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# **Controls on lode gold mineralization, Romite deposit, South Eastern Desert, Egypt**

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#### **KEYWORDS**

Romite gold deposit; Orogenic lodes; Hamisana Zone; Stable isotopes; Egypt **Abstract** Field and remote sensing studies reveal that Au-bearing quartz  $\pm$  carbonate lodes in Romite deposit, in the extreme South Eastern Desert of Egypt, are controlled by NNE-striking shear zones that splay from the ca. 660–550 Ma Hamisana Zone. Quartz in releasing bends with sinistral shear geometry and abundant boudinaged quartz-carbonate lodes with serrate ribboned fabrics suggest vein formation throughout a transpressive wrench system. Ubiquitous hydrothermal quartz, carbonate, and subordinate chlorite and sericite within the shear zones and as slivers in veins, indicate that gold deposition and hydrothermal alteration occurred under greenschist facies conditions. The Al (IV) in chlorite indicates a formation temperature of ~ 300 °C, comparable with temperatures estimated from arsenopyrite composition for grains intimately associated with gold in quartz veins.

The new geological and geochemical data indicate that splays off the Hamisana Zone are potential gold exploration targets. Quartz veins along the high order (2nd or 3rd) structures of this crustal-scale shear zone are favorable targets. In the Romite deposit and in surrounding areas, a Au-As-Cu-Sb-Co-Zn geochemical signature characterizes mineralized zones, and particularly rock chips with >1000 ppm As and high contents of Cu, Zn, and Co target the better mineralized areas.

The carbonate  $\delta^{13}C_{PDB}$  and  $\delta^{18}O_{SMOW}$  isotope signatures preclude an organic source of the ore fluid, but metamorphic and magmatic sources are still valid candidates. The intense deformation and lack of magmatism in the deposit area argue for metamorphic dewatering of greenstone rocks as the most likely fluid source. The narrow ranges of  $\delta^{13}C(-4.6\%_{00} \text{ to } -3.1\%_{00})$  and  $\delta^{18}O(11.9\%_{00}-13.7\%_{00})$  in carbonate minerals in lodes imply a corresponding uniformity to the ambient temperature and  $\delta^{13}C_{CO_2}$  ( $\delta^{13}C_{\Sigma C}$ ) of the ore fluids.

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The calculated  $\delta^{18}O_{H_2O}$  values of 6.9% for ore fluids, based on  $\delta^{18}O$  values of vein quartz further suggest a likely metamorphic origin.

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# 1. Introduction

The Arabian-Nubian Shield (ANS) is well recognized example of an accretionary orogen with numerous terranes and suture zones (e.g., Kröner et al., 1987; Stern, 1994; Abdelsalam and Stern, 1996; Abdelsalam et al., 2003; Kusky and Matsah, 2003). The sutures, typically reactivated as transpressional/transcurrent zones, are located across the shield (e.g., Johnson et al., 2011, and references therein). Late deformation included the occurrence of lateral escape tectonics along transtensional or transpressional systems during the final stages of orogeny (e.g., Burke and Sengör, 1986; Stern et al., 1989; Miller and Dixon, 1992; Stern, 1994; Johnson and Kattan, 1999; de Wall et al., 2001).

According to Abdeen and Abdelghaffar (2011), the tectonic evolution of the southern part of the Eastern Desert of Egypt, a part of the ANS, involves two main episodes of terrane amalgamation: an early terrane accretion along the Allaqi-Heiani-Gerf-Onib-Sol Hamed-Yanbu suture at ca. 750–720 Ma and after consumption of oceanic basins above a north-dipping subduction zone, and a late collision between the East and West Gondwana blocks at ca. 700–550 Ma (Stern et al., 1989; Abdelsalam and Stern, 1996). The late collision deformed the Allaqi-Heiani-Gerf-Onib-Sol Hamed-Yanbu suture along N- and NNW-trending shortening zones and major NW- and NE-trending transpressional faults.

The Eastern Desert of Egypt has a long history of gold mining from at least one hundred localities. Gold in the majority of these localities is present in milky or gray quartz veins with abundant pyrite and arsenopyrite. The distribution of gold occurrences in the Eastern Desert is controlled by major wrench faults and shear zones (e.g., Loizenbauer and Neumayr, 1996; Helmy et al., 2004; Zoheir et al., 2008; Zoheir, 2011). Gold deposits across the southern part of the Eastern Desert are mostly related to NW- or NNW-striking shear zones generally reflecting reactivated earlier accretionary suture zones (e.g., Kusky and Ramadan, 2002; Zoheir, 2008a,b, 2011). However, auriferous quartz veins confined to NNE-striking zones along the Allaqi-Heiani-Gerf-Onib-Sol Hamed-Yanbu suture are only present at the Romite and Haimur deposits.

The Romite gold deposit is located in the extreme southern part to the Eastern Desert approximately 90 km south of the costal village at Shalateen. Scarcity of information on this deposit is attributed to its remoteness and relative inaccessibility. This study is aimed at to understand the setting and evolution of this deposit in relation to the regional structures. It includes the results of detailed geological mapping and mineralogical and geochemical studies. In addition, stable isotope systematics is interpreted to constrain the source and evolution of ore fluids.

# 2. Geologic setting, structures and gold mineralization

The Romite area is part of the major, curvilinear, Allaqi-Heiani-Onib-Sol Hamed suture, which is commonly marked by ophiolite mafic and ultramafic rocks and which was later deformed by the N-trending Hamisana Zone (Fig. 1). The latter is a complex belt of deformation characterized by east—west crustal shortening fabrics, steep folds, and thrust faults. Calc-alkaline magmatism was contemporaneous with and outlasted the main phase deformation along the zone, and likely defines an evolving, subduction-related continental arc setting (Miller and Dixon, 1992). Based on Rb-Sr and U-Pb geochronological studies, Stern et al. (1989) suggested that the northern part of the Hamisana Zone was magmatically active until ca. 550 Ma. Deformation and metamorphism along the Hamisana Zone clearly post-date terrane accretion and probably are closely related to the ca. 655–540 Ma Najd tectonic cycle of the Pan-African orogen (Stern et al., 1989).

Field work, aided by processed satellite imagery data, enabled detailed geological mapping of the deposit area and surroundings. False color composite images of Landsat ETM+ band ratios (Fig. 2a, b) have been found to be exceptionally useful in the identification of lithological units and geological structures in the study area. Abrams et al. (1983) used the TM band ratios 5/7 and 3/1 because clay and iron-rich minerals have reflectance and absorptions features in these bands, whereas band ratio 4/5 identifies more common silicate minerals. In his band ratio combination method, Sultan et al. (1986) employed a threshold classifier based on three reflectance ratios that included (1) band 5/7 for estimating the abundance of hydroxyl-bearing phases; (2) band 5/ 1 for magnetite content; and (3) the calculated value of reflectance for band 4, based on a linear interpolation between bands 3 and 5, divided by the observed band-4 reflectance. The third ratio was used to identify rocks rich in iron-bearing aluminosilicates and thereby to distinguish mafic rocks containing substantial amounts of magnetite and hydroxyl-bearing phases. This method was successfully applied to map suture zones in the Arabian-Nubian Shield (e.g., Sultan et al., 1988, 1993).

Integration of field and satellite data reveals that the study area is underlain by popped-up core complex of granodiorite gneiss, which is tectonically overlain by ophiolitic metabasaltmetagabbro, and metamorphosed volcanic, volcaniclastic, and plutonic island arc rocks, all intruded by syn-orogenic granitoids (Fig. 3). The island arc plutonic rocks include gabbro-diorite (quartz-diorite) complex variably deformed and slightly metamorphosed. Small masses of late- and post-orogenic granites cut the metavolcanic rocks and older granitoids. Anorogenic syenite forms a small circular massif that cuts the Gebel Warabeit metabasalt in the northern part of the area. Numerous basaltic and aplitic dikes cut all country rocks in different directions, but commonly they are NNE-striking. Northeast-trending pegmatite dikes are common in the western part of the mapped area, cutting metavolcanic and metagabbro rocks. Discrete masses of basalt flows (Oligocene?) are locally exposed in the northern part of the study area. This basalt flows may be related to the Red Sea rift.

Abundant close/tight folds and shear foliations define highly wrenched, branching shear zones in the deposit area and surroundings (see Fig. 1). Northwest-southeast foliation is overprinted by NE-SW cleavage and shear foliation, particularly



Figure 1 ETM mosaic showing the N-trending Hamisana Zone, cutting Neoproterozoic greenstone rocks in south Egypt and north Sudan.

within and adjacent to the shear zones. The NW-trending foliation is, however, well preserved in the metagabbroic rocks in the northwestern part of the area. The most prominent structure in the area is the  $\sim$ 15-km-wide, ENE-trending shear zone, which comprises sericite-chlorite schist and highly tectonized ophiolitic mélange (Fig. 2a, b). Gneisses occur north and west of this shear zone, whereas the southern and eastern sides are dominated by

ophiolites and island arc metavolcanic rocks (see Fig. 2a, b). Intense schistosity, recrystallization, isoclinal folds, and sigmodial features indicate ductile deformation pervailed within this shear zone (Fig. 2c). The strike of this shear zone is marked by a complex pattern of splays and en-echelon steps. This zone is cut by NNE- and NNW-trending wrench shear/faults ( $\leq$ 3-km-wide zones), characterized by mylonitization and displacement.



**Figure 2** False color composite ratio images (FCC) of the area around Romite mine. (a) ETM band ratios 5/7, 5/1 and  $5/4 \times 3/4$  in R, G, B channels, respectively (e.g., Sultan et al., 1986); (b) Abrams et al. (1983)'s band ratios image (5/7, 4/5 and 3/1 in R, G, B, respectively) used for detailed mapping of the lithologic units in Romite area; (c) Structural interpretation map based on field and satellite imagery data. Notice splays of the post-accretionary sinistral Hamisana Zone define a scissor-like structure (see also Fig. 1).

Sinistral displacement along the NNE-trending shear zone measures  $\sim 1$  km, whereas, the NW-trending faults accommodate a dextral strike-slip offset of about 400 m. It is interpreted that the ENE-trending shear zone is splaying off the major N-S trending Hamisana Zone; Fig. 1, whereas the NNE- and NNW-trending faults and shear zones are either higher order splays or reactivations of the older structures. These anastomosing shear zones may define a major scissor-like structure, implying a compressional regime. Quartz diorite is composed of altered andesine chloritized hornblende, biotite, quartz, and minor sphene, magnetite, and ilmenite. Where sheared, quartz and feldspar porphyroblasts are embedded in a chlorite-sericite-carbonate matrix. Gold mineralization is confined to quartz-diorite rocks (part of the island arc intrusive complex in the area) that are highly sheared by the NNE-trending shear/fault zones (Fig. 3), which show a reverse-slip and sinistral wrench motion, based on plunging stretching lineations and inclined slickensides on gold-bearing quartz vein walls.

Gold occurs in quartz and quartz-carbonate veins, and disseminated in iron-stained carbonate-altered and silicified wallrocks (Fig. 4a–e). Abundant NNE-trending mylonite zones with quartz and carbonate stringers cut through the quartz-diorite rocks. Milky quartz veins vary in thickness from a few centimeters to 3 m, and are characterized by pinch and swell structures (Fig. 4b, c). Morphology, asymmetries, and quartz textures of the mineralized lodes suggest formation of syn-kinematic with the NNE-striking shear/fault zones. The mineralized quartz veins trend NNE and dip steeply to NW. Abundant disseminated, highly oxidized pyrite crystals are associated with silicified, ferroan dolomite-bearing alteration zones (Fig. 4e, f). Other, thinner

(≤20-cm-thick), NW-trending quartz veins are generally barren and characterized by open space structures filled with iron-stained crystalline calcite and quartz. These veins dip gently or moderately ( $30^{\circ}-50^{\circ}$  to NE). Based on the comb quartz textures and shallow dips, these veins are interpreted as tensional gashes. Old mining workings are exposed in numerous trenches and open pits along the mylonitized quartz diorite, particularly where NNEtrending quartz and carbonate veins are abundant. Numerous stone huts reflect a significant amount of historic mining activity, mostly of primitive nature, likely from the Roman eras as the mine name (Romite) suggests.

# 3. Hydrothermal alteration and orebodies

Intense sulfidation, carbonatization, silicification, and chloritization characterize the host quartz-diorite rocks adjacent to the mineralized quartz veins. The latter vary in length from <10 to 300 m in a NNE-SSW direction and in width from 5 to 150 cm. Mineralogy of the mineralized quartz veins includes pyrite and arsenopyrite, lesser chalcopyrite and pyrrhotite, and free gold. Hydrothermally altered rocks are confined to the discrete shear/ mylonite zones that coincide with NNE-trending, anastomosing shear zones (Fig. 5). The alteration halos cover areas of up to 0.3 km<sup>3</sup> (see Fig. 4). The tonnage and ore grades are totally missing information on this poorly studied deposit. Several ppms Au are reported in grab samples collected from the mineralized quartz veins, while the altered wallrocks contain traces of gold, commonly less than 1 ppm.



Figure 2 (continued).



Figure 3 Geological map of the Romite gold mine area and surroundings. Field, petrographic and satellite imagery data have been integrated to aid detailed mapping of the area (white rectangular in Fig. 2b).

The mineralized veins (up to  $\sim$ 7 ppm Au) are composed mainly of quartz with abundant slivers of highly iron-stained and chloritized quartz diorite (Fig. 6e, f). Calcite and Fe-dolomite are common both in the altered wallrocks and as major constituents in the quartz veins (Fig. 6a-d). Chlorite and sericite are less abundant than carbonate in the lodes, and commonly are associated with quartz sub-grains and wallrock materials in the mineralized lodes (Fig. 6b-e). The mineralized quartz veins exhibit numerous features representative of ductile deformation (Fig. 6a-f). Undulose extinction, serrated grain boundaries, deformation lamellae, and sub-grain development are common in the veins (Fig. 6e, f). In several samples, grain boundary migration is associated with rotated porphyroblasts and wrapped chlorite flakes surrounding sub-rounded quartz grains. Sutured and serrated grain boundaries provide evidence of bulging recrystallization (e.g., Stipp et al., 2002). According to Passchier and Trouw (1996), undulose extinction and deformation lamellae in quartz imply vein formation under conditions of 300-400 °C.

# 4. Methods

### 4.1. Mineralogy and geochemistry

Petrographic examination and preliminary mineral identification were done on polished and thin sections using a Zeiss Axion microscope, and aided by SEM back-scattered electron imaging. Mineral chemistry of hydrothermal ore minerals and some gangue silicate and carbonate minerals is intended to reveal more information about the mineralizing fluid and conditions of gold deposition based on the appropriate geothermometers. Electron microprobe analyses of ore and some gangue minerals were obtained with a Cameca SX100 four spectrometer, fully automated electron microprobe using wavelength-dispersive X-ray spectrometry at TU-Clausthal, Germany. Analyses of sulfide minerals were made at 30 keV accelerating voltage and 40 nA (and 300 nA for Au, Sb, Ag, Ni, Co) beam current, and counting times of 10–300 s, using a 2  $\mu$ m beam diameter (probe spot). Carbonate minerals, sericite and chlorite were analyzed under operating conditions of 15 kV, 20  $\eta$ A beam current and a 5  $\mu$ m beam diameter. Relative accuracy of the analyses, based upon comparison between measured and published compositions of standard reference materials, is ~1%-2% for concentrations >1 wt% and ~5%-10% for concentrations <1 wt%.

#### 4.2. Stable isotopes

Samples of vein carbonate were roughly crushed, then handpicked for purity under technical-grade ethanol using a binocular microscope. Calcite and Fe-dolomite separates were reacted with H<sub>3</sub>PO<sub>4</sub> acid at 50 °C for four days to release CO<sub>2</sub>. A fractionation factor of 1.0106 was used to correct for fractionation of oxygen between the sample and the acid (e.g., Kontak and Kerrich, 1997). The samples were analyzed in the Denver stable isotope laboratory of the USGS. A Finnigan MAT 251 dual-inlet, multiplecollector, magnetic-sector, gas mass spectrometer was used to analyze the carbon and oxygen isotopes. The samples were introduced into the mass spectrometer as CO2 gas. Both O and C isotope ratios are given in delta ( $\delta$ ) notation. Oxygen isotope ratios are reported relative to Vienna Standard Mean Ocean Water (VSMOW), and carbon isotope ratios are reported relative to PDB (Pee Dee Belemnite). The carbonate stable isotope values have a  $2\sigma$  error of 0.1%. Repeat analyses, conducted on several samples, confirmed the reproducibility of the results.

Vein quartz separates were hand-picked, dried, and crushed to less than 0.2 mm, then cleaned in a 3:1 mix of concentrated



**Figure 4** Field relationships of the gold oreshoots at the Romite mine area. (a, b) Old open pits and extensive trenches spread over the entire area of the mine. Notice the boudinage quartz-carbonate veins and the intensely sheared/foliated diorite host rocks. Orebodies are commonly associated with carbonate-rich and iron-stained wallrocks; (c) Quartz boudins along highly foliated diorite associated with little alteration; (d) Quartz lodes associated with pervasive carbonate alteration in zones where foliation is distorted; (e) Disseminated, coarse-grained oxidized pyrite in quartz lodes of milky to greyish quartz; (f) Quartz-carbonate lodes (main ore bodies) with abundant iron-stained wallrock material and fine disseminations of sulfides.

hydrochloric and nitric acid on a hotplate at approximately 100 °C for 2 h. Quartz separates were then rinsed with deionized water ten times, rinsed twice with technical-grade acetone to ensure all water was removed, and dried on a hotplate. The samples were then loaded to the mass spectrometer for measurement. Oxygen isotope reference standard NBS-28 (+9.6%) was run to normalize the  $\delta^{18}$ O data to VSMOW. The silicate stable isotope results have a  $2\sigma$  error of 0.2%. Repeat analyses conducted on several samples confirmed the reproducibility of the results.

# 5. Mineralogical and geochemical characteristics

Disseminated sulfide grains in the auriferous quartz veins are moderately to pervasively oxidized, particularly where carbonate alteration is well developed. Pyrite occurs as isolated and aggregated grains, commonly with abundant inclusions of pyrrhotite and chalcopyrite. Pyrite is variably altered to rhythmic goethite. Gold occurs as free grains, finely disseminated or along microfractures, in the quartz veins, or closely associated with oxidized pyrite and arsenopyrite in chloritized wallrocks or in slivers of wallrock material in the veins. Electron microprobe analysis (EMPA) data reveal the presence of As in pyrite and traces of Au in arsenopyrite (Table 1). Gold grains show high Au fineness composition (>940), which is typical of orogenic gold deposits (e.g., Morrison et al., 1991). Arsenopyrite intergrown pyrrhotite, and pyrite contains 30.1%-31.0% of As, corresponding to formation temperatures of  $\sim 310-360$  °C (Kretschmar and Scott, 1976; Cathelineau, 1988).

#### 5.1. Carbonate, chlorite composition and geothermometry

In the mineralized quartz veins, chlorite laths typically fill microfractures, along with quartz and carbonate. The EMPA data



Figure 5 Mineralization/alteration zones and quartz lodes at the Romite gold mine area. Possible placer deposits occur in the southern part of the altered rock hills.

show that chlorites in veins and in altered host rocks have generally identical composition. Chlorite is notably more abundant in wallrock slivers enclosed in quartz veins than in wallrocks bordering the quartz veins.

Chlorite and carbonate slivers in lodes have been studied by electron microprobe to determine the homogeneity or heterogeneity in their compositions and calculate formation temperatures of the hydrothermal alteration (Tables 2 and 3). The EMPA data indicate that calcite and dolomite have nearly stoichiometric compositions with small amounts of FeO, particularly in dolomite (Table 2). Calcite contains traces of w(FeO) (<0.87%), w(MgO) (<0.71%), w(MnO) (<0.26%), and w(SrO) (<0.13%), whereas dolomite is more Fe-bearing (1.26%-4.01% w(FeO)). Chlorite shows homogenous compositions in veins and wallrocks (Table 3). The Fe/(Fe + Mg) value varies from 0.35 to 0.37 in chlorite from veins, and from 0.31 to 0.37 in wallrocks. The Mg in chlorite from wallrocks (2.83-3.31) is similar to those in chlorite from veins (2.75-3.03). The temperatures derived from chlorites in veins and altered wallrocks are both approximately 300 °C (e.g., Cathelineau and Nieva, 1985; Kranidiotis and Maclean, 1987; Cathelineau, 1988). This estimate is in agreement with the vein quartz textures (recrystallization and serrate ribbon fabrics) and is close to arsenopyrite temperature estimates.

#### 5.2. Geochemistry of the mineralization

Geochemical characteristics of the Romite gold deposit are based on a number of whole-rock geochemical analyses of the auriferous veins and hydrothermally altered wallrocks (Table 4). Gold mineralization in the study area is characterized by an Au-As-Cu-Sb-Co-Zn geochemical signature. As shown in Table 4, As, Co, Cr, Cu, Sc, Sb, Mo, V and Ni are detected in the all or most of the samples, but Ag and W contents are mostly absent. Au concentrations greater than 1 ppm are confined to iron-stained quartz veins and altered wallrocks that are highly seamed with malachite. Elevated levels of As (>1000 ppm) are the best indicator of Au >1 ppm, and high contents of Cu, Zn, and Co provide further indication of Au concentration (Table 5). The highest anomalous gold concentration is from a highly iron-stained quartz vein sample (R-25), which contains 43%  $w(Fe_2O_3^t)$  and high w(S)(0.23%). Correlation between gold and major elements indicates that Au correlates mildly with Fe<sub>2</sub>O<sub>3</sub> and CaO, but strongly with S. Enrichments in Fe, Ca, and Mg, together with highly depleted K and Na, can be directly correlated to pervasive carbonate, sulfide, and chlorite alteration in the ore zone. Calcium and Fe required to form carbonate and sulfides were likely sourced from destruction of feldspars and biotite in the highly sheared dioritic host rocks.

#### 5.3. C, O isotope values

Twelve quartz, nine calcite and six dolomite separates were obtained from twelve vein samples from the Romite deposit. The results of O and C isotope measurements on quartz and carbonate separates are given in Table 6. Dolomite and calcite show tightly clustered values of  $\delta^{13}$ C (-4.6% to -3.1%, n = 15) and  $\delta^{18}$ O



Figure 6 Microscopic features of the gold oreshoots at the Romite mine area. (a) Carbonatized, sericitized wallrock slivers in quartz lodes associated with disseminated sulfides; (b) Highly sheared quartz-carbonate lode showing intense foliation of sigmoidal quartz aggregates embedded in carbonate-chlorite-sericite matrix; (c) Patchy calcite associated with sub-grain development in quartz-carbonate lodes; (d) Dolomite and chlorite intermingle in quartz-carbonate lodes with abundant disseminated sulfides; (e) Sericite-bearing serrate planes along relatively passive large quartz blasts and fine-grained re-crystallized quartz; (f) Highly serrate, quartz ribbons in quartz vein with less abundant carbonate material.

 $(11.9\%_{00}-13.7\%_{00}, n = 15)$ . The  $\delta^{18}$ O composition of vein quartz varies by only  $1\%_{00}$  ( $13.8\%_{00}-14.8\%_{00}, n = 12$ ). Although generally light in carbon signature, calcite shows slightly enriched C and O-isotope values relative to Fe-dolomite. No systematic variation has been detected in samples from different quartz lodes with variable amounts of carbonate minerals. This observation may suggest a single mineralization phase and/or a homogenous ore fluid.

The  $\delta^{18}O_{H_2O}$  and  $\delta^{13}C_{CO_2}$  of the hydrothermal fluid responsible for quartz and carbonate in gold lodes have been calculated at

temperature of 300 °C, based on vein chlorite thermometry (Table 2). The applied fractionation factors (equations) and calculation results are given in Table 6. The determined  $\delta^{18}O_{H_2O}$  for carbonate spans  $5.8\%_{oo}-8.1\%_{oo}$ , with an average value of  $6.8\%_{oo}$  (Table 2). The fluid in equilibrium with quartz from mineralized veins was determined to have  $\delta^{18}O_{H_2O}$  values of  $6.9\%_{oo}-7.9\%_{oo}$ , with an average value of  $7.3\%_{oo}$  (Table 6). Considering that quartz is much more resistant than carbonates to oxygen isotope changes after mineral precipitation (e.g., Gregory and Criss, 1986), the

									.34	.17	.70	.03	.25					
									6 4	7 0	8 94	3 0	4 99					
									3.8(	0.1'	95.78	0.0	99.82					
									4.16	0.17	94.48	0.04	98.85					
	Gold								5.01	0.18	93.85	0.03	99.07					
		35.24	20.83	42.50	0.13	0.13	0.00	0.01	0.01	0.00	0.22	0.26	99.30		34.00	35.01	30.57	
		34.28	20.86	42.77	0.06	0.23	0.00	0.03	0.01	0.00	0.23	0.14	98.61		33.30	35.31	30.97	
		35.51	21.02	42.99	0.01	0.01	0.00	0.00	0.03	0.00	0.21	0.27	100.05		34.02	35.08	30.70	
		35.46	21.07	42.09	0.00	0.02	0.00	0.00	0.06	0.00	0.19	0.41	99.30		34.15	35.35	30.22	
eposit.		35.49	20.80	42.30	0.00	0.02	0.00	0.00	0.08	0.00	0.24	0.79	99.72		34.21	34.93	30.39	
komite gold deposi		35.61	21.71	42.28	0.00	0.02	0.00	0.00	0.00	0.00	0.18	0.02	99.82		33.91	36.01	30.01	
s in Rom		35.16	21.03	42.06	0.01	0.01	0.00	0.00	0.05	0.00	0.23	0.14	98.69		34.03	35.46	30.34	
lized lode	/rite	35.77	21.55	42.33	0.02	0.01	0.00	0.00	0.00	0.00	0.21	0.12	100.01		34.07	35.75	30.05	
n mineral	Arsenopy	35.70	21.60	42.35	0.02	0.01	0.00	0.00	0.00	0.00	0.20	0.06	99.94		34.00	35.83	30.06	
gold froi		52.03	47.29	0.41	0.00	0.00	0.00	0.01	0.04	0.00	0.00	0.00	99.78		1.16	1.83	0.01	
yrite and		47.03	51.93	0.03	0.00	0.12	0.13	0.01	0.04	0.00	0.00	0.00	99.29		1.02	1.97	0.00	
e, arsenop		51.85	47.74	0.59	0.00	0.00	0.00	0.03	0.02	0.00	0.00	0.00	100.23		1.15	1.84	0.01	
a of pyrit		51.41	48.24	0.23	0.00	0.00	0.00	0.02	0.05	0.00	0.00	0.00	99.95		1.14	1.86	0.00	
probe dat		51.31	48.27	0.04	0.00	0.00	0.00	0.02	0.03	0.02	0.00	0.00	69.66		1.14	1.86	0.00	
n microl	g pyrite	51.53	47.88	0.15	0.00	0.00	0.00	0.00	0.03	0.02	0.00	0.00	99.61		1.14	1.85	0.00	
Electro	s-bearin;	2.03 5	7.29 4	.41	00.0	00.0	00.0	0.01	0.04	00.0	00.0	00.0	3.78 9			.83	0.01	
able 1	A	52	4	s (	0 (	i (	u (	л (	50	0	n (	, (	1m 95	%			s (	
Ľ		Fe	5	A	Ŭ	Ż	Ũ	N	A	He	Ā	St	S	at	Fe	3	A	ſ

oxygen isotope compositions calculated from quartz analyses are best estimates of the ore fluid  $\delta^{18}O_{H_2O}$ . Quartz-calcite pairs further confirm suggested vein formation temperatures of ~300 °C. The calculated  $\delta^{13}C_{CO_2}$  values of equilibrium fluids (waters) vary from -3.3 to -2.2 for dolomite and from -1.7 to -1.1 for calcite.

#### 6. Discussion and conclusions

According to Weinberg et al. (2004), gold endowment of the brittle-ductile shear zones is related to the interplay of several factors: (1) extreme lithologic competency contrasts that lead to more heterogeneous fluid flow; (2) degree of straining of the rock package, exemplified by the attenuation of the stratigraphy; (3) metamorphic facies, particularly its role in the volume of infiltrating fluids (e.g., Phillips et al., 1996); (4) rock permeability (e.g., Manning and Ingebritsen, 1999); and (5) variety of orientation of lithological contacts and structures giving rise to zones of dilation.

Shear zones in which fluids flow with little perturbation, and including highly attenuated/sheared rocks metamorphosed at amphibolite facies with little angular discordance, should be assigned low exploration priority. On the other hand, greenschist facies shear zones with varied orientation of lithological contacts and structures, varied lithologies, and close to regional seals, should be assigned highest priorities (e.g., Weinberg et al., 2004, and references therein).

Elsamani et al. (2001) suggested that gold mineralization in the Pan-African domains should be targeted near recognized sulfide concentrations, in collapse zones of extensional basins, within accretionary sutures, and along the shear zones that formed during the 650–550 Ma orogeny. The N-S Hamisana shear zone in the northern Red Sea Hills extends for more than 300 km, with an approximate width of 50 km (e.g., Bellevier et al., 1980; Stern et al., 1989). It contains internal evidence of polyphase ductile shearing followed by brittle deformation (e.g., Almond and Ahmed, 1987).

Gold mineralization at the Romite deposit is related to quartz and quartz-carbonate veins controlled by NNE-trending shear/ fault zones. Vein morphology and quartz textures indicate intense sinistral shearing, suggesting syn-kinematic mineralization. Carbonatization, sulfidation, and chloritization are the dominant hydrothermal alteration styles, with refractory gold present in arsenopyrite and As-rich pyrite, as is typical for orogenic gold deposits sensu Groves et al. (2003). Inclined stretching lineations and slickenside in silicified shear zones and on vein walls and shallow dips of extensional veins attest to their formation during crustal shortening (e.g., Sibson et al., 1988; Robert and Poulsen, 2001).

Stable isotope measurements indicate that  $\delta^{13}C$  of carbonate minerals from the quartz-carbonate lodes ranges from  $-4.6\%_{o}$  to  $-3.1\%_{o}$ , and  $\delta^{18}O$  values vary from  $11.9\%_{o}$  to  $13.7\%_{o}$ , whereas vein quartz gives  $\delta^{18}O$  of  $13.8\%_{o}-14.8\%_{o}$ . The calculated  $\delta^{18}O_{H_2O}$  and  $\delta^{13}C_{CO_2}$  values in fluids at 300 °C (Al (IV) in chlorite and minimum temperature of sulfide assemblage) are  $6.9\%_{o}\pm1.1\%_{o}$  and  $-2.2\%_{o}\pm1.1\%_{o}$ , respectively.

Metamorphic dewatering of igneous and volcanogenic sedimentary rocks in greenstone belts typically produces fluids with  $\delta^{18}O_{H_2O}$  compositions of 5%, whereas magmatic waters have  $\delta^{18}O_{H_2O}$  compositions of 5.5%, 10% (Taylor, 1979). The calculated  $\delta^{18}O_{H_2O}$  for the Romite lodes fall within both of these ranges, and, therefore, either metamorphic or magmatic sources B.A. Zoheir / Geoscience Frontiers 3(5) (2012) 571-585

Table 2   Electron	microprob	e data of	chlorite in	n lodes an	d dissemi	nated in a	ltered wal	lrock fron	n Romite n	nine.		
	In quart	z veins, a	nd associa	ted with s	sulfides			In wallr	ock, associ	ated with	sulfides	
SiO <sub>2</sub>	29.34	28.71	28.97	27.17	28.85	28.64	29.01	27.62	28.91	28.63	28.66	28.57
TiO <sub>2</sub>	0.05	0.07	0.06	0.06	0.08	0.06	0.08	0.09	0.07	0.07	0.10	0.06
$Al_2O_3$	20.80	20.14	20.22	20.18	21.02	21.28	21.01	20.01	20.16	20.25	20.65	20.06
FeO	19.01	18.75	19.26	19.84	18.59	18.79	19.12	17.68	19.12	18.06	18.93	19.37
MnO	0.13	0.22	0.20	0.14	0.20	0.19	0.15	0.18	0.17	0.17	0.15	0.14
MgO	19.23	19.18	18.64	19.80	18.64	18.83	18.30	21.96	18.67	20.23	19.88	18.68
CaO	0.03	0.04	0.90	0.05	0.05	0.05	0.10	0.08	0.07	0.08	0.15	0.14
BaO	0.00	0.02	0.00	0.00	0.01	0.00	0.01	0.01	0.02	0.00	0.00	0.00
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K <sub>2</sub> O	0.01	0.00	0.02	0.03	0.02	0.05	0.05	0.02	0.01	0.09	0.04	0.03
Total	88.61	87.12	88.27	87.29	87.46	87.89	87.84	87.66	87.20	87.58	88.56	87.05
Si	2.93	2.92	2.92	2.79	2.92	2.88	2.93	2.79	2.94	2.89	2.87	2.92
Ti	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00
Al (IV)	2.45	2.41	2.40	2.44	2.50	2.53	2.50	2.38	2.42	2.41	2.44	2.42
Al (VI)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.45	2.41	2.40	2.44	2.50	2.53	2.50	2.38	2.42	2.41	2.44	2.42
Fe (II)	1.59	1.60	1.62	1.70	1.57	1.58	1.61	1.49	1.63	1.52	1.59	1.65
Mn	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Mg	2.86	2.91	2.80	3.03	2.81	2.83	2.75	3.31	2.83	3.04	2.97	2.85
Ca	0.00	0.00	0.10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Κ	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00
Total	9.84	9.87	9.87	9.99	9.83	9.85	9.82	10.01	9.85	9.91	9.90	9.87
XFe Fe/(Fe + Mg)	0.36	0.35	0.37	0.36	0.36	0.36	0.37	0.31	0.36	0.33	0.35	0.37
$T^{\mathbf{a}}$ (°C)	304	300	300	303	310	312	310	294	301	298	302	301

Formula calculated on the basis of 14 oxygens.

 $T^{a}$  - Temperatures estimated using equation of Kranidiotis and MacLean (1987).

Tuble e	Lieet		roprobe	uutu OI	calence	und doi	onnice n	quartz	100003 11		inte goi	u uepos	it.				
	Calcite										Dolomi	te					
CaO	51.91	49.65	49.01	50.09	50.53	51.22	50.89	49.96	51.36	50.81	26.85	28.34	29.30	27.63	26.55	29.33	27.22
MgO	0.69	0.53	0.33	0.61	0.29	0.32	0.19	0.25	0.56	0.71	18.55	20.11	19.30	17.68	19.51	18.82	16.98
FeO	0.19	0.66	0.87	0.34	0.41	0.34	0.22	0.19	0.16	0.63	3.11	1.26	2.68	4.01	2.28	1.49	3.44
MnO	0.06	0.08	0.03	0.07	0.02	0.05	0.09	0.26	0.12	0.02	0.06	0.02	0.08	0.12	0.08	0.11	0.16
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.02	0.00	0.04	0.00
SrO	0.00	0.07	0.06	0.00	0.08	0.05	0.06	0.13	0.08	0.07	0.00	0.00	0.05	0.00	0.00	0.00	0.00
Total	52.85	50.99	50.30	51.11	51.33	51.98	51.45	50.79	52.28	52.24	48.60	49.73	51.41	49.46	48.42	49.79	47.80
Ca	1.96	1.95	1.95	1.96	1.97	1.97	1.98	1.97	1.96	1.95	1.10	1.14	1.14	1.12	1.10	1.18	1.14
Mg	0.03	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.03	0.76	0.81	0.75	0.71	0.81	0.76	0.71
Fe	0.01	0.03	0.03	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.13	0.05	0.10	0.16	0.09	0.06	0.14
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
mol %																	
CaCO <sub>3</sub>	98.22	97.37	97.44	98.00	98.44	98.54	98.91	98.37	98.24	97.26	55.25	56.99	56.99	55.86	54.83	58.91	56.95
MgCO <sub>3</sub>	1.31	1.04	0.66	1.19	0.56	0.62	0.37	0.49	1.07	1.36	38.17	40.44	37.54	35.75	40.29	37.80	35.52
FeCO <sub>3</sub>	0.36	1.29	1.73	0.67	0.80	0.65	0.43	0.37	0.31	1.21	6.40	2.53	5.21	8.11	4.71	2.99	7.20
$MnCO_3$	0.11	0.16	0.06	0.14	0.04	0.10	0.17	0.51	0.23	0.04	0.12	0.04	0.16	0.24	0.17	0.22	0.33
BaCO <sub>3</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.04	0.00	0.07	0.00
SrCO <sub>3</sub>	0.00	0.14	0.12	0.00	0.16	0.10	0.12	0.26	0.15	0.13	0.00	0.00	0.10	0.00	0.00	0.00	0.00
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

 Table 3
 Electron microprobe data of calcite and dolomite in quartz lodes from Romite gold deposit.

Structural formula calculated on the basis of 6 oxygens, 2 cations.

Table 4	Geoche	Geochemical data of representative samples of wallrock and orebodies from Romite gold deposit.															
	*	**	R-6	R-23	R-24	R-29	R-31	R-45	R-27	R-60	R-25	R-49	R-58	R-59	R-22	R-33	R-19
Au	ppb	2	506	_	_	1406	605	60	2449	_	6780	341	44	_	14	867	704
Ag	ppm	0.3	_	—	_		_	_	0.4	_	0.9	—	_	_	_	_	-
Cu	ppm	1	_	67	71	217	49	3	827	49	1450	62	12	57	69	165	10
Cd	ppm	0.3	_	—	_	0.8	0.7	_	1.3	—	1.3	—	_	_	0.5	0.8	-
Мо	ppm	1	_	2	2	4	3	3	3	2	2	12	_	3	2	4	4
Pb	ppm	3	3	—	—	—	_	_	4	—	_	—	_	_	—	—	-
Ni	ppm	1	399	440	388	158	312	10	111	23	129	7	15	12	409	138	21
Zn	ppm	1	126	85	85	89	75	24	302	9	450	10	17	4	99	69	3
As	ppm	0.5	193	59.6	88.5	1238	99	88.4	3177	155	9250	147	20.5	_	94	831	54.4
Co	ppm	1	34	52	39	39	32	2	168	11	211	5	5	4	42	29	2
Cr	ppm	2	1520	608	723	514	884	295	167	456	186	212	64	332	950	486	683
Eu	ppm	0.2	0.5	0.5	0.6	1.0	0.5	1.7	0.3	1.0	0.3	1.4	1.7	_	0.8	1.1	-
Rb	ppm	5	13	11	10	12	9	_	13	8	_	_	_	_	_	_	_
Sb	ppm	0.1	1.5	0.1	0.8	1.1	0.8	0.1	3.2	1.2	4.1	0.9	0.7	0.6	0.8	0.9	0.8
Sc	ppm	0.1	27.7	23.8	24.4	11.4	19.1	6.3	13.5	3.8	6.4	6	5.3	2.5	25.3	11.1	0.6
Sr	ppm	1	43	23	20	65	22	64	66	45	83	94	227	32	29	75	2
Th	ppm	0.2	2.2	_	0.5	_	_	0.7	_	_	_	_	_	_	_	_	_
U	ppm	0.5	_	_	_	1	_	0.9	_	_	_	_	_	_	_	_	_
Та	ppm	0.5	_	0.7	0.6	0.8	0.7		0.6	0.9							
V	ppm	2	166	171	179	78	131	20	101	36	92	15	32	22	162	71	8
W	ppm	1	5	—	_	5	5	2	—	4	_	7	_	4	2	4	5
Y	ppm	1	8	6	10	9	7	23	15	8	13	5	10	1	8	10	3
La	ppm	0.5	6.7	5	5.5	4.3	4.7	7	5.9	0.9	4.1	1.9	6.3	0.7	5.7	4.6	1.5
Ce	ppm	3	12	12	14	15	13	17	21	—	22	—	_	_	13	15	_
Nd	ppm	5	_	—	—	7	_	8	—	7	6	—	_	_	—	—	-
Sm	ppm	0.1	1.8	1.5	2.1	1.7	1.4	3.7	2.8	1.9	3.1	0.8	1.8	0.2	1.9	1.8	0.3
Tb	ppm	0.5	_	0.6	_	0.6	_	0.7	_	_	0.5	_	_	_	_	0.7	_
Yb	ppm	0.2	1.1	2	2.2	1.6	1.5	3.7	2.4	0.7	2.5	0.6	1.2	0.2	1.8	1.6	0.5
Lu	ppm	0.05	0.26	0.39	0.44	0.32	0.29	0.66	0.46	0.10	0.45	0.12	0.2	_	0.36	0.35	0.06
$w(Al_2O_3)$	%	0.01	6.51	5.06	5.22	0.64	2.25	0.64	2.52	1.86	0.40	0.10	2.77	0.57	5.60	1.03	0.20
w(TiO <sub>2</sub> )	%	0.01	0.26	0.17	0.25	0.11	0.23	0.02	0.10	0.10	0.03	_	0.03	0.03	0.23	0.11	_
$w(P_2O_5)$	%	0.01	0.04	0.04	0.05	0.03	0.04	0.01	0.04	0.03	0.07	0.01	0.02	0.01	0.04	0.02	0.01
w(MnO)	%	0.01	0.13	0.11	0.10	0.10	0.09	0.16	0.11	0.11	0.03	0.10	0.21	0.03	0.12	0.11	0.01
$w(Fe_2O_3)^t$	%	0.01	8.50	6.36	7.07	8.04	5.68	1.78	17.9	9.84	43.4	1.12	2.74	0.63	7.31	6.11	0.77
w(MgO)	%	0.01	7.05	7.10	7.49	2.77	5.43	0.17	0.45	2.34	0.13	0.09	2.66	0.12	7.21	2.58	0.09
w(CaO)	%	0.01	6.71	3.24	2.08	6.90	3.03	11.3	2.44	7.78	0.33	12.0	21.6	4.74	4.01	8.61	0.10
$W(K_2O)$	%	0.01	0.01	-	_	0.07	0.03	0.07	0.03	0.07	0.02	0.02	0.03	0.31	0.01	0.07	0.04
w(Na <sub>2</sub> O)	%	0.01	0.04	0.02	0.04	0.05	0.04	0.11	0.07	0.06	0.05	0.02	0.11	0.02	0.05	0.06	0.04
$w(SO_3)$	%	0.01	_	_	0.06	0.07	0.06	0.01	0.12	0.08	0.23	0.02	0.04	_	0.08	0.10	-

\*Unit of measurement, \*\*Detection limit, - below detection limit.

Analyses were made by the ACTLABS Group, Canada, using the INAA and ICP-MS techniques (Code 1H).

Sample description: R-6: silicified/carbonatized sheared diorite with abundant disseminated goethite; R-29: highly silicified/carbonatized wallrocks with disseminated altered sulfides; R-31: highly ferruginated/carbonatized silicified wallrock; R-27: ferruginated/chloritized diorite wallrock; R-24: carbonatized highly sheared quartz diorite with disseminated goethite; R-23: chloritized sheared quartz diorite with disseminated goethite; R-23: chloritized sheared quartz diorite with disseminated goethite; R-60: highly silicified/carbonatized diorite; R-19: greyish quartz lode (10-cm-wide) cuts the sheared diorite adjacent to milky quartz vein; R-25: malachite-bearing densely ferruginated quartz vein; R-49: mixed greyish and milky quartz lode with a considerable carbonate content; R-33: milky quartz lode with slivers of carbonatized wallrock; R-58: carbonate-rich lode with kaolinite and opaque minerals; R-59: carbonate-dominant vein with ferruginated wallrock slivers; R-22: quartz-carbonate vein with disseminated goethite crystals.

are permissive. The restricted individual ranges of  $\delta^{13}$ C values imply a corresponding uniformity to the ambient temperature and  $\delta^{13}C_{CO_2}$  ( $\delta^{13}C_{\Sigma C}$ ) of the ore-forming fluids. The fluid  $\delta^{13}C_{CO_2}$ values calculated from the calcite-CO<sub>2</sub> and dolomite-CO<sub>2</sub> fractionation (-3.3% to -1.1%) could represent a possible crustal carbon source (e.g., Stemler et al., 2006; Klein et al., 2008). The calculated  $\delta^{13}C_{CO_2}$  values are slightly heavier than juvenile magmatic carbon (-3% to -7%) and lighter than CO<sub>2</sub> produced by decarbonization or leaching of marine carbonate from sedimentary and igneous rocks (0.4%  $\pm 2.7\%$ ; Schidlowski et al., 1975; Ohmoto and Rye, 1979).

The  $\delta^{13}$ C and  $\delta^{18}$ O signatures for ore-associated carbonate from the Romite deposit (Table 6) are not diagnostic of a unique source, typical of orogenic gold deposits ( $-8\%_{oo}$  to  $-2\%_{oo}$ , and  $8\%_{oo}-15\%_{oo}$ , respectively; e.g., Zegers et al., 2002). Ore fluids in these deposits are commonly assumed to be derived from B.A. Zoheir / Geoscience Frontiers 3(5) (2012) 571-585

Table	5 Pearson c	correlation mat	rix of Au and	important trac	e elements in	the Romite de	eposit.			
	Au	Cu	Sb	Zn	Sc	Sr	As	Ni	Co	V
Au	1.000									
Cu	0.969	1.000								
Sb	0.924	0.978	1.000							
Zn	0.929	0.982	0.968	1.000						
Sc	-0.164	-0.069	-0.036	0.106	1.000					
Sr	-0.020	0.019	0.012	-0.045	-0.324	1.000				
As	0.993	0.978	0.926	0.944	-0.137	0.037	1.000			
Ni	-0.015	0.009	0.025	0.170	0.937	-0.440	-0.100	1.000		
Co	0.902	0.974	0.979	0.994	0.105	-0.047	0.914	0.146	1.000	
V	0.202	0.273	0.299	0.436	0.920	-0.325	0.218	0.943	0.425	1.000
Shaded	l values indicat	e significant po	sitive correlatio	m						

a combination of metamorphic and magmatic sources (e.g., Rye et al., 1976; Golding and Wilson, 1983; Ohmoto, 1986; McCuaig and Kerrich, 1998; Sarangi et al., 2010). However, considering the intense deformation of the host rocks and lack of prominent magmatism in the mine area, a most likely metamorphic fluid origin is suggested.

In conclusion, understanding the geologic setting should remain an important underpinning of future gold exploration

programs. The Romite gold deposit belongs to the orogenic lode style mineralization, which is typically structurally-controlled. The high order splays off the Hamisana Zone should be prime zones for further exploration. Along the NNE-trending shear zones, gold exploration targets can be evaluated using As (>1000 ppm) as the best indicator of Au > 1 ppm, and high contents of Cu, Zn, and Co may provide further indication of Au concentration.

Table 6	C and O isotope values of carbonate and quartz in lodes from Romite gold deposit.													
Sample	Mineral	$\delta^{13} C_{PDB}$	$\delta^{18} O_{VSMOW}$	Fluid	Fluid	$\delta^{18}$ O qtz-cal								
		(‰)	(‰)	$\delta^{13}C_{CO_2} (\%)^a$	$\delta^{18}O_{H_2O} (\%)^{b}$	$T (^{\circ}C)^{c}$								
R-217	Fe-dolo	-3.7	12.1	-2.4	6.0									
R-252	Fe-dolo	-3.9	12.5	-2.6	6.4									
R-260	Fe-dolo	-3.5	11.9	-2.2	5.8									
R-204	Fe-dolo	-4.6	12.4	-3.3	6.3									
R-205	Fe-dolo	-4.2	12.0	-2.9	5.9									
R-255	Fe-dolo	-4.0	12.2	-2.7	6.1									
R-217	Calcite	-3.3	12.9	-1.3	6.8	280								
R-252	Calcite	-3.6	13.7	-1.6	8.1	335								
R-219	Calcite	-3.1	12.9	-1.1	7.3	353								
R-210	Calcite	-3.2	13.1	-1.2	7.5	317								
R-221	Calcite	-3.5	12.8	-1.5	7.2	299								
R-255	Calcite	-3.6	13.5	-1.6	7.9	300								
R-260	Calcite	-3.2	13.2	-1.2	7.6	341								
R-214	Calcite	-3.7	12.6	-1.7	7.0	299								
R-250	Calcite	-3.5	12.9	-1.5	7.3	297								
R-217	Quartz		14.3		7.4									
R-252	Quartz		14.8		7.9									
R-219	Quartz		13.9		7.0									
R-210	Quartz		14.3		7.4									
R-221	Quartz		14.1		7.2									
R-255	Quartz		14.8		7.9									
R-260	Quartz		14.3		7.4									
R-214	Quartz		13.9		7.0									
R-250	Quartz		14.2		7.3									
R-201	Quartz		13.8		6.9									
R-204	Quartz		14.1		7.2									
R-205	Quartz		14.5		7.6									

<sup>a</sup> CO<sub>2</sub>-calcite and CO<sub>2</sub>-dolomite equations of Ohmoto and Rye (1979).

<sup>b</sup> Equation of oxygen isotopic fractionation of dolomite-water (Matthews and Katz, 1977), calcite-water (O'Neil et al., 1969), and quartz-water (Matsuhisa et al., 1979).

<sup>c</sup> Quartz-calcite temperatures (equation of Sheppard and Schwarcz, 1970).

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