Mineralogic, fluid inclusion, and sulfur isotope evidence for the genesis of Sechangi lead–zinc (–copper) deposit, Eastern Iran

Azadeh Malekzadeh Shafaroudi *, Mohammad Hassan Karimpour

Research Center for Ore Deposit of Eastern Iran, Ferdowsi University of Mashhad, P.O. Box 91775-1436, Mashhad, Iran

**Abstract**

The Sechangi lead–zinc (–copper) deposit lies in the Lut block metallogenic province of Eastern Iran. This deposit consists of ore-bearing vein emplaced along fault zone and hosted by Late Eocene monzonite porphyry. Hydrothermal alteration minerals developed in the wall rock include quartz, kaolinite, illite, and calcite. Microscopic studies reveal that the vein contains galena and sphalerite with minor chalcopyrite and pyrite as hypogene minerals and cerussite, anglesite, covellite, malachite, hematite, and goethite as secondary minerals. Fluorite and quartz are the dominant gangue minerals and show a close relationship with sulfide mineralization. Calculated $\delta^{34}S$ values for the ore fluid vary between $+9.9\%$ and $+5.9\%$. Sulfur isotopic compositions suggest that the ore-forming aqueous solutions were derived from magmatic source and mixed with isotopically light sulfur, probably leached from the volcanic and plutonic country rocks. Microthermometric study of fluid inclusions indicates homogenization temperatures of 151–352 °C. Salinities of ore-forming fluids ranged from 0.2 to 16.5 wt.% NaCl equivalent. The ore-forming fluids of the Sechangi deposit are medium- to low-temperature and salinity. Fluid mixing may have played an important role during Pb–Zn (–Cu) mineralization. The key factors allowing for metal transport and precipitation during ore formation include the sourcing of magmatic fluids with high contents of metallogenic elements and the mixing of these hydrothermal fluids with meteoric waters resulting in the formation of deposit. In terms of the genetic type of deposit, the Sechangi is classified as a volcanic–subvolcanic hydrothermal-related vein deposit.

© 2015 Elsevier Ltd. All rights reserved.

**1. Introduction**

Cenozoic magmatic rocks in Iran are distributed mostly in four belts (Fig. 1A). The Urumieh-Dokhtar magmatic arc extends for over 1700 km in the NW–SE direction, which includes world-class porphyry copper deposits such as Sarcheshmeh and Miduk (Waterman and Hamilton, 1975; Forster, 1978; Berberian et al., 1982; Mohajjel et al., 2003; Shahabpour, 2005, 2007; Chasemi and Talbot, 2006; Shafiei et al., 2009; Boomeri et al., 2009). The Alborz-Azarbaijan magmatic belt, in the north, extends for 800 km, varying between NW–SE and W–E directions (Nabavi, 1976); the western end of this belt merges into the Urumieh-Dokhtar belt (Fig. 1A). The west of the belt, known as Arasbaran metallogenic zone, hosts the world-class Sungun porphyry Cu–Mo deposit (Calagari et al., 2001; Calagari, 2003), Anjerd, Sungun, and Mazraeh Cu skarn deposits (Karimzadeh Somarin and Hosseinzadeh, 2002; Karimzadeh Somarin, 2004), and several epithermal style gold occurrences. Hassanzadeh et al. (2002) presented evidence for an intra-arc rifting in Urumieh-Dokhtar magmatic belt during Oligocene–Miocene, leading to the separation and northward movement of what is now known as Alborz-Azarbaijan magmatic belt (Fig. 1A). The Khat-Kashmar-Bardaskan magmatic belt crosses NE Iran (Fig. 1A), which has significant potential for iron oxide type mineralization, including iron-oxide copper–gold (IOCG) and magnetite deposits, such as Kuh-e-Zar, Shahrak, Tannurjeh, and Sangan (Karimpour, 2004; Mazloumi et al., 2009; Yousefi et al., 2009). The east-trending, ~50 km wide belt extends ~400 km along the north side of the Duroneh Fault (Malekzadeh Shafaroudi et al., 2013a). The Eastern Iran belt extends for 1000 km in the N–S direction, within the Lut block (Fig. 1A). This block is bounded to the east by the Nehbandan and associated faults, to the north by the Doruneh and related faults (Sabzevar zone), and to the west by the Nayband Fault (Fig. 1A and B). The Lut block is the main metallogenic province in east of Iran (Karimpour et al., 2012) that comprises numerous porphyry Cu and Cu–Au deposits, low and high sulfidation epithermal Au deposits, and Cu–Pb–Zn vein-type...
deposits (Malekzadeh Shafaroudi, 2009; Arjmandzadeh et al., 2011; Karimpour et al., 2012; Richards et al., 2012; Malekzadeh Shafaroudi and Karimpour, 2013a). Karimpour et al. (2012) studied the relationship of Rb–Sr isotope, geochemistry, and age data of Tertiary granitoid rocks (syn-mineralization units) with different types of mineralization in the Lut block. They concluded that the age of these intrusions is between middle Eocene to lower Oligocene (43.3–33.3 Ma.). In addition, the initial \( {^{87}}\text{Sr}/^{86}\text{Sr} \) ratios

---

**Fig. 1.** A. A simplified map showing the main geological divisions, and the distribution of the Cenozoic magmatic assemblages, in Iran (after Stocklin, 1968; Alavi, 1996). B. Tertiary igneous rocks of the Lut block, Eastern Iran, showing the locations of Sechangi and some base metal vein-type deposits. Based on maps from the Geological Survey of Iran (1989, 2009, and various 1:250,000-series maps).
vary from 0.7051 to 0.7047, which indicate that these magmas originated from oceanic crust. Therefore, the period during which the formation of the ore minerals took place coincides with Middle Eocene to Lower Oligocene. This period, which is referred to as the metallogenic epoch for the Lut block also corresponds to the subsequent phase of the Pyrenean episode of the Middle Alpine orogeny (Karimpour et al., 2012).

The Sechangi Pb–Zn (−Cu) deposit is situated approximately 123 km southwest of the town of Birjand, South Khorasan province, in Eastern Iran (Fig. 1B). This deposit is one of the many igneous basement-hosted hydrothermal base-metal vein deposits in the Lut block mineral district (Fig. 1B). The mining history of the Sechangi deposit goes back to ancient time when the mine probably supplied the first known lead products in the area. It was reopened in 1963 but insufficient development work (drill core was not drilled) and late 1975 saw its closure. Many vertical shafts exist in the area that are unavailable due to collapse damage. Azimi and Saeedi (1975) reported a daily production of 30 tons, averaging 6% Pb and 3% Zn. Underground work has followed the ore to a depth of 140 m, where the zinc/lead ratio increases (up to 3). The zinc/lead ratio is less than 1 at shallower levels.

Mineralization in the Sechangi deposit was described in general by Bazin and Hubner (1969) and Tarkian et al. (1984), but they did not study mineral paragenesis, fluid evolution and ore genesis. In this paper, therefore, we carried out first geological investigations, including field geology, ore microscopy, fluid inclusion microthermometry, and sulfur isotope geochemistry, which help to clarify the ore genesis of the Sechangi Pb–Zn (−Cu) deposit.

2. Geological background

Tectonically, the Sechangi Pb–Zn (−Cu) deposit is located in the west of Lut block near the Nayband fault (Fig. 1B) and hosted by Tertiary igneous rocks. This block is one of the several microcontinental blocks interpreted to have rifted from the northern margin of Gondwana during the Permian opening of the Neo-Tethys Ocean, which was subsequently accreted to the Eurasian continent in the Late Triassic during the closing of the Paleo-Tethys Ocean (Golonka, 2004). Previous studies on the tectonic and magmatic evolution of the Lut block yielded contradictory results of plate tectonic models. Along the eastern margin of the block, the arcuate branches of the bordering N–S fault system extend into the interior of the block. Berberian (1973) suggested that the Lut block behaved rigidly and it has been argued that the block underwent a large anticlockwise rotation in response to the collision between India and Eurasia (Westphal et al., 1986; Besse et al., 1998; Bagheri, 2008).

The present eastern border of the Lut block would have belonged to the active margin of the subducted Neotethys Ocean (Dercourt et al., 1986; Golonka, 2004; Bagheri and Stampfli, 2008). This ocean closed in Eastern Iran, between the Afghan and Lut plates, in Oligocene Middle Miocene (Sengör and Natalin, 1996). The Eastern Iran ophiolite complex marks the boundary between the Lut and Afghan continental blocks. Some authors denied the influence of a subduction zone and attributed the mineralization in the Lut block to an extensional geotectonic zone (Jung et al., 1983; Samani and Ashkari, 1992). However, Saccani et al. (2010) studied the ophiolitic complex of Eastern Iran, between the Lut and the Afghan continental blocks, and considered that the subduction of oceanic lithosphere played a major role and that it should have taken place beneath the Afghan block. On the other hand, Eftekharnejad (1981) proposed that magmatism in the northern Lut area resulted from subduction beneath the Lut block. Additionally, Berberian (1983) showed that igneous rocks of this block have calc-alkaline signatures. The accretionary prism–forearc basin polarity, the structural vergence, and younging of the accretionary prism to the southwest are consistent with a north-east-dipping subduction (Tirrul et al., 1983). Recently, asymmetric subduction models have been discussed for situations similar to that of the Lut block (Dolgioni et al., 2009; Arjmandzadeh et al., 2011).

The Lut block extends some 900 km from the Duruneh fault in the north to the Juz–Morian basin in the south, but is only ~200 km wide (Stocklin and Nabavi, 1973; Dehghani, 1981). The Lut block is consist of pre-Jurassic metamorphic basement, Jurassic sediments and several generations of Late Mesozoic and Cenozoic intrusive and/or volcanic rocks (Camp and Griﬃs, 1982; Tirrul et al., 1983). Radiometric age data indicate that the oldest magmatic activity in the central Lut block took place in the Jurassic (Tarkian et al., 1984). Rb–Sr isotope determinations, based on whole-rock and biotites from the Sorkh Kuh granitoid yield Middle to Late Jurassic ages (164.8 ± 1.9 Ma and 170 ± 1.9 Ma, respectively). Intrusive igneous activity of a similar age is also recognized in the Deh-Salm metamorphic complex in the eastern Lut block (Mahmoudi et al., 2010). Further to the north, magmatic activity started in the Upper Cretaceous time (75 Ma) and generated both volcanic and intrusive rocks (Tarkian et al., 1984). The Middle Eocene (47 Ma) was characterized by alkaline and shoshonitic volcanism (Tarkian et al., 1984). Volcanic activity peak is at the end of the Eocene. In addition, calc-alkaline series basalts and basaltic andesite erupted in the Eocene–Oligocene (40–31 Ma).

The geology of the Sechangi district is dominated by volcanic rocks of Eocene age, which cover an area of about 50 km² and comprise biotite–pyroxene latite and biotite–pyroxene trachydendrite (Fig. 2). These porphyritic rocks composed mainly of plagioclase (andesine–oligoclase), alkalifeldspar, quartz, biotite, pyroxene (augite–diopside), magnetite, and zircon. Subvolcanic intrusions occur in the Sechangi area, the largest of which is the biotite–pyroxene monzonite porphyry stock, which occurs in the north to northeast of the district where it intrudes the volcanic rocks (Figs. 2 and 3A). The Pb–Zn (−Cu) vein mineralization is hosted by biotite–pyroxene monzonite porphyry and this unit is altered by ore-fluid in the vicinity of vein (Figs. 2 and 3B). Geochronological study by Kluvyer et al. (1978) gave a K/Ar age of 37.5 ± 2 Ma (Late Eocene) for the rock. The biotite–pyroxene monzonite porphyry has porphyritic (0.4–5 mm) and gregomorphorphic textures with medium-grained groundmass. The modal amount of phenocrysts is up to 35–40 vol.% in total, including 16–18 vol.% plagioclase (andesine–oligoclase), 14–16 vol.% K-feldspar, 3–4 vol.% clinopyroxene (augite–diopside), and 1–2 vol.% biotite. The same minerals are also present in the groundmass. Accessory minerals are magnetite, zircon and apatite. Common secondary minerals in the vicinity of vein are quartz, calcite, kaolinite and illite. This rock is characterized by 61–64 wt.% SiO₂, 14–15 wt.% Al₂O₃, 4.5–6 wt.% K₂O, 1.7–1.9 K₂O/Na₂O ratio, enrichment in large ion lithophile elements (LILE) and LREE, low high field strength elements (HFSE) and HREE depletion ([La/Yb]N = 9–16.5). This has features typical of high–K calc–alkaline rock and is metaluminous formed in a volcanic arc setting. The magma exhibit low degree of partial melting (>0.1 to <3) from a garnet–spinel Iherzolite source, which is contaminated by continental crust (Malekzadeh Shafaroudi et al., 2013b).

The biotite syenite porphyry is other subvolcanic intrusion in the area, which is exposed in the northwest of the map (Figs. 2 and 3C), extensively altered to argillic–silicification alteration zones. This rock has a porphyritic texture (0.2–4 mm) with medium-grained groundmass. The rock consists of 5–6 vol.% plagioclase, 15–20 vol.% K-feldspar, and 1–2 vol.% biotite as phenocrysts. The same minerals are also present in the groundmass. Accessory minerals include magnetite and zircon. Quartz, kaolinite, and illite are the main secondary minerals. Feldspar phenocrysts, especially plagioclase, have been altered to clay minerals.
Fig. 2. Geologic-alteration map of the Sechangi deposit.

Fig. 3. A. Typical outcrop of light gray to green biotite–pyroxene monzonite porphyry. B. Vertical shaft on Pb–Zn (–Cu) vein hosted by biotite–pyroxene monzonite porphyry. C. Typical outcrop of biotite syenite porphyry in the northeastern Sechangi deposit.
3. Hydrothermal alteration

Much of the host rock to the vein mineralization has suffered the effects of hydrothermal alteration and most of the metasomatic changes are clearly associated with the mineral vein. This wall rock alteration is not consistently developed, but three distinct assemblages have been recognized: silicification (quartz vein), argillic, and carbonatization (calcite vein). Alteration styles directly related to Pb–Zn (–Cu) mineralization are fluoritization and silicification associated with minor argillic and carbonatization (Fig. 2). These various alteration styles are briefly described below.

(1) Silicification. Silicification occurs in wall rock as quartz veins and accompanied vein mineralization as quartz–fluorite–galena and quartz–galena veins (generally with open space filling texture) and/or is the dominant gangue mineral in matrix of ore-bearing breccia with lesser amounts of kaolinite and calcite (Fig. 4A, B, and D). Quartz formed in two distinct stages: early-stage quartz–sulfide veins and late quartz as veins and matrix.

(2) Argillic. Argillic is mainly observed within wall rocks near vein mineralization. The alteration minerals, as determined from petrographic and X-ray diffraction studies, include quartz, kaolinite, and illite. Minor clay minerals exist in matrix of galena-bearing breccia.

(3) Carbonization. Carbonatization is late stage of alteration, occurring mainly in wall rocks as calcite veins associated with minor calcite in matrix of breccia. It is clear that the calcite veins are younger than the late-stage quartz veins (Fig. 4C).

(4) Fluoritization. Fluoritization, which is mainly in the form of green granular aggregates, show a close relationship with galena mineralization. In some samples, galena is formed along the borders, cracks, and cleavages of fluorite (Fig. 4E and F). The higher amounts of fluorite and galena grains are brecciated in fault zone and re-deposited associated with quartz ± Fe–oxide ± clay minerals ± calcite as matrix (Fig. 3D). Although, quartz–flourite–galena veins are observed in places.

4. Ore mineralogy

Fault systems are widespread in the Sechangi ore district, reflecting the regional tectonic history of the area. The Pb–Zn (–Cu) deposit in the study area occurs as ore vein situated along fault zone that developed within the Late Eocene biotite–pyroxene monzonite porphyry (Fig. 2). Ore/host-rock relations suggest that post-Late Eocene (younger than 37.5 Ma) faulting prepared an environment appropriate for mineralization. The strike and dip of the vein are N45°W and 80–85°NE, respectively. Vein thickness varies considerably from half a meter to 8 m with 1 to 3 m being...
5. Fluid inclusion studies

5.1. Sampling and methodology

Fluid inclusion data were obtained from surface, trenches, and shallower levels of the vertical shafts of the ore-bearing vein in the area. Fifteen doubly polished wafers (150 μm thick) of fluorite and early-stage quartz crystals prepared for fluid inclusion studies were examined petrographically. They were studied using standard techniques (Roedder, 1958, 1972, 1984) and Linkam THM 600 heating–freezing stage (from −190 to 600 °C) mounted on an Olympus TH4–200 microscope stage at Ferdowsi University of Mashhad, Iran.

The accuracy is estimated to be ±0.2 °C on freezing, ±2 °C below 350 °C and about ±4 above 350 °C on heating. The stage was calibrated at low temperatures with heptane (−90.6 °C), chloroform (−63.0 °C), chlorobenzene (−45.6 °C), n-dodecane (−9.6 °C) and distilled water (0.0 °C). Calibration at 45 °C was made with Merck melting point standard 9645, and at 306 °C with sodium nitrate. Salinity of the fluids trapped in fluid inclusions is calculated based on the temperature of final ice melting ($T_m$) and the equation of Bodnar (1993). Densities are calculated using Flincor software according to microthermometric data (Brown and Lamb, 1989).

5.2. Morphology and inclusion types

Petrographic studies of fluid inclusions in fluorite and early-stage quartz were conducted to identify the hydrothermal fluids and decipher fluid evolution processes. The fluorite and quartz samples were dominated by primary fluid inclusions (with minor secondary fluid inclusions) that are interpreted as representing the fluids present at the time of hydrothermal mineral growth. Primary fluid inclusions are abundant with moderate to large size (typically 8–37 μm, average 22 μm) in fluorite samples (Fig. 6), whereas quartz contains fewer primary fluid inclusions with small size (typically 5–13 μm) (Table 1). Fluid inclusion shapes include elliptical, rod-shaped, round, irregular, and some directional elongated. Fluid inclusions were distributed as clusters, single inclusions, linear arrays, and along fractures or grain boundaries.

At room temperature, all of the measured inclusions are considered primary because they are confined within specific growth zones of the host mineral (Roedder, 1984). The type of inclusions in both fluorite and quartz are two-phase, liquid-rich with a 5–20% vapour in volume percentage inclusions that homogenize into a liquid state upon heating (Fig. 7). The absence of liquid CO$_2$ or clathrate formation during freezing experiments suggests that none of the inclusions contained significant quantities of CO$_2$. Despite many measurements, fluid inclusion evidence for a fluid boiling process in the Sechangi samples is not clear.

5.3. Microthermometric measurements

Homogenization temperatures ($T_h$) values range from 151 to 352 °C (average 251 °C, $n = 621$) in fluorite and 161 to 215 °C (average 185 °C, $n = 58$) in quartz (Table 1 and Fig. 8A). These $T_h$ values represent a minimum temperature of trapping of the hydrothermal fluid in the inclusion. The precise pressure during mineralization is unknown in the area. On the other hand, no boiling phenomena are seen in the fluid inclusions; according to the data of Hass (1971) this would indicate that if a hydrostatic head is assumed, then the temperature of mineralization could not have been more than about 330 °C. Thus the $T_h$ values are probably quite close to the true (“trapping”) temperatures, and only a minimal temperature correction would be necessary. The average $T_h$ values of primary
inclusions in fluorite and quartz indicate that the temperature of the mineralizing fluids was slightly higher during fluorite precipitation in the earliest stage, and decreased through later stages of mineralization (quartz precipitation) (Fig. 8A). Fluorite and galena show a close relationship with another. The results of microthermometric measurements confirm that the deposit can be classified as a medium- to low-temperature deposit.

The first melting temperatures (\(T_{fm}\)) values of primary inclusions in both fluorite and quartz crystals cluster between \(-55\) and \(-52.2\) °C (average \(-53.6\) °C, \(n = 679\)). Comparison of the values to the eutectic temperatures of various water–salt systems (Shepherd et al., 1985; Gokce, 2000) suggests that they indicate hydrothermal fluids containing salts of CaCl\(_2\), MgCl\(_2\), and NaCl. No difference between samples collected from surface and mine exposures was detected; this indicates that the salt composition of the fluid was homogenous during earlier and later mineralizing episodes. These salt types and compositions may be a result of circulation of the mineralizing fluid through various Tertiary igneous rocks.

The final ice melting temperatures (\(T_{m,ice}\)) values range from 0.1 to \(-12.6\) °C (average \(-7.1\) °C, \(n = 621\)) in fluorite and 0.1 to \(-6.4\) °C (average \(-4.3\) °C, \(n = 58\)) in quartz (Table 1 and Fig. 8B). Salinities...
Table 1
Microthermometric data of primary fluid inclusions of the Sechangi deposit.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Host mineral</th>
<th>Number</th>
<th>Size (μm)</th>
<th>$T_h$ (°C)</th>
<th>$T_{mice}$ (°C)</th>
<th>Salinity (NaCl wt.% equiv.)</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC18-2</td>
<td>Fluorite</td>
<td>40</td>
<td>8–30</td>
<td>151–265</td>
<td>-4 to -9.3</td>
<td>6.4–13.2</td>
<td>0.89–0.98</td>
</tr>
<tr>
<td>SC32</td>
<td>Quartz</td>
<td>7</td>
<td>5–10</td>
<td>161–202</td>
<td>-4.2 to -6.4</td>
<td>6.7–9.7</td>
<td>0.93–0.97</td>
</tr>
<tr>
<td>SC44</td>
<td>Fluorite</td>
<td>21</td>
<td>7–20</td>
<td>184–245</td>
<td>-3.2 to -6.4</td>
<td>5.2–9.7</td>
<td>0.89–0.93</td>
</tr>
<tr>
<td>SC26</td>
<td>Fluorite</td>
<td>40</td>
<td>10–35</td>
<td>190–301</td>
<td>-5 to -12.3</td>
<td>7.8–15.4</td>
<td>0.87–0.97</td>
</tr>
<tr>
<td>SC3</td>
<td>Fluorite</td>
<td>5</td>
<td>5–10</td>
<td>167–197</td>
<td>0.1 to -4.2</td>
<td>0–6.7</td>
<td>0.88–0.92</td>
</tr>
<tr>
<td>SC37 Fluorite</td>
<td>15</td>
<td>7–27</td>
<td>151–245</td>
<td>0.1 to -5.2</td>
<td>0.2–8.1</td>
<td>0.88–0.96</td>
<td></td>
</tr>
<tr>
<td>SC46 Fluorite</td>
<td>37</td>
<td>12–30</td>
<td>165–279</td>
<td>-1 to -11.2</td>
<td>1.6–15.2</td>
<td>0.86–0.94</td>
<td></td>
</tr>
<tr>
<td>SC46 Fluorite</td>
<td>79</td>
<td>11–37</td>
<td>171–341</td>
<td>-3.2 to -12.4</td>
<td>5.2–16.3</td>
<td>0.83–0.95</td>
<td></td>
</tr>
<tr>
<td>SC38 Fluorite</td>
<td>43</td>
<td>9–29</td>
<td>176–300</td>
<td>-3.4 to -11.5</td>
<td>5.5–15.5</td>
<td>0.87–0.95</td>
<td></td>
</tr>
<tr>
<td>SC30 Fluorite</td>
<td>103</td>
<td>8–32</td>
<td>166–352</td>
<td>-2.6 to -12.8</td>
<td>4.2–16.5</td>
<td>0.83–0.94</td>
<td></td>
</tr>
<tr>
<td>SC18 Fluorite</td>
<td>32</td>
<td>8–26</td>
<td>202–312</td>
<td>-2.5 to -11.4</td>
<td>4.1–15.4</td>
<td>0.86–0.9</td>
<td></td>
</tr>
<tr>
<td>SC29 Fluorite</td>
<td>54</td>
<td>12–36</td>
<td>222–324</td>
<td>-3.2 to -12.4</td>
<td>5.2–16.3</td>
<td>0.85–0.9</td>
<td></td>
</tr>
<tr>
<td>SC33 Quartz</td>
<td>26</td>
<td>5–12</td>
<td>166–212</td>
<td>-2.2 to -5.5</td>
<td>3.6–8.5</td>
<td>0.91–0.95</td>
<td></td>
</tr>
<tr>
<td>SC33 Quartz</td>
<td>26</td>
<td>9–31</td>
<td>200–252</td>
<td>-2.1 to -6.8</td>
<td>3.4–10.2</td>
<td>0.87–0.93</td>
<td></td>
</tr>
<tr>
<td>SC42 Fluorite</td>
<td>40</td>
<td>8–34</td>
<td>184–285</td>
<td>-3.2 to -9.5</td>
<td>5.2–13.4</td>
<td>0.88–0.93</td>
<td></td>
</tr>
<tr>
<td>SC47 Fluorite</td>
<td>39</td>
<td>11–27</td>
<td>214–330</td>
<td>-3.2 to -12.4</td>
<td>5.2–16.3</td>
<td>0.85–0.9</td>
<td></td>
</tr>
<tr>
<td>SC47 Quartz</td>
<td>11</td>
<td>5–13</td>
<td>175–214</td>
<td>-3.2 to -5.3</td>
<td>5.2–8.2</td>
<td>0.91–0.95</td>
<td></td>
</tr>
<tr>
<td>SC48 Quartz</td>
<td>8</td>
<td>5–10</td>
<td>174–215</td>
<td>-2.2 to -5.6</td>
<td>3.6–8.7</td>
<td>0.91–0.95</td>
<td></td>
</tr>
<tr>
<td>SC48 Fluorite</td>
<td>27</td>
<td>10–27</td>
<td>254–340</td>
<td>-6.2 to -12.2</td>
<td>9.5–16.2</td>
<td>0.84–0.9</td>
<td></td>
</tr>
<tr>
<td>SC45 Fluorite</td>
<td>25</td>
<td>8–29</td>
<td>216–289</td>
<td>-4.3 to -9.4</td>
<td>6.8–13.3</td>
<td>0.87–0.89</td>
<td></td>
</tr>
</tbody>
</table>

$T_h$, homogenization temperature; $T_{mice}$, temperature for final ice melting.

Fig. 7. Micropictures of liquid–vapour inclusions in the Sechangi deposit.

Fig. 8. Histogram showing the thermodynamic data of primary fluid inclusions in the Sechangi deposit. A. Homogenization temperature histogram, B. Final ice melting temperature histogram, and C. Salinity (wt.% NaCl equivalent) histogram.
gas in a continuous-flow gas-ratio mass spectrometer using an elemental analyzer (Costech) (Ohmoto and Rye, 1979). The sulfur isotope compositions of the Sechangi deposit. 

Many studies have demonstrated the importance of isotopic analyses in elucidating the origin of hydrothermal fluids (Criss and Farquhar, 2008; Huang et al., 2011). Galena in the vein at the Sechangi ranges in \( \delta^{34}S \) values from around −12.3‰ to −8.3‰ (average −9.3‰) and the \( \delta^{34}S_{\text{fluid}} \) in equilibrium with galena were estimated to be in the range of −9.9‰ to −5.9‰ (average −7.9‰). The absence of sulfate minerals in the vein suggests that sulfur was transported in a reduced state, most likely as HS\(^-\) or H\(_2\)S. The negative \( \delta^{34}S \) values do not point to a specific source for sulfur and other metallogenic elements and help to decipher the conditions of formation of sulfides in ore deposits (Ohmoto, 1972; Ohmoto and Goldhaber, 1997). Sulfur isotopic results are listed in Table 2. The sulfur isotopic compositions (i.e. \( \delta^{34}S \)) of these samples were −12.3‰ to −8.3‰, with an average value of −9.3‰ (n = 13). In term of \( \delta^{34}S \) values, there is not a significant difference between the analyzed samples. Under the physical and chemical conditions (T < 300 °C, low pH and Eh) envisaged for the main stage fluids the major sulfur species would be H\(_2\)S (Ohmoto and Rye, 1979). At these temperatures, sulfide dominance results in sulfide mineral \( \delta^{34}S \) values being close to the original fluid \( \delta^{34}S_{\text{fluid}} \) (Ohmoto and Rye, 1979). The \( \delta^{34}S_{\text{CĐT}} \) values of H\(_2\)S in equilibrium with galena were estimated to be in the range of −9.9‰ to −5.9‰ (average −7.9‰) by evaluating the \( \delta^{34}S \) values of galena and the average temperature of the hydrothermal fluid during the galena mineralization episode as 201–290 °C (determined by homogenization temperature measurements during fluid inclusion studies in the fluorite samples as closely relationship with galena), using the equation suggested by Li and Liu (2006) (Table 2) (Fig. 9).

6. Discussion

7.1. Evolution of ore-forming fluids

Many studies have demonstrated the importance of isotopic analyses in elucidating the origin of hydrothermal fluids (Criss and Farquhar, 2008; Huang et al., 2011). Galena in the vein at the Sechangi ranges in \( \delta^{34}S \) values from around −12.3‰ to −8.3‰ (average −9.3‰) and the \( \delta^{34}S_{\text{fluid}} \) in equilibrium with galena were estimated to be in the range of −9.9‰ to −5.9‰ (average −7.9‰). The absence of sulfate minerals in the vein suggests that sulfur was transported in a reduced state, most likely as H\(_2\)S, and that the negative \( \delta^{34}S \) values cannot be attributed to fractionation processes. The \( \delta^{34}S \) values do not point to a specific source for sulfur. The negative \( \delta^{34}S \) values do not necessarily rule out a direct magmatic source, as a wide spread in \( \delta^{34}S \) values, −10‰ to over +10‰ has been indicated for much arc- and rift-related magma
The relatively low salinities argue against a direct magmatic source for fluids. A possible source for $^{34}$S-depleted sulfur would be sulfide-bearing sedimentary rocks. However, such rocks are not identified in the area around the deposit. We suggest that sulfur was likely supplied through leaching of the older volcanic and plutonic rocks. Oxygen and hydrogen isotope data are required to be able to further discuss the source of the ore fluids.

Our analyses of fluid inclusions of the Sechangi Pb–Zn (–Cu) deposit revealed that the ore-forming fluids were medium–low temperature and medium–low salinity H$_2$O–NaCl system fluid. The pressure determined for Sechangi deposit is ca. <20 MPa, which is equivalent to a depth of approximately <2 km and <1 km, assuming hydrostatic and lithostatic pressure, respectively (Fig. 10). This implies that the vein was formed at shallow depth.

On the fluid evolution diagram (Fig. 11), homogenization temperature shows a positive correlation with fluid salinity. Previous studies have shown that homogenization temperature and fluid salinity, as well as fluid salinity and enthalpy, show positive correlation the process of fluid mixing, whereas the data show negative correlation trends during fluid boiling (Shepherd et al., 1985). According to the evidence for fluid mixing outlined by Zhang (1997), the characteristics of fluid evolution of the Sechangi deposit are consistent with a fluid-mixing scenario. Specifically, the salinity-homogenization temperature diagram showed a fluid evolution trend shifting from relatively high to relatively low homogenization temperature and salinity (Fig. 11). The homogenization temperature and salinity of the mineralizing fluids was slightly higher during fluorite precipitation in the earliest stage associated with galena, and decreased through later stages of mineralization (quartz precipitation) (Fig. 11). Based on these arguments, it is suggested that fluid mixing occurred during the fluid evolution. It is well known that this mechanism can play an important role in explaining the origin and formation of large hydrothermal ore deposits (Zhu et al., 2001; Cooke and McPhail, 2001).

---

**Fig. 10.** Pressure–temperature diagram showing phase relationships in the NaCl–H$_2$O system at lithostatic and hydrostatic pressures (Fournier, 1999). L = liquid, V = vapor, H = halite. Thin dashed lines are contours of constant wt percent NaCl dissolved in brine. Filled gray line indicates granite minimum melting curve. Filled dark line shows the three-phase boundary, L + V + H, for the system NaCl–KCl–H$_2$O with Na/K in solution fixed by equilibration with albite and K-feldspar at the indicated temperatures. Location of fluorite and quartz fluid inclusions plotted on it.

**Fig. 11.** Homogenization temperature versus salinity diagram for fluid inclusions in the Sechangi deposit. Several possible trends of fluid evolution in a temperature–salinity diagram from Shepherd et al. (1985). Trend 1 represents primitive fluid A mixed with cold and low salinity fluid B, trends 2 and 3 represent the result of fluid A isothermally mixing with different salinity fluid B, trend 4 represents the salinity of residual phase increased, caused by boiling of fluid A, trend 5 represents cooling of fluid A, trend 6 represents necking of the fluid inclusion, trend 7 represents leakage of fluid inclusions during heating.
2001; Fan et al., 2011; Gu et al., 2011; Zhai et al., 2013), and it seems clear for the Sechangi deposit that fluid mixing played an important role. Also, relationship between homogenization temperature, salinity, and fields for various fluid types (Fig. 12) probably indicates that magmatic–meteoric mixing fluid was responsible for ore mineralization at the Sechangi. Although, oxygen and hydrogen isotope data are required to confirm this claim. There is also overlap with metamorphic fluids in Fig. 12, but there is no evidence of metamorphic rocks or regional metamorphism in the area. Fig. 13 represents the most of homogenization temperature and salinity data of fluid inclusions plotted in the field of epithermal deposit.

7.2. Mineralization model and genetic type

The Lut block has a great potential for porphyry Cu and Cu–Au, related-epithermal Au, and Cu–Pb–Zn vein-type deposits due to its past subduction zone tectonic setting between the Lut and the Afghan blocks, which led to extensive magmatic activity forming igneous rocks of different geochemical compositions (Malekzadeh Shafaroudi, 2009; Karimpour et al., 2011). A few detailed studies were reported about genetic model and formation of base-metal epithermal deposits in the Lut block (Lotfi, 1982; Mehrabi and Talefazel, 2011; Mehrabi et al., 2011; Mirzaei Rayeni et al., 2012; Malekzadeh Shafaroudi and Karimpour, 2013b).

![Fig. 13. Homogenization temperature–salinity diagram illustrating typical ranges for inclusions from different deposit types (modified after Wilkinson, 2001). The most microthermometric data of fluid inclusions in the Sechangi deposit plot in the epithermal deposit field.](image1)

![Fig. 14. Model for formation of the Sechangi deposit (see text for detail-not to scale).](image2)
The Sechangi deposit is one of the many epithermal Pb–Zn (–Cu) deposits, which is occurred in metallogenic epoch of the Lut block (Middle Eocene to Lower Oligocene), as suggested by Karimpour et al. (2012). A geologic and genetic relation between ore vein and Late Eocene biotite–pyroxene monzonite porphyry appears to be lacking. Therefore, the age of mineralization is younger than 37.5 Ma. On the basis of the regional episodes of prolific magmatic activity, a widespread episode of mineralization, and the specifics of ore deposit geology, we consider the formation of the Sechangi deposit to be directly linked to volcanic–subvolcanic hydrothermal activity of Late Eocene (younger than 37.5 Ma) and/or a few after it period. Coupled with late-stage addition of meteoric water, these magmatic fluids created favorable conditions for the metallogenic elements to accumulate and precipitate during the formation of such a relatively large ore deposit. During the Late Eocene and after it periods, intense magmatic activity in the Sechangi region resulted in the generation of a series of calc-alkaline magmas. In addition, NW–SE and minor NE–SW-trending faults were formed due to these intense tectonic and magmatic activities. Subvolcanic intrusions were formed from magmas ascending along favorable structural pathways (such as faults or fractures).

The early ore-forming fluids had relatively high temperature, salinity, and concentration of metallogenic elements such as Pb²⁺, Zn²⁺, and Cu²⁺, and were formed by magmatic differentiation and by the evolution of volcanic and subvolcanic fluids (Fig. 14). Ore-forming fluids ascended along favorable structures and reacted with wall rock, changing the physicochemical conditions and isotopic compositions of the fluids. In addition, the fluids seem to have ascended to a sufficiently shallow depth to allow for efficient fluid mixing with meteoric water (Fig. 14). Through the reaction of mineralizing fluids with wall rock and heat recharge by magma or geothermal anomalies in the region, the meteoric water, which initially had relatively low temperature and salinity, might have extracted significant amounts of metallogenic materials from host rock. Through mixing between fluids with different properties and metal contents, these combined fluids changed the conditions of the ore-forming fluid system, destroying the chemical equilibrium of solutions and initiating important chemical reactions, ultimately resulting in the precipitation from solution of metallogenic materials during the formation of this relatively large ore deposit (Fig. 14). Consequently, fluid mixing seems to represent an important mechanism for explaining the formation of the Sechangi deposit, which can be confirmed by oxygen and hydrogen isotope data. In addition, the genetic type of the Sechangi Pb–Zn (–Cu) deposit is classified as a volcanic–subvolcanic hydrothermal-related vein deposit.

8. Conclusions

(1) The Sechangi Pb–Zn (–Cu) deposit occurs in an area covered by the Eocene felsic-intermediate volcanic and intrusive rocks, in the western Lut block. The distribution of ore body within the area was controlled primarily by fault. The alteration zone is marked by an assemblage of quartz, kaolinite, illite, and calcite. The ore vein contains galena and sphalerite with minor chalcopyrite and pyrite as hypogene minerals and cerussite, anglesite, covellite, malachite, hematite, and goethite as secondary minerals. Fluorite and quartz are the dominant gangue minerals.

(2) The δ⁸⁷S values for Galena samples from the Sechangi fall in the range −12.3‰ to −8.3‰. The δ³⁴S_COSD values of H₂S in equilibrium with galena were estimated to be in the range of −9.9‰ to −5.9‰ (average −7‰). The sulfur isotope ratios could be explained by derivation from a magmatic source, or leaching of sulfides from the country rocks.

(3) Fluid inclusion data indicate that the ore forming fluids contain significant quantities of divalent cations (CaCl₂ and MgCl₂), along with NaCl. The homogenization of liquid temperatures are in the range 151–352 °C (average 251 °C) in fluorite and decrease down to 161–215 °C (average 185 °C) in quartz. The salinity of fluids was in the range of 0.2–16.5 wt.% NaCl equivalent (average 10.4 wt.% NaCl equivalent) in fluorite and 0.9–9.7 wt.% NaCl equivalent (average 6.7 wt.% NaCl equivalent) in quartz. Microthermometric studies and composition measurements of fluid inclusions show that the general features of the ore-forming fluids involved medium- to low-temperature and medium- to low-salinity in the NaCl–H₂O system.

(4) The positive correlation between homogenization temperature and fluid salinity, combined with ore deposit geology, provides evidence that aqueous mixing was an important process in the evolution of the ore-forming fluids. The latter can be divided into two end-member compositions: magmatic and meteoric. Mixing of fluids with different properties and metal contents was an important factor contributing to the formation of Pb–Zn (–Cu) ores in the Sechangi deposit. The sulfur isotopic evidence suggests that two or more fluids existed during the formation of the Sechangi deposit.

(5) The formation of the Sechangi Pb–Zn (–Cu) ore deposit was controlled by hydrothermal fluids related to Late Eocene (younger than 37.5 Ma) and/or a few later magmatic activity in the Lut block. Mineralization was a product of magmatism derived from a mantle source. In terms of the genetic type of deposit, the Sechangi is classified as a volcanic–subvolcanic hydrothermal-related vein deposit. Prospecting for new deposits should be concentrated in the Lut block.

Acknowledgments

The Research Foundation of Ferdowsi University of Mashhad, Iran, supported this study (Project No. 22745.2). Thanks to Dr. Chris Eastoe (University of Arizona) for the S-isotope analyses and anonymous reviewers for their constructive and helpful reviews on this manuscript.

References

Berberian, M., 1982. Continental Deformation on the Iranian Plateau. Geological Survey of Iran, supported this study (Project No. 22745.2). Thanks to Dr. Chris Eastoe (University of Arizona) for the S-isotope analyses and anonymous reviewers for their constructive and helpful reviews on this manuscript.

References

