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Geochemistry, geochronology, isotope and fluid inclusion studies of the Kuh-e-Zar deposit, Khaf-Kashmar-Bardaskan magmatic belt, NE Iran: Evidence of gold-rich iron oxide–copper–gold deposit

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A B S T R A C T

The Kuh-e-Zar deposit is located in the central part of the Khaf-Kashmar-Bardaskan Tertiary magmatic belt, NE Iran. The prevailing stratigraphic unit is composed of Cenozoic volcanic rocks (rhyolitic to andesitic in composition), which are intruded by subvolcanic plutons. Intrusive rocks spatially close to mineralization include metaluminous to peraluminous, calc-alkaline and I-type diorite, granodiorite, quartz monzonite, quartz monzodiorite, and syenogranite. The quartz monzonite and quartz monzodiorite have identical zircon U–Pb ages of ca. 40.7–41.2 Ma. The intrusions are characterized by enrichment in large-ion-lithophile elements (LILEs) and light rare-earth-elements (LREEs), depletion in heavy rare-earth-elements (REEs, $La_N/Yb_N \approx 7$ to 9.07) and high-field-strength-elements (HFSEs) and εNd(t) ranging from −0.06 to −2.93 at $^{86}Sr/^{87}Sr(t) = 0.7054$–0.7064 and $^{206}Pb/^{204}Pbi = 18.6$–18.71. The intrusive rocks of Kuh-e-Zar are products of crustal assimilation by melts derived from the metasomatized mantle wedge above the subducting Neotethyan Ocean slab beneath SW Eurasia.

Field work and mineralogical, petrological studies show that, the hydrothermal alteration produced a zone of silicification, propylitic alteration, and albitization associated with minor sericitic-argillic alteration. The mineralization of Kuh-e-Zar occurs in veins, stockworks, and breccias, which is located near or within NE − SW and NW − SE faults cutting through volcanic rocks and wall rocks. The ore minerals are dominated by specular hematite and gold with small amounts of pyrite, chalcopyrite, and galena. Hematite, goethite, malachite, covellite, and cerussite are secondary minerals. The main gangue minerals include quartz, siderite, chlorite, and albite. Microthermometric study of fluid inclusions shows homogenization temperatures at medium-high temperature of 248 to 491 °C. Salinities of ore-forming fluids are medium-low ranged from 4 to 19.2 wt% NaCl equivalent. The sulfur isotope composition of chalcopyrite ($\delta^{34}S = -2.5$ to 0.9‰) suggests that sulfur was derived mainly from igneous rocks. The oxygen isotopic data ($\delta^{18}O_{water} = 7.4$–7.9‰) indicate that the ore fluids were in magmatic origin.

The mineralogy, alteration, geochemistry, stable isotopes, and petrogenesis of intrusions of the Kuh-e-Zar deposit indicate it is an Eocene gold-rich iron oxide-copper-gold (IOCG) deposit.

1. Introduction

The geological settings, hydrothermal alteration and mineralizing fluid compositions vary between deposits of the “IOCG-type” (Hitzman et al., 1992; Sillitoe, 2003). However, they are a class of Cu ± Au deposits containing abundant low-Ti iron oxide (magnetite and/or hematite) and extensive hydrothermal alkali (Na/Ca/K) alteration. Such deposits also show strong structural controls, and a temporal but not a close spatial association with igneous rocks (Williams et al., 2005). They formed in rift or subduction settings (Hitzman, 2000; Barton, 2014) from the Late Archean to Pliocene (Groves et al., 2010). Available data suggest that IOCG deposits formed from

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magmatic–hydrothermal systems where the ore-forming fluids were at moderate temperature (~300–450 °C), and had high salinity and CO_2 (e.g. Pollard, 2001, 2006; Fu et al., 2003; Rieger et al., 2012). However, many IOCG deposits, particularly during the Cu-Au mineralization stage, are characterized by high-salinity fluids with variable CO_2 content and medium-to-low temperature (< 300 °C). According to Williams (2010), IOCG deposits formed in a variety of hydrological systems, including high-level systems, in which cool surficial fluids interacted with deep sourced magmatic fluids. Although there is good evidence for the genesis of IOCG deposits, there is a controversy on the nature of ore-forming fluids responsible for Cu-Au mineralization and their relationship with IOCG deposits during the preceding magnetite mineralization (Chen et al., 2011).

The Khaf-Kashmar-Bardaskan magmatic belt (KKBMB), located in northeastern Iran, is one of the most important metallogenic province in Iran that comprises numerous porphyry Au-Cu and Cu deposits, iron-oxide copper-gold (IOCG) deposits, skarn Fe deposits, vein-type Cu-Au and Au-Ag deposits, stratabound Cu deposits, and kaolin deposits (Karimpour, 2006; Karimpour and Malekzadeh Shafaroudi, 2006; Saadat et al., 2007; Yousefi et al., 2009; Golmohammadi et al., 2015; Almasi et al., 2015; Mahvashi and Malekzadeh Shafaroudi, 2016) (Fig. 1a and b). Karimpour (2004) suggested the KKBMB has good potential for IOCG-type mineralization in NE Iran.

The Kuh-e-Zar deposit is located in the center of the KKBMB, approximately 40 km NW of the town called Torbat (Fig. 1b). Having a proven reserve of over 3 Mt gold ore @ 3 ppm Au, and with low concentrations of As, the Kuh-e-Zar represents a unique gold deposit in Iran. The gold mineralization consists of fifteen blocks defined in the mine. Modern mining activity only started after 1997. Extensive exploration began in 1999.

Previous studies were mainly limited to the exploration reports of Zarmehr Company (1999a,b, 2000, 2002, 2005a,b), MS.C. thesis (Shahbazian, 2000; Gurabjiripour, 2001; Shirzad, 2002; Ansari Jafari, 2014), and Iranian journal papers (Karimpour and Mazloumi Bajestani, 1999; Abedi, 2003; Mazloumi Bajestani et al., 2007; Mazloumi Bajestani and Rasa, 2010). The geology of deposit, structural analysis, and minor geochemistry of intrusions and orebodies that create them (Karimpour and Mazloumi Bajestani, 1999; Abedi, 2003; Mazloumi Bajestani et al., 2007; Mazloumi Bajestani and Rasa, 2010) had been relatively well studied. In contrast, paragenetic assemblages of alteration and mineralization, age and petrogenesis of intrusive rocks and their relationship to mineralization, and nature of ore-fluid have not been investigated in detail yet. Yaghoubpour et al. (1999) and Shahbazian (2000) suggested that the Kuh-e-Zar deposit is a low sulfide epithermal Au deposit, whereas many features of the Kuh-e-Zar deposit are typical of IOCG deposits that are now widely recognized as a global class of ore deposits (e.g., Hitzman et al., 1992; Barton and Johnson, 1996; Hitzman, 2000; Sillitoe, 2003; Groves et al., 2010).

This paper is based on field works over two decades that focused on the geologic-alteration mapping, recognition of different mineralized zones and mineral paragenesis, intrusive bodies and their relationship to mineralization, their geochronology and petrogenesis, and the mineralogy, fluid inclusion, and stable isotope studies of the deposit. The primary outcome of this study was the recognition of the Kuh-e-Zar deposit as an iron oxide-copper-gold (IOCG) deposit with enrichment of Au and depletion of Cu.

2. Geological background

Cenozoic igneous rocks in Iran are distributed in five belts (Fig. 1a) including the KKBMB in northeastern Iran. The KKBMB is an arcuate, W-E to NW-SE trending, Cenozoic volcano-plutonic arc of 400 km in length and 50 km in width, which located in the north of the major Doruneh Fault (Fig. 1a and b). This belt has significant potential for iron, copper, gold, and silver deposits (Karimpour, 2004; Yousefi et al., 2009; Malekzadeh Shafaroudi et al., 2013; Golmohammadi et al., 2015) (Fig. 1b). The regional tectonomorphology are resulted from the Alpidic orogenesis, whereas the main lineaments and the general strike of the mountain ranges reflect reactivation of earlier Assyntic orogenic structures (Eftekharnejad, 1981).The two blocks of Sabzevar in the north and Lut in the south of the Doruneh Fault show dextral and sinistral movements in different periods respectively, with the dextral movement being the most recent (Aghanabati, 2004). The structural features of the region, such as faults and foldings, as well as the strike of the formations, follow the NW-SE to NE-SW direction of the major Doruneh Fault (Fig. 1b). A series of NW-SE and NE-SW striking faults (N140) with sinistral and dextral movements have played a role in the formation of the Khu-e-Zar orebodies.

The major rock types in the Kuh-e-Zar deposit are Cenozoic calc-alkaline volcanic rocks and subvolcanic intrusive stocks and dikes intruded into volcanic rocks (Fig. 2). The volcanic rocks mainly consist of Paleocene to middle Eocene rhyolitic-dacitic pyroclastic rocks, rhyolitic lapilli tuff, quartz latite, trachyt, hornblende quartz latite, and trachyandesite and minor rhyolitic welded tuff and ignimbrite, and andesitic agglomerate. These volcanic rocks are intensely altered, especially in the vicinity of the mineralized zones in the southeastern part of the area, and they are the primary hosts of gold ± copper mineralization veins in the Kuh-e-Zar deposit. Pleistocene-Quaternary pyroxene andesite and basalt also occur in the area (Fig. 2).

The plutonic and subvolcanic intrusive rocks, which are exposed as stocks and dikes in the northern, northeastern, and southwestern parts of the area, consist of six compositional groups, which include 1) hornblende-pyroxene diorite porphyry; 2) hornblende-biotite granodiorite; 3) biotite-hornblende quartz monzonite porphyry; 4) biotite-hornblende quartz monzodiorite porphyry; 5) syenogranite; and 6) hornblende quartz monzonite porphyry (Figs. 2 and 3a to h). The ~40 Ma zircon U-Pb ages obtained from the quartz monzodiorite and quartz monzonite indicate a Middle Eocene intrusion (see Section 7.2). These acidic to intermediate intrusions have spatial relationship to mineralization and they are host rock in a few places (Fig. 3i), but temporal relationship is unclear. However, we could to suggest the intrusions with the same composition and age in depth probably led to the development of a variety of alteration and formation of mineralized zones in their host volcanic rocks in the area.

3. Petrography of the plutonic and subvolcanic intrusions

Hornblende-pyroxene diorite porphyry occurs as two small outcrops in the western part of the Kuh-e-Zar deposit (Fig. 2). Hornblende-pyroxene diorite porphyry consists of ~40% phenocrysts, including 20–25% plagioclase, 8–10% augite, and 3–5% hornblende in a fine-grained groundmass (Fig. 4a). Magnetite is common accessory mineral. The diorite is weakly to moderately altered, with chlorite being a common alteration mineral.

Biotite-hornblende quartz monzodiorite porphyry is one of the most widely exposed intrusive rocks in the study area (Figs. 2 and 3e). The biotite-hornblende quartz monzodiorite porphyry has porphyritic, glomeroporphyritic, and granophyric texture with medium-grained groundmass and normally contains up to 50% phenocrysts, including 20–25% plagioclase, 5–8% K-feldspar, 4–6% hornblende, 5–8% quartz, and 2–3% biotite. The same minerals are also present in the groundmass (Fig. 4b). Accessory minerals are magnetite, zircon, and apatite. Hornblende and biotite are replaced by chlorite in some places. A small amount of feldspar phenocrysts have been altered to sericite and albite. Minor secondary quartz also exists in the groundmass.

Biotite-hornblende quartz monzonite porphyry crops out as stocks in the western to southwestern part of the Kuh-e-Zar deposit (Figs. 2 and 3c). The biotite-hornblende quartz monzonite porphyry has a porphyritic and glomeroporphyritic texture with fine-grained groundmass. The phenocrysts consist of 10–12% plagioclase, 15–20% K-feldspar, 5–8% quartz, 2–3% hornblende, and 1–2% biotite (Fig. 4c). Magnetite and zircon are accessory minerals. Sericite is the main