Research Article

Fluid Inclusion and H–O–S–Pb Isotope Geochemistry of the Yuka Orogenic Gold Deposit, Northern Qaidam, China

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The Yuka gold deposit, located in the western part of northern Qaidam, contains Au orebodies hosted in early Paleozoic metamorphic basic volcanoclastic rocks. The Yuka mineralization can be divided into three stages: early quartz-pyrite (stage-I), middle quartz-gold-polymetallic sulfide (stage-II), and late quartz-carbonate (stage-III). Gold deposition is primarily contained within stage-II. Three types of fluid inclusions were identified in the vein mineral assemblages using petrography and laser Raman spectroscopy: H₂O-CO₂-NaCl (C-type), H₂O-NaCl (W-type), and pure CO₂ (PC-type). Stage-I fluids record medium temperatures (205.2°C to 285.5°C) and H₂O-CO₂-NaCl±CH₄ fluids with variable salinities (0.6–8.5 wt.% NaCl equiv.). Stage-II fluids evolved towards a more H₂O-rich composition within a H₂O-CO₂-NaCl±CH₄ hydrothermal system at medium temperatures (193.1°C to 271.1°C), with variable salinities (0.4–11.7 wt.% NaCl equiv.). Stage-III fluids are almost pure H₂O and characterized by low temperatures (188.1°C to 248.5°C) and salinities (0.4–16.1 wt.% NaCl equiv.). These data indicate that ore-forming fluids are characterized by low to medium homogenization temperatures and low salinity and are evolved from a CO₂-rich metamorphogenic fluid to a CO₂-poor fluid due to inputs of meteoric waters, which is similar to orogenic-type gold deposits. The average $\delta^{18}\text{O}_w$ of quartz varies from 3.3‰ in stage-I to 2.1‰ in stage-II and to 1.4‰ in stage-III, with the δD values ranging from −41.6‰ to −58.5‰, suggesting that ore-forming fluids formed from metamorphic fluids mixed with meteoric waters. Auriferous pyrite $\delta_{34}\text{S}$ ranges from 0.5 to 7.4‰ with a mean value of 4.43‰, suggesting that fluids were partially derived from Paleozoic rocks via fluid-wall rock interactions. Auriferous pyrites have $^{206}\text{Pb}/^{204}\text{Pb}$ of 18.238–18.600 (average of 18.313), $^{207}\text{Pb}/^{204}\text{Pb}$ of 15.590–15.618 (average of 15.604), and $^{208}\text{Pb}/^{204}\text{Pb}$ of 38.039–38.775 (average of 38.1697) and stem from the upper crust. Basing on geological characteristics of the ore deposit as well as new data from the ore-forming fluids, and H–O–S–Pb isotopes, the Yuka gold deposit is best described as an orogenic-type gold deposit.

1. Introduction

Orogenic gold deposits are an important type of deposit formally proposed by Groves et al. [1], which account for more than 30% of the world's gold reserves. Orogenic gold deposits form in accretionary and collisional orogenic belts dominated by extrusion, and strike-slip deformation is associated with relatively low-stress areas, such as secondary fractures [1, 2]. Most orogenic gold deposits are formed under greenschist facies metamorphic conditions [3–6]. Fluids within

orogenic gold deposits have low salinity ($\leq 10\%$ NaCl eqv.), high carbon (CO₂+CH₄ content is 5%–30%), low Cl, and high S content [7]. Au is considered to be transported by the Au(HS)₂[−] complex in fluids [3]. Ore-forming fluids may come from a variety of sources including (1) rock metamorphism [8], (2) carbonaceous sediment deposits [9], (3) magmatic fluids [10], (4) seawater [11], and (5) metamorphic dehydration [12, 13].

Orogenic gold deposits have been an important source of gold in China [2] and are widely distributed in the Tian Shan

FIGURE 1: (a) Distribution of major continental blocks and oceanic plates around China, based on Google Earth. (b) Space-time distribution of investigated gold deposits in mainland of China (modified after Deng and Wang [5]).

orogenic belt [14, 15], Ailaoshan tectonic belt [16–18], northern margin of North China Craton [19–21], and orogenic belts of northwestern China [22, 23] (Figure 1). The northern Qaidam orogenic belt (NQOB) is an orogenic belt in northwestern China that hosts a range of Au, Cu, Pb, and Zn deposits [23–28]. However, little research has been published on these gold deposits in international literature until now, which restricts our understanding of these gold deposits in NQOB.

The Yuka gold deposit is hosted within metamorphic rocks and contains 5.6 t of Au at an average grade of 2.14 g/t in the northwestern NQOB [29]. To date, no published researches of the Yuka gold deposit exist, and its genesis as well as the ore-forming fluids that remains unclear. An accurate assessment of the nature and composition of the mineralizing fluids is a key to understanding the origin of the deposit [30, 31]. In this paper, we report dating from fluid inclusion and H–O–S–Pb isotope of the ores from the Yuka

FIGURE 2: (a) Schematic map showing the major tectonic units in NW China (modified after Song et al. [40]); (b) simplified map showing the tectonic framework of the northern margin of the Qaidam basin and spatial location of the Yuka gold deposit. Orogenic gold mineral deposits: 2: Yeluotuoquan; 3: Qianmeiling; 4: Hongliugou; 5: Qinglonggou; 6: Tanjianshan; 9: Saibagou; 10: Qiulute; 12: Yuka. Cu(Au) porphyry mineral deposits: 1: Xiaosaishitengshan. Sedex Pb-Zn(Au): 8: Xitieshan. VHMS Cu(Au): 7: Luliangshan; 11: Qinglongtan (modified after Zhang et al. [23]).

gold deposit. This approach provides an excellent opportunity to determine the direct link between the ore-forming fluid character and ore genesis. Our research would be helpful to understanding of this class of orogenic gold deposit, which might be helpful for further exploration of the orogenic belts of northwestern China.

2. Geological Setting and Ore Geology

2.1. Geological Setting. The NQOB strikes NW-SE, is about 900 km long, and is 25 to 160 km wide (Figure 2). Paleozoic to Mesozoic sedimentary rocks deposited on the Precambrian basement make up the Qilian block in the north. To the south lies the Qaidam block (or Qaidam basin), which is a Mesozoic to Cenozoic intracontinental basin developed on the Precambrian crystalline basement (Figure 2) [32]. The Qaidam boundary faults (Figure 2) separate the NQOB from the Oulongbuluke block to the north and formed the Qaidam block to the south [33, 34]. At its northwestern ter-

mination, the orogenic belt is cut by the Altyn Tagh fault [35] (Figure 2). Several studies have suggested that the northern Qaidam ocean basin was subducted during the Early Ordovician, and collision with Qilian block occurred during the Late Ordovician to Middle Devonian [36–39].

Major lithostratigraphic units of the NQOB consist of the Paleoproterozoic Dakendaban Group, Early Paleozoic arc-related volcanic and sedimentary rocks of Tanjianshan Group and Devonian molasse, and Early Paleozoic granitic rocks [37–45]. Previous studies have interpreted geochronological and geochemical studies of HP/UHP metamorphic rocks (eclogite and gneiss) from NQOB as reflecting the evolution of a continental orogen from early seafloor subduction (>440 Ma) to continental subduction and collision (440–420 Ma), to the exhumation of the subducted slab (420–390 Ma), and to the final orogen collapse (390–360 Ma) [32, 36, 39, 40, 46–52]. Moreover, Wu et al. [53] have summarized data for NQOB granitoids; the following five periods of granitic magmatism occurred between the Ordovician and

Triassic: (1) oceanic crust subduction (465–473 Ma), (2) continental crust subduction (423–446 Ma), (3) slab broke off and exhumation of the north Oulongbruk block rifting (391–413 Ma), (4) lithosphere mantle delamination and Zongwulong ocean forming (372–383 Ma), and (5) Zongwulong oceanic crust subduction (240–271 Ma). Many magmatism of accretion-related crustal thickening had occurred during Late Silurian and Early Devonian [54].

Metallogenic models for subduction-related accretionary orogeny predict that the NQOB should be favorable for orogenic-type mineralization [4, 5, 16, 31]. Actually, the NQOB contains numerous orogenic gold deposits (e.g., Yeluotuoquan, Qianmeiling, Hongliugou, Qinglonggou, Tanjianshan, Saibagou, Qiulute, and Yuka), which are mainly divided into two types: quartz vein types and altered rock [16, 23, 55–57]. These orogenic gold deposits are a primarily altered rock type hosted in shear zones developed in Mesoproterozoic, Cambrian, and Ordovician low-grade metamorphic rocks [5]. Some deposits have reported metallogenic ages, such as the sericite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 409.4 ± 2.3 Ma, 425.5 ± 2.1 Ma, and 246 ± 3 Ma for the Qinglonggou, Saibagou, and Yeluotuoquan deposits, respectively [23, 55–57]. The Tanjianshan gold deposit is the largest gold deposit in the NQOB. While the mineralization age is not well constrained, sericite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 400 Ma and 284 Ma for [57], a K–Ar age of 268.9 ± 4.3 Ma and a Rb–Sr isochron age of 288 ± 9.7 Ma for hydrothermal minerals [23], and zircon U–Pb age of 344.7 ± 2.0 Ma for a granite [58] from Tanjianshan gold deposit have been reported.

As part of a regional large-scale NW-trending shear zone in the NQOB, shear zones within the study area experienced two main deformation events and directly control gold deposition [23]. Based on tectonic and geochronological data for the metallogenic events, Zhang et al. [23] have divided the gold mineralization, which is closely associated with accretionary and collisional orogeny in the NQOB, into two phases: Early Paleozoic and Late Paleozoic to Early Mesozoic. The above metallogenic ages indicate that gold deposits in the NQOB are related to plutonic or metamorphic/tectonic events that happen during composite orogenic processes.

2.2. Geology of the Yuka Gold Deposit. The Yuka eclogite-gneiss terrane is located in western NQOB, which mainly consists of Yukahe Group (granitic gneisses and pelitic schists/gneisses) that is in fault contact with the Early Paleozoic island arc volcanic rocks of the Tanjianshan Group and Cambrian gabbros in the east (Figure 3(a)). Two types of eclogite have been recognized as layer- or lens-shaped blocks and bound in aged dykes within granitic and pelitic schists/gneisses [59–62]. In situ zircon dating has established that the Yukahe gneiss group eclogite experienced UHP metamorphic ages of ca. 430–434 Ma [33, 51, 63]. For granitic gneisses in the Yukahe gneiss group, zircon U–Pb dating yielded 0.9–1.0 Ga protolith ages and 420–480 Ma metamorphic ages [64, 65].

The Yuka gold deposit is located in east Yuka eclogite-gneiss terrane and is hosted within thick-layered intermediate-basic volcanoclastic rocks ascribed to the Tanjianshan Group. A series of NW- to WNW-trending ductile

shear zones are marked by well-defined mylonites overprinting the metamorphic volcanoclastic rocks (basaltic tuff or tuffaceous slate) of the Tanjianshan Group and constrain the occurrence of gold deposits. These narrow mylonite zones are defined by a mylonitic foliation generally dipping NE at $45\text{--}70^\circ$ and have an along-strike length of about 300–800 m. Shear zone width ranges from meters to tens of meters. Gold mineralization occurs primarily in shear zone centers and decreases sharply away from the shear zones.

Gold orebodies in the Yuka gold deposit are stratiform or lenticular in shape, centimeter- to meter-thick, and parallel to the mylonitic foliation (Figure 3(b)). The longest single ore body is 800 m long, and gold grade varies from 1 to 28 g/t [29]. Mineralization types generally include gold-bearing quartz veins (Figures 4(a) and 4(d)) and altered gold-bearing mylonites (Figures 4(b) and 4(c)). The main ore minerals are comprised of native gold, pyrite, and chalcopyrite. Secondary oxidized minerals include limonite, malachite, hematite, and covellite. The predominant gangue minerals are quartz and calcite, with a small amount of epidote and chlorite.

There are three stages of the hydrothermal ore-forming processes of Yuka gold deposit on the basis of field observations, mineral assemblages, and cross-cutting relationships. Stage-I quartz veins are characterized by a pyrite-quartz mineral assemblage with little gold mineralization (Figure 4(d)). Pyrite within stage-I quartz veins is mostly idiomorphic and is middle fine to middle coarse (Figures 4(g) and 4(h)). Stage-II quartz veins, which are regarded as the main ore-forming stage, cross-cut early-stage ore minerals (Figure 4(f)). Disseminated sulfide minerals (e.g., pyrite and chalcopyrite) and native gold fill gaps in stage-II quartz veins (Figures 4(g) and 4(h)). Stage-III calcite-quartz veins are without gold (Figure 4(e)).

3. Samples and Analytical Methods

3.1. Fluid Inclusions. Samples in this research are mainly collected from the Zk0702 and Zk0703 drill holes, which related to no. 3 orebody. The sampling method accounted for observations from the drill core and the three-stage mineralization evolution (Figure 3(c)). 18 quartz-rich samples from different forming stages of orebody were made doubly polished and ~ 0.20 mm thick thin sections (Figure 3(c)). The spatial distribution, shape, and vapor/liquid ratios of fluid inclusions were observed.

Representative fluid inclusions were analyzed using microthermometric measurements and laser Raman spectroscopy analysis. The microthermometric study was completed at the State Key Laboratory of Geological Processes and Mineral Resources (GPMR), China University of Geosciences (Wuhan), using a Linkam THMS600 heating-freezing stage with a temperature range of -196°C to $+600^\circ\text{C}$. The reproducibility of these measurements is $\pm 0.1^\circ\text{C}$ below 30°C , and heating and freezing temperatures are reproducible within $\pm 1^\circ\text{C}$ and $\pm 0.1^\circ\text{C}$, respectively. NaCl–H₂O inclusion salinities were calculated using the final melting temperatures of ice [66]. The melting temperature of clathrate of CO₂-bearing fluid inclusions is used to calculate the salinity [67].

FIGURE 3: (a) Regional geological map of the Yuka district; (b) geology and distribution of the Yuka gold deposit; (c) geological section along the 07 exploration line of Yuka gold deposit.

FIGURE 4: Photographs and photomicrographs of microstructures from the Yuka gold deposit. (a) Gold quartz vein. (b) Gold-containing altered mylonite. (c) Stage-II quartz and sericite schist. (d) Stage-I quartz and stage-II quartz. (e) Stage-II quartz and stage-III calcite + quartz. (f) Stage-I pyrite and stage-II pyrite with chalcopyrite. (g) Stage-II pyrite with native gold. (h) Cubic crystal stage-I pyrite. Abbreviation: Mal = malachite; Qtz = quartz; Py = pyrite; Ccp = chalcopyrite; Cal = calcite.

FIGURE 5: Photomicrographs of typical fluid inclusions in the Yuka gold deposit. (a) Primary PC-type fluid inclusion in stage-I quartz. (b) Primary C-type fluid inclusion in stage-I quartz. (c) Primary C- and W-type fluid inclusions in stage-II quartz. (d) W-type fluid inclusions in stage-II quartz. Abbreviation: V_{CO_2} = vapor CO_2 ; L_{CO_2} = liquid CO_2 ; V_{H_2O} = vapor H_2O ; L_{H_2O} = liquid H_2O .

3.2. Oxygen and Hydrogen Isotope Analysis. Oxygen and hydrogen isotope analysis of ten ore-related quartz samples was carried out at the Analytical Laboratory in Beijing Research Institute of Uranium Geology, China National Nuclear Corporation (CNNC), using a MAT253-EM mass spectrometer. Oxygen was extracted from 10 to 20 mg of quartz using the BrF₅ method [68]. The hydrogen isotope compositions of fluid inclusions in quartz were analyzed using the decrepitation of fluid inclusions. The analytical precisions are $\pm 0.2\%$ and $\pm 0.2\%$ for $\delta^{18}O$ and δD , respectively. Oxygen isotope ratios of water in equilibrium with quartz were calculated using the equation $1000 \ln \alpha_{\text{quartz-H}_2O} = 3.38 \times 10^6 T^{-2} - 3.40$ [69], where T is the maximum homogenization temperature of fluid inclusions.

3.3. Sulfur Isotope Analysis. Sulfur isotopic analysis was carried out on ten pyrite samples from the stage-II quartz from the no. 2 and no. 3 orebodies. Sulfur isotopic ratios were determined using a MAT-251 mass spectrometer at the Analytical Laboratory in Beijing Research Institute of Uranium Geology, CNNC. Sulfur isotopic compositions of sulfide minerals were measured using the conventional combustion method [70]. The results are reported as $\delta^{34}S$ relative to Vienna Canon Diablo Troilite (V-CDT) sulfide, and the analytical precision is better than $\pm 0.2\%$.

3.4. Lead Isotopes. Ten of the sulfur isotope samples (pyrite) were analyzed for Pb isotopic compositions. Lead isotopic compositions were measured using a MAT-261 thermal ionization mass spectrometer with the standard sample NBS 981 at the analytical laboratory of Beijing Research Institute of Uranium Geology. The analytical precision for $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ is better than $\pm 0.05\%$.

4. Results

4.1. Fluid Inclusions

4.1.1. Petrography and Classification. Petrographic observations indicate that fluid inclusion assemblages (FIs) are widely distributed in quartz veins from the Yuka gold deposit. According to textures, compositions, and phase proportions at room temperature [71], we divide FIs into the following three major types: (1) aqueous-carbonic (H_2O - CO_2 -NaCl; C-type), (2) aqueous (H_2O -NaCl; W-type), and (3) pure carbonic (CO_2 ; PC-type) (Figure 5). In descending order, the abundance of fluid inclusions is C-type > W-type > PC-type.

C-type FIs are two-phase inclusions (liquid H_2O +liquid CO_2) with multiphase compositions (liquid H_2O +liquid

TABLE 1: Microthermometric data for fluid inclusions of different stages from the Yuka gold deposit. Table 1 is reproduced from Chai et al. [77], (under the Creative Commons Attribution License/public domain).

Sample no.	Host mineral	FI type	Number	T_{m-CO_2} (°C)	T_{m-cla} (°C)	T_{h-CO_2} (°C)	T_{m-ice} (°C)	T_h (°C) (L-V)	Salinity (wt.% NaCl equiv.)	Stage
ZK0702-12	Quartz	PC	7	-59.4~-56.7		12.4~28.1				I
ZK0702-8	Quartz	C	21	-60.0~-56.6	5.4~9.5	15.6~29.4		205.2~266.4	1.0~8.5	I
ZK0702-9	Quartz	C	23	-59.4~-56.6	5.7~9.6	15.9~29.1		233~285.5	0.8~8.0	I
ZK0702-10	Quartz	C	28	-59.5~-56.7	5.9~9.7	16.6~29.4		206~274.5	0.6~7.8	I
ZK0703-4	Quartz	C	18	-59.8~-56.8	5.6~9.4	17.8~29.3		233~284.3	1.2~8.1	I
ZK0702-11	Quartz	C	22	-60.0~-56.6	5.9~9.5	12.9~26.8		223.4~255.5	1.0~7.8	II
ZK0703-5	Quartz	C	18	-60.5~-56.7	5.4~9.6	14.8~29.4		222.2~256.1	0.8~8.5	II
ZK0702-13	Quartz	PC	5	-58.4~-56.6		7.7~27.6				II
ZK0702-1	Quartz	W	26				-0.7~-5.3	210.4~265.0	1.3~10.8	II
ZK0702-2	Quartz	W	24				-0.5~-4.9	193.1~257.1	0.9~9.9	II
ZK0702-3	Quartz	W	29				-0.2~-5.3	196.0~253.1	0.4~10.8	II
ZK0702-4	Quartz	W	16				-1.3~-4.9	209.4~268.1	2.4~9.9	II
ZK0702-5	Quartz	W	25				-1.2~-4.5	198.0~267.5	2.2~9.0	II
ZK0702-6	Quartz	W	20				-0.2~-5.7	203~271.1	0.4~11.7	II
ZK0703-1	Quartz	W	21				-0.8~-4.9	188.1~248.5	1.5~9.9	III
ZK0703-2	Quartz	W	21				-1.6~-4.4	193.4~241.2	3.0~8.7	III
ZK0703-3	Quartz	W	32				-0.8~-4.9	190.2~242.4	1.5~9.9	III
ZK0702-7	Quartz	W	17				-0.2~-4.5	188.1~241.6	0.4~9.0	III

Note: T_{m-CO_2} = final melting temperature of solid CO_2 ; T_{m-cla} = final melting temperature of CO_2 - H_2O clathrate; T_{h-CO_2} = homogenization temperature of CO_2 phases; T_{m-ice} = final melting temperature of ice; T_h = homogenization temperature; wt.% NaCl equiv. = weight percent NaCl equivalent.

CO_2 +vapor CO_2) at room temperature (Figures 5(b) and 5(c)) and are the primary and pseudosecondary inclusion types in stage-I quartz and stage-II quartz. C-type FIs are commonly flat, irregularly shaped, or in long strips, containing a vapor bubble that represents <20 vol% of the respective inclusion. W-type FIs consist of vapor and liquid water aqueous inclusions and are formed during stage-II to stage-III (Figures 5(c) and 5(d)). W-type FIs account for 50% of the total FI population. PC-type FIs are either single-phase or two-phase (liquid CO_2 +liquid CO_2) and only formed during stage-I (Figure 5(a)).

4.1.2. Homogenization Temperatures and Salinities. The dating from the primary liquid-rich fluid inclusions ($n = 377$) was obtained from the three forming stages of Yuka gold deposit (Table 1) (Figure 6).

(1) Stage-I Quartz

Stage-I quartz crystals contain dominantly C-type with rare PC-type fluid inclusions. Homogenization temperatures of C-type FIs ($n = 90$) vary from 205.2°C to 285.5°C. The first melting temperatures (T_{m-CO_2}) of solid CO_2 in C-type FIs range from -60.0°C to -56.6°C. Clathrate melting temperatures (T_{m-cla}) range from 5.4°C to 9.7°C, which correspond to salinities ranging from 0.6 to 8.5 wt.% NaCl equiv. (Figure 6, Table 1). The CO_2 phase of C-type FIs is completely homogenized when temperatures (T_{h-CO_2}) are between 15.6°C and 29.4°C. PC-type FIs ($n = 7$) yield melting temperatures (T_{m-CO_2}) of solid CO_2 ranging from -59.4°C to -56.7°C and homogenization temperatures (T_{h-CO_2}) of CO_2 ranging from 12.4°C to 28.1°C (Table 1).

(2) Stage-II Quartz

Quartz crystals from the main gold stage-II contain many C-type and W-type and relatively few PC-type FIs. C-type FIs ($n = 40$) were homogenized at 222.2~256.1°C. Clathrate melting temperatures (T_{m-cla}) range from 5.4°C to 9.6°C, which corresponds to salinities between 0.8 wt.% and 8.5 wt.% NaCl equiv. (Figure 6, Table 1). Homogenization temperatures (T_{h-CO_2}) of CO_2 are between 12.5°C and 29.4°C. W-type FIs ($n = 140$) were homogenized at 193.1~271.1°C and contain salinities between 0.4 wt.% and 11.7 wt.% NaCl equiv. (Figure 6, Table 1). PC-type FIs ($n = 5$) yield melting temperatures (T_{m-CO_2}) of solid CO_2 ranging from -58.4°C to -56.6°C and homogenization temperatures (T_{h-CO_2}) of CO_2 ranging from 7.7°C to 27.6°C (Table 1).

(3) Stage-III Quartz

Stage-III quartz only observed W-type fluid inclusions, which were homogenized to liquid at temperatures ranging from 188.1°C to 248.5°C. Their final ice melting temperatures range from -4.9°C to -0.2°C, and salinities range from 0.4 wt.% to 9.9 wt.% NaCl equiv. (Figure 6, Table 1).

Generally, temperatures decrease from stage-I to stage-III, but salinity shows nearly the same range for all stages, and maximum values are slightly higher in stage-II.

4.1.3. Laser Raman Spectroscopy. Laser Raman spectroscopy studies indicate that the ingredient (Figure 7(b)) of the primary C-type FIs from stage-I and stage-II contains a CO_2 vapor phase (1285 cm^{-1} and 1388 cm^{-1}) with minor amounts of CH_4 (2916 cm^{-1}) and a liquid phase with a large amount of water (3438 cm^{-1}). The primary component of W-type FIs is

FIGURE 6: Histograms of total homogenization temperatures (T_h) and salinities of fluid inclusions in different stages.

H₂O (3424–3447 cm⁻¹). Additionally, W-type inclusions of stage-II contain CO₂ (1284 cm⁻¹ and 1387 cm⁻¹) and CH₄ (2916 cm⁻¹) in the vapor phase (Figures 7(c) and 7(d)). PC-type FIs from stage-I and stage-II show well-defined CO₂ peaks (1285 cm⁻¹ and 1387 cm⁻¹) and some CH₄ peaks (2917 cm⁻¹) (Figure 7(a)).

4.2. Oxygen and Hydrogen. Oxygen and hydrogen isotopic results from the Yuka gold deposit are given in Table 2 and Figure 8. Measured $\delta^{18}\text{O}_m$ values for quartz veins in connection with gold mineralization at Yuka are ranged from 11.4‰ to 12.7‰. $\delta^{18}\text{O}_w$ values vary between 0.6‰ and 3.6‰. Hydrogen isotopic compositions are calculated directly from inclusion fluid, which is between -58.5‰ and -41.6‰.

4.3. Sulfur and Lead Isotopic Results. Sulfur isotopic results from the Yuka gold deposit are given in Table 3 and Figure 9. The $\delta^{34}\text{S}$ values of pyrite are between 0.5 and 7.4‰ (average of 4.43‰). Lead isotopic results from the Yuka gold deposit are given in Table 4 and Figure 10. Pyrite separates have $^{206}\text{Pb}/^{204}\text{Pb}$ ratios ranging from 18.238 to 18.600 with an average of 18.313. $^{207}\text{Pb}/^{204}\text{Pb}$ ratios range from 15.590 to 15.618 with an average of 15.604, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios range from 38.039 to 38.775 with an average of 38.1697.

5. Discussion

5.1. Evolution of Ore-Forming Fluids. Although the origin of fluid inclusions of orogenic gold deposits is unknown, FIs are still important targets for studying ore-forming

FIGURE 7: Microstructures and laser Raman spectra for fluid inclusions in Yuka gold deposit.

TABLE 2: The δD_{V-SMOW} , $\delta^{18}O_{V-SMOW}$, and $\delta^{18}O_{H_2O}$ (‰) of the Yuka gold deposit.

Sample no.	Stage	Mineral	Average T_h (°C)	δD_{V-SMOW} (‰)	$\delta^{18}O_{V-SMOW}$ (‰)	$\delta^{18}O_{H_2O}$
ZK0702-8	I	Quartz	246.3	-58.5	12.6	3.5
ZK0702-9	I	Quartz	234	-55.6	12.5	2.8
ZK0702-10	I	Quartz	258.5	-56.5	12.2	3.6
ZK0702-11	II	Quartz	239.3	-51.8	11.8	2.3
ZK0702-2	II	Quartz	234.1	-52.5	11.5	1.8
ZK0702-3	II	Quartz	226.1	-50.5	12.4	2.2
ZK0702-4	II	Quartz	242.5	-53.5	11.4	2.1
ZK0703-1	III	Quartz	218.3	-41.6	12.7	2.1
ZK0703-2	III	Quartz	217.4	-43.5	12.1	1.4
ZK0703-3	III	Quartz	215.2	-44.6	11.4	0.6

processes in hydrothermal systems [6]. The three stages of FIs have implications for the ore-forming fluids in the Yuka gold deposit.

Stage-II fluids evolved towards a more H_2O -rich composition within a H_2O - CO_2 - $NaCl \pm CH_4$ hydrothermal system at medium temperatures (193.1°C to 271.1°C) with variable salinities (0.4–11.7 wt.% NaCl equiv.). Moreover, the frequency of C- and PC-type fluid inclusions in the stage-II fluids is less than that in the stage-I fluids. These features show that stage-II fluids evolved into a lower CO_2 concentration at low-moderate temperatures and variable salinities, indicating a change in physicochemical conditions. A decrease in CO_2 would have brought about an increase in pH of the original ore fluid [77]. This change may have made

the Au-S complexes unstable and soluble reduction, so that in deposit of more gold or polymetallic sulfides [77–79]. This result is consistent with the observed stage-II quartz veins, which is the main stage of gold mineralization (Figures 4(c)–4(h)). Lastly, following gold precipitation, stage-III fluids were almost pure H_2O (>90%). CO_2 and CH_4 were present at an earlier stage but are no longer present due to decreased solubility at lower temperatures (188.1°C to 248.5°C) and salinities (0.4–16.1 wt.% NaCl equiv.). These data, from stage-I to stage-III, indicate that the ore-forming fluids are characterized by low to medium homogenization temperatures and low salinities and are CO_2 -rich, which is consistent with other regional orogenic-type gold deposits [1, 6, 7, 80].

FIGURE 8: $\delta^{18}\text{O}$ – δD plots of the ore fluids of the Yuka gold deposit. Primary magmatic and metamorphic water boxes and meteoric water line are from Taylor [72]. Organic water field is quoted from Sheppard [73]. The data from Tanjianshan and Qinglonggou deposits are quoted from Zhang [74].

TABLE 3: The $\delta^{34}\text{S}$ values of ores and rocks in the Yuka gold deposit.

Sample no.	Position	Ore no.	Mineral	$\delta^{34}\text{S}_{\text{CDR}}$ (‰)
YQS-01	Surface	3	Pyrite	0.5
YQS-02	Surface	3	Pyrite	3.9
YQS-03	Surface	3	Pyrite	3.5
YQS-04	Surface	3	Pyrite	4.9
YQS-05	ZK0702-2	3	Pyrite	4.9
YQS-06	ZK0702-3	3	Pyrite	3.9
YQS-07	ZK0702-4	3	Pyrite	4.5
YQS-08	Surface	2	Pyrite	6.7
YQS-09	Surface	2	Pyrite	7.4
YQS-10	Surface	2	Pyrite	4.1

5.2. Sources of Ore-Forming Fluids and Metals. H and O isotope research is of high efficiency and universality to understand the development of hydrothermal solutions in the mineralization system, especially to determine the origin of the fluids (magmatic, metamorphic, meteoric, or admixture) [71, 77].

$\delta^{18}\text{O}_m$ values from quartz at all stages of the Yuka gold deposit range from 11.4 to 12.7‰ (Table 2). These values are similar to orogenic gold deposits elsewhere ($\delta^{18}\text{O}_m = 10$ to 18‰) [3, 31, 80, 81]. Moreover, the calculated quartz $\delta^{18}\text{O}_w$ values at all stages demonstrate a limit range from 0.6‰ to 3.6‰ (Table 2), which is within the scope of $\delta^{18}\text{O}_w$ values from orogenic gold deposits in Northern Qaidam ($\delta^{18}\text{O}_w = -1.7‰$ to 5.6‰) [74]. Furthermore, δD values of $-58.5‰$ to $-41.6‰$ from the Yuka gold deposit are

comparable to most typical orogenic gold deposits ($\delta\text{D} = -20‰$ to $-80‰$) [81, 82]. Fluid inclusions with low salinity and CO_2 -rich indicate that the original ore fluids for the Yuka gold mineralization were metamorphic water, which is similar to a result of metamorphic devolatilization of such mafic successions [13]. Data from the δD vs. $\delta^{18}\text{O}_w$ diagram (Figure 8) shows a trend from metamorphic water towards the meteoric water line, indicating that the original ore fluids may have mixed with metamorphic and meteoric waters through the rock-fluid reactions during mineralization [83, 84].

The investigated pyrite samples yield $\delta^{34}\text{S}$ values ranging from 0.5 to 7.4‰ (Table 3) and overlap with those of orogenic gold deposits in the Chinese Qinling-Qilian-Kunlun orogenic belt, such as Wulonggou [85], Hanshan [86], Tanjianshan [74], Qinglonggou [74], Houliugou [74], and Shuangwang [87] (Figure 9). Moreover, $\delta^{34}\text{S}$ values are comparable to those of orogenic gold deposits elsewhere in China [5]. In addition, $\delta^{34}\text{S}$ values of pyrites in the Yuka deposit (Figure 9) are lower than those of regional Paleozoic intrusions (8.6‰ to 8.8‰ [76]) and Proterozoic strata (5.3‰ to 8.54‰ [74]), manifesting that the pyrites are not formed from magmatic hydrothermal fluids and that their genesis cannot be explained by a magmatic-hydrothermal system. However, the $\delta^{34}\text{S}$ values are similar to those of regional Paleozoic strata (3.3‰ to 12.6‰ [75]), which derive from Paleozoic rocks through fluid-wall rock interactions. Furthermore, the average $\delta^{34}\text{S}$ value is within the range for the most of the metamorphic rock (Figure 9), so we deduce that the ore-forming fluids stem from the Paleozoic strata metamorphic.

FIGURE 9: Histogram of sulfur (S) isotopic compositions of sulfides from the Yuka gold deposit and related lithologies. $\delta^{34}\text{S}$ values of Paleozoic strata are quoted from Zhu et al. [75]; $\delta^{34}\text{S}$ values of Paleozoic intrusions are quoted from Guo and Chen [76]; $\delta^{34}\text{S}$ values of Proterozoic strata are quoted from Zhang [74]. Other $\delta^{34}\text{S}$ values are quoted from Deng and Wang [5].

The diagrams of $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (Figures 10(a) and 10(b)) mainly plot in the area between the orogenic belt and the upper crust evolution line. Therefore, the primary source of Pb in the Yuka gold deposit and by reference the Pb isotopes was contributed by the upper crust; however, a minor contribution of mantle-derived Pb is also present.

5.3. Ore Genetic Type. The Yuka gold deposit was formed in an early Paleozoic collisional orogeny. Based on the above discussions and comparisons of geological and geochemical characteristics with typical orogenic gold deposits, we propose that the Yuka gold deposit has features similar to those of typical orogenic-type gold

deposits [1, 6, 7, 81, 88]: (1) the Yuka gold deposit ore-forming fluid is of low salinity (average < 10 wt.%NaCl eqv.) and CO_2 -rich, which is a characteristic of orogenic-type deposits [6, 7]. (2) The H-O-S-Pb isotope signatures of Yuka gold deposit described above supports an orogenic genetic model [1, 14, 15, 81, 89–91]. Hence, we conclude that the Yuka gold deposit is formed during the orogenic-type system development of Northern Qaidam.

6. Conclusions

- (1) The ore-forming fluids from Yuka gold deposit show low to medium temperatures and low salinities and are CO_2 -rich

TABLE 4: Lead isotope ratios of ores in the Yuka gold deposit, reproduced from Chai et al. [77], (under the Creative Commons Attribution License/public domain).

Sample no.	Position	Ore no.	Mineral	$^{208}\text{Pb}/^{204}\text{Pb}$	2σ (‰)	$^{207}\text{Pb}/^{204}\text{Pb}$	2σ (‰)	$^{206}\text{Pb}/^{204}\text{Pb}$	2σ (‰)
YQS-01	Surface	3	Pyrite	38.132	0.005	15.615	0.002	18.285	0.002
YQS-02	Surface	3	Pyrite	38.103	0.015	15.618	0.006	18.287	0.007
YQS-03	Surface	3	Pyrite	38.043	0.004	15.599	0.002	18.257	0.002
YQS-04	Surface	3	Pyrite	38.063	0.004	15.603	0.002	18.248	0.002
YQS-05	ZK0702-2	3	Pyrite	38.065	0.004	15.6	0.002	18.238	0.002
YQS-06	ZK0702-3	3	Pyrite	38.039	0.004	15.597	0.002	18.263	0.002
YQS-07	ZK0702-4	3	Pyrite	38.048	0.004	15.599	0.001	18.262	0.002
YQS-08	Surface	2	Pyrite	38.775	0.004	15.611	0.002	18.62	0.002
YQS-09	Surface	2	Pyrite	38.285	0.004	15.59	0.002	18.371	0.002
YQS-10	Surface	2	Pyrite	38.144	0.004	15.608	0.002	18.302	0.002

FIGURE 10: Lead isotopic compositions from the Yuka gold deposit. (a) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and (b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$. The evolution curves of the upper crust, lower crust, mantle, and orogen are from Zartman and Doe (1981). Data from Paleozoic strata are quoted from Zhu et al. [75]; data from Paleozoic intrusions are quoted from Guo and Chen [76]; data from Proterozoic strata are quoted from Zhang [74].

- (2) H, O, S, and Pb isotopes of Yuka gold deposit demonstrate that the ore-forming materials were stemmed from mixed sources, which comprised Proterozoic rocks and ore-forming metamorphogenic fluids. The origin of ore-forming fluids is primarily metamorphic but may have mixed with meteoric fluids at upper crustal levels
- (3) According to regional geology, deposit characteristics, ore-forming fluid characteristics, and H-O-S-Pb isotopic characteristics indicate that the Yuka gold deposit is an orogenic gold deposit

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they do not have any commercial or associative interest that represents conflicts of interest in connection with the submitted work.

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