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RESEARCH PAPER

Metamorphic rock-hosted orogenic gold deposit style at Lakhshak deposit: Their key features and significances for gold exploration in Sistan suture zone

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Abstract
This paper focuses on metamorphic rock-hosted gold mineralization in Lakhshak gold-antimony deposit, lies along the southwestern margin of the Sistan suture zone. The area is occupied by metamorphosed Eocene volcano-sedimentary rocks, Oligocene granitoid intrusion, dikes, and quartz veins/veinlets. At Lakhshak, gold-bearing quartz-veins are hosted by the Eocene metamorphic complex. At least two generations of quartz veins are identified in Lakhshak deposit. The first is parallel to the foliation of the host rock, the second crosscuts the first generation of veins as well as the foliation. Gold grades in the first-stage veins are on average higher than that in the second veins. Ore mineral comprises pyrite, stibnite, arsenopyrite, chalcopyrite, pyrrhotite, sphalerite, native gold, and electrum. The mineralized- alteration zone controlled by NE-SW-trending ductile-brittle shear zone. Fluid inclusions in parallel quartz vein types consist of 4 phases including V-rich, L-rich, L-V-rich and L_1-L_2-V (CO_2)-rich phases. Homogenization temperatures and salinities vary from 200 to 330 ºC and 8 to 13 wt. % NaCl eq., respectively. Microthermometric and Laser Raman Spectroscopy studies of fluid inclusions indicate abundant N_2, $CH_4 \pm CO_2$ fluids. Crush-leach analysis of fluid inclusions suggests that the halogen fluid chemistry is not identical to sea water, magmatic or epithermal related fluids, but tends to be similar to fluids in orogenic-type gold deposits. Based on those key features, gold mineralization in Lakhshak deposit tends to meet the characteristics of orogenic, mesothermal types of gold deposit. Metamorphic rock-hosted gold deposits could represent the new targets for gold exploration particularly in Sistan suture zone.

Keywords: Characteristics, Orogenic Gold, Lakhshak Deposit, Sistan Suture Zone.

Introduction

Iran comprises eight major tectonic zones, including Alborz, Kopeh-Dogh, Urumieh-Dokhtar magmatic belt, Central Iran block, Zagros fold-thrust belt, Sanandaj-Sirjan, Sistan suture zone, and Makran (Berberian, 2014; Shafaii Moghadam & Stern, 2015; Stern et al., 2021) (Fig. 1). The Sistan suture zone and ophiolites represent an important and largely N–S trending segment of the Neo-Tethyan ocean (e.g., the Sistan Ocean) (Zarrinkoub et al., 2012). The Sistan suture zone has a length of 700–km and a width of 200 km in the southeast of Iran, predominantly composed of rocks extending between the Gondwana-derived blocks of Lut in the west and the Afghan block in the east (Camp & Griffis, 1982; Tirrul et al., 1983; Agard et al., 2011).

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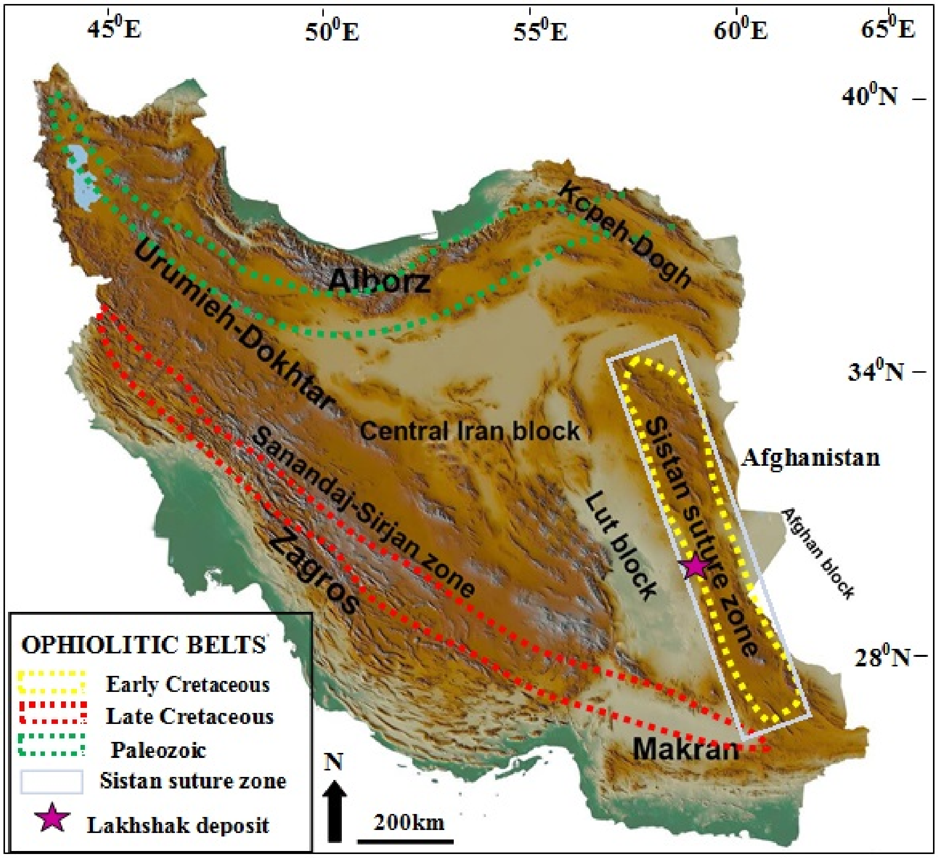

Figure 1. Distribution of tectonic zones and ophiolitic belts of Iran. The location of the Lakhshak Au–Sb deposit is marked by a star (modified after Stampfli et al., 2002; Agard et al., 2011)

This zone is a highly endowed metallogenic province, hosting numerous antimony and gold-antimony deposits.

During last few decades, in Sistan suture zone antimony and gold-antimony has mostly been extracted from volcanic-hosted hydrothermal deposits, including epithermal type e.g. Baout (Mojadadi Moghadam & Boomeri, 2021), Sefidabeh (Eliaspour et al., 2010), Sefidsang and Dargiaban (Boomeri, 2014), and Tuzgi and Shurchah (Moradi et al., 2012). However, currently gold is not only found in volcanic terrain, but also many discoveries of primary gold mineralization are genetically occurred in association with metamorphic rocks, for instance, Lakhshak deposit (Iran Minerals Production and Supply Company (IMPASCO), 2016; Niroomand, 2018). In Lakhshak (SW Sistan suture zone) (Fig.1), gold deposit is hosted by metamorphic rocks type e.g. calc-schist. The genetic type of the Lakhshak gold mineralization is still debatable. This paper is aimed to discuss some key characteristics of the primary deposit including host rock petrology, quartz vein texture and structure, hydrothermal alteration, ore mineral and chemistry and mineralizing hydrothermal fluid properties. It is expected that the result would be important for a better understanding of the genesis of the gold mineralization, and would be useful in designing future exploration strategy for gold deposits in Sistan suture zone.

Research Methods

This study has been carried out through several approaches including desk study, fieldwork and sampling for laboratory analyses. There is no previous detailed study and publication that was focused specifically on the primary gold mineralization in Lakhshak deposit. Quartz vein samples were taken, and geochemically analyzed by Fire Assay and an inductively coupled plasma-mass spectrometer (ICP-MS) at the Zarazma Mineral Studies Company in Iran. Mineral chemistry of stibnite as a diagnostic ore mineral was also analyzed using EPMA (Electron Probe Micro Analyzer) at Iran Mineral Processing Research Center. Fluid inclusion in various generations of quartz veins was micro thermometrically analyzed by Linkam THMS600 freezing and heating stage at Microthermometric Laboratory, University of Tehran. Laser Raman Spectroscopy and crush-leach analysis of fluid inclusion was done at the Leoben University.

Deposit Geology

The Lakhshak area is known for its gold–antimony resources and is located in the southwestern margin of the Sistan suture zone in the Sistan and Baluchistan province, about 28 km northwest of Zahedan (Fig. 1). The area is occupied by metamorphosed Eocene volcano-sedimentary rocks, Oligocene granitoid intrusion, rhyolitic/dacitic dikes, and quartz veins/veinlets (Fig. 2). The metamorphic rocks consist of calc-schist and quartz schist. Gold mineralization in Lakhshak is hosted by Eocene calc-schist and occurred in form of quartz veins/veinlets (Heydarian Dehkordi et al., 2021). Iran Minerals Production and Supply Company (IMPASCO) (2016) reported that the average Au grade in the Lakhshak deposit had been estimated at approximately 3.25 g/t with 5833 tonnes of ore reserve, and the ore reserve of Sb with an average grade of 1.35% has been estimated about 8017 tonnes.

The geological map of Lakhshak deposit is shown in Fig. 2. Calc-schists are commonly characterized by the presence of quartz veins/veinlets with various widths up to 2 meters, containing gold in some places. The formed first generation of quartz veins and mineralization are structurally controlled by a NE–SW-trending ductile-brittle shear zone in the granitoid intrusion and calc-schist contacts (Fig. 3).

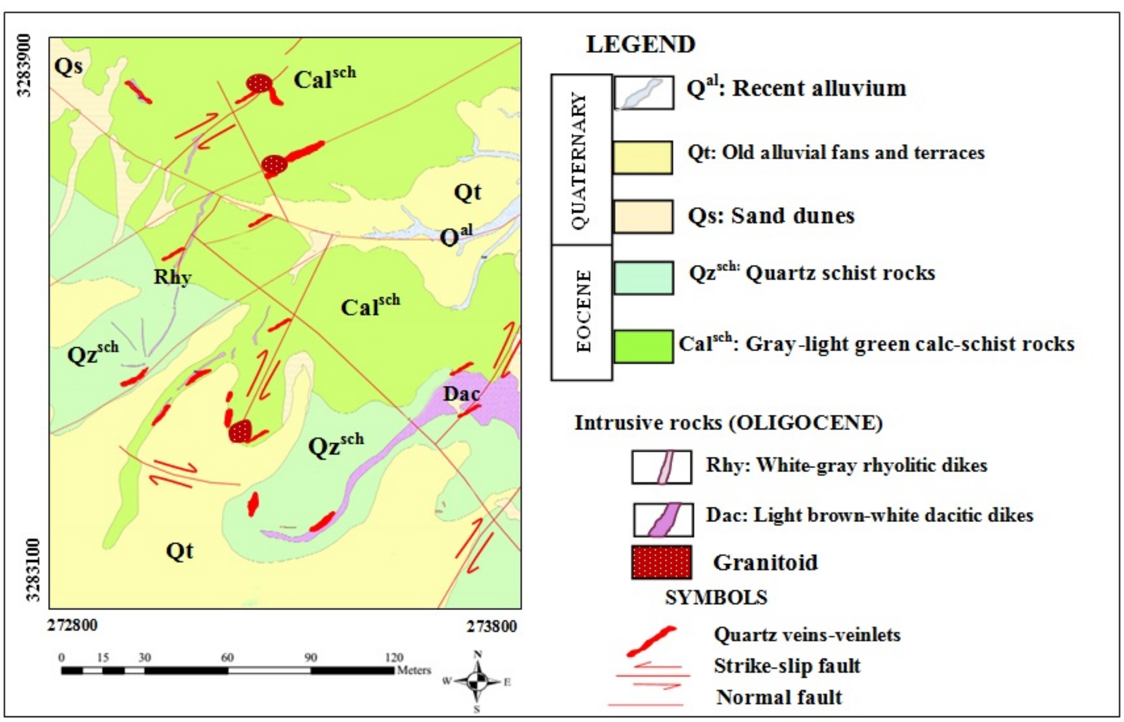

Figure 2. Geological map of Lakhshak gold-antimony deposit (modified after Kavoshgaran Consultant Engineers, 2016)

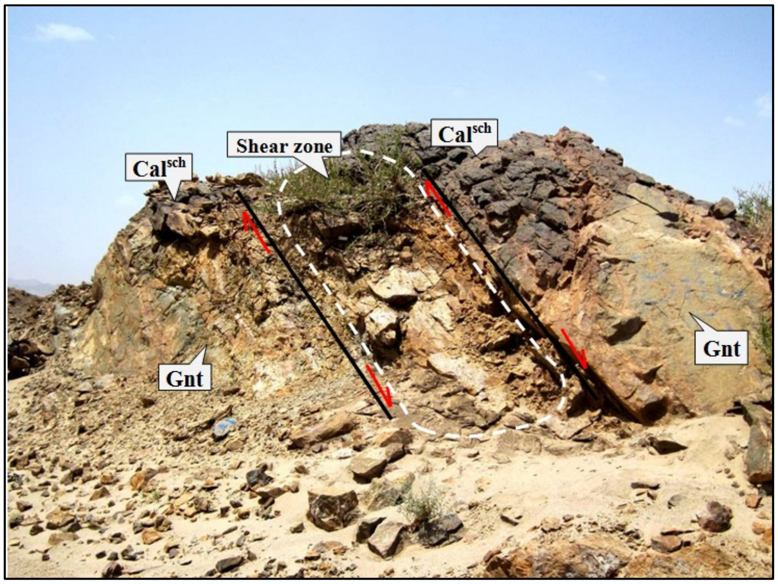

Figure 3. Photographs of the NE–SW-trending ductile-brittle shear zone located in the contact zone of calc-schist and granitoid units. Gold-bearing ores are mostly found as sulfide-bearing quartz veins and veinlets. (Cal^{sch}: calc-schist; Gnt: granitoid) (Abbreviations are given from the Whitney and Evans, 2010)

As explained previously, the quartz veins are predominantly hosted by metamorphic rocks particularly calc-schist. Calc-schist is the predominant rock type in the area. Petrographic study of the calc-schist indicates that the rock is abundantly composed of chlorite, muscovite and quartz with a small amount of sericite, albite actinolite, epidote, and opaque minerals (Heydarian Dehkordi et al., 2022). Based on those mineral assemblages, it is considered that the metamorphic rock is categorized into green schist facies. It is also important to note that the majority of the metamorphogenic-related gold deposits worldwide are hosted by greenschist facies (Goldfarb et al., 2014).

Discussion

Gold-bearing quartz veins/veinlets

At least there are two generations of the quartz veins/veinlets identified. The first generation of quartz vein/veinlet is parallel to the foliation of calc-schist and granitoid intrusion (Fig. 4a, b). It was occasionally observed that this first generation of quartz vein is crosscut by quartz veinlets/stockwork/stringers. The second quartz vein generation crosscut the first-generation quartz veins and as well as the foliation of host-rocks (Fig. 4c, d). The first generation of quartz veins (that are parallel to foliation) are commonly 2 cm to 2 m in width, whereas the second phase quartz veins have commonly less than 10 cm in width. The first generations of quartz veins are mostly massive to crystalline, occasionally brecciated and sigmoidal, whereas the second quartz veins are narrower than the first and relatively brecciated. Field and hand specimen observation indicates that gold-bearing quartz veins/veinlets are characterized by banded texture following host rock foliation and sulfide banding (Fig. 5a) and brecciated texture. The Fig. 6 a, b shows hand specimen of first quartz veins/veinlets parallel to the calc-schist foliation and the Fig. 6 c, d hand specimen of second quartz vein type crosscuts the first generation of veins as well as the foliation. Ore chemistry indicates that 16 out of 20 samples yielded more than 1 g/t Au, in which 7 of them graded in excess of 3.5 g/t Au. Interestingly, most of the high-grade samples contain also high concentrations of Sb (up to 3276 ppm), As (up to 864 ppm), and Hg (up to 65 ppm).

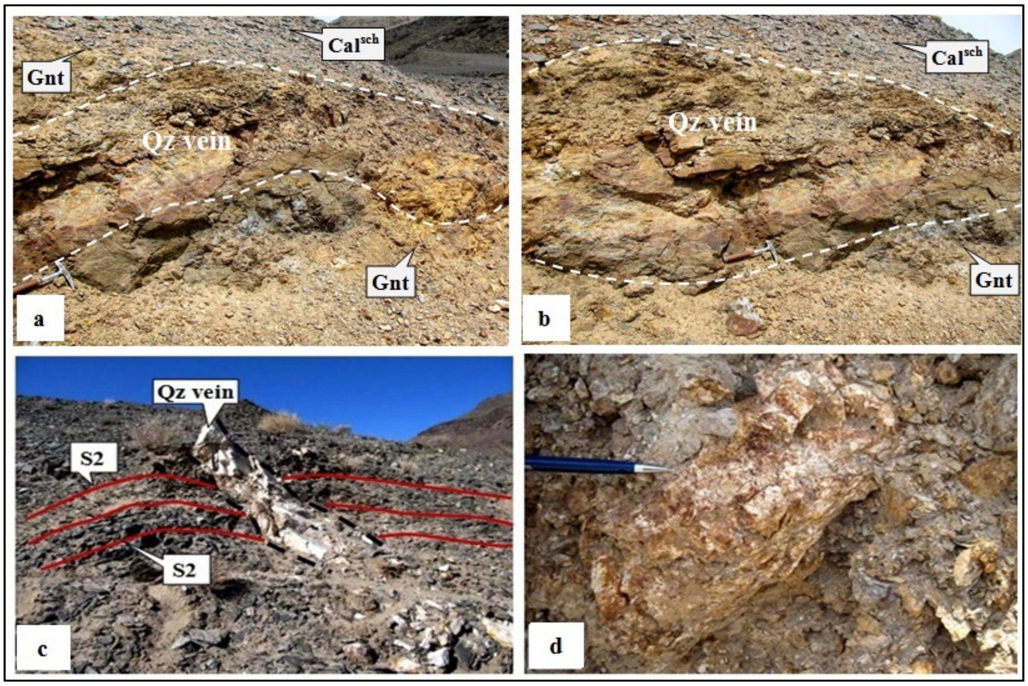

Figure 4. (a, b) Photographs of the first generation of quartz vein/veinlet are parallel to the foliation of calc-schist and granitoid intrusion. (c, d). Photographs of the second quartz vein generation crosscut the first-generation quartz veins and as well as the foliation of host-rocks

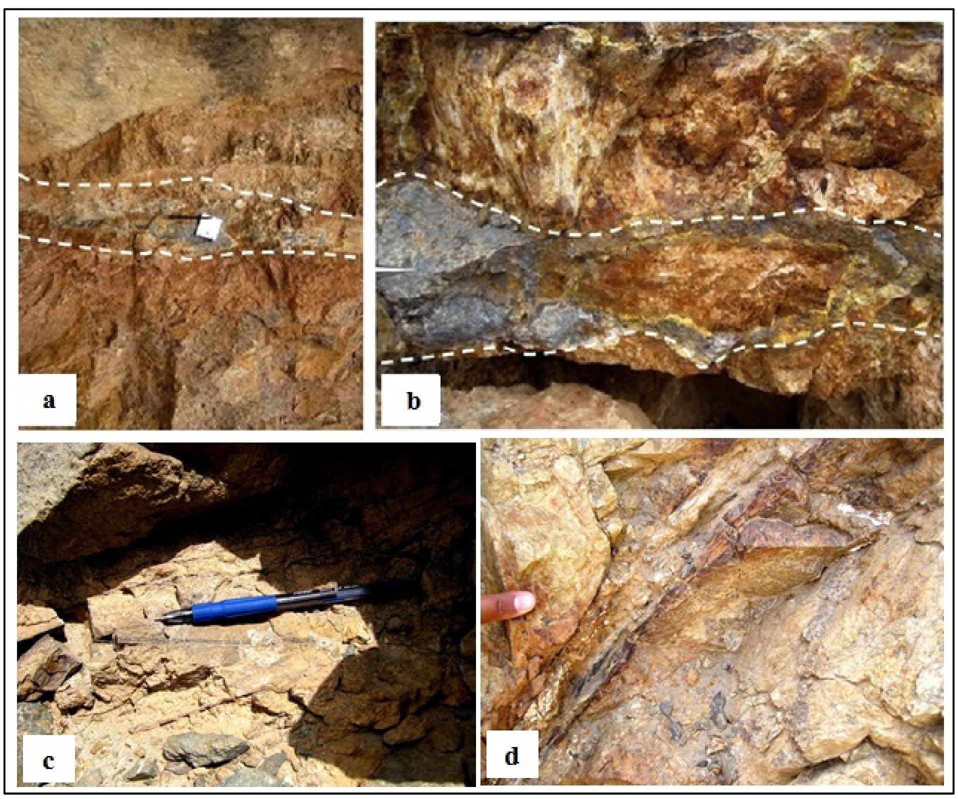

Figure 5. Gold-bearing orogenic quartz vein characteristics: (a, b) highly sulfidized/oxidized /mineralized deformed first quartz vein parallel to the foliation. Brecciated/deformed quartz vein (first generation) which is parallel to the foliation of the calc-schist. (c, d) Lowly sulfidized/oxidized/mineralized deformed second quartz vein cross cutting foliation

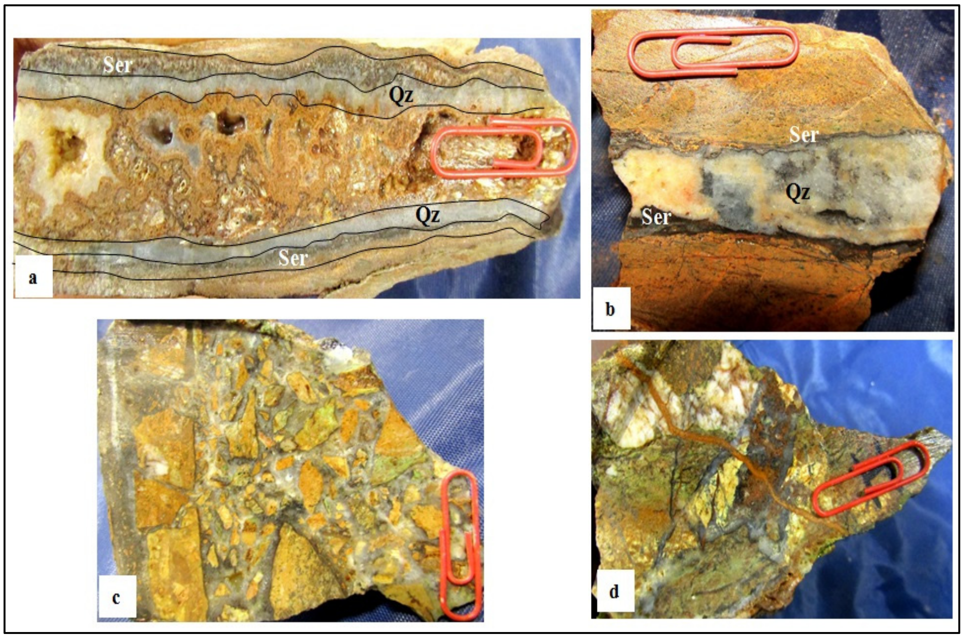

Figure 6. (a) Hand specimen of first quartz veins/veinlets parallel to the calc-schist foliation, (b) hand specimen of second quartz vein type crosscuts the first generation of veins as well as the foliation

Alteration and Ore Mineralogy

The wall rocks (metamorphic rocks) are strongly weathered, so it is very rare to observe good outcrops in the area. The hydrothermal alteration types recognized in the field includes silicification, sulfidation, carbonate alteration and carbonization, and sericitization. Silicification and sulfidation are represented by silicified and sulfide calc-schist and granitoid, respectively, whereas sericite and carbonate alteration are typified by the presence of sericite and calcite veinlets, respectively. The carbonization is considered to be one of the alteration type characteristics, associated with orogenic/metamorphic-hosted gold deposit. The alteration zones involving the mineralization comprise quartz±carbonate–feldspar–chlorite-sericite–sulfide minerals. Quartz veins/veinlets contain very small amount of sulfide minerals (up to 5 %). Pyrite, stibnite, arsenopyrite, pyrrhotite, chalcopyrite, and sphalerite are present in the quartz veins and sulfide/silicified metamorphic wall rocks. Pyrite and stibnite seem to be filling fractures parallel to foliations (Fig. 7) and disseminated within the silicified wall rocks. In general, gold is very fine-grain, but occasionally native gold is visible in quartz veins. Gold is mainly present in the form of inclusion and vein/veinlets in pyrite and free gold among quartz (Fig. 8). Electrum such as gold is mainly present free among quartz, inclusion, and vein/veinlets in pyrit (Fig. 8).

Pyrite and stibnite are genetically closely related to gold mineralization. Those sulfides could be pathfinder minerals for the exploration of the metamorphic-hosted gold deposit (Groves & Goldfarb, 2003; Pitcairn et al., 2021). Few of the typical pathfinder minerals associated with metamorphic-hosted/orogenic gold deposit are stibnite and stibiconite. The chemical composition of the minerals analyzed using EPMA indicates that both antimony-bearing minerals (stibnite and stibiconite) contain a significant amount of As of up to 1 wt. % (Heydarian Dehkordi et al., 2022).

As outlined above, gold mineralization zone is intimately associated with sulfidic/silisic-altered calc-schist. Ore mineralization is characterized by pyrite, stibnite, arsenopyrite, chalcopyrite, pyrrhotite, electrum, and native gold. This is consistent with mineralogical features of other metamorphic rock-hosted gold mineralizations worldwide.

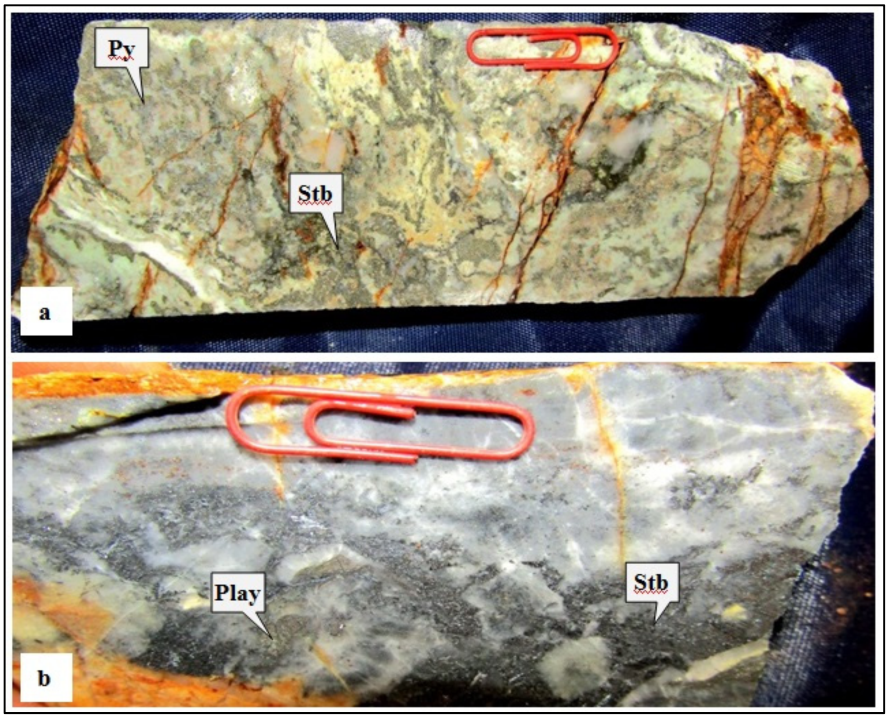

Figure 7. (a, b) Diagnostic sulfides (stibnite and pyrite) associated with Lakhshak orogenic gold mineralization. (Stb: stibnite; Py: pyrite) (Abbreviations are given from the Whitney and Evans, 2010)

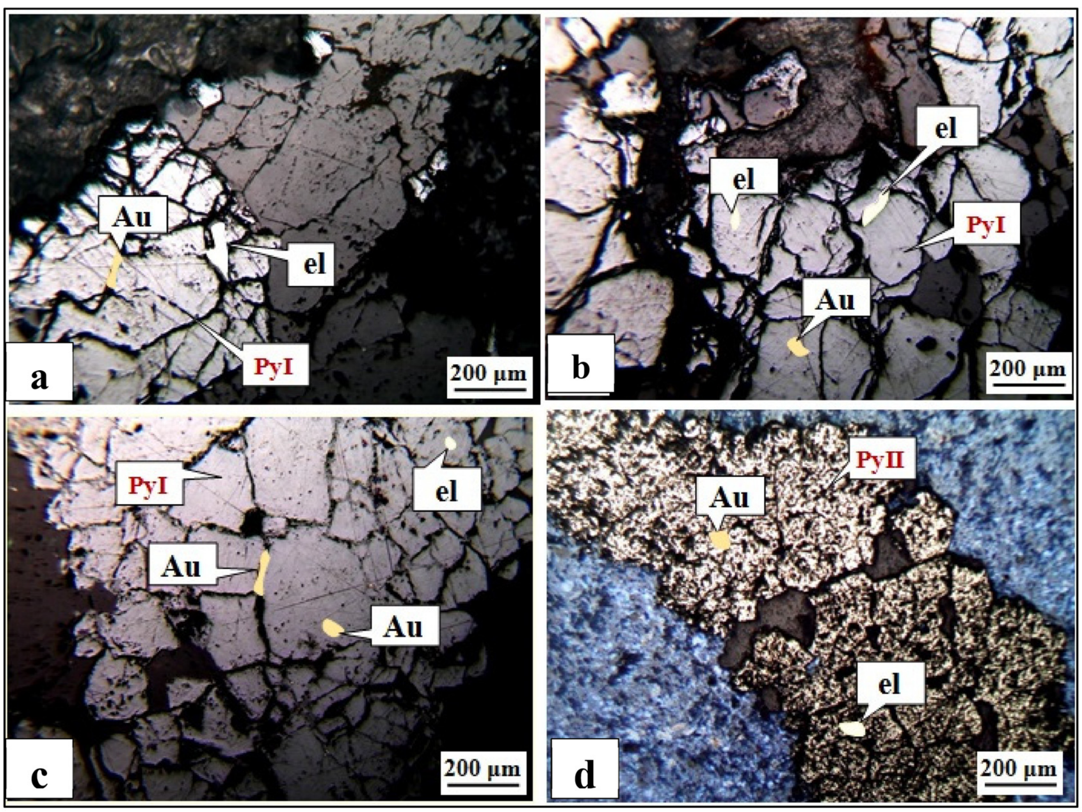

Figure 8. Fotomicrograph of free gold (Au) and (el) electrum in quartz vein, inclusion, and vein/veinlets in pyrite

Ore Mineralizing Fluids

A total of 9 quartz veins/veinlets from one generation (parallel quartz veins/veinlets) were prepared for fluid inclusion analysis. This study has enabled to understand the characteristics including temperature, salinity and composition of mineralizing hydrothermal fluids that formed the first generations of quartz veins/veinlets. Petrographic study indicates that fluid inclusions in parallel quartz veins/veinlets consist of 4 phases including V-rich, L-rich, L-V-rich and L_1-L_2-V (CO_2)-rich phases. Type I and II are rare, and no data were collected due to their smaller size for microthermometry experiments and in this study; therefore, type III (L-V) and IV (L_1-L_2-$V_{(CO2)}$) were only studied due to the primary size (Table 1 and Fig. 9). Type III involves negative crystals with spherical, elongated, or irregular shapes and the size ranging from 5 to 17 µm, predominantly consisting of two phases (liquid-vapor) at room temperature (Fig. 9a–c). Type IV involves irregular, triangular, and ellipsoidal crystals with the size ranging from 4 to 19 µm and predominantly consists of three phases ($liquid_{CO2}$-$liquid_{H2O}$-$vapor_{CO2}$) at room temperature (Fig. 9d–f). The microthermometric measurements in Table 1 were obtained using type III and IV primary fluid inclusions.

Based on the microthermometric measurements, the homogenization temperature, T_{mice}, and salinity for type III (L-V) are between 200 and 280°C, -4.0 to -7.0°, and between 9 to 11 wt. % NaCl eq., respectively.

Table 1. Microtermometric data of fluid inclusions within quartz veins/veinlets associated with gold mineralization in Lakhshak deposit

Incl.type	Size (µm)	Salinity (%NaCl)	T_h (°C)	T_{mCO2} (°C)	T_{hCO2} (°C)	T_{mclath} (°C)	T_{mice} (°C)
Type III (L-V)	5-17	9-11	200-280	-	-	-	-7 to -4
Type IV (L_{CO2}-L_{H2O}-V_{CO2})	4-19	8-13	300-330	-58.8 to -56.8	6.1 to 16.2	1.3 to 4.6	-

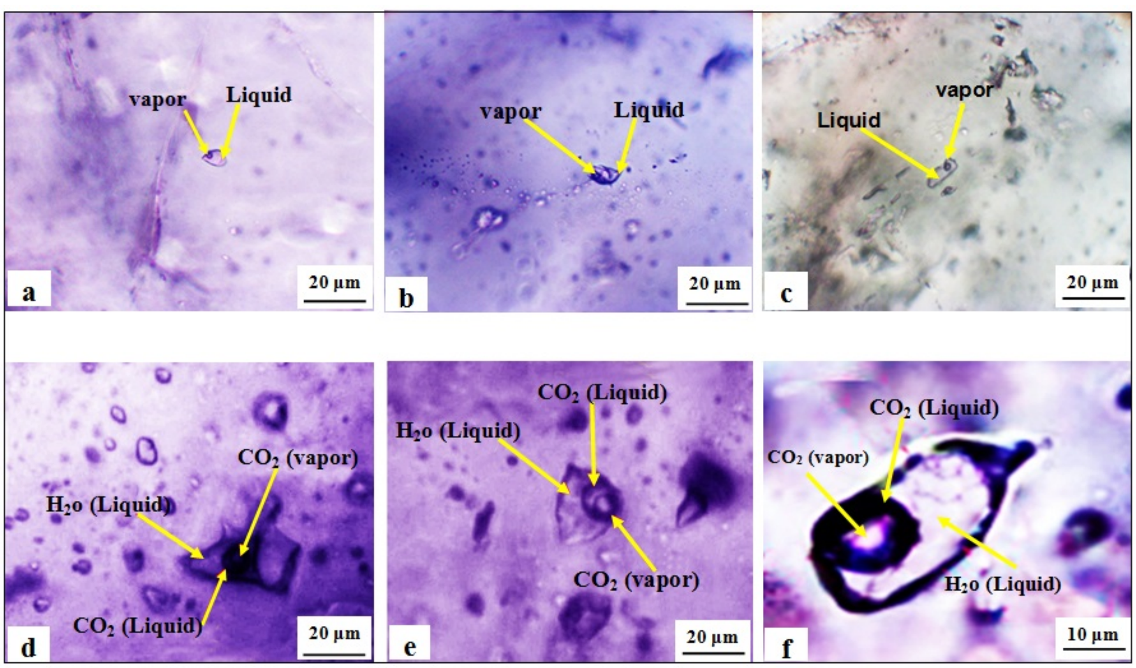

Figure 9. Petrographic images of FI types (a, b, c) two-phase (L-V) (Type III), (d, e, f) L_1-L_2-V (CO_2)-rich phases (Type IV) fluid inclusions

This indicates a low salinity for type III trapped in the inclusions interpreted as primary. The homogenization temperature for type IV (L_{CO2}-L_{H2O}-V_{CO2}) is between 300 to 330°C with a sharp peak at 320°C. The carbonic inclusion showed T_{mCO2} and T_{hCO2} ranging from -58.8 to -56.8°C and 6.1 to 16.2°C, respectively. The clathrate melting (T_{mclath}) for type IV was determined between 1.3 and 4.6°C, indicating relatively more saline fluids of about 8–13 wt. % NaCl eq. (with a high frequency at 12 wt. % NaCl eq.). Fig. 10 displays the plotting between T_h and salinity of fluid inclusions from first quartz vein generations. Based on Fig 10, the fluid mixing (metamorphic and meteoric fluids) and dilution processes are essential for gold deposition in the Lakhshak district.

Raman spectrometric analysis confirms the presence of dissolved carbon dioxide (CO_2) in primary fluid inclusion with a certainty between 98-100 mol%. The evidences of the contribution of metamorphic fluid, hydrothermal magmatic fluids and meteoric water that formed the quartz veins are represented by H_2O, N_2, $CH_4 \pm CO_2$ fluid inclusions (Fig. 11).

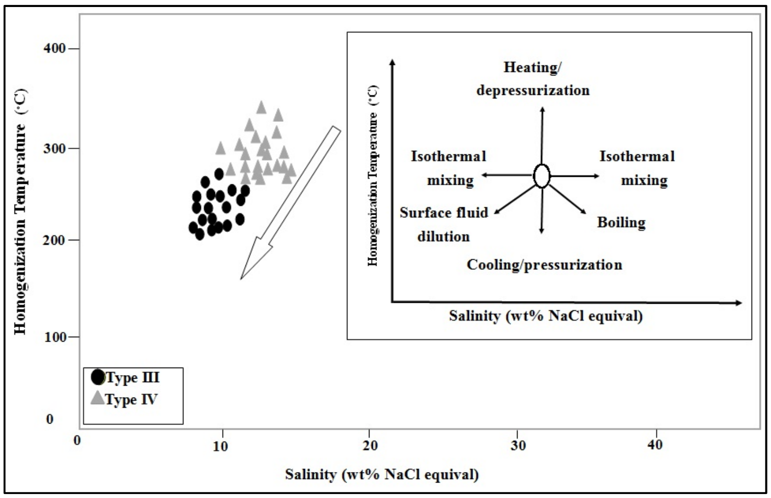

Figure 10. Temperature of homogenization (T_h) vs salinity of fluid inclusions from quartz veins/veinlets at Lakhshak metamorphic-hosted gold deposit (Wilkinson, 2001). The hydrothermal fluid evolution of these veins/veinlets are also shown and discussed in the text. Schematic model of fluid evolution is adapted from Shepherd et al. (1985)

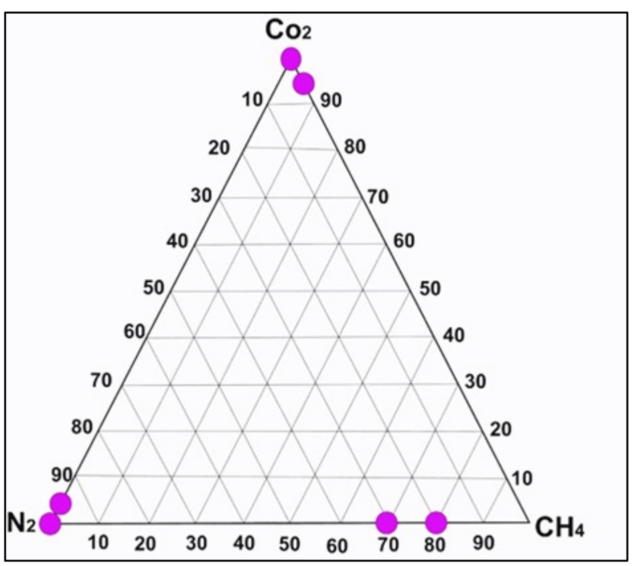

Figure 11. Ternary plot of three gaseous components such as CO_2 (98-100 mol %), CH_4 (92-100 mol %), and N_2 (70-80 mol %) in the Lakhshak gold-antimony deposit

Petrographically the carbonic fluid inclusions are occasionally observed and may contain small portion of CO_2, N_2, and CH_4 probably max 98-100 mol%, 92-100 mol%, and 70-80 mol%, respectively. Crush-leach analysis of fluid inclusions from Lakhshak deposit gold veins suggests that the halogen fluid chemistry (Br/Cl vs I/Cl plot) is not identical to magmatic or epithermal related fluids, but tends to be similar to fluids in mesothermal-type gold deposits (Fig. 12).

Hydrothermal fluid is typified by CO_2-rich fluid, moderate temperature of 300-330 °C and typical salinity (8-13 wt. % NaCl eq.), fluid chemistry (Br/Cl vs I/Cl plot), which suggests that the metamorphic fluid is responsible for the formation of the Lakhshak deposit. The main characteristics of the results of this deposit are similar to known orogenic gold deposits.

Conclusions

Briefly concluded that primary gold mineralization in Lakhshak area, in the southwestern part of the Sistan suture zone, is predominantly hosted by calc-schist which is composed of muscovite, chlorite, and sericite, and petrologically categorized into greenschist facies. This type of metamorphic facies mostly hosts the orogenic gold deposits Iran (Sanandaj-sirjan zone), e.g. Kharapeh (Niroomand, 2004; Niroomand et al., 2011), Ghabaqloujeh (Tajeddin et al., 2011), Kervian (Heidari, 2004), Qolqoleh (Aliyari et al., 2014), Hamzeh-Gharanein (Maghsoudi et al., 2017), Muteh and Chah Bagh (Kouhestani et al., 2006), and Zartorosht gold deposit (Rastgo Moghadam et al., 2003; Aliyari et al., 2014). Mineralized zone may strongly be controlled by NE-SW-trending shear zone in the contact zone of granitoid and calc-schist units. Quartz-sulfide vein texture is characterized by brecciated, banding texture such as sulfide banding. Host rock is altered to sulfidic, silicic, sericitic, and carbonation. Pyrite, arsenopyrite, stibnite, native gold, stibiconite, and goethite are identified, those mineral are indicative of mineralization systems of orogenic gold. Assay results indicate that 16 of 20 samples yielded more than 1 g/t Au, in which 7 of them are in excess of 3.5 g/t Au. Interestingly, most of the high-grade samples contain also high grade Sb (up to 3276 ppm), As (up to 864 ppm), and Hg (up to 65 ppm). The presence of pathfinder minerals such as sulfide minerals (pyrite, stibnite, arsenopyrite), goethite, and stibiconite genetically indicates that the orogenic gold deposit in the Lakhshak deposit is emplaced into transition between epizonal and mesozonal referred to the conceptual model of orogenic gold deposit (cf. Groves & Goldfarb, 2003; Groves et al., 2005) (Fig. 13).

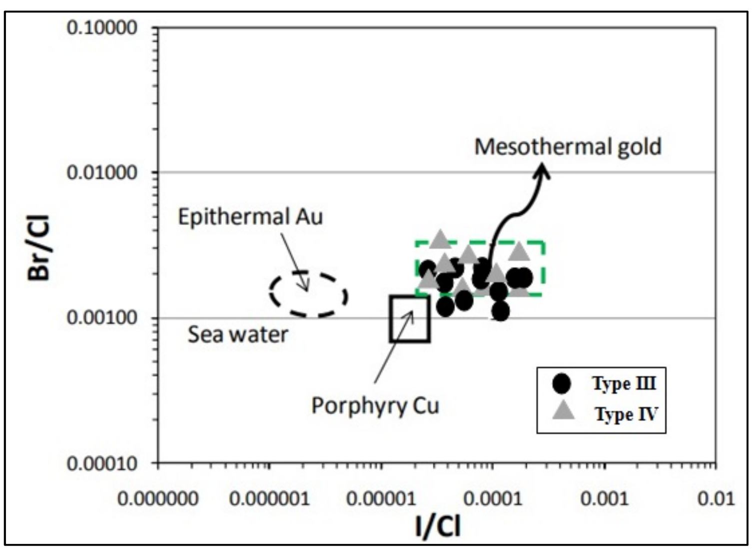

Figure 12. Crush-leach analysis of halogen content (I/Cl and Br/Cl ratios) in fluid inclusion showing mineralizing fluids are not identical to magmatic fluid, epithermal (meteoric water-dominated) and porphyry Cu, but tends to be similar to fluids in mesothermal-type (or orogenic) gold deposits

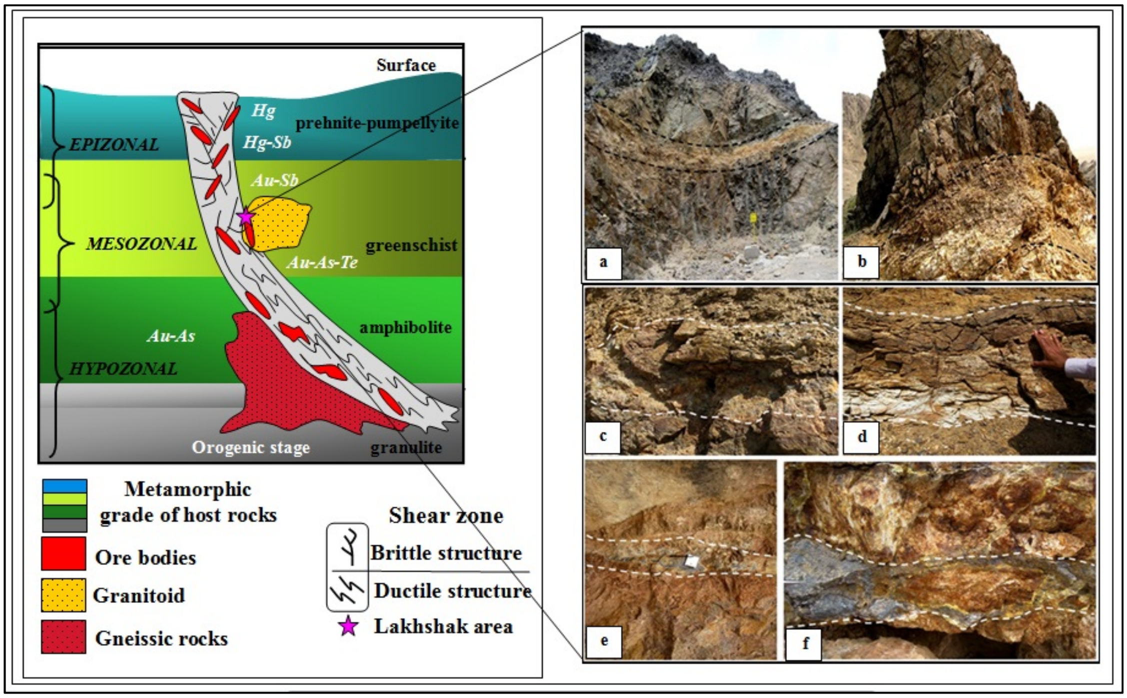

Figure 13. The Lakhshak metamorphic-hosted gold deposit plotted on the conceptual orogenic gold deposit model from Groves and Goldfarb (2003) and Groves et al. (2005) emplaced into shallow level at the transition between epizonal and mesozonal (approximately 5-10 km depth below paleosurface)

It implies that the mineralization may be formed at approximately 5-10 km depth below paleosurface. In addition, the observable characteristics of gold-bearing quartz veins/veinlets have met with the criteria of orogenic gold type, i.e. sheared/deformed, segmented, brecciated and occasionally sigmoidal, which are the key indications for brittle condition of the epizonal-mesozonal transition. Ore mineralizing fluid is characterized by moderate to low salinity ranging from 8 to 13 and 9-11 wt. % NaCl eq. as well as moderate to low temperature of homogenization (T_h) varying from 300 to 330 °C and 200 to 280°C for quartz-sulfide veins/veinlets. CO_2-rich fluid inclusion is present in small portion, but its presence is well confirmed by Raman spectrometric data. Crush-leach analysis of fluid inclusion shows that mineralizing fluid characteristics are not identical to both epithermal (meteoric water-dominated) and magmatic fluids, but tends to fit with the properties of mesothermal related fluids. Hydrothermal fluid is typified by CO_2-rich fluid, moderate temperature of 300-330 °C and typical salinity (8-13 wt. % NaCl eq.), which suggests that the metamorphic fluid is responsible for the formation of the Lakhshak deposit. The main characteristics of the results of this deposit are similar to known orogenic gold deposits. It is expected that the result would be important for a better understanding of the genesis of the gold mineralization, and would be useful in designing future exploration strategy for gold deposits in Sistan suture zone.

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