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Genesis of the Zhilington gold deposit, Zhejiang Province, China: constraints from fluid inclusions and H–O–S–Pb isotope systematics

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The Zhilington gold deposit in Zhejiang Province, China, is located in the Qin-Hang metallogenic belt and hosted within Paleoproterozoic Badu Group gneiss. Geologic and isotopic analyses reveal that the gold mineralization is associated with a concealed biotite monzogranite (230 ± 1 Ma) and developed along the contact zone with gneiss. Ore-forming fluids, characterized by moderate–high temperatures (237–376°C) and low salinities (1.90–6.72 wt.% NaCl eqv), originated from a magmatic source and were later diluted by meteoric water, leading to gold precipitation. Pb isotopes indicate a crustal origin for lead, closely related to the Badu Group gneiss. The deposit likely formed in a late Triassic postcollisional extensional setting during the Indosinian orogeny involving the South China and North China blocks, suggesting an intrusion-related gold deposit (IRGD) model with excellent potential for further exploration.

KEYWORDS

fluid inclusions, H–O isotopes, S–Pb isotopes, zhilington gold deposit, South China

1 Introduction

Gold deposits are often found to be spatially associated with various granitoid bodies around the world. When detailed geochronological analyses are conducted, it becomes evident that these gold deposits and the granitoid intrusions believed to be productive often form at the same time (Cameron and Hattori, 1987; Goldfarb et al., 2005; Mair et al., 2011; Li et al., 2020; 2023; Liang et al., 2021; Yu et al., 2022). Chronology and stable isotope studies suggest that such intrusions, particularly I-type granitoids, play an essential role in the mineralization process, as they provide both the ore-forming fluids and the metals that contribute to the formation of gold deposits (Cameron and Hattori, 1987; Goldfarb et al., 2005; Mair et al., 2011; Liang et al., 2021; Cai et al., 2021; Cai et al., 2024). These gold deposits, often termed intrusion-related gold deposits (IRGDs), exhibit certain characteristics that overlap with those of orogenic gold deposits (Thompson et al., 1999; Lang et al., 2000). This overlap has caused some confusion in distinguishing the two types of

deposits. Orogenic gold deposits generally result from fluids and metals released from coeval intrusive magmas or through the metamorphic devolatilization of volcanic-sedimentary rocks (Goldfarb et al., 2001; Groves et al., 2020; Patten et al., 2020). Although IRGDs form through similar ore-forming fluids, they differ by exhibiting multiple styles of hydrothermal mineralization that are directly related to the emplacement and cooling of granitic plutons (Hart et al., 2004; Mernagh et al., 2007).

The Qin-Hang metallogenic belt in South China Block (SCB), which is a large Cu–Au polymetallic ore district that includes several large or giant Cu–Au deposits (e.g., Dexing porphyry Cu deposit, Yinshan epithermal Cu–Au–Pb–Zn–Ag deposit, Yongping porphyry Cu deposit, Jinshan orogenic Au deposit; Ni et al., 2005; Wang et al., 2012; Zhao et al., 2013; Wang et al., 2015). Recent studies have advanced the understanding of the region's tectonomagmatic and metallogenic evolution. The numerous deposits within the SCB are closely related to Indosinian and Yanshanian intrusive rocks. The Zhilongtou gold deposit, which exemplifies a lode gold deposit, was identified in 1965 by a geophysical exploration team from the Zhejiang Provincial Bureau of Geology and Mineral Resources. This study presents findings from microthermometric analyses of fluid inclusions (FIs), along with oxygen and hydrogen isotope analyses of quartz, sulfur, and lead isotope analyses of pyrite. The newly acquired data provide new insights into the origin of the ore fluids and metals elucidate the roles of fluid-rock interaction and fluid mixing in gold deposition, and improve our understanding of the genesis and mineralization model of the intrusion-related gold deposit in comparable geologic settings elsewhere.

2 Geological setting

The SCB is a geologically complex region in South China formed by the amalgamation of the Yangtze and Cathaysia blocks along the Jiangshan-Shaoxing Fault during the Neoproterozoic Jiangnan Orogeny. The region subsequently underwent significant continental rifting during the Nanhua Rift, which led to extensive sedimentation in the Nanhua Basin. In the late Paleozoic, the evolution of the Paleo-Tethys Ocean began to impact the SCB, and the Triassic Indosinian Orogeny further modified its tectonic framework. During this period, a major collision between the SCB and North China Block occurred along the Qinling-Dabie orogenic belt. During the late Mesozoic, the SCB experienced extensive tectono-magmatic activities, resulting in the formation of numerous large-scale metal deposits of W, Sn, Cu, Au, Mo, Pb, Zn, Ag, as well as a series of non-metallic deposits such as fluorite and pyrophyllite (Figure 1; Hua, 2005; Mao et al., 2011; Mao et al., 2013; Sun et al., 2012). Mao et al. (2007), Mao et al. (2008) summarized the mineral deposits in the region and divided the formation ages of Mesozoic deposits in South China into the following three stages: the Late Triassic (230–210 Ma) W–Sn–Nb–Ta deposits associated with peraluminous biotite granite, the Middle–Late Jurassic (170–150 Ma) porphyry–skarn Cu deposits (170–160 Ma) related to I-type or adakitic rocks and W–Sn polymetallic deposits (160–150 Ma) associated with highly fractionated granite, and the Early–Middle Cretaceous (134–80 Ma, with a peak mineralization period from 100 to 90 Ma) epithermal low-sulfidation Cu–Ag–Au deposits and W–Sn–Cu polymetallic deposits related to granite.

In recent years, numerous scholars have conducted extensive research on the tectonic-magmatic-sedimentary activities of the Indosinian orogeny in South China (e.g., Ren, 1984; Hsü et al., 1990; Guo, 1992; Wang et al., 2001; Zhou et al., 2006; 2015; Zhang et al., 2009; Bai et al., 2012). Wang et al. (2001) correlated the Triassic granites with the collision of the North China and South China blocks. Zhou et al. (2006) further suggested that the collision time can be inferred to be in the Early Triassic, consistent with the formation time of the Songma Suture. Zhang et al. (2009) argued that the near east-west trending fold belt in South China during the Indosinian period is closely related to the collision of the North–South blocks of the South China continent. The Middle to Late Triassic was a post-collisional environment, with Late Triassic tectonic deformation and magmatic rocks formed in the tectonic setting of the multi-block convergence of South China, North China, Indochina, and the Paleo-Pacific (Wang et al., 2013; Gao et al., 2017). This environment led to a series of Late Triassic low-temperature gold and lead-zinc deposits in the Southwestern Yangtze Block of South China, under the intraplate orogenic tectonic environment (Hu et al., 2017). The Indosinian orogeny caused folding and thickening of the Devonian–Triassic strata in the SCB, resulting in the widespread distribution of peraluminous, potassic-rich granites ($A/CNK > 1.00$, $K_2O > 3.0\%$) in the region (Guo et al., 2012; Wang et al., 2013). These granites have isotopic compositions similar to those of South China gneissic rocks (Jia, 1998; Chen and Jahn, 1998), and their formation may be related to the dehydration melting of muscovite and biotite minerals in the lower-middle crustal metamorphic rocks (Deng et al., 1995; Jia, 1998).

The Zhilongtou gold deposit is located in southwestern Zhejiang, Cathaysia Block. The basement rocks predominantly consist of the Proterozoic Badu, Longquan, and Chencai Groups, of which the Badu Group is the oldest known rock in the Cathaysia Block (ca. 2.5 Ga, Li et al., 2010; Shu et al., 2011; Yu et al., 2012). The cover lithologies are primarily composed of Cretaceous volcanic rocks, including the Dashuang, Gaowu, Xishantou, Chawan, Jiuliping, Guantou, Chaochuan, and Fangyan Groups (Bureau of Geology and Mineral Resources of Zhejiang Province, 1989). The volcanic rocks mainly belong to a calc-alkaline series, consisting primarily of andesite, dacite, and rhyolite. These rocks range from ~140 to 110 Ma for the older group and from 110 to 85 Ma for the younger group (Lapierre et al., 1997; He and Xu, 2012). Both volcanic and intrusive rocks are distributed along several regional faults, which are oriented NE–SW, NNE–SSW, and NW–SE.

3 Ore deposit geology

The Zhilongtou gold deposit has a long mining history, dating back to the Tang Dynasty. Lead-zinc and molybdenum deposits were subsequently discovered in the area. The Zhilongtou deposit proved reserves of 26.1 t Au (average grade = 11 g/t) and 594 t Ag (average grade = 255 g/t; Ni et al., 2012). Pb–Zn and Mo mineralization with resources of 0.24 Mt Pb–Zn at an average grade of 2% and more than 0.06 Mt Mo at an average grade of 0.07% Mo. The abundance and diversity of resources have attracted significant attention from scholars and experts. Re–Os dating of molybdenite constrains the Mo mineralization at 113.0 ± 2.4 Ma and Ar–Ar dating on sphalerite shows that the Pb–Zn mineralization likely

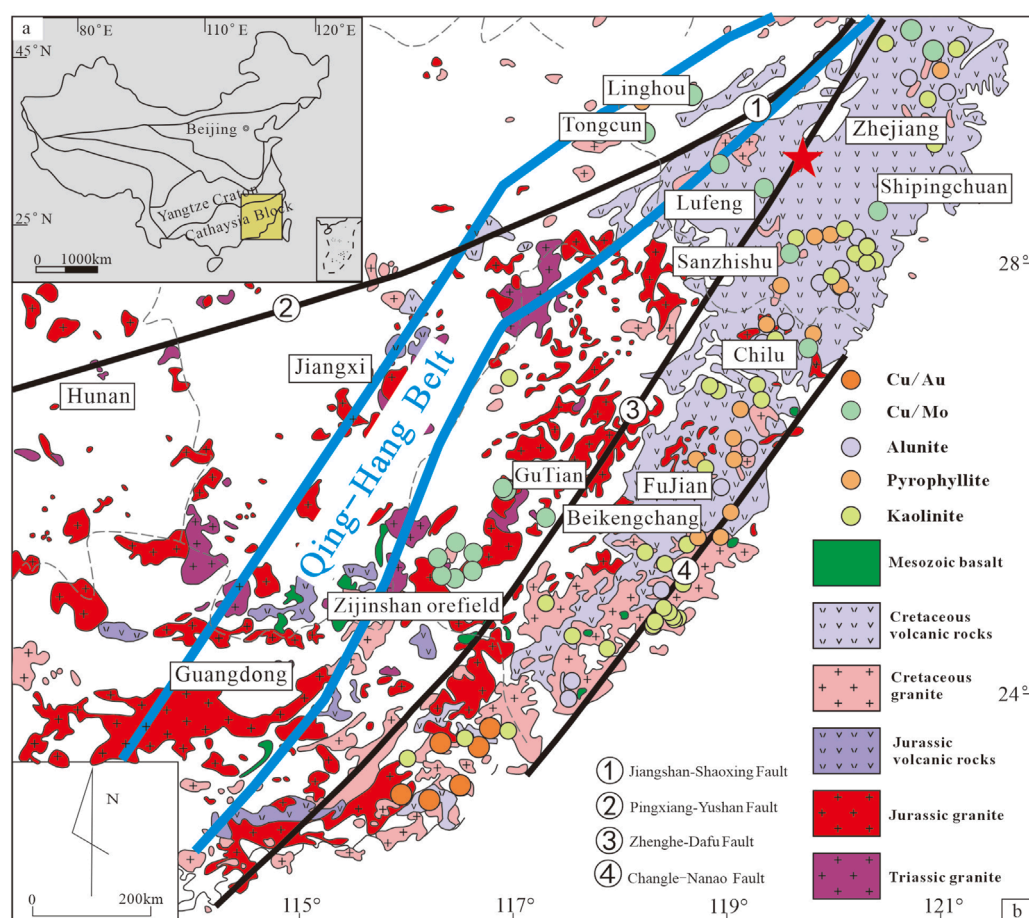


FIGURE 1

(a) Tectonic sketch map of SE China and (b) geologic map showing the distribution of Mesozoic granitoids and significant deposits in the southeastern coastal metallogenic belt (modified after Zhou et al., 2006; Li et al., 2016; Liu et al., 2018).

formed at 113.9 ± 4.0 Ma (Wang, 2014). The Au mineralization age can be constrained at 230 ± 2.0 Ma using hydrothermal rutile and monazite U-Pb ages (Liu et al., 2025a). The spatial relationships between Au, Pb-Zn, and Mo mineralization in the Zhilintou area are characterized by distinct zonation and structural control. The Mo mineralization is primarily associated with porphyry Mo deposits in the central and deeper parts of the system, hosted within granite porphyry and biotite-plagioclase gneiss. The Au-Ag mineralization occurs in the shallower levels and peripheral areas, hosted by late Paleoproterozoic gneiss and controlled by concealed faults associated with the Huafengjian volcanic edifice. The Pb-Zn mineralization is distributed within the Huafengjian caldera, hosted by rhyolite and gneiss. The Badu Group consists of biotite-plagioclase gneiss, mica schist, and migmatite. The rocks are characterized by complex deformation and metamorphism, intense migmatization, and belong to the amphibolite-facies zone. The Dashuang Group comprises mainly medium-to coarse-grained quartz sandstone, rhyolitic tuff, and rhyolitic breccia. LA-ICP-MS zircon U-Pb dating results indicate that the Dashuang Group formed between 127 and 110 Ma (Ni et al., 2012).

The tectonic structures in the Zhilintou area can be categorized primarily into volcanic edifices and local faults, both of which

play crucial roles in the mineralization processes within the mining area and the spatial distribution of orebodies. The local faults primarily display E-W and NE-SW orientations, which are correlated with the majority of gold deposits. By contrast, most NE-SW faults intersect the ore bodies, suggesting that their formation occurred subsequent to the mineralization event. A network of circular and radial faults around the Huafengjian volcanic edifice has developed in the vicinity, influencing the distribution of vein-type lead-zinc mineralization. This edifice manifests as an elliptical depression trending N-S, encompassing an area of 2 km^2 . The central volcanic vent is characterized by the presence of rhyolitic volcanoclastic rocks, rhyolite porphyry, and cryptoexploded brecciated lead-zinc mineralization, which penetrate significantly into the molybdenum-bearing granite porphyry.

In addition to the Cretaceous Dashuang volcanic rocks, the area features coeval granite porphyry (~ 110 Ma, Ni et al., 2012; Zeng et al., 2012; Liu et al., 2023) and rhyolite porphyry. The granite porphyry is located 700 m beneath the surface and is primarily composed of quartz, K-feldspar, plagioclase, and biotite, with magnetite, zircon, and apatite as accessory minerals. There is apparent Mo mineralization inside, closely related to the formation

of molybdenum orebodies between 50 and 500 m depth in the mining area. In addition, the mining area has three stages of volcanic magmatic activity. These consist of (i) Triassic K-feldspar granite (230 ± 1 Ma; Liu et al., 2025b) and biotite monzogranite (230 ± 1 Ma; Liu et al., 2025b), neither of which are exposed at the surface. The biotite monzogranite is exposed at 420 m depth and is closely related to the formation of gold; (ii) the early Cretaceous altered quartz monzonitic porphyry (137 ± 1 Ma; Liu et al., 2023); (iii) the late Cretaceous felsite (98 ± 1 Ma; Hua and Liu, 2022) and the quartz monzonite (97 ± 1 Ma; Liu et al., 2023), both of which are concealed vein rocks, and the two types of rocks cut through the biotite monzogranite, gold and molybdenum orebodies.

4 Characteristics of the mineralization

Twelve orebodies have been identified in the mining area, occurring within the Badu Group and concealed beneath the volcanic rocks. The orebodies are located north of the Huafengjian volcanic edifice, with a general strike nearly E-W and a dip toward the SW-SE. The strike extends over 1,400 m, and the dip extends vertically to approximately 200 m. These orebodies can be divided into eastern, middle, and western sections by the F1 and F42 faults (Figures 2, 3). The western section contains three major orebodies: V-1, V-2, and V-3; the middle section contains seven major orebodies: III-1, III-2, VIII, IV-1, IV-2, IV-4, and IV-5; and the eastern section contains one primary orebody, IV-6. The VI orebody is also present within the F1 fault zone and is fault-controlled.

The gold orebodies predominantly occur in stockwork, vein-like, and lens-shaped forms within the Badu Group's biotite-plagioclase gneisses. The primary minerals are argentite, electrum, pyrite, sphalerite, galena, and magnetite, with secondary minerals including native silver, acanthite, chalcocopyrite, and trace amounts of native gold, telluride, and manganese sulfides. The gangue minerals are mainly quartz, sericite, chalcedony, and minor rhodochrosite. Some accessory minerals, such as rutile and monazite, are also present (Table 1; Figures 4, 5).

On the basis of field observations, hand samples, microscopic cross-cutting relationships, and mineral assemblages, the mineralization of the Zhilingtou gold deposit can be divided into three stages:

- i. Pyrite-Quartz Stage (stage I): This stage represents the early phase of gold mineralization, with a mineral assemblage primarily consisting of quartz and minor pyrite. The quartz is predominantly milky-white to gray, exhibiting fine-grained textures and occurring in vein-like and stockworks alongside sulfides. Pyrite, typically coarser in grain size, often appears as aggregates (Figures 4a,b).
- ii. Polymetallic sulfide -Quartz Stage (Stage II): This stage marks the main phase of gold mineralization, characterized by an assemblage of silicified quartz, pyrite, sericite, sphalerite, galena, and minor chalcocopyrite and calcite. In this stage, pyrite is altered and disseminated throughout the quartz as impregnation textures (Figures 4c-h).
- iii. Quartz-Calcite Stage (Stage III): The final stage of hydrothermal evolution is characterized by a scarcity of sulfide

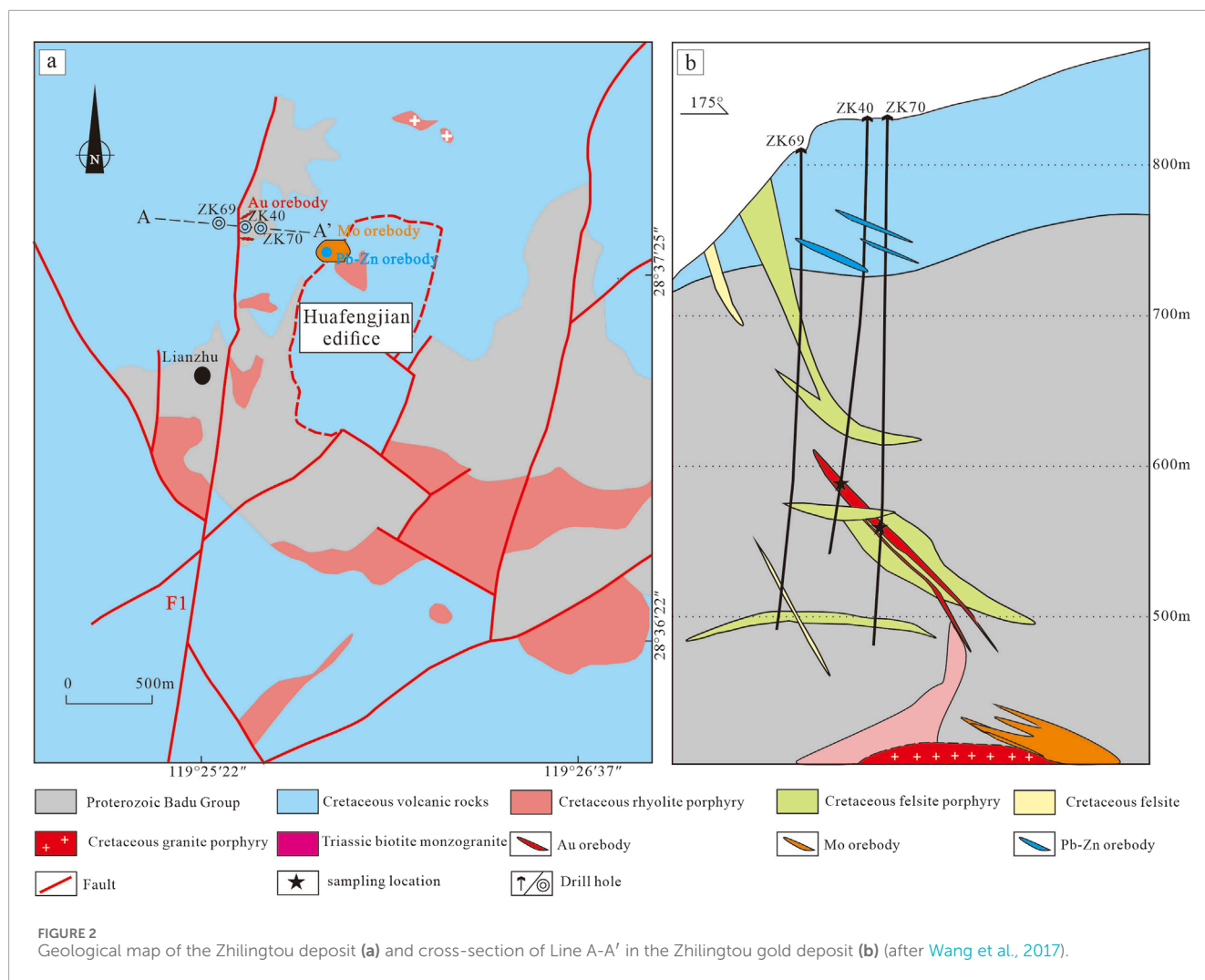
minerals and is dominated by quartz and calcite. Occasional pyrite grains with altered morphologies are also observed. The gold grades in this stage are generally low (Figures 4e,i).

The surrounding rocks of the gold orebodies exhibit intense alteration, primarily silicification, sericitization, chloritization, and carbonation (Figure 6). The orebodies are hosted within strongly silicified zones, with silicification most closely related to the ore formation process (Figures 6a,b). During stage II of mineralization, hydrothermal fluids infiltrated and replaced the host rocks along structural fractures and minor faults, forming silicified quartz veins. These veins are typically milky-white to smoky gray or dark gray, with gold particles disseminated in impregnation textures within smoky or dark gray quartz vein fractures and interstitial spaces. The zones of intense silicification tend to correlate with higher gold grades and more abundant gold deposition. In the silicified quartz veins of Stage III, sulfides and gold are scarce, and the quartz is typically milky-white to transparent with coarser grain sizes, reflecting a weakened silicification process. Hydrothermal activity has replaced plagioclase with sericite, which appears as microsheets. Locally, alteration remnants and pseudomorphs of plagioclase and k-feldspar are observed. Dark minerals such as biotite are typically replaced by chlorite, which is often replaced by sericite (Figures 6c-f). The relationship between sericitization and mineralization is relatively weak. Carbonatization is primarily observed during Stages II and III, with the majority occurring in Stage III. It manifests predominantly as delicate calcite veins or quartz-calcite veinlets that cut through the orebodies and surrounding rocks (Figures 6b,f). The widespread occurrence of these veins signifies that hydrothermal activity has entered its late stages.

5 Sampling and analytical methods

5.1 Fluid inclusion analysis

The samples selected from the Zhilingtou gold deposit for fluid inclusion analysis were obtained from ZK404 (Figure 2b). These samples were subsequently prepared into doubly polished thin sections 0.20–0.30 mm thick for microthermometric analysis. Before analysis, the samples were immersed in acetone for 3–4 h and then dried. Fluid inclusion petrography was conducted at the Institute of Mineral Resources, Chinese Academy of Geological Sciences (CAGS), Beijing, via a Zeiss Axiolab microscope. This study focused on primary FIs randomly or regularly distributed along growth bands or healed fractures within ore-bearing quartz and calcite crystals, although they may also occur individually. Secondary FIs, typically observed as trails that cross crystal boundaries, are also present locally (Lu et al., 2004; Ouyang et al., 2014). Microthermometric measurements were performed via a Linkam THMSG-600 heating-freezing stage, with temperatures ranging from -196°C to 600°C . The stage was calibrated at temperatures of -56.6 , -10.7 , and 0.0°C , using synthetic FIs provided by FLUID INC. The precision of the measurements was $\pm 0.1^{\circ}\text{C}$ for temperatures below 31°C and $\pm 2^{\circ}\text{C}$ for temperatures above 300°C . The data were processed via the MacFlincon software (Brown and



Hagemann, 1995). The salinity of aqueous FIs was calculated on the basis of Bodnar. (1993) for the NaCl-H₂O system, whereas the salinity of daughter-mineral-bearing FIs was estimated via Bodnar. (1994).

5.2 H–O isotopes

Hydrogen–oxygen isotope analyses were conducted on quartz samples from Stages I and II and calcite samples from Stage III, which were processed at CAGS, Beijing, China. Hydrogen isotope analysis was carried out via the zinc reduction method. Initially, the samples were dried at low temperatures to remove adsorbed water and secondary inclusions. The samples were then heated to 600°C to extract the water from primary FIs, after which the hydrogen in the water was replaced with zinc. The resulting hydrogen gas (H₂) was analysed via mass spectrometry (Friedman, 1953).

For oxygen isotope analysis, 20 mg of quartz separates were reacted with BrF₅ to release oxygen (Clayton and Mayeda, 1963). The oxygen was then converted to CO₂ on a platinum-coated carbon rod for isotope measurement. The values of $\delta^{18}\text{O}_{\text{quartz}}$ and $\delta\text{D}_{\text{H}_2\text{O}}$ are expressed relative to Vienna Standard Mean Ocean

Water (V-SMOW), with analytical uncertainties (1 σ) of $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}_{\text{quartz}}$ and $\pm 1\text{‰}$ for $\delta\text{D}_{\text{H}_2\text{O}}$.

5.3 S–Pb isotope analysis

For whole-rock sulfur isotope analysis, 24 pyrite samples were collected from the drill hole (Figure 2b). To ensure a purity of at least 99%, the pyrite mineral separates were purified by hand under a microscope. With the conventional combustion method, sulfur isotope analysis was conducted at the Beijing Research Institute of Uranium Geology (CNNC) (Robinson and Kusakabe, 1975). The sulfur isotopic compositions of the sulfide minerals were measured, and the results are reported per mil relative to the Vienna Canon Diablo Troilite (V-CDT) standard, with an analytical uncertainty (1 σ) of $\pm 0.2\text{‰}$ for $\delta^{34}\text{S}$.

In situ lead isotope analyses of sulfide were performed on a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Bremen, Germany) equipped with a Geolas HD excimer ArF laser ablation system (Coherent, Göttingen, Germany) at the Wuhan Sample Solution Analytical Technology Co., Ltd, Hubei, China. In the laser ablation system, helium was used as the carrier gas for the ablation

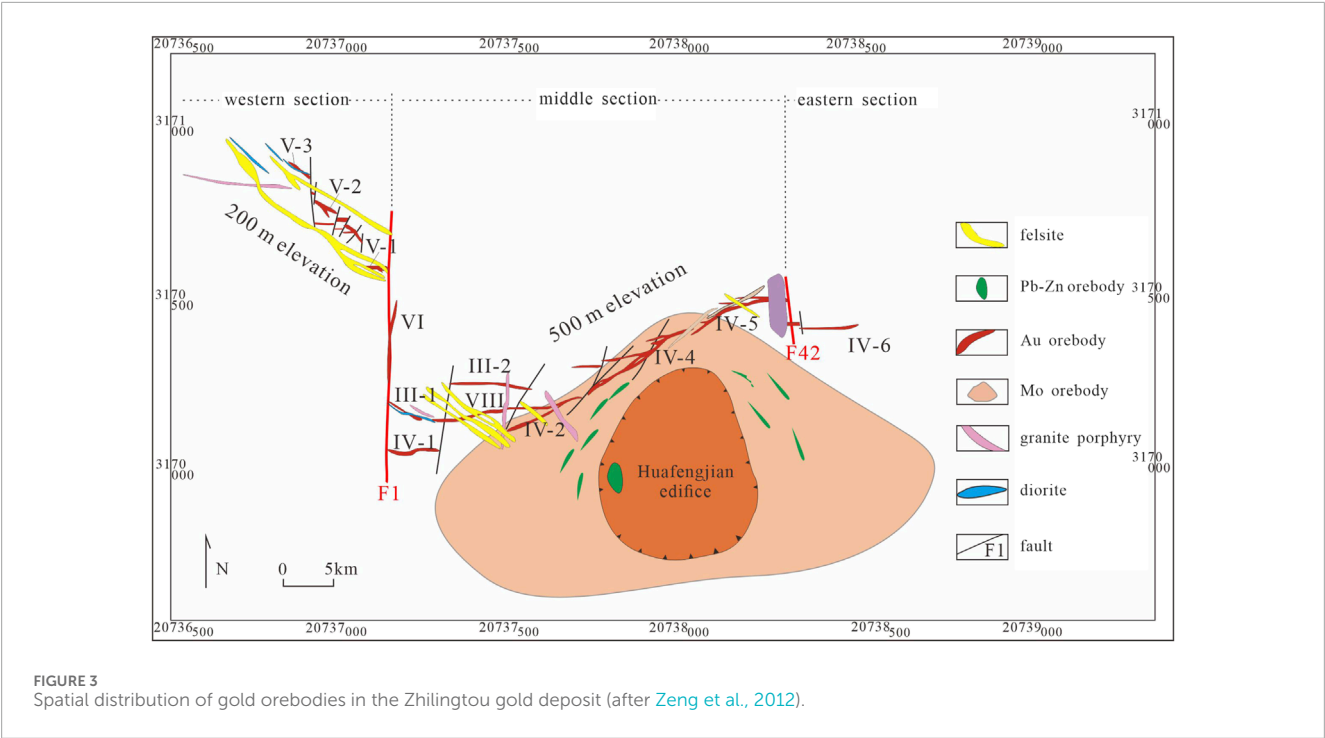


TABLE 1 Characteristics of the gold orebodies in the Zhilongtou gold deposit.

Mineralization		Western section			Middle section							Eastern section	VI
Gold orebody		V-1	V-2	V-3	III-1	III-2	IV-1	IV-2	IV-4	IV-5	VIII	IV-6	
Ore type		Stockwork, vein-like and lens-shaped											
Attitude of ore body	dip direction	170–199	187–253	210–300	160–179	170–189	170–190	150	140–170	148–192	180–200	S-SW	NE
	dip angle	45–64	50–85	39–78	46–56	32–65	36–50	46	41–51	31–65	53–62	36–57	70
Dimension of the ore body	Length (m)	85	190	80	365	112	127	35	360	225	133	175	160
	Thickness (m)	3.54	4.46	2.01	3	1.95	2.9	2.19	4.68	3.7	3.02	3.89	~1
Grade	Au (g/t)	12.06	18.82	12.41	40.12	11.88	8.71	8.88	9.46	5.41	15.47	4.858	14.6
	Ag (g/t)	187.05	232.95	205.79	589.23	241.03	68.88	24.22	377.1	204.38	109.05	182.76	78.57
Metal mineral		argentite, electrum, pyrite, sphalerite, galena, magnetite, native silver, acanthite, chalcocopyrite, native gold, telluride											
Gangue mineral		quartz, calcite, sericite, chlorite											
Alteration		silicification, sericitization, chloritization, carbonation											

cell and was mixed with argon (makeup gas) after the ablation cell. The spot diameter ranged from 44 to 90 μm dependent on the Pb signal intensity. The pulse frequency ranged from 4 to 10 Hz, but the laser fluence remained constant at $\sim 5\text{ J}/\text{cm}^2$. A new signal-smoothing and mercury-removing device was used downstream from the sample cell to efficiently eliminate the short-term variation of the signal and remove the mercury from the background and sample aerosol particles (Hu et al., 2015). The Neptune Plus

was equipped with nine Faraday cups fitted with $10^{11}\Omega$ resistors. Isotopes ^{208}Pb , ^{207}Pb , ^{206}Pb , ^{204}Pb , ^{205}Tl , ^{203}Tl , and ^{202}Hg were collected in Faraday cups in static mode. The mass discrimination factor for Pb was determined using a Tl solution nebulized at the same time as the sample using an Aridus II desolvating nebulizer. The mass fractionation of Pb isotopes was corrected by $^{205}\text{Tl}/^{203}\text{Tl}$ with the exponential law. Note that the optimized values of $^{205}\text{Tl}/^{203}\text{Tl}$, which were calibrated from measuring 2 Pb

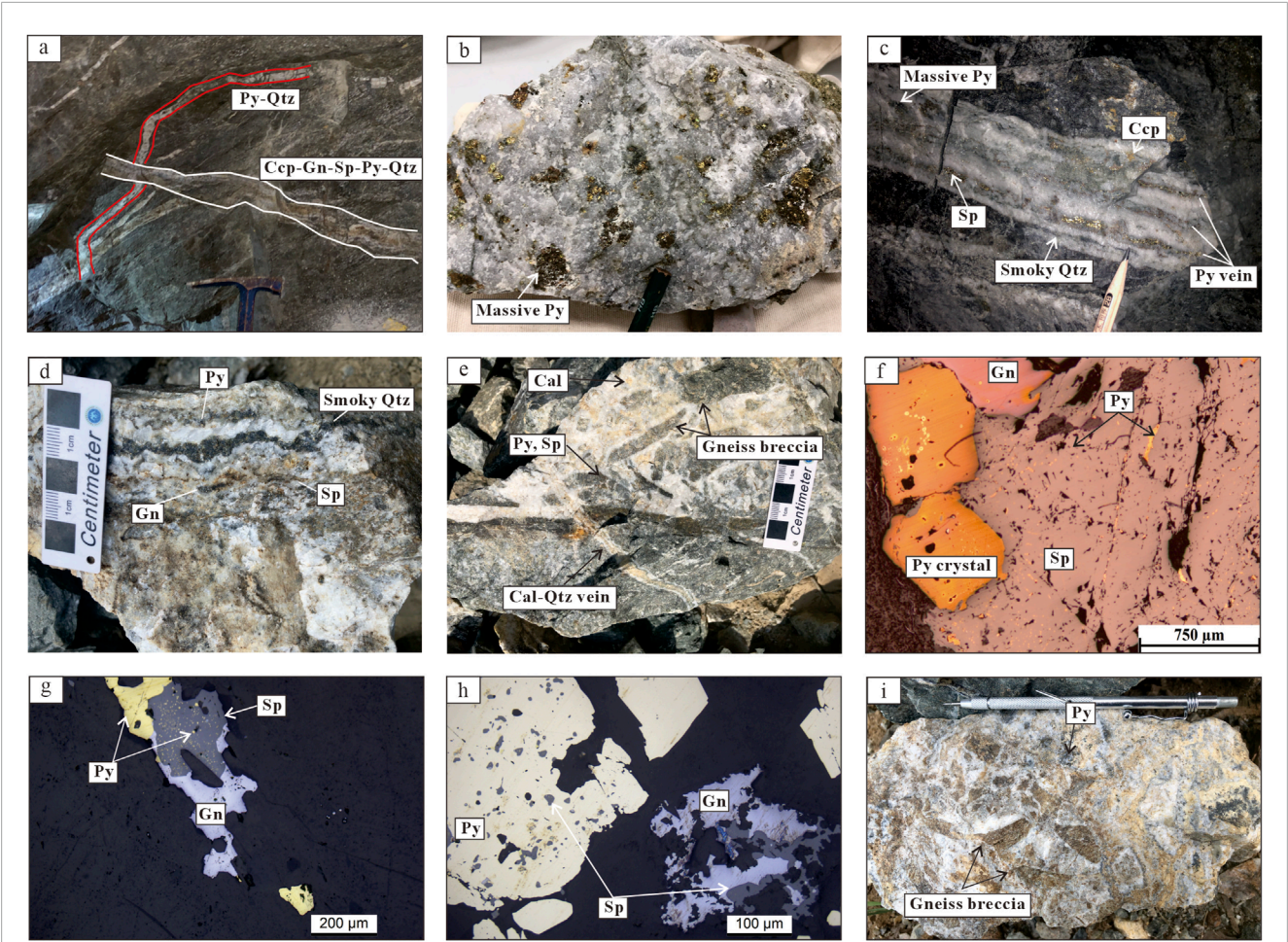
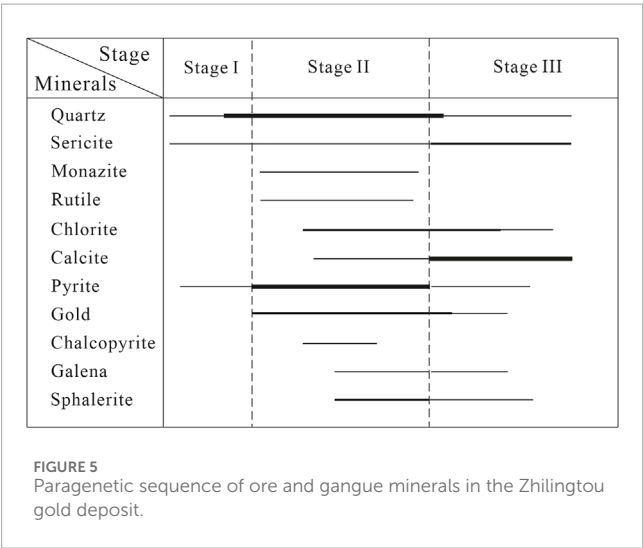


FIGURE 4 Ore crosscutting relationships and gold distribution characteristics of the Zhilingtou deposit. (a) Chalcopyrite + galena + sphalerite + pyrite + quartz vein (Stage II) cut pyrite + quartz vein (Stage I); (b) Pyrite occurs in quartz veins as massive aggregates; (c,d) Chalcopyrite + sphalerite + massive and vein-type pyrite occur in the smoky quartz vein (Stage II); (e) Calcite-quartz veins (Stage III) show calcite alteration and gneiss breccia; (f-h). Microscopic images show that pyrite formed simultaneously with sphalerite and galena; (i) Calcite-quartz veins (Stage III) develop calcite alteration, gneiss breccia, and pyrite crystals. Abbreviations: Cal: calcite; Qtz: quartz; Py: pyrite; Sp: sphalerite; Gn: galena; Ccp: chalcopyrite.



isotope standards, MASS-1 (USGS) and Sph-HYLM (sphalerite, an in-house standard), replaced the natural Tl isotopic composition for the mass fractionation correction of Pb isotopes. The ^{202}Hg signal was used to correct the remaining ^{204}Hg interference on ^{204}Pb , using the natural $^{202}\text{Hg}/^{204}\text{Hg}$ ratio (0.2301). In addition, the mass fractionation of $^{204}\text{Hg}/^{202}\text{Hg}$ was corrected by the $^{205}\text{Tl}/^{203}\text{Tl}$ normalization. In this case, we assumed identical mass fractionation factors for $^{204}\text{Hg}/^{202}\text{Hg}$ and $^{205}\text{Tl}/^{203}\text{Tl}$. Sph-HYLM was used to monitor the precision and accuracy of the measurements after ten sample analyses, over the entire period of analysis. The obtained accuracy is estimated to be equal to or better than $\pm 0.2\%$ for $^{208}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{206}\text{Pb}/^{204}\text{Pb}$ compared to the solution value by MC-ICP-MS, with a typical precision of 0.4% (2σ). More details on the *in situ* Pb isotope analytical method were described in Zhang et al. (2016). All data reduction for the MC-ICP-MS analysis of Pb isotope ratios was conducted using “Iso-Compass” software (Zhang et al., 2020).

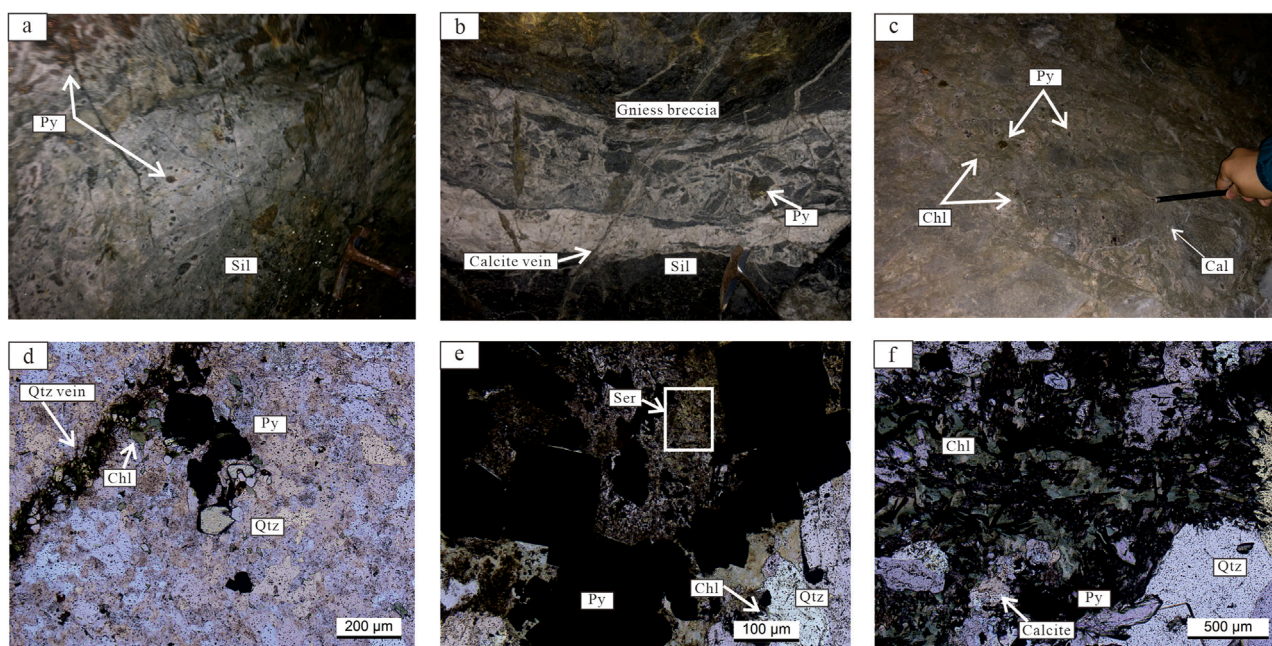


FIGURE 6
Representative photographs and photomicrographs showing ore-related hydrothermal alterations. (a,b) Silicification developed in the Stage I; (c-f), Sericitization, chloritization and carbonatization developed in the Stages II and III. Abbreviations: Py, pyrite; Sil, Silicification; Chl, chloritization; Ca, calcite; Qtz, quartz.

5.4 Fire assay analysis

The Fire Assay Analysis method adds a flux composed of lead oxide, sodium carbonate, borax, silica sand, and other reagents to the sample, followed by silver free of gold. The mixture is then subjected to high-temperature fusion and cupellation to form gold-silver beads. The gold-silver beads are then dissolved with diluted nitric acid and placed in a microwave digestion system to remove silver. Next, concentrated hydrochloric acid was added to dissolve the gold further. After digestion, the solution was cooled, diluted to a known volume with deionized water, and analyzed via an Agilent 5,110 inductively coupled plasma optical emission spectrometer (ICP-OES). The precision is controlled with a relative deviation of <10%, and the accuracy is controlled with a relative error of <6%. The instrument's calibration curve is constructed by matching standard solutions. The detection range was 0.001–10 g/t.

6 Results

6.1 Fluid inclusions

The studied inclusions have consistent vapor-to-total ratios, and the similar homogenization temperatures among neighboring inclusions indicate that they were captured as a homogeneous phase with minimal post-entrapment alteration (Chi and Lu, 2008).

In the Zhilongtou gold deposit, the ore-stage quartz contains abundant primary elliptical negative crystal-shaped FIs. FIs in Stage I are mainly 2–8 μm, with a few exceeding 10 μm; Stage II FIs are mainly 4–10 μm, with some below 3 μm, while in Stage III, the size of FIs is mostly 2–10 μm. Based on the vapor-liquid ratio, phase,

and composition of FIs at room temperature (23°C), these inclusions can be categorized into four types (Roedder, 1984; Lu et al., 2004), i.e., two-phase FIs (L-type), gas-rich FIs (V-type), CO₂-bearing two-phase/three-phase inclusions (C-type), and three-phase FIs containing daughter minerals (S-type). L-type inclusions are mainly composed of a liquid phase and gas bubbles, with a gas phase ratio of approximately 10%–30%. V-type inclusions are mainly composed of a liquid phase and gas bubbles, with relatively high gas-liquid ratios, generally >50%. The overall color of these types of inclusions tends to be dark, indicating their low-density characteristics. C-type inclusions are composed of the liquid phase of H₂O and a two-phase gas-liquid mixture of CO₂ at room temperature, with a wide range of gas-liquid ratios of CO₂, approximately 40%–90%. S-type inclusions mainly consist of gas bubbles, solid daughter minerals, and a liquid phase. The daughter minerals are generally cubic, colorless, transparent, and presumed to be NaCl crystals, accounting for approximately 10%–30% of the volume.

6.2 Microthermometry

The samples were collected from the V-1 orebody of the western section and the III-1 orebody of the middle section. L-type and V-type inclusions are well developed, C-type can be seen in the western section, and S-type FIs are developed more in the middle section (Figure 7).

For the middle section, 210 FIs measurements from ore-stage quartz were performed (Table 2; Figures 7a–c). In stage I, L-type inclusions homogenized into liquid completely at 273°C–352°C (avg. 314°C), ice melting temperatures are −3.2 to −2.1°C, corresponding to salinities of 3.53–5.09 wt.% NaCl eqv (avg.

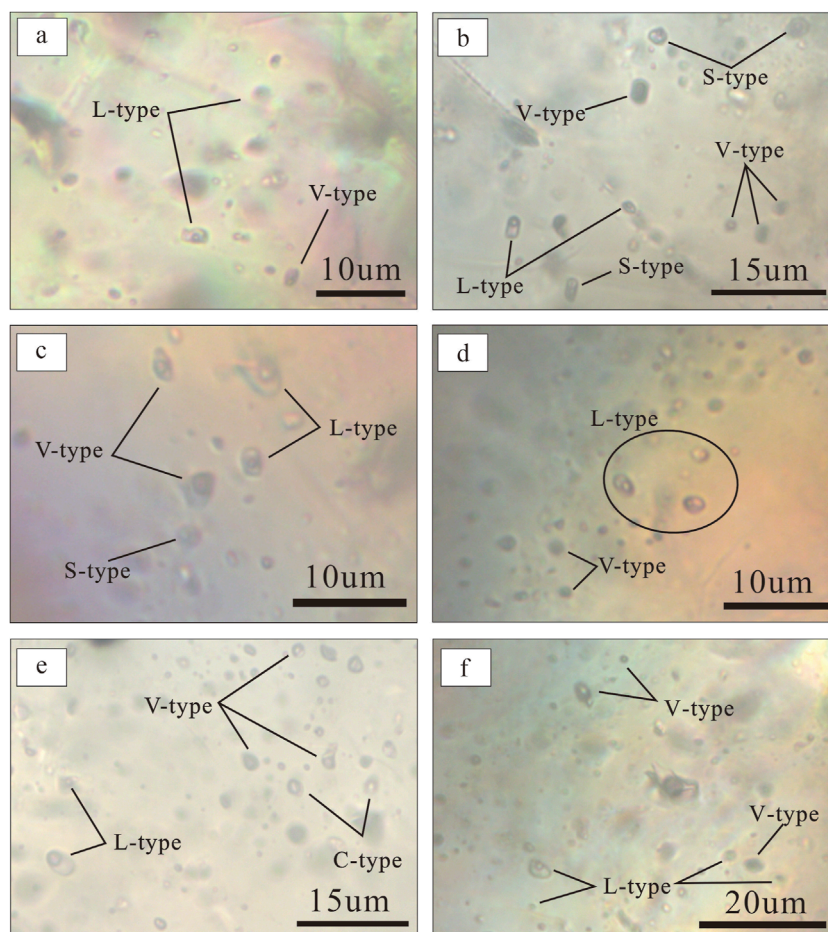


FIGURE 7

Photomicrographs of representative primary fluid inclusions in auriferous quartz from the middle (a–c) and western (d–f) sections of the Zhilingtuo gold deposit.

4.54 wt.% NaCl eqv). V-type inclusions homogenized into gas completely at 293°C–367°C (avg. 330°C), ice melting temperatures are –2.6 to –1.8°C, corresponding to 3.05 to 4.32 wt.% NaCl eqv (avg. 3.84 wt.% NaCl eqv). S-type inclusions have their daughter minerals melted into liquid when heated to 295.3°C–376.8°C, homogenized into liquid completely at 300°C–376°C (avg. 346°C), corresponding to salinities of 37.78–44.92 wt.% NaCl eqv (avg. 40.59 wt.% NaCl eqv). In Stage II, L-type inclusions homogenized into liquid completely at 273°C–326°C (avg. 304°C), ice melting temperatures are –4.6 to –3.2°C, corresponding to 5.25 to 7.30 wt.% NaCl eqv (avg. 6.17 wt.% NaCl eqv). V-type inclusions homogenized into gas completely at 262°C–319°C (avg. 294°C), ice melting temperatures are –2.8 to –2.1°C, corresponding to 3.53 to 4.63 wt.% NaCl eqv (avg. 4.08 wt.% NaCl eqv). C-type inclusions homogenized at 276°C–328°C (avg. 304°C); solid CO₂ melted at approximately –58°C, and CO₂ clathrates melted at < 10°C, corresponding to salinities of 2.22–5.05 wt.% NaCl eqv (avg. 3.93 wt.% NaCl eqv). S-type inclusions have their daughter minerals melted into liquid when heated to 264.2°C–338.2°C, and homogenized into liquid completely at 298°C–338°C (avg. 314°C), corresponding to salinities of 35.57–41.31 wt.% NaCl eqv (avg. 38.17 wt.% NaCl eqv). In Stage III, L-type inclusions homogenized into liquid completely

at 234°C–263°C (avg. 249°C), ice melting temperatures are –1.3 to –0.8°C, corresponding to salinities of 1.39–2.23 wt.% NaCl eqv (avg. 1.82 wt.% NaCl eqv). V-type inclusions homogenized into gas completely at 248°C–280°C (avg. 262°C), and ice melting temperatures are –2.5 to –1.6°C, corresponding to salinities of 2.73–4.17 wt.% NaCl eqv (avg. 3.47 wt.% NaCl eqv).

For the western section, we obtained temperature and salinity data on 141 inclusions in the three ore-stage quartz (Table 2; Figures 7d–f). In Stage I, the L-type inclusions homogenized into liquid completely at 237°C–316°C (avg. 271°C), and ice melting temperatures are –4.2 to –1.2°C, corresponding to salinities of 2.06–6.72 wt.% NaCl eqv (avg. 4.75 wt.% NaCl eqv). V-type inclusions homogenized into gas completely at 251°C–308°C (avg. 279°C), and ice melting temperatures are –2.0 to –1.1°C, corresponding to salinities of 1.90–3.37 wt.% NaCl eqv (avg. 2.75 wt.% NaCl eqv). In Stage II, L-type inclusions homogenized into liquid completely at 200°C–251°C (avg. 222°C), and ice melting temperatures are –3.6 to –1.0°C, corresponding to salinities of 1.73–5.85 wt.% NaCl eqv (avg. 4.35 wt.% NaCl eqv). V-type inclusions homogenized into gas completely at 190°C–278°C (avg. 232°C), and ice melting temperatures are –2.6 to –1.2°C, corresponding to salinities of 2.06–4.32 wt.% NaCl

TABLE 2 Microthermometric data of fluid inclusions from hydrothermal quartz in the Zhilington deposit.

Mineralization	Stage	Host mineral	Inclusion type	Size (μm)	Tm-ice (°C)	Tm-halite (°C)	Tm- _{CO2-v} (°C)	Tm-clath (°C)	Th-total (°C)	Salinity (wt% nacl eqv)	
Middle section	I	Quartz	L-type (30)	2–12	−3.2~−2.1	-			273–352	3.53–5.09	
			V-type (28)	1–10	−2.6~−1.8	-			293–367	3.05–4.32	
			S-type (13)	2–10	-	295.3–376.8			300–376	37.78–44.92	
	II		L-type (34)	1–12	−4.6~−3.2	-			273–326	5.25–7.30	
			V-type (21)	3–10	−2.8~−2.1	-			262–319	3.53–4.63	
			S-type (18)	2–8	-	264.2–338.2			298–338	35.57–41.31	
			C-type (16)	1–10	-	-	−58.8~−57.1	7.4–8.9	276–328	2.22–5.05	
	III		Calcite	L-type (28)	2–8	−1.3~−0.8	-			234–263	1.39–2.23
				V-type (22)	2–10	−2.5~−1.6	-			248–280	2.73–4.17
Western section	I	Quartz	L-type (25)	2–12	−4.2~−1.2	-			237–316	2.06–6.72	
			V-type (18)	3–10	−2.0~−1.1	-			251–308	1.90–3.37	
	II		L-type (25)	2–10	−3.6~−1.0	-			200–251	1.73–5.85	
			V-type (19)	2–10	−2.6~−1.2	-			190–278	2.06–4.32	
			C-type (18)	2–8	-	-	−58.7~−58.1	6.9–7.8	210–280	4.32–5.94	
	III	Calcite	L-type (20)	2–10	−1.8–1.2	-			180–227	2.06–3.05	
			V-type (16)	3–6	−1.8~−1.1	-			167–230	1.90–3.05	

eqv (avg. 3.28 wt.% NaCl eqv). C-type inclusions homogenized at 210°C–280°C (avg. 244°C), solid CO₂ melted at approximately −58°C, and CO₂ clathrates melted at < 8°C, corresponding to salinities of 4.32–5.94 wt.% NaCl eqv (avg. 5.27 wt.% NaCl eqv). In Stage III, L-type inclusions homogenized into liquid completely at 180°C–227°C (avg. 201°C), and ice melting temperatures are −1.8 to −1.2°C, corresponding to salinities of 2.06–3.05 wt.% NaCl eqv (avg. 2.63 wt.% NaCl eqv). V-type inclusions homogenized into gas completely at 190°C–278°C (avg. 202°C), and ice melting temperatures are −1.8 to −1.1°C, corresponding to salinities of 1.90–3.05 wt.% NaCl eqv (avg. 2.52 wt.% NaCl eqv).

6.3 H-O stable isotopes

In this study, hydrogen-oxygen isotope analysis of FIs was conducted on single quartz minerals from the III-1 orebody in the middle section and the V-1 orebody in the western section, far from volcanic structures. The results are summarized in Table 3. The fluid δ¹⁸O_{H₂O-SMOW} values were calculated based on the homogenization temperatures of the FIs and the mineral-water oxygen isotope equation in the section on fluid inclusion microthermometry. The oxygen isotope equilibrium equation between quartz and water, as proposed by Clayton et al. (1972), is used: 10³lnα_{quartz-water} = 3.38 ×

10⁶/T² - 3.40. Since the homogenization temperature of FIs is typically lower than the accurate mineralization temperature, the maximum homogenization temperature of the inclusions is used as an approximation for calculating the temperature (T value).

For the middle section of gold mineralization, the δD_{V-SMOW} values from Stage I to Stage III are −81~−68‰, −80~−62‰, and −60~−57‰, respectively, and the δ¹⁸O_{H₂O-SMOW} values are 2.6–5.0‰, −0.7–1.5‰, and −1.8~−1.2‰, respectively. For the western section, the δD_{V-SMOW} values from Stage I to Stage III are −82~−74‰, −81~−65‰, and −79~−61‰, respectively, and the δ¹⁸O_{H₂O-SMOW} values are −0.5–1‰, −3.1~−2.4‰, and −9.2~−7.3‰, respectively.

6.4 S-Pb isotopes

The δ³⁴S_{CDT} values for the middle section range from 3.30‰ to 7.67‰ (average of 6.39‰), whereas the δ³⁴S_{CDT} values for the western section range from 3.16‰ to 6.26‰ (average of 4.89‰). The overall δ³⁴S_{CDT} values are positive and follow a symmetric distribution pattern (Table 4; Figure 8).

Table 5 lists the *in situ* Pb isotope results. Nine gold ore samples were analyzed, with the following isotope ratios: ²⁰⁶Pb/²⁰⁴Pb ranging from 17.560 to 18.075, ²⁰⁷Pb/²⁰⁴Pb ranging from 15.639 to 15.686,

TABLE 3 Oxygen and hydrogen isotope data for quartz from the Zhilingtou gold deposit.

Sample	Mineralization stage	Sample no.	Mineral	$\delta^{18}\text{O}_{\text{V-SMOW}}(\text{‰})$	$\delta\text{D}_{\text{V-SMOW}}(\text{‰})$	T(°C)	$\delta^{18}\text{O}_{\text{H}_2\text{O-SMOW}}(\text{‰})$
Middle section	I	420-5	quartz	7	−78	380	3.3
		420-5-1		6.9	−80		3.2
		420-5-2		6.3	−68		2.6
		420-5-3		8.7	−81		5
	II	420-6		6.6	−80	340	1.4
		420-6-1		6.7	−78		1.5
		420-6-2		4.5	−62		−0.7
		420-6-3		5.9	−68		0.7
	III	220-13		6.9	−57	270	−1.2
		180-1		6.3	−60		−1.8
Western section	I	420-7	quartz	5.7	−74	320	−0.5
		420-7-1		6.6	−82		0.4
		420-7-2		7.2	−76		1
		420-7-3		6.9	−77		0.7
	II	420-8		6.2	−81	280	−2.7
		420-9		6.5	−74		−2.4
		420-8-1		5.8	−65		−3.1
		420-8-2		6.3	−72		−2.6
	III	420-10		4.9	−79	230	−9.2
		420-10-1		6.3	−63		−7.8
		420-10-2		6.8	−61		−7.3
		420-10-3		5.6	−63		−8.5

and $^{208}\text{Pb}/^{204}\text{Pb}$ ranging from 38.832 to 40.105. These results are similar to those for gneiss in the Zhilingtou area (Table 5; Chu et al., 2020).

6.5 Gold content analysis

The geological units distributed within the Zhilingtou area primarily include Paleoproterozoic Badu Group gneiss, Triassic biotite monzogranite and K-feldspar granite, Cretaceous volcanic rocks and granite porphyry. These lithologies collectively control the formation and distribution of gold orebodies in the Zhilingtou area. This study analyzed the gold content in several geological units and ores from the Zhilingtou area via fire assay methods, yielding the following results (Table 6). In the V-1 gold orebody,

the gold content exceeded the detection limit. The Triassic biotite granodiorite (230 ± 1 Ma, Liu et al., 2025a) and the Badu Group gneiss also have measurable gold contents ($>0.001 \mu\text{g/g}$), suggesting a possible association with gold mineralization. By contrast, other geological units, such as k-feldspar granite, granite porphyry, and tuff, presented gold contents below the detection limit.

7 Discussion

7.1 Nature and evolution of the ore-forming fluids

The fluid inclusion petrographic characteristics and the variations in temperature and salinity between the two sections of

TABLE 4 Sulfur isotope data of sulfides from the Zhilingtou gold deposit.

Sample location	Sample no.	Mineral	$\delta^{34}\text{S}_{\text{V-CDT}}$	Source
Middle section	420-10-1	pyrite	6.41	this study
	420-10-2		6.85	
	420-10-3		6.88	
	420-10-4		7.67	
	420-10-5		7.41	
	420-10-6		6.65	
	420-10-7		3.30	
	420-10-8		6.34	
	420-10-9		6.02	
Western section	180-15-1		5.87	
	180-15-2			
	180-15-3			
	180-15-4			
	180-15-5			
	180-15-6			
	220-11-1			
	220-11-2			
	220-11-3			
	220-11-4			
	220-11-5			
	220-11-6			
	220-11-7			
	220-11-8			
	220-11-9			
Gniess	1-1	pyrite	6.04	Hua (2005)
	1-2		9.08	
	2-1		3.34	
	3-1		6.95	

the Zhilingtou gold deposit reflect the changes in and evolutionary processes of the ore-forming fluid from Stage I to Stage III. The prominent characteristics of FIs in quartz veins from different ore-forming stages in the western section are the close relationships among L-, V-, and C-type inclusions, with S-type inclusions being rare or occasionally observed. By contrast, S-type inclusions are relatively well developed in the middle section. Considering the locations of the two sections, the types of inclusions and their homogenization temperatures, and previous studies on Yanshanian molybdenum mineralization near the middle section,

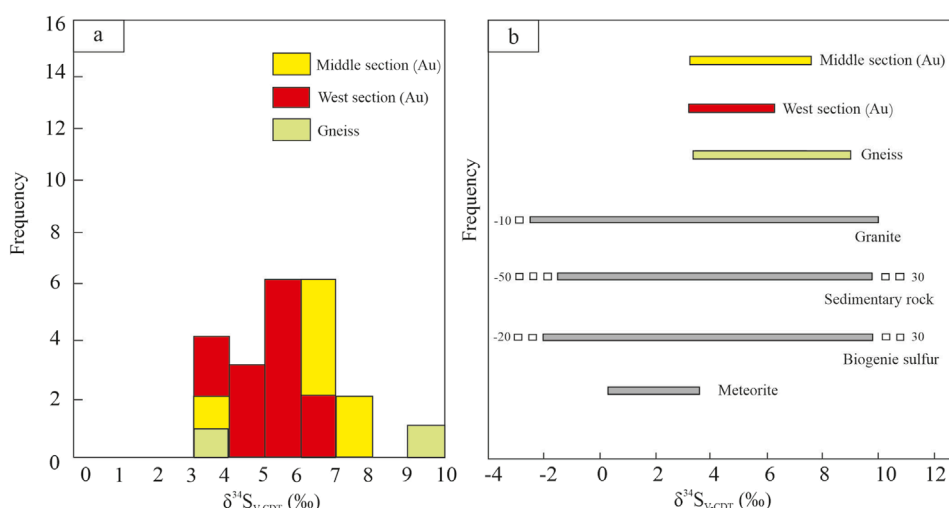


FIGURE 8 $\delta^{34}\text{S}$ values for sulfide minerals (a) and comparison with other geological units (b) within the Zhilongtou gold deposit (b, modified after Hoefs, 2009).

the development of many S-type inclusions was identified as a fluid boiling system (Wang, 2014). We believe that Yanshanian hydrothermal activity had a strong superimposed and modifying effect on the gold mineralization of the middle section, whereas its impact on the western section was relatively minor. As the fluid evolves from Stage I to Stage II, the number of S-type inclusions decreases, and they no longer develop in Stage III. Additionally, the abundance of V-type inclusions also decreases. The homogenization temperature and salinity of inclusions of the same type gradually decrease over time (Figure 9). These changes suggest that the fluid evolved from medium to high temperatures (237°C–316°C) and low salinities (1.90–6.72 wt.% NaCl eqv) in Stage I to a medium- to low-temperature (167°C–230°C), low-salinity (1.90–3.05 wt.% NaCl eqv) state in Stage III.

This evolution reflects the transition of the initial fluid, which was related to magmatic activity, as it mixed with meteoric water and underwent water-rock interactions with surrounding rocks during its ascent toward the surface, ultimately leading to mineral precipitation. Geographically, the middle section of the gold deposit is closer to the Huafengjian volcanic edifice, making it more susceptible to the effects of Yanshanian volcanic activity. This interpretation is further supported by the presence of S-type inclusions in the auriferous quartz veins of the middle section, which are absent in the western section.

7.2 Source of the ore-forming fluids

In the $\delta^{18}\text{O}_{\text{H}_2\text{O-SMOW}}$ vs. $\delta\text{D}_{\text{V-SMOW}}$ diagram, a distinct trend is observed from the early to late stages of mineralization in both the middle and western sections (Figure 10). The data for Stages I and II plot closer to the magmatic water range, whereas the data for Stage III are generally closer to the meteoric water range. This suggests that from Stage I to Stage III, the source of the fluid gradually migrated toward meteoric water. This trend implies that the ore-forming fluid consisted initially of magmatic water, which then progressively

mixed with meteoric water. This process is recorded by the changes of H–O isotope composition (Wu and Li, 2016).

7.3 Source of ore-forming materials

7.3.1 Sulfur isotopes

Sulfur isotopes have been extensively used to trace the source of ore-forming materials. However, the preparation of single mineral sulfide samples is susceptible to contamination from multiple generations and stages of sulfides, which can result in the mixing of sulfur isotopes from different sulfide stages, leading to significant distortion of the data. In this study, sulfur isotope analysis was conducted on pyrite from each stage of gold mineralization, with a total of 30 samples analyzed (Table 4). No sulfate minerals were observed in the main ore-forming stage of gold mineralization, and the sulfur isotopic compositions exhibited a relatively narrow range. This suggests that the ore-forming process occurred under conditions of low oxygen fugacity, during which the sulfur in the fluid predominantly existed in the form of HS^- and S^{2-} . Pyrite, as the main sulfur-bearing mineral, can be considered to approximate the overall $\delta^{34}\text{S}_{\Sigma}$ value of a fluid (Ohmoto, 1972; Wang et al., 2023).

The $\delta^{34}\text{S}_{\text{CDT}}$ values of the gold orebodies typically overlap with the sulfur isotope range observed in ore deposits related to magmatism (approximately –10‰ to 10‰; Kerrich, 1987; Kerrich, 1989; Partington and Williams, 2000), which contrasts with the sulfur values derived from a single, homogeneous magmatic source (ranging from –3 to 1‰, Hoefs, 2009; mantle-derived sulfur: ± 0 ‰) or from marine or seawater sulfur (approximately 20‰; Ohmoto, 1972; Seal, 2006), exhibiting there is a certain degree of external sulfur input during the mineralization process. Additionally, the sulfur isotope range of the gneiss from the Paleoproterozoic Badu Group (3.34‰–9.08‰) overlaps with the $\delta^{34}\text{S}_{\text{CDT}}$ values observed in the gold orebodies, suggesting a close relationship between gold mineralization and the Paleoproterozoic Badu Group (Figure 8). Furthermore, in combination with previous findings, it is inferred

TABLE 5 Pb isotopic compositions of granitic feldspar and sulfide from the Zhilington gold deposit.

Sample	Sample no.	Mineral	²⁰⁶ Pb/ ²⁰⁴ Pb		²⁰⁷ Pb/ ²⁰⁴ Pb		²⁰⁸ Pb/ ²⁰⁴ Pb		Source
			Ratio	1σ	Ratio	1σ	Ratio	1σ	
Gold orebodies	1-t-c-1	chalcopyrite	18.043	0.008	15.686	0.007	39.082	0.017	this study
	6-t1-2	pyrite	18.037	0.006	15.655	0.004	38.947	0.013	
	1-t-p-1		18.021	0.003	15.667	0.003	39.030	0.009	
	2-t-p-10		18.075	0.007	15.681	0.005	39.026	0.015	
	8-t1-4		18.008	0.005	15.683	0.002	39.227	0.016	
	420–17-p-1		17.560	0.015	15.648	0.013	40.105	0.033	
	10-t2-24		17.995	0.004	15.655	0.003	39.127	0.013	
	212-t-18		18.024	0.004	15.645	0.003	38.846	0.009	
	212-t-4		18.019	0.001	15.639	0.002	38.833	0.005	
	Gniess		III-R-1		17.509	-	15.576	-	
III-R-2		17.861	-		15.658	-	39.150	-	
ZK1205		18.031	-		15.644	-	38.902	-	
		18.026	-		15.642	-	38.845	-	
ZK12-35		plagioclase	18.457	-	15.659	-	39.705	-	
ZK12-37			18.426	-	15.639	-	39.564	-	
ZK12-41			18.249	-	15.662	-	39.259	-	
ZK1204		pyrite	18.043	-	15.633	-	38.514	-	
D07-1			18.078	-	15.412	-	39.096	-	
D08			18.084	-	15.716	-	39.120	-	
540-1-2			18.177	-	15.711	-	39.105	-	
540-3-1			18.052	-	15.678	-	38.993	-	
2007–23			17.999	-	15.651	-	38.841	-	
2007–15	18.014		-	15.663	-	38.880	-		

that during stages II and III of ore formation, meteoric water likely mixed with hydrothermal fluid and reacted with the surrounding gneiss, introducing new $\delta^{34}\text{S}_{\text{CDT}}$ values into the ore-forming system.

7.3.2 Lead isotopes

The *in situ* Pb isotope analysis of pyrite and chalcopyrite from the gold sections is shown in Figure 11 and Table 5. In the ²⁰⁶Pb/²⁰⁴Pb vs. ²⁰⁷Pb/²⁰⁴Pb diagram (Figure 11a), the values are relatively uniform except for some apparent outliers. The values and previous data are distributed on both sides of the upper crust evolution line, indicating characteristics consistent

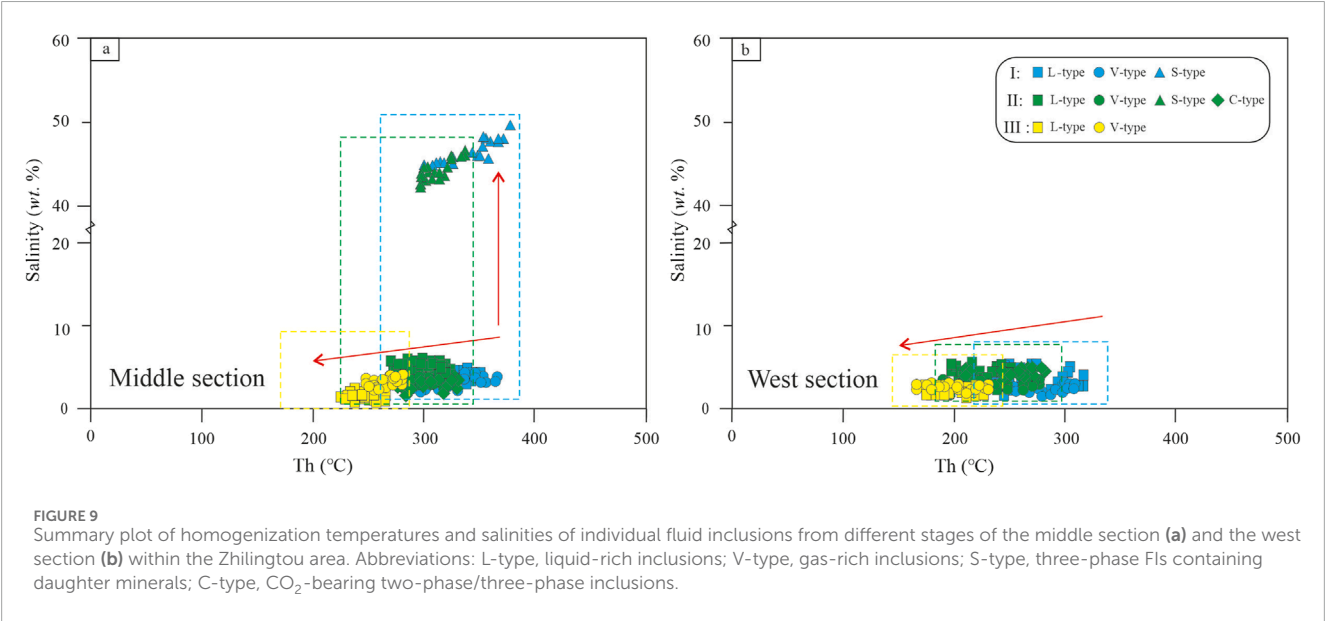
with a crustal source for mineralization. In the ²⁰⁶Pb/²⁰⁴Pb vs. ²⁰⁸Pb/²⁰⁴Pb diagram (Figure 11b), all the data plot within the lower crust and orogenic belt fields and plot closer to the lower crust evolution line, reflecting a crustal source.

7.4 Genetic classification

The genesis of the Zhilington gold deposit has been the subject of ongoing debate since its discovery, with several critical hypotheses proposed regarding its formation. One perspective links it to a Proterozoic orogenic gold system (Ni et al., 2012),

TABLE 6 Summary of the gold contents of various units in the Zhilingtonou area.

Rock	Sample no.	Detection limit (ug/g)	Gold content(ug/g)
biotite monzogranite	BPA-1	0.001	<0.001
	BPA-2		0.002
	BPA-3		0.002
K-feldspar granite	SLY-1		<0.001
	SLY-2		<0.001
	SLY-3		<0.001
granite porphyry	700-1		0.001
	700-2		<0.001
	700-3		<0.001
gold orebodies (V-1)	420-1		0.006
	420-2		0.003
	420-3		0.002
gneiss	420-4		0.001
	420-5		<0.001
	420-6		0.001
tuff	110-1		<0.001
	110-2		<0.001
	110-3		<0.001



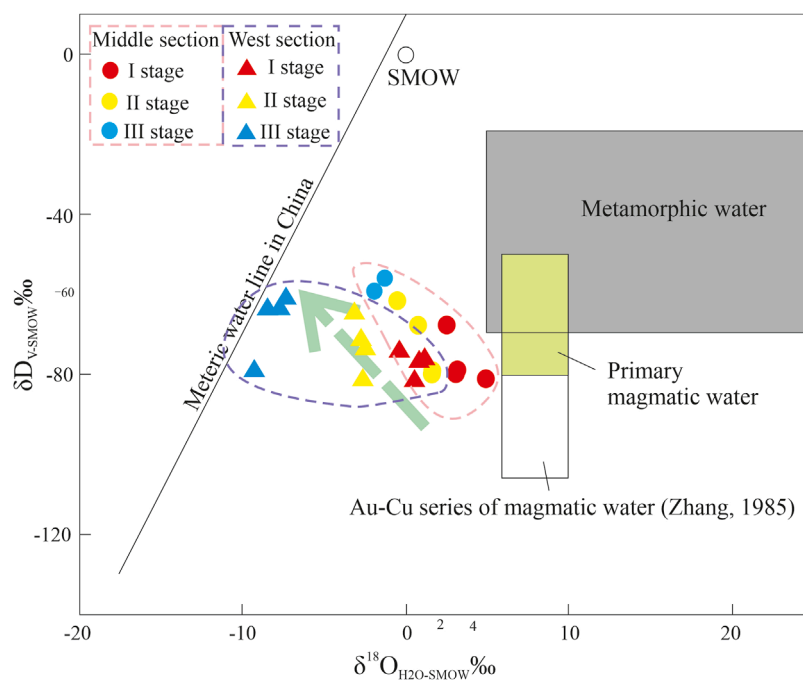


FIGURE 10
 $\delta^{18}\text{O}$ – δD diagram (after Taylor, 1974) for the ore fluids from the Zhilington gold deposit. The field of the Au–Cu magmatic water series is from Zhang (1985).

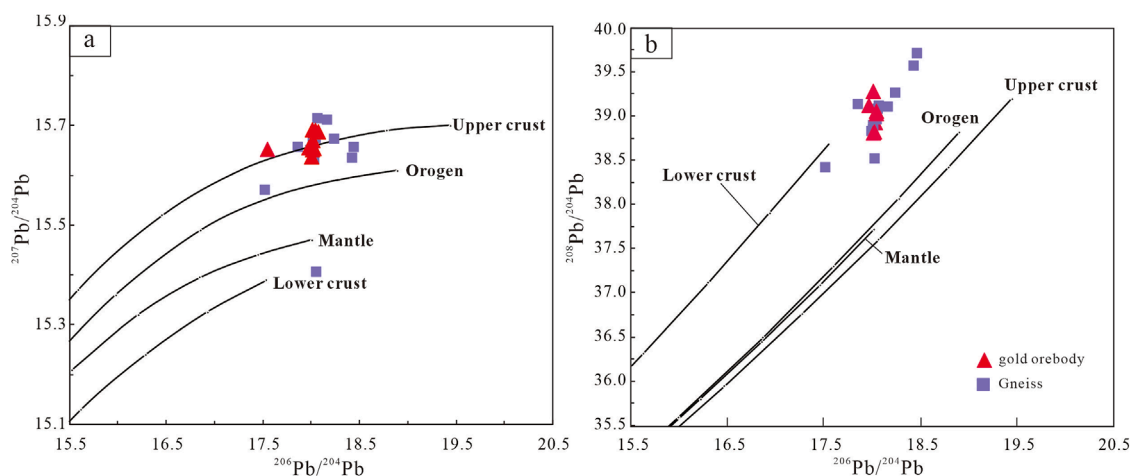


FIGURE 11
 Lead isotopic compositions of the Zhilington gold deposit. (a) $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ diagram, (b) $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ diagram. Mantle, orogen, upper crust and lower crust are modified after Zartman and Doe. (1981).

whereas another attributes its formation to an early Cretaceous mineralization event involving molybdenum, lead–zinc, and hydrothermal gold (Wang, 2014; Wang et al., 2020). Additionally, early metamorphism of sedimentary rocks is thought to have contributed to gold enrichment, which was further enhanced by volcanic and hydrothermal activity in the Badu Group (Xu et al., 1987; Zhang et al., 1991).

In this study, we conclude that the Zhilington gold orebodies are predominantly distributed along WNW- to nearly E-W-trending

faults. These faults are intersected by N–S-oriented F1 and F42 faults. However, the orebodies are exclusively hosted within the Proterozoic Badu Group biotite plagioclase gneiss and concealed beneath the volcanic rocks. The metaluminous to peraluminous biotite monzogranite (230 ± 1 Ma, Liu et al., 2025b), coeval with gold mineralization (230 ± 2 Ma, Liu et al., 2025a), is present within the mining area and serves as the ore-forming rock for the gold deposit. Furthermore, a spatial relationship and similar hydrothermal alteration types exist between the orebodies and the

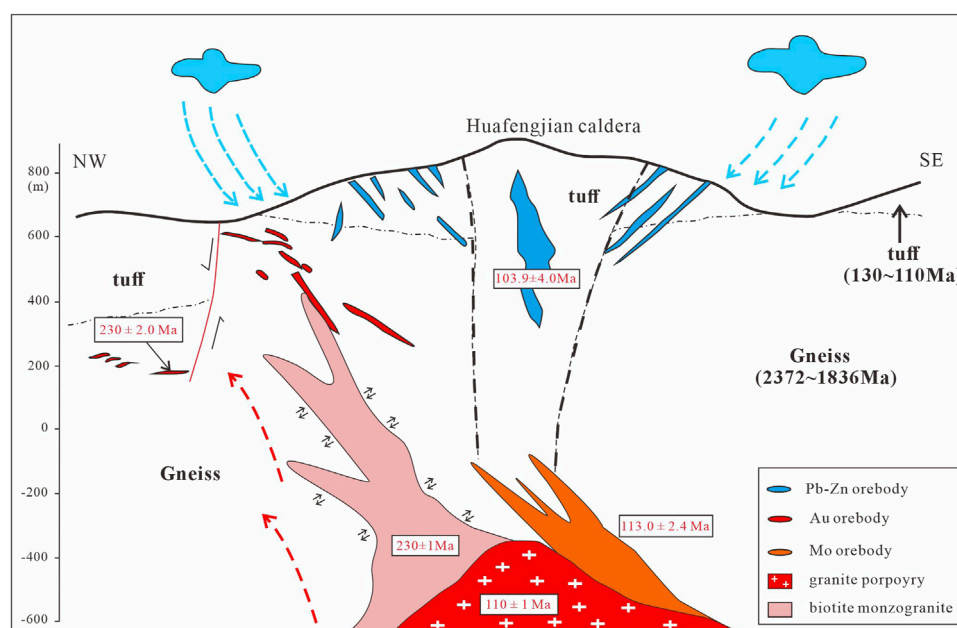


FIGURE 12
Genetic model of Zhilington Au–Pb–Zn–Mo mineralization system.

biotite monzogranite (Liu et al., 2025b). Fluid inclusion analyses and H–O–S isotopic compositions show that the ore-forming fluid is derived from a magmatic source and exhibits multiple stages of evolution. With the continuous mixing of meteoric water and the decrease in temperature and pressure, the ore-forming fluid continuously reacted with the country rock through hydrothermal alteration, and the ore-forming hydrothermal fluid showed evident external sulfur input. The tectonic discrimination diagrams based on Pb isotopes show that the lead in the Zhilington gold deposit mainly derived from the crust, which is consistent with the characteristics of the biotite monzogranite that originated mainly from the partial melting of late Paleoproterozoic basement in the lower crust (Liu et al., 2025b). In addition, all the samples from previous studies (Chu et al., 2020) and our study define a linear trend between the Cathaysia metamorphic basement and gold orebody curves (Figure 11), suggesting that both the biotite monzogranite and metamorphic basement contributed ore-forming materials for the gold mineralization at Zhilington. The measured gold contents reveal the genetic relationships among the gneisses of the Badu Group, biotite monzogranite and gold mineralization. Zheng and Liu (1986) have shown that the gold contents of gneisses near gold orebodies have significantly decreased (average = 4.77 ppb). The unaltered gneisses, which are far from mineralization, have higher gold contents (average = 11.9 ppb, Zheng and Liu, 1986). This finding also indicates that the surrounding gneisses play an important role in the accumulation and precipitation of gold mineralization. The influx of magma further extracts and activates some of the ore-forming elements in the gneiss and carries them away. However, the gold mineralization differs from low-sulfidation epithermal gold deposits in many geological and geochemical characteristics, such as the lack of typical adularia–sericite alteration (Heald et al.,

1987), the metal suite of Au–Te–Bi–As–Sb, and the close association with dioritic dikes. Instead, these characteristics are very similar to those of epizonal IRGDs, as described by Lang et al. (2000), Baker (2002), and Hart (2005). Therefore, the Zhilington gold deposit is speculated to be an IRGD formed in the Triassic. The ore-forming fluid, carrying gold and other ore-forming elements, experiences a gradual decrease in temperature and pressure during its ascent. As it mixes with meteoric water, it continuously reacts with the surrounding gneiss, mobilizing and activating some of the gold elements and transporting them to fault zones, where the orebodies ultimately form (Figure 12).

7.5 Tectonic setting

Discussions regarding the formation mechanisms and tectonic setting of the South China's Triassic magmatic–hydrothermal processes have been diverse (Pirajno and Bagas, 2002; Sun et al., 2010; Zhou et al., 2006; Zhou and Li, 2000; Mao et al., 2008), including an intracontinental collision orogeny (Zhou et al., 2006; Wang et al., 2013) and a Paleo-Pacific plate subduction model (Li et al., 2006; Li and Li, 2007). An increasing consensus among scholars suggests that the extensive granites and associated polymetallic mineralization during the Yanshanian period were closely linked to the subduction of the Paleo-Pacific plate beneath the Eurasian plate (Zhou et al., 2006; Mao et al., 2006; Mao et al., 2007; Mao et al., 2010; Mao et al., 2013; Li and Li, 2007; Sun et al., 2010). Early Indosinian north–south compression and early Yanshanian east–west compression mark the transition from the Tethyan tectonic domain, which is predominantly characterized by east–west structures, to the early Yanshanian Pacific margin

tectonic domain, which is dominated by NNE-oriented structures (Zhang et al., 2009). Following a period of relatively subdued tectonic-magmatic activity between approximately 205 and 180 Ma (Zhou et al., 2006), the prevailing tectonic regime shifted toward the Pacific tectonic domain. This transformation was likely the result of oblique subduction of the Izanagi plate at the ancient Pacific margin (Maruyama et al., 1997). The northwestward migration of the Izanagi plate toward the Eurasian continent is believed to have triggered intense tectonic activity beginning at approximately 175 Ma (Maruyama and Send, 1986; Moore, 1989; Wan, 1993; Mao et al., 2007; 2008; 2011). Recently, Mao et al. (2021) identified a middle-late Jurassic magmatic–hydrothermal copper mineralization belt along the southeastern coast of China, with an age range of 171–153 Ma, extending approximately 2,000 km in a northeastward direction. This mineralization event coincided with the Sn–W mineralization event in the Lingnan region (165–150 Ma), which occurred in a back-arc extensional setting, thus reflecting a typical subduction-related ore-forming model. Similar views have been proposed by Wang et al. (2012), Wang et al. (2015) and Zhang et al. (2020), Zhang et al. (2022), who suggested that the copper deposits in the Qin–Hang belt of South China formed in an intracontinental extensional environment induced by far-field stress from the subduction of the ancient Pacific plate at approximately 170–160 Ma. This evidence strongly supports the occurrence of a subduction event along the East Asian continental margin during the Jurassic period in South China, bearing significant similarities to the ore-forming evolution observed in the middle segment of the Andes during the Cenozoic.

By contrast, the intracontinental collision orogeny has gained recognition from many scholars (Guo et al., 1983; Ren, 1984; Hsü et al., 1990; Guo, 1992; Xie et al., 1999; Wang et al., 2001; Zhou et al., 2006; Zhang et al., 2009; Bai et al., 2012; Zhou et al., 2015). Wang et al. (2001) linked Triassic granites with the collision of North China and South China blocks. Zhou et al. (2006) identified 257 Ma postcollisional granites in the Shilu and Bangxi areas of Hainan and 255 Ma synorogenic granites in the Lelai area of Qiongdong (Xie et al., 1999), indicating that the collision likely occurred in the early Triassic, coinciding with the timing of the Songma suture zone formation. Zhang et al. (2009) suggested that South China's E–W-trending fold belts during the Indosinian period were closely related to the collision between the southern and northern source blocks of the South China continental margin. The late Triassic, corresponding to a postcollisional setting, experienced tectonic deformation and magmatic activity against a tectonic background shaped by the convergence of multiple plates, including South China, North China, Indochina, and the paleo-Pacific plate (Wang et al., 2013; Gao et al., 2017), resulting in a series of late Triassic low-temperature gold and lead–zinc deposits west of South China's Yangtze Block (Hu et al., 2017). The postcollisional intracontinental extension during the Indosinian orogeny, controlled by the continuation of Tethyan tectonic movements, led to the formation of an intraplate rift system in the South Lingnan volcanic–intrusive belt, which is composed of basic–ultrabasic rocks, bimodal volcanic rocks, and A-type granites (200–180 Ma).

Overall, we believe that the Zhilongtou gold deposit formed in a tectonic environment characterized by postcompression

extension. The mineralized hydrothermal fluids provided the necessary ingredients for gold mineralization. The water–rock reactions between the strata and the hydrothermal fluids created conditions for the activation and enrichment of gold. The faults provided pathways and spaces for fluid migration and mineral precipitation and controlled the distribution of the gold ore bodies.

8 Conclusion

1. The mineralization of the Zhilongtou gold deposit can be classified into three distinct stages: (i) pyrite–quartz, (ii) polymetallic sulfide–quartz, and (iii) quartz–calcite. Gold is largely enriched and precipitated during Stage II.
2. Fluid inclusion analysis and H–O isotopes indicate that gold mineralization occurred within a medium–high temperatures (237°C–316°C) and low salinities (1.90–6.72 wt.% NaCl eqv) NaCl–H₂O–CO₂ hydrothermal system. Initially, the mineralizing fluid was magmatic in origin, but it continuously mixed with meteoric water over time.
3. Sulfur and lead isotopes suggest that gold mineralization is closely related to magmatic activity, and the Proterozoic gneiss also made a certain contribution to its formation. Some of the gold may have originated from leaching or exchange processes between hydrothermal fluids and adjacent gneisses.
4. The Zhilongtou gold deposit is an intrusion-related gold deposit formed in the Triassic period, which was in an extensional tectonic environment following the collision of the Indosinian, South China, and North China blocks.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

HL: Formal Analysis, Methodology, Writing – original draft, Data curation, Investigation. XY: Project administration, Supervision, Writing – review and editing. SD: Data curation, Methodology, Writing – review and editing. YS: Data curation, Methodology, Writing – review and editing. YW: Data curation, Writing – review and editing. JM: Project administration, Supervision, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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