 of type IIIa inclusions homogenizes to a liquid-phase CO2, and the inclusions in the first and second mineralization stages of the ore can be found. Type IIIb are the single-phase saltwater inclusions (Fig. 4g), mostly oval, or long stripe, with a size of 3–8 μm. Most of these inclusions are secondary inclusions appearing along the microfractures.

- Type IV CO2-containing three-phase fluid inclusions were the inclusions containing liquid CO2, gas CO2, and liquid H2O phases at room temperature. The proportion of the CO2 phase is generally between 50 and 70%. Generally, vapor CO2/liquid CO2 ratios are approximately 60%. The size of the inclusions is generally 6–15 μm, with a nearly oval shape, and they occur as scattered inclusions in quartz and in groups with other inclusions (Fig. 4h). The liquid-phase CO2 and liquid-phase H2O were frozen by cooling, and the solid-phase CO2 disappeared during the heating process. The CO2 clathrate compound formed and disappeared, and the gas-phase CO2 homogenized to liquid, and the liquid CO2 was completely homogeneous. The number of fluid inclusions is very small, and they only appeared in the second and third metallogenic stages.
Microthermometrics of fluid inclusions

We have obtained the results of homogenization temperatures for the different mineralization stages, and the results are shown in Table 2 and Fig. 5.

The first stage: Quartz + a small amount of pyrite. Quartz contains type I two-phase, type II gas-rich inclusions, and single liquid inclusions as well as type IIIa pure CO$_2$ liquid inclusions. During the cooling and heating process, we obtained an ice point temperature of $-7.1$ to $-0.4^\circ$C from gas–liquid two-phase inclusions, and the average was $-2.9^\circ$C. The salinity ranged from 0.35 to 10.61 wt% NaCl equiv., and the average was 7.69 wt% NaCl equiv. The homogenization temperature ranged from 147 to $353^\circ$C, and the average was 309.11 $^\circ$C. Based on the homogenization temperature and salinity, we calculated a fluid density of 0.60–0.98 g/cm$^3$.

During the cooling and heating process, we obtained ice point temperatures of $-6.1$ to $-0.4^\circ$C from gas–liquid two-phase inclusions, and the average was $-3.46^\circ$C. The salinity ranged from 0.71 to 21.47 wt% NaCl equiv., and the average was 7.69 wt% NaCl equiv. The homogenization temperature ranged from 147 to 353$^\circ$C, and the average was 309.11$^\circ$C. Based on the homogenization temperature and salinity, we calculated a fluid density of 0.62–0.95 g/cm$^3$.

The solid CO$_2$ melting temperatures ranged from $-57.3$ to $-56.6^\circ$C during the cooling and heating process of pure CO$_2$ fluid inclusion.

The second stage: Quartz + pyrite. Quartz contains type I gas–liquid two-phase inclusions, type II gas-rich fluid inclusions, type IIIa single-liquid fluid inclusions, pure CO$_2$ liquid-fluid inclusions, and type IV CO$_2$-containing three-phase fluid inclusions.

During the cooling and heating process, we obtained ice point temperatures of $-18.7$ to $-0.4^\circ$C from gas–liquid two-phase fluid inclusions, and the average was $-3.62^\circ$C. The salinity ranged from 0.71 to 21.47 wt% NaCl equiv., and the homogenization temperature ranged from 243.5 to 340$^\circ$C, concentrated at 250–300$^\circ$C. Based on the homogenization temperature and salinity, we calculated a fluid density of 0.62–0.95 g/cm$^3$.

During the cooling and heating process, we obtained ice point temperatures of $-7.1$ to $-0.4^\circ$C from gas-rich fluid inclusions, and the salinity ranged from 0.35 to 10.61 wt% NaCl equiv., and the average was 7.69 wt% NaCl equiv. The homogenization temperature ranged from 147 to 353$^\circ$C, and the average was 309.11$^\circ$C. Based on the homogenization temperature and salinity, we calculated a fluid density of 0.60–0.98 g/cm$^3$.
Fluid inclusions and isotope geochemistry

Table 2

<table>
<thead>
<tr>
<th>Metallogenic stage</th>
<th>Fl. size (μm)</th>
<th>Fl. type</th>
<th>CO₂ - CO₂ (wt% NaCl)</th>
<th>Salinity (wt% NaCl)</th>
<th>TH (°C)</th>
<th>Tm, CO₂ (°C)</th>
<th>Tm, cha (°C)</th>
<th>LCO₂/LH₂O</th>
<th>VCO₂/LCO₂</th>
</tr>
</thead>
</table>

The second stage: The third stage: Quartz + polymetallic sulfide. Type I gas-liquid two-phase fluid inclusions, type II gas-rich fluid inclusions, type IIIa single-liquid fluid inclusions, pure CO₂ liquid fluid inclusions, and type IV CO₂-containing three-phase fluid inclusions developed in the quartz.

During the cooling and heating process, we obtained ice point temperatures of −15.9 to −0.4°C from gas-liquid two-phase fluid inclusions, and the average was −4.72°C. The salinity ranged from 7 to 10 wt% NaCl equiv. The homogenization temperature ranged from 152 to 251°C, concentrated at 180–230°C. Based on the homogenization temperature and salinity, we calculated a fluid density of 0.50–1.05 g/cm³.

During the cooling and heating process, we obtained ice point temperatures of −6.9 to −0.5°C from gas-rich fluid inclusions, and the salinity ranged from 0.88 to 10.36 wt% NaCl equiv., concentrated at 8–9 wt% NaCl equiv. The homogenization temperature ranged from 152 to 270°C. Based on the homogenization temperature and salinity, we calculated a fluid density of 0.80–1.00 g/cm³.

CO₂-containing three-phase fluid inclusions are in a three-phase state at room temperature. When completely frozen at −120°C, the solid CO₂ melting temperatures ranged from −58.2 to −56.4°C, and the CO₂ clathrate compound disappearance temperature ranged from 3.1 to 6.2°C. The salinity ranged from 7.05 to 11.75 wt% NaCl equiv. The CO₂ partial homogeneity temperature is 29.4–31°C, and the inclusions are completely homogeneous at a temperature of 189–253°C. Based on the homogeneous temperature and salinity value, we calculated a fluid density of 0.82–0.95 g/cm³.
The fourth stage: Quartz + calcite + pyrite. Type I gas–liquid two-phase fluid inclusions developed in quartz and calcite. During the cooling and heating process, we obtained ice point temperatures of $-10.1$ to $-0.2^\circ C$ from gas–liquid two-phase fluid inclusions, and the average was $-3.56^\circ C$. The salinity ranged from 0.35 to 10.11 wt% NaCl equiv., concentrated at 7–9 wt% NaCl. The homogenization temperature ranged from 80 to 230$^\circ C$, concentrated at 140–170$^\circ C$. Based on the homogenization temperature and salinity, we calculated a fluid density of 0.90–1.05 g/cm$^3$.

5.3 Composition of fluid inclusions

Laser Raman microprobe analysis of the gas and liquid components of the fluid inclusions of different mineralization stages shows that the host mineral quartz has distinct characteristic peaks of 490 and 1160 cm$^{-1}$. The main components of the liquid inclusions are H$_2$O with characteristic peaks from 3310 to 3610 cm$^{-1}$; the gas phases are mainly H$_2$O with characteristic peaks of 3310–3610 cm$^{-1}$ (Fig. 6a–d), CO$_2$ with characteristic peaks of 1283–1386 cm$^{-1}$ (Fig. 6a–e), and CH$_4$ with a characteristic peak of 2904 cm$^{-1}$ (Fig. 6e, f). In addition, for type IV CO$_2$-containing three-phase fluid inclusions, besides the CO$_2$ peak, there is a CH$_4$ peak (Fig. 6e). Because the freezing point of the type IV three-phase inclusions of different phases is obviously lower than the ice-melting temperature ($-56.5^\circ C$) of pure CO$_2$ inclusions, this indicates that the gas phase contains a certain amount of CH$_4$ (the ice-melting temperature is between $-90$ and $-10.1^\circ C$).
Fig. 6 Laser Raman spectra of fluid inclusions in the Zhuanshanzi deposit.
Wang et al. (1994) argued that the gas components of the fluid inclusions in the Zhuanshanzi gold deposit were dominated by water vapor, followed by CO₂, while CH₄ was a small portion of the volatiles. This is consistent with this study.

5.4 Stable isotope C—H—O—S test

The H—O isotopic compositions of quartz and calcite of different stages are listed in Table 3, where δDᵥ-SMOW is generally the direct measurement of primary or pseudosecondary inclusions in vein quartz, and δ¹⁸Oᵥ-H₂O is calculated based on the determination of the δ¹⁸O value and the equilibrium temperature of the mineral (quartz). When the equilibrium temperature is between 200 and 500°C, we can calculate δ¹⁸Oᵥ-H₂O using the equilibrium fractionation equation

\[
\delta^{18}O_{H_2O} = \delta^{18}O_{Quartz} - 3.38 \times 10^6 T - 2 + 3.40 \quad \text{(Clayton et al., 1972)}
\]

and using δ¹⁸O-Mineral-SMOW − δ¹⁸Oᵥ-H₂O-SMOW = 2.788 × 10⁶ T − 2 – 2.89 in calcite (Zheng et al., 2000). The equilibrium temperature T is the average temperature of the fluid inclusions in different stages.

In the first stage, the δ¹⁸Oᵥ-H₂O value ranges from 2.82 to 3.42, and the δDᵥ-SMOW value ranges from −94 to −90. In the second stage, the δ¹⁸Oᵥ-H₂O value ranges from 0.96 to 1.06, and the δDᵥ-SMOW value ranges from −106 to −103. In the third stage, the δ¹⁸Oᵥ-H₂O value ranges from 0.32 to 3.88, and the δDᵥ-SMOW value ranges from −108 to −102. In the fourth stage, the δ¹⁸Oᵥ-H₂O value ranges from −13.03 to −2.05, and the δDᵥ-SMOW value ranges from −124.4 to −121.4.

The calcite veins appeared in the late period of the Zhuanshanzi gold deposit, and there was no graphite found. Thus, the calcite C isotope composition can represent the total carbon isotopic composition of the hydrothermal system during mineral deposition (Sverjensky, 1997). All the results are shown in Table 4. The δ¹³Cᵥ-PDB values of the calcite samples ranged from −3.66 to −2.74‰, and the δ¹⁸Oᵥ-SMOW values ranged from −2.73 to −0.05‰. The small variation in the δ¹³C value indicates that the secondary carbon introduced by cyclic hydrothermal or

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**Table 3** Hydrogen and oxygen isotope compositions of fluid inclusions from the Zhuanshanzi gold deposit

<table>
<thead>
<tr>
<th>Samples no.</th>
<th>Metallogenic stages</th>
<th>Minerals</th>
<th>δDᵥ-SMOW (%)</th>
<th>δ¹⁸Oᵥ-H₂O (%)</th>
<th>δ¹⁸Oᵥ-SMOW (%)</th>
<th>Calculating temperature (°C)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZHSZ-1</td>
<td>The first stage</td>
<td>Quartz</td>
<td>−90</td>
<td>3.42</td>
<td>9.3</td>
<td>330</td>
<td>This study</td>
</tr>
<tr>
<td>ZHSZ-2</td>
<td>The first stage</td>
<td>Quartz</td>
<td>−94</td>
<td>2.82</td>
<td>8.7</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>ZHSZ-3</td>
<td>The second stage</td>
<td>Quartz</td>
<td>−106</td>
<td>0.96</td>
<td>9.0</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>ZHSZ-4</td>
<td>The second stage</td>
<td>Quartz</td>
<td>−103</td>
<td>1.06</td>
<td>9.1</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>ZHSZ-5</td>
<td>The third stage</td>
<td>Quartz</td>
<td>−104</td>
<td>0.32</td>
<td>10.8</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>ZHSZ-6</td>
<td>The third stage</td>
<td>Quartz</td>
<td>−108</td>
<td>0.72</td>
<td>11.2</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>ZHSZ-7</td>
<td>The third stage</td>
<td>Quartz</td>
<td>−102</td>
<td>3.88</td>
<td>12.4</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>84-4-2-18</td>
<td>The fourth stage</td>
<td>Calcite</td>
<td>−121.4</td>
<td>−7.08</td>
<td>5.53</td>
<td>150</td>
<td>Wang et al., 1994</td>
</tr>
<tr>
<td>84-4-2-19</td>
<td>The fourth stage</td>
<td>Calcite</td>
<td>−124.4</td>
<td>−13.03</td>
<td>−0.42</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>84-4-2-20</td>
<td>The fourth stage</td>
<td>Calcite</td>
<td>−124.4</td>
<td>−2.05</td>
<td>10.56</td>
<td>150</td>
<td></td>
</tr>
</tbody>
</table>

---

**Table 4** Carbon and oxygen isotope compositions of calcite from the Zhuanshanzi gold deposit

<table>
<thead>
<tr>
<th>Mineral</th>
<th>δ¹³Cᵥ-PDB (%)</th>
<th>δ¹³Cᵥ-CO₂ (%)</th>
<th>δ¹⁸Oᵥ-SMOW (%)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite</td>
<td>−3.18</td>
<td>−3.25</td>
<td>−2.50</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>−3.14</td>
<td>−3.14</td>
<td>−2.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−3.21</td>
<td>−3.14</td>
<td>−2.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−3.07</td>
<td>−3.07</td>
<td>−0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−3.66</td>
<td>−3.66</td>
<td>−2.20</td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td>−2.37 to −3.39</td>
<td>−3.01</td>
<td>−1.89 (4)</td>
<td>Sverjensky, 1997</td>
</tr>
<tr>
<td>Inclusions of</td>
<td></td>
<td>−1.60 to −2.27</td>
<td>−4.48 (2)</td>
<td></td>
</tr>
<tr>
<td>quartz in ore</td>
<td></td>
<td>−3.89 to −5.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vein</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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groundwater and $T_f CO_2$ and pH had little effect on its fractionation.

The composition of $\delta^{34}S_{V-CDT}$ during the different mineralization stages of the Zhuanshanzi gold deposit ranged from $-0.8$ to $2.9\%$ (Table 5), with a max–min of $3.7\%$ and an average of $0.817\%$. The $\delta^{34}S_{V-CDT}$ of pyrite in the first ore-forming stage is between $1.6$ and $2.0\%$, with a max–min of $0.4\%$ and an average of $1.8\%$ (Wang et al., 2016). The $\delta^{34}S_{V-CDT}$ values of pyrite in the second and third ore-forming stages are between $0.2$ and $1.8\%$, with a max–min of $1.6\%$ and an average of $0.87\%$. The sphalerite $\delta^{34}S_{V-CDT}$ value is between $-0.85$ and $0.5\%$, with a max–min of $1.3\%$ and an average of $0.39\%$ (Wang et al., 2016). In the fourth stage, the $\delta^{34}S_{V-CDT}$ value in pyrite ranged from $-0.8$ to $2.9\%$, with a max–min of $3.7\%$ and an average of $0.77\%$.

### 6. Discussion

#### 6.1 Nature and evolution of the ore-forming fluid

Multistage quartz (calcite) veins developed in the Zhuanshanzi gold deposit, showing the characteristic of multistage hydrothermal activities. The fluid inclusions’ petrographic and Laser Raman spectroscopy analysis show that there are mainly gas–liquid two-phase inclusions and CO$_2$-containing three-phase fluid inclusions in the deposit, and the gas components are dominantly H$_2$O and CO$_2$. This indicates that the metallogenic system is a CO$_2$–H$_2$O–NaCl system. The homogenization temperature of the ore-forming fluid in the Zhuanshanzi gold deposit gradually develops from medium temperature to medium–low temperature, and the temperature of the fluid during the late stage further decreases, and the fluid usually lacks CO$_2$ and evolves into a simple NaCl–H$_2$O hydrothermal system.

The homogenization temperatures of various types of fluid inclusions during the four mineralization stages showed a decreasing trend, and CO$_2$-containing inclusions presented during the second and third stages of quartz provided the possibility of estimating the fluid-capture pressure (Hu et al., 2008). According to the results of the microscopic temperature data, the ore-forming pressure of the four stages shows a decreasing trend, which indicates that the ore-forming fluid is in a trend of decreasing temperature and decreasing pressure. In addition, with the development of mineralization, the properties of the ore-forming fluid also change (Fig. 7).

During the first three mineralization stages of the gold deposits, there are gas–liquid two-phase fluid inclusions, gas-rich fluid inclusions, and CO$_2$-containing three-phase fluid inclusions. The homogenization temperature of various types of fluid inclusions is usually in the same range during a single stage. The most notable feature of the quartz in the second and third stages (main mineralization stage) is the coexistence of CO$_2$-containing three-phase fluid inclusions and gas–liquid two-phase fluid inclusions. The gas–liquid two-phase fluid inclusions are homogeneous to the liquid phase, and the gas-rich fluid inclusions are homogeneous to the gas phase. The homogenization temperature of the second-stage gas–liquid two-phase fluid inclusions is $230$–$340^\circ$C, which is consistent with the homogenization temperature of CO$_2$-containing three-phase fluid inclusions, which is $230$–$310^\circ$C. The homogenization temperatures of the third-stage gas–liquid two-phase fluid inclusions range from $152$ to $251^\circ$C, which is consistent with the homogenization temperatures of CO$_2$-containing three-phase fluid inclusions, which range

---

**Table 5** Sulfur isotope compositions of ore sulfides from the Zhuanshanzi gold deposit

<table>
<thead>
<tr>
<th>Samples no.</th>
<th>Metallogenic stages</th>
<th>Mineral</th>
<th>$\delta^{34}S_{V-CDT}$ (‰)</th>
<th>Range (‰)</th>
<th>Average (‰)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZSZ-01-03</td>
<td>The first stage</td>
<td>Pyrite</td>
<td>1.6 to 2</td>
<td>0.4</td>
<td>1.8</td>
<td>Wang et al., 2016</td>
</tr>
<tr>
<td>ZHSZ-P-1</td>
<td>The second and third stages</td>
<td>Pyrite</td>
<td>1.8</td>
<td>1.6</td>
<td>0.87</td>
<td>This study</td>
</tr>
<tr>
<td>ZHSZ-P-2</td>
<td>Pyrite</td>
<td></td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZHSZ-P-3</td>
<td>Pyrite</td>
<td></td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZSZ-04-11</td>
<td>Pyrite</td>
<td></td>
<td>-0.1 to 1.0</td>
<td>1.1</td>
<td>0.61</td>
<td>Wang et al., 2016</td>
</tr>
<tr>
<td>ZSZ-12-18</td>
<td>Sphalerite</td>
<td></td>
<td>-0.8 to 0.5</td>
<td>1.3</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>ZHSZ-P-4</td>
<td>The fourth stage</td>
<td>Pyrite</td>
<td>-0.8</td>
<td>3.7</td>
<td>0.77</td>
<td>This study</td>
</tr>
<tr>
<td>ZHSZ-P-5</td>
<td>Pyrite</td>
<td></td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZHSZ-P-6</td>
<td>Pyrite</td>
<td></td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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from 189 to 253°C. This suggested obvious phase separation (immiscibility) of ore-bearing hydrothermal fluids during the mineralization (Lu, 2008). However, in the first stage of mineralization, few CO₂-containing three-phase fluid inclusions are usually present, and the number of the pure CO₂ fluid inclusions is relatively lower, while in the second and third mineralization phases, the number of CO₂-containing three-phase fluid inclusions and pure CO₂ fluid inclusions in the quartz increased significantly. This indicated that, with the progress of mineralization, the ore-bearing hydrothermal fluid underwent an initial immiscible to strongly immiscible evolution process due to the gradual decrease in pressure and temperature during upward migration. There were gas–liquid two-phase fluid inclusions in the fourth stage, indicating that the mineralization was affected by the mixing of atmospheric precipitation later.

6.2 Ore-forming fluids and material sources

Most vein-like gold deposits may undergo a complicated geological evolution during the source–transport–storage–change–preservation process (Goldfarb & Groves, 2015). Hydrogen and oxygen isotopes and fluid inclusions are good indicators of the evolutionary history of ore-forming fluids, such as H–O isotopes (McCuaig & Kerrich, 1998), rare gas, and halogen isotopes (Kendrick et al., 2011) and so on. We studied the H–O isotopic composition of quartz veins during the different stages of the Zhiuan Shanzi gold deposit (Table 2, Fig. 8). In the first metallogenic stage, the composition of H–O isotopes is close to magmatic water, which is obviously different from metamorphic water. This may be because the ore-forming fluid was mainly dominated by magmatic water during the early stage. The second and third mineralization stages δD showed a decreasing trend, which may represent mixed hydrothermal characteristics. However, in the fourth stage, hydrothermal fluids showed obvious δD and δ¹⁸O losses, and this represented a large amount of precipitation during the late stage of metallogenesis.

The δ¹³C(‰) of inclusions in calcite veins and some quartz veins demonstrates that the average carbon isotope of calcite is generally between −3.66 and −3.07‰. The main sources of carbon in hydrothermal fluids are as follows: (i) in deep sources of mantle gas or magmatic sources, δ¹³C ranges between −5 to −2‰ and −9 to −3‰, respectively; (ii) for carbonate from dissolution of sedimentary rocks, the δ¹³C ranges from −3 to −2‰; and (iii) for organic-generated carbon, the δ¹³C ranges from −30 to −15‰. To a certain extent, this implies that the carbon in the mineralization system of the Zhiuan Shanzi gold deposit is mainly from a deep source and may be affected by the surrounding rock. At the same time, the average δ¹³C of CO₂ inclusions in the ore ranges from −5.67 to −3.89‰ with a concentration of −5.0‰,
indicating that the ore-forming fluid was derived from mantle magma (Li et al., 2008).

Gold is usually in the form of native gold Au (free gold) or microscopic gold or visible/invisible gold occurring in quartz/sulfide. However, discussing the origin of metallogenic materials is usually based on closely associated gold mineralization minerals as the research object, indirectly inferring the ore-forming material sources. The fractionation of sulfur isotopes is mainly affected by the physicochemical conditions of the evolution of the thermal fluid in the source area (Sverjensky, 1997). There are no sulfates in the Zhuanshanzi gold deposit, and the sulfur-bearing minerals are mainly sulfides such as pyrites, indicating that the $f_{O_2}$ of the ore-forming system is relatively low. The $\delta^{34}S$ of the sulfides can represent the characteristics of $\delta^{34}S_{\text{org}}$ in the ore-forming fluid. The S isotopic composition of different sulfides during different metallogenic stages shows that the $\delta^{34}S$ range is very small and basically varies near 0‰, which is similar to the S isotope composition of sulfur in mantle and meteorites, suggesting that the ore-forming fluids have the same origin and a deep source.

It should be noted that the different sulfide $\delta^{34}S$ extremes are different during the different mineralization stages. This indicates that the gold mine had characteristics of multistage mineralization and different orders of different sulfide precipitation. Pyrite is a common and important gold-bearing mineral in gold deposits (Deditius et al., 2008; Prolledesma et al., 2010; Yan et al., 2013) and is also a penetrating mineral in most gold deposits. It can occur in various mineralization stages (Mao et al., 1999; Deng et al., 2005; Liu et al., 2014). Yan et al. (2012) analyzed the S isotopic composition of pyrites in gold deposits of various genetic types (Fig. 9) and noted that the sulfur isotopic composition of epithermal gold deposits ranged from $-0.4$ to $11$‰, similar to the S isotopic composition of a meteorite. The sulfur isotopic composition of a magmatic hydrothermal gold deposit varies from $0.9$ to $13.63$‰, which is similar to the S isotopic composition of granite. Meanwhile, Wang et al. (1994) thought that the $\delta^{34}S_{\text{org}}$ value of the sulfides in the Zhuanshanzi gold deposit was close to 0‰, suggesting that the sulfur source of the ore may be dominated by magmatic sulfur (Wang et al., 1994), with a small amount of crustal sulfur (Wang et al., 2016). According to the sulfide isotopic characteristics and geological characteristics of the Ersazan gold deposit, it is speculated that the sulfur in the ore-forming fluid of the Zhuanshanzi gold deposit is mainly derived from the deep magma mixed with a small amount of crustal sulfur.

Fig. 8 The diagram of $\delta D$ versus $\delta^{18}O_{\text{H}_2\text{O}}$ Zhuanshanzi gold deposit (modified from Ohara et al., 1997).
The Pb isotope is an effective geochemical tracer and is the most direct and effective method to trace the source of ore-forming materials and to explore the genesis of a deposit (Zhang, 1985; Feng et al., 2003). Zartman and Doe (1981) used the theory of plate tectonics to integrate the evolution of Pb isotopes with plate tectonic systems, and tectonic dynamics such that Pb isotopes have tectonic significance. In addition, he elucidated the evolution of metallogenic geological tectonics and mineralization using the material balance and kinetic perspectives, providing geochemical indicators and models for mineral prediction.

The Pb isotopic values of the Zhuanshanzi granites, pyrite, sphalerite, and galena fall into a region between the mantle and lower crust and are mostly concentrated along the evolution line of the orogenic belt (Fig. 10a, b), demonstrating features of mantle lead and lower crust lead. This agrees with the geological background in this area. This also shows that the mineralization was affected by magmatism. Lead was mainly related to magmatism and generally shows the characteristics of crust–mantle mixing.

### 6.3 Migration, precipitation, and enrichment mechanisms of gold

Lu (2008) systematically summarizes the spatial distribution of CO\textsubscript{2} and Au in gold deposits, noting that both are closely related. Because of the low chemical affinity between CO\textsubscript{2} and Au, CO\textsubscript{2} cannot play a direct role in the migration of Au. However, as a weak acid, H\textsubscript{2}CO\textsubscript{3} formed by CO\textsubscript{2} has a buffer effect on the pH value of ore-forming fluids and, thus, is beneficial to the stable migration of Au complexes (Phillips & Evans, 2004). When the ore-forming fluid is immiscible, it will lead to the formation of CO\textsubscript{2}-rich fluid inclusions during the same period (Lu, 2008).

Previous studies have shown that gold was mainly a gold–sulfur complex in the hydrothermal solution in gold deposits. Its equilibrium equation (Seward, 1973, 1984; Seward & Tulloch, 1991) is Au + H\textsubscript{2}S (aq) + HS\textsuperscript{-} = Au (HS\textsubscript{2})\textsuperscript{−} + 0.5H\textsubscript{2} (g). During the late stage of mineralization, Au may migrate in the form of AuCl\textsubscript{3}, AuCl\textsubscript{2}\textsuperscript{−}, and complex anions such as [AuCl\textsubscript{4}]\textsuperscript{−}, [AuCl\textsubscript{2}]\textsuperscript{−}, or [AuCl(OH)]\textsuperscript{−}. The physicochemical conditions, such as sulfur fugacity, oxygen fugacity, and the pH value of the solution, can be significantly changed by the immiscibility of the fluid. This can lead to the disintegration of the gold–sulfur complexes in the hydrothermal solution and lead to a large amount of gold to precipitate and deposit (Lu, 2011; Ni et al., 2015). This is also one of the important reasons that the first mineralization phase is relatively poor, and the second and third mineralization phases are relatively rich in gold. By the fourth mineralization stage, mixing of a large amount of atmospheric precipitation has led to the transformation of the ore-forming fluid into a simple NaCl–H\textsubscript{2}O hydrothermal system. At this time, due to the immiscibility of the fluid, a large amount of gold is precipitated in the hydrothermal solution, and the remaining gold decreases, so the stage of mineralization also becomes weak.

CH\textsubscript{4} gas plays an important role in the precipitation enrichment of Au; it not only expands the temperature range of immiscibility of fluids, and it is also favorable for the precipitation of Au in ore-forming fluids in a larger temperature range (Naden & Shepherd, 1989), but it also changes the redox state of the ore-forming fluid and undergoes the following reactions ((1) and (2)), leading to a decrease in the stability of the gold complex, inducing the precipitation of Au (Kendrick et al., 2011).

\begin{align*}
2\text{AuHS} + 0.5\text{H}_{2}\text{O} + 0.25\text{CH}_{4} &= 2\text{Au} + 0.25\text{CO}_{2} + 2 \text{H}_{2}\text{S} \quad (1) \\
8\text{AuHS} + 3\text{CO}_{2} + 5\text{CH}_{4} &= 8\text{Au} + 8\text{C} + 8\text{H}_{2}\text{S} + 6 \text{H}_{2}\text{O} \quad (2)
\end{align*}

The Laser Raman spectroscopy of the ore-forming fluids shows that there is a small amount of CH\textsubscript{4} in fluid inclusions during the main mineralization stage.
of the Zhuanshanzi gold deposit (Fig. 6e, f), which has a positive effect on the precipitation enrichment of Au. However, further study of CH$_4$ in this gold deposit is still required because CH$_4$ in hydrothermal fluids may have many causes and sources, such as a biogenic (Whiticar, 1999; Ueno et al., 2006) or magmatic origin (Beeskow et al., 2006) or water–rock interactions (Fiebig et al., 2009; Cao et al., 2014). In this study, C–H–O isotope analyses of quartz veins and calcite veins demonstrated that ore-forming fluids and ore-forming materials are mainly derived from deep magmas. Wang et al. (1994) carried out C–O isotopic analysis of CO$_2$ and gas components in fluid inclusions in quartz veins (Table 3), showing that the ore-forming fluids and ore-forming materials had features of deep magma.

### 6.4 Ore genesis

Our predecessors have studied the genesis of the Zhuanshanzi gold deposit and the gold deposits in the metallogenic belt. The main hypotheses are a (magmatic) hydrothermal type (Zhang, 1990; Chu and Jia, 2000; Zhang et al., 2002; Sun et al., 2006; Xu, 2007; Hou et al., 2014), a granitic greenstone belt type (Chen et al., 1998), a volcano–subvolcanic action medium–low temperature hydrothermal type (Lin et al., 1994; Jia et al., 2001; Chen, 2006), an epithermal deposit type (Hart et al., 2002), a shallow orogenic gold deposit type (Sun, 2013), and an intrusion-related gold deposit type (Wei, 2001; Wang et al., 2016). There are many different viewpoints regarding deposit genesis. The reason may be different criteria for the classification of genetic types of deposits, such as focusing on the source of metallogenic materials, mineralization, the temperature of formation, and the metallogenic tectonic setting.

Numerous studies suggest that the major genetic types of gold deposits include orogenic gold deposits, Carlin-type gold deposits, intrusion-related gold deposits, and hydrothermal vein-type gold deposits (Kerrich et al., 2000). By comparing the geological characteristics of different types of gold deposits, it is clear that the Zhuanshanzi gold deposit is not a typical orogenic gold deposit because the ore-forming fluid of a typical orogenic gold deposit is mainly metamorphic fluid (Groves et al., 1998; Kerrich et al., 2000), while there is no evidence for the existence of metamorphic fluids in the Zhuanshanzi gold deposit. There is a large amount of free gold in the Zhuanshanzi gold deposit, and it is obviously different from a Carlin-type gold deposit characterized by invisible gold (Cline et al., 2005). Numerous studies show that a magmatic hydrothermal metallogenic system generally develops in a plate-collision orogenic environment, a tensile environment, or an intraplate rift environment. Indosinian granite (245.8 ± 3.1 Ma) (Sun et al., 2016) and Yanshanian granite (173.14 ± 0.82, 156.0 ± 2.1, 132.6 ± 2.1 Ma) (Wang, 2016) developed in the Zhuanshanzi gold mining area and formed in an extensional environment of different tectonic
systems. This favors the formation of magmatic hydrothermal deposits.

The gold mineralization in the Chifeng–Chaoyang region can be divided into the Triassic (about 243 Ma) and the Cretaceous (126–132 Ma) in the Mesozoic, and it is considered to be consistent with the early Triassic and early Cretaceous tectonic–magmatic activities (Fu, 2012). The weighted mean age of LA-ICP-MS zircon U–Pb from the Zhuanshanzi rock mass formed in the early gold mineralization stage is 245.8 ± 3.1 Ma (Sun et al., 2016); the Re–Os isochron date for molybdenite from the Jinchanggouliang gold deposit is 244.7 ± 2.5 Ma, which is within the error of the weighted mean age of 243.5 ± 1.3 Ma (Hou, 2011); and the weighted mean age of LA-ICP-MS zircons U–Pb from the Jianggoushan rock mass closely related to the Xiaotazigou gold deposit is 239 ± 2 and 233 ± 4 Ma (Song et al., 2010), respectively. These data indicate that there are gold (molybdenum) mineralization events in the Triassic, but more data show that the gold mineralization of the Jinchanggoulian gold deposit was 131.45 ± 2 Ma (Hou, 2011; Zhang et al., 2014), and the Erdaogou gold mineralization age was 126 ± 1 Ma (Miao et al., 2003), and the age of Nineolingou gold deposit was 125.5 ± 0.87 Ma (Sun, 2013). These gold deposits are similar to the age 123 Ma of the Zhuanshanzi rock measured in the Zhuanshanzi gold deposit (Wei, 2001), and all of them belong to the late Yanshan (the early Cretaceous); this indicates that the main mineralization period of the Zhuanshanzi gold deposit was in the early Cretaceous, and eastern China became the part of the Pacific tectonic domain, and its magmatism and mineralization were related to the subduction of the Pacific plate (Pearce et al., 1984; Zhao et al., 1999; Zhou et al., 2009). The Pacific plate subducted rapidly to Eurasia, with large-scale rapid thinning of the lithosphere and intense magmatic activity. At the same time, a large number of granitic intrusions formed in the tectonic environment of lithospheric extension and thinning, and mineralization also took place in the same period (125–132 Ma).

Wang et al. (2016) noted that both the metallogenesis and Zhuanshanzi rock diagenesis were consistent, and they considered them the intrusion-related gold deposit. Magmatic hydrothermal deposits and intrusion-related gold deposits have the following characteristics: (i) they are closely related to medium-acidic and felsic intrusive rock intrusions; (ii) typical sheeted veins develop; (iii) combinations of metallogenic elements (Bi + W + As + Mo + Te + Sb) are presented; and (iv) ore-forming fluids are characterized by CO$_2$–H$_2$O–CH$_4$ and vary greatly in temperature and salinity (Thompson et al., 1999; Thompson & Newberry, 2000; Lang & Baker, 2001; Baker, 2002). The geological conditions and fluid inclusions of the Zhuanshanzi gold deposit are the same as given above.

At the same time, C–H–O–S–Pb isotope studies on the Zhuanshanzi gold deposit indicate that the origin of the ore-forming fluids and metallogenic materials is closely related to magmatism. The metallogenic temperature shows that the Zhuanshanzi gold deposit is a medium- and low-temperature magmatic hydrothermal vein-typed deposit.

7. Conclusions

1. The Zhuanshanzi gold deposit lies in the eastern section of the Xingmeng orogenic belt. The gold veins are strictly controlled by a NW-oriented shear fault zone. The deposits can be divided into four mineralization stages, and the second and third metallogenic stages are the main metallogenic stage. The gold mine is a medium- and low-temperature magmatic hydrothermal deposit.

2. Fluid inclusions can be divided into four types: (i) type I gas–liquid two-phase inclusions, (ii) type II gas-rich fluid inclusions, (iii) type III single-liquid fluid inclusions, and (iv) type IV CO$_2$-containing three-phase fluid inclusions. Type I inclusions, especially type Ib inclusions, are present in all four stages of the ore deposits. Type II inclusions are present in the first three stages of mineralization. Type III inclusions are mostly secondary inclusions distributed along microfissures. Type IV inclusions are only present in the second and third ore-forming stages.

3. The Zhuanshanzi gold deposit is characterized by multiphase (stage) hydrothermal activation. The homogenization temperature and the metallogenic pressure of all the types of fluid inclusions in the four metallogenic stages show a decreasing trend, reflecting that the ore-forming fluid is generally cooled and demonstrating a decompression trend of evolution. Gas–liquid two-phase inclusions and CO$_2$-containing three-phase fluid inclusions are most commonly found in this mine, and the gas components are mainly H$_2$O and CO$_2$, indicating that the ore-forming system is a CO$_2$–H$_2$O–NaCl system. The homogenization temperature of the ore-forming fluid evolved from middle temperature to low temperature, and the temperature of the fluid was further reduced because
of the mixing of meteoric water during the late stage, as well as a lack of CO₂ components, and it evolved into a simple NaCl–H₂O hydrothermal system later. 4 The C–H–O–S–Pb isotope proved that the ore-forming fluids are mainly magmatic in the early stage, but abundant meteoric water mixed in the late stage; ore-forming materials came mainly from hypomagma and may have been influenced by the surrounding rocks. This suggested that the ore-forming materials were mainly magmatic hydrothermal deposits, with a small amount of crustal components. The fluid immiscibility and the CO₂ and CH₄ gases in the fluids played an active and important role in the precipitation and enrichment of Au during the different metallogenic stages.

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References


Fluid inclusions and isotope geochemistry


