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Carbonic fluids in the Hamadi gold deposit, Sudan: Origin and contribution to gold mineralization

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Abstract

The Hamadi gold deposit, located in North Sudan, occurs in the Neoproterozoic metamorphic strata of the Arabian-Nubian Shield (ANS). Two types of gold mineralization can be divided: gold-bearing quartz veins and altered rock ores near ductile shear zones. The gold-bearing quartz veins are composed of white to gray quartz associated with small amounts of pyrite and other polymetallic sulfide minerals. Wallrock alterations mainly include beresitization, epidotization, chloritization, and carbonatization. CO₂-rich inclusions are commonly seen in gold-bearing quartz veins and quartz veinlets from gold-bearing altered rocks, which mainly include one-phase carbonic (CO₂±CH₄±N₂) inclusions and CO₂-H₂O inclusions with CO₂/H₂O volumetric ratios of 30~80%. Laser Raman analysis does not show the H₂O peak in carbonic inclusions. For quartz veins, the solid CO₂ melting temperatures (T_{m,CO_2}) of carbonic inclusions have a narrow range of -59.6°C to -56.8°C. Carbonic inclusions also have T_{h,CO_2} from -28.3°C to +23.7°C, with most of the values clustering between +4.0 and +20°C, all of these inclusions homogenized into the liquid CO₂ state. The densities range from 0.73 to 1.03g/cm³. X_{CH_4} of carbonic fluid inclusions ranges from 0.004 to 0.14, and with most of X_{CH_4} around 0.05. In CO₂-H₂O fluid inclusions, T_{m,CO_2} values were recorded mostly around -57.5°C. The melting temperatures of clathrate are from 3.8 to 8.9°C. It is suggested that the lowest trapping pressures of CO₂ fluids would be 100~400 MPa based on T_{h,CO_2} of L_{CO2} inclusions and $T_{h,tot}$ of paragenetic L_{CO2}-L_{H2O} inclusions. For altered rocks, the solid CO₂ melting temperatures (T_{m,CO_2}) of carbonic inclusions have a narrow range of

–58.4~–57.0 °C, whereas the homogenization temperatures (T_{h,CO_2}) vary widely (–19 °C ~ + 29 °C), most of carbonic inclusions and the carbonic phases in the CO₂-H₂O inclusions are homogenized to liquid CO₂ phases, which correspond to the densities being 0.70~1.00 g/cm³. Fluid inclusions in a single FIA have narrow T_{m,CO_2} and T_{h,CO_2} values, but they vary widely in different FIAs and non-FIAs, which indicates that there was a wide range of trapping P - T conditions during the ore-forming process in late retrograde metamorphism after metamorphism peak period. The carbonic inclusions in the Hamadi gold deposit are interpreted to have resulted from unmixing of an originally homogeneous aqueous-carbonic mixture during retrograde metamorphism due to decreasing of P - T conditions. CO₂ contributed to gold mineralization by buffering the pH range and increasing the gold concentration in the fluids.

Keywords: Carbonic fluid inclusions; gold-bearing quartz veins; metamorphic environment; Hamadi gold deposit; North Sudan

1. Introduction

Since the term of “orogenic gold deposit” was first used by Bohlke (1982) and comprehensively introduced by Groves et al. (1998), orogenic-type gold deposits have been well documented in ore geology, geochemistry and tectonic setting (Groves et al. 1998; Goldfarb et al. 2005). It is well known that low salinities and CO₂-rich fluids are one of the most important characteristics of the orogenic gold deposits (e.g., Groves et al. 1998; Goldfarb et al. 2001; Goldfarb et al. 2005; Phillips et al. 2004;

Ridley and Diamond 2000). Carbonic fluid inclusions lacking visible H₂O at room temperatures were found in orogenic gold deposits in last decades, such as the gold mineralization of the Ashanti Belt, Ghana (Schmidt Mumm et al. 1997), the Muruntau gold deposit of Uzbekistan (Graupner et al. 2001; Wilde et al. 2001), the Campbell-Red Lake gold deposit in Canada (Chi et al. 2006), the Carará deposit of Brazil (Klein and Fuzikawa 2010), and the Sarekoubu gold deposit of southern Altay in China (Xu et al. 2005). The source of these carbonic fluid inclusions and their contribution to gold mineralization are still controversial.

The Arabian-Nubian Shield (ANS) hosts a great number of orogenic gold and VMS deposits (Ghebreab et al. 2009; Botros 2002; Tadesse et al. 2003; Schmidt Mumm et al. 1997). The eastern part of ANS has been extensively explored since the 1970s, with numerous discoveries of deposits including gold, silver, copper, molybdenum, and zinc, but the west ANS has received less exploration attention in the last decades (Trench and Groves 2015). The geological characteristics show that there is great potential for the prospecting of gold deposit in the area. Our recent study on the Hamadi gold deposit, which occurs in the Neoproterozoic metamorphic strata of the west ANS, shows that there are numerous carbonic fluid inclusions both in gold-bearing quartz veins and veinlets in altered wall rocks. Where did these carbonic fluids come from and how did they contribute to gold mineralization? These questions remain to be answered for the origin of the Hamadi gold deposit. In this paper, we present fluid inclusion studies on mineralized quartz veins and altered rocks from the Hamadi gold deposit and attempt to illustrate the origin of the carbonic inclusions and

the contribution of the carbonic fluids to gold mineralization.

2. Geological Setting

2.1. Regional geology

The Arabian-Nubian Shield (ANS) was an accretion orogenic belt that formed during convergence between the East and West Gondwana land at the end of the Wilson cycle from 900 to 500Ma, which is called the Pan-African orogeny (El-Gaby et al. 1988; Pohl 1988; Stern et al. 1994). The Hamadi gold deposit is located in the Neoproterozoic greenstone belt of the Arabian-Nubian Shield (ANS) in North Sudan, which is formed by crustal growth during the Neoproterozoic Pan-African orogenic period (Fig. 1). It is situated on the splicing structure zone of Kerns (Stern et al. 1994). Four periods of regional magmatic intrusion events can be identified: (1) intermediate-acid magmatic intrusion in Paleoproterozoic; (2) intermediate-acid and ultramafic intrusion during the Neoproterozoic; (3) intermediate-acid magmatic intrusion and eruption during Palaeozoic-Mesozoic; and (4) eruption of basaltic magma during Cenozoic. Gold mineralization in this area is associated with tectonic hydrothermal events caused by three periods of magma activities (El-Gaby et al. 1998; Stern et al. 1994).

There are three periods of regional tectonic events: 1) during the period of the Neoproterozoic, forming tight and overturned folds; 2) during the period of the Palaeozoic to Mesozoic, forming the Bayuda metamorphic core complex, generally manifested as tectonic basins and radial fractures; 3) during the period of the

Cenozoic, forming a series of N-S tensional fractures (Stern et al. 1994). Dominantly NE- to E-trending relict fold structures are present in North Sudan. Collision-related granulite to amphibolite facies metamorphism in the region occurred between 720 and 700 Ma (Stern et al. 1994). The basement of the Wadi Singeir basin consists of Paleoproterozoic to Mesoproterozoic metamorphic strata, which are mainly composed of granitic gneiss. The overlying strata are composed of Neoproterozoic metasediment and metavolcanic rocks. In addition, there is a large outcrop composed of Cenozoic basalt. In the Arabian-Nubian Shield, gold mineralization is widely associated with post-tectonic granitoid rocks (El-Gaby et al. 1988; Pohl 1988). The majority of gold deposits occur as Au-bearing quartz veins with a polymetallic sulphide assemblage, exhibiting pinch-swell vein textures and showing evidence of multiple stages of mineralization (Hilmy and Osman 1989; Hussein 1990; Harraz and El-Dahhar 1993). *P-T* conditions at or below greenschist metamorphic boundary favoured establishment of brittle–ductile and brittle structures in which gold deposits were selectively sited (El-Gaby et al. 1988). Formation of gold-bearing silicified shear zones in these shields was likely contemporaneous with greenschist-grade metamorphism and granitoid diapirism (Goldfarb et al. 2005), or as a result of brittle–ductile shearing and folding (e.g., Reinhardt and Davison 1990). Strata in North Sudan mainly consist of medium-low metamorphic grade metasedimentary and metavolcanic rocks, which are equivalent to greenschist facies to epidote-amphibolite facies. Metamorphic rocks of this region suffered from multiple stages deformation and metamorphism (Almond and Shaddad 1984).

2.2. Ore deposit geology

The Hamadi gold deposit, situated on the splicing structure zone of Kerns (Deschamps and Lescuyer 2002), is hosted in plagioclase hornblende gneiss, mica plagioclase gneiss, mica quartz schist, chlorite schist, and hornblende schist of Neoproterozoic metamorphic strata (Fig. 1). Gold reserves were estimated to be 13 tones of Au by Tianjin North China Geological Exploration Bureau during 2006 to 2008, and potential resource was expected to be 65 tones of Au (Yang and Liu 2009). The gold veins at the Hamadi gold deposit are mainly controlled by the shear zone and fold. The vein systems, striking SN and dipping 42° - 44° to west, are composed of vein I, vein II. The ore shoots are 100-500 m in length and 2.5-7.0 m in width, with 1.0-5.4 m in thickness. Gold grades in the veins and wall rocks vary significantly along mineralized zones, from 0.73 to 65.54g/t and 0.75 to 21.75g/t, respectively. Gold mineralization is mainly controlled by deformation zones which are characterized by silicification, pyritization and sericitization zones in 100m-500m width (Fig. 2). Two types of gold mineralization are found in this area, including gold-bearing quartz veins and altered rock ores near ductile shear zones. The gold-bearing quartz veins are composed of white to gray quartz associated with small amounts of pyrite and other polymetallic sulfide minerals, which have variable thickness from 0.3m to 8m. The altered rock ores are mainly characterized by gold-bearing pyritization and carbonatization in biotite-quartz schist, carbonatization in hornblende-quartz schist, and beresitization in mylonitic schist (Fig. 3).

Sericitization, pyritization, and silicification (beresitization) are intensive in gold mineralization zones, and carbonatization, chloritization, and epidotization are also found of the some portions in mineralizing areas.

Ore minerals in the vein systems mainly include native gold, pyrite, chalcopyrite, and pyrrhotite (Figs. 4A-D). Gangue minerals are dominated by quartz, calcite, garnet, chlorite, and plagioclase. Pyrite is main host mineral of gold, and occurs as disseminated or veinlets in the ores and usually was replaced by chalcopyrite (Figs. 4E-I). Pyrite in the alteration zone occurs dominantly as veinlet and disseminated (Fig. 3A and 3B). In mylonitic schist, pyrite metacrysts may occur as rotated grains (Fig. 3C) or as stretched grains (Fig. 3D). The ore shoots occur in places where both pyrite and quartz veins are developed. Carbonatization is also related to gold mineralization, and is characterized by disseminated calcite replacing earlier generation of minerals or calcite-quartz veinlets. Gold occurs mainly in the tiny fissures within quartz (Fig. 4E), or as inclusions within coarse pyrite grains (Fig. 4F). Gold grains occur mainly as fissure-filling gold and inclusive gold in tiny fissures of pyrite, marcasite and quartz, or as inclusions in pyrite crystals. The size of gold grains range from 0.01 to 0.40 mm (Li and Hu 2012).

On the basis of field geology and ore assemblages, three hydrothermal-structural stages can be distinguished: (I) A disseminated pyrite stage, characterized by disseminated pyrite within altered wall rocks; (II) A pyrite-quartz vein stage, characterized by small amounts of disseminated coarse pyrite grains associated with large portion of white quartz in veins crosscut by polymetallic sulfides; (III) A

polymetallic sulfide stage, marked by metal sulfides including chalcopyrite, sphalerite, galena, and pyrrhotite. Stages I and II are the main gold mineralization stages.

3. Fluid Inclusion Study

3.1. Sampling and analytical techniques

More than twenty samples of pyrite-quartz veins and altered rocks from outcrops and drill cores were collected to be made into doubly polished thin sections for fluid inclusion studies. Five samples of quartz veins and four samples of altered rock ores in which fluid inclusions are abundant were selected for microthermometry.

Fluid inclusion microthermometry was done at the fluid inclusions laboratory of University of Science and Technology Beijing using a Linkam THMS600 heating-freezing stage (from -196°C to 550°C). During the microthermometric work several runs have been undertaken down to the lowest limit of temperature of the heating freezing stage, in order to detect the presence of CH_4 and/or N_2 . However, all inclusions froze between -100 and -120°C , and no further freezing event was observed below these temperatures, indicating that CH_4 and/or N_2 are not present in significant amounts. The estimated accuracy for temperatures is $\pm 0.1^{\circ}\text{C}$ for CO_2 solid melting points, CO_2 partial homogenization temperatures, clathrate melting temperatures and ice melting temperatures, and $\pm 1^{\circ}\text{C}$ for total homogenization temperatures. The fluid inclusion assemblage (FIA) method (Goldstein and Reynolds 1994; Chi and Lu 2008) was applied in petrographic study and microthermometry data analysis. Fluid Inclusion Assemblage (FIA) refers to discriminate a group of

petrographically associated fluid inclusions (Goldstein and Reynolds 1994) that are cogenetic, forming at the same time and from the same fluid. Fluid inclusions that occur within healed tiny fissures or within growth zones of host mineral may be identified as FIA (Chi and Lu 2008). We also use abbreviation “non-FIA” to represent those fluid inclusions which occur as isolated and randomly distributed, but not in healed microfractures. Salinities of aqueous FIs were estimated using the reference data of Bodnar (1993) for the NaCl-H₂O system. Salinities of CO₂-rich FIs were calculated using the equations of Collins (1979).

Raman analyses of fluid inclusions were undertaken using a LABHR-VISLabRAM HR800 Raman spectrometer at the Fluid Inclusion Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG-CAS). The wave length was 532 nm for the argon ion laser.

3.2. Fluid inclusion petrography

Fluid inclusions suitable for microthermometric study were found mostly in quartz grains from the main stages of mineralization in the Hamadi gold deposit. According to their nature, phases at room temperature and phase transitions during heating and cooling, and laser Raman spectroscopy, three types of fluid inclusions from the Hamadi gold deposit can be distinguished at room temperatures, including carbonic inclusions (C) (one-phase of CO₂ with small amounts of CH₄ or N₂), CO₂-H₂O inclusions (CW) (two phases composed of H₂O-rich liquid phase and CO₂-rich liquid (or gas) phase, with 30~80% of CO₂/H₂O ratios) (Figs. 5A, 5B, 5C), and aqueous

inclusions (W) (two phases composed of water and vapor phases).

3.2.1. Carbonic inclusions (Type C)

Carbonic fluid inclusions are non-aqueous fluid inclusions described by the system $\text{CO}_2\text{-CH}_4\text{-N}_2$ (Van den Kerkhof and Thiery 2001). Fluid inclusions in gold-bearing veins from the Hamadi gold deposit are characterized by the abundance of carbonic inclusions including pure CO_2 and mostly $\text{CO}_2\text{-CH}_4$ inclusions. Carbonic inclusions occupy more than 90% of the total fluid inclusions observed in auriferous quartz veins (Fig. 6). They generally occur in monophasic, only composed of liquid CO_2 at room temperature, or consist of a liquid CO_2 phase and a vapour CO_2 bubble, commonly in sizes of several microns and up to tens of microns. Most of the carbonic fluid inclusions occur as isolated or randomly distributed ones (Figs. 5D, 5E), indicating that these inclusions are primary or pseudo-secondary. Fluid inclusions that occur within healed microfractures (Figs. 5F, 5G) or within growth zones of host mineral can be easily identified as FIA. In many cases, fluid inclusion within individual FIAs show similar microthermometric attributes, suggesting that these inclusions were entrapped as a homogeneous phase. These fluid inclusions occur as FIAs in quartz of gold-bearing veins, which can be observed in two groups: (1) primary (or pseudo-secondary) carbonic fluid inclusions mainly in the gold-bearing veins of the Hamadi gold deposit; which are sometimes associated with $\text{CO}_2\text{-H}_2\text{O}$ inclusions. Group 1 fluid inclusions are either rounded or negative crystal shapes whose occurrence is limited to internal fissure planes of quartz crystals, and (2) secondary carbonic fluid inclusion in fissures formed after the growth of the quartz crystals,

commonly in sizes of several microns, generally in elongated quartz crystal fragments where fluid inclusions are perpendicular to the direction of foliation (or schistosity) in quartz veins. Secondary carbonic fluid inclusion distributed as oriented healed fractures, and generally cut across the boundaries of the quartz grains and truncate.

3.2.2. CO₂-H₂O inclusions (Type CW)

They appear irregular, ellipsoid and negative quartz crystal in shape, 5 to 20 μm in size, isolated or as clusters in occurrence. CO₂-H₂O inclusions are composed of a liquid CO₂ phase and an aqueous phase at room temperatures and 30~80% CO₂/H₂O ratios. These inclusions occur occasionally in the main stage of gold mineralization. Some CO₂-H₂O inclusions show three phases: a CO₂ liquid phase, a CO₂ vapor phase, and an aqueous phase at room temperatures. The CW type fluid inclusions are not abundant in main stages of mineralization and can be further divided into two subtypes. The type CW1 fluid inclusions contain more CO₂ than H₂O (Fig. 5I) while the type CW2 inclusions have more H₂O than CO₂ (Fig. 5I). Most of the CO₂-H₂O inclusions occur as randomly distributed or isolated inclusions, indicating primary origin, and sometimes are associated with carbonic inclusions (Figs. 5H, 5I).

3.2.3. Aqueous inclusions (Type W)

The W type inclusions consist of aqueous vapor and liquid at room temperature. Secondary aqueous inclusions can be found in the latest fissures. They occur along the tiny fractures cutting quartz grains. Salt-aqueous inclusions occur as FIAs in the quartz veins of the Hamadi deposit. These inclusions form only a small percentage of all fluid inclusions in study altered rock samples. Aqueous inclusions associated with

a few CO₂-H₂O inclusions. Their sizes range from 3 to 8 µm and the vapor phase account for 5-20 volume %.

3.3. Fluid inclusion microthermometry

3.3.1. Microthermometry for quartz veins

More than four fluid inclusion assemblages (FIA) can be identified in some samples of vein quartz (Figs. 5D, 5E). Microthermometric measurements on 28 FIAs and 309 non-FIAs were performed. The microthermometric data are summarized in Table 1 and Table 2. The microthermometric data and behaviors of fluid inclusions during microthermometry are described as follows.

(1) Carbonic inclusions (type C). A bubble (V_{CO2}) appears in monophasic CO₂ when they are cooled down from room temperatures (down to -30°C), indicating that the inclusions are composed of liquid CO₂ at room temperature. The liquid CO₂ freeze into solid CO₂ after they are continually cooled down to -95°C. The melting of solid CO₂ happens at above -60°C after heating from these low temperatures. The melting temperatures of solid CO₂ (T_{m,CO2}) range in a very narrow interval between -56.6°C and -59.6°C, with a sharp peak being observed at -57.0 °C, which indicates that CO₂ are dominant and other gases such as CH₄ and N₂ are subordinate. The solid CO₂ melting temperatures (T_{m,CO2}) of carbonic inclusions range from -59.6°C to -56.8°C for 23 different FIAs, and from -59.6°C to -56.9°C for 122 non-FIA inclusions (Fig. 7A). The result indicates that CO₂ is dominant at the main mineralization stages of hydrothermal event, with small amounts of other volatiles like CH₄ and N₂ (Roedder

1984). The homogenization temperatures of (T_{h,CO_2}) of carbonic inclusions, all into the liquid phase, range widely from -28.3°C to $+23.7^{\circ}\text{C}$ (23 FIAs), and from -7.4°C to $+20.8^{\circ}\text{C}$ (122 non-FIA inclusions) (Fig. 7B). The CO_2 fluid densities range from 0.73 to 1.03g/cm^3 , which were calculated by using p - T_h - X_{CH_4} phase diagram of Swanenberg (1979) (Table 1 and Table 2). All the FIAs show a considerable narrow range of homogenization temperatures. For example, type carbonic fluid inclusions within a single FIA have a very narrow ranges of T_{m,CO_2} and T_{h,CO_2} , such as from -57.6 to -57.2°C (T_{m,CO_2}) and from 10.2 to 11.6°C (T_{h,CO_2} homogenized to liquid CO_2 phase) in sample HMD202-d (Fig. 8). The estimated CO_2 densities of carbonic inclusions are from 0.80 to 0.88g/cm^3 .

(2) CO_2 - H_2O inclusions (type CW). The cooling and heating behavior of CO_2 phases in CO_2 - H_2O inclusions is similar to those of carbonic CO_2 inclusions. The T_{m,CO_2} of CO_2 - H_2O inclusions occurring in FIAs range from -57.9°C to -56.8°C for 5 different FIAs, and from -57.8°C to -56.9°C for isolated or randomly distributed CO_2 - H_2O inclusions for 47 non-FIA inclusions (Fig. 7C). The CO_2 partial homogenization temperatures (T_{h,CO_2}) range from -9.5°C to 27.2°C for 5 different FIAs, and generally homogenize to liquid. The CO_2 partial homogenization temperatures (T_{h,CO_2}) range from -10.1°C to 28.8°C for 47 non-FIA inclusions, and generally homogenize to liquid. (Fig. 7D). Most of the CO_2 - H_2O inclusions with high $\text{CO}_2/\text{H}_2\text{O}$ volume ratios were decrepitated before final homogenization, only a few total homogenization temperatures ($T_{h,tot}$) of these inclusions were obtained. Some CO_2 - H_2O inclusions homogenized into the liquid CO_2 state, and few inclusions

homogenized into the gas CO_2 , which are corresponding to the densities being $0.62\sim 0.96\text{g/cm}^3$ calculated by using ρ - T_h phase diagram of Shepherd et al. (1985). It seems that there are no obvious differences between FIAs and non-FIA inclusions from T_{m,CO_2} and T_{h,CO_2} , but the total homogenization temperatures ($T_{h,\text{tot}}$) for CO_2 - H_2O inclusions are different. The values of $T_{h,\text{tot}}$ for FIA range from 264°C to 301°C , whereas those of non-FIA range from 243°C to 398°C (Table 2; Fig. 7E). For example, CO_2 - H_2O inclusions within a single FIA have a very narrow ranges of T_{m,CO_2} , T_{h,CO_2} and $T_{h,\text{tot}}$ such as from -56.8 to -57.0°C (T_{m,CO_2}), from 26.8 to 27.2°C (T_{h,CO_2} homogenized to liquid CO_2 phase) and from 301 to 307°C ($T_{h,\text{tot}}$) in sample HMD203-a. It is noted that the values of $T_{h,\text{tot}}$ of FIAs are lower than those of non-FIA inclusions, indicating that those FIAs might represent later events. The clathrates melted ranges from 3.8°C to 8.9°C , indicating salinities around 2.2 to 10.7 wt.% NaCl equiv.(Fig. 7F).

3.3.2. Microthermometry for altered rocks

(1) Carbonic fluid inclusions in quartz veinlets from gold-bearing altered rocks were also studied for microthermometry (Table 3). Primary carbonic inclusions in quartz veinlets either occur as isolated or as randomly distributed inclusions, whereas secondary carbonic inclusions occur in microfractures. The solid CO_2 melting temperatures (T_{m,CO_2}) of carbonic inclusions have a narrow range of $-58.4\sim -57.0^\circ\text{C}$, whereas the homogenization temperatures (T_{h,CO_2}) vary widely ($-19^\circ\text{C}\sim +29^\circ\text{C}$), which correspond to the densities being $0.70\sim 1.00\text{g/cm}^3$ calculated by using ρ - T_h - X_{CH_4} phase diagram of Swanenberg (1979).

(2) Aqueous inclusions. Aqueous inclusions (L-V) have $-5.2\sim-0.9^{\circ}\text{C}$ of ice melting temperature, with the salinities being 1.57%~8.14% NaCl equiv. and the densities being $0.85\sim1.01\text{g/cm}^3$ (density was calculated using T-W-p phase diagram from Bodnar 1983). Most of inclusions show total homogenization temperatures ($T_{\text{h,total}}$) ($109\sim227^{\circ}\text{C}$).

3.4. Laser Raman spectroscopy

The gas compositions of individual carbonic fluid inclusions and carbonic-aqueous inclusions from five doubly polished sections were analyzed with laser Raman spectrometry (Fig. 9). Laser Raman spectroscopy reveals that the carbonic fluid inclusions contain dominantly CO_2 and little and variable amounts of CH_4 . This is consistent with the triple point of CO_2 phase being slightly lower than -56.6°C . Laser Raman analysis does not show the H_2O peak in carbonic inclusions.

3.5. Summary of published stable isotope data

Li and Hu (2012) conducted a reconnaissance stable isotope study in gold-bearing quartz veins from the Hamadi gold deposit, and compared them to the fields of metamorphic and magmatic fluids compiled by Taylor (1997), in order to trace possible sources for the ore-bearing fluid. The $\delta^{18}\text{O}_{\text{V-SMOW}}$ values of quartz range from +9.8‰ to +11.1‰ in the gold-bearing quartz veins, and the $\delta\text{D}_{\text{V-SMOW}}$ values of fluid inclusions range from -49‰ to -67‰ . The results were normalized with V-SMOW standards and the precisions were $\pm 2\text{‰}$ and $\pm 0.2\text{‰}$ for δD and $\delta^{18}\text{O}$,

respectively. The oxygen isotope ratios of water in equilibrium with quartz were calculated by the equation $1000\ln\alpha_{\text{quartz-H}_2\text{O}} = 3.38 \times 10^6 T^{-2} - 3.40$ (Clayton et al. 1972). The average temperature of 310°C (from this study) is adopted to calculate the average $\delta^{18}\text{O}$ values of the fluids. As a result, the quartz from the Au-bearing ores shows the $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values ranging from 3.88‰ to 4.73‰.

Sulfur isotopic compositions of sulfide minerals (pyrite and arsenopyrite) in the Hamadi gold deposit have been measured (Li and Hu 2012). The $\delta^{34}\text{S}_{\text{CDT}}$ values of pyrite vary from -2.6‰ to -4.6‰. The $\delta^{34}\text{S}_{\text{CDT}}$ value of arsenopyrite is -4.3‰.

4. Discussion

4.1. Sources of ore-forming fluids and materials

The quartz from the Au-bearing ores shows the $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values ranging from 3.88‰ to 4.73‰, and the corresponding $\delta\text{D}_{\text{H}_2\text{O}}$ values of fluid vary from -49‰ to -67‰. The oxygen and hydrogen isotope values lie within the metamorphic sources for the water in the gold-bearing quartz veins at Hamadi gold deposit, which suggests that metamorphic fluids may have a major source of the ore-forming fluids (Fig. 10). The fluid inclusion homogenization temperature and salinity are also consistent with a metamorphic fluid source (Fig. 11). In particular, the generally low salinities, CO_2 -rich characteristics and the absence of any solid bearing fluid inclusions clearly show features of metamorphic water identified in most orogenic-type deposits (Chen et al. 2007). From the data presented above, we suggest that the gold veins at Hamadi were deposited at intermediate temperatures between 243 and 398°C from a

H₂O-CO₂-NaCl fluid system with low-moderate salinities of 2.2~10.7wt.% NaCl equiv. This mineralizing fluid shares many similarities with typical orogenic gold systems although with relatively higher salinities (mostly <12 wt.% NaCl equiv. for the orogenic gold deposit, Fig. 12; Goldfarb et al. 2005).

The $\delta^{34}\text{S}$ values of sulfides from pyrite and arsenopyrite have a narrow range of -2.6‰ to -4.6‰, with an average of -3.6‰. They are comparable to those of many orogenic gold lode deposits, such as Bendigo (-7.4‰ to 8.1‰; Jia et al. 2001), Sawayaerdun (-1.8‰ to 0.9‰; Chen et al. 2012), and Juneau (-17.8‰ to 1.2‰; Goldfarb et al. 1991) in which ore-forming fluids were inferred to be metamorphic in origin. The narrow range of sulfide $\delta^{34}\text{S}$ values indicate that the sulfur in the Hamadi gold deposit was derived from a single source, which may have a connection with the mantle. Ore mineral assemblages mainly include pyrite, pyrrhotite and arsenopyrite. The sulfur belongs to low valence state within these minerals, which indicates that the oxygen fugacity is low during the formation of the sulfide minerals.

4.2. Mineralizing *P-T* conditions from extremely CO₂-rich fluids

The pressure-temperature trapping conditions of fluid inclusions can be constructed from the microthermometric data, in combination with mineral phase equilibrium, and geological evidence. It is clear that primary fluid inclusions in the Hamadi gold deposit are predominantly carbonic inclusions with high densities, some of which are higher than 1.0 g/cm³. Meanwhile, some carbonic fluid inclusions occur as FIAs in quartz of gold-bearing veins, indicating the later tectonic hydrothermal events after host quartz formed.

Since no N_2 was found in Laser Raman spectroscopy, only the X_{CH_4} values of carbonic phases were calculated according to T_{m,CO_2} and T_{h,CO_2} of carbonic and CO_2 - H_2O inclusions by using the V-X phase diagram (Thiry et al. 1994; Van den Kerkhof and Thiry 2001). As shown in Fig. 13, X_{CH_4} of carbonic fluid inclusions at the Hamadi gold deposit may be from 0.004 to 0.14, with most of which are around 0.05. Considering mixing with a little water, we presume that 270~390C, the lower homogenization temperatures of coexisting L_{CO_2} - L_{H_2O} inclusions, were the lowest trapping temperatures of CO_2 fluids. Thus, we roughly estimate the trapping pressures of CO_2 -rich fluid inclusions in the gold-bearing quartz veins. It is suggested that the lowest trapping pressures of CO_2 fluids would be 100~400 MPa based on T_{h,CO_2} of L_{CO_2} inclusions and $T_{h,tot}$ of paragenetic L_{CO_2} - L_{H_2O} inclusions at high temperature and pressure of Van den Kerkhof and Thiry (2001). As shown in Fig. 14, the trapping temperatures (270~390C) and the pressures (100~400 MPa) were lower than the metamorphic P-T conditions of green schist-facies. These are similar to the Atud gold deposit, located in neighbouring Egypt, which was inferred to have formed over a temperature range of 270~430C and pressures of 160~272 MPa (6~11 km depths) (Harraz 2002), and was related to fluid phase separation, sulphidization and carbonatization of host dioritic rocks. These P-T conditions show that the gold mineralization occurred in the late retrograde metamorphism after peak metamorphism.

4.3. Origin of carbonic fluid inclusions in the Hamadi gold deposit

The origin of the characteristic CO₂-CH₄ fluids in orogenic gold deposits is still controversial (e.g., Ridley and Diamond 2000; Goldfarb et al. 2005; Hrstka et al. 2011). In addition, the presence of variable amounts of non-aqueous volatiles, such as CH₄-N₂ and their fraction variations (e.g. CH₄ and N₂), has also been reported (Fu et al. 2014). These non-aqueous volatiles were formed locally by the interaction of mixed CO₂ and magmatic fluid during the emplacement of post-orogenic intrusions (Fu et al. 2014). Fluid inclusions in gold-bearing veins and altered rocks from the Hamadi gold deposit are characterized by CO₂-rich inclusions, including carbonic inclusions and CO₂-H₂O inclusions, whereas aqueous inclusions are rare. These carbonic inclusions seem to have a close relationship with gold mineralization during the post-collision orogeny process of 600 to 550 Ma in ANS. However, where the CO₂-rich fluids come from and how these fluids contributed to gold mineralization are still unclear.

The source of CO₂ in gold deposits in metamorphic terranes has usually been considered as relics of mantle and/or lower crustal (magmatic and/or metamorphic) fluids (e.g., Phillips and Powell 1993; Klemd and Hirdes 1997; Schmidt Mumm et al. 1997; Lowenstern 2001) that might have been transported to higher levels in the crust during magma ascent (Xavier and Foster 1999) and/or channeled along major structures (Chi et al. 2009). Devolatilisation of supracrustal sequences during prograde metamorphism is the more accepted hypothesis for the origin of CO₂ in this type of deposits (Phillips and Powell 1993; Kerrick and Caldera 1998). Alternatively, CO₂-dominated fluids may exsolve from felsic magmas formed at depths greater than

5 km in the crust; they are a typical feature of intrusion-related deposits (Baker 2002). Furthermore, these fluids are also associated with granulite facies metamorphism (Santosh et al. 1991; Wilmar et al. 1991). Schimdt Mumm et al. (1997) proposed that the gold mineralization of the Ashanti belt formed from gas- or volatile-rich, nearly water free ($\text{CO}_2 \gg \text{H}_2\text{O}$) hydrothermal systems. The extent of this event suggests that it is related to regional crustal processes. A crustal origin of the mineralizing fluids is also favoured by Oberthür et al. (1996) based on extensive stable isotope studies. However, this conclusion was challenged by Klemd (1998). With decreasing temperatures during ductile deformation H_2O was almost completely removed, since H_2O , due to a lower dihedral angle ($<60^\circ$) at low temperatures ($<450^\circ\text{C}$ at 4 kbar), is more mobile along quartz-quartz grain boundaries than CO_2 (Holness 1993).

The degree of consistency of microthermometric data of fluid inclusions within such FIAs provides a measure of the degree of modification of the inclusions after entrapment. In our study of the Hamadi gold deposit, the homogenization temperatures of CO_2 phases (T_{h,CO_2}) are highly variable among different FIAs, but show a relatively narrow range within individual FIAs. We also summarize the microthermometry data of fluid inclusions from the representative orogenic gold deposits in the world, which are characterized by H_2O -poor, CO_2 -dominated, and compare them with those from the Hamadi gold deposit (Table 4). The results illustrate that there are similarities of fluid inclusions among the Hamadi deposit and other orogenic gold deposits in the world. Meanwhile, we put forward several key questions in this paper concerning: (1) whether host minerals of carbonic fluid

inclusions suffer from the influence of ductile deformation; (2) whether gold-bearing lodes have close relationship with the strong chloritization, sericitization and epidotization. Fluid inclusions within a single FIA should have the same homogenization temperature if they have not been modified after entrapment (Goldstein and Reynolds 1994), excluding heterogeneous trapping. If fluid inclusions in a FIA are subjected to modification after entrapment, their specific volumes will be changed to variable degrees depending on the size and shape of individual inclusions (Bodnar 2003), which will be reflected by the variation of homogenization temperatures of fluid inclusions within the FIA. Our study shows that most Th_{CO_2} of carbonic inclusions within a single FIA from the Hamadi gold deposit have a narrow range of (Table 1), which means that they have not been modified after entrapment if they were trapped from a single water-free carbonic fluid. However, different FIAs have variable ranges of Th_{CO_2} , especially for the sample HMD201 which have very low Th_{CO_2} ($-28.3 \sim -18.0^\circ\text{C}$) in some FIA, indicating that carbonic fluids had higher densities and more complicated components (such as much high CH_4) in the late stage than in the early. Carbonic inclusions occur as secondary FIAs within quartz veins in the Hamadi gold deposit, whereas they may also occur as primary inclusions in quartz veins, and are associated with CO_2 - H_2O fluid inclusions. From these petrographic relationships, we can deduce that the fluids in the Hamadi deposit were originally CO_2 - H_2O fluids during the formation of quartz veins.

Chi et al. (2006) studied the origin of CO_2 -only fluid inclusions in the Campbell-Red Lake gold deposit, and put forward a question that whether the

carbonic inclusions were originally entrapped from water-free carbonic fluids, or trapped from $\text{CO}_2\text{-H}_2\text{O}$ fluids that experienced water loss during wall rock alteration. Similar questions, such as the origin of CO_2 -only fluid inclusions, have been asked and discussed in studies of the other gold deposits dominated by carbonic inclusions (e.g., Garba and Akande 1992; Schmidt-Mumm et al. 1997, 1998; Klemd 1998; Xavier and Foster 1999; Wille and Klemd 2004). For the Hamadi gold deposit, carbonic fluid inclusions are so abundant but lack of simultaneous aqueous inclusions that it is hard to believe that CO_2 came from a phase separation from an initial $\text{CO}_2\text{-H}_2\text{O}$ fluid. However, Li and Hu (2012) have measured the H-O isotopic compositions of fluid inclusions in gold-bearing quartz veins from the Hamadi gold deposit, and result showed the existence of water in the fluid inclusions. Wall rock alterations, including sericitization, chloritization and epidotization are fairly well developed, which illustrated that H_2O took part in the wall rock alteration and H_2O may have been consumed in hydrothermal alteration. The deformation of gold-bearing quartz vein is weak, and many carbonic fluid inclusions are randomly distributed or isolated and keep very complete fluid inclusions shape (Fig. 5), which is difficult to explain if the host mineral's deformation caused the preferential leakage of water from $\text{CO}_2\text{-H}_2\text{O}$ salt fluid inclusions under retrograde greenschist-facies condition. However, some of the carbonic inclusions occur as secondary FIAs within quartz veins, which may be due to the preferential leakage of water from $\text{CO}_2\text{-H}_2\text{O}$ -salt fluid inclusions.

Therefore, the source of carbonic fluid inclusions in the Hamadi gold deposit could

be explained according to what has been discussed above as follows: the CO₂-H₂O fluids in relation to granulite or amphibolite facies were derived from the deep crust in the process of regional metamorphism. Unmixing took place at relatively high levels of the crust because of the P-T condition decline during the retrograde metamorphism and gold mineralization (Chi et al. 2006). Water took part in the wall rock alteration, which was depleted in the process of hydrothermal alteration, and then carbonic components were significantly enriched relative to H₂O, which lead to the decrease of SiO₂ solubility. Eventually, quartz veins are formed in fractures, and the rich-CO₂ fluid was trapped in the quartz vein.

4.4. The contribution of carbonic fluids to gold mineralization

Deformation and metamorphism might have caused remobilization and enrichment of the ore elements (Marshall and Gilligan 1987) since primary ores were modified to mineralized tectonite to varying degrees or even to mineralized mylonite (Gu et al. 2007). Despite the ubiquitous association of CO₂ with hydrothermal ore deposits, little is known about the role of CO₂ as a ligand or its direct participation in ore formation. Few studies provide any indication of metal mobilization by this volatile (Keppler and Wyllie 1990). Phillips and Evans (2004) examined CO₂-rich and CO₂-poor auriferous fluids, and argued that CO₂ played a key role in gold mineralization, through buffering the pH range, and increasing gold concentration of the auriferous fluid. For the gold mineralization in the Hamadi gold deposit, the P-T conditions are estimated to be 270~390°C and 100~400 MPa. According to Benning

and Seward (1986), $[\text{Au}(\text{HS})_2]^-$ is the dominant gold-hydrosulphide complex in the ore-forming solutions within the range of temperatures between 200 and 400°C, pressures around 200 MPa, as well as near-neutral pH, so the gold in the ore-forming fluids in the Hamadi gold deposit might exist as $[\text{Au}(\text{HS})_2]^-$. Furthermore, CO_2 , as a weak acid, might help gold transport by buffering the fluid in a pH range where high gold concentration could be maintained by reduced sulphur complexes. Moreover, study of Lai and Chi (2007) suggests that CO_2 -rich vapour is capable of transporting large amounts of Cu, and possibly Au. The unmixing of fluids is also an important factor in gold deposition (Bower 1991). CH_4 plays a more important role in unmixing than CO_2 at 300°C. The fluid will not be unmixed until the concentration of CO_2 is above 15 mol%, but when CH_4 is more than 5 mol%, unmixing may occur (Van den Kerkhof and Thiery 2001). As shown above, X_{CH_4} of carbonic fluid inclusions ranges from 0.4 to 14 mol%, with most of X_{CH_4} around 5 mol% in the gold-rich quartz veins of the Hamadi gold deposit, which indicate that unmixing occurred and played an important role in gold precipitation. Therefore, high CO_2 content of fluid inclusions in gold mineralization at the Hamadi gold deposit, which is an important category of ore forming fluids, and CO_2 - H_2O unmixing promotes the precipitation of Au in the Hamadi gold deposit. The Hamadi gold deposit displays features in accordance with orogenic type deposits (Groves et al. 2003; Table 5). The geological characteristics of the Hamadi gold deposit are also similar with other lode gold deposits in the Pan-African metallogenic belt from northeast Africa desert.

5. Conclusions

(1) Carbonic fluid inclusions are dominant both in gold-bearing veins and tiny veinlets in altered rocks at the Hamadi gold deposit. The melting temperatures of solid CO_2 (T_{m,CO_2}) in both carbonic and $\text{CO}_2\text{-H}_2\text{O}$ inclusions have a relatively narrow range (-59.6°C ~ -56.6°C), and the homogenization temperatures of carbonic phases (T_{h,CO_2}) vary widely from -26.9 to $+23.7^\circ\text{C}$, with most of the values clustering between $+4.0$ and $+20^\circ\text{C}$, corresponding to densities from 0.73 to 1.03g/cm^3 .

(2) The carbonic inclusions in the Hamadi gold deposit are interpreted to have resulted from unmixing of an aqueous-carbonic mixture during retrogress metamorphism because of decreasing of P-T conditions; most of the water in the $\text{CO}_2\text{-H}_2\text{O}$ fluids in the Hamadi deposit entered altered minerals such as sericite and biotite during intensive hydrothermal alteration and then CO_2 was enriched relative to H_2O , which lead to the decrease of SiO_2 solubility. Eventually, quartz veins are formed in fractures, and CO_2 was trapped as carbonic inclusion in vein quartz.

(3) The CO_2 -rich fluid inclusions in the Hamadi gold deposit have been trapped with the minimum temperatures ranging from 270 to 390°C . The estimated minimum trapping pressures range from 100 to 400 MPa , which are in agreement with the P-T conditions of regional metamorphism suggested by previous researchers. The gold in the ore-forming fluids in the Hamadi gold deposit might exist as $[\text{Au}(\text{HS})_2]^-$. CO_2 had contributed to gold mineralization by buffering pH range and increasing the gold concentration in the fluids.

(4) The Hamadi gold deposit is characterized by medium-high homogenization temperatures, medium-low salinities, high density, and rich in $\text{CO}_2\text{-CH}_4$, controlled by

shearing structures, which has similar metamorphic, structural, and mineralogical features that are characteristic of orogenic type deposits.

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Figure Captions

Fig. 1 Regional map of the Hamadi gold deposit, Sudan (Modified from Bailo et al. 2003)

Fig. 2 Mine map of the Hamadi gold deposit, Sudan (Modified from Bailo et al. 2003)

Fig. 3 Photographs of wallrock alteration at the Hamadi gold deposit

(A) Disseminated pyrite occurring as thin filament in pyritizatic and carbonificatic biotite-quartz schist, HMD112-1; (B) Sparse pyrite in carbonificatic hornblende-quartz schist, HMD109-1; (C) A rotated pyrite metacryst in beresitizatic mylonitic schist, HMD111-1; (D) Stretched pyrite metacrysts in beresitizatic schist, HMD114-1, reflected-light.

Fig. 4 Photomicrographs showing assemblages of ore mineral in the Hamadi gold deposit

(A) Chalcopyrite (Ccp) replacing pyrite in a tiny vein within altered amphibole-quartz schist, HMD109-4, reflected-light; (B) Disseminated pyrite occurring in pyritizatic and carbonificatic biotite-quartz schist, pyritization schist, HMD111-1, (+); (C) A rotated pyrite metacryst in beresitizatic mylonitic schist, HMD114-3; (D) Stretched pyrite metacrysts in beresitizatic schist, HMD111-3; (E) Gold gains (Au) occurring in fissures within quartz of Au-bearing pyritization schist, HMD111-b1, reflected-light; (F) Gold gains (Au) occurring as inclusions in a coarse pyrite (Py) grain of pyritization schist, HMD111-b1, reflected-light; (G) Sparse pyrite in carbonificatic hornblende-quartz schist, HMD109-1, reflected-light; (H) Disseminated pyrite occurring in pyritizatic and carbonificatic biotite-quartz schist, pyritization schist, HMD111-1, (+); (I) Coarse-grain is replaced, pyritization schist, HMD112-1, reflected-light.

Fig. 5 Fluid inclusions in gold-bearing veins of the Hamadi gold deposit, Sudan

(A) Carbonic fluid inclusions within a quartz grain, HMD201; (B) Isolated CO₂-H₂O inclusions in gray

vein quartz, HMD201; (C) CO₂-H₂O inclusions in gray vein quartz, HMD203; (D) Carbonic fluid inclusions distributed randomly within a quartz grain, HMD201; (E) Isolated carbonic inclusions occurring in a quartz grain, associated with CO₂-H₂O inclusions, HMD204; (F) Two FIAs composed of carbonic inclusions in vein quartz, HMD203; (G) Several carbonic FIAs occurring within healed fissures in vein quartz, HMD205; (H) Isolated CO₂-H₂O inclusions associated with carbonic fluid inclusions in gray vein quartz, HMD203; (I) A group of CO₂-H₂O inclusions distributed randomly, associated with a few isolated carbonic inclusions in gray vein quartz, HMD201

Fig. 6 Carbonic fluid inclusions in pyrite quartz veins at the Hamadi gold deposit, North Sudan.

(A) Carbonic fluid inclusions associated with a few CO₂-H₂O inclusions, not cutting a quartz grain, HMD113; (B) carbonic fluid inclusions associated with a few CO₂-H₂O inclusions, not cutting a quartz grain, distributed in short healed fractures, HMD115; (C) one group of carbonic fluid inclusions (NE-SW, late) and one group of carbonic fluid inclusions (NW-SE, early) in quartz vein, HMD205-b; (D) carbonic fluid inclusions, not cutting a quartz grain, HMD112. Note: The direction 'NW-SE' described in the pictures is not a real orientation. The upper points to north so as to read easily,

Fig. 7 Histograms showing solid CO₂ melting temperatures (T_{m,CO_2}), CO₂ homogenization temperatures (T_{h,CO_2}) and final homogenization temperatures ($T_{h,tot}$) for FIA and non-FIA carbonic (C type) and CO₂-H₂O inclusions (CW type) in the Hamadi deposit. Note: the temperature value used for FIAs is average of each FIA, not every inclusion, e.g., type carbonic fluid inclusions within a single FIA have a very narrow ranges of T_{m,CO_2} and T_{h,CO_2} , such as from -56.7 to -57.0 °C (T_{m,CO_2}) and from 3.2 to 4.0 °C (T_{h,CO_2} homogenized to liquid CO₂ phase) in sample HMD201.

Fig. 8 An example of thermometry data for a carbonic fluid inclusion assemblage (FIA)

(A) Carbonic inclusions occurring as clusters (FIA) in a quartz grain (Sample HMD202-d); (B) Histograms of the melting temperatures of solid CO₂ (T_{m,CO_2}); (C) Homogenization temperatures (T_{h,CO_2} , to liquid CO₂) within the FIA

Fig. 9 Laser Raman Microspectra of carbonic fluid inclusions

(A) CH₄- and CO₂-spectrum of single phase in carbonic fluid inclusion, HMD201; (B) CH₄- and CO₂-spectrum of single phase in carbonic fluid inclusion, HMD202; (C) N₂-CH₄- and CO₂-spectrum of vapor-liquid two phase in fluid inclusion, HMD204; (D) CH₄- and CO₂-spectrum of single phase in carbonic fluid inclusion, HMD205.

Fig. 10 $\delta^{18}O_{H_2O}$ - δD_{H_2O} plots of the ore fluids at the Hamadi gold deposit. Domains for metamorphic and magmatic fluids are cited from Taylor (1997). The field for the Juneau gold belts revised after Goldfarb et al. (1991). The field for Majority of lode gold deposits revised after Goldfarb et al. (2004).

Fig. 11 Homogenization temperature versus salinity diagram for fluid inclusions in Hamadi gold deposit. Fields for various fluid types after Beane (1983).

Fig. 12 Homogenization temperatures versus salinities diagram. After Wilkinson (2001).

Fig. 13 T_{m,CO_2} - T_{h,CO_2} of carbonic inclusions and carbonic phase in H₂O-CO₂ inclusions (drawing after Thiéry et al. 1994 and van den Kerkhof and Thiéry 2001)

Fig. 14 Trapping P - T conditions of carbonic fluid inclusions at the Hamadi gold

deposit (phase diagram after Winter 2001)

Table Captions

Table 1 Microthermometric data of fluid inclusions occurring in FIAs from vein quartz in the Hamadi gold deposit

Table 2 Microthermometric data of fluid inclusions occurring in Non-FIAs from vein quartz in the Hamadi gold deposit

Table 3 Comprehensive thermometry of fluid inclusions in quartz veinlets from gold-bearing altered rocks of the the Hamadi gold deposit

Table 4 Comparisons of major characteristics of the Hamadi gold deposit and other deposit by H₂O-poor, CO₂-dominated fluids

Table 5 Comparisons of major characteristics of the Hamadi gold deposit and orogenic deposits

Fig.1 Regional map of the Hamadi gold deposit, Sudan (Modified from Bailo et al., 2003)

197x360mm (300 x 300 DPI)

Fig.2 Mine map of the Hamadi gold deposit, Sudan (Modified from Bailo et al., 2003)

315x624mm (300 x 300 DPI)

Fig. 3 Photographs of wallrock alteration at the Hamadi gold deposit
(A) Disseminated pyrite occurring as thin filament in pyritized and carbonificated biotite-quartz schist. HMD112-1 ; (B) Sparse pyrite in carbonificated hornblende-quartz schist. HMD109-1; (C) A rotated pyrite metacryst in beresitized mylonitic schist, HMD111-1; (D) Stretched pyrite metacrysts in beresitized schist, HMD114-1, reflected-light.

230x183mm (300 x 300 DPI)

Fig. 4 Photomicrographs showing assemblages of ore mineral in the Hamadi gold deposit (A) Chalcopyrite (Ccp) replacing pyrite in a tiny vein within altered amphibole-quartz schist, HMD109-4, reflected-light; (B) Disseminated pyrite occurring in pyritizatic and carbonificatic biotite-quartz schist, pyritization schist, HMD111-1, (+); (C) A rotated pyrite metacryst in beresitizatic mylonitic schist, HMD114-3; (D) Stretched pyrite metacrysts in beresitizatic schist, HMD111-3; (E) Gold gains (Au) occurring in fissures within quartz of Au-bearing pyritization schist, HMD111-b1, reflected-light; (F) Gold gains (Au) occurring as inclusions in a coarse pyrite (Py) grain of pyritization schist, HMD111-b1, reflected-light; (G) Sparse pyrite in carbonificatic hornblende-quartz schist, HMD109-1, reflected-light; (H) Disseminated pyrite occurring in pyritizatic and carbonificatic biotite-quartz schist, pyritization schist, HMD111-1, (+); (I) Coarse-grain is replaced, pyritization schist, HMD112-1, reflected-light.

380x310mm (300 x 300 DPI)

Fig. 5 Fluid inclusions in gold-bearing veins of the Hamadi gold deposit, Sudan
 (A) Carbonic fluid inclusions within a quartz grain, HMD201; (B) Isolated CO₂-H₂O inclusions in gray vein quartz, HMD201; (C) CO₂-H₂O inclusions in gray vein quartz, HMD203; (D) Carbonic fluid inclusions distributed randomly within a quartz grain, HMD201; (E) Isolated carbonic inclusions occurring in a quartz grain, associated with CO₂-H₂O inclusions, HMD204; (F) Two FIAs composed of carbonic inclusions in vein quartz, HMD203; (G) Several carbonic FIAs occurring within healed fissures in vein quartz, HMD205; (H) Isolated CO₂-H₂O inclusions associated with carbonic fluid inclusions in gray vein quartz, HMD203; (I) A group of CO₂-H₂O inclusions distributed randomly, associated with a few isolated carbonic inclusions in gray vein quartz, HMD201

106x151mm (300 x 300 DPI)

Draft

Fig.6 Carbonic fluid inclusions in pyrite quartz veins at the Hamadi gold deposit, North Sudan.
(A) Carbonic fluid inclusions associated with a few CO₂-H₂O inclusions, not cutting a quartz grain, HMD113;
(B) carbonic fluid inclusions associated with a few CO₂-H₂O inclusions, not cutting a quartz grain, distributed in short healed fractures, HMD115; (C) one group of carbonic fluid inclusions(NE-SW, late) and one group of carbonic fluid inclusions(NW-SE, early) in quartz vein, HMD205-b; (D) carbonic fluid inclusions, not cutting a quartz grain, HMD112. Note:The direction 'NW-SE' described in the pictures is not a real orientation. The upper points to north so as to read easily,

190x152mm (300 x 300 DPI)

Fig.7 Histograms showing solid CO₂ melting temperatures (T_m,CO₂), CO₂ homogenization temperatures (Th,CO₂) and final homogenization temperatures (Th,tot) for FIA and non-FIA carbonic (C type) and CO₂-H₂O inclusions (CW type) in the Hamadi deposit. Note: the temperature value used for FIAs is average of each FIA, not every inclusion, e.g., type carbonic fluid inclusions within a single FIA have a very narrow ranges of T_m,CO₂ and Th,CO₂, such as from -56.7 to -57.0°C (T_m,CO₂) and from 3.2 to 4.0°C (Th,CO₂ homogenized to liquid CO₂ phase) in sample HMD201.

177x237mm (300 x 300 DPI)

Fig. 8 An example of thermometry data for a carbonic fluid inclusion assemblage (FIA)
(A) Carbonic inclusions occurring as clusters (FIA) in a quartz grain (Sample HMD202-d); (B) Histograms of the melting temperatures of solid CO₂ (T_m,CO₂); (C) Homogenization temperatures (Th,CO₂, to liquid CO₂) within the FIA

519x134mm (300 x 300 DPI)

Fig. 9 Laser Raman Microspectra of carbonic fluid inclusions
 (A) CH₄- and CO₂-spectrum of single phase in carbonic fluid inclusion, HMD201; (B) CH₄- and CO₂-spectrum of single phase in carbonic fluid inclusion, HMD202; (C) N₂-CH₄- and CO₂-spectrum of vapor-liquid two phase in fluid inclusion, HMD204; (D) CH₄- and CO₂-spectrum of single phase in carbonic fluid inclusion, HMD205.

417x257mm (300 x 300 DPI)

Fig. 10 $\delta^{18}O_{H_2O}$ - δD_{H_2O} plots of the ore fluids at the Hamadi gold deposit. Domains for metamorphic and magmatic fluids are cited from Taylor (1997). The field for the Juneau gold belts revised after Goldfarb et al. (1991). The field for Majority of lode gold deposits revised after Goldfarb et al. (2004).

183x133mm (300 x 300 DPI)

Fig. 11 Homogenization temperature versus salinity diagram for fluid inclusions in Hamadi gold deposit. Fields for various fluid types after Beane (1983).

Fig. 12 Homogenization temperatures versus salinities diagram. After Wilkinson (2001).

232x186mm (300 x 300 DPI)

Fig. 13 T_{m,CO_2} - T_{h,CO_2} of carbonic inclusions and carbonic phase in H₂O-CO₂ inclusions (drawing after van den Kerkhof and Thiéry, 2001 and Thiéry et al., 1994)

235x185mm (300 x 300 DPI)

Fig. 14 Trapping P-T conditions of carbonic fluid inclusions at the Hamadi gold deposit (phase diagram after Winter, 2001)

195x139mm (300 x 300 DPI)

Table 1 Microthermometric data of fluid inclusions occurring in FIAs from vein quartz in the Hamadi gold deposit

Sample	Sample Characteristic	Occurrence	Type of inclusions	Size (μm)	Tm, CO ₂ (□) Range(Number); Average	Th, CO ₂ (⊗) Range(Number); Average	Th,total,(⊗) Range(Number); Average	ρ/g·cm ⁻³	XCH ₄
HMD201	quartz vein, containing calcite and pyrite, carbonic fluid inclusions distributed in the healed cracks of quartz grains	FIA	C	5~6	-57.0~-56.7(7); -56.8	3.2~4.0(7) L; 3.7		0.88	0.013
		FIA	C	3~4	-57.2~-57.0(3); -57.1	-2.2~-1.9(3) L; -2.0		0.92	0.012
		FIA	C	2~4	-57.4~-57.0(7); -57.1	-18.0~-19.8(7) L; -18.8		1.01	0.019
		FIA	C	4~10	-57.6~-56.9(6); -57.2	-28.3~-26.8(6) L; -27.4		1.03	0.021
		FIA	CW	4~9	-57.5~-57.1(4); -57.2	20.3~21.2(4) L; 20.8	270~302(4) L; 283		
		FIA	CW	4~5	-57.2~-57.0(6); -57.1	-10.1~-9.0(6) L; -9.5	292~303(6) L; 297		
		FIA	CW	7~13	-57.2~-57.0(5); -57.1	26.7~27.8(5) L; 27.2	296~305(6) L; 301		
		FIA	C	4~5	-57.5~ -57.1(10); -57.3	10.4~11.6(10) L; 10.9		0.84	0.021
		FIA	C	3~12	-57.1~-56.8(7); -56.9	-3.3~-1.8(7) L; -2.5		0.91	0.013
		FIA	C	4~6	-57.4~-57.1(6); -57.2	10.0~13.8(6) L; 12.0		0.82	0.016
HMD202		FIA	C	5~8	-57.5~-57.3(7); -57.4	18.1~19.6(7) L; 18.8		0.76	0.023
		FIA	C	4~10	-57.4~-57.9(5); -57.7	2.8~3.8(5) L; 3.4		0.87	0.037
		FIA	CW	5~13	-57.4~-57.0(5); -57.2	23.4~24.8(5) L; 24.0	270~284(6) L; 279		
		FIA	CW	6~10	-57.9~-57.6(6); -57.7	18.7~19.3(6) L; 19.1	280~289(6) L; 281		

HMD203	FIA	C	4~9	-57.9~-57.4(8); -57.3	8.7~9.6(8) L; 9.1	0.83	0.034
	FIA	C	3~7	-58.3~-57.6(8); -57.9	7.8~8.6(8) L; 8.3	0.84	0.042
	FIA	C	3~8	-57.6~-57.4(10); -57.4	9.9~12.2(10) L; 11.5	0.83	0.028
	FIA	C	2~6	-57.3~-57.1(9); -57.2	11.7~12.3(9) L; 11.9	0.83	0.019
	FIA	C	3~8	-57.6~-57.4(8); -57.4	22.9~24.2(8) L; 23.7	0.71	0.025
HMD204	FIA	C	4~6	-57.9~-57.8(5); -57.8	13.8~14.5(5) L; 14.1	0.77	0.039
	FIA	C	5~8	-60.3~-59.2(10); -59.6	7.9~8.9(10) L; 8.4	0.81	0.097
	FIA	C	3~7	-57.6~-57.2(7); -57.4	18.5~19.8(7) L; 19.1	0.75	0.026
	FIA	C	4~8	-57.6~-57.2(8); -57.4	9.4~10.5(8) L; 9.8	0.85	0.023
	FIA	C	3~6	-58.1~-57.6(7); -57.8	9.5~10.9(7) L; 10.1	0.82	0.036
HMD205	FIA	C	3~5	-57.5~-57.2(10); -57.3	5.2~6.4(10) L; 5.8	0.86	0.025
	FIA	C	5~9	-57.3~-56.9(6); -57.1	8.2~9.4(6) L; 8.9	0.82	0.018
	FIA	C	4~10	-57.8~-57.3(7); -57.5	9.2~10.5(7) L; 9.8	0.84	0.022
	FIA	C	3~7	-57.2~-56.9(10); -57.0	11.7~12.8(10) L; 12.3	0.84	0.005

Note: 1) numbers in brackets are fluid inclusions measured. L-homogenized in liquid, V-homogenized in gas; 2) T_h: homogenization temperature, T_{h-CO2}: CO₂ partial homogenization temperatur, T_m: melting temperature of solid CO₂

Table 2 Microthermometric data of fluid inclusions occurring in Non-FIAs from vein quartz in the Hamadi gold deposit

Sample	Distributed state	Type of inclusions	Occurrence	Size(μm) (Number)	$T_{\text{m, CO}_2}$ ($^{\circ}\text{C}$)Range (Number)	$T_{\text{h, CO}_2}$ ($^{\circ}\text{C}$)Range (Number)	$T_{\text{h, total}}$ ($^{\circ}\text{C}$) Range (Number)	ρ g/cm ³
HMD201	RD	C	Non-FIA	4.98~12.6(24)	-57.8~-57.2(24)	-0.8~+18.6(24)		0.75~0.93
		CW		3.69~10.3(8)	-57.2~-56.9(8)	19.2~22.7(8)	298~393(L)	0.72~0.81
	Is	C	Non-FIA	2.87~10.85(8)	-57.8~-57.1(8)	-2.6~+15.1(8)		0.76~0.94
		CW		6.98~10.32(7)	-57.4~-56.9(7)	-1.3~+24.8(7)	261~304(V)(3); 243~356(L)(4)	0.65~0.96
HMD202	RD	C	Non-FIA	5.7~10.6(15)	-57.4~-56.9(15)	-2.1~16.9(15)		0.81~0.92
		CW		4.89~6.21(6)	-57.5~-56.9(6)	-10.1~+8.6(6)	382~394(6)(L)	0.88~0.96
	Is	C	Non-FIA	--	--	--	--	--
		CW		4.81~10.2(10)	-57.5~-57.1(10)	2.1~22.4(6)	267~390(6)(L)	0.72~0.86
HMD203	RD	C	Non-FIA	3.24~6.00(6)	-58.1~-57.4(6)	8.9~12.8(6)		0.76~0.88
		CW		5.53~14.89(12)	-57.8~-57.2(12)	7.8~27.7(12)	281~338(8)(L); 309~313(4)(V)	0.65~0.92
	Is	C	Non-FIA	--	--	--	--	--
		CW		4.29~10.11(9)	-57.8~-56.9(9)	13.9~28.8(9)	298~365(4)(V); 276~332(5)(L)	0.62~0.88
HMD204	RD	C	Non-FIA	3.5~12.4 (36)	-59.6~-56.9 (36)	-4.0~20.8 (36)		0.76~0.94
HMD205	RD	C	Non-FIA	3.4~10.4(40)	-58.3~-56.9(40)	-7.4~19.8(40)		0.76~0.96
		CW		6.28~11.73(6)	-57.1~-57.0(6)	+27.4~+28.8(6)	341~346(6)	0.60~0.67

Note: 1) numbers in brackets are fluid inclusions measured. L-homogenized in liquid, V-homogenized in gas. 2) Non-FIA including: RD—Randomly distributed; Is—Isolated; --: No data

Table 3 Comprehensive thermometry of fluid inclusions in quartz veinlets from gold-bearing altered rocks of the the Hamadi gold deposit

Sample Number	Characteristics of samples	Type of inclusions	Size/ μm	$T_{\text{m,CO}_2}/^{\circ}\text{C}$	$T_{\text{h,CO}_2}/^{\circ}\text{C}$	$T_{\text{h,TOT}}/^{\circ}\text{C}$	X_{CH_4}	$\rho/\text{g}\cdot\text{cm}^{-3}$
HMD112	Pyrite-quartz veinlets in carbonificatic biotite-quartz schist	C, most	3~10	-57.4~ -57.1(20)	-19~ -12.7(3); +7.3~+15.8(16)	287~305(13)	0.015~0.028	0.78~1.00
		CW, rarely	3~10	-58.5~ -57.5(13)	+14.5~+27.8(14)			
HMD113	Pyrite-quartz veinlets in altered rocks	C abundance	2~20	-58.3~ -57.0(40)	-6.8~ -0.2(21,L); +12.1~+28.9(14,L)		0.02~0.06	0.73~0.94
		CW, most	4~15	-58.1~ -57.0(14)	-8.3~ -8.3(2); +0.4~+22.3(8,L)			
HMD115	Quartz veinlets in mylonite chlorite quartz schist	CW	3~8	-57.9~ -56.8(4)	+26.7~+28.7(4)	339~363(5)	0.03~0.04	0.70~0.95
		Very rarely	3~8	-57.9~ -56.8(4)	+26.7~+28.7(4)			
HMD116	Pyrite-calcite-quartz veinlets in altered rocks	C, most	3~12	-58.4~ -57.0(15)	-11.0(1,C); +1.1~ +17.1(15,L)	341~346(16)	0.01~0.07	0.73~0.88
		CW, rarely	3~9	-58.5~ -57.5(16)	+26.5~+28.7(16)			

Note: 1) The numbers in brackets represent inclusion numbers; 2) L-Homogenized into liquid CO₂, V- Homogenized into gas CO₂, C- Homogenized into critical point

Table 4 Comparisons of major characteristics of the Hamadi gold deposit and other deposit by H₂O-poor, CO₂-dominated fluids

Location	Deposit	FIs type	Size/ μm	$T_{\text{m,CO}_2}/^{\circ}\text{C}$	$T_{\text{h,CO}_2}/^{\circ}\text{C}$	$T_{\text{h,TOT}}/^{\circ}\text{C}$	$\rho/\text{g}\cdot\text{cm}^{-3}$	P-T condition	References
Xijiang, China	Sarekuobu deposit	gold L _{CO2} abundance	2.8~12.1	-78.1~-61.9	-33.7~-17.7	254~276	0.74~1.02	150~320 MPa; 250~280	Xu et al. 2005
Muruntau, Uzbekistan	Muruntau gold deposit	L _{CO2-CH4} abundance	5.5~20	-65~-58.6	-27.5~-27.8		0.56~1.00		Xu et al. 2007
Campbell-RedLake, Canada	Campbell-Red gold deposit	Lake L _{CO2} abundance	3~26	-59.2~-56.7	-5~-31	250~390			Chi et al. 2006
Ipitinga Auriferous, northern Brazil	Carará gold deposit	L _{CO2} abundance	5~15	-58.2~-56.6	-28.5~-29.9	350~475	0.89~1.07	180~360MPa	Evandro and Kazuo 2010
Ashanti Belt, Ghana	gold deposits in the Ashanti Belt	L _{CO2} abundance	6~17	-57.1~-61.4	-15~-9.8	150~440	0.89~0.99	170~540MPa	Mummá et al. 1997
Hamadi, North Sudan	Hamadi gold deposit	L _{CO2} abundance	3~15	-59.6~-56.6	-28.3~-24.2	270~400	0.73~1.03	270~400°C; 100~400MPa	This study

Table 5 Comparisons of major characteristics of the Hamadi gold deposit and orogenic deposits

Orogenic gold deposit(Kerrich et al. 2000)		Hamadi gold deposit(this study)
Tectonic background	Hyperplastic orogen belt or collision orogenic belt	Pan-African orogenic belt
Structural style	Ductile to brittle-ductile, reverse, strike-slip faults or oblique-slip; anticlinal domes.	secondary fault developed in northernWadi Singeir basin
Mineralization style	Veins, breccias, disseminated.	Veins
Conduit	Sedimentary rock, metamorphic rock,volcanic rock and	Lithology consists of plagioclase hornblende gneiss, mica
ore-bearing	granite(Most of rocks are	plagioclase gneiss, hornblende schist, quartz mica-schist,
wall rocks	located in greenschist facies metamorphic terrane)	and mica-schist
wall rock alteration	muscovitization, pyrite mineralization,	beresitization, epidotization, chloritization, and
	medium-temperature silicide, chloritization, calcium carbide	carbonatation, pyritization alteration.
	gasification	
P-T conditions	220-500°C, 50-400MPa	275~400°C, 100-400MPa
Ore fluids	Low salinity, CO ₂ -rich inclusions	medium-high homogenization temperatures, medium-low salinity, high density, CO ₂ -rich inclusions
Isotopes (water)	δD=-20‰--80‰; δ ¹⁸ O =6‰-10‰	δD =-49‰--67‰; δ ¹⁸ O =9.8‰-11‰ (Li and Hu 2012)
Fluid evolution and mechanism	temperature dropped from early stage to late stage, salinity decreased, and unmixing or boiling led to mineralization	Unmixing range expanded because of the P-T condition decline during the retrograde metamorphism period of gold mineralization. The water take part in the wall rock alteration, and then carbonic components are significantly enriched relative to H ₂ O, which led to the decrease of SiO ₂ solubility. Eventually, the quartz vein is formed in fracture, and the rich-CO ₂ fluid has been trapped in the quartz vein.

Research Highlights

I. Carbonic fluid inclusions are dominant both in quartz of gold-bearing veins and altered rocks at the Hamadi gold deposit, Sudan.

II. Carbonic inclusions in the Hamadi gold deposit came from an immiscible aqueous-carbonic mixing fluids during retrogress metamorphism.

III. The formation of Hamadi gold deposit was related with extremely CO₂-rich fluids.

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