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Fluid inclusion and H–O–S isotope constraints on the genesis of the Ashawayi gold deposit, Southern Tianshan, Xinjiang, NW China

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The Ashawayi gold deposit is situated in the eastern part of the Southern Tianshan Sb–Hg–Au metallogenic belt, a significant source of gold in China. This deposit exhibits typical disseminated mineralization controlled by faults or fractures. This study presents a comprehensive set of petrological, fluid inclusion, and H–O–S isotopic data for the deposit. Fluid inclusions can be classified into three main types, namely, NaCl–H₂O, CO₂-bearing aqueous solutions, and pure CO₂. The quartz from the ore contains fluid inclusions predominantly composed of NaCl–H₂O and CO₂. The homogenization temperatures of these inclusions range from 200°C to 360°C. Estimates based on fluid inclusion pressures suggest that mineralization occurred at depths of approximately 2–4 km. Mineralization is associated with fault healing and fracturing, which induce secondary fluid immiscibility. Fluid boiling features indicate rapid upwelling of ore fluids from depth, with metal precipitation occurring through decompression at shallower levels. H–O–S isotopes suggest that metals were extracted from the country rock and that the ores were formed through the mixing of metamorphic fluids with meteoric water. A combined analysis classifies the Ashawayi gold deposit as a hypabyssal orogenic gold deposit.

KEYWORDS

fluid inclusions, H–O–S isotopes, Ashawayi gold deposit, orogenic gold deposit, Southern Tianshan

1 Introduction

The Southern Tianshan orogen extends across Uzbekistan, Kyrgyzstan, and China, forming a significant gold metallogenic belt in Central Asia and one of

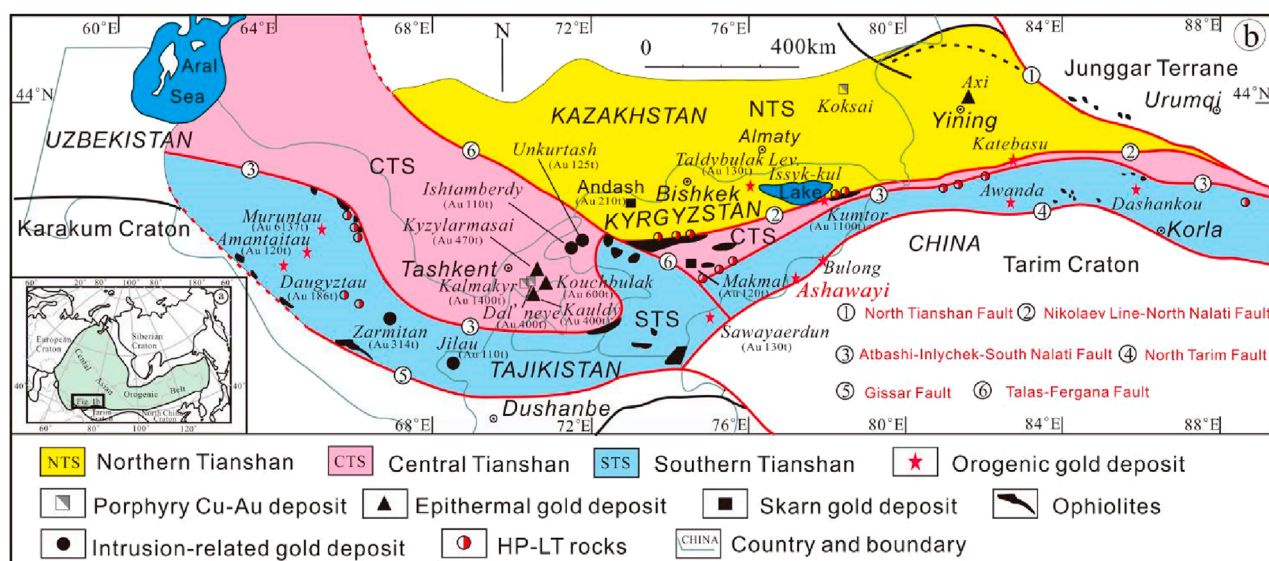


FIGURE 1

(a) Tectonic map of the Central Asian Orogenic Belt (modified from Gao et al., 2009); (b) Sketch map of west Tianshan showing the location of the Ashawayi gold deposit (modified from Xue et al., 2014b; Zhang et al., 2017).

the world's most renowned mineralization belts (Wilde et al., 2001; Graupner et al., 2006; Kempe et al., 2015; Mao et al., 2004; Yang J. G. et al., 2004; Abzalov, 2007; Morelli et al., 2007; Frimmel, 2008; Pasava et al., 2010; 2013; Bierlein and Wilde, 2010; Chen et al., 2012a; 2012b; Goldfarb et al., 2014; Xue et al., 2014b). This region hosts numerous gold deposits, including super-large (>100t Au) and large (20–100t Au) deposits. Notable super-large deposits include Muruntau (Au 6137t; Frimmel, 2008), Daugyztau (Au 186t; Bierlein and Wilde, 2010), Amantaitau (Au 120t; Pasava et al., 2010), and Zarmitan (Au 314t; Abzalov, 2007) in Uzbekistan; Jilau (Au 110t; Cole et al., 2000) in Tajikistan; and Kumtor (Au 1100t; Mao et al., 2004) in Kyrgyzstan (Figure 1).

The Southern Tianshan in Xinjiang is the eastern extension of Southern Tianshan in Central Asia and exhibits metallogenic conditions similar to those in neighboring countries. Several gold deposits have been discovered in this area, including Sawayaerdun, Dashankou, Sahentouhai, and Bulon, along with some promising exploration sites (Ye et al., 1999a; Ye et al., 1999b; Liu et al., 2002a; Liu et al., 2002b; Liu et al., 2007; Yang F. Q. et al., 2004; Yang et al., 2006; Yang et al., 2007; Liu et al., 2007). Although these deposits show good potential for further exploration, they do not match the number and scale of deposits in the adjacent regions of foreign countries, and the level of mineral resource development and research remains insufficient. The Sawayaerdun gold deposit, with reserves exceeding 100t and an inferred resource of at least 300t (Rui et al., 2002; Xue et al., 2014a; 2014b; 2015), is currently the largest gold deposit in southwestern Tianshan, China, and has received the highest level of research attention (Rui et al., 2002; Chen et al., 2012a; Chen et al., 2012b; Xue et al., 2014a; Xue et al., 2014b; Xue et al., 2015; Zhang et al., 2017). The Ashawayi gold deposit is located east of the Sawayaerdun gold deposit and south of the world-class Kumtor gold deposit. Recent geological exploration has revealed that the Ashawayi gold deposit has become

a medium-scale mine and ranks as the third largest gold deposit in the region. However, limited research has been conducted on this deposit (Chen B et al., 2019; Zhang et al., 2020; Zhang et al., 2023; Feng et al., 2021; Zhou et al., 2023).

In this paper, we present a comprehensive set of mineralogical, petrological, fluid inclusion, and H–O–S stable isotope studies on the newly discovered Ashawayi gold deposit. We investigate the ore-forming P–T conditions and sources, as well as the possible relationship between fluid pressure conversion and gold precipitation. This study aims to elucidate potential mineralization mechanisms and their implications for tectonic evolution.

2 Geological settings

The Tianshan orogen is a critical component of the Central Asian Orogenic Belt, situated between the Siberian Plate, the Eastern European Craton, the Karakum Plate, the Tarim Plate, and the North China Plate (Figure 1a). The Tianshan orogenic belt is bounded to the north by the Junggar Basin and to the south by the Tarim Basin. From north to south, it comprises three tectonic units, namely, Northern Tianshan, Central Tianshan, and Southern Tianshan. These units are delineated by the North Tianshan Fault, Nikolaev Line–North Nalati Fault, Atbashi–Inlychek–South Nalati Fault, and North Tarim (Kalatieke) Fault, respectively (Figure 1b; Gao et al., 2009; Xue et al., 2014a; Xue et al., 2014b; Zhao et al., 2014; Zhao et al., 2015; Zhang et al., 2017). Additionally, the NW-striking Talas–Fergana dextral strike-slip fault transects three tectonic units obliquely (Figure 1b; Zhang et al., 2017).

The Southern Tianshan primarily consists of Precambrian metamorphic rocks overlain by Cambrian–Carboniferous marine carbonates and clastic rocks with volcanic interlayers (Allen et al., 1993; Gao et al., 2009). In the central part of the Southern Tianshan,

Permian fluvial sedimentary and volcanic rocks unconformably overlie the Carboniferous carbonate rocks (Huang et al., 2012). Sporadically exposed along the Atbashi–Inlychek–South Nalati Fault are ophiolites and high-pressure/low-temperature metamorphic (HP–LT) rocks (Figure 1b; Gao et al., 2006; Xiao et al., 2013). The glaucophane in the ophiolites has a K–Ar age of 360 ± 10 Ma (Gao et al., 2009), indicating that the ophiolites formed during the northward subduction of the Southern Tianshan Ocean. The phengite and metamorphic zircon in the HP–LT rocks have ^{40}Ar – ^{39}Ar ages of 331–310 Ma and U–Pb ages of 320 Ma, respectively (Klemd et al., 2005; Su et al., 2010; Gao et al., 2011), suggesting that the collision between the Tarim craton and the Central Tianshan terrane occurred during the Late Carboniferous (Gao et al., 2009; Huang et al., 2012). Intrusive rocks, which constitute approximately 5% of the total area of the Southern Tianshan, were mainly emplaced from the Late Carboniferous to Early Permian (Huang et al., 2012). Post-collisional granites have ages of 298–260 Ma (Solomovich, 2007; Konopelko et al., 2007; Long et al., 2008; Gao et al., 2011), consistent with the inference that the closure of the Southern Tianshan Ocean took place during the Late Carboniferous (Zhang et al., 2017).

The Ashawayi gold deposit is located in the eastern part of Southern Tianshan, regionally between the NE-trending Karatik fault and the Keletibik fault (Figure 2). The gold ore is primarily hosted within quartz auriferous veins emplaced in Carboniferous sericite phyllite and relic sandstone (Figures 4c,d). Gold mineralization is structurally controlled by NNE- to NE-trending (30° – 50°) ductile–brittle shear zones (Figure 3). These shear zones are crosscut by some NW-trending brittle faults that are generally not mineralized (Figure 3). Gold ores in the sub-surface zone (Figures 4a,b) exhibit fracturing and strong alteration. At depth, the ores gradually transition to primary ore with diminishing fracturing. The dominant ore mineral is pyrite, along with minor amounts of arsenopyrite, stibnite, galena, sphalerite, and chalcopyrite (Figures 5c–i). Gold occurs predominantly in pyrite and arsenopyrite. Based on mineralogical, textural, and crosscutting relationships observed in the deposit and hand samples, three stages of hydrothermal alteration were identified in the Ashawayi gold deposit. From oldest to youngest, these stages are (I) an early non-mineralization or quartz-growth stage (Figure 4e), (II) a middle quartz–polymetallic sulfide stage (Figures 4f–i), and (III) a late quartz and carbonatization stage (Figure 4g). Wall-rock alterations in the Ashawayi gold deposit commonly include silicification, pyritization (secondary ferritization), arsenopyritization, sericitization, carbonatization, chloritization, and kaolinization. Pyritization and silicification are closely associated with ore mineralization.

3 Sampling and analytical methods

3.1 Sampling

In this study, systematic sampling was conducted from various ore bodies and different wall rocks. Due to the strong weathering and oxidation of the outcrops, representative samples were primarily collected from the drill core. Only a limited number of relatively fresh samples were obtained from outcrops. A total of 92

samples were used to select representative fluid inclusions for laser Raman spectroscopy and temperature measurements. A total of 14 samples from the main ore-forming phase were selected for H–O isotope analysis. Individual minerals such as pyrite, arsenopyrite, and antimonite were selected from 12 ore samples, four wall-rock samples, and two rock-body samples for S isotope analysis. The 14 samples selected for H–O isotope analysis are characterized by siliceous metasomatism associated with auriferous quartz or net-like veins. A summary of sample locations, rock types, and selected individual minerals is provided in Table 1. Representative field photographs are shown in Figure 4, and photomicrographs of typical mineral assemblages are presented in Figure 5.

3.2 Fluid inclusion studies

Doubly polished wafers of representative samples were prepared for inclusion petrography, which was conducted at the University of the Chinese Academy of Sciences using an optical polarizing microscope. Microthermometry studies involving heating and freezing runs of the fluid inclusions were performed using a LINKAM THMS600 housed at the fluid inclusion laboratory of the North China University of Science and Technology. This equipment operates within a temperature range of -180°C to $+600^\circ\text{C}$. Calibration was conducted at -56.6°C and 0°C using synthetic fluid inclusion standards and pure water to ensure measurement accuracy. The samples were first frozen and then heated gradually to prevent inclusion bursting. The heating rate varied from 0.1°C to $10^\circ\text{C}/\text{min}$, with a slower rate of $0.1^\circ\text{C}/\text{min}$ when approaching phase transitions. Repeated measurements were conducted to ensure the accuracy of the measured phase transition temperatures.

Laser Raman spectroscopy of fluid inclusions from doubly polished wafers of representative samples was performed using the LABHR–VIS LabRAM HR800 machine at the Solid Mineral Resource Key Laboratory under the Institute of Geology and Geophysics, Chinese Academy of Sciences. The laser source was a yttrium aluminum garnet (YAG) laser with a wavelength of 532 nm and a power of 1,000 mW. Each spectral line involved an integration time of 10 s, with 10 integrations performed per line. The spectral resolution was $\pm 2\text{ cm}^{-1}$ with a beam size of $2\text{ }\mu\text{m}$.

3.3 H–O–S stable isotopic studies

The H–O–S isotopes were analyzed at the Research Center for Analysis and Measurement, affiliated with the Beijing Uranium Geology Research Institute. For the extraction of H_2O from fluid inclusion in quartz, a decrement method was employed. The extracted H_2O was prepared for the H isotope component measurement. The measurement procedure was as follows: individual quartz samples were first baked low temperature to remove the adsorbed water. The samples were then heated until they fractured, releasing the volatiles. Water vapor was extracted and subjected to a reduction reaction with zinc at 400°C to produce hydrogen. The resulting hydrogen was frozen with liquid

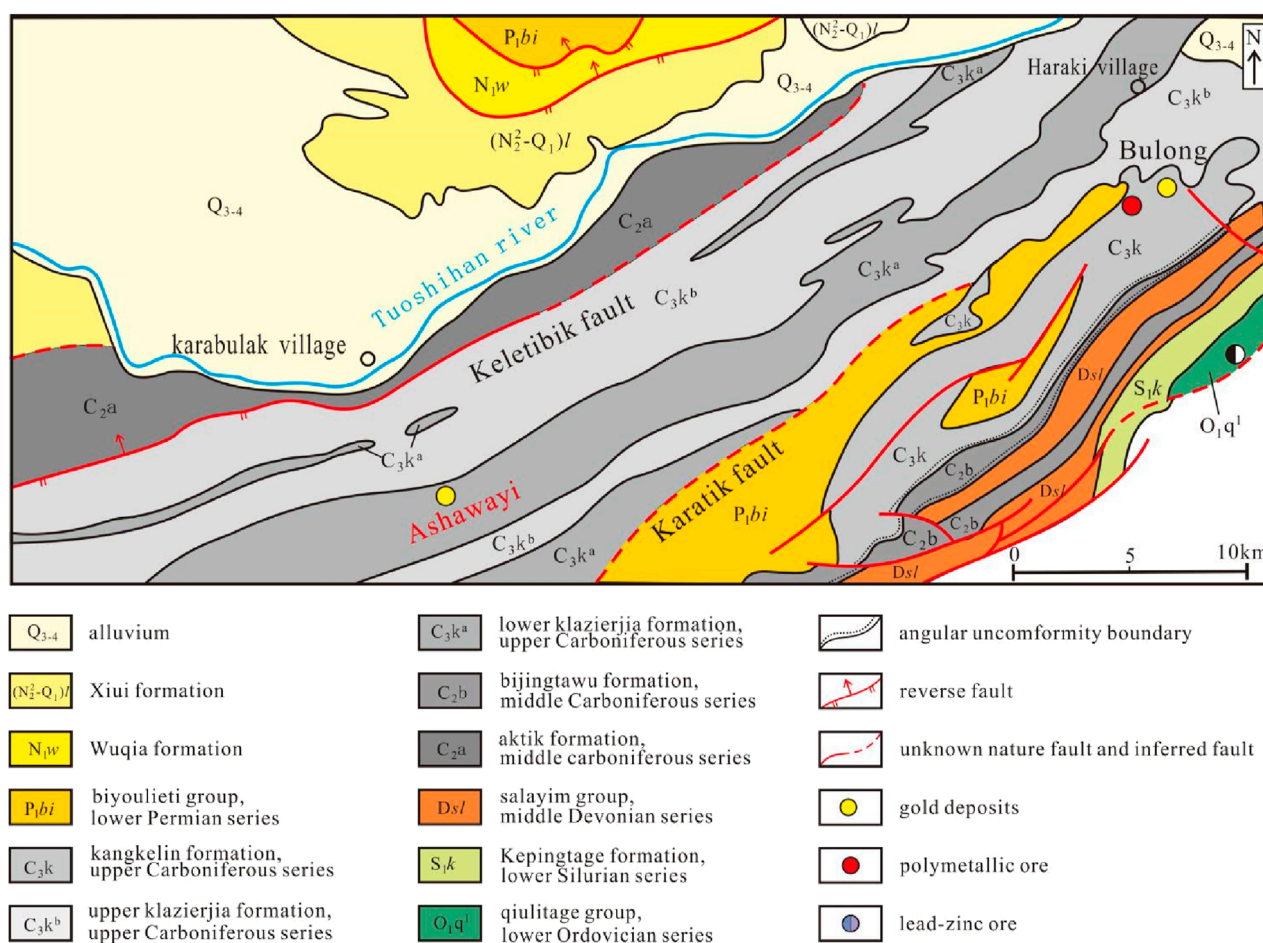


FIGURE 2
Geological map of the Ashawayi area (modified from Chen K. et al., 2007).

nitrogen and collected in a sample bottle containing active carbon. Finally, its isotope component was analyzed using a MAT-253 mass spectrometer, calibrated with the international standard V-SMOW, with an analytical accuracy of $\pm 2\%$.

For the analysis of the O isotope in quartz, the BrF₅ method was used as follows: a 12 mg pure quartz sample was reacted with BrF₅ under vacuum and high-temperature conditions for 15 h. Oxygen was extracted, and a resistance graphite rod was burnt with oxygen to produce CO₂ at 700°C. Its O isotope component was analyzed using a Delta V Advantage mass spectrometer, calibrated with the international standard V-SMOW, with an analytical accuracy of $\pm 0.2\%$.

The S isotopic composition was measured according to the following procedure: first, individual metal sulfides were uniformly mixed with cuprous oxide—ground to 200 mesh—using a precision scale. The mixture was then heated under vacuum condition at 2.0 Pa. Subsequently, the mixture was subjected to an oxidizing reaction at 980°C to produce SO₂. SO₂ was collected using the freezing method under vacuum conditions. The S isotope component was analyzed using the Delta V Plus mass spectrometer, calibrated with the CDT standard, with an analytical accuracy better than $\pm 0.2\%$.

4 Results

4.1 Petrography

The ore characteristics of the various stages are listed below:

Stage I: During this stage, mineralization is either absent or occurs to a minimal extent. Well-developed quartz veins and quartz lenses are present, characterized by coarse brownish-white quartz grains ranging in size from 0.5 to 1 mm (Figure 4e). The average thickness of quartz veins is 1–3 cm, with the thickest reaching 30 cm. Small amounts of cubic-type pyrite occur within the quartz veins at this stage. The characteristics of quartz veins are similar to those observed in the earliest stage of the Muruntau gold deposit (Wilde et al., 2001).

Stage II (quartz polymetallic sulfide stage): This is the main stage of gold mineralization. In contrast to the barren quartz veins, mineralized quartz veins have experienced intense structural deformation, fracturing, and hydrothermal alteration. These mineralized quartz veins exhibit fine-grained or net-like textures and are commonly found within altered and fractured zones. The quartz grains range in color from deep gray to light gray, with grain

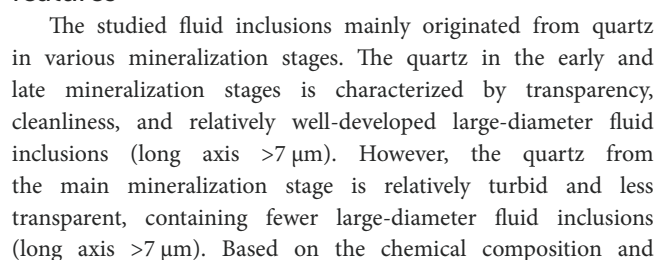




FIGURE 4

Characteristics of oxidized and primary ores and wall-rock samples from the Ashawayi gold deposit. (a) Surface-oxidized ore (produced from interlayer slip plane F0 and a little late thrust fault F1); (b) surface-oxidized ore (the gold grade of the ore collected from the breccia zone is 2.89 g/t and 1.31 g/t from the cleavage zone); (c) siltstone of wall rock; (d) phyllite of wall rock; (e) non- or poor-mineralized quartz vein sample produced from the early stage; (f) late-stage quartz cemented by smoky gray quartz breccia produced in the middle stage; breccia contains pyrite; (g) late-stage white quartz replaced the smoky quartz produced from the main stage of mineralization; (h) breccias ore (experienced through ductile and brittle deformation); (i) massive stibnite ore.

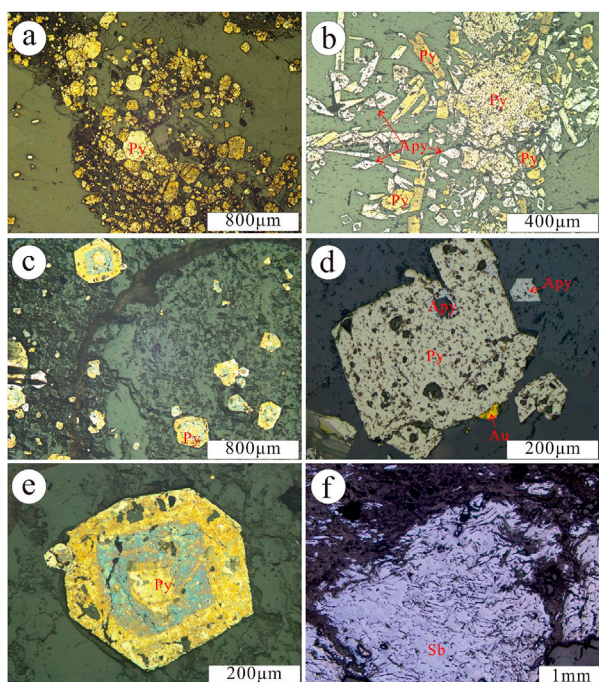


FIGURE 5
Photomicrographs of the Ashawayi gold deposit. (a) Anhedra and subhedral pyrite in gold ore; (b) pyrite–arsenopyrite assemblage in the gold ore; (c) euhedral and subhedral pyrite in the gold ore (developed zoning texture shows multi-period genesis); (d) native gold grains confined to the margin of pyrite; (e) clear zoning texture of pyrite; (f) massive stibnite ore.

physical characteristics at room temperature, the primary fluid inclusions are classified into three types, namely, NaCl–H₂O type inclusions, CO₂-bearing aqueous solution inclusions, and pure CO₂ inclusions.

4.2.1.1 Type I inclusion

The NaCl–H₂O type inclusions consist of two phases (liquid NaCl–H₂O + vapor H₂O) at room temperature and account for approximately 90% of all inclusions (Figures 6a–d). The liquid phase dominates, with the vapor phase comprising 5%–30% of the inclusion volume, mostly between 5% and 10%. Type I inclusions exhibit oval, nearly round, or irregular shapes. Smaller inclusions have a long axis ranging from 4 to 12 μ m, while larger inclusions can reach up to 30 μ m. NaCl–H₂O type inclusions hosted in quartz occur in almost all mineralization stages.

4.2.1.2 Type II inclusion

Comprising approximately 10% of total inclusions, these CO₂-bearing aqueous solution inclusions primarily consist of two phases (liquid H₂O–NaCl + liquid CO₂) at room temperature. Occasionally, three-phase inclusions (liquid H₂O–NaCl + liquid CO₂ $\pm$ vapor CO₂) are observed (Figures 6b, c). Type II inclusions are more prevalent in the early stage than the middle stage and are underdeveloped in the late stage. This type of inclusion is further divided into two subtypes: Type II₁ inclusions, which contain lower concentrations of CO₂ (Figure 6b), and

Type II₂ inclusions, which are richer in CO₂ (Figure 6c). Type II₁ inclusions constitute 10%–50%, while Type II₂ inclusions make up 50%–90%. The long axes of Type II inclusions range from 5 to 35 μ m, which are larger than those of Type I inclusions. These inclusions are oval or irregular and show minor elongation signs.

4.2.1.3 Type III inclusions

Representing less than 1% of the total inclusions, these inclusions consist solely of pure CO₂ and predominantly occur in the early and middle stages. They can be either single-phase or two-phase. Upon freezing, single-phase inclusions produce vapor CO₂. Type III inclusions are oval, strip-like, or irregular, with long axes measuring 5–25 μ m.

4.2.2 Laser Raman spectrum analysis

The measurement and analysis of various types of fluid inclusions (Figure 7) reveal that Type I (H₂O–NaCl) inclusions are present across mineralization stages. Consequently, representative Type II (CO₂–H₂O) and Type III (pure CO₂) inclusions with varying CO₂/H₂O ratios are selected for further analysis. The results indicate that in addition to the characteristic peaks of the host mineral quartz, distinct peaks corresponding to CO₂ and liquid H₂O are also observed. The components identified from the laser Raman spectrum are consistent with those of types I, II, and III inclusions within the H₂O–CO₂–NaCl system. Notably, no CH₄ peaks were detected, likely due to the extremely low abundance of CH₄ inclusions, which is insufficient for detection.

4.2.3 Homogenization temperature and salinity of fluid inclusion

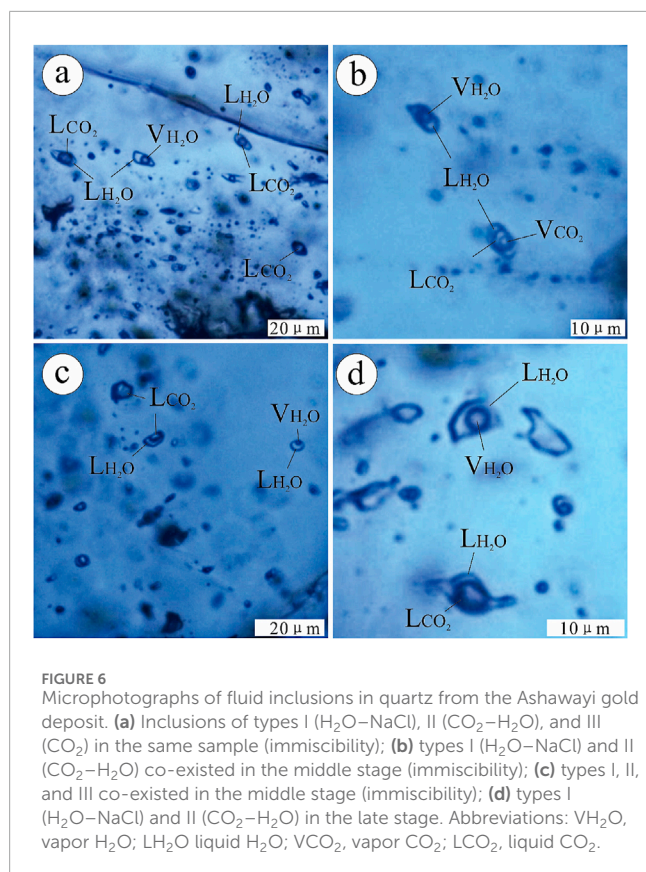
The homogenization temperature (T) and salinity of fluid inclusions were obtained from 147 fluid inclusions across three stages, derived from 16 samples (Table 2). The ice-melting temperature (T_{m,ice}) is used to calculate the salinity of two phases (vapor and liquid) of fluid inclusions, following the formula presented by Hall et al. (1988). For the CO₂-bearing H₂O solution, salinity was calculated using the FLINCOR program developed by Brown (1989).

The types and proportions of fluid inclusions vary significantly across each mineralization stage. In the early non-mineralized stage, H₂O–NaCl inclusions (Type I) account for 75%, followed by CO₂–H₂O inclusions (Type II), and pure CO₂ inclusions (Type III) are less than 1%. During the middle quartz–polymetallic sulfide stage, which is the main mineralization phase, the proportion of H₂O–NaCl inclusions (Type I) increases to approximately 90%, while the proportion of CO₂–H₂O inclusions (Type II) decreases significantly to approximately 10%, compared to the early ore-free stage with minimal sulfide content. In the late quartz–carbonate stage, H₂O–NaCl inclusions (Type I) remain predominant, with occasional occurrences of CO₂–H₂O inclusions (Type II). From the early to the late stage, the number of CO₂–H₂O inclusions (Type II) gradually decreases.

The homogenization temperature of fluid inclusions exhibits two peaks in each stage (Figure 8). The homogenization temperature peak concentrations of quartz inclusions in different stages show

TABLE 1 Details of 14 samples analyzed for the H–O isotope and 18 samples analyzed for the S isotope from the Ashawayi gold deposit.

No.	Sample no.	Rock type	Location	Sample depth	Selected mineral	Analysis
1	As10	Ore	N40°42'17.59"; E77°35'43.65"	Outcrop	Quartz	H–O isotope
2	As11	Ore	N40°42'22.26"; E77°35'52.03"	Outcrop	Quartz	
3	As12	Ore	N40°42'13.71"; E77°35'19.37"	Outcrop	Quartz	
4	As13	Ore	N40°43'50.59"; E77°38'07.52"	211 m	Quartz	
5	As17	Ore	N40°43'50.33"; E77°38'07.24"	140 m	Quartz	
6	As19	Ore	N40°43'46.05"; E77°38'03.12"	196 m	Quartz	
7	As22	Ore	N40°43'47.81"; E77°38'05.54"	183 m	Quartz	
8	As35	Ore	N40°43'34.35"; E77°37'50.76"	291.5 m	Quartz	
9	As36	Ore	N40°43'34.35"; E77°37'50.76"	292.8 m	Quartz	
10	As38	Ore	N40°43'32.55"; E77°37'48.40"	314.5 m	Quartz	
11	As50	Ore	N40°42'57.53"; E77°35'28.79"	Outcrop	Quartz	
12	As57	Ore	N40°43'31.11"; E77°37'43.40"	340 m	Quartz	
13	As70	Ore	N40°43'22.53"; E77°37'32.19"	Outcrop	Quartz	
14	As72	Ore	N40°43'50.39"; E77°38'28.49"	Outcrop	Quartz	
1	As2	Diorite	N40°43'55.91"; E77°38'17.60"	Outcrop	Pyrite	S isotope
2	As3	Diorite	N40°42'57.15"; E77°36'01.75"	Outcrop	Pyrite	
3	As13	Ore	N40°43'50.59"; E77°38'07.52"	211 m	Pyrite	
4	As17	Ore	N40°43'50.33"; E77°38'07.24"	140 m	Pyrite	
5	As19	Ore	N40°43'46.05"; E77°38'03.12"	196 m	Pyrite	
6	As22	Ore	N40°43'47.81"; E77°38'05.54"	183 m	Pyrite	
7	As23	Ore	N40°43'50.15"; E77°38'08.52"	234 m	Pyrite	
8	As26-1	Siltstone	N40°43'52.27"; E77°38'09.08"	193 m	Pyrite	
9	As26-2	Siltstone	N40°43'52.27"; E77°38'09.08"	193 m	Arsenopyrite	
10	As27	Phyllite	N40°43'56.38"; E77°38'13.75"	207 m	Pyrite	
11	As28	Siltstone	N40°43'56.28"; E77°38'13.92"	215 m	Pyrite	
12	As35	Ore	N40°43'34.35"; E77°37'50.76"	340 m	Pyrite	
13	As36	Ore	N40°43'34.35"; E77°37'50.76"	292.8 m	Pyrite	
14	As38-1	Ore	N40°43'32.55"; E77°37'48.40"	314.5 m	Pyrite	
15	As38-2	Ore	N40°43'32.55"; E77°37'48.40"	314.5 m	Arsenopyrite	
16	As57	Ore	N40°43'31.11"; E77°37'43.40"	340 m	Pyrite	
17	As70	Ore	N40°43'22.53"; E77°37'32.19"	Outcrop	Stibnite	
18	As72	Ore	N40°43'50.39"; E77°38'28.49"	Outcrop	Stibnite	



a generally consistent superposition phenomenon, such as the overlap of low-temperature peaks in the early and middle stages and high-temperature peaks in the late stage. This indicates the superposition effect of fluids from the middle and late stages on minerals formed in the early stage. Specifically, the homogenization temperature range for quartz inclusions in the early stage is 320°C–360°C, while that in the late stage is concentrated between 180°C and 200°C, excluding factors affecting fluid superposition. The presence of two peaks (220°C–250°C and 280°C–300°C) in the middle stage may not result from vein superposition but rather from the presence of different inclusion types. The low-temperature peak (220°C–250°C) corresponds to the homogenization temperature of H₂O–NaCl inclusions (Type I), while the high-temperature peak (280°C–300°C) primarily represents the homogenization temperature of CO₂–H₂O inclusions (Type II). This result may be related to fluid inclusions trapped in an immiscible system.

The salinity of fluid inclusions in each stage is generally low (Figure 8). The peak salinity range for quartz fluid inclusions in the early stage is the lowest (3%–5% NaCl_{eqv}), concentrated at approximately 4% NaCl_{eqv}. The salinity of the fluid inclusions in the middle stage is generally higher than that in the early stage, with salinity increasing as temperature decreases, resulting in two peaks. Type II inclusions are predominantly found in the low-salinity region, while Type I inclusions are found in the high-salinity region. The peak salinity range for fluid inclusion in late-stage quartz is generally lower than that in middle-stage quartz.

4.3 H–O–S isotopes

4.3.1 H–O isotopes

A total of 14 quartz samples from the middle mineralization stage were selected for H–O isotope analysis. The results are summarized in Table 3, where $\delta^{18}\text{O}_w$ was calculated using the oxygen isotope equilibrium fractionation equation $1000\ln\alpha_{\text{quartz-water}} = 3.38 \times 10^6/T^2 - 3.40$ (Clayton et al., 1972), based on the homogeneous temperature of fluid inclusions and the oxygen isotope balance between quartz and water, while the remaining values were measured directly.

4.3.2 Sulfur isotopes

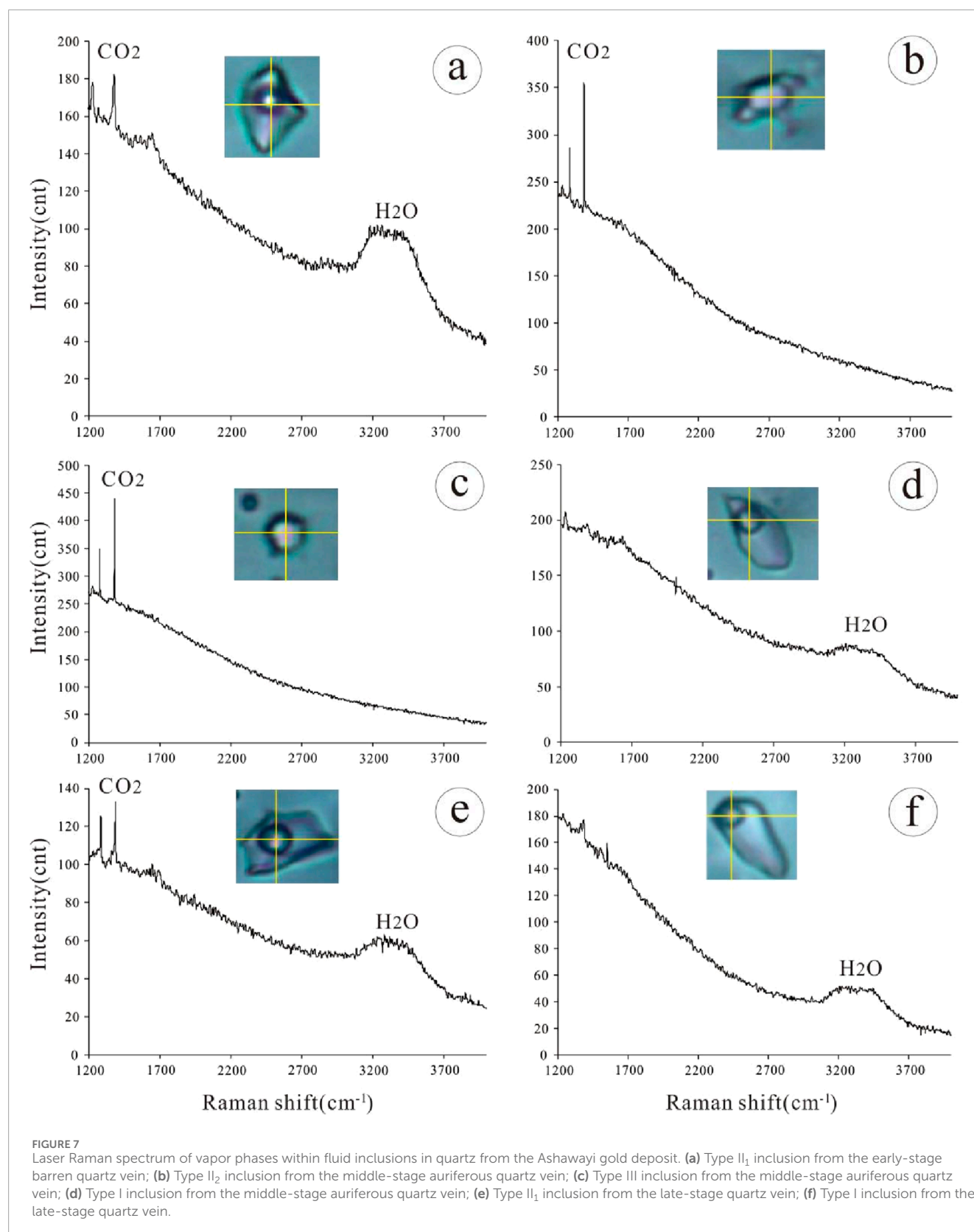
Twelve samples, including nine pyrite, one arsenopyrite, and two stibnite samples, were collected from gold ore bodies in the Ashaway gold deposit. Their $\delta^{34}\text{S}$ values range from 13.8‰ to 24.4‰ (Table 4). Specifically, pyrite and arsenopyrite, as gold-hosting minerals, exhibit $\delta^{34}\text{S}$ values ranging from 16.8‰ to 24.4‰, with an average of 18.6‰. Four samples of pyrite and arsenopyrite from wall rocks (phyllite or siltstone) have $\delta^{34}\text{S}$ values ranging from 17.1‰ to 18.5‰. Two samples from the fine-grained diorite rock have $\delta^{34}\text{S}$ values ranging from –6.9‰ to 1.5‰. Notably, $\delta^{34}\text{S}$ values of the ore bodies are similar to those of the wall rocks but differ significantly from those of the granitic rocks.

5 Discussion

5.1 Genetic type of deposit

Orogenic gold deposits form during compressional to transpressional deformation processes at convergent plate margins in accretionary and collisional orogens. These deposits exhibit temporal and spatial association with orogeny (Groves et al., 1998). They display similar geodynamic settings and geochemical characteristics, forming at various depths ranging from the earth's surface to 2–20 km, including the superficial zone (<6 km), middle zone (6–12 km), and deep zone (>12 km) (Groves et al., 1998). As an important mineralization type, 23 gold deposits worldwide, each with reserves exceeding 500 t, belong to the orogenic gold deposit category (Bierlein et al., 2006). Since the concept of orogenic gold deposits was introduced, extensive research has been conducted on their tectonic settings, mineralization characteristics, formation ages, ore-forming fluid features, and mineralization mechanisms (Bierlein and Maher, 2001; Wilde et al., 2001; Goldfarb et al., 2001; Groves et al., 2003; Mao et al., 2002; Chen YJ et al., 2004; Chen YJ, 2006; Bodnar et al., 2014; Derek et al., 2016; Damien, 2019). Concurrently, numerous orogenic-type gold deposits have been discovered.

A comprehensive comparison (Table 5) between the Ashaway gold deposit and the typical orogenic gold deposit was carried out regarding geological and mineralization fluid characteristics (Groves et al., 1998; Kerrich et al., 2000; Goldfarb et al., 2001; Chen YJ, 2006; Chen Y. J. et al., 2007). The Ashaway gold deposit shares many similarities with the typical orogenic gold deposit, including structural environment, host rock features,



ore-controlling structures, ore body shapes, ore types, mineral assemblages, fluid inclusion types, fluid properties, original fluid characteristics, main mineralization temperature, fluid pressure

system, and fluid evolution. Therefore, we propose that the genetic type of the Ashaway gold deposit is defined as an orogenic gold deposit.

TABLE 2 Microthermometric data on fluid inclusions in quartz from the Ashawayi gold deposit.

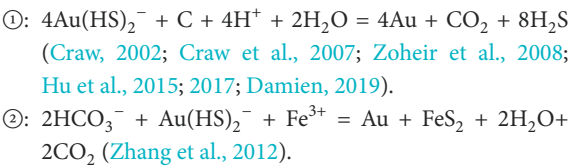
Sample	Type of inclusion	T _{m,CO2} (°C)	T _{m,cla} (°C)	T _{m,ice} (°C)	T _{h,CO2} (°C)	T _{h,tot} (°C)	C (NaCl eq.)
Early-stage quartz	I (26)			−0.1 to −4.3	206.8–351.4		0.12–6.88
	II ₁ (12)	−58.2 to −56.8	7.9–9.0		301.0–396.2	18.2–22.8	2.00–4.07
	II ₂ (2)	−57.6	8.5–8.6		427.8–428.4	18.7–22.6	2.77
	III (1)					23.0	
Middle-stage quartz	I (64)			−0.1to −9.1	111.2–321.8		0.18–12.96
	II ₁ (11)	−58.7 to −57.4	7.4–8.2		257.1–319.0	23.00–24.20	3.52–4.98
	II ₂ (4)	−58.6 to −57.9	7.5–7.6		299.8–351.4	16.8–17.5	4.60–4.80
	III (1)					18.6	
Late-stage quartz	I (24)			−1.3 to −6.0	144.9–248.6		2.24–9.21
	II ₁ (2)	−58	8.1		200.5	21.2	5.13

Note: T_{m,CO2}, CO₂-melting temperature of the solid phase; T_{m,cla}, CO₂-melting temperature of the cage compound; T_{h,CO2}, CO₂ part homogenization temperature; T_{m,ice}, ice-melting temperature; T_{h,tot}, complete homogenization temperature.

5.2 Fluid immiscibility and gold enrichment and deposition

The heterogeneous capture of fluid inclusions is prevalent in the Ashawayi gold deposit, with types I, II, and III inclusions coexisting within the same sample (Figure 6c). Two distinct types of fluid inclusions with differing characteristics occur in close association within the same sample, indicating simultaneous trapping. The simultaneous capture of fluids with distinct properties by minerals is most likely caused by heterogeneous trapping, which is an important indicator of fluid immiscibility or mixing (Ramboz et al., 1982; Roedder, 1984). The evolution of salinity and homogenization temperature of fluid inclusions during each metallogenic stage further supports the occurrence of fluid immiscibility: ① from the early to the middle stage of mineralization, fluid salinity increases and disperses as temperature decreases, contradicting the general trend that solubility decreases with decreasing temperature. High salinity predominantly occurs in type I inclusions, while type II inclusions are mainly characterized by low salinity (Figures 8, 9). This phenomenon may result from fluid concentration due to the escape of the gas phase, i.e., boiling. ② Some fluid inclusions exhibit varying salinities within approximately the same temperature range. Thus, the metallogenic process of the Ashawayi gold deposit resembles that of most vein-type mesothermal hydrothermal deposits worldwide, where fluid immiscibility plays a significant role in gold deposit formation (Drummond SE and Ohmoto H, 1985; Cox et al., 1995; McCuaig and Kerrich, 1998; Sibson et al., 1988; Jia et al., 2000; Chen YJ et al., 2005; Chen et al., 2006; Chen et al., 2012a; Chen et al., 2012b; Chen B et al., 2019; Skinner, 1997; Wilkinson, 2001). Between 320°C and 360°C, the fluid underwent its first immiscibility event, leading to the formation of various types of fluid inclusions through heterogeneous trapping. During this stage, initial gold mineralization occurred, although it was generally low, forming quartz veins with little to no mineralization.

In the temperature range of 220°C–300°C, primarily between 220°C–250°C, secondary fluid immiscibility occurred after the early fluid evolution stage. This resulted in higher salinity in the liquid phase and the formation of low-salinity and gas-rich inclusions, specifically high-salinity type I inclusions and low-salinity type II inclusions. Continuous CO₂ escape from the fluid ore-forming system led to fluid concentration and supersaturation, promoting the rapid precipitation of ore-forming materials (Sui et al., 2000; Chen H. Y. et al., 2007; Chen et al., 2012a; Chen et al., 2012b). Meanwhile, the escape of CO₂ will disrupt the stability of the Au(HS)₂[−] complex in the fluid, prompting the decomposition of the Au(HS)₂[−] complex and leading to the enrichment and precipitation of Au. The reaction equations are as follows:



In conclusion, secondary fluid immiscibility is thus a critical mechanism for gold enrichment and precipitation. Additionally, the water–rock reaction between the fluid and the surrounding rock may contribute to gold precipitation to some extent. These reactions not only extract ore-forming substances from the surrounding rock to promote fluid saturation but also consume H₂O during the reaction, further enhancing fluid concentration. For example, $\text{C} + 2\text{H}_2\text{O} = \text{CO}_2 + 2\text{H}_2$ (Cox et al., 1995; Naden and Shepherd, 1989). In the late stage, at temperatures between 180°C and 200°C, fluid immiscibility becomes less pronounced, characterized by temperature decrease. This stage is marked by occasional type II inclusions, absence of type III inclusions, homogenization of the fluid to the liquid phase, and decreased fluid salinity. Quartz–carbonate veins develop during this stage, with very weak or nominal mineralization.

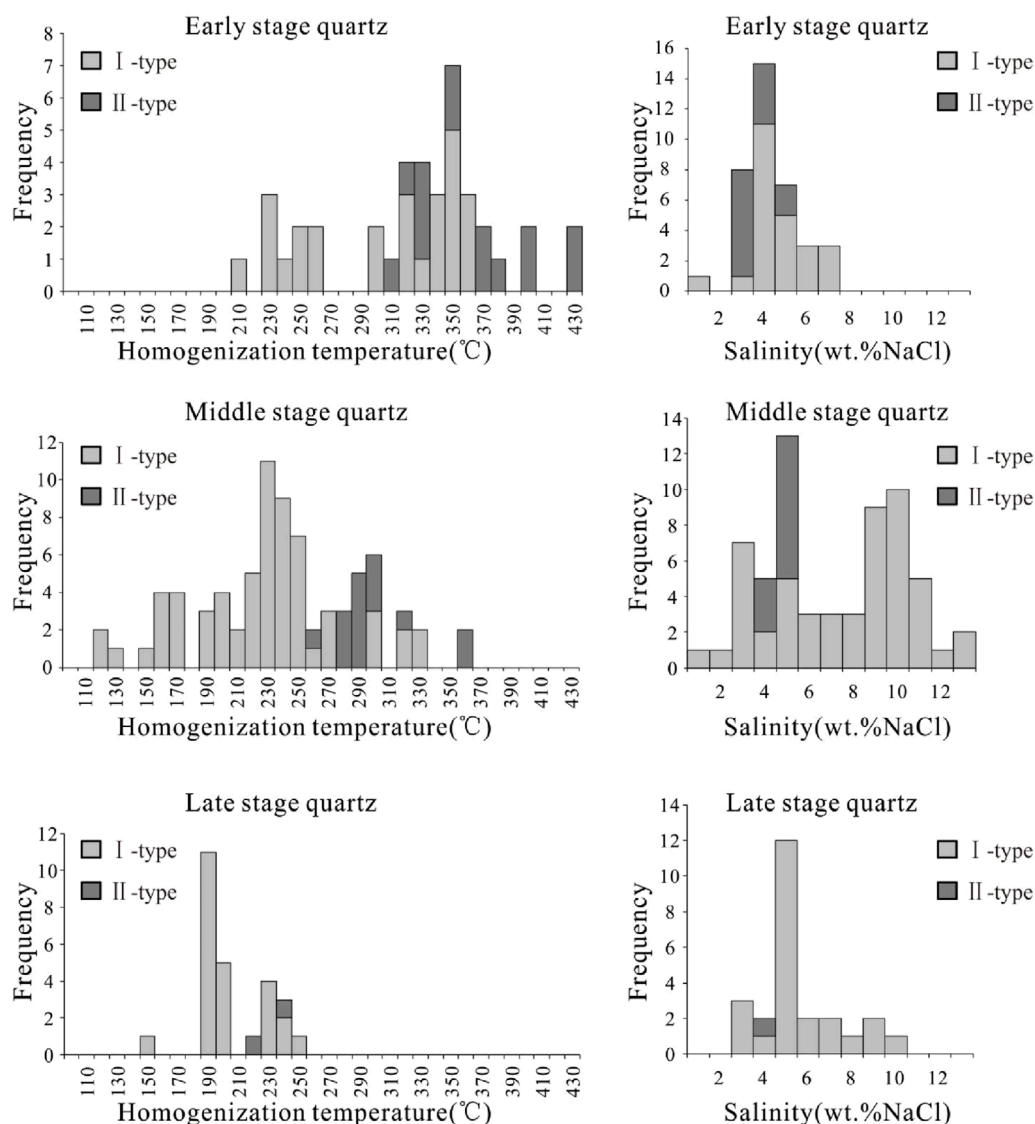


FIGURE 8
Histograms of salinities and homogenization temperatures of fluid inclusions in quartz from different mineralization stages of the Ashawayi gold deposit.

5.3 Pressure and depth estimation of the ore-forming fluid

The homogenization temperature (T) and pressure (P) of fluid inclusions trapped in the fluid boiling state are theoretically equal to the temperature and pressure at the time of trapping (Pichavant et al., 1982; Ramboz et al., 1982; Brown, 1998). However, this hypothetical condition does not apply to the Ashawayi gold deposit. As previously discussed, the fluids in the Ashawayi gold deposit underwent a complex inhomogeneous trapping process. Nevertheless, the mineralization depth was estimated using the homogenization pressure of fluid inclusions as the minimum trapping pressure.

After excluding homogenization temperatures from the main mineralization stage that were influenced by late-stage fluids

(homogenization T < 200°C), the depth is estimated using all remaining Type I and Type II inclusions, based on the minimum capture pressure. The pressures of types I and II inclusions are estimated based on the methods described by Bodnar and Vityk (1994) and the FLINCOR Program proposed by Brown (1989), respectively. The H₂O–CO₂–NaCl system was selected to estimate the mineralization depth. The results show two distinct pressure ranges: a low-pressure range (16.2–36.7 MPa) and a high-pressure range (75.0–103.6 MPa). The uncertainty in estimating the fluid capture depth (mineralization depth) makes it difficult to determine whether the estimated capture pressure is lithostatic or hydrostatic, which depends on the degree of opening and closing of the fault (Roedder, 1984). Fluid immiscibility indicated by fluid inclusions has special implications for the hydrodynamics of mineralization. One of the major causes of fluid immiscibility is the decrease

TABLE 3 H–O isotopic compositions in the fluid inclusions of quartz separated from ores in the Ashawayi gold deposit.

Sample	$\delta^{18}\text{O}_{\text{quartz}}$ (%)	T (°C)	$\delta^{18}\text{O}_{\text{water}}$ (%)	$\delta^{18}\text{D}_{\text{water}}$ (%)
As10	21.3	235	11.6	−82.8
As11	20.7	235	11.0	−73.6
As12	19.1	235	9.4	−84.8
As13	20.3	235	10.6	−72.6
As17	20.7	216	10.0	−72.3
As19	21.5	216	10.8	−69.2
As22	21.6	216	10.9	−71.4
As35	22	220	11.5	−69.8
As36	20.3	220	9.8	−71.3
As38	20.8	220	10.3	−73.7
As50	18.6	220	8.1	−72.2
As57	19.8	220	9.3	−72.2
As70	23.6	220	13.1	−83.6
As72	23.2	220	12.7	−84.1

in fluid pressure, which is directly related to fluid flow driving forces (Guoxiang and Steele-Macinnis, 2025). The co-existence or alternative appearance of lithostatic and hydrostatic pressure results from oscillations in fault healing and fracturing in orogenic gold deposits, as described using the Fault Valve Model (Sibson et al., 1988; Kerrich et al., 2000; Cox et al., 2001). When faults heal, fluids are under (super)lithostatic pressure due to tectonic overpressure, and when fracturing or hydrofracturing occurs, fluids are under hydrostatic pressure. The disappearance of vapor components removes heat, causing a decrease in the mineralization temperature and an increase in the salinity of the remaining fluid—sometimes to the point of oversaturation, thereby leading to the rapid deposition of ore-forming materials and subsequent fracture healing (Deng et al., 2008). Determining the values of these two types of pressures is crucial for accurate estimates. The mineralization depth remains relatively constant during the fluid deposition process, with pressure fluctuations triggered by changes between different pressure types. Lithostatic and hydrostatic pressures frequently change during fault closure and opening. If trapped fluid inclusions record both pressure types, the end members of the two pressure ranges can be considered. Since lithostatic pressure is higher than hydrostatic pressure at the same depth, the low-value pressure endmember is closer to hydrostatic pressure, while the high-value pressure endmember is closer to lithostatic pressure (Xu et al., 1995). The Ashawayi gold deposit is located in a thrust fault system. Ores' fabric features indicate that the mineralization process experienced a transition from compressive stress to intense stress with multistage action characteristics, suggesting multiple

fracture and closure processes that cause consistent fluctuations in fluid pressure.

Accordingly, we assume that the high- and low-pressure range fluids are under the pressure systems of static rock pressure and static hydrostatic pressure, respectively, and estimate them using the general formula for the pressure–depth relationship, $P = \rho gh$, taking ρ as the average rock density of the mining area at 2.6 g/cm^3 when the fluids are under the static rock pressure system and ρ as the density of various inclusions calculated at the time when the fluids are under the static hydrostatic pressure system. The corresponding fluid depth ranges are 1.8–4.2 km for the high-pressure range and 2.9–4.2 km for the low-pressure range. The high values of the depth ranges of the two are close, so the fluid may be in the depth range of 1.8–4.2 km due to the complex non-miscible process caused by the co-existence and alternation of static rock pressure and static hydrostatic pressure, resulting in the precipitation of gold. The following three points also directly or indirectly support the above viewpoint: (1) the estimated pressure range of Type II inclusions falls entirely within the low-pressure range, and the peak of the low-pressure range is located in the temperature range of 220°C–250°C, which is consistent with the result that Type I and Type II fluid inclusions are captured simultaneously by the fluid inclusions in the temperature range of 220°C–250°C due to the immiscibility of the fluid inclusions in this temperature range. (2) No Type II inclusions are found in the high-pressure range, only a part of Type I inclusions, i.e., no Type II inclusions are captured in the high-pressure peak range, which is consistent with the fact that the closed-system hydrofluids in the static rock pressure

TABLE 4 Sulfur isotopic compositions of sulfides from the Ashawayi gold deposit.

Sample	Mineral	$\delta^{34}\text{S}$ (‰)	Host rock
As2	Pyrite	−6.9	Fine-grained diorite
As3	Pyrite	1.5	Fine-grained diorite
As13	Pyrite	16.8	Ore
As17	Pyrite	18.6	Ore
As19	Pyrite	17.8	Ore
As22	Pyrite	18.0	Ore
As23	Pyrite	18.1	Ore
As26-1	Pyrite	18.4	Siltstone (wall rock)
As26-2	Arsenopyrite	18.5	Siltstone (wall rock)
As27	Pyrite	17.2	Phyllite (wall rock)
As28	Pyrite	17.1	Siltstone (wall rock)
As35	Pyrite	17.1	Ore
As36	Pyrite	17.9	Ore
As38-1	Pyrite	18.0	Ore
As38-2	Arsenopyrite	18.8	Ore
As57	Pyrite	24.4	Ore
As70	Stibnite	14.3	Ore
As72	Stibnite	13.8	Ore

system do not undergo obvious immiscibility. (3) Type I inclusions account for the majority of the total inclusions in the temperature range of 220°C–250°C, which is considered representative of the mineralization conditions.

It is noteworthy that the homogenization temperature range (220°C–250°C) under low-pressure conditions is comparable to the peak values observed in well-known mesothermal gold deposits such as the Muruntau, Kumtor, and Sawayaerdun deposits (Ivanove, 2000; Wilde et al., 2001; Graupner et al., 2001; Chen et al., 2012a) and other typical mesothermal vein-type gold deposits (Spooner et al., 1987; Goldfarb et al., 1989; Fan et al., 2003; Zhang et al., 2009; Hagemann and Luders, 2003). However, the corresponding mineralization depth (1.8–4.2 km) is significantly shallower than that of the Sawayaerdun gold deposit in Chinese Tianshan (Chen et al., 2012a).

5.4 Origins of ore-forming fluids and components

The $\delta^{18}\text{O}$ values of mineralized quartz from the Ashawayi gold deposit range from 18.6‰ to 23.6‰ (Table 3; Figure 10).

These values are higher than those of most lode gold deposits ($\delta^{18}\text{O} = 10\text{‰}–18\text{‰}$) (Kyser et al., 1986; Kerrich, 1987; Goldfarb et al., 1991; 1997; McCuaig and Kerrich, 1998; Ivanove, 2000; Kerrich et al., 2000; Jia et al., 2001; Chen et al., 2012b) but are similar to those of the Sawayaerdun gold deposit in southwestern Tianshan, China (Chen et al., 2012b). The elevated $\delta^{18}\text{O}_{\text{quartz}}$ values compared to those of other vein-type gold deposits (commonly in the temperature of 300°C–350°C; Ridley and Diamond, 2000) were likely caused by strong isotope fractionation under low-mineralization temperature conditions. The calculated $\delta^{18}\text{O}$ values of the mineralization fluid range from 8.1‰ to 13.1‰, which is consistent with those of most lode deposits.

The $\delta^{18}\text{D}$ values of the mineral-forming fluid range from −84.8 to −69.2‰ (Table 3; Figure 11). This range falls within that of most vein-type gold deposits (Kerrich, 1987; McCuaig and Kerrich, 1998; Ridley and Diamond, 2000; Chen et al., 2012b), but the interval is narrower than that of the Juneau gold mineralization belt in Alaska, United States (Goldfarb et al., 1991), and the Sawayaerdun gold deposit in China (Chen et al., 2012b). The peak value of $\delta^{18}\text{D}_{\text{water}}$ in the range of −68 to −72‰ is close to the $\delta^{18}\text{D}_{\text{water}}$ value of meteoric water (−70‰) in the Tianshan region, suggesting that part of the mineralization fluid may be derived from atmospheric precipitation. However, according to the low $\delta^{18}\text{D}_{\text{water}}$ value (<−80‰) obtained from lode gold deposits hosted by carbonaceous turbidite, the fluid is also sourced from reactions between deep-source non-atmospheric water and organic substances in the host rock, leading to depleted $\delta^{18}\text{D}_{\text{water}}$ (Goldfarb et al., 1989; McCuaig and Kerrich, 1998; Jia et al., 2001). As shown in Figure 12, the mineralization fluid of the Ashawayi gold deposit plots to the right of the metamorphic and igneous water fields, consistent with most vein-type gold deposits. It is comparable to the Juneau orogenic gold deposit belt (Goldfarb et al., 1991) and the Sawayaerdun gold deposit (Yang et al., 2006; Chen et al., 2012b). In conclusion, the fluids of the Ashawayi gold deposit are likely derived from a mixture of metamorphic fluid and meteoric water.

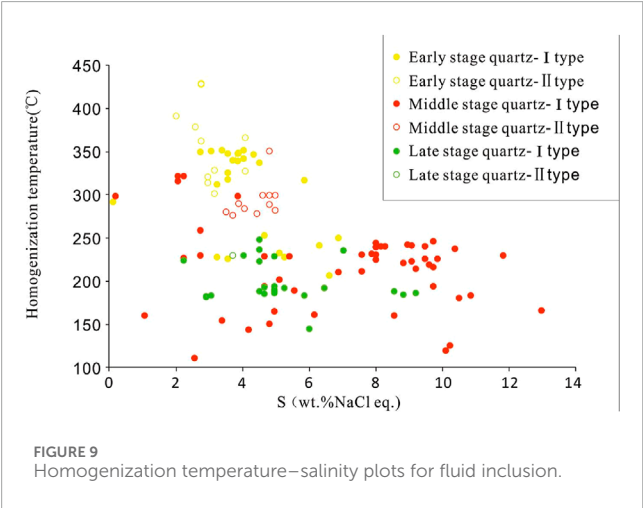
The amount of sulfides increases significantly from the early to the main mineralization phase, while the ratio of $\text{CO}_2\text{--H}_2\text{O}$ inclusions to total inclusions decreases markedly. This indicates a transition in the mineralized fluid from high oxygen fugacity during the early stage to low oxygen fugacity during the main stage. This feature is consistent with the low $\text{SO}_2/\text{H}_2\text{S}$ redox level observed in most orogenic gold deposits (Phillips and Groves, 1983; Mikucki and Ridley, 1993; McCuaig and Kerrich, 1998; Jia et al., 2000; Kerrich et al., 2000). At low oxygen fugacity and moderate temperature (220°C–250°C), S isotope fractionation between sulfide and fluid is generally minimal (<2‰, Ohmoto and Goldhaber, 1997). Therefore, the $\delta^{34}\text{S}_{\text{V-CDT}}$ values of sulfide and fluid in the main mineralization stage are similar.

The sulfides from orogenic gold deposits exhibit a wide range of $\delta^{34}\text{S}_{\text{V-CDT}}$ values, but the range of the S isotope in the S-complexion of mineralization fluid remains inconclusive (McCuaig and Kerrich, 1998; Goldfarb et al., 2005). For example, the $\delta^{34}\text{S}_{\text{V-CDT}}$ values of sulfides in Archean orogenic gold deposits range from 0‰ to 9‰ (Kerrich, 1987; Golding et al., 1990; McCuaig and Kerrich, 1998), whereas those in Phanerozoic orogenic gold deposits range

TABLE 5 Comparison of key features between the Ashaway gold deposit and orogenic deposits.

Comparison item	Typical orogenic gold deposit	Ashawayi gold deposit
Structural environment	Accretion wedge or collisional orogenic belt	Orogenic belt
Country rocks	Metamorphic rocks	Carbonaceous phyllite and siltstone
Ore-controlling structure	Ductile and brittle shear zone	Ductile and brittle shear zone
Shapes and occurrence of ore bodies	Vein and vertical extension	Vein, layer-like, mineralization in the range of 1300 m dispersion in the vertical direction; individual ore body is not controlled in the vertical direction
Typical texture and structure	Big vein, breccia, and net vein	Thin vein, breccia, and net vein
Alteration of wall rocks	Clear zoning in the side direction; not obvious in the vertical direction	Side zoning: silication, sericitization, carbonatization, and chloritization; not clear in the vertical direction
Ore types	Quartz vein and altered rocks	Thin quartz vein, silicified and pyritized phyllite, and siltstone
Mineral assemblage of ores	Main pyrite	Main pyrite and less arsenopyrite and stibnite
Mineralization element assemblage	Au and Ag ($\pm$ As, Sb, Te, W, Mo, Bi, and B)	Au–As–Sb
Inclusion types	CO ₂ -bearing and CO ₂ –H ₂ O. solution	H ₂ O (type I), CO ₂ –H ₂ O (type II), and CO ₂ (type III)
Indicative characters of fluids	Low-salinity; rich in CO ₂	Low-salinity; rich in CO ₂
Property of original fluids	Metamorphic fluid	Metamorphic fluid $\pm$ meteoric water (discussed later)
Main mineralization temperature	200°C–500°C	220°C–250°C
System of fluid pressure	Lithostatic–hydrostatic	Lithostatic and hydrostatic co-existed or alternatively appeared (discussed later)
Fluid evolution	Fluid rich in CO ₂ evolved into H ₂ O inclusion by releasing CO ₂ , immiscibility, or boiling; the salinity of the relict fluid increases	CO ₂ -bearing inclusion occurs 25% in the early stage and 10% in the middle stage, with occasional occurrence in the late stage; the salinity of the relict fluid in the middle stage is obviously higher than that in the early stage and decreases in the late stage (discussed later)

Note: The main reference materials for the characters of the orogenic gold deposit are obtained from the studies by Groves et al. (1998), Kerrich et al. (2000), Goldfarb et al. (2001), Chen YJ (2006), and Chen Y. J. et al. (2007).



–20‰–25‰ (Peters and Golding, 1989; Kontak et al., 1990). The $\delta^{34}\text{S}_{\text{V-CDT}}$ values of pyrite, arsenopyrite, and stibnite in the ore bodies range from +13.8‰ to 24.4‰ (Table 4). Specifically, pyrite and arsenopyrite, as gold-carrying minerals, have $\delta^{34}\text{S}_{\text{V-CDT}}$ values ranging from +16.8‰ to 24.4‰, with an average of +18.3‰. These values fall within the ranges typical of metamorphic and sedimentary rock and are significantly higher than those of basaltic and granitic rocks. They are consistent with the $\delta^{34}\text{S}_{\text{V-CDT}}$ values (17.1‰–18.5‰) of pyrite and arsenopyrite in phyllite and siltstone, which are the wall rocks of the ore bodies. In contrast, the $\delta^{34}\text{S}_{\text{V-CDT}}$ values (–6.9‰–1.5‰) of the rock body in the diggings (Figure 13) indicate that the ore components are derived from wall rocks. Compared with that in other well-known orogenic gold deposits, such as the Juneau gold belt (Goldfarb et al., 1989), the Bendigo in Australia (Jia et al., 2001), the Kumtor in Kyrgyzstan (Ivanove, 2000), and the Sawayaerdun in China (Chen et al., 2012b), the positive anomaly of $\delta^{34}\text{S}_{\text{V-CDT}}$ in the Ashawayi

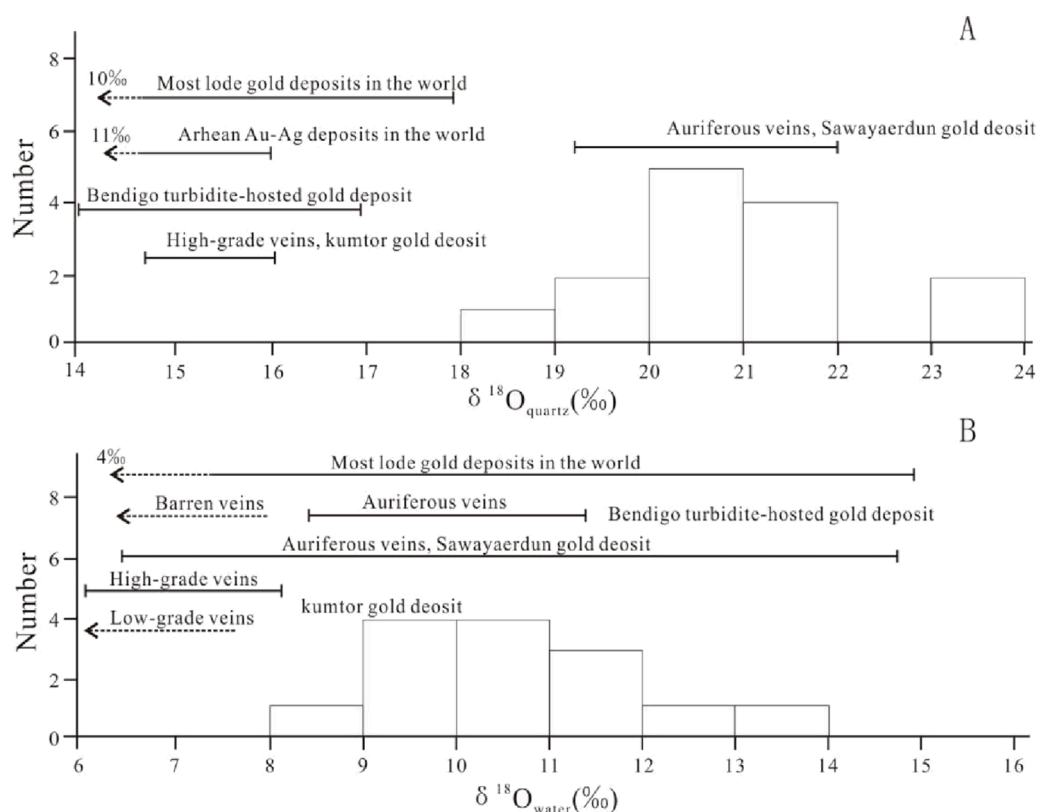


FIGURE 10
Oxygen isotopic compositions of quartz (A) and ore-forming fluids (B). References for the isotopic ranges of deposits are given in the text.

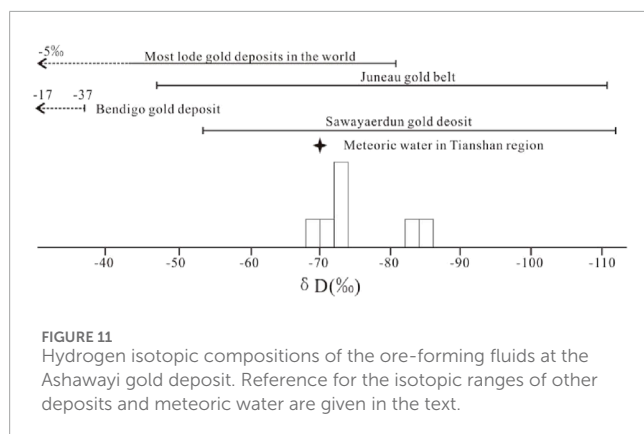


FIGURE 11
Hydrogen isotopic compositions of the ore-forming fluids at the Ashawayi gold deposit. Reference for the isotopic ranges of other deposits and meteoric water are given in the text.

gold deposit suggests that the sulfur in the ores originates primarily from a shallow position within the orogenic belt and upper crust.

5.5 Comparison of metallogenic setting and prospecting direction

Numerous giant and ultra-large orogenic gold deposits have been discovered in the Southern Tianshan region of Central Asia. In contrast, only one ultra-large deposit, Sawayaerdun, has been

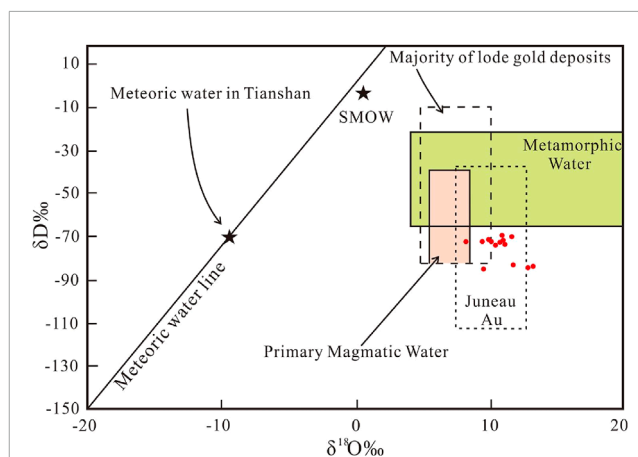
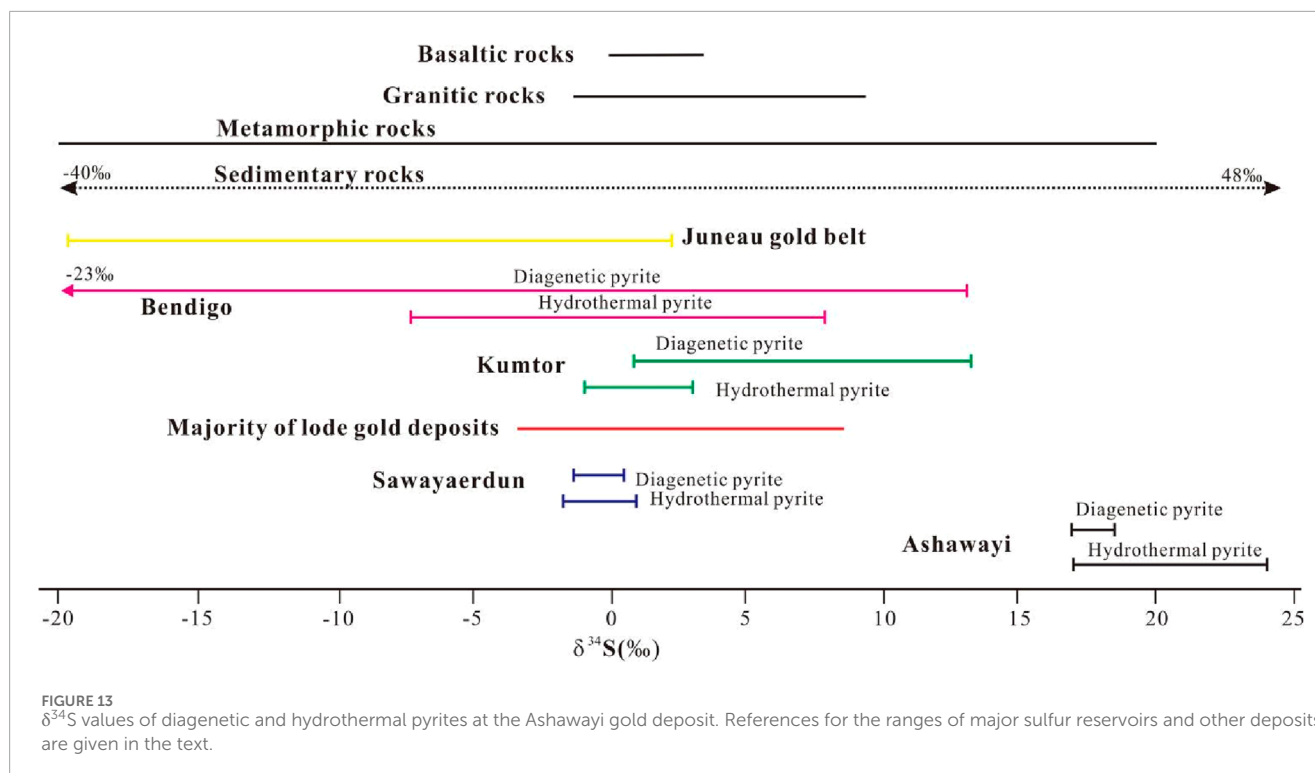


FIGURE 12
Calculated δD and $\delta^{18}\text{O}$ values of the fluid at the Ashawayi gold deposit. References for the fields of other deposits are given in the text [Fields for magmatic and metamorphic waters are obtained from Taylor (1997)].

identified in Southern Tianshan in Xinjiang Province. Although the Ashawayi gold deposit ranks second in scale, it is only moderately large and has relatively low gold grades. To understand the significant disparity in gold scale and ore grade between deposits formed within the same geological evolution history, we compare



factors such as the ore-hosting formation background, structural superposition, magmatic activity, and ore denudation. The reasons for the lower size and grade of the Southern Tianshan deposits in Xinjiang Province than those in Central Asia can be summarized as follows: (1) the ore-hosted strata in the Southern Tianshan of Xinjiang Province are relatively young and thin and have a low carbon content, lacking a material basis for large-scale gold mineralization. (2) The crust in the Southern Tianshan of Xinjiang Province is relatively thick, leading to shallow fracture depths, limited denudation, weak deformation, and low metamorphism. (3) Magmatic activity in the Southern Tianshan of Xinjiang Province is relatively weak, resulting in less intense crust–mantle interaction and a relative lack of magmatic activation and re-enrichment processes for gold.

Based on this analysis, future prospecting efforts at Ashawayi should focus on strata with high carbon content formations and areas subject to strong structural deformation and metamorphism, such as the intersection of low-angle and high-angle faults to the northeast of the mining area.

6 Conclusion

- (1) The Ashawayi gold deposit is classified as an orogenic gold deposit in the Southern Tianshan. It shares similar characteristics with most orogenic gold deposits worldwide in terms of ore-forming structural environments, fluid characteristics and evolution, mechanisms of gold enrichment, and estimates of ore-forming conditions (temperature and pressure).
- (2) The mineralization process can be divided into three stages: the early stage is a quartz-growth stage with minimal or no

mineralization; the intermediate stage is a quartz–polymetallic sulfide stage; the late stage is a quartz–carbonatization stage.

- (3) Three types of fluid inclusions have been identified, namely, $\text{NaCl-H}_2\text{O}$, CO_2 -bearing aqueous solution, and pure CO_2 . Fluid inclusion temperature ranges from 320°C to 360°C in the early stage and 220°C–300°C in the late stage, indicating that the Ashawayi gold deposit belongs to the medium–low temperature hydrothermal deposit. Distinct fluid immiscibility features are observed from the early to the intermediate stage, with continuous CO_2 release. In the main mineralization stage, low homogenization pressures (16.2–36.7 MPa) and high homogenization pressures (75.0–103.6 MPa) suggest the co-existence or alternation of hydrostatic and lithostatic pressure systems at depths of 1.8–4.2 km. Fault healing and fracturing, controlled by fault–valve action, induce secondary fluid immiscibility, which is a critical mechanism for gold enrichment and deposition.
- (4) The H–O–S isotopic characteristics of the mineralization fluid indicate that ore components are derived from the country rocks, while the ore-forming fluids originate from metamorphic fluid and meteoric water.

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 authors.

Author contributions

BC: Investigation, Methodology, Project administration, and Writing – original draft. HC: Data curation, Formal analysis, Writing – review and editing. WX: Data curation, Methodology, Writing – review and editing. YW: Data curation, Supervision, Writing – review and editing. YZ: Supervision, Validation, 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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