Original Article

Geology and Metallogenesis of the Sawayaerdun Gold Deposit in the Southwestern Tianshan Mountains, Xinjiang, China

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Abstract

The Sawayaerdun gold deposit, located in Wuqia County, Southwest Tianshan, China, occurs in Upper Silurian and Lower Devonian low-grade metamorphic carbonaceous turbidites. The orebodies are controlled by a series of NE-NNE-trending, brittle–ductile shear zones. Twenty-four gold mineralized zones have been recognized in the Sawayaerdun ore deposit. Among these, the up to 4-km-long and 200-m wide No. IV mineralized zone is economically the most important. The average gold grade is 1–6 g/t. Gold reserves of the Sawayaerdun deposit have been identified at approximately 37 tonnes and an inferred resource of 123 tonnes. Hydrothermal alteration is characterized by silicification, pyritization, arsenopyritization, sericitization, carbonatization and chloritization. On the basis of field evidence and petrographic analysis, five stages of vein emplacement and hydrothermal mineralization can be distinguished: stage 1, early quartz stage, characterized by the occurrence of quartz veins; stage 2, arsenopyrite–pyrite–quartz stage, characterized by the formation of auriferous quartz veinlets and stockworks; stage 3, polymetallic sulfide quartz stage, characterized by the presence of auriferous polymetallic sulfide quartz veinlets and stockworks; stage 4, antimony–quartz stage, characterized by the formation of stibnite–jamesonite quartz veins; and stage 5, quartz–carbonate vein stage. Stages 2 and 3 represent the main gold mineralization, with stage 4 representing a major antimony mineralization episode in the Sawayaerdun deposit. Two types of fluid inclusion, namely H2O–NaCl and H2O–CO2–NaCl types, have been recognized in quartz and calcite. Aqueous inclusions show a wide range of homogenization temperatures from 125 to 340°C, and can be correlated with the mineralization stage during which the inclusions formed. Similarly, salinities and densities of these fluids range for each stage of mineralization from 2.57 to 22 equivalent wt% NaCl and 0.76 to 1.05 g/cm3, respectively. The ore-forming fluids thus are representative of a medium- to low-temperature, low- to medium-salinity H2O–NaCl–CO2–CH4–N2 system. The δ34S_CDT values of sulfides associated with mineralization fall into a narrow range of −3.0 to +2.6 ‰ with a mean of +0.1 ‰. The δ13C_PDB values of dolomite and siderite from the Sawayaerdun gold deposit range from −5.4 to −0.6 ‰, possibly reflecting derivation of the carbonate carbon from a mixed magmatic/sedimentary source. Changes in physico-chemical conditions and composition of the hydrothermal fluids, water–rock exchange and immiscibility of hydrothermal fluids are inferred to have played important roles in the ore-forming process of the Sawayaerdun gold–antimony deposit.

Keywords: brittle–ductile shear zone, China, fluid inclusions, metallogenesis, orogenic gold, Sawayaerdun, stable isotopes, Tienshan.

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1. Introduction

The Tienshan (or Tian Shan) is one of the largest gold provinces on Earth and contains several world-class gold deposits, such as Muruntau and Kumtor. Muruntau in Uzbekistan is the world’s largest known gold deposit (175 Moz; Yakubchuk et al., 2002), outside the Witwatersrand, and Kumtor in eastern Kyrgyzstan is one of the world’s 10 largest gold mines (18 Moz; Yakubchuk et al., 2002). The Chinese Southwestern Tianshan gold deposits are the eastward extension of this orogen, with recently discovered gold deposits at Sawayaerdun, Dashankou, Sahentuohai and Bulong (Yang et al., 2004), highlighting the economic potential of the Southwestern Tianshan Mountains. The Sawayaerdun gold deposit is located in the northwestern Wuqia County, Xinjiang Uygur Autonomous Region, along the China–Kyrgyzstan border and represents the largest recognized gold deposit in the Southern Tianshan orogenic belt. In fact, the Sawayaerdun deposit in China and the Savoyardi deposit in Kyrgyzstan belong to the same gold field, which extends across both sides of the national border. Discovered in 1993, geological reconnaissance was conducted in the Sawayaerdun area between 1994 and 1999 by the No. 2 Geological Party of the Xinjiang Bureau of Geology and Mineral Exploration and Development. The Sawayaerdun gold deposit currently consists of an identified reserve of approximately 37 tonnes of gold (No. 2 Geological Party of the Xinjiang Bureau of Geology and Mineral Exploration and Development, 1999), and an inferred resource of 123 tonnes (Zheng et al., 2001). The deposit was mined in 2000–2002 at a small scale. Since 1995, a number of researchers have studied the geology, geochemistry, mineralogy, isotope geochemistry, fluid inclusions, and age of mineralization of the deposit (Li & Luo, 1997; Liu et al., 1999, 2002a, b; Ye et al., 1999a, b, c; Yang & Fu, 2000; Zheng et al., 2001; Chen et al., 2004). However, most of the documentation of the Sawayaerdun deposit has been reported in the Chinese-language literature, and thus, the international geological community knows little about this deposit.

This paper describes the metallogenic setting and geological characteristics of the Sawayaerdun gold deposit. Systematic fluid inclusion investigations, S, C and O stable isotope data are also presented and combined with data previously published in order to better constrain the metallogenic processes that led to the formation of the Sawayaerdun deposit.

2. Regional geology

The Sawayaerdun gold deposit is situated in the north of the East Alai Mountains, approximately 28 km northwest of Wulukeqiati Township, Wuqia County, Xinjiang (Fig. 1). The deposit is tectonically located at the western end of the Chinese Southwest Tianshan Hercynian orogenic belt, at the junction between the Ili-Issyk Lake microplate and North Tarim marginal mobile belt (He, 2000; Fig. 1). The Sawayaerdun-Jigen fault separates the gold district into two parts: the western part belongs to the Ili-Issyk Lake microplate, and the eastern part to the Late Paleozoic continental-margin basin of the North Tarim marginal mobile belt.

The basement of the Southwest Tianshan Mountains is Paleoproterozoic to Mesoproterozoic in age and composed of gneiss, schist and granulite with quartzite. It is covered by Neoproterozoic–Middle Ordovician continuous sedimentary rocks. Early Cambrian rocks exposed in the Kalpin area comprise a suite of phosphatic siliceous rocks. In the Middle Cambrian–Middle Ordovician neritic–littoral carbonate rocks and clastic rocks were deposited. During the Late Ordovician–Late Silurian period, the “early Paleo-Tianshan Ocean” (Gao et al., 1995) led to the deposition of neritic clastic and carbonate rocks. A flysch and carbonate sequence occurs in the East Alai Mountains and the Haerk area. In the late Silurian or Early Devonian, the early Paleo-Tianshan oceanic crust was subducted northward beneath the southern margin of the Ili-Issyk Lake microplate, resulting in development of paired metamorphic belts and island arc volcanic rocks in the Narat area. The “late Paleo-Tianshan initial ocean basin” developed during the Early Devonian–Early Carboniferous period, when extension of the passive continental margin of the Tarim plate resulted in the formation of the South Tianshan initial ocean basin and deposition of littoral–neritic clastic rocks and carbonate rocks, locally accompanied by volcanic eruptions. In the Early Carboniferous, the late Paleo-Tianshan Ocean closed (Gao et al., 1995), and continent–continent collision in the north of the South Tianshan Mountains gave rise to the formation of continental crust extensive collisional plutonism. Continent–continent collision of the Tarim plate and Ili-Issyk Lake microplate took place in the Early Permian (Liu et al., 1996). During the collision, a number of ductile shear zones, thrust faults and thrust nappes developed in the Southwest Tianshan, accompanied by volcanism in the south of the Haerk area and Kalpin area.

Following the Early Permian, this area underwent intracontinental tectonic deformation that included the
emplacement of minor A-type granitoids. Paleozoic sedimentary rocks were folded and intruded by Middle Permian alkali granitoids at 260–275 Ma (Jiang et al., 1999; Yang et al., 2001). In the Triassic the area was uplifted and progressively denuded. Mesozoic sediments (e.g. fluvio-lacustrine clastic rocks with local coal beds and terrestrial volcanic rocks) were deposited in the foreland and several intermontane basins of the South-west Tianshan Mountains. The Paleogene to Neogene in the study area consists of terrestrial clastic rocks intercalated with gypsum and locally carbonate rocks. Collision between the Indian and Eurasian plates in the Cenozoic initiated large-scale intracontinental deformation in the Tianshan and its neighboring areas, causing mountain uplift and crustal thickening, and Paleozoic strata were thrust over Meso-Cenozoic strata.
3. Deposit geology
3.1. Stratigraphy
The exposed strata in the Sawayaerdun gold district includes the Upper Silurian, Lower to Middle Devonian, and Upper Carboniferous (Fig. 2), of which the Upper Silurian and Lower Devonian are host rocks for the gold mineralization. The Upper Silurian Taertekuli Formation consists of a suite of low-grade metamorphic carbonaceous clastic rocks. Based on rock associations,
the Taertekuli Formation can be subdivided into four members: (i) alternating carbonaceous phyllite and thin-beded metasiltstone, forming a rhythmic layer 1–3 cm thick; (ii) alternating beds of metasandstone, metasiltstone and carbonaceous phyllite; (iii) carbonaceous phyllite with phylitic slate, siliceous rocks and conglomerate, the base of which is marked by banded limestone lenses, yielding fusulinids, corals, crinoids, brachiopods ostracods and algae (Liu et al., 1999; Wang et al., 2000); and (iv) metasandstone and siliceous rocks with carbonaceous phyllite, with radiolarians found in siliceous rocks (He, 2000). The Lower Devonian Sawayaerdun Formation is subdivided into two members: (i) thin-beded carbonaceous phyllite intercalated with medium- to thick-beded, fine-grained metasandstone; and (ii) medium- to thick-beded, fine-grained calcareous metasandstone with carbonaceous phyllite and locally also with metasiltstone. The Middle Devonian Tuogemaiti Formation consists of marble limestone. The Upper Carboniferous is composed of carbonaceous phyllite intercalated with thin-beded calcareous meta-siltstone and a lens of limestone, of which base consists of marl and bioclastic limestone. Liu et al. (1999) and Wang et al. (2000) recognized algae, crinoids, brachiopods, ostracodes, corals and conodonts in the bioclastic limestone.

The ore-hosting rocks at Sawayaerdun comprise a sequence of carbonaceous turbidites that shows well-developed rhythmic stratification, graded horizontal and convolute bedding, and ripple bedding. Compared with other strata in the region, the host strata of the Sawayaerdun deposit yields elevated gold contents, suggesting that the carbonaceous matter and clay minerals have a strong gold adsorption capacity during deposition, and that gold was primarily concentrated in the turbidites (Ye et al., 1999a).

The age of the host strata of the Sawayaerdun gold deposit has been strongly debated in the past several years. Based on the characteristics of the strata and regional comparisons, most researchers (Li & Luo, 1997; No. 1 Regional Geological Survey Party of the Xinjiang Bureau of Geology and Mineral Exploration and Development, 1998; No. 2 Geological Party of the Xinjiang Bureau of Geology and Mineral Exploration and Development, 1999; Ma et al., 1999; Ye et al., 1999a, b, c; Chen & Li, 2003) have argued that the age of the host strata is Late Silurian or Late Silurian–Early Devonian. In contrast, in light of the fossil conodonts recognized in the lower part of the host rocks (Upper Carboniferous in Fig. 2) and fossil fusulinids in the upper part of the host rocks (the Third Member of the Upper Silurian Taertekuli Formation), Wang et al. (2000) suggested that the host strata are Early Devonian and Late Carboniferous. Due to the fossil hapsiphyllum and fusulina recognized in bioclastic limestone and meta-siltstone at the base (Upper Carboniferous in Fig. 2) and the upper part of the host rocks (Third Member of the Upper Silurian Taertekuli Formation) and whole-rock Rb-Sr isochron ages (305 ± 12 and 288 ± 18 Ma) of carbonaceous slate (First Member of the Taertekuli Formation and Second Member of the Sawayaerdun Formation), Liu et al. (1999, 2002a), Zheng et al. (2001, 2002) and Hu et al. (2002) proposed a Late Carboniferous age for the host rocks of the Sawayaerdun gold deposit.

3.2. Tectonic characteristics and magmatic rocks

North–northeast-trending faults are well developed in the region, extending for tens to hundreds of kilometers. The Sawayaerdun–Jigen regional ductile shear zone (Figs 1, 2) not only hints at a Paleozoic suture between the Ili-Issyk Lake microplate and North Tarim marginal mobile belt, but may also represent a first-order ore-controlling structure in the area. The brittle–ductile shear zone, over 40 km long and 2–3 km wide, trends NE–NNE and dips NNW–NW at 50–85°, and clearly strikes obliquely to the strike of the strata. Foliation is well developed within the brittle–ductile shear zone and is characterized by the occurrence of intense schistosity (Fig. 3a). Most of the schistosity trends N40°–50°E and dips 310–320° at 60–85° (Ma et al., 1999). A set of foliation is developed in the district, while foliation oriented in other directions is not developed and “S–C” foliation (shear foliation and mylonite foliation) occurs only locally (Fig. 3b). The brittle–ductile shear zone is composed of mylonite, intense schistosity zones, structural lenses (Fig. 3c), stretching lineation and A-type folds (Fig. 3d). Strong deformation zones are interlayered by weak deformation zones. A-type folds are widely developed, and generally small in scale (10–40 cm wide, <20 cm high and 0.5–2 m long), and are mostly represented by complicated chevron folds and open symmetrical folds.

A series of NE-trending brittle faults in the ore district are post-mineral formation, but have no significant influence on the distribution of orebodies. Magmatism is only weakly developed in the Sawayaerdun gold field and comprises rare mafic lavas, diabase dikes, ultramafic lenses and monzonite-porphry dikes (single zircon U-Pb ages of 134–131 Ma; Chen & Li, 2003) in the ore district and its surroundings. Zheng et al. (2002) obtained K-Ar isochron ages of
206–169 Ma for diabase dikes in the ore district. Ophiolitic remnants are exposed in the surroundings of the ore district and the Jigen area. These consist of mafic lavas, ultramafic rocks and gabbro (He, 2000; Wang, 2000). A Sm-Nd isochron age of 392 ± 15 Ma obtained for the mafic lavas has been interpreted as the ophiolite formation age (Xu et al., 2003), suggesting that the ophiolite represents a fragment of oceanic crust of the Late Paleozoic Paleo-South Tianshan Ocean.

3.3. Geological characteristics of mineralized zones and orebodies

In the Sawayaerdun ore district, 24 mineralized zones (labeled as I–XXIV; Fig. 2) have been recognized within an area of 5 km (N-S) by 4 km (E-W). The mineralized zones occur in the Upper Silurian Taertekuli Formation and Lower Devonian Sawayaerdun Formation, and the host rocks are carbonaceous phyllites, meta-sandstone and meta-siltstone. Gold mineralized zones and orebodies are controlled by a NE-NNE-trending brittle–ductile shear zone. These gold mineralized zones are sub-parallel to each other and extend in a NE direction (Fig. 2). They have similar geological characteristics, and the IV, I, II and XI zones are particularly large in size (Table 1).

The IV zone, which extends for more than 4 km and is 15–200 m wide, represents the largest mineralized system, and occurs at the contact between the Taertekuli Formation and Sawayaerdun Formation. The zone generally strikes 25° and dips NW at 53–80°, cutting the strike of the strata obliquely. Within this ore zone, nine orebodies have been delineated, of which three orebodies, namely, IV 1, IV 2 and IV 3, are the most significant with a length of 860–1390 m, a thickness of 0.9–48.6 m and depth extents of between 70 and 505 m. Smaller orebodies are all <100 m in length. The average gold grade of the Sawayaerdun deposit is 1.0–5.9 g/t (Table 1). The orebodies of the Sawayaerdun deposit appear in tabular form (Fig. 4), vein and podiform. In plan view, the gold orebodies describe an en echelon pattern. The mineralization in orebody IV 2 shows clear vertical zonation, with gold orebody in the upper and antimony orebody in the lower part of the ore zone, whereas other orebodies and mineralized zones show no such clear mineralization zonation. The antimony-enriched orebody is 2.5–12.2 m thick with an average antimony grade of 1.28%.
The XI mineralized zone is located in the northeast of the ore district (Fig. 2). Within this zone, three orebodies have been defined, which occur as regular veins 260–380 m in length and 0.7–6.0 m in thickness and generally have gold grades of 1.0–2.7 g/t. On the Kyrgyzstan side of the border, the possible continuation of the Sawayaerdun gold deposit within Early and Middle Devonian phyllite is known as the Savoyardi deposit (Rui et al., 2002), and these deposits on both sides of the China–Kyrgyzstan border probably belong to same ore field. The gold orebodies of the Savoyardi deposit in Kyrgyzstan also occur along NE-trending fault zones, possibly extending into the XI mineralized zone in China. The Savoyardi gold deposit displays the following features: the gold orebodies occur in a zone of auriferous quartz veins with grades averaging 6.1–8.7 g/t and also contain antimony, silver, lead, zinc and copper. The gold reserve at Savoyardi has been estimated at 40 tonnes. Typical values for arsenopyrite-rich quartz veins in the Savoyardi gold deposit are 6.5 g/t Au, 4.5% Sb, 10% Pb and 41.5 g/t Ag (Rui et al., 2002).

### 3.4. Ore assemblages and textures

The gold ores of the Sawayaerdun deposit can be divided into primary ore and oxidized ore. According to mineral association and their occurrence, primary ores can be classified into four types: (i) auriferous quartz veinlet type; (ii) auriferous quartz stockwork type; (iii) auriferous altered carbonaceous phyllite type; and (iv) auriferous silicified siltstone type. In addition, five mineral assemblages can be recognized, that is, gold–arsenopyrite–pyrite–quartz, gold–pyrite–jamesonite–(stibnite)–quartz, gold–jamesonite–(stibnite), gold–quartz–siderite, and gold–pyrite–pyrrhotite–quartz (Liu et al., 2002b).
Primary ore assemblages mainly have euhedral, subhedral and anhedral granular, exsolution, mesomorphic, poikilitic and crush textures. Ore textures include disseminated, veinlet-stockwork, banded, massive and brecciated. Disseminated ores, pyrite and arsenopyrite are hosted in quartz and altered carbonaceous phyllite. Pyrite, arsenopyrite and stibnite occur as veinlet-dissemination in fissures of altered rock. The banded ores are made up of arsenopyrite, pyrite, pyrrhotite, chalcopyrite and quartz.

Some 40 species of minerals have been recognized in the ore. Metallic minerals are mainly pyrite, arsenopyrite, jamesonite, chalcopyrite and stibnite, with minor pyrrhotite, electrum, galena, sphalerite and tetrahedrite. Non-metallic minerals mainly comprise quartz, calcite, sericite, siderite and carbonaceous matter.

3.5. Mineralization periods and stages

Based on cross-cutting relationships between veins, mineral assemblages, ore fabrics and the mineral-hosting sequence (Fig. 5), the ore-forming process can be divided into two mineralization periods: hydrothermal period and supergene period. The hydrothermal period can be further divided into five mineralization stages (Zheng et al., 2001). Stage 1 is early quartz stage, characterized by the occurrence of quartz veins. They are commonly boudinaged, lensoid and isodinally folded. These veins are interpreted to correlate with the regional metamorphism and deformation of ductile shear zone. Stage 2 is arsenopyrite–pyrite–quartz stage, characterized by the formation of auriferous quartz veinlets and stockworks, which cut the early quartz veins. Stage 3 is polymetallic sulfide quartz stage, characterized by the presence of auriferous polymetallic sulfide quartz veinlets and stockworks. They occur both parallel to and oblique to the main foliation of the host rocks. The mineralogy of stage 3 is characterized by the occurrence of large amounts of sulfides. Stage 4 is antimony–quartz stage, characterized by the formation of stibnite–jamesonite quartz veins. They are distributed in the II and IV mineralized zones and cross-cut previously formed quartz stockwork. Antimony grade is 0.6–3.3%. Stage 5 is the quartz–carbonate vein stage. Stages 2 and 3 represent the main gold mineralization, with stage 4 representing a major antimony mineralization episode in the Sawayaerdun deposit. Five mineralization stage characteristics are listed in Table 2.

3.6. Hydrothermal alteration

Alteration is well developed in wall rocks of the mineralized zones. The main hydrothermal alteration types

![Fig. 5](image-url) Different types of veins from the Sawayaerdun gold deposit. (a) The earliest quartz–carbonate veins at Sawayaerdun, which are generally parallel to the dominant foliation of the host carbonaceous phyllites and relic bedding; (b) auriferous arsenopyrite–pyrite–quartz veinlets distributed in the carbonaceous phyllites and metasiltstone; (c, d) pyrite (Py), chalcopyrite (Cp) and pyrrhotite (Pyr) in quartz (Q) of the polymetallic sulfide quartz vein; (e) stibnite–quartz veins in the carbonaceous phyllites and metasiltstone; (f) late quartz–carbonate veins striking obliquely to the strata.
are silicification, pyritization, arsenopyritization, sericitization, carbonatization and chloritization, of which silicification, pyritization, arsenopyritization and sericitization are spatially closely associated with the gold mineralization. Silicification is well developed in the deposit and can be divided into two types: (i) pervasive silicification occurs as quartz veinlets, stockworks and bands along the fractures in the wall rocks and orebodies, these veinlets, stockworks and bands are 0.2–10 mm wide and several centimeters to tens of centimeters long; quartz is often intergrown with sericite and pyrite; and (ii) free quartz also occurs as disseminations, patches and nodules in cataclasites. There is secondary quartzite in local wall rocks of the I and II mineralized zones. Pyritization is widely distributed, occurring as grains or veinlets. Arsenopyrite occurs as disseminations or forms veinlets with pyrite and quartz in the orebody and wall rocks. Arsenopyrite is one of the gold carrier minerals. Electron microprobe analysis shows that the content of gold in arsenopyrite ranges from 0.004 to 2.92% (Zheng et al., 2001), indicating that arsenopyrite was one of the gold carrier minerals. Sericitization is best developed in the orebody and wall rocks adjacent to ore. It occurs as flaky aggregates along the foliation and fissures of mylonite and coexists with other alteration minerals. Generally, sulfide mineral content correlates well with increases in gold grade within the intensely altered wall rocks.

As is the case with wall-rock alteration, mineralization zoning is not pronounced and can be observed only in mineralized zone IV. Based on variation in mineral assemblage and alteration intensity from distal wall rocks to the orebody, hydrothermal alteration in the center of mineralized zone IV may be divided into three zones: (i) a pyritized cataclasite zone, in which pyrite occurs as patches or disseminations, while other sulfides are scarce; (ii) an arsenopyritized and pyritized cataclasitic zone, which is characterized by more pyrite and arsenopyrite, and relatively high gold contents; and (iii) a stibnitized and pyritized cataclasitic zone, which is characterized by stibnite veinlets and marked decrease of arsenopyrite content.

### 3.7. Modes of gold occurrence

Gold occurs mainly in the form of electrum, with minor native gold, and has three modes of occurrence: (i) electrum microveinlets or electrum-chalcopyrite-quartz microveinlets distributed in fissures of arsenopyrite and pyrite; (ii) intergranular gold between quartz grains; and (iii) gold mineral hosted in arsenopyrite,
quartz grains or pyrite grains. The grain size of electron is generally 30–50 μm and a few may be as large as 10 × 100 μm.

4. Fluid inclusion studies

4.1. Methods

The petrographic characteristics of fluid inclusions were studied and types and assemblages of fluid inclusions were distinguished by optical microscopy in doubly polished sections (approx. 200–300 μm thick). Microthermometric measurements were carried out on a Linkam THMSG 600 programmable heating-freezing stage (−180 to +600°C) at the Laboratory of Geochemistry, China University of Geosciences, Beijing, and on a Chaixmeca heating-freezing stage at the Institute of Mineral Resources, Chinese Academy of Geological Sciences. The stage was calibrated using synthetic fluid inclusions. The heating rate was 0.1–0.5°C/min below 0°C and −30°C, with a reproducibility of ±0.2°C. The heating rate was 5–10°C/min at higher temperatures (>100°C), with a reproducibility of ±1°C.

The composition of fluid inclusions was analyzed at the Key Laboratory of Research Center for Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences. For the analysis of gas components, the gas in fluid inclusions was extracted using the decrepitation method. The analytical procedure is as follows (Zhu et al., 2003). Each sample weighed 500 mg. It was loaded into a quartz tube and gradually heated to 100°C to remove absorbed gas and secondary inclusions below 100°C when the vacuity in the tube was 6 × 10⁻⁶ Pa. The sample was heated to 500°C at a heating rate of 1°C/s, and then the readings of the manometer were recorded. Then the sample was frozen for 5 min in liquid nitrogen and then frozen for 5 min in the solid carbon dioxide, and the manometer readings were again recorded in order to calculate the water content. The gas composition was measured on an Ulvac RG202 quadrupole mass spectrometer (Ulvac, Kanagawa, Japan). The analytical reproducibility in the present study was <5%.

4.2. Inclusion types and characteristics

Abundant fluid inclusions in quartz and calcite grains from five mineralization stages at Sawayaerdun were observed in the present study. Measurements in transparent minerals were typically restricted to primary or pseudosecondary inclusions. These inclusions are dispersed in transparent mineral grains and in a few cases occur along microcracks within mineral grains. Primary fluid inclusions may be classified into types of H₂O-NaCl and H₂O-CO₂-NaCl based on their phase relationships and chemical compositions at room temperature. The H₂O-NaCl type can be further divided into two-phase (L + V), liquid-rich, vapor-rich aqueous-type inclusions and polyphase inclusions with daughter crystals. At room temperature, the H₂O–CO₂–NaCl type can be divided into three-phase-type and two-phase-type inclusions.

Two-phase (L + V) aqueous-type inclusions (Fig. 6a) consist of an aqueous liquid and a vapor phase, with a vapor : liquid ratio of 5–50% and mainly 5–20%. The inclusions generally range in diameter from 2 to 6 μm and in a few cases range from 8 to 10 μm. Most inclusions have elliptical, rounded, elongated, triangle and irregular shapes and a few show negative crystal or incomplete negative crystal shapes. The two-phase aqueous-type inclusions in quartz grains from the main stage of gold mineralization are more abundant and larger than those in the other stages, and range in diameter from 2 to 8 μm and a few may be as large as 10 μm. These aqueous-type inclusions are the most abundant and occur in all the mineralization stages. They are the main fluid inclusion type in the Sawayaerdun gold deposit and usually coexist with the other types of inclusion.

Liquid-rich aqueous-type inclusions consist of an aqueous liquid and minor vapor phase, with a vapor : liquid ratio of <5%. These inclusions are mainly elliptical and rounded in shape and mostly 1–5 μm in diameter. These aqueous-type inclusions are the main fluid inclusion type in the antimony–quartz stage and quartz–carbonate stage, but they are relatively rare in the other stages. This type of inclusion generally coexists with vapor-rich, two-phase aqueous-type inclusions and CO₂-H₂O type inclusion.

Vapor-rich aqueous-type inclusions (Fig. 6b), with a vapor : liquid ratio of 70–90%, homogenize to a vapor phase when heated. Some of the fluid inclusions are vapor–pure aqueous-type inclusions and consist of a
vapor phase (Fig. 6c). These have an irregular and elongated shape and are approximately 3–15 \( \mu \text{m} \) in size. This type of inclusion coexists with the other type of inclusions. Vapor-rich aqueous-type inclusions are relatively rare, and unevenly distributed.

Polyphase inclusions with daughter crystals (Fig. 6d,e) consist of vapor, liquid and daughter crystals. They are mainly irregular in shape and mostly 2–10 \( \mu \text{m} \) in diameter. Vapor bubbles constitute 5–20\% of the total volume of each inclusion. The size of daughter crystals is typically close to that of the corresponding vapor bubble, but in some inclusions the daughter crystals are larger (Fig. 6d). The daughter crystals occur in cubic and rectangular shapes. Microscopic study suggests that the daughter crystals are commonly halite. Inclusions of this type occur in quartz grains formed in all the mineralization stages, but they are scarce, and unevenly distributed. This type of inclusion generally coexists with the other type of inclusions.

CO\(_2\)-H\(_2\)O type inclusions consist of aqueous liquid, carbonic liquid and vapor (Fig. 6f). At room temperature, most of them consist of three phases (liquid water + liquid CO\(_2\) + CO\(_2\)-rich vapor), and some of the two-phase fluid inclusions also nucleated a third phase during slight cooling below room temperature. The CO\(_2\) phase varies generally in volume between 5 and 80 \( \% \). These have irregular, elongated, elliptical or negative crystal shapes and are approximately 2–6 \( \mu \text{m} \) in diameter and a few may be as large as 8 \( \mu \text{m} \). CO\(_2\)-H\(_2\)O-type inclusions are well developed and occurred in all the mineralization stages, but they are relatively rare, and unevenly distributed. This type of inclusion generally coexists with the other type inclusions. CO\(_2\)-H\(_2\)O-type inclusions are too small for microthermometry, and almost all the analyzed inclusions of this phase decrepitated prior to homogenization.

### 4.3. Microthermometric results

A total of 130 NaCl–H\(_2\)O inclusions in quartz from five mineralization stages were measured, and the data are summarized in Fig. 7. The homogenization temperatures of the aqueous inclusions in the quartz stage range from 172 to 350°C, clustering at 190 and 270°C. The salinities of the aqueous inclusions, determined from ice-melting temperatures ranging from −1.5 to −17.7°C, correspondingly vary from 2.57 to 20.75 equivalent wt\% NaCl (Bodnar, 1992). We obtained corresponding fluid densities between 0.76 and 1.05 g/cm\(^3\) from calculations by Liu and Shen (1999) when using the homogenization temperatures and salinities of the aqueous fluid inclusions.
The aqueous inclusions for the arsenopyrite–pyrite–quartz stage show final homogenization to liquid at temperatures between 250 and 310°C with a peak around 280°C, and melting of ice in a range of −1.9 to −4.0°C. The melting temperatures correspond to salinities from 3.23 to 6.45 equivalent wt% NaCl. These values correspond to fluid densities between 0.76 and 0.83 g/cm³.

The homogenization temperatures of aqueous inclusions for the polymetallic sulfide quartz stage range from 159 to 225°C with a peak temperature of 210°C. The ice-melting temperatures range from −2.3 to −6.0°C. The salinities range from 3.87 to 9.21 equivalent wt% NaCl for aqueous inclusions, and fluid densities between 0.91 and 0.93 g/cm³.

The homogenization temperatures of aqueous inclusions for the antimony–quartz stage range from 159 to 220°C with a peak around 200°C, and melting of ice in a range of −1.9 to −4.0°C. The melting temperatures correspond to salinities from 3.23 to 6.45 equivalent wt% NaCl. These values correspond to fluid densities between 0.76 and 0.83 g/cm³.

Microthermometric measurements of aqueous inclusions in quartz formed in the antimony–quartz stage yielded homogenization temperatures ranging from 159 to 220°C with a peak around 180°C, ice-melting temperatures of −3.6 to −6.7°C, salinities of 5.86 to 10.11 equivalent wt% NaCl and fluid densities between 0.93 and 0.96 g/cm³.

The homogenization temperature ($T_h$) of two-phase inclusions in the quartz-carbonate stage range from 125 to 314°C and show a bimodal distribution of two temperature intervals, that is, from 140 to 220°C and from 260 to 300°C. The ice-melting temperatures range from −2.1 to −19.6°C. The salinity estimated from ice-melting data of two-phase inclusions range from 3.55 to 22.10 equivalent wt% NaCl with the majority of salinities ranging between 5 and 10 equivalent wt% NaCl and 20–22 equivalent wt% NaCl, and fluid densities between 0.86 and 0.99 g/cm³.

Polyphase inclusions with daughter crystals in quartz from five mineralization stages were also measured. These are supersaturated saline inclusions, in which the melting temperatures of daughter crystals are higher than the vapor–liquid homogenization temperatures. The vapor–liquid homogenization temperatures range from 205 to 340°C, but the melting temperatures of daughter crystals are 270–451°C. According to the appropriate parameter table of Liu and Shen (1999), the salinities range from 35.99 to 53.32 equivalent wt% NaCl, which indicate that the fluids are hypersaline.

### 4.4. Components of fluid inclusions analysis

The liquid and gaseous components of fluid inclusions in 10 quartz samples from all five of the mineralization stages in the Sawayaerdun gold deposit are given in Tables 3 and 4. The liquid components of fluid inclusions are mainly Na⁺ and Cl⁻, with minor amounts of Ca²⁺, K⁺, Mg²⁺ and SO₄²⁻. The content of F⁻ remained below the detection limit in all analyses. The gas components of fluid inclusions are mainly H₂O (72.37–96.56 mol%) and CO₂ (2.08–24.36 mol%), with minor amounts of CH₄ (0.14–3.71 mol%) and N₂ (0.41–2.65 mol%). Trace amounts of C₂H₆ (0.03–0.09 mol%), H₂S (0.00–0.01 mol%) and He were also detected. The fluid inclusions in the ores contain Au 0.031 g/t, Ag 0.19 g/t, Cu 0.19 g/t, Pb 1.96 g/t and Zn 0.24 g/t. In summary, the ore-forming fluid in the Sawayaerdun gold deposit can be described as a middle- to low-salinity H₂O-NaCl-CO₂-CH₄-N₂ fluid with low H₂S.

### 5. Sulfur, carbon and oxygen isotopes

#### 5.1. Samples and analytic methods

Eleven fresh pyrite samples were collected for sulfur isotope measurements, including six samples from the IV mineralized zone, two from the I mineralized zone and three samples from barren quartz veins (stages 1–3). SO₂ gas was prepared from the pyrite by baking with Cu₂O as oxidizer for sulfur isotope analysis. Taking the
CDT (Canyon Diablo Troilite Standard) as standard, the accuracy of analyses is ±0.2‰.

Eight dolomite samples for oxygen and carbon isotope analysis were collected from surface, adit and drill core from the IV mineralized zone. For oxygen and carbon isotope analysis, dolomite was reacted with phosphoric acid 50°C. The $^{13}$C PDB values of samples were directly obtained from the extracted CO$_2$. The analyzing process is described in detail in Mao et al. (2002a).

All SO$_2$ and CO$_2$ were analyzed in a Finnigan MAT 251 mass spectrometer, at the Stable Isotope Laboratory of the Institute of Mineral Resources, Chinese Academy of Geological Sciences. Analytical reproducibility in the present study is ±0.2‰ for O and C isotopes.

5.2. Results

All sulfur isotope data obtained in the present study are presented in Table 5. The $^{34}$S values of pyrite from the Sawayaerdun gold deposit range from −2.2 to +1.1‰ with a mean of −0.4‰. These data have a very narrow range and $^{34}$S values that are generally close to zero. The $^{34}$S values of pyrite from an early gold-free quartz vein are slightly higher than those of the gold mineralization stage (stages 2 and 3).

The analytical results of carbon and oxygen stable isotope analyses of the Sawayaerdun gold deposit are shown in Table 6. The $^{13}$C PDB values of dolomite vary between −5.1 and −0.6‰ with an average of −3.1‰. The $^{18}$O SMOW values of dolomite range from 16.4 to 21.1‰ with a mean of 18.9‰.

6. Discussion

6.1. Evolution of ore-forming fluids

The CO$_2$ contents of the fluid inclusions increase significantly from the first to fourth stages, averaging values from 3.2 → 11.9 → 9.2 → 22.5 mol% and decrease...
significantly in the last stage (to 3.6 mol%). The variations of the \( \text{N}_2 \) and \( \text{CH}_4 \) contents are similar to those of \( \text{CO}_2 \) and imply that gold and antimony mineralization was closely related to variations in the \( \text{CO}_2 \) and \( \text{CH}_4 \) contents of the ore-forming fluids.

### 6.2. Immiscibility of ore fluids

\( \text{H}_2\text{O} – \text{CO}_2 – \text{NaCl} \) inclusions in the Sawayaerdun deposit show a wide range in phase ratios extending to almost pure \( \text{CO}_2 \) and \( \text{H}_2\text{O} \)-rich inclusions. Coexistence of \( \text{H}_2\text{O} – \text{CO}_2 – \text{NaCl} \) inclusions with \( \text{H}_2\text{O} – \text{NaCl} \) inclusions and close homogenization temperatures also suggest that two types of immiscible fluids were captured at the same time. The ratios of \( \text{CO}_2/\text{CH}_4 \) increase during boiling of hydrothermal fluids due to preferential loss to the vapor phase of the more volatile gas \( \text{CH}_4 \) relative to \( \text{CO}_2 \) (Moore et al., 2000; Brathwaite & Faure, 2002). For the Sawayaerdun deposit, from the arsenopyrite–pyrite–quartz stage to quartz–calcite stage the \( \text{CO}_2/\text{CH}_4 \) values have a tendency to increase (8.7 → 9.5 → 18.3 → 19.2). The data imply that fluid boiling occurred during ore-forming processes.

The liquid-rich, two-phase (L + V) and vapor-rich aqueous-type inclusions in the Sawayaerdun deposit form a continuous variation series. They coexist with polyphase inclusions with daughter crystals, indicating that the fluid inclusions were trapped during fluid immiscibility (fluid boiling; Zhang & Chen, 1993; Mao et al., 2003). Based on the fluid inclusion investigations, Chen et al. (2004) believe that the fluid boiling occurred probably at 350 and 250°C, which might cause the formation of quartz veins and polymetallic sulfide stockworks.

Salinity determination shows that there are a more abundant, low-salinity inclusion cluster and a less abundant, high-salinity inclusion cluster in five mineralization stages of the Sawayaerdun gold deposit, which might imply mixing of two kinds of fluids with similar temperatures but different salinities (Zhang et al., 2003a). There are three interpretations about the halite-bearing polyphase inclusions (Zhang et al., 2003a): (i) they formed directly from the magmatic hydrothermal system; (ii) they were generated by immiscibility of hydrothermal fluids; and (iii) they were generated by direct exsolution from shallow magma in the last stage of magmatic crystallization (Bodnar, 1994). Highly saline inclusions in the Sawayaerdun deposit were probably generated by immiscibility (including boiling) of hydrothermal fluids, an assumption based on fluid inclusion investigations and geology of the Sawayaerdun gold deposit. Because these inclusions are relatively rare, their relationship to the gold ores and the main generation of heterogeneously trapped fluids is uncertain.

### Table 5 \( \delta^{34}\text{S}_{\text{CDT}} \) values (‰) of pyrite from the Sawayaerdun gold deposit

<table>
<thead>
<tr>
<th>Serial no.</th>
<th>Sample no.</th>
<th>Mineral</th>
<th>( \delta^{34}\text{S}_{\text{CDT}} ) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S02-3</td>
<td>Dolomite</td>
<td>−1.9</td>
</tr>
<tr>
<td>2</td>
<td>S02-5</td>
<td>Dolomite</td>
<td>−2.2</td>
</tr>
<tr>
<td>3</td>
<td>S04-1</td>
<td>Dolomite</td>
<td>−0.2</td>
</tr>
<tr>
<td>4</td>
<td>S04-2</td>
<td>Dolomite</td>
<td>−0.9</td>
</tr>
<tr>
<td>5</td>
<td>S04-5</td>
<td>Dolomite</td>
<td>−0.2</td>
</tr>
<tr>
<td>6</td>
<td>S04-10</td>
<td>Dolomite</td>
<td>−0.9</td>
</tr>
<tr>
<td>7</td>
<td>S06-4</td>
<td>Dolomite</td>
<td>−0.9</td>
</tr>
<tr>
<td>8</td>
<td>CM2702-1</td>
<td>Dolomite</td>
<td>−0.9</td>
</tr>
<tr>
<td>9</td>
<td>97SW-21</td>
<td>Siderite</td>
<td>−5.3</td>
</tr>
<tr>
<td>10</td>
<td>97SW-21</td>
<td>Siderite</td>
<td>−5.4</td>
</tr>
<tr>
<td>11</td>
<td>S018</td>
<td>Siderite</td>
<td>−3.4</td>
</tr>
</tbody>
</table>

Serial nos. 9–11 are after Zheng et al. (2001).

### Table 6 Carbon and oxygen isotope data of the Sawayaerdun gold deposit

<table>
<thead>
<tr>
<th>Serial no.</th>
<th>Sample no.</th>
<th>Mineral</th>
<th>( \delta^{13}\text{C}_{\text{PDB}} ) (‰)</th>
<th>( \delta^{18}\text{O}_{\text{V-SMOW}} ) (‰)</th>
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</thead>
<tbody>
<tr>
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<td>−4.3</td>
<td>18.8</td>
</tr>
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<td>2</td>
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<td>Dolomite</td>
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<td>18.5</td>
</tr>
<tr>
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<td>S04-1</td>
<td>Dolomite</td>
<td>−5.1</td>
<td>18.4</td>
</tr>
<tr>
<td>4</td>
<td>S04-2</td>
<td>Dolomite</td>
<td>−2.7</td>
<td>16.4</td>
</tr>
<tr>
<td>5</td>
<td>S04-5</td>
<td>Dolomite</td>
<td>−4.2</td>
<td>19.3</td>
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<tr>
<td>6</td>
<td>S04-10</td>
<td>Dolomite</td>
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<td>S06-4</td>
<td>Dolomite</td>
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<td>Siderite</td>
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<td>25.2</td>
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<td>S018</td>
<td>Siderite</td>
<td>−3.4</td>
<td>17.8</td>
</tr>
</tbody>
</table>

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6.3. Genetic implications of sulfur, carbon and oxygen stable isotopes

The δ^{34}S values of sulfides of 41 samples (11 samples from this study and 30 samples from Zheng et al., 2001) have a very narrow range between −3.0 and +2.6‰, with a peak value of +0.5‰ (Fig. 8), and generally close to zero. According to Ohmoto and Rye (1979), the average value of δ^{34}S values of minerals can represent that of the total sulfur in the hydrothermal fluids when the mineral association is simple and if reducing conditions prevailed during sulfide deposition. The fluids could have been relatively oxidized, causing 34S/32S fractionation between H2SO4 and H2S and the resulting minerals; also, the average value is meaningless as far as the δ^{34}S fluid composition is concerned; nevertheless, the values cluster around zero, and therefore we can make the assumption that the total sulfur in the hydrothermal fluids was also close to zero. δ^{34}S values range from −2.2 to +2.6‰ with a mean of +0.0‰ for 29 pyrites, from +0.4 to +1.0‰ with a mean of +0.7‰ for three arsenopyrites, from −0.3 to +0.3‰ with a mean of −0.1‰ for three pyrrhotites, from −3.0 to −0.5‰ with a mean of −1.6‰ for five jamesonites, and from −1.4‰ for stibnite. The δ^{34}S values of different sulfide minerals have the following order of abundance: δ^{34}S arsenopyrite > δ^{34}S pyrite > δ^{34}S pyrrhotite > δ^{34}S stibnite > δ^{34}S jamesonite, indicating that the sulfur isotopes reach an equilibrium among the sulfides. On the whole, the δ^{34}S values of five minerals are close to each other. There is a possibility that the δ^{34}S values in the hydrothermal fluids derived either from the mantle or from mantle-related magmas that were slightly modified by sulfur in sedimentary rocks during its ascent from the depth (Mao et al., 2002a).

The δ^{18}O values of 11 samples of dolomite and siderite range from 16.4 to 25.2‰, and the δ^{13}C values range from −5.4 to −0.6‰. The mean of δ^{13}C values, −3.5‰, is in the range of mantle carbon (−5 ± 2‰) defined by Hoefs (1997), and shows the characteristics of mantle-derived carbon.

In the δ^{13}C versus δ^{18}O diagram (Fig. 9), the projected points of the Sawayaerdun deposit display a trend of subhorizontal distribution. This might be caused by CO2 degassing or fluid/rock interaction between fluids and surrounding rocks (Zheng & Hoefs, 1993; Liu et al., 2004). The dolomite and siderite samples fall in a field between marine carbonates and magma–mante, indicating that carbon was derived from a mixture of marine carbonates and the mantle, and was affected by low-temperature alteration. The δ^{13}C values of carbonate are higher than those of the magma–mantle source region, which possibly indicates that isotopic exchange took place between mantle fluids or magmatic fluids and carbonate host rocks during ore formation, and there is a shift toward an increase in δ^{13}C values.

Studies of orogenic gold deposits by, for example, Kerrich et al. (2001) and Mao et al. (2002b) in the past several years have shown that this type of gold
deposit is characterized by the common presence of abundant carbonate veins or quartz-carbonate veins in the late stage, and it has been suggested by these authors that ore-forming fluids contain high CO_2 concentrations which were, at least in part, derived from mantle fluids. Examples are the Kanggur gold deposit (Wang et al., 2004; Mao et al., 2005) and deposits in the Jiaodong gold province in China (Mao et al., 2002b) and gold deposits in the Yilgarn Craton, Western Australia (Groves et al., 2000). The δ^{13}C_PDB values of carbonates in veins at Sawayaerdun range from −5.4 to −0.6 ‰, suggesting the involvement of fluids from the mantle in the ore-forming process of the Sawayaerdun gold deposit.

6.4. Gold transport and deposition

Gold in hydrothermal ore fluids is commonly transported as hydrosulfide complexes at medium to low temperatures and as chloride complexes at elevated temperatures (Wilkinson, 2001; Brathwaite et al., 2002; Shen et al., 2004). Ore-forming temperatures in the Sawayaerdun gold deposit were medium to low (125–340°C), and the ore-forming fluids contain SO_4^{2−} and H_2S, suggesting that the gold was transported as hydrosulfide complex.

Phase separation of fluids has been cited as a main mechanism for gold deposition in many orogenic gold deposits (Wilkinson, 2001). As ore-bearing fluids migrate upward along faults to the shallower levels of the crust, with decreasing temperature, CO_2 and NaCl-H_2O immiscibility occurs and CO_2 degasses from the hydrothermal fluids; as a result, the fluid components are reduced, the pressures decrease, the solubility of the gold–sulfide complex is lowered, and gold precipitates from the ore fluids (Wilkinson, 2001).

6.5. Gold metallogenesis

Due to lack of appropriate minerals and techniques for precise and reliable age determinations, the age of mineralization in the Sawayaerdun gold deposit has been strongly debated (Ye et al., 1999a,c; Hu et al., 2000; Zheng et al., 2002; Liu et al., 2002a). Based on the published data (Rb-Sr isochron ages of 246 ± 16 and 231 ± 10 Ma for auriferous quartz veins, Ye et al., 1999c; Chen & Li, 2003; and Ar/Ar plateau age of 210 ± 0.99 Ma on an auriferous quartz vein, Liu et al., 2002a), we favor a model whereby the main stage (stages 2 and 3) of gold mineralization in the Sawayaerdun gold deposit occurred in the Triassic. This genetic model is outlined in the following.

The formation of the Sawayaerdun-Jigen ductile shear zone progressed through a process of deformation from ductile compression in the early stage through brittle–ductile shear to brittle extension and fracturing in the late stage, and which represents the deformation process of the shear zone rising gradually from the deep level of the crust to a shallow level. Gold mineralized zones are controlled by a group of NE-NNE-trending brittle–ductile shear zones and gold orebodies are controlled by dilational fracture zones within these brittle–ductile shear zones. Like many orogenic gold deposits elsewhere, such as the Kanggur (Zhang et al., 2003b), the ductile shear zone probably provided the conduits for the transport of ore-forming fluids and structural sites for deposition of gold and antimony.

The characteristics of rock magnetic fabrics and their relationship to gold mineralization in the Sawayaerdun gold deposit show that the gold orebodies formed in an extensional setting following ductile deformation (Chen et al., 2001). The host rocks are compact and less permeable in the ductile field, which was unfavorable for the penetration and transport of fluids. In addition, higher pressure–temperature conditions of the ductile field were also unfavorable to the precipitation of metallic minerals.

In the late orogenic stage, that is, the Triassic, the early-stage ductile zone was uplifted and eroded, resulting in the formation of the brittle–ductile shear zone and brittle fault successively in the ductile shear zone. Meteoric water and possibly a minor amount of magmatic fluids migrated upward along shear zones, and generate the ore-forming system (hydrogen and oxygen isotope studies show that the ore-forming fluids were mainly derived from meteoric water, with a minor part from magmatic fluid; Ye et al., 1999a). Driven by temperature and pressure gradients, these fluids circulated and extracted part ore-forming materials from the country rocks and migrated into brittle–ductile shear zones and brittle fracture zones. In medium- to low-temperature and low-pressure conditions, with decreasing temperatures, CO_2 and H_2O-NaCl immiscibility occurred. Gold hydrosulfide complexes in the hydrothermal ore solutions became unstable and the ore was precipitated in veinlets, stockworks, and as disseminations in altered rock. The specific type of gold mineralization within the Sawayaerdun deposit is considered to be controlled by shear deformation:
veinlet-disseminated altered mylonite ores occur in the ductile deformation zone and fractured–altered rock ores and auriferous quartz veinlets occur in the brittle–ductile deformation zone and brittle deformation zone.

7. Conclusions

Sawayaerdun gold deposit is an orogenic gold deposit. Gold mineralized zones and orebodies are controlled by north–northeast-trending brittle–ductile shear zones. Based on mineral assemblages and crosscutting relationship between veins, five mineralization stages during the ore-forming process have been identified. These are (i) an early quartz stage; (ii) arsenopyrite–pyrite–quartz stage; (iii) polymetallic sulfide quartz stage; (iv) antimony–quartz stage; and (v) late-stage quartz–carbonate vein stage. Stages (ii) and (iii) represent the main stage of gold mineralization in the Sawayaerdun deposit whereas (iv) represents the main stage of antimony mineralization.

The fluid inclusions in the Sawayaerdun deposit show characteristics of complex inclusion type. Five types of fluid inclusions, namely two-phase (L + V), liquid-rich, vapor-rich aqueous-type inclusions, polyphase inclusions with daughter crystals and three-phase CO2-type inclusions, have been recognized in quartz and calcite. The ore-forming fluids exhibit a middle-low temperature (125–340°C), low–moderate salinity (2.57–22.10 wt% NaCl equiv.) H2O–NaCl–CO2–CH4–N2 system. The $^34$S values of sulfides show isotopic characteristics of mantle-derived sulfur. The $^{13}$C values of dolomite and siderite imply that the carbon came mainly from the mantle and some input from marine carbonate rocks. Changes in physico-chemical conditions, water–rock and immiscibility of hydrothermal fluids are inferred to have played important roles in the ore-forming process of the Sawayaerdun gold–antimony deposit.

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