



Stable isotope record of hydrothermal sulfate, sulfide and silicate minerals in the Darreh-Zar porphyry copper deposit in Kerman, southeastern Iran: Implications for petrogenesis and exploration



A. Parsapoor^{a,*}, J.H. Dilles^b, M. Khalili^a, M.A. Mackizadeh^a, M. Maghami^c

^a Department of Geology, University of Isfahan, Isfahan, Iran

^b College of Geology, Ocean & Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA

^c National Iranian Copper Industries Corporation, Iran

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ABSTRACT

The Darreh-Zar porphyry copper deposit is found together with other porphyries such as Sar-Cheshmeh and Sungun in the Cenozoic age Urumieh–Dokhtar magmatic belt that is related to the subduction of the Arabian plate beneath Central Iranian microcontinent. The deposit is associated with Miocene granodiorite porphyry intrusions into Eocene basaltic volcanic rocks. The principal hydrothermal facies of the area are a core zone of potassic alteration enclosed by a peripheral zone of propylitic alteration. Chlorite-sericite, sericitic, advanced argillic and intermediate argillic alteration zones cut the upper part of the potassic zone and are developed near the interface between the potassic and propylitic zones. Chalcopyrite, pyrite or local bornite, and associated anhydrite are the chief hypogene sulfide minerals, and constitute <0.1 to 0.8 wt.% Cu ores. A ~50-m-thick supergene zone containing 0.8 to 1.5 wt.% Cu, characterized by covellite and chalcocite, underlies an oxidized and partially leached ~20-m-thick zone containing chrysocolla, malachite and azurite.

The hydrogen isotopic composition of biotite from Darreh-Zar ranges from δD of -89 to -101‰ , and the calculated aqueous fluids (δD of -66 to -78‰) in equilibrium with biotite are consistent with a large component of magmatic fluid. Epidote varies from δD of -56 to -53‰ , and yields calculated fluids responsible for the propylitic alteration that range from -22 to -19‰ . Oxygen isotopic data for the studied quartz, biotite, anhydrite and epidote vary between $\delta^{18}O$ of 0.8 to 9.0‰. The calculated $\delta^{18}O$ values for aqueous fluids in equilibrium with the biotite, quartz (from barren type and A veins), anhydrite (from B veins) and epidote are 7.8 ± 0.4 , 5.1 ± 0.6 , 2.6 ± 0.5 and $-1.1 \pm 0.1\text{‰}$, respectively. This marked decrease likely reflects a change from magmatic-derived fluids in central potassic zone to meteoric or sedimentary-derived fluids in the outer propylitic zone. Sulfur isotope compositions are 11.8 to 14.0‰, for anhydrite ($n = 3$), 2.4‰ for molybdenite ($n = 1$), 1.7 to 3.9‰ for pyrite ($n = 17$), and 1.6 to 2.9‰ for chalcopyrite ($n = 2$). The sulfide data, alone, suggest a conventionally 'magmatic' value of about 1.6 to 2.9‰ for Darreh-Zar sulfur. However, the fairly oxidized granitic parental magma shows relatively heavy bulk sulfur ($\delta^{34}S_{SS} \approx +5\text{‰}$) and sulfate–sulfide sulfur isotopic fractionation is consistent with an approach to isotopic equilibrium at calculated temperatures of 520 ± 50 °C for most of the coexisting anhydrite–pyrite pairs ($n = 4$). An exploration implication is that the identification of isotopically high sulfur isotopic compositions of gypsum from near-surface samples determines a hydrothermal system that contains deeper hypogene anhydrite, a common indicator of large porphyry Cu–Mo deposits. In contrast, isotopically low sulfur isotopic values similar to and derived from weathering of pyrite and other sulfides are common in many hydrothermal environments.

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1. Introduction

Sulfur isotope data have long been used in studies of ore genesis. Jensen (1967) and Ohmoto and Rye (1979) are among the earliest efforts investigating the genesis of sulfide-bearing minerals. As Rye (2005) stated, the sulfur isotope data of coexisting anhydrite and pyrite

in porphyry systems indicate a range of SO_4^{2-} to H_2S^- dominant hydrothermal fluids that probably reflect the range in oxidation states of their parent magmas. Sulfur isotopic equilibrium is generally attained and maintained between the sulfate and sulfide that precipitate in the magmatic-hydrothermal system from H_2SO_4 and H_2S formed by the disproportionation of SO_2 in condensing magmatic vapor plumes. Consequently, sulfate–sulfide sulfur isotope fractionation has been widely applied as a geothermometer (Rye, 2005). Along with sulfur isotopes, the oxygen and hydrogen isotopes have been widely used to identify

* Corresponding author. Tel.: +989133176409.

E-mail address: anis_parsa@yahoo.com (A. Parsapoor).

the sources of hydrothermal waters and to elucidate their mode of formation in the hydrothermal system.

The Alpine-Himalayan fold-thrust belt forms a complex network of suture zones and micro-plates which extends from the Iberian Peninsula to Southeast Asia (Ricou, 1994; Roberston et al., 2004; Sengör and Yilmaz, 1981). During the Mesozoic, the southern active margin of the Eurasian plate featured closure of the Paleo-Tethys Ocean. The timing of this closure, concerning when Arabia started colliding with Eurasia, however, has been highly controversial, ranging from the Late Cretaceous to as late as the Pliocene (Agard et al., 2011; Alavi, 1994; Galoyan et al., 2009; Sengör, 1990). This convergence was manifested by subduction, obduction, micro-plate accretion and finally by continent–continent collision. Following the collision, the Zagros orogenic belt developed in a zone extending approximately 2000 km eastward from the Anatolian fault in Turkey to the Oman line in southern Iran. The Zagros belt is subdivided into three major parallel tectonic units, from south to north, that include the Zagros fold-thrust belt, the Sanandaj–Sirjan magmatic belt, and the Urumieh–Dokhtar magmatic belt. According to Dimitrijevic (1973), the Urumieh–Dokhtar magmatic belt forms a NW–SE topographic ridge separating the Sanandaj–Sirjan zone from Central Iran, and contains large thickness, in places >10 km thick, of Tertiary volcanic and sedimentary deposits. The igneous rocks have been described as dominantly of arc type (Berberian and Berberian, 1981; Berberian et al., 1982; Emami, 2000) or alternatively as island-arc type of Eocene age (Shahabpour, 2005). In contrast, abundant intrusions emplaced into the volcanic and sedimentary rocks are predominantly of Oligocene and Miocene age (Berberian and Berberian, 1981).

Major porphyry Cu deposits (e.g. Sungun and Sar-Cheshmeh) in Iran are hosted by the Urumieh–Dokhtar magmatic belt. The Sungun porphyry copper deposit is a large porphyry style deposit with reserves of >500 million tons of sulfide grading 0.76% Cu and 0.01% Mo (Hezarkhani, 1997). The Sungun complex is located in the NW of the Urumieh–Dokhtar magmatic belt in Azarbaijan province where initial voluminous eruptions of Eocene andesite to rhyolite volcanic rocks were followed by Upper Miocene plutonic rocks (granodiorites, granites and monzonites) associated with copper ores. The plutonic episode was an expression of Andean-type magmatism that developed along the continental margin in response to subduction towards the northeast (Berberian, 1983; Berberian and King, 1981).

In contrast, the Sar-Cheshmeh complex lies in the southeast part of the Urumieh–Dokhtar magmatic belt in Kerman Province where mineralization is associated with an intrusive complex of diorite, granodiorite, and granodiorite porphyry (including dykes) with outcrop dimensions of 1.1 × 2.2 km (Hezarkhani, 2004a,b). Sar-Cheshmeh contains a resource of 450 million tons of sulfide ore with an average grade of 1.13% Cu and 0.03% Mo (Waterman and Hamilton, 1975).

The Darreh-Zar porphyry copper deposit is located adjacent to the Sar-Cheshmeh copper mine in the Urumieh–Dokhtar magmatic belt (latitude 29°53' N, longitude 55°53' E; Fig. 1). The initial mining operations commenced by a Selection Trust Company between 1967 and 1969, and were continued by National Iranian Copper Industries Corporation. About 24,000 m of drilling was completed in 2011 to depths of up to 700 m and provide an estimate that the Darreh-Zar porphyry contains an inferred resource of ~500 million tons of sulfide ore with an average grade of 0.35% Cu and 0.03% Mo. In the recent years, several research studies have been carried out on the geology and hydrothermal alteration facies as well as geochemistry of this deposit (Alizadeh Sevari and Hezarkhani, 2012; Derakhshani and Abdolzadeh, 2009; Hezarkhani, 2010), but no comprehensive isotopic description has been published so far. Therefore, the physicochemical condition and isotopic characteristics for evolution of the Darreh-Zar porphyry Cu are poorly understood.

The specific purpose of the work presented here is to report the geology and petrology of the Darreh-Zar porphyry copper deposit with particular focus on the stable isotope systematics of hydrothermal

sulfate, sulfide and silicate minerals as a case study to guide exploration and improve geologic understanding. The present paper also considers the use of isotopic data on these mineral assemblages to distinguish the sulfur sources as well as the nature and the physicochemical conditions of hydrothermal fluids during ore formation.

2. Local geological setting

The local geology at Darreh-Zar is illustrated by the geologic map and one cross-section in Fig. 2. Two main lithologic groups are represented in the area of the deposit. The older Eocene volcanic sequence consists of calc-alkaline basalt, trachybasalt, basaltic andesite and dacite are predominantly not only lavas but also silicic pyroclastic rocks including tuff and ignimbrite. The younger Miocene series are arc-related granodioritic rocks (Darreh-Zar porphyry) that emplaced into the Eocene volcanic sequence (Fig. 1b; Alavi, 1994; Walker and Jackson, 2002; Shahabpour, 2005). The porphyry is closely associated with hydrothermal alteration and Cu mineralization. The last stage of magmatic activity is manifested by diabasic to dioritic dike swarms that cut both the Eocene and Miocene igneous rocks.

The fault systems include 1) faults with E–W strike formed prior to the porphyry intrusion (Fig. 2a), whose long axis is aligned with the fault, 2) more abundant NE–SW striking faults which cut the granodiorite porphyry, and 3) younger faults with N–S strike (Fig. 2a) that effect the extent and distribution of supergene mineralization. Further structural observations demonstrate that prominent joints both in the NW and SE directions. Many of these faults served as conduits of hydrothermal fluids and are crystallized with pyrite, chalcopyrite, and Fe–oxides, chlorite, and sericite.

2.1. Petrography of igneous rocks

The local stratigraphy of Eocene volcanic rocks at Darreh-Zar is not well known. The igneous sequence is up to 1000 m thick and dominated by basalt and basaltic andesite lavas and layers of dacitic tuffs and lesser basaltic andesite in the upper part of the section (Fig. 2a). Petrographic characterization of basaltic host rocks bases on observations of about one hundred polished thin sections from different parts of the Darreh-Zar complex. The essential minerals of the rocks studied are primary olivine, plagioclase, clinopyroxene, and magnetite that form a distinct porphyritic texture with 35 to 50% phenocrysts (Fig. 3a, b). Olivine grains are strongly altered to red–brown iddingsite along their edges and fractures or pseudomorphed completely by carbonate. Clinopyroxene (augite) is a common major mafic mineral which forms unzoned grains up to 2 mm in size, and usually has a glomeroporphyritic texture with plagioclase. Plagioclase generally appears as zoned phenocrysts (An_{85-100} or 85 to 60 mol% anorthite) that often display a sieve texture (on rim, interior) (P1 in Fig. 3a), large phenocrysts (P2, An_{60}) occasionally with dusty rims and resorption margins (Fig. 3a), and tabular microlite crystals intergrowth with pyroxene and oxides in the groundmass (P3 in Fig. 3, An_{25-15}). Pyroclastic rocks range in composition from basaltic andesite to dacite. Andesitic ash flow tuffs commonly contain phenocrysts of plagioclase plus pyroxene in a devitrified and holocrystalline matrix of fine-grained plagioclase and clinopyroxene. Rheomorphic flow texture is sometimes observed. Dacite ash flow tuffs are crystal-rich and contain phenocrysts of plagioclase, broken quartz, and opaque minerals set in a fine-grained devitrified matrix of quartz, chlorite, and feldspar.

In contrast to the huge volume of volcanic rocks, the Darreh-Zar porphyry is a small, elliptical exposure <1 km long by 400 m wide of granodiorite composition. In detail, this porphyry body consists of a series of dike-like intrusions 50–150 m wide whose orientations and dips are poorly defined by drilling and core-logging but apparently have steep dips (Fig. 2b). The porphyry is characterized by subequal proportions of phenocrysts 0.5–2 mm long and an aplitic or sugary 0.02 mm (20 μ m) groundmass mainly composed of quartz and alkali feldspar (Fig. 3c, d). The field observations as well as petrographic studies

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