Mineralium Deposita

The Chahmir sediment hosted Zn-Pb deposit, Central Iran: An example of vent-proximal SEDEX mineralization

--Manuscript Draft--

Manuscript Number:	
Full Title:	The Chahmir sediment hosted Zn-Pb deposit, Central Iran: An example of vent-proximal SEDEX mineralization
Article Type:	Regular Articles
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Abstract:	<p>The Chahmir zinc-lead deposit, located in Central Iran, is one among several sedimentary-exhalative (SEDEX) Zn-Pb deposits hosted in the Zarigan-Chahmir basin (e.g. Koushk, Darreh-Dehu and Zarigan). The host unit consists of carbonaceous, fine-grained black siltstones with intercalations of lithic crystal and silty tuffs. It corresponds to the upper part of the Early Cambrian volcano-sedimentary sequence (ECVSS), which was deposited on the Posht-e-Badam Block attending back-arc rifting of the continental margin of Central Iran. Based on the cross-cutting relationships, mineralogy and textures of sulfide mineralization, four different facies can be distinguished in the Chahmir deposit: feeder zone (stockwork), vent complex, bedded ore, and distal facies (exhalites). Silicification, carbonatization, sericitization and chloritization are the main wall-rock alterations; alteration intensity increases toward the proximal feeder zone. Whole-rock trace element (including REE) analyses were performed and normalized to the NASC standard. The REE patterns show a weak positive anomaly of Eu in the bedded ore relative to the vent complex. In addition, there is a strong enrichment of Ba in the distal facies (up to 2.57 %).</p> <p>Fluid inclusion microthermometry was carried out on quartz associated to sulfide ores of the vent complex. Temperature of homogenization (Th) of primary, two-phase inclusions ranged from 170° to 226° C, with an average of 202° C. This mean (and mode) temperature could represent the main hydrothermal stage recognized in the vent complex. Ice melting temperatures (Tml) ranged from -8.8° to -2.5° C, corresponding to salinities of 4.2 to 12.7 wt. % NaCl eq., with an average of 9 wt. % NaCl eq. and a mode around 9–10 wt. % NaCl eq. Microthermometry suggests that mineralizing fluids were of moderately high temperature (~202° C) and salinity (9 wt. % NaCl eq.), whereas reduced and acidic conditions have been inferred from trace element contents</p> <p>The $\delta^{34}\text{S}$ of pyrite, sphalerite and galena ranges from +10.9 to +29.8 ‰ (n=12). The highest $\delta^{34}\text{S}$ values correspond to the bedded ore (+28.6 to +29.8 ‰) and the lowest to the vent complex (+10.9 to +14.7 ‰) and the feeder zone (+11.3 and +12.1 ‰). The overall range of $\delta^{34}\text{S}$ is well above than the typical magmatic values, being consistent with a sedimentary environment where sulfide sulfur was derived from seawater sulfate</p>

	<p>reduction. The abundance of ^{34}S-enriched values in the bedded ore reflects marine inputs into a restricted setting in the Zarigan-Chahmir basin that may have been shut off from the open ocean. Sulfur isotopes, along with the sedimentological, textural, mineralogical, fluid inclusion and geochemical characteristics of the Chahmir deposit are in agreement with a vent-proximal (Selwyn type) SEDEX ore deposit model.</p>
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The Chahmir sediment hosted Zn-Pb deposit, Central Iran: An example of vent-proximal SEDEX mineralization

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Abstract

The Chahmir zinc-lead deposit, located in Central Iran, is one among several sedimentary-exhalative (SEDEX) Zn-Pb deposits hosted in the Zarigan-Chahmir basin (e.g. Koushk, Darreh-Dehu and Zarigan). The host unit consists of carbonaceous, fine-grained black siltstones with intercalations of lithic crystal and silty tuffs. It corresponds to the upper part of the Early Cambrian volcano-sedimentary sequence (ECVSS), which was deposited on the Posht-e-Badam Block attending back-arc rifting of the continental margin of Central Iran. Based on the cross-cutting relationships, mineralogy and textures of sulfide mineralization, four different facies can be distinguished in the Chahmir deposit: feeder zone (stockwork), vent complex, bedded ore, and distal facies (exhalites). Silicification, carbonatization, sericitization and chloritization are the main wall-rock alterations; alteration intensity increases toward the proximal feeder zone. Whole-rock trace element (including REE) analyses were performed and normalized to the NASC standard. The REE patterns show a weak positive anomaly of Eu in the bedded ore relative to the vent complex. In addition, there is a strong enrichment of Ba in the distal facies (up to 2.57 %).

Fluid inclusion microthermometry was carried out on quartz associated to sulfide ores of the vent complex. Temperature of homogenization (T_h) of primary, two-phase inclusions ranged from 170° to 226° C, with an average of 202° C. This mean (and mode) temperature could represent the main hydrothermal stage recognized in the vent complex. Ice melting temperatures (T_{ml}) ranged from -8.8° to -2.5° C, corresponding to salinities of 4.2 to 12.7 wt. % NaCl eq., with an average of 9 wt. % NaCl eq. and a mode around 9–10 wt. % NaCl eq. Microthermometry suggests that mineralizing fluids were of moderately high temperature (~202° C) and salinity (9 wt. % NaCl eq.), whereas reduced and acidic conditions have been inferred from trace element contents

The $\delta^{34}\text{S}$ of pyrite, sphalerite and galena ranges from +10.9 to +29.8 ‰ (n=12). The highest $\delta^{34}\text{S}$ values correspond to the bedded ore (+28.6 to +29.8 ‰) and the lowest to the vent complex (+10.9 to +14.7 ‰) and the feeder zone (+11.3 and +12.1 ‰). The overall range of $\delta^{34}\text{S}$ is well above than the typical magmatic values, being consistent with a sedimentary environment where sulfide sulfur was

1 derived from seawater sulfate reduction. The abundance of ^{34}S -enriched values in the bedded ore
2 reflects marine inputs into a restricted setting in the Zarigan-Chahmir basin that may has been shut off
3 from the open ocean. Sulfur isotopes, along with the sedimentological, textural, mineralogical, fluid
4 inclusion and geochemical characteristics of the Chahmir deposit are in agreement with a vent-
5 proximal (Selwyn type) SEDEX ore deposit model.
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14 *Keywords:* Sulfate reduction. Hydrothermal vents. Posht-e-Badam Block. Sulfur isotopes. Fluid
15 inclusions. Trace-element geochemistry.
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21 **Introduction**

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26 The Zarigan-Chahmir basin (Fig. 1a), which extends along the major part of the Central Iranian
27 micro-continent, is endowed with a large number of mineral deposits, particularly iron oxide-apatite,
28 Kiruna-type deposits, and Zn-Pb deposits hosted by both clastic and carbonate Phanerozoic rocks.
29 Although many of the Zn-Pb deposits are MVT, the largest (Koushk, Zarigan, Chahmir and Darreh-
30 Dehu; Fig. 1b) belong to the SEDEX type (e.g. [Yaghubpur and Mehrabi 1997](#); [Rajabi et al. 2008](#);
31 [Rajabi et al. 2011a](#)). However, there are relatively few published data about the Iranian SEDEX
32 deposits, and their classification, formation conditions and tectonic setting are still poorly understood.
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41 Many SEDEX deposits worldwide hindered extensive recrystallization of sulfides and destruction
42 of primary textures during post-ore deformation and metamorphism; so that, only few deposits, such
43 as HYC, Australia ([Large et al. 2005](#)) and the Iranian deposits, preserve most of their primary,
44 synsedimentary features. Herein, we present a textural and mineralogical characterization, together
45 with sulfur isotope and fluid inclusion data of the Chahmir Zn-Pb deposit, located in the southeast of
46 Bafq district. The weakly deformed and unmetamorphosed Chahmir deposit is probably the best
47 preserved among the Iranian SEDEX deposits.
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1 Bafq Mines Company discovered the Chahmir deposit in 1990, by recognition of traces of ancient
2 mining, and the operation of the mine began in 2006 with the Anguran Mining Group (AMG). The
3 geological exploration techniques by AMG led to the sitting of 34 diamond drill holes, which
4 intersected 40–50 m of sulfide mineralization at a depth of 5–55 m. Cores from this drilling campaign
5 provided the samples on which the present study is based. Based on data of the AMG company that
6 conducted the resource evaluation, the Chahmir deposit contains 1.5 Mt of ore at 6 % Zn and 2 % Pb.
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9 This paper, besides presenting new field and laboratory data, has the aim of revising the tectonic
10 and sedimentary setting of the Chahmir Zn-Pb SEDEX deposit and establishing a reliable
11 metallogenic model for its genesis.
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14 **Tectonic evolution**

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22 The Zarigan-Chahmir basin forms a 150 km long N-S striking central domain of the Posht-e-
23 Badam Block, which in turn is part of the Central Iranian continental micro-plate ([Rajabi et al. 2011b](#))
24 and consists of a Precambrian basement with an Early Cambrian to Tertiary cover ([Haghipour 1974](#)).
25 This basin is bordered by the Kuhbanan-Naein Fault to the east and the Posht-e-Badam Fault to the
26 west. The basin contains thick volcanic and siliciclastic series of the Early Cambrian volcano-
27 sedimentary sequence (ECVSS), which are stratigraphically equivalent to the Rizu and Desu series or
28 Esfordi Formation of the central part of the Posht-e-Badam Block (Fig. 1a, b; [Rajabi et al. 2011b](#)).
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43 The evolution of the Central Iranian micro-continent is related to the orogenic events and growth
44 of Gondwana ([Foster and Jafarzadeh 1994](#)). This micro-continent is divided into three
45 tectonostratigraphic domains: (a) the Lut Block to the east, (b) the Tabas Block in the center, and (c)
46 the Yazd Block to the west. Additionally, [Alavi \(1991\)](#) distinguished the Posht-e-Badam Block (or
47 Kashmar-Kerman tectonic zone; [Ramezani and Tucker 2003](#)) between the Tabas and Yazd blocks.
48 [Berberian and King \(1981\)](#) proposed that this zone has evolved during the Pan-African crustal
49 extension. [Talbot and Alavi \(1996\)](#) suggested that an aborted continental rift took place along the
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northern margin of Gondwana during the Late Neoproterozoic-Early Cambrian. This intra-continental rift was favorable to the SEDEX mineralization processes, leading the formation of the Koushk deposit (Yaghubpur and Mehrabi 1997). Conversely, [Ramezani and Tacker \(2003\)](#) suggested that ages and geochemical characteristics of the Cambrian granitoid suite (~533 Ma) and the Boneh-Shurow granites (542 ±9 Ma), in the Kashmar-Kerman tectonic zone, contradict the intra-continental rift model since marks the termination of the arc magmatism in the west of this zone.

Neoproterozoic paleogeographic reconstructions (e.g. [Stampfli and Borel 2004](#)) and paleomagnetic studies ([Becker et al. 1973](#); [Soffel and Forster 1981](#)) place the Central Iranian micro-continent beside the Arabian and Indian plates, along the Proto-Tethyan margin of Gondwana (Fig. 2). Therefore, new U-Pb zircon dating and studies of the Cambrian granitic rocks ([Ramezani and Tucker 2003](#)) suggest that, during the Late Neoproterozoic–Early Cambrian, the Central Iranian micro-continent developed a magmatic arc on an active continental margin (Peri-Gondwana; Fig. 2). But, the occurrence of bimodal volcanism (rhyolitic and basaltic) to the east of this arc, the extensive spilitic basalts that stretch along several km at Zarigan area ([Rajabi 2008](#)) associated to the thick sequence of detrital and volcano-sedimentary rocks of the ECVSS, suggests an episode of back-arc extension affecting a continental margin ([Rajabi 2008](#); [Rajabi et al. 2011b](#)). It was during that episode when major SEDEX deposits, including Chahmir, formed in the Posht-e-Badam Block.

Geological setting

Late Neoproterozoic, siliciclastic, basaltic and volcanoclastic rocks of the Zarigan-Chahmir basin (Tashk Formation, 627–533 Ma; [Ramezani and Tucker 2003](#)), which appear weakly metamorphosed and folded, unconformably lie on the Boneh-Shurow metamorphic complex (617–602 Ma; [Ramezani and Tucker 2003](#)). The age data restrict the overall depositional age of the Tashk Formation from 627 Ma to Early Cambrian ($^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages; [Ramezani and Tucker 2003](#)). Early Cambrian arc plutons intruded this formation and were followed by felsic to intermediate volcanism of the ECVSS. The basis of the ECVSS hosts the volcanic rhyodacite of the Douzakh-Darreh mountain and the

1 dacitic porphyry of the Zarigan mountain, yielding a $^{206}\text{Pb}/^{238}\text{U}$ zircon age of 528.2 ± 0.8 Ma
2 (Ramezani and Tucker 2003). The 1500–2000 m-thick ECVSS unconformably overlies the Tashk
3 Formation (Haghipour 1974), and is an unmetamorphosed sequence of intermediate to felsic and
4 basaltic lavas, volcanoclastic and tuffaceous rocks, sandstones, shales, black siltstones, dolomites and
5 dolomitic limestones, and minor gypsum beds (Haghipour 1974; Samani 1988; Ramezani and Tucker
6 2003). SEDEX deposits occur within the upper part of the ECVSS. Volcanic rocks are dominant to
7 the basis of this sequence (exposed near the Esfordi and Zarigan areas, in western and northwestern
8 part of the Zarigan-Chahmir basin), while sedimentary rocks are predominant to the top of the
9 sequence (near the Koushk and Chahmir areas, central and eastern parts of the basin) (Rajabi 2008).

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11 The ECVSS is unconformably overlain by Early Cambrian red sandstones and conglomerates
12 (Lalun or Dahu Formation) in the Zarigan and Chahmir areas as well as in the Bafq district (Forster
13 and Jafarzadeh 1994; Rajabi 2008).

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Stratigraphy of the ore-bearing series

1 The Chahmir Zn-Pb deposit is hosted within the upper part of the ECVSS in the southeastern
2 Zarigan-Chahmir basin (Fig. 1b). The footwall rocks are purple to gray shales with interbedded
3 sandstones (litharenites) and sandy tuffs (Fig. 3; Lotfi 2008; Rajabi 2008). The ore-bearing interval
4 (Fig. 4a) consists of carbonaceous, fine-grained black siltstones (Fig. 4b) with intercalations of lithic
5 crystal to silty tuffs (Fig. 4c). This unit is overlain by green tuffs and bedded cherts (Figs. 3, and 4a).
6 Locally, there are sedimentary breccias and debris flow (Fig. 4e) as a typical feature of Chahmir
7 deposit. They form debris flows, both stratiform and discordant (Figs. 4a, e), in the lower part of
8 Chahmir Unit, within an interval of black siltstones with dolomitic nodules (Fig. 4d). Clasts came
9 from rock units that occur stratigraphically below the Chahmir deposit itself. These debris flows
10 abruptly increase in thickness towards the Chahmir Fault, in the northeastern portion of the deposit
11 (Fig. 5). Interfingering of debris flows with fine-grained sediments, along with abrupt lateral changes

in facies and thickness, indicates the proximity of a synsedimentary fault (Lydon 1995; Goodfellow 2004; Large et al. 2005).

Sampling and analytical methods

Documentation of the mineralogy and paragenesis of the Chahmir deposit are based on logging of drill cores and petrographic study of over 60 polished thin and thick sections, supplemented by XL30 scanning electron microscopy conducted at the Tarbiat Modares University, Iran. In addition, polished thin sections were analyzed with a Jeol JXA-8900R electron microprobe at the *Laboratorio Universitario de Petrología* of the *Instituto de Geofísica* (UNAM, Mexico), which allowed us to obtain back-scattered electron (BSE) images and energy dispersive spectrometry (EDS) qualitative analyses.

Doubly polished wafer specimens of quartz crystals were used for fluid inclusion analyses. Samples from drilled cores (nº. 1 and 6) taken within the major massive sulfide ore zone in the deposit and containing quartz crystals and veinlets were selected for investigation. Only inclusions consistent with the criteria of Roedder (1984) for a primary origin and large enough to permit microthermometry measurements were examined. Microthermometry analysis was conducted on the USGS-adopted fluid inclusion freezing and heating stage to determine the liquid–vapor homogenization temperature (Th) and the Ice melting temperatures (Tml). This analysis was conducted at the Department of Geology, Tarbiat Modares University, Tehran, Iran.

For studying the geochemical characteristics and to determine the Zn, Pb, Cu, Cd, Ag and Fe distribution in different parts of the deposit, atomic absorption spectroscopy (AAS) and inductively coupled mass spectrometry (ICP-MS) analyses (821 and 15, respectively) have been performed on whole-rock samples collected from bore holes. The AAS analyses were performed in the Esfordi and AMG laboratories of Iran, and the ICP-MS analyses of selected rock samples, representative of different parts of ore facies, were carried out in the ALS-Chemex laboratories of Canada.

Sulfur isotope data were obtained from pyrite, sphalerite and galena separates from diamond drill cores of the Chahmir deposit. Sulfides were separated obtaining almost monomineralic samples using a microdrill under a binocular microscope. The microdrill was cleaned between each sample extraction to avoid contamination. Samples were analyzed by mass spectrometry using a Delta C Finnigan MAT continuous flow isotope-ratio mass spectrometer with an elemental analyzer, a TC-EA. These analyses were carried out at the *Serveis Científic-Tècnics* of the *Universitat de Barcelona*, Spain. The results are given as $\delta^{34}\text{S}$ ‰ values relative to the V-CDT standard. The analytical precision is within ± 0.1 ‰ at 1 σ .

Mineralization

The sulfide lens of the Chahmir deposit do not crop out, so that the geological setting of the deposit has been reconstructed from drill core logs and lithogeochemical data for samples collected from drill cores. A NE-SW cross-section of the deposit is shown in Fig. 5.

Sulfide mineralization occurs as a stretched wedge within the carbonaceous black siltstones and has a moderately high (13) aspect ratio (i.e. ratio of lateral extent to the thickness of ore lens). The northeastern part of the deposit has a stratabound geometry, but toward the southwest, as thickness decreases, the mineralization becomes stratiform and concordant to host sediments (Fig. 5).

The Chahmir deposit consists of four ore facies, which are, from proximal (NE) to distal (SW) from the synsedimentary fault (Fig. 5): (1) a feeder zone: a stockwork of sulfide-, carbonate- and quartz-bearing veins; (2) a vent complex: a massive sulfide zone with sulfide breccias; (3) bedded ore: a banded body of pyrite, sphalerite and disseminated galena; and (4) a distal facies (exhalites): beds of chert with barite and disseminated pyrite.

Feeder Zone

1 The stockwork system, through which mineralizing fluids vented to the seafloor (Goodfellow,
2 2004), consists of irregular veins of fine-grained quartz, pyrite, sphalerite, galena and dolomite cutting
3 altered and brecciated sediments (Fig. 6). Dolomite and quartz occur within the center of veins (Fig.
4 6c). Veins range from <1 mm to 2 cm in width and constitute up to 7 % of the host rock. Density of
5 veining increases stratigraphically upwards, until the base of the vent complex (Fig. 5). This vein
6 mineralization occurs adjacent to the Chahmir synsedimentary fault (Fig. 6d). Debris flows and abrupt
7 facies changes occur adjacent to the feeder zone (Fig. 5). Most of the sulfide veins present an
8 alteration halo and show a partial replacement of pyrite by sphalerite.

19 ***Vent Complex***

25 The vent complex forms the thickest orebody and lies over the feeder zone, in the NE part of the
26 deposit. This facies displays massive, replacive and brecciated textures (Fig. 7), and shows mineral
27 and textural zoning from core to margin as follow (Fig. 5): (1) stockwork and massive sulfide-silica-
28 carbonate (SSC) sub-facies: massive pyrite and Fe-rich sphalerite with veins of galena and quartz
29 (Figs. 7a, b, c, d); and (2) massive sulfide-carbonate (SC) sub-facies: brecciated pyrite colloform
30 aggregates that are replaced by sphalerite within a ferroan carbonate matrix, crosscut by minor galena
31 veins (Figs. 7e, f, g). In general, pyrite grains are partly replaced by sphalerite.

41 The SSC sub-facies is much higher in grade (15–39 % Zn+Pb) than the SC sub-facies (10–20 %
42 Zn+Pb).

48 ***Bedded Ore facies***

51 The bedded ore facies consist in low-grade, layered ores that occur in the center of the deposit,
52 southwest of the Vent Complex (Fig. 5). They form stratiform bodies of laminated to banded sulfides,
53 mostly pyrite (py₁) and sphalerite (sph₁) that are concordantly interbedded with the host sedimentary
54 rocks. Galena occurs as disseminated grains. Four lamina types have been recognized at the

millimeter scale (Fig. 8): (1) silt laminae, (2) organic matter-rich laminae, (3) sulfide-rich laminae, and (4) mixed laminae (Fig. 8g) that consist of mixtures of sulfides, silt and carbonaceous matter. The silt laminae (Fig. 8a, b) are commonly 100–500 μm thick, but layers up to several centimeters are also present. Organic matter-rich laminae (Fig. 8c) are up to 300 μm thick and does not extend laterally (Fig. 8h), usually forming short lenses (Fig. 8c). The sulfide-rich laminae are commonly 100–350 μm thick and are composed of pyrite and sphalerite, usually forming almost monomineralic bands (Fig. 8d, e, f). Contacts between sulfide and silt laminae can be sharp or diffuse. At the microscopic scale, pyrite forms framboidal aggregates (Fig. 9a, b). Sphalerite (sph_1) laminae are less common than pyrite laminae; they are only ubiquitous in the high-grade part of the bedded ore facies. Sulfide laminae show sedimentary structures such as load-casts (Fig. 8h). Barite occurs in trace amounts, as disseminated grains within this facies.

The bedded ore facies can be divided into low-grade and high-grade (Fig. 5), so that sphalerite-rich laminae are scarce within the low-grade parts of the bedded ore.

Distal facies

The outer southwestern margin of the deposit consists of exhalites, i.e. bedded hydrothermal products, which are mostly banded cherts with pyrite, dolomite and barite (Fig. 10). This facies has no economic value, and represents the most distal part of the hydrothermal deposit (Fig. 5).

Disseminated barite occurs associated to manganoan dolomite (Fig. 10a). Barite is a common component in the distal facies of most Paleozoic and younger vent-proximal SEDEX deposits, but it is absent in the entire vent-Distal SEDEX deposits, mostly Proterozoic in age (Cooke et al. 2000). It is very common in the distal facies of the Chahmir deposit, although also occurs in the bedded ore. Manganese contents attain 4050–6000 ppm in the dolomite-bearing exhalites (Fig. 11a) and decrease away from southwest of the deposit.

Hydrothermal alteration

Several SEDEX deposits worldwide are known to be underlain by stockwork mineralizations assumed as ancient hydrothermal feeder zones; however, the hydrothermal alteration usually developed around these stockworks has been rarely documented and mapped in detail (Goodfellow and Lydon 2007). The host rocks of the Chahmir deposit show intense hydrothermal alteration, consisting in sericitization, silicification, carbonatization and chloritization. The overall hydrothermal alteration pattern is illustrated by the NE-SW cross-section of deposit (Fig. 11b).

Sericitization is the broadest alteration in the deposit and strongly affects the coarse sedimentary breccias at stratigraphic levels beneath the high-grade bedded ore horizon (Fig. 11b). Under the microscope, it is observed as a replacement of feldspars by sericite. The intensity of this alteration increases towards the feeder zone.

Silicification is the main alteration within the SSC and occurs as open space filling and quartz veins accompanied with galena (PbS), being associated with the high-grade ores (Fig. 7a, b). Also, this alteration occurs in the feeder zone (Fig. 6d).

Carbonate alteration is developed particularly in the footwall siltstones adjacent to the feeder zone, but extends away laterally along the most permeable sedimentary layers. Hence, it resulted in the formation of calcite and dolomite within the vent complex (mostly in SC, Fig. 7c) and around the feeder zone, and manganoan dolomite within distal facies (Fig. 11b).

Chloritization is the less developed alteration zone, being restricted to the tuffaceous layers of the Chahmir Unit, adjacent to the feeder zone in the northeastern part of the deposit (Fig. 11b). It resulted in the formation of Mg-rich chlorite after mafic grains, especially biotite.

Paragenetic Sequence

1 The sulfide mineralogy of the Chahmir deposit is dominated by pyrite, sphalerite and galena, with
2 minor chalcopyrite. Traces of native gold and apatite are associated with these sulfides in the bedded
3 ore. Quartz, calcite, dolomite, barite, albite, illite, chlorite and sericite are the most common gangue
4 minerals. The sphalerite content of the massive ore lens increases from the base to top, and the content
5 of other sulfides concomitantly decreases.
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10 Based on mineral textures and crosscutting relationships, two main stages of primary sulfide
11 mineralization are recognized (Fig. 12). These hydrothermal stages probably were not discrete
12 episodes but likely overlapped temporally, as has been documented for other SEDEX deposits in
13 Central Iran ([Rajabi et al. 2011a](#)):
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20 1) The first stage of mineralization was responsible for the formation of framboidal and
21 laminated pyrite (py_1) (Figs. 8e, f, and 9a, b), colloform pyrite (Fig. 9c), laminated and
22 disseminated Fe-poor sphalerite (sph_1) (Fig. 8g) and fine-grained disseminated galena (gn_1), mainly
23 in the bedded ore and rarely in the distal facies. There is euhedral fine grained pyrite or galena at
24 the core of the framboidal aggregates of pyrite (Fig. 9a, b). Colloform pyrite aggregates are
25 common in the SC of the vent complex, but were brecciated during the next stage of mineralization.
26 Some of these colloform textures show pyrite and galena alternating layers (Fig. 9d, e). Associated
27 with this stage, some disseminated gold and apatite precipitated in the bedded ore facies (Fig. 9a),
28 and barite in the distal facies (Fig. 10a) and, to a lesser degree, in the bedded ore. Sulfides show
29 some sedimentary structures affecting the laminae formed during this stage (e.g. load casts; Fig.
30 8g).
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45 2) The second stage indicates zone refining of mineralization and includes massive, vein and
46 replacement pyrite (py_2), Fe-rich sphalerite (sph_2) and coarse grained galena (gn_2), mainly in vent
47 complex (Fig. 7). The low ratio of clastic to hydrothermal components and the complex mineral
48 paragenesis are the main features of this stage of mineralization. These features indicate multiple
49 episodes of hydrothermal discharge from the same vent and rapid fluid evolution during discharge
50 to the seafloor. This main stage is divided in two mineralization sub-stages that cannot be
51 completely separated each other:
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2 A) A first sub-stage is characterized by the occurrence of veins of sulfides, mainly coarse-grained pyrite (py₂), and carbonates, throughout the vent complex and the feeder zone. It is associated to breccification of sulfides (colloform pyrite) and to carbonate alteration in the vent complex (Fig. 7e, g) and around the feeder zone.

2 B) A second sub-stage replaces earlier phases and produced sphalerite, galena and quartz veins within the core of the vent complex and the feeder zone (Figs. 7a, b, c and f). During this sub-stage, pyrite (py₂) was replaced by an assemblage of sphalerite (sph₂), galena (gn₂) and arsenopyrite (Fig. 9f), and quartz formed within the massive sulfide ores (Fig. 9g). This sub-stage caused the silicification of the SSC sub-facies of vent complex and the growth of massive sulfide ores in the northeastern deposit.

A third generation of pyrite (py₃) formed coating the framboidal and colloform aggregates (Fig. 13), commonly in the bedded ore and the vent complex. This pyrite forms euhedral cubic crystals as overgrowths on py₁. Taking into account these textures, we consider that py₃ has nucleated on the preexisting py₁, marking a post-mineralization, diagenetic stage of the deposit.

Textural and metal zonation

One of the most characteristic features of SEDEX deposits is the vertical and lateral zonation of textures, minerals and metals (Goodfellow 2004). In the Chahmir deposit, there is a gradual change, away from the feeder zone, from (a) veins and massive replacement textures in the vent complex, to (b) sedimentary textures (laminated, disseminated and framboidal), in the bedded ore and distal facies (Fig. 5). This trend is accompanied a decrease in the number and thickness of individual sulfide beds. This zonation is controlled mostly by zone refining in the vent complex (Cooke et al. 2000; Goodfellow and Lydon 2007).

The deposit has a marked chemical zonation. In terms of metal ratios, there is a decrease in the Pb/Zn ratio outwards from vent complex (from 0.39 to 0.05), with a maximum value of combined

base metals (Zn+Pb = 31.61 %) in the thickest part of the deposit (vent complex) (Fig. 5). Iron is mostly contained in pyrite, and ratios of Fe/Pb and Fe/Zn also increase with distance from the vent complex, as base metals decrease (Fig. 14). Moreover, the Chahmir deposit has a strong vertical zonation, especially within the vent complex (Fig. 5). So, there is an upward increase of Zn and Pb and a decrease of Cu/(Zn+Pb), Cu/(Zn+Cu), Ag/(Pb+Ag) and Cu (Fig. 15). Within the vent complex, the Cd/(Zn+Cd) ratio increases upwards, reflecting an increase in the Cd content of sphalerite (Fig. 15).

Rare earth element geochemistry

Rare earth element (REE) analysis of rock samples from the bedded ore, vent complex and distal facies are shown in table 1. REE were normalized to the NASC standard (North American Shale Composite; [Gromet et al. 1984](#)), and the Eu anomaly was obtained according the equation:

$$Eu_{NASC}/Eu^*_{NASC} = Eu_N/\sqrt{(Sm_N \times Gd_N)}$$

The NASC-normalized REE contents of the analyzed samples are shown in Fig. 16, and give flat patterns. The most distinctive features of these patterns are a slight enrichment in Eu ($Eu_{NASC}/Eu^*_{NASC} > 1$) in the bedded ore, and a marked negative anomaly in the vent complex. In addition, ΣREE increases from the vent complex (average of 15 ppm for SSC, and 35 ppm for SC) to the bedded ore (average 81 ppm) and the distal facies (average 170 ppm). This zonation indicates high values of ΣREE in the stratiform mineralization (average 103 ppm) than massive vent complex facies (average 23 ppm) of deposit.

Sulfur isotope systematics

For understanding the distribution of $\delta^{34}S$ ‰ values within the most representative SEDEX deposits of Central Iran, we compared Koushk ([Rajabi et al. 2011a](#)) and Chahmir deposits. In total, 5

pyrite, 12 sphalerite, and 9 galena samples from bedded ore, vent complex and feeder zone were analyzed in both deposits (Table 2; Fig. 17a, b).

The $\delta^{34}\text{S}$ shows a wide range of variation and overall high values: from +10.9 to +29.8 ‰ in the Chahmir deposit, and from +6.5 to +36.7 ‰ in the Koushk deposit. Significant differences in $\delta^{34}\text{S}$ were found among textural types and also with depth (as measured in the drill core). In Chahmir deposit $\delta^{34}\text{S}$ increases upwards. The spatial distribution of the $\delta^{34}\text{S}$ samples are shown in Figure 5.

In both deposits, the highest $\delta^{34}\text{S}$ values correspond to the bedded ore (Koushk: +23.8 to +36.7 ‰; Chahmir: +28.6 to +29.8 ‰), whereas lowest to the Vent Complex (Koushk: +6.5 to +17.8 ‰; Chahmir: +10.9 to +14.7 ‰). Two galena samples from the Feeder Zone of the Chahmir deposit were analyzed, with +11.3 and +12.1 ‰ (Table 1). The range of $\delta^{34}\text{S}$ values in this deposit is higher in stage I (+28.6 to +29.8 ‰) than in stage II (+10.9 to +14.7 ‰), suggesting probably different formation processes.

Fluid inclusion microthermometry

Fluid inclusions suitable for microthermometry analysis were found in quartz crystals associated to sulfide mineralization in the vent complex of the Chahmir deposit. The analyzed quartz crystals are concomitant with galena of the stage 2 (gn₂) and occur within massive sulfides. Both one- and two-phase primary fluid inclusions have been identified at room temperature. One-phase inclusions are 2 to 4 μm in size, whereas two-phase inclusions range from 3 to 5 μm . The two-phase inclusions were used for microthermometry measurements; the liquid (aqueous) phase represents 50–67 vol. % in most cases.

Homogenization temperature (T_h) ranges from 170° to 226° C, with an average of 202° C (Table 3). A temperature peak (mode; from 190° to 210° C) is revealed in the T_h histogram (Fig. 18a). This peak could represent the main hydrothermal stage recognized in the SSC. The ice melting temperatures (T_{ml}) range from -8.8° to -2.5° C (Table 3). Eutectic temperatures were around -21.1°

C, indicating that the solutions belong to the H₂O–NaCl system (cf. Crawford 1981; Davis et al. 1990). Salinities and isochores were calculated assuming this chemical system, using the equations of Bodnar and Vityk (1994). Measured ice melting temperatures corresponding to salinities of 4.2 to 12.7 wt. % NaCl eq., with an average of 8.9 wt.% NaCl eq. and a mode around 9–10 wt. % NaCl eq. (Fig. 18b).

The temperature vs. salinity diagram, which indicates the seawater isodensity and the lower limit of the field of buoyancy reversal lines (Sato 1972; Turner and Campbell 1987; Haas 1976; Sangster 2002), shows that hydrothermal fluids of the Chahmir mineralization were less dense than seawater (Fig. 18c). There is no evidence of boiling during mineralization, and show no trends of decreasing T_{ml} with T_h (Canet et al. 2011). The P-V-T properties of fluids in H₂O-NaCl system (Brown and Lamb 1989; Bodnar and Vityk 1994; Driesner 2007) indicate approximately 15bars of pressure and about 155 m depth for Chahmir mineralization system under hydrostatic conditions.

Discussion

Tectonosedimentary environment

The basin and structural setting must have exerted a strong influence on the formation of the Chahmir SEDEX deposit. The main orebody of this deposit occurs in the thickest section of a black siltstone unit, next to a synsedimentary fault. The main evidences of a synsedimentary fault controlling the mineralization are: (a) The wedge shape of the sulfide deposit, (b) abrupt changes in thickness and facies of the host rocks, and (c) occurrence of debris flows (breccias). In addition, these evidences indicate developing of half-graben structures in sedimentary environment (Betts and Lister 2002). Synsedimentary faults are considered the highly favorable (i.e. as hydrothermal fluid upflow pathways) for the formation of SEDEX deposits (Lydon 1995). In the Chahmir deposit, the possible feeder zone developed next to a synsedimentary fault. This fact, along with metal zonation and an

1 increase of hydrothermal alteration as we approach the feeder zone, and the interfingering of
2 sedimentary breccias with fine-grained sediments, suggests that this fault was active during ore
3 formation and provided permeable conduits for the mineralizing fluid upflow.
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6 The sedimentary environment and oxic/anoxic basin conditions are key control factors on the
7 deposition and preservation of SEDEX deposits, especially in the Phanerozoic (Betts and Lister 2002;
8 Large et al. 2002; Lyons et al. 2006). The development of a half-graben structure was associated with
9 the formation of anoxic basin (presence of organic matter and high contents of V and U in the black
10 siltstones) at the mineralization time in the Chahmir area.
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13 Based on fluid inclusion data for the Tom and Jason deposits of Yukon, Canada, Haas (1976)
14 proposed that the minimum water depth necessary to prevent boiling ranges between 250 and 800 m
15 for these SEDEX deposits. This depth is 125 m for the Chahmir deposit that was calculated in base of
16 P-V-T properties (Brown and Lamb 1989; Bodnar and Vityk 1994) of fluid inclusions. Anoxic
17 environment can control deposition of sulfide minerals and provide some sulfur for sulfide deposition.
18 Petrographic evidences of SEDEX deposits (McGoldrick 1999) indicate the microbial role in sulfide
19 formation in anoxic basins. In particular, “crinkly-wavy” laminated pyrite beds (Fig. 19), which are
20 ubiquitous in the bedded ore facies of the Chahmir deposit, reveal this microbial influence in sulfide
21 formation in the anoxic Zarigan-Chahmir basin. Similar crinkly-wavy laminated pyrites are
22 interpreted as “pyritized microbial mats” in the Australian SEDEX deposits (McGoldrick 1999;
23 McGoldrick et al. 1999).
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45 *Physicochemical conditions of the mineralizing fluids*

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50 Normalized REE patterns revealed a slight Eu enrichment ($\text{Eu}_{\text{NASC}}/\text{Eu}^*_{\text{NASC}} > 1$) in the Bedded Ore
51 and a marked negative anomaly ($\text{Eu}_{\text{NASC}}/\text{Eu}^*_{\text{NASC}} < 1$) in the vent complex (Fig. 16). The Eu anomaly
52 in the bedded ore probably reflects the hydrothermal activity (Canet et al. 2004). The mobility of Eu
53 strongly depends on the redox conditions and temperature. Thus, an Eu enrichment involves hot and
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1 reduced fluids, whereas Eu negative anomalies imply cold and oxidizing fluids (Parr 1992). The first
2 conditions are compatible with the hydrothermal activity responsible for exhalative submarine
3 deposits (e.g. Large et al. 2005). Among the REE, Eu is the only significantly mobile element in
4 hydrothermal fluids (Michard et al. 1983). In fact, this behavior is confirmed by an Eu enrichment
5 detected in present-day vent fluids (Manikyamba et al. 1993); in addition, Eu positive anomalies have
6 been documented in several ancient SEDEX deposits (e.g. Canet et al. 2004). Therefore, the weak
7 positive Eu anomaly found in the bedded ore suggests that the Chahmir sulfide mineralization
8 originated from hot and reduced hydrothermal fluids. In contrast, there is no enrichment of Eu and
9 there are conspicuous depletions of Ho and Tm within the Vent Complex (Fig. 16 and Table 1), which
10 is explained by the low capacity of sulfide minerals to concentrate REE. Tm and Ho gradually
11 decrease from the bedded ore to the vent complex, reflecting a gradual increase in sulfide content.
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14 Barium occurs as disseminated barite within the distal facies ($Ba > 2.5\%$) and its content decreases
15 from this facies toward the bedded ore ($> 1\%$) and the vent complex (2340 ppm). Barite is a common
16 component of the Selwyn type (vent-proximal) SEDEX deposits, but is absent in the McArthur type
17 (vent-distal) deposits, except for Lady Loretta, Australia (Cooke et al. 2000). Barium can form
18 aqueous chloride, carbonate and hydroxide complexes in hydrothermal solutions (Cooke et al. 2000).
19 Under reduced, acidic conditions, significant amounts of barium (> 100 ppm) can be transported
20 (Cooke et al. 2000). Barite is extremely insoluble under oxidized (sulfate-stable) conditions (Lydon
21 1983); thus, no significant barium transport can occur in oxidized brines, unless $m_{\Sigma S}$ is low (< 0.0001
22 m) or pH is under 2 (Cooke et al. 2000). Because the Chahmir deposit contains abundant barite,
23 especially in the exhalites of the distal facies, the mineralizing fluids were probably reducing
24 ($H_2S \gg SO_4^{2-}$) and acidic, in agreement with the REE results.
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52 *Evolution of sulfide mineralization and zone refining*

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56 One of the most prominent characteristics of the Chahmir deposit is the mineralogical and metal
57 zonation. Mineralogical and chemical zoning similar to that of the Chahmir deposit is present in many
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1 other vent-proximal SEDEX deposits (Goodfellow 2004). Metal zonation within sulfide ore has been
2 used in many studies to determine the flow direction of hydrothermal fluids, and thus provide a vector
3 to the critical feeder fault structure (Large et al. 2002). Lydon (2001) provided evidence that the Pb to
4 Zn zonation at Sullivan is related to zone refining process of an original syngenetic sulfide
5 mineralization by on-going hydrothermal activity. Most authors have argued for the temperature
6 controlled replacement and zone refinement process producing the metal zonation that reflects the
7 temperature gradient between the feeder zone and the distal part of the mineralization (Large et al.
8 2002; Lydon 2000; Goodfellow 2004).

17 In spite of its salinity (8.9 wt. % NaCl eq.), the ore-forming fluid of Chahmir deposit was less
18 dense than seawater (Fig. 18c). Then, when it was released at the seafloor, it rose as buoyant plumes
19 instead of forming the brine pool that Sangster (2002) proposed for vent-distal SEDEX deposits. Base
20 metals should precipitate from these buoyant plumes as sulfides by quenching of the fluid due to
21 contact with cool seawater, thereby generating an ore deposit on the seafloor (stage 1). The stage 1 of
22 mineralization consists in fine-grained, framboidal to colloform, laminated pyrite, together with
23 disseminated to banded sphalerite and galena (Figs. 8, and 9a, b). Formation of laminated textures and
24 the presence of sedimentary structures (e.g. load casts) are consistent with a synsedimentary origin of
25 the mineralization, caused by submarine exhalative hydrothermal activity.

37 During the stage 2 of mineralization, coarse-grained sulfides formed by replacement of early
38 minerals as fluid temperatures increased near the feeder zone. The Chahmir synsedimentary fault
39 acted as a high-permeability conduit driving hydrothermal fluid flow, and caused development of
40 feeder veins, breccia debris flows and carbonate alteration (Fig. 7e, g).

47 Beneath the seafloor, hydrothermal activity produced silicification and
48 replacement/recrystallization of preexisting sulfides by coarse-grained, higher temperature
49 assemblages (Fig. 7a, b, c, F). In the upper part of the feeder zone, veins merge with massive sulfide
50 laminae, causing disruption, replacement and recrystallization of sulfides. Some of the sulfide veins
51 and veinlets extend to the vent complex. These features indicate a refining process (Goodfellow and
52 Lydon 2007) that lead the growth of the vent complex and increased ore grades.

Sulfur isotopic model

The distribution of $\delta^{34}\text{S}$ among different ore facies in both Koushk (Rajabi et al. 2011a) and Chahmir deposits depicts a new geochemical model for SEDEX deposits of Central Iran, which is characterized by higher $\delta^{34}\text{S}$ values in the bedded ore and lower in the vent complex. Both Koushk and Chahmir deposits show high $\delta^{34}\text{S}$ values (+6.5 to +36.7 ‰ and +10.9 to +29.8 ‰, respectively), with the highest values corresponding to sulfides of the bedded ores. In the Chahmir deposit the $\delta^{34}\text{S}$ values increase upwards, from +10.9 to +14.7 ‰ in the vent complex (Fig. 5 and Table 2). Other SEDEX deposits, as Tom and Jason in the Anvil Range of Yukon, Canada (Ansdell et al. 1989; Shanks et al. 1987; Goodfellow 2004), and the Rammelsberg deposit, Germany (Nielsen 1985), also have overall high values of $\delta^{34}\text{S}$ and show an upward increase of $\delta^{34}\text{S}$. Taylor and Beaudoin (2000) attributed the stratigraphic trends toward heavier values to an increase in the proportion of hydrothermally supplied sulfide. Nevertheless, Leach et al. (2005) suggested that trend toward heavier sulfur values upward might reflect sulfate reduction under restricted or closed conditions or an evolution toward a dominance of hydrothermal sulfur.

The distribution of the $\delta^{34}\text{S}$ values in the Chahmir deposit suggests that sulfides formed from sulfur that came from two sources. One of them was sulfate reduced from a hydrothermal fluid rising through the feeder zone to the seafloor, and the other was a sulfate reduced from residual seawater in a closed or semiclosed basin that may have been shut off from the open ocean. Sulfur isotope composition of seawater sulfate in Early Cambrian was of +30 to +35 ‰, according to the curves of Claypool (1980) and Bottrell and Newton (2006). The Chahmir deposit is mineralogically and geochemically zoned away from the feeder zone, reflecting a temperature gradient and the effect of zone refining (Goodfellow and Lydon 2007). So, at the margins of the system (bedded ore and distal facies), temperatures would have been low enough to sustain bacterial sulfate reduction (BSR). If temperature of fluids is below 150° C microbial processes are important in sulfate reduction (Southam and Saunders 2005). However $\delta^{34}\text{S}$ values in bedded sulfides of SEDEX deposits of Central Iran are

close to $\delta^{34}\text{S}$ of Early Cambrian seawater sulfate (Fig. 17c), but BSR typically yields strong depletion in heavy sulfur relative to the parent sulfate (Lyons et al. 2006). Then, the high $\delta^{34}\text{S}$ values in sulfides from the bedded ores indicate that these sulfides could have been formed from a process of BSR in a closed or semi-closed system (for sulfate) following a Rayleigh distillation process (e.g. Canet et al. 2005). The formation of framboidal aggregates of pyrite and crinkly-wavy laminated pyrites are consistent with a biogenic origin (Fig. 9a, b).

On the other hand, the vent complex has $\delta^{34}\text{S}$ values 15–18 ‰ lighter than the bedded ore sulfides and fluid inclusion data show high temperatures, so that thermochemical sulfate reduction (TSR) of seawater sulfate during deep hydrothermal circulation probably was the prevailing source process for sulfur in the proximal parts of the deposit.

Genetic classification of the Chahmir deposit

The Chahmir deposit has a prominent feeder zone and well developed vent complex, and thus would be classified as a vent-proximal SEDEX type deposit (Lydon 1995; Sangster 2002; Goodfellow and Lydon 2007; Large et al. 2005; Leach et al. 2005). Geochemical models of Cooke et al. (2000) indicate that two types of hydrothermal fluids are capable of transporting Zn and Pb to form a SEDEX deposit: (a) oxidized brines of low to moderate (100°–200° C) temperature and near neutral pH, which deposit metals due to reduction of hydrothermal SO_4^{2-} to H_2S (McArthur type deposits); and (b) reduced brines of moderate to high temperature (150°–300° C) and acid pH which deposit metals due to cooling and mixing with seawater (Selwyn type deposits). Following this classification, the Chahmir deposit is affine to the Selwyn type (vent-proximal) SEDEX.

Conclusions

Chahmir is a well preserved vent-proximal SEDEX deposit consisting of: (1) a stockwork of sulfide veins, with a hydrothermal alteration halo, discordantly underlying the main orebody, (2) a massive sulfide orebody comprised of pyrite, sphalerite and galena with quartz and dolomite, (3) a bedded ore that includes laminated sulfides with sedimentary structures, and (4) distal exhalites consisting in banded cherts with disseminated barite and minor pyrite.

Sulfide minerals were deposited from buoyant hydrothermal fluids that were vented into a large, heavily-sedimented marine basin affected by synsedimentary faulting and developed as a half-graben in a continental back-arc environment (Fig. 20). Fluid inclusions along with trace-element contents indicate that the mineralizing fluids were high-temperature (~202° C), saline (8.9 wt.% NaCl eq.), reducing and acidic.

The $\delta^{34}\text{S}$ values in sulfides (+10.9 to +29.8 ‰) are much higher than those expected for magmatic sulfur, and their distribution in the bedded ore, vent complex and feeder zone suggest a mixed source of fluids. In addition, high $\delta^{34}\text{S}$ values in the bedded ore reflect restricted setting that may have been shut off from the open ocean. Whereas in the vent complex thermochemical reduction of sulfate could take place during the formation and ascent of the hydrothermal fluids, in the bedded ore sulfide sulfur originated by bacterial reduction of seawater sulfate.

Acknowledgements

The Tarbiat Modares University of Tehran provided financial support for the research. In addition, The *Serveis Científic-Tècnics de la Universitat de Barcelona* and the research grant 2009SGR-00444 of the *Departament d'Universitats, Recerca i Societat de la Informació (Generalitat de Catalunya)* supported sulfur isotope analyses. Also the *Instituto de Geofísica* of the *Universidad Nacional Autónoma de México* (UNAM) supported electron microprobe analyses.

The authors thank the Anguran Mining Co. and Mohamadi Niaei for allowing access to the deposit and their records. The first author especially thanks Prof. Don Sangster for several years of collaborations, consultations and numerous discussions on the geology of Central Iran and genesis of

SEDEX deposits. We are grateful to Dr. Lotfi for their help on realization the deposit geology. Prof. J. Talbot is thanked for critically revising geodynamic aspect of earlier version and Prof. Don Sangster and Prof. Spry for for additional constructive comments that upgraded the manuscript.

Tables

Table 1 Selected minor and trace elements contents (in ppm), have been analyzed in whole-rock samples, by ICP-MS method.

Table 2 The $\delta^{34}\text{S}$ values for the Koushk (Rajabi et al. 2011a) and Chahmir deposit. The “I” and “II” suffixes here denote Stage I and Stage II, respectively, as in **Figure 17**.

Table 3 Summary of the microthermometric characteristics for the quartz fluid inclusions within SSC.

Figure Captions

Fig. 1 a Geological map showing the main faults of Posht-e-Badam Block and its sub-zones. The Zarigan-Chahmir basin (ZCB) is marked by the volcano-sedimentary sequence that hosts Sedex deposits of Central Iran (Rajabi et al. 2011 a). **b** Simplified geological map of Zarigan-Chahmir basin (ZCB) in the Posht-e-Badam block, showing the location of Sedex deposits within this basin (Rajabi et al. 2011a). Y: Yazd block, P: Posht-e-Badam block, T: Tabas block, An: Anar fault, CF: Chapedony fault, PF: Posht-e-Badam fault, NF: Naein fault, KF: Kalmard fault, KbF: Kuhbanan fault, ZKF: Zarin-Kharanagh fault. Numbers show Zarigan deposit (1), Koushk deposit, Chahgaz, Wedge and Cheshmeh-Firuz occurrences (2), Chahmir deposit and Darreh-Dehu occurrence (3).

Fig. 2 Gondwana reconstruction in Early-Cambrian (Ramezani and Tucker 2003). The Central Iranian Terrane (CIT (white arrow)) was located along the active continental margin of Gondwana. (See the W-E cross section in **Figure 20**).

Fig. 3 Geological map of Chahmir deposit (modified after Rajabi 2008). (A-B: The SE-NW cross-section of deposit in **Figure. 5**).

Fig. 4 a Schematic stratigraphic section of the mineralized part of the ECVSS in Chahmir area that illustrates the lithology and Ore horizon. Organic matter-bearing black siltstone (**b**) and contact of lithic tuff and oxidized black siltstone (**c**). **d** Handspecimen photograph black siltstone with dolomitic nodules. **e** Handspecimen photograph of debris flow from Chahmir deposit, which is occurred inter-fingering with fine-grained mineralized host rocks and increased in thickness toward the Chahmir fault.

Fig. 5 The northeast-southwest cross-section (A-B, **Fig. 3**) of Chahmir Zn-Pb deposit, shows the different ore facies. Black circles and numbers show sulfide samples location of **Table 2**.

Fig. 6 Handspecimen (**a** and **d**) and microscopic (**b** and **c**) photographs of Feeder zone. **a** Sulfide veins and veinlets that crosscut the sulfide and siltstone laminae. **b** Magnification of white b square in **a**. Margin of sulfide vein cuts framboidal laminated pyrite and siltstone laminae. **c** Magnification of white c square in **a**. Illustration of center of sulfide vein, consists of pyrite (Py₂), sphalerite (Sp₂) and calcite (Cc) from margin to core. **d** Quartz and carbonate veins, in brecciated sediments, accompanied by sulfide veins and veinlets.

Fig. 7 Handspecimen (**a** and **e**) and microscopic (**b**, **c**, **d** and **f**) photographs of the Vent Complex (SSC and Sc sub-facies). **a** and **b** SSC: Heterogeneous massive sulfide texture consists of pyrite (Py), black-brown sphalerite (Sp₂), galena vein (Gn₂) and quartz (Qz) (**b** shows binocular microscopic photograph of SSC). **c** SSC: Replacement of sphalerite (Sp₂) within pyrite (Py₂). **d** SSC: Chalcopyrite disease within Sp₂. **e** SC: Massive pyrite and sphalerite accompanying with carbonate alteration. **f** SC: Replacement and crosscutting of brecciated collomorphic pyrite with sphalerite. **g** Brecciated collomorphic pyrite within SC.

Fig. 8 Handspecimen (**a** and **c**) and microscopic (**b**, **d**, and **e**) photographs of the Bedded Ore facies. **a** Alternation of silty laminae (black gray) and sulfides (light gray). **b** Light silty laminae consist of

feldspar, quartz, sericite and clay minerals alternation with black opaque laminae (pyrite). **c** Photograph of typical sulfide laminae (light gray) and black organic matter (Cm). The organic matter occurs as a laminae and/or lens within sulfide laminae. **d** Laminated sphalerite (gray), sphalerite-rich silty band and pyrite within high-grade Bedded Ore. **e** and **f** Photographs of laminated framboidal pyrite within Bedded ore facies. The box indicates **Figure 9a, b. g** Microscopic photograph of hybrid laminae consist of mixtures of sulfides, silt and carbonaceous matter within Bedded ore facies. 1: Sphalerite-pyrite laminae, 2: Silty laminae, 3: Sphalerite-pyrite silty laminae, 4: Pyrite-sphalerite silty lamina. **b** Handspecimen of Bedded ore with sedimentary structures within laminated sulfides. Laminated sulfide bearing clast (black arrow) within sulfide laminae of Bedded Ore and load cast under this clast (lower white arrow). Cm: Organic matter.

Fig. 9 Scanning electron microscope image, in backscattering mode. **a** and **b** Spherical framboidal pyrite (Py₁) grains with a galena (Gn₁) core. One micron-sized gold (Au) grain was found. Ap, apatite; Qz, quartz. **c** Pyrite (Py) botryoidal-layered aggregates, with scattered grains of galena (Gn) and sphalerite (Sp). **d** and **e** Rhythmic layered aggregates of pyrite (Py₁) and Galena (Gn₁) that replaced by stage II galena (Gn₂) in some parts of sulfide-carbonate sub-facies of Vent Complex. Cc: calcite. **f** Inclusions of arsenopyrite (Apy) in galena (Gn₂). **g** Galena (Gn₂) mineralization associated with silicification in the sulfide-silica-carbonate sub-facies of Vent Complex.

Fig. 10 Distal facies of Chahmir deposit. **a** Microscopic photograph of disseminated barite (Ba) and Fe-bearing dolomite (Do) within silty crystal tuff. **b** and **c** Handspecimen photographs of cherty bands in Distal facies.

Fig. 11 a Schematic Mn halo map of Chahmir deposit. **b** Northeast-Southwest cross-section (A-B **Fig. 3**) through the Chahmir deposit shows the alteration pattern around Feeder zone and Vent Complex. The intensity of alteration increases from the deposit margin toward the Feeder zone facies.

Fig. 12 Paragenesis of different ore stages.

Fig. 13 Microscopic photographs of Bedded ore that indicate the growth of py_3 on small spherical framboidal pyrite (Py_1) within pyrite and pyrite-sphalerite laminae. These textural relations reveal that py_3 has nucleated on the preexisting pyrite (py_1) and grown by displacement within the preexisting framboidal pyrite laminae.

Fig. 14 Lateral zonations of Pb (a), Zn (b) and Fe (c) from northeast to Southwest across the deposit.

Fig. 15 Vertical zonation of metals and metal ratios in DDH1 that intersects the Vent Complex (see **Fig. 5**). The $Zn/(Zn+Pb)$, $Zn/(Zn+Fe)$ ratios and Zn and Pb contents increase, and $Cu/(Zn+Pb)$, $Cu/(Zn+Cu)$ and $Ag/(Pb+Ag)$ ratios decrease, upward. (S: Siltstone, M: Massive sulfide, T: Tuff, Sd: Siltstone with dolomitic nodules and debris below)

Fig. 16 REE patterns of different facies and host rock of Chahmir deposit normalized to NASC (Gromet et al. 1984).

Fig. 17 Histogram of $\delta^{34}S$ values of sulfides from the Koushk (a Rajabi et al. 2011a) and Chahmir deposit (b). c Comparison of $\delta^{34}S$ values for Chahmir and Koushk deposits sulfides with other Sedex deposits of Neoproterozoic and Paleozoic and sulfur isotope composition of Early-Cambrian seawater sulfates. Sedex deposits of Central Iran have heavy $\delta^{34}S$ values relative these deposits. References and location information are as follows: Anvil District, Canada (Shanks et al. 1987); Howards Pass, Canada (Goodfellow and Jonasson 1987); HYC, Australia (Ireland 2001); Koushk, Iran (Rajabi et al. 2011a); Meggen, Germany (Buschendorf et al. 1963); Mt Isa, Australia (Large et al. 2005); Rammelsberg, Germany (Anger et al. 1966); Reocin and Troya, Spain (Velasco et al. 1994); Sullivan, Canada (Lydone 2004); Tom and Jason, Canada (Goodfellow 2004); Sulfur isotope composition of Early-Cambrian seawater sulfates (Bottrell and Newton 2006).

Fig. 18 Histogram of homogenization temperature (a) and salinity (b) for inclusions within quartz of Vent Complex, Chahmir deposit. c Temperature versus salinity plots (Sangster 2002). Ore fluids of Chahmir deposit are plotted below seawater isodensity line and show less density than seawater.

Fig. 19 Core photos showing microbial mat-like textures preserved in pyrite and laminated base metal sulfide ore. Polished slabbed core showing crinkly laminations in bedded pyrite (Clp in **a**, **b** and **c**) and microbial nodular pyrites (Np in **a**). Om: organic matter, Bms: laminated base metal sulfides include sphalerite and pyrite, Flp: framboidal laminated pyrite.

Fig. 20 Tectonic model for the development of Bafq district and Sedex mineralization in the Zarigan-Chahmir back arc basin. The Central Iranian Micro-Continent in the Posht-e-Badam block broke up during Late Neoproterozoic-Early Cambrian continental margin back arc rifting, parallel to convergence (Proto-Tethyan) along the continental margin (Ramezani and Tucker 2003). The exhalative processes within this environment formed vent-proximal Zn-Pb Sedex deposits (e.g., Chahmir, Koushk, and Zarigan) (Rajabi et al. 2011a, modified after Rajabi 2008).

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Table 1
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Ore Facies	SSC Sub-Facies			SC Sub-Facies		Bedded Ore						Distal Facies			
Rock	Massive Sulfide					Black Siltstone									
Sample	SSC1	SSC2	SSC3	SC1	SC2	B1	B2	B3	B4	B5	B6	D1	D2	S1	S2
El															
Ag	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba	2340	2030	2134	501	525	>10000	2479	>10000	796	1320	1580	>10000	1060	2290	1687
Ce	5.6	6.5	7.3	11	16.6	44.3	17	19.7	33.6	25	41.9	67	67.8	60.5	55
Co	1.4	1.5	1.4	0.9	0.9	2.5	10	8.5	11.7	10.1	10.6	3.2	3.8	2.3	2.5
Cr	90	102	86	<10	<10	20	55	50	60	64	80	29	30	30	32
Cs	0.17	0.18	0.16	0.3	0.4	0.68	4	3.67	2.88	2.32	0.63	5	5.08	0.24	0.22
Cu	54	67	52	134	122	19	22	370	17	26	44	7	7	66	51
Dy	0.48	0.61	0.5	1.3	1.54	2.68	2.5	2.09	3.1	2.9	4.35	6.8	6.89	6.01	5.78
Er	0.19	0.26	0.21	0.85	0.92	1.67	1.46	1.36	1.74	1.85	2.31	4	4.08	3.28	2.45
Eu	0.06	0.08	0.07	0.13	0.18	0.76	0.89	0.46	0.74	0.85	0.84	1.5	1.53	0.78	0.71
Ga	1.6	1.7	1.64	1.5	1.7	2.5	9	7	11.5	8	10.9	14	15.1	7.9	7.3
Gd	0.51	0.58	0.53	1	1.47	2.83	3	2.06	3.22	3	3.42	6.99	6.96	6.58	6.44
Hf	0.8	0.9	0.8	1.26	1.3	1.3	3	2.5	5.2	4.9	4.5	12.3	12.4	6.2	5.9
Ho	0.01	0.02	0.02	0.15	0.25	0.53	0.47	0.37	0.54	0.49	0.79	1.2	1.29	1.07	0.96
La	1.8	2.7	2	7	9.9	27.2	17	10.5	17.4	18.1	20.5	30	33	29.8	26.7
Lu	<0.01	<0.01	<0.01	0.05	0.07	0.14	0.17	0.16	0.18	0.17.8	0.22	0.6	0.6	0.41	0.37
Mo	18	20	21	8	6	3	8	9	5	45	4	2	2	2	3
Nb	0.3	0.4	0.4	0.2	0.2	0.8	4	3.8	5.9	42	9.3	9.8	9.8	6.8	6.01
Nd	2.8	3.1	3	3.9	6.6	15.6	11	9.8	15.6	13.54	20	28	30.9	28.3	26
Ni	<5	<5	<5	<5	<5	<5	52	66	16	18.3	20	30	<5	<5	<5
Pb	>10000	>10000	>10000	3987	4140	3730	322	3250	389	389	456	20	80	430	235
Pr	0.63	0.8	0.72	1	1.84	4.48	3.2	2.36	4.06	4.22	5.1	8	8.08	6.99	6.37
Rb	1	1.2	1	2	2.2	6.1	45	42.8	49	43	50.5	83	86.1	6.4	8
Sm	0.61	0.74	0.6	1	1.33	2.7	2.5	1.93	3.2	3.5	3.1	7	7.05	6.04	5.89
Sn	<1	<1	<1	<1	<1	<1	1	2	2	1	1	1	3	1	1
Sr	125	153	135	170	178.5	371	344	1665	154	147	129.5	189	175	374	4
Ta	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.2	0.4	0.3	0.5	0.1	0.6	0.4	0.4
Tb	0.11	0.15	0.12	0.19	0.29	0.49	0.51	0.36	0.56	0.55	0.77	1.23	1.23	1.09	0.97
Th	<0.05	<0.05	<0.05	0.21	0.37	1.1	4.71	4.59	6.65	6.34	6.06	11	12	6.15	6.09
Ti	4.7	5.3	5	37	42.7	34.8	5	42	4.1	4	4.1	7	6.9	1.3	2.2
Tm	0.0075	0.0075	0.0075	0.05	0.07	0.17	0.13	0.11	0.17	0.19	0.24	0.5	0.57	0.43	0.35
U	0.19	0.21	0.22	0.35	0.44	0.44	2	1.65	1.71	1.69	1.75	2	3.03	2.35	2.55
V	<5	<5	<5	<5	5	13	77	62	95	89	85	68	18	25	29
W	9	8	7	1.3	1	2	5	6	3	2.9	6	2	5	3	3
Y	2.6	3	3	3	10.8	20.8	17	15.5	18.1	19.5	25.7	15	40.3	34.8	30.1
Yb	0.18	0.24	0.2	0.74	0.94	1.41	1.51	1.4	1.65	1.8	2.08	3.5	4.34	3.29	2.93
Zn	>10000	>10000	>10000	>10000	>10000	>10000	>10000	>10000	857	897	701	245	908	3020	2034
Zr	39	46	42	50	57	50	80	89	195	185	170	279	485	227	171
Σ REE	12.99	17.79	15.28	26.36	42.00	104.96	61.34	52.66	65.76	75.99	105.62	166.32	174.34	154.55	140.92

Table 2

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Deposit	Number	Sample	Mineral	Ore Facies	$\delta^{34}\text{S}$
Koushk	-	K-Bg	Sphalerite ₁	Bedded ore	23.8
	-	Zr-7	Sphalerite ₁	Bedded ore	23.95
	-	K-P1	Pyrite ₁	Bedded ore	36.7
	-	K-P2	Pyrite ₁	Bedded ore	34.5
	-	K-BP	Pyrite ₁	Bedded ore	31.37
	-	K-G2	Galena ₂	Vent complex	17.0
	-	K-GV1	Galena ₂	Vent complex	16.7
	-	K-GS1	Galena ₂	Vent complex	17.8
	-	K-VS1	Sphalerite ₂	Vent complex	6.7
	-	K-VS2	Sphalerite ₂	Vent complex	6.5
	-	K-VP	Pyrite ₂	Vent complex	11.7
	-	F-GL	Galena ₂	Feeder zone	21.84
	-	F-SL	Sphalerite ₂	Feeder zone	25.14
	-	F-S2	Sphalerite ₂	Feeder zone	24.23
Chahmir	1	CH-B1	Pyrite ₁	Bedded Ore	29.4
	1	CH-B1	Sphalerite ₁	Bedded Ore	28.6
	2	CH-B2	Sphalerite ₁	Bedded Ore	29.8
	5	V5-S	Sphalerite ₂	Vent Complex	14.7
	7	V1-G	Galena ₂	Vent Complex	10.9
	3	V3-S	Sphalerite ₂	Vent Complex	11.3
	8	V4-S	Sphalerite ₂	Vent Complex	11.9
	6	V6-S	Sphalerite ₂	Vent Complex	13.2
	4	V7-G	Galena ₂	Vent Complex	12.5
	9	V8-G	Galena ₂	Vent Complex	11.0
	10	V9-G	Galena ₂	Feeder zone	12.1
	11	V10-G	Galena ₂	Feeder zone	11.3

Table 3

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Sample no. and description	T _{ml} °C	T _h °C	Salinity Wt. % NaCl
CHM-3: massive sulfide (SSC) with quartz and galena	-5.40	205	8.41
	-5.61	175	8.7
	-4.18	210	6.7
	-6.17	181	9.4
	-4.31	190	6.9
	-6.46	195	9.8
	-5.32	215	8.3
	-6.30	199	9.6
	-5.54	200	8.6
	-6.34	226	9.64
CHM-4a: massive sulfide (SSC) with quartz	-2.51	187	4.2
	-6.93	209	10.4
	-4.90	192	7.73
	-5.05	201	7.93
	-5.02	193	7.9
	-6.22	178	9.5
	-5.80	198	8.95
CHM-4b: massive sulfide (SSC) vein of quartz with galena	-5.76	202	8.9
	-4.27	214	6.8
	-8.88	184	12.7
	-7.67	208	11.3
	-4.95	188	7.8
	-5.78	224	8.92
	-6.70	199	10.11
CHM-5: massive sulfide (SSC) vein of quartz with galena	-6.86	170	10.3
	-5.45	198	8.63
	-5.64	195	8.73
	-6.42	205	9.75
	-5.93	208	9.12
	-5.68	209	8.79
	-5.88	209	9.05
	-6.21	208	9.48
CHM-6: massive sulfide (SSC) with quartz	-6.30	219	9.62
	-7.30	221	10.87
	-5.35	216	8.34
	-5.87	203	9.04
	-5.03	219	9.69
	-5.09	223	9.04
	-5.96	189	9.16
	-5.91	211	9.09