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Erratum to: Stable Isotopes (O, H, and S) in the Muteh Gold Deposit, Golpaygan Area, Iran

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Stable Isotopes (O, H, and S) in the Muteh Gold Deposit, Golpaygan Area, Iran

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The Muteh gold district with nine gold deposits is located in the Sanandaj-Sirjan metamorphic zone. Gold mineralization occurs in a pre-Permian complex which mainly consists of green schists, meta-volcanics, and gneiss rocks. Shear zones are the host of gold mineralization. Gold paragenesis minerals include pyrite, chalcopyrite, pyrrhotite, and secondary minerals. Pyrites occur as pre-, syn-, and post-metamorphism minerals. To determine the source of the ore-bearing fluids, fifty samples were selected for petrographical and stable isotope studies. The mean values of 12.4‰, and −42‰ for $\delta^{18}O$ and δD isotopes, respectively, and a mean value of 7.75‰ of calculated fractionation factors for $\delta^{18}O$ H_2O, from quartz veins indicate that metamorphic host rocks are the most important source for the fluids and gold mineralization. Three generations of pyrite can be distinguished showing a wide range of $\delta^{34}S$. Gold mineralization is closely associated with intense hydrothermal alteration along the ductile shear zones. The characteristics of the gold mineralization in the study area are similar to those of orogenic gold deposits elsewhere.

KEY WORDS: Gold deposit, Muteh, isotope, metamorphic zone, pyrite, quartz veins, Sanandaj–Sirjan zone.

INTRODUCTION

The Muteh district has nine known gold deposits and numerous anomalous gold indications. It is located in the Golpaygan area in Isfahan Province, Central Iran about 240 km southwest of the capital city of Tehran and within the Sanandaj–Sirjan metamorphic zone of the Zagros Structural Belt (see Fig. 1). The Muteh gold district is the major gold plant in Iran producing 450 kg of gold per year from the Chah-Khatoon and Senjedeh open pits. The gold deposits are moderate to steeply dipping vein and lode type, hosted by the pre-Permian schists that are intruded by the Muteh leucogranite. Gold is the ancient ore mineral in the study area occurring as very fine-grained (1–5 lm) inclusions in pyrite (Khoei, 1987) and is associated with intensive silicification, sericitization, and bleaching of host rocks. The Chah Khatoon and Senjedeh open pits have been classified as having oxide ore and sulfide ores. The ore has been weakly oxidized near the surface, forming a thin, oxidized cap on the deposit. Oxidation has resulted in the formation of limonite pseudomorphs after pyrite.

Historically, these deposits are the most productive gold deposits in Iran. They have been mined and explored since 1950. Muteh contains more than 1,200,000 tons of reserves at 4 g/tons Au (BHP, 1991, 1992). The gold mineralization is associated with metamorphic rocks of predominantly meta-volcanic composition. This metamorphic complex is

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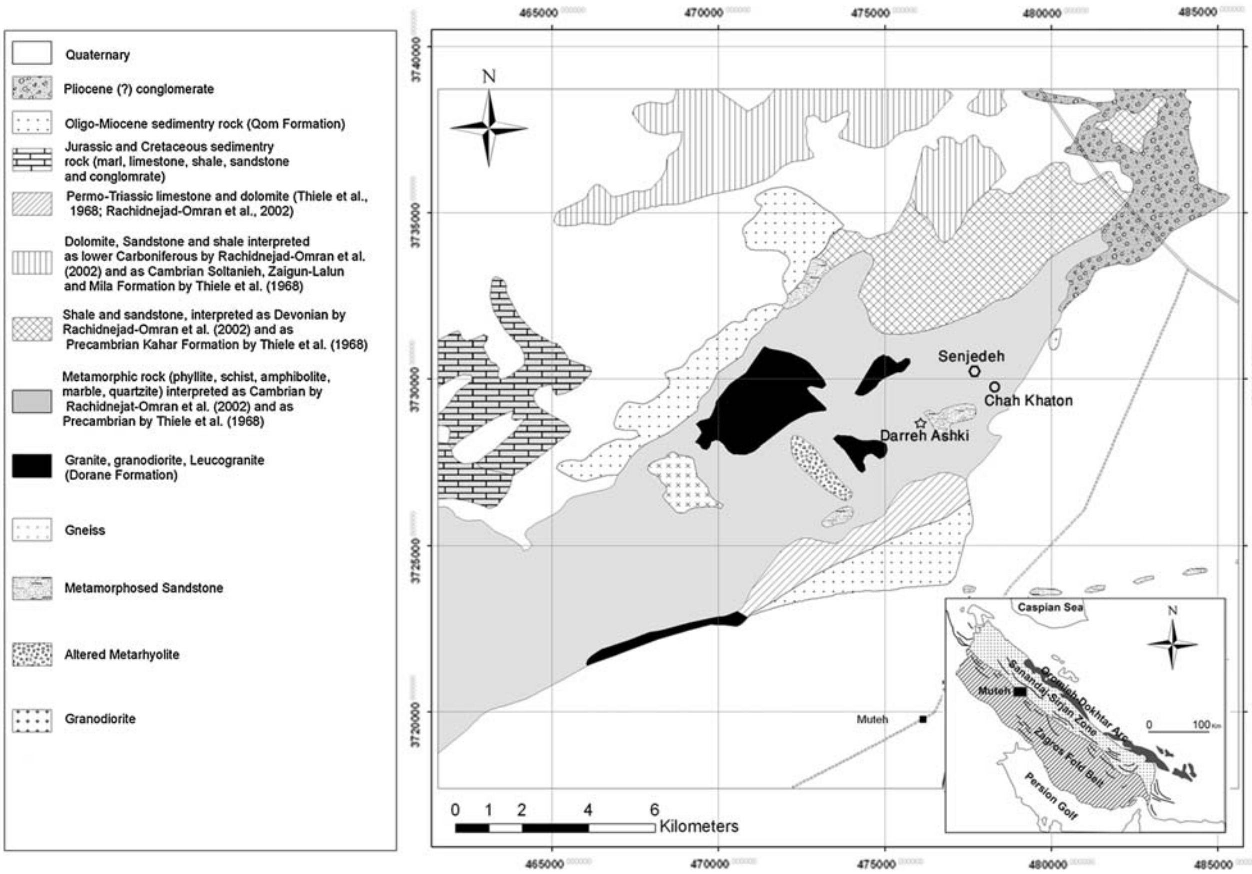

Figure 1. Geographical situation of the SSZ and simplified regional geological map of the Muteh district.

located in the Sanandaj–Sirjan zone (SSZ) similar to most metamorphic bodies in Iran. The Muteh complex consists of a high-grade metamorphic core (mainly gneiss and amphibolite) and low-grade metamorphic cover rocks (mainly schists and marbles). There are several previous studies on the genesis of gold mineralization in the Muteh area (Khoei, 1987; Farhanghi, 1991; BHP Engineering Co., 1991, 1992; Darehbidi, 1994; Moritz and Ghazban, 1995; Rashidnejad Omran, 2002; Yousefinia, 2004; Abdollahi and others, 2006; Moritz, Ghazban, and Singer, 2006). The metamorphic complex, which hosts the Muteh gold deposit, is of greenschist grade (Paidar-Sarvi, 1989; Farhanghi, 1991), with an assemblage predominantly composed of albite–chlorite–muscovite–biotite–quartz ± epidote, which overprints the amphibolite assemblage according to Thiele (1966) and Thiele and others (1968). The extensive petrological work by Rashidnejad Omran (2002) also identified a greenstone belt gold mineralization for the Muteh deposits. The gold mineralization is related to hydrothermal activity (Moritz and Ghazban, 1995). The source of fluids and gold mineralization are the most fundamental questions in the Muteh gold-bearing area. This study uses a combination of oxygen, hydrogen, and sulfur isotope studies to help assess the source of fluids. The Muteh gold mining district is situated in a deformed and complex area; therefore, these data in combination with REE geochemistry and full data fluid-inclusion studies are necessary to have a better sense of the genesis and source of mineralizing fluids.

BACKGROUND

Regional Geology of the SSZ

The geotectonic setting of Iran with respect to the Scytho-Turanian plate in the north and the

Arabian plate (Gondwana) in the south is still a matter of controversy (Soffel and others, 1996; Moritz, Ghazban, and Singer, 2006). They argue that the development of the SSZ is related to the generation of the Tethys Ocean and its subsequent destruction during Cretaceous and Tertiary convergence and continental collision between the Afro-Arabian and Eurasian plates. During the Mesozoic, subduction between the Iranian and Afro-Arabian plates defined three main parallel tectonic zones: (1) the Zagros fold and thrust belt, (2) the SSZ, and (3) the Urumieh-Dokhtar belt (see Fig. 1). Most metamorphic rocks associated with different mineralization are in the SSZ. This belt is considered to be an integral part of the Zagros orogenic belt (Stocklin, 1968; Alavi, 1994), which is in turn part of the Alpine–Himalayan orogenic/metallogenic belt. The SSZ is a narrow band measuring approximately 1500 km in length and 150–200 km in width. It lays between the towns of Sirjan and Esfandagheh in the southeast, and Urumieh and Sanandaj in the northwest. The rocks in this zone are the most highly deformed in the Zagros orogen and share the NW–SE trend of its structures.

Geology of the Muteh District

The exposed rocks in the Muteh area are metamorphic complexes composed of green schists, ortho- and para-gneisses, limestone- and dolomite-marbles, amphibolites, mica schists, quartzites, and phyllites. Although Thiele (1966) and Thiele and others (1968) assigned a Precambrian age to the metamorphic rocks, new petrological and isotopic studies by Rashidnejad Omran (2002) and Moritz, Ghazban, and Singer (2006) suggest a younger age for these formations. Granite intrusions near the Muteh gold district are younger than these metamorphic rocks and are accompanied by gold–pyrite mineralization as disseminated and vienlet type (see Figs. 1–3). In the northern area, the metamorphic rocks are followed by a sequence of rocks which are very slightly metamorphic to entirely non-metamorphic, comprising from bottom to top: several hundred meters of sandy slates with intercalations of acidic to intermediate effusive rocks, a dolomitic complex of up to 1000-m thickness, several hundred meters of micaceous sandy slates and sandstones, and on top, dark dolomites grading into light-colored limestones with scarce trilobite remains (Thiele and others, 1968). According to Moritz, Ghazban, and Singer (2006), the unmetamorphosed dolomite, sandstone, and shale bordering the metamorphosed complex are Early Carboniferous and Devonian in age rather than Cambrian and Precambrian.

In general, the metamorphic basement is directly overlain by sandstones, shales, limestones, and greenschists of Permian age. These Permian rocks are in part slightly metamorphic, and their contact with the pre-Permian basement is occasionally marked by basal conglomerates and by a distinct angular nonconformity. The Permian dolomites are followed, with no sharply defined junction, by a thick alternation of dolomites and more or less dolomitic limestones representing possibly lower to Middle Triassic time (Thiele and others, 1968). The metamorphic complex and Upper Paleozoic formations are overlapped transgressively by an Upper Triassic–Jurassic–Lower Cretaceous sequence comprising a polygenic basal conglomerate and several hundred meters of sandy marls, sandy limestones, and some oolitic limestones (Thiele and others, 1968).

Volcanic rocks (in part, probably submarine extrusions) are found locally at the base of the Middle Cretaceous sequence and might be associated with scattered mineralization. The Middle Cretaceous marls and limestones are followed, locally with a slight nonconformity, by a monotonous sequence of shales, marls, and marly limestone more than 1000 m thick and, based on the scarce fossils found there, believed to be Upper Cretaceous in age. In the northern part of the area, these rocks are pierced by small dioritic to gabbro-dioritic stocks.

Two Au deposits (Senjedeh and Chah-Khatoon) are currently mined in the Muteh district. The Muteh Au deposits are primarily hosted by a pre-Permian metamorphic (see Figs. 1–3) that consists of gneisses and meta-volcanics of greenschist to amphibolite facies. The basic metamorphic rocks consist of hornblende, plagioclase, garnet, brown biotite, quartz, ilmenite, magnetite, and sphene. The metapelitic rocks tend to consist of the following: quartz, biotite, muscovite, chlorite, garnet, ilmenite, rutile, and staurolite. These basic metamorphic and metapelitic rocks indicate the amphibolite facie. The greenschist facies are indicated by the occurrence of green hornblende, plagioclase, alkali feldspar, green biotite, quartz, ilmenite, magnetite, chlorite, actinolite, and epidote in green mafic schists and the occurrence of sodic-plagioclase, alkali feldspar, green biotite, muscovite, quartz, ilmenite, chlorite, rutile, epidote, and sphene in the felsic schists. Based

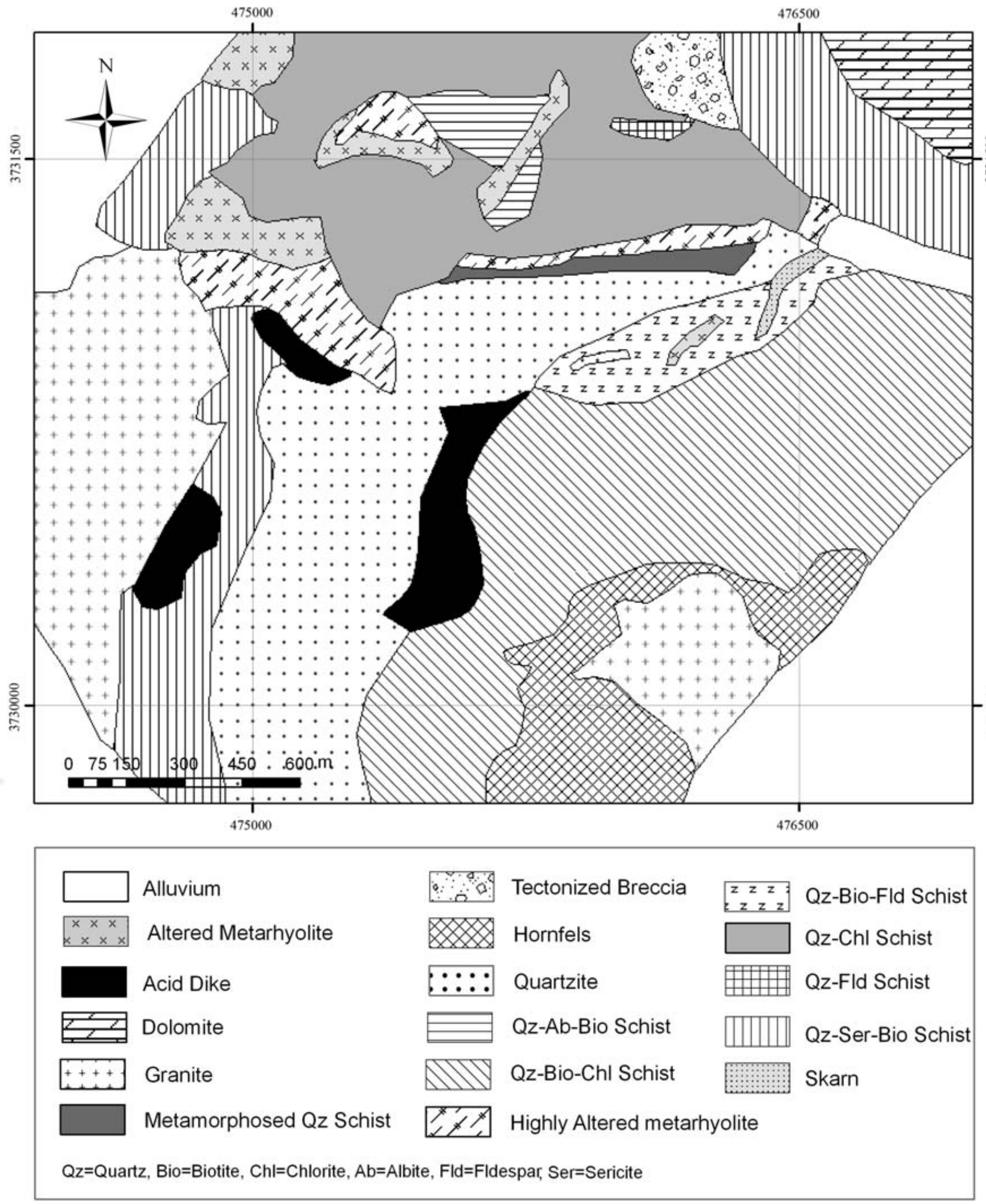

Figure 2. Simplified geological map of the Chah-Khatoon gold deposit.

on Rashidnejad Omran (2002), the metamorphic complex in these areas can be divided into three main parts: (1) gneisses-meta-volcanics, (2) amphibolites and greenschists, and (3) schists to slates. The main hosts of the mineralization are parts one and two. Granitoid bodies of mica granites in the Darreh-Ashki area north of Chah-Khatoon and Senjedeh mines are peraluminous and metaluminous. Regionally and locally, all the metamorphic units are affected by subhorizontal foliation (Moritz and Ghazban, 1995). Moritz and Ghazban (1995) show that the two main gold mineralization phases can be

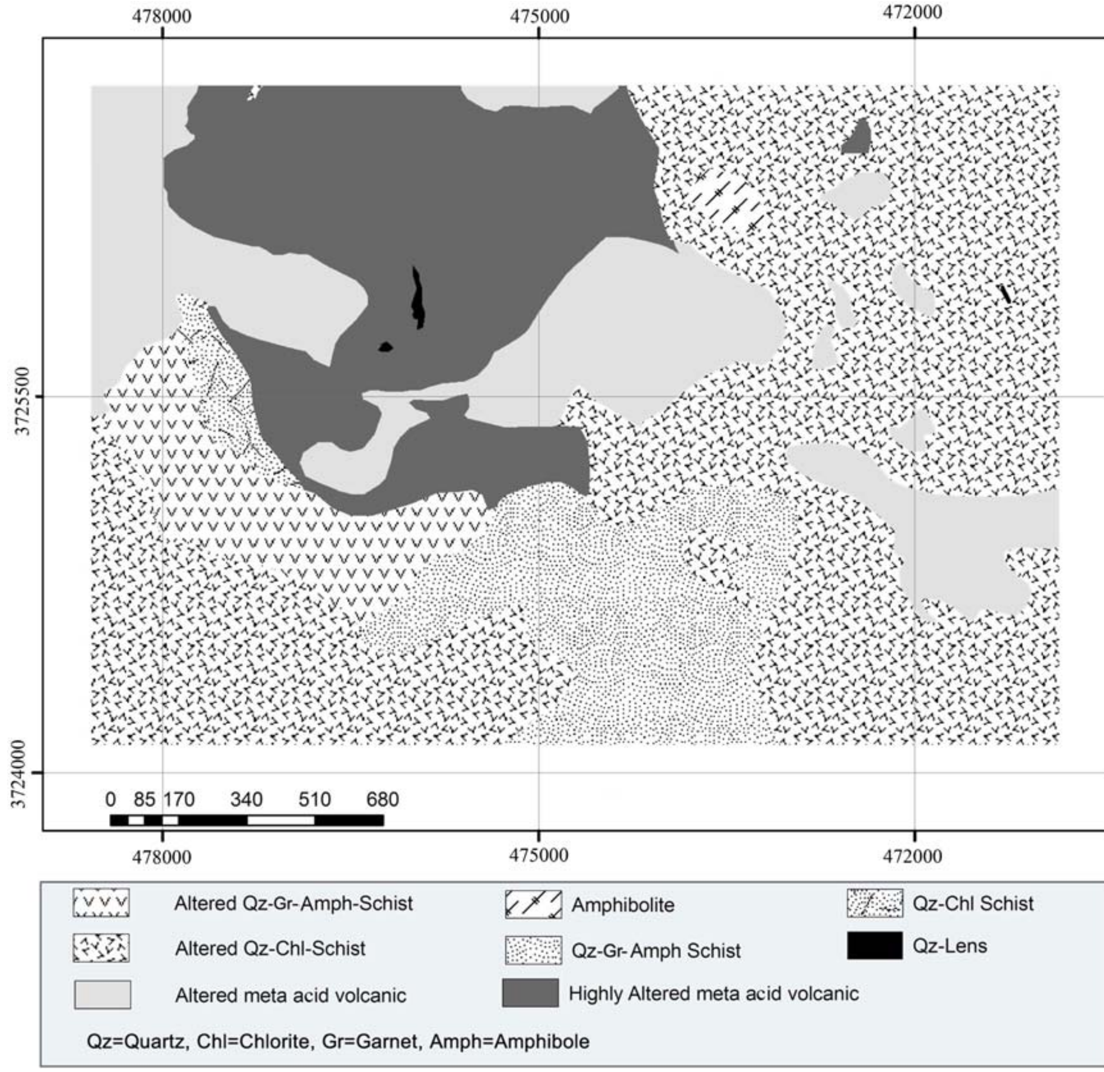

Figure 3. Simplified geological map of the Senjedeh gold deposit.

distinguished in the Muteh gold-bearing area using alteration mineralogy, fluid-inclusion studies, and structural investigations. The structural investigations would consist of (1) NW trending normal faults within the gneisses and meta-volcanics and (2) intersection of these faults with lithological contacts in the Chah-Khatoon and Senjedeh mines. In the Senjedeh mine, basaltic dykes are metamorphosed to amphibolite facies. Granitic intrusions (see Fig. 1) with a small patch of metamorphism halo are located in the northern parts of the mineralized zone. High-grade gold mineralization is situated in sheared and brecciate zones. Silicification and carbonatization are the most important alteration features in the gold-bearing host rocks. Two types of quartz veins can be observed on the regional and local scales. In mineralized zones, quartz veins are associated with gold-bearing pyrite grains as disseminated and open space-filling styles. A set of thick quartz veins cuts almost all metamorphic rocks in the study area. These veins are barren or with weak mineralization. All of these lithological units are covered by Cambrian-to-Oligocene sedimentary rocks.

METHODOLOGY

Detailed field study has been carried out at different scales on the metamorphic rocks at the Muteh district, at two Chah-Khatoon and Senjedeh deposits.

Field study and sampling were carried out during the summer of 2004–2005. About 50 outcrop samples from different types of quartz veins-associated metamorphic rocks were examined. All these samples were studied petrographically. Petrography was characterized by optical microscopy, scanning electron microscopy (SEM), and X-ray powder diffraction (XRD) analysis at Shahid Chamran University of Ahvaz, Iran. Among them, 15 samples containing veinlets of sulfides and quartz were selected for stable isotope analysis. Field work and sampling for isotope studies were carried out at the Chah-Khatoon and Senjedeh gold deposits on the local and regional veins of quartz and gold-bearing outcrops. The samples were examined for suitable minerals by microscope and XRD, and representative samples containing veinlets of sulfides, quartz, and carbonates were selected for stable isotope analysis. Sulfur, oxygen, and hydrogen isotope values of pyrite, quartz, biotite, K-feldspar, and chlorite were determined on hand-picked mineral separated at the Isotope Laboratory, Department of Earth Sciences, Queens University, Canada, using a continuous flow elemental analyzer (Carlo Erba NA 1500) attached to a VG Prism II mass spectrometer. These minerals were separated from the crushed and sieved samples using conventional heavy liquids (sodium polytungstate; specific gravity = 2.9) followed by hand-picking under a binocular microscope.

PETROGRAPHY

Due to intense alteration and deformation especially in shear zones, determination of primary minerals and the protolith is very difficult. Mineralization at Muteh occurs within the amphibolites, meta-volcanics, and schists. The age of the host rock was not determined by geochronology in this study but Moritz, Ghazban, and Singer (2006) suggest a Cambrian age for the metamorphic rocks of gneiss, marble, amphibolite, schist, phyllite, and quartzite. Based on the field observations and petrographical studies, three main host rocks (meta-volcanic, schist, and amphibolite) occur in the two active gold mines in the Muteh district (Chah-Khatoon and Senjedeh mines).

Meta-volcanics

Meta-volcanic rocks with felsic composition mainly consist of primary quartz, K-feldspar, and muscovite (see Fig. 4A). Sericitification and silicification are the most important alteration features in these rocks. Three generations of quartz can be observed: euhedral quartz grains in the matrix of the rocks, veinlet of quartz with gold-bearing pyrite mineralization, and veins of quartz which cut the first two generations. In some instances, these three can be distinguished in SEM pictures as seen in Figure 4B. Figure 4C shows that increasing deformation in shear zones has created mylonites and ultra-mylonites in the felsic rocks.

Schists

These rocks with sericite schist, biotite schist, muscovite schist, and epidote schist consist mainly of quartz, biotite, chlorite, and sericite that show greenschist facies (see Fig. 4D). Ore minerals in these rocks are pyrite, chalcopyrite, and pyrrhotite (Mortiz and Ghazban, 1995). Mineralization is parallel to foliation without any deformation. This indicates that some pyrite mineralization is syn-metamorphism. Post-metamorphism pyrites are also abundant in these rocks. Quartz veinlets with pyrite mineralization cut these rocks. Disseminated pyrite mineralization also can be observed in schists. Schists and gneisses are host rocks of the gold deposits at Chah-Khatoon open pit and the study area.

Amphibolites

Amphibolites are located in the northern parts of the Senjedeh deposit in dark brown color. Distribution of plagioclase in these rocks presents a basic source (e.g., gabbro or basalt) for these rocks. Using discriminate diagrams for geochemical analysis also revealed that depleted MORB was the protoliths of amphibolites at Muteh area. Hornblende, chlorite, and plagioclase show that the retrograde metamorphisms are the main minerals in the amphibolites as seen in Figure 4E (Abdollahi and others, 2006; Rashidnejad Omran, 2002). Biotite also can be found in these rocks. Pyrite mineralization is weak here but in some parts it occurs as dissemination.

Granites

The granites and gneisses are located in adjacent areas such as Darreh-Ashki and the northern

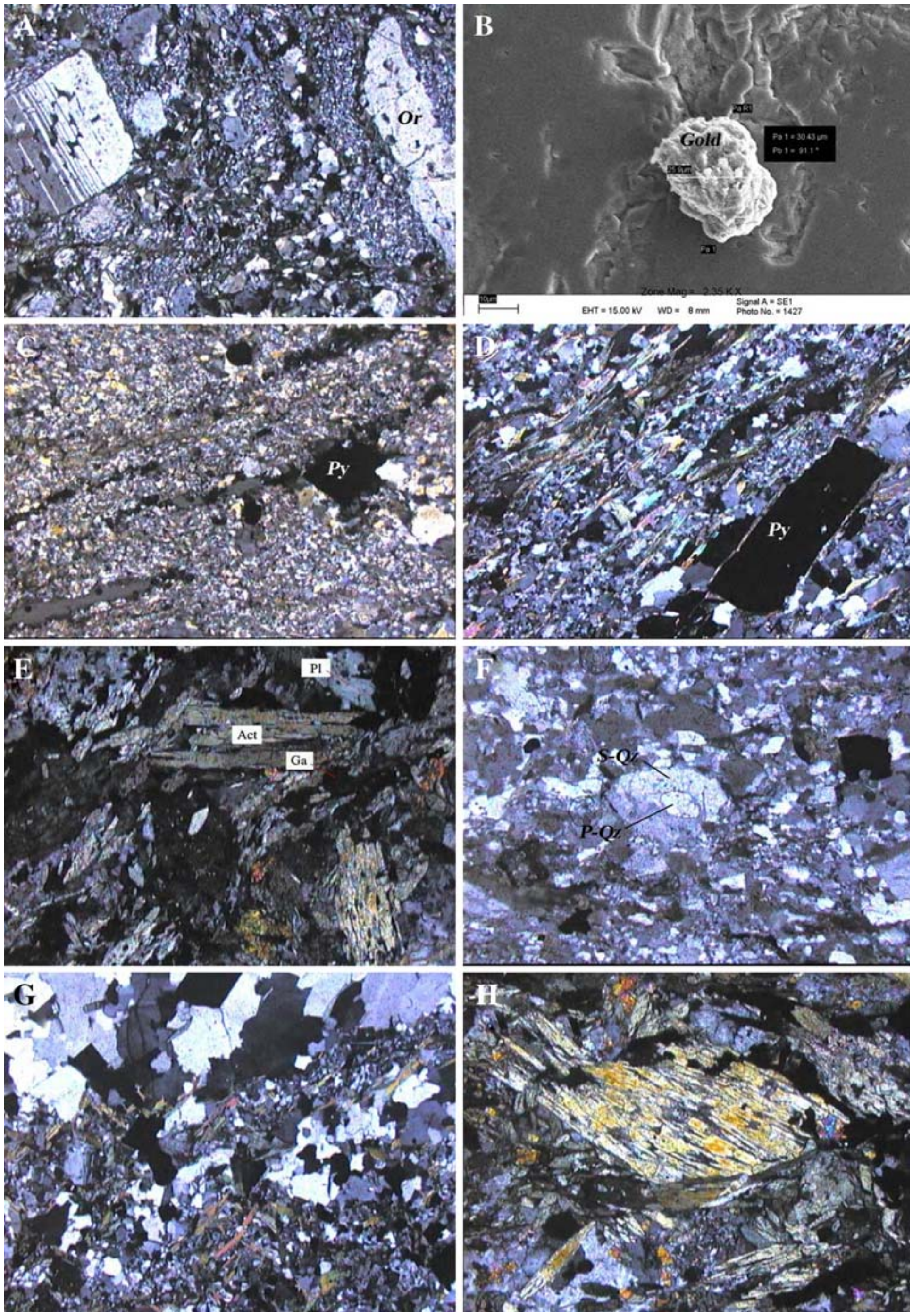

Figure 4. (A) Microphotograph of the meta-volcanic rocks in the study area (20×, L.P.), (B) SEM photo of the gold a grain in the meta-volcanic rocks, (C) microphotograph of the mylonites in the shear zones in the study area (20×, L.P.), (D) microphotograph of the biotite–schists in the study area (20×, L.P.), (E) microphotograph of the amphibolites in the study area (20×, L.P.), (F) Microphotograph of the biotite–schists in Chah-Khatoon open pit showing quartz overgrowth (20×, L.P.), (G) quartz vienlet crosscutting in the Chah Khatoon deposit (20×, L.P.), (H) hydrothermal alteration in the Chah-Khatoon deposit (20×, L.P.). Abbreviations: Qz, quartz; Fld, feldspar; Py, pyrite; Bio, biotite; Mu, muscovite; Ga, garnet; Act, actinolite; Pl, plagioclase; P-Qz, primary quartz; S-Qz, secondary quartz; CV, carbonate vein.

part of the Muteh area. These granites are relatively fresh without any alteration haloes. A weak pyrite and gold mineralization can be observed in these rocks. Mineralization occurs at the contacts of these rocks and schists. Malachite and copper mineralization is formed among the faults and shear zones of these granites.

Alteration

Silicification is the most important alteration event in this area (see Fig. 4). Hydrothermal and supergene alteration are characterized by intense bleaching of the hosts rocks (Moritz and Ghazban, 1995) in some areas as shown in Figure 4. Carbonatization may occur in some parts of selected rocks. The silicified zones (especially in shear zones) consist of crystalline to microcrystalline quartz veinlets, mica, pyrite, and carbonate. Chlorites, sericites, epidotes, and rutiles are the result of retrograde metamorphism and weathering of primary minerals in the rocks. Carbonate and quartz show open space-filling texture in meta-volcanics and schists. Quartz appears as veinlets crosscutting the foliation of host rocks and in some places it has boudinaged shape. Gold mineralization is mainly associated with quartz, carbonate, and pyrite veinlets in sheared and altered zones. These alteration assemblages overprint the primary minerals and metamorphic minerals and textures in metamorphic and igneous rocks in the mineralized zones and adjacent areas (Moritz and Ghazban, 1995). In some parts, alteration veinlets cut foliation of the metamorphic rocks. Gold is typically associated with pyrite, but according to Paidar-Sarvi (1989) chalcopyrite, bismuth, galena, sphalerite, and pyrrhotite are other specific minerals in the Muteh area. A summary of the list of the minerals of the host rocks in the study area is shown in Table 1. In some parts, gold mineralization post-dates metamorphism and ductile deformation of the host rocks. In these rocks, mineralization is found within the sheared zones which are cutting the metamorphosed rocks showing that mineralization is younger than the regional metamorphism.

Isotope Studies

Stable isotope studies help in identifying the sources of the gold and associated metals, determine the mechanisms that led to the transport and concentration of the gold, and establish the mechanisms involved in the liberation and mobilization of elements into the environment. They can also be used to study geologic events that have disturbed the original conditions of the mineralized rocks and to identify the original conditions. To reach these points, doubly polished thick sections of pure quartz samples were examined by microscope to determine those that could be used for fluid-inclusions for H-isotope measurements. Fluorine of biotite was measured by microprobe, and low F-bearing biotite was selected for the O and H isotopes. Pyrite grains were studied under the microscope, microprobe, and SEM. Three generations of pyrite were distinguished in this study. Gold mineralization is associated with high arsenic pyrites. Paragenically

Table 1. Mineralogical Sequences of Different Rocks at the Muteh Area

Mineral	Metamorphic rocks	Alteration	Veins	Supergene	Hypogene
Quartz	*	*	*	*	*
Muscovite	*	*	*		*
Biotite	*	*			
Albite	*				
K-feldspar	*				
Hornblende	*	*			*
Rutile	*	*			*
Apatite	*				
Sericite	*	*		*	*
Chlorite	*	*		*	*
Calcite		*	*	*	
Pyrite	*	*	*	*	*
Chalcopyrite		*	*	*	*
Iron-oxides	*	*	*	*	*
Clay minerals		*		*	*

co-existing quartz, sulfides, biotite, and K-feldspar mineral phases were the main target for isotopic analyses. Separation of sulfides (pyrite, chalcopyrite), biotite, K-feldspar, and quartz were prepared through crushing, sieving, and hand-picking. Isotope analyses of S, O, and H were carried out in the isotope lab at Queen's University, Canada. Isotopic data are reported in the δ notation relative to standard mean ocean water (SMOW) for O and H, and the Canyon Diablo Troilite (CDT) for S. The standard error is ±0.2‰ for O and S, and ±2‰ for H-isotopic analyses.

Oxygen Isotopes

The $\delta^{18}O$ and δD values of the quartz veins, biotite, feldspar, and chlorite in the Chah-Khatoon and Senjedeh deposits (AB-1 to AB-6) and adjacent areas (AB-7 to AB-10) are shown in Table 2. There are two types of quartz veins identified at the Muteh gold deposit. The first type is barren without ore mineralization. The second type of quartz veins in the Chah-Khatoon and Senjedeh open pits contain pyrites and gold-bearing pyrite. In the adjacent areas, almost all veins are barren or show weak mineralization. The analyses of isotopic compositions were done directly on quartz samples in shear zones with mineralization. The $\delta^{18}O$ values of the quartz samples (AB-1, AB-4, AB-5, and AB-6) vary from 11.6 to 14.3‰ for the samples in the Chah-Khatoon and Senjedeh deposits (see Table 2) relative to SMOW with a mean of 12.4‰. On the basis of the number of fluid-inclusion phases at room temperature and their microthermometric behavior, four fluid-inclusion types were recognized by Yousefinia (2004) and Moritz, Ghazban, and Singer (2006). The total homogenization temperatures obtained by these authors range between 298 and 302°C, respectively. Since the temperature controls stable isotope fractionation between mineral and fluid, using 300°C as the highest temperature of the vein formation, the total range of $\delta^{18}O$ values of hydrothermal fluid can be calculated. This temperature correlates with the fluid inclusion from this study and the study of Moritz, Ghazban, and Singer (2006). Based on Meheut and others (2007), the quartz samples mentioned earlier have a fractionation factor for $\delta^{18}O_{H_2O}$ values ranging from +6 to +8.7‰ with a mean of 6.92‰ ($\delta^{18}O_{H_2O}$ values of the samples being equal to 6, 6.4, 6.6, and 8.7‰, respectively, Table 2). The samples AB-1 and AB-4 are collected from barren veinlets and the samples AB-5 and AB-6 are veinlets from mineralized zones. Microscopic studies show that the last two samples contain pyrite, chlorite, and carbonate veins. The pyrites are secondary to quartz, and the calcite veins are late in paragenesis.

The sample AB-2 is mineralized biotite schist containing pyrite and chalcopyrite minerals from Senjedeh deposit. Biotite, pyrite, and chalcopyrite are the dominant minerals in this rock and coarse quartz veinlets crosscut the subhorizontal foliation of the host rocks. Coarse quartz grains of this rock are barren, and mineralization occurs in biotite schist and not in quartz veinlets. Two types of pyrites can be distinguished here: the first type of pyrite is fine grained to only millimeters in dimensions, and the second type is coarse grained with their dimensions reaching up to a centimeter. The $\delta^{18}O$ value was measured for the coarse quartz grains. Since veinlets are cutting metamorphic host rocks, it can

Table 2. Oxygen and hydrogen isotope data from different rocks of the Muteh area

Sample no.	Field no.	Rock	Mineral	Yield	$\delta^{18}O$ (SMOW)	$\delta^{18}O$ Hydrothermal	δD (SMOW)	δD H_2O	wt% H_2O
AB-1	SE-2	Quartz veinlet	Quartz	16.5	11.6	6.00*	−35	−35	0.06
AB-2	SE-5-1	Biotite-schist	Quartz	15.5	11.4	5.8*	n.d.		n.d.
AB-3	SE-7-1	Meta-volcanic	Quartz	16.1	13.2	7.6*	n.d.		n.d.
AB-4	CHK-15-2	Quartz veinlet	Quartz	16.7	12	6.4*	n.d.		n.d.
AB-5	CHK-13-2	Quartz veinlet	Quartz	17.0	12.2	6.6*	−49.4	−49.4	0.2
AB-6	CHK-15-1	Quartz veinlet	Quartz	15.5	14.3	8.7*	n.d.		n.d.
AB-7	DAg	Granite	K-spar	15.2	10	10	n.d.		n.d.
AB-8	D-A-3-2	Biotite-schist	Biotite	13.1	8	6.87**	−64	−29	3.7
AB-9	5B	Biotite-muscovite schist	Biotite	14.1	6.4	5.27**	−63	−28	5.0
AB-10	5C	Biotite-muscovite schist	Chlorite	13.5	4.1	3.92***	−49	−14	12.2

Fractionation factor used for calculations of the isotopic fluids are taken from * Meheut and others (2007) for quartz samples, ** Zheng (1993) for biotite minerals, *** Cole and Ripley (1998) for chlorites.

be suggested that the mineralization is younger than the regional metamorphism.

AB-3 is a meta-volcanic rock from Senjedeh deposit. Silicification is abundant here and quartz grains occur as open space-filling growth and recrystallized quartz. These quartz grains are barren and are not related to mineralization, but the rock contains pyrite, chalcopyrite, and chalcocite. Here again, the pyrite grain sizes are similar to AB-2. The $\delta^{18}O_{H_2O}$ values of these two samples are equal to 5.8 and 7.6‰, respectively, as shown in Table 2 with a mean of 6.7‰. These values overlap not only with those of magmatic origin or water equilibrated at high temperature with magmatic rocks (+5 to +10‰), but also with those considered to be of metamorphic origin from +5 to +20‰ (Sheppard, 1986). It seems that these two quartz veins and grains formed during metamorphism. AB-7 is an igneous rock of the Darreh-Ashki granite and its $\delta^{18}O$ value is 10‰ measured in K-feldspar. At high temperatures, the equilibrium constant for isotopic exchange tends toward unity, i.e., at $T \rightarrow \infty$, the fractionations factor $\alpha \rightarrow 1$, because small differences in mass are less important when all the molecules have very high kinetic and vibration energies. Therefore, for the igneous rock (AB-7), the $\delta^{18}O$ isotopic data will not change significantly (O'Neil and Taylor, 1967; Zhao and Zheng, 2003). The decreases for these calculations are less than 0.5. Due to the lack of water in K-feldspars, the δD was not measured, and therefore, it could not be plotted within Figure 5.

In addition to the geochemical studies, field observations also show that the gold mineralization at Muteh is not related to the Darreh-Ashki leucogranite–granite intrusions that crop out in the western part of the metamorphic complex. All the boundaries of these intrusions are separated from the host rocks by faults, and aureole haloes are observed only in one small location.

Sample AB-8 is biotite schist, and samples AB-9 and AB-10 are biotite–muscovite schists. Their outcrops are in the northwest and north of the Chah-Khatoon adjacent to Darreh-Ashki granite. Field data and petrographic studies show that these three samples were formed due to metamorphism. Meteoric waters overprinted AB-10. The $\delta^{18}O$ values of AB-8 to AB-10 samples vary from 4.1 to 8‰ (see Table 2) relative to SMOW with a mean of 6.1‰, and their calculated fractionation factor (based on Zheng, 1993; Cole and Ripley, 1998) for $\delta^{18}O_{H_2O}$ values range from +3.92 to +6.87‰ with a mean of 5.35‰. These data are related to mineralization events. Biotite and chlorite are coarse grained in these three rocks.

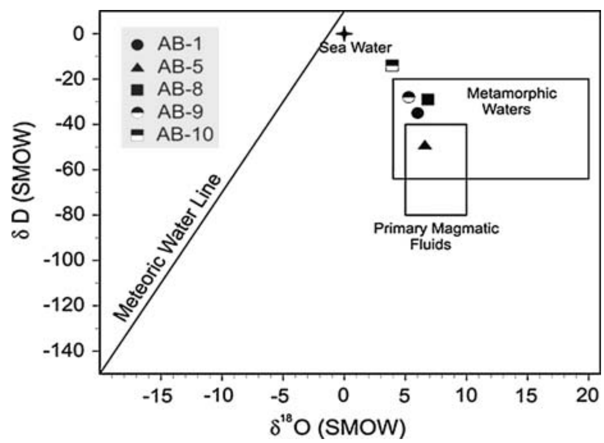

Figure 5. A plot of $\delta^{18}O$ versus δD values of the mineralizing fluids at the Muteh district (Taylor, 1979). The primary magmatic fluids box is as proposed by Sheppard (1986).

Based on the oxygen isotope results, it can be suggested that the hydrothermal fluid as shown in Figure 5 was of metamorphic origin and then partially overprinted by magmatic fluids. It should be mentioned that mineralogical studies have shown that if quartz recrystallized, the $\delta^{18}O_{quartz}$ values could be partially or completely re-equilibrated, depending on the extent and temperature of recrystallization (Voll, 1976; Kerrich, Beckinsale, and Durham, 1977; O'Hara and others, 1997). Since silicification is the most abundant hydrothermal alteration in the study area and occurs as quartz veins, recrystallization of quartz, open-space growth, and overgrowth of quartz grains, the variation in $\delta^{18}O$ of quartz veins may be partially due to these phenomena (see Fig. 4F).

Hydrogen Isotopes

Hydrogen is the most suitable stable isotope system to monitor the origin and the conditions during hydrothermal precipitation (Simon, 2001). It is well established that hydrogen is incorporated into quartz predominantly as (a) H_2O in fluid inclusions, and (b) molecular H_2O or OH bonded to quartz surfaces (Simon, 2001). In this study, δD values have measured biotite, chlorite, and fluid inclusions of quartz veinlets. There are some problems with fluid-inclusion compositions in quartz veins, for example, several generations of fluid inclusions are caused by poly-metamorphism and almost all the fluid inclusions are not liquid-rich two phases. Due to the paragenesis of the gold, and because the fluid inclusions in many cases are the only host rock of the gold, the δD was measured in the two quartz samples, AB-1 and AB-5. These two-phase fluid inclusions in the quartz-mineralized and weakly mineralized veinlets show Th: 100–300°C and Salinity between 10 and 30% (eq. NaCl). These ranges of temperature and salinity are similar to the Moritz and Ghazban (1995) studies. Due to the lack of water in most quartz samples, it was not possible to measure the δD values in the other quartz samples. The δD value of fluid inclusions of AB-5 quartz sample is $-49.4‰$ relative to SMOW (see Table 2). Since this quartz sample is homogeneous and formed during hydrothermal processes, the hydrothermal fluids trapped in samples can act as a closed system and their δD values directly are to be used. According to Taylor (1997), two basic methods are utilized in determining $^{18}O/^{16}O$ and D/H ratios of natural hydrothermal fluids:

(1) Direct measurement of the fluids discharging in a geothermal area or of primary fluids trapped as inclusions in the minerals of an ore deposit
(2) Isotopic analysis of mineral. The δD value of fluid inclusions of AB-1 quartz sample is $-35‰$ relative to SMOW as shown in Table 2 and the plots in the metamorphic waters box.

The δD values were also measured in biotite and chlorite grains of the three schist samples AB-8, AB-9, and AB-10. The δD values in these three samples were -64, -63, and $-49‰$, respectively. As mentioned above, these rocks are biotite schist and biotite–muscovite schists. Since at low temperatures (below 400°C) the hydrogen fractionation curves are not well establish (Ulrich, Gunther, and Heinrich, 2001) except for kaolinite (e.g., Sheppard and Gilg, 1996), the fractionation factors $(1000 \ln \acute{\alpha}_{\text{mineral-water}})$ at a low temperature for biotite and chlorite were extrapolated from equilibrium hydrogen isotope fractionation curves for various mineral–H_2O as proposed by Taylor (1997, p. 234). The fractionation factors for biotite and chlorite are $-35‰$ for both biotite and chlorite—samples AB-8 and AB-9 plot in the metamorphic waters box and sample AB-10 plots in the meteoric waters box (Fig. 5). This may be the result of mixing deep-crustal meteoric water and metamorphic waters that have generated the mineralizing fluids (e.g., Sheppard and Gilg, 1996).

Sulfur Isotopes

Variation of $\delta^{34}S$ values of sulfide minerals and fluids may be caused by variations in temperature, redox state, pH, and the isotope value of the sources of the sulfur (Ohmoto, 1972). Pyrite is the dominant opaque mineral at the Muteh gold district and is the major phase associated with gold. Chalcopyrite, marcasite galenobismutite, bismuth, galena, sphalerite, and pyrrhotite are subsidiary to rare phases (Moritz, Ghazban, and Singer, 2006). The sulfur isotope data at the Muteh was measured on pyrite within quartz veinlets, biotite schist, and metavolcanic rocks (see Table 3). The pyrrhotite deposited early with pyrite, and the remaining opaque minerals, together with gold occurred mostly along fractures, and post-date pyrite deposition. The chalcopyrite deposited during both the stages (Paidar-Sarvi, 1989; Moritz, Ghazban, and Singer, 2006).

Petrographical studies by optical microscope, content of sulfur, and SEM analysis show three different generations of pyrite within the quartz veinlets and host rocks. The first generation is Anhedral pyrite disseminated in the host rocks that may be pre-metamorphism ores. The second generation is fine grained with no Au-bearing pyrite disseminated along the foliation of the host rocks. The third generation is coarse grained, euhedral to subhedral

Table 3. Sulfur Isotope Data From the Gold-Bearing Pyrites of the Muteh Area

Sample no.	Field no.	Rock	Mineral	Approx %S	$\delta^{34}S$ (CDT)	$\delta^{34}S$* Hydrothermal
AB-11	5-1	Biotite-schist	Pyrite	22.7	16.9	15.68
AB-12	SE-5-2	Biotite-schist	Pyrite	57.0	2.2	0.98
AB-13	SE-7-2	Meta-Volcanic	Pyrite	65.8	9.1	7.88
AB-14	CHK-13-1	Quartz veinlet	Pyrite	58.2	13.9	12.68
AB-15	CHK-15-1-1	Quartz veinlet	Pyrite	59.8	6.6	5.38

* $\delta^{34}S$ fluid is calculated by using Ohmoto and Rye (1979) equation.

pyrite in veins or in the host rocks, crosscutting the foliation of the host rocks. Generation 2 can be counted as syn-metamorphism, and generation 3 might be post-metamorphism. Sulfur isotope compositions of sulfides from the gold mineralization pyrite at Chah-Khatoon and Senjedeh gold deposits show a very broad range from 2.2 to 16.9‰, and their calculated values for 300°C using the Ohmoto and Rye (1979) formula range from 0.98 to 15.68‰.

AB-11 and AB-12 are biotite schists from Chah-Khatoon and Senjedeh deposits, respectively. Both samples were collected from mineralized zones. Mineralization in AB-11 is parallel to foliation without any deformation. Quartz veinlets and quartz grains are abundant and are also parallel with foliation. Chlorite is also abundant and probably forms after biotite by hydrothermal alteration. The δ^{34}S hydrothermal value of this rock is 15.65‰. The opaque minerals of AB-12 are pyrite. The δ^{34}S hydrothermal value from the pyrite of this rock is 0.98‰. AB-13 is a meta-volcanic rock from Senjedeh deposit and was collected nearby AB-12 in the sulfide zone. This rock contains pyrite, chalcopyrite, and chalcocite as opaque mineral. The measured δ^{34}S hydrothermal value from pyrite of this rock is 7.88‰. AB-14 and AB-15 are pyrite within quartz veinlets of the sulfide zone of the Chah-Khatoon open pit. Pyrite and chalcopyrite grains are abundant in AB-14, and its δ^{34}S hydrothermal value from pyrites of this rock is 12.68‰. AB-15 is a sample of mineralized quartz veinlet with coarse-grained pyrite (6.6‰). Its oxygen and hydrogen isotope compositions were also measured and mentioned above as AB-6.

Source of Ore-Forming Fluids and Materials

As discussed above, the ore-forming fluids at the Muteh gold deposits are gold bearing similar to orogenic gold deposits in greenschist–amphibolite facies. Although metamorphic components have predominantly been proposed for the fluid source of these types of deposits (Goldfarb and others, 1988), meteoric waters have also been proposed for the greenschist or sub-greenschist facies deposits (Goldfarb and others, 1988). In the case of the Muteh deposit, regional metamorphic fluids are a viable source for most ore-forming fluids, but magmatic-related fluid is also important in the Muteh gold district. The main mineralization occurs in metamorphic rocks of pre-Permian age. The close temporal and spatial association between mineralized zones and the shear zones suggests that deep-crustal meteoric water also could have generated the mineralizing fluids and mixing phenomena. The calculated values of O and H-isotope composition of the fluids are shown in Table 2.

Kerrich (1987) points out that the distinct uniformity of δ^{18}O values of quartz in Au-Ag vein deposits implies a corresponding isotopic homogeneity of the hydrothermal fluids, and similar ambient temperatures of mineralization. The values for oxygen and hydrogen isotopes were measured in quartz, biotite, and chlorite and show a relatively narrow range of the δ^{18}O values. These findings suggest that the isotopic character of the ore-forming fluids did not significantly change temporally and spatially for most of the quartz veinlets and other minerals during the formation. The δ^{18}O values of quartz correspond to the range of data (11.4–14.3‰) typical for vein quartz from hydrothermal gold deposits of all ages (Kerrich, 1987). The range of δ^{18}O and δD values for AB-1, AB-4, and AB-6 quartz samples are consistent with a dominantly metamorphic source for the quartz vein-forming fluids. The isotope values of schists AB-2, AB-3, AB-8, and AB-9 show the same conditions. The δ^{18}O and δD values for AB-5 and AB-7 indicate that the isotopic source of the K-feldspar and quartz in these rocks tends to be of magmatic water. Analysis of the δ^{18}O and δD data suggests that the mineralized quartz veinlets fall within the metamorphic waters box, which indicates that the ore-forming fluids isotopically possessed dominantly metamorphic characteristics during the formation of the quartz veinlets (see Fig. 5).

The S-bearing minerals at Muteh are mainly sulfides. The available data are highly variable from the same types of hosted rocks. It is accepted that, only the range of δ^{34}S values cannot infer the source of sulfur. Simply assuming that the sulfur came from the metamorphic fluid or pre-existing sulfur-bearing minerals is not appropriate. Therefore, the petrographic study and consideration of equilibrium temperature or co-existing sulfur-bearing minerals may be helpful.

At Muteh area, it seems that the source of the sulfur is not isotopically uniform and the formation of pyrite is not related to one event. It is empirically evident that hypogene sulfides occurring in a magmatic hydrothermal deposit, and even throughout a mining district, rarely vary in composition by more than about ±5‰, and generally vary by even less (Barnes, 1979). The fractionation factors calculated for $\delta^{34}S_{hydrothermal}$ values of pyrite from Chah-Khatoon and Senjedeh open pit range from +0.98 to +15.68‰. Since the $\delta^{34}S_{H_2O}$ variations of pyrite are more than ±5‰, it is not possible to relate all of them as magmatic–hydrothermal in origin. As mentioned earlier, there are three generations of the pyrite in the Muteh gold district. The sulfur might have been derived either directly from regional metamorphism that produced the metamorphic fluid or through dissolution and leaching of pre-existing sulfide-bearing minerals (Ohmoto and Rye, 1979). This feature may reflect that metamorphic rocks (e.g., meta-volcanics and greenschists in the Muteh area) could have provided sulfur to the fluid system.

The bulk of the $\delta^{34}S$ values at Muteh during the main mineralizing stage are restricted to an average of 12.08‰ for the three samples AB-11, AB-13, and AB-14 (see Table 3). This average can be interpreted to indicate that the fluid redox state was below the SO_2/H_2S boundary, and H_2S was the dominant reduced sulfur species in the fluids (Ohmoto and Rye, 1979). The $\delta^{34}S$ values of pyrite separated from ores are similar to those of both pyrites from metamorphic country rocks and whole rock sulfur of metamorphic country rocks. This feature may reflect that pre-Permian metamorphic rocks could have provided sulfur to the fluid system. The $\delta^{34}S$ values of AB-12 and AB-15 are not close to the mean values of the other samples and may indicate different generations. The $\delta^{34}S_{H_2O}$ have values 0.98 and 5.38 which are different from those already described and may show two different generations of pyrite, shown in Table 3. Sulfur isotope composition of AB-12 falls in the ‘‘mantle/magmatic’’ range from −4 to +4‰ CDT. This implies a general paucity of oxidized sulfur relative to reduced sulfur species in the hydrothermal fluid during formation of this type of pyrite.

Based on sulfur isotope compositions the source of the mineralizing fluid of the Muteh area cannot be uniform. These $\delta^{34}S$ values in sulfides at Muteh suggest that the sulfides were formed by fluids whose sulfur was derived from metamorphic host rocks sources (Ohmoto and Rye, 1979) and then overprinted partially by hydrothermal fluid of magmatic origin.

DISCUSSION

The Muteh gold district and its two currently mined deposits (Chah-Khatoon and Senjedeh open pits) and seven smaller occurrences are mainly hosted in metamorphic rocks of the SSZ and are structurally controlled by sets of ductile shear zones. Gold mineralization is closely associated with intense hydrothermal alteration along the ductile shear zones. The tectonic setting, alteration type (e.g., silicification and carbonatization) and deformation of the metamorphic rocks are typical of orogenic gold deposits described by Groves and others (1998). The $\delta^{34}S$ values of different forms of pyrite range from 2.2 to 16.9‰ (mean of 12.08‰ for the three samples). The ranges correlate well with those of Ashanti and Mother lode in India and USA (Groves and others, 1998).

The average $\delta^{34}S$ values of pyrites in most samples indicate that the sulfur source was probably metamorphic at Muteh. Some samples tend to show a magmatic source which is the result of igneous rocks in the study area. Hydrogen and oxygen stable isotope analyses, along with petrographic evidence, showed that the ore-bearing fluids during the development of the quartz and pyrites veinlets which are thought to be contemporaneous with hydrothermal alteration processes had predominantly metamorphic isotopic signatures.

The close temporal and spatial association between mineralization and the shear-brecciaed zones suggests that faulting during the uplifting in the SSZ would have generated the crustal thickening, leaching, and concentration of mineralizing fluids (Mohajjel and Fergusson, 2000). Circulation of these fluids within the greenschists and meta-volcanics provided veinlet-style gold-bearing pyrites. Close relation between gold deposits and shear zones at Muteh gold district indicate that these features are the most important ones in the development of mineralization and alteration.

In the case of the Muteh Au deposit, hydrothermal alteration starts with silicification and carbonatization of the host rocks in the core of the metamorphic complex (Moritz and Ghazban, 1995). Uplift and development of normal faults during a change in the tectonic regime from compressional to extensional (Zhang and others, 2005) formed retrograde metamorphic rocks and quartz, pyrite gold-bearing veinlets with biotite, chlorite, sericite, and chalcopyrite metamorphic assemblages (Gebre-Mariam, Hagemann, and Groves, 1995).

The Muteh Au deposit shares many characteristics in common with gold deposits in metamorphic belts especially with greenschist facies environments. These deposit types were mostly formed during compressional to transpressional deformation processes at convergent plate margins in accretion and collision orogen, and thus should be genetically classified as orogenic gold deposit (Groves and others, 1998).

CONCLUSIONS

The research around these formations has allowed the authors to draw the following six conclusions:

(1) The Muteh gold district is primarily hosted by pre-Permian (?) gneisses, amphibolites, meta-volcanics, and greenschists of the SSZ. All host rocks have been strongly fractured and sheared, varying from incipient mylonite and mylonite to ultra-mylonite.

(2) The distribution and mineralization of the Muteh gold deposits are structurally controlled by ductile shear zones.

(3) Gold mineralization is closely associated with intense hydrothermal alterations controlled mainly by shear zones, with typical greenschist facies alteration assemblages of chlorite + calcite + biotite + quartz, and gold-bearing quartz–pyrite veinlets.

(4) Moritz, Ghazban, and Singer (2006) stated that the dehydration of under-thrusted rocks might have been a source of ore-forming fluids. This may be supported by the knowledge that ore fluids escaped along the extensional structures hosting the ore bodies at Muteh. However, the hydrogen, oxygen, and sulfur isotopes of the host rocks indicate that the Muteh gold district formed from metamorphic fluids in a regional metamorphism system and an intrusion-related model might link with remobilization of the ore formed from metamorphic fluids.

(5) Whereas ore bodies are typically hosted by reverse component shear zones, which were formed during the main phase of crustal shortening in compressional or transpressional regimes (Groves and others, 2003; Goldfarb and others, 2005) and the tectonic setting, alteration type, and deformation of the metamorphic rocks are also typical of orogenic gold deposits, and it is plausible to relate Muteh ore formation to regional metamorphism. This study also indicates that intrusion related ore forming cannot be ruled out, and it is a distinct feature in some samples.

(6) Identification of geological, geochemical, and tectonic settings, combined with physicochemical characteristics of mineralized fluids can be helpful for the determination of genesis and style of gold mineralization in this region.

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