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 volcanioclastic 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 δ18O B 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 δ34S 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 206Pb/204Pb of 18.238–18.600 (average of 18.313), 207Pb/204Pb of 15.590–15.618 (average of 15.604), and 208Pb/204Pb 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 (≤10% NaCl equiv.), 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...
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 it is 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 gold deposit.
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 [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 termination, 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 sea floor 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

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**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: Hongligou; 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]).
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 Zongwuloung 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].

Metallocenic 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., Yeluoouqian, Qianmeiling, Hongliugou, Qinglonggou, Tanjianshan, Saibagou, Qjulute, 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 metamorphic ages, such as the sericite 40Ar/39Ar ages of 409.4 ± 2.3 Ma, 425.5 ± 2.1 Ma, and 246 ± 3 Ma for the Qinglonggou, Saibagou, and Yeluoouqian 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 40Ar/39Ar 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 metallocenic 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 metamorphic 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 volcaniclastic 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 volcaniclastic 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 45–70° 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 °C. The reproducibility of these measurements is ±0.1 °C below 30 °C, and heating and freezing temperatures are reproducible within ±1 °C and ±0.1 °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.
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 ±0.2‰ and ±0.2‰ for δ18O and δD, respectively. Oxygen isotope ratios of water in equilibrium with quartz were calculated using the equation

\[
1000 \ln \frac{\alpha_{\text{H}_2\text{O}}}{\alpha_{\text{H}_2\text{O}}^\text{quartz}} = 3.38 \times 10^6 T^{-2} - 3.40
\]

[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. Sulfur isotopic compositions of sulfide minerals were measured using the conventional combustion method [70]. The results are reported as δ34S relative to Vienna Canon Diablo Troilite (V-CDT) sulfide, and the analytical precision is better than ±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 208Pb/204Pb, 207Pb/204Pb, and 206Pb/204Pb is better than ±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 (H2O-CO2-NaCl; C-type), (2) aqueous (H2O-NaCl; W-type), and (3) pure carbonic (CO2; 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 H2O+liquid CO2) with multiphase compositions (liquid H2O+liquid...
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 \((T_{m-Co2})\) of solid CO₂ 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 CO₂ phase of C-type FIs is completely homogenized when temperatures \((T_{h-Co2})\) are between 15.6°C and 29.4°C. PC-type FIs \((n = 7)\) yield melting temperatures \((T_{m-Co2})\) of solid CO₂ ranging from -59.4°C to -56.7°C and homogenization temperatures \((T_{h-Co2})\) of CO₂ ranging from 12.4°C to 28.1°C (Table 1).

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).

<table>
<thead>
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<th>Sample no.</th>
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<th>FI type</th>
<th>Number</th>
<th>(T_{m-Co2}) (°C)</th>
<th>(T_{m-cla}) (°C)</th>
<th>(T_{h-Co2}) (°C)</th>
<th>(T_{h-ice}) (°C)</th>
<th>Salinity (wt.% NaCl equiv.)</th>
<th>Stage</th>
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<td>5.4 to 9.5</td>
<td>15.6 to 29.4</td>
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</tr>
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<td>15.9 to 29.1</td>
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<td>0.4 to 9.0</td>
<td></td>
<td></td>
<td>III</td>
</tr>
</tbody>
</table>

Note: \(T_{m-Co2}\) = final melting temperature of solid CO₂; \(T_{m-cla}\) = final melting temperature of CO₂-H₂O clathrate; \(T_{h-Co2}\) = homogenization temperature of CO₂ phases; \(T_{h-ice}\) = final melting temperature of ice; \(T_{h}\) = homogenization temperature; wt.% NaCl equiv. = weight percent NaCl equivalent.

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 CO₂ vapor phase \((1285 \text{ cm}^{-1} \text{ and } 1388 \text{ cm}^{-1})\) with minor amounts of CH₄ \((2916 \text{ cm}^{-1})\) and a liquid phase with a large amount of water \((3438 \text{ cm}^{-1})\). The primary component of W-type FIs is CO₂+vapor CO₂ at room temperature (Figures 5(b) and 5(c)) and are the primary and pseudosecondary inclusions 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 CO₂+liquid CO₂) and only formed during stage-I (Figure 5(a)).
H$_2$O (3424–3447 cm$^{-1}$). Additionally, W-type inclusions of stage-II contain CO$_2$ (1284 cm$^{-1}$ and 1387 cm$^{-1}$) and CH$_4$ (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 CO$_2$ peaks (1285 cm$^{-1}$ and 1387 cm$^{-1}$) and some CH$_4$ 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 $\delta^{18}$O$_{m}$ values for quartz veins in connection with gold mineralization at Yuka are ranged from 11.4‰ to 12.7‰. $\delta^{18}$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 $\delta^{34}$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
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 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.). 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 CO2 concentration at low-moderate temperatures and variable salinities, indicating a change in physicochemical conditions. A decrease in CO2 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 H2O (>90%). CO2 and CH4 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 CO2-rich, which is consistent with other regional orogenic-type gold deposits [1, 6, 7, 80].
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].

δ¹⁸Om 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 (δ¹⁸Om = 10 to 18‰) [3, 31, 80, 81]. Moreover, the calculated quartz δ¹⁸OW values at all stages demonstrate a limit range from 0.6‰ to 3.6‰ (Table 2), which is within the scope of δ¹⁸OW values from orogenic gold deposits in Northern Qaidam (δ¹⁸OW = −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 (δD = −20‰ to −80‰) [81, 82]. Fluid inclusions with low salinity and CO₂-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. δ¹⁸OW 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 δ³⁴S 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, δ³⁴S values are comparable to those of orogenic gold deposits elsewhere in China [5]. In addition, δ³⁴S 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 δ³⁴S 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 δ³⁴S 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 8: δ¹⁸O – 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].](image-url)

Table 3: The δ³⁴S values of ores and rocks in the Yuka gold deposit.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Position</th>
<th>Ore no.</th>
<th>Mineral</th>
<th>δ³⁴S_{CDR} (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YQS-01</td>
<td>Surface</td>
<td>3</td>
<td>Pyrite</td>
<td>0.5</td>
</tr>
<tr>
<td>YQS-02</td>
<td>Surface</td>
<td>3</td>
<td>Pyrite</td>
<td>3.9</td>
</tr>
<tr>
<td>YQS-03</td>
<td>Surface</td>
<td>3</td>
<td>Pyrite</td>
<td>3.5</td>
</tr>
<tr>
<td>YQS-04</td>
<td>Surface</td>
<td>3</td>
<td>Pyrite</td>
<td>4.9</td>
</tr>
<tr>
<td>YQS-05</td>
<td>ZK0702-2</td>
<td>3</td>
<td>Pyrite</td>
<td>4.9</td>
</tr>
<tr>
<td>YQS-06</td>
<td>ZK0702-3</td>
<td>3</td>
<td>Pyrite</td>
<td>3.9</td>
</tr>
<tr>
<td>YQS-07</td>
<td>ZK0702-4</td>
<td>3</td>
<td>Pyrite</td>
<td>4.5</td>
</tr>
<tr>
<td>YQS-08</td>
<td>Surface</td>
<td>2</td>
<td>Pyrite</td>
<td>6.7</td>
</tr>
<tr>
<td>YQS-09</td>
<td>Surface</td>
<td>2</td>
<td>Pyrite</td>
<td>7.4</td>
</tr>
<tr>
<td>YQS-10</td>
<td>Surface</td>
<td>2</td>
<td>Pyrite</td>
<td>4.1</td>
</tr>
</tbody>
</table>
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, 81–91]. 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).

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

Figure 10: Lead isotopic compositions from the Yuka gold deposit. (a) \( \frac{207\text{Pb}}{204\text{Pb}} \) vs. \( \frac{206\text{Pb}}{204\text{Pb}} \) and (b) \( \frac{208\text{Pb}}{204\text{Pb}} \) vs. \( \frac{206\text{Pb}}{204\text{Pb}} \). 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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References


Y. Ren, D. Chen, D. E. Kelsey, X. Gong, and L. Liu, "Petrology and geochemistry of the lawsonite (pseudomorph)-bearing eclogite in Yuka terrane, North Qaidam UHPM belt: an


