Geology, ore facies and sulphur isotopes of the Koushk vent-proximal sedimentary-exhalative deposit, Posht-e-Badam Block, Central Iran

Abdorrahman Rajabi a, Ebrahim Rastad a, Pura Alfonso b & Carles Canet c

a Department of Geology, Faculty of Basic Sciences, Tarbiat Modares University, Tehran, Iran
b Departament d'Enginyeria Minera i Recursos Minerals, Universitat Politècnica de Catalunya, Catalunya, Spain
c Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad Universitaria, México, D F, Mexico

Published online: 08 Feb 2012.

To cite this article: Abdorrahman Rajabi , Ebrahim Rastad , Pura Alfonso & Carles Canet (2012) Geology, ore facies and sulphur isotopes of the Koushk vent-proximal sedimentary-exhalative deposit, Posht-e-Badam Block, Central Iran, International Geology Review, 54:14, 1635-1648, DOI: 10.1080/00206814.2012.659106

To link to this article: http://dx.doi.org/10.1080/00206814.2012.659106

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions
Geology, ore facies, and sulphur isotopes of the Koushk vent-proximal sedimentary-exhalative deposit, Posht-e-Badam Block, Central Iran

Abdorrahman Rajabi a, Ebrahim Rastad a *, Pura Alfonso b and Carles Canet c

aDepartment of Geology, Faculty of Basic Sciences, Tarbiat Modares University, Tehran, Iran; bDepartament d’Enginyeria Minera i Recursos Minerals, Universitat Politècnica de Catalunya, Catalunya, Spain; cInstituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad Universitaria, México D F, Mexico

(Accepted 30 December 2011)

The Koushk zinc–lead deposit in the central part of the Zarigan–Chahmir basin, central Iran, is the largest of several sedimentary–exhalative (SEDEX) deposits in this basin, including the Chahmir, Zarigan, and Darreh-Dehu deposits. The host-rock sequence consists of carbonaceous, fine-grained black siltstone with interlayered rhyolitic tuffs. It corresponds to the upper part of the Lower Cambrian volcano-sedimentary sequence that was deposited on the Posht-e-Badam Block due to back-arc rifting of the continental margin of the Central Iranian Microcontinent. This block includes the late Neoproterozoic metamorphic basement of the Iran plate, overlain by rocks dating from the Early Cambrian to the Mesozoic.

Based on ore body structure, mineralogy, and ore fabric, we recognize four different ore facies in the Koushk deposit: (1) a stockwork/feeder zone, consisting of a discordant mineralization of sulphides forming a stockwork of sulphide-bearing dolomite (quartz) veins cutting the footwall sedimentary rocks; (2) a massive ore/vent complex, consisting of massive replacement pyrite, galena, and sphalerite with minor arsenopyrite and chalcopyrite; (3) bedded ore, with laminated to disseminated pyrite, sphalerite, and galena; and (4) a distal facies, with minor disseminated and laminated pyrite, banded cherts, and disseminated barite. Carbonatization and sericitization are the main wall-rock alterations; alteration intensity increases towards the feeder zone. The $\delta^{34}$S composition of pyrite, sphalerite, and galena ranges from +6.5 to +36.7‰. The highest $\delta^{34}$S values correspond to bedded ore (+23.8 to +36.7‰) and the lowest to massive ore (+6.5 to +17.8‰). The overall range of $\delta^{34}$S is remarkably higher than typical magmatic values, suggesting that sulphides formed from the reduction of seawater sulphate by bacteriogenic sulphate reduction in a closed or semi-closed system in the bedded ore, whereas thermochemical sulphate reduction likely played an important role in the feeder zone. Sulphur isotopes, along with sedimentological, textural, mineralogical, and geochemical evidences, suggest that this deposit should be classified as a vent-proximal SEDEX ore deposit.

Keywords: ore facies; hydrothermal vents; Posht-e-Badam Block; zinc–lead massive sulphides; sedimentary-exhalative deposit; central Iran

Introduction

The Zarigan–Chahmir basin, located in the Posht-e-Badam Block of the Central Iranian Microcontinent, is the most fertile area for Zn–Pb sedimentary-exhalative (SEDEX) deposits in Iran. It hosts several SEDEX deposits, including Koushk (Yaghupur and Mehrabi 1997), Chahmir (Rajabi 2008), Zarigan, and Darreh-Dehu (Rajabi et al. 2008) (Figure 1). Koushk is the largest and economically most important massive sulphide deposit (Yaghupur and Mehrabi 1997) in the central part of the Zarigan–Chahmir basin, with total reserves of 20 Mt, averaging 7% Zn and 1.5% Pb (Koushk Mining Co., Koushk, Iran). This part of the basin also hosts several small occurrences to the north of the Koushk deposit, such as Wedge, Chahgaz, and Cheshmeh-Firuz (Figure 1). As a result of field and petrographic studies conducted in the 1970s and 1980s (Gibbs 1976), the Koushk deposit was classified as a Kuroko-type volcanogenic massive sulphide deposit (cf. Sato 1973). On the basis of the occurrence of exhalative-hydrothermal features such as laminated sulphide textures, a SEDEX model was proposed by Mehrabi (1991) and Yaghupur and Mehrabi (1997), who considered an intra-continental rift setting for the Koushk deposit. Rajabi (2008) studied the Chahmir deposit, which is located in the southeastern part of the Zarigan–Chahmir basin (Figure 1), and classified it as a vent-proximal (or Selwyn-type) SEDEX deposit model (cf. Cooke et al. 2000; Goodfellow and Lydon 2007). He further proposed that the formation of SEDEX deposits in this basin is related to the evolution of an extensional continental margin in a back-arc environment that affected the Central Iranian Microcontinent.
Figure 1. Geological map showing the main faults of the Posht-e-Badam Block and its lithotectonic domains. The Zarigan–Chahmir basin is marked by the volcano-sedimentary sequence that hosts the SEDEX deposits of the Central Iranian Microcontinent. LCMA: Lower Cambrian magmatic arc; LCVSS: Lower Cambrian volcano-sedimentary sequence.

Despite the above-mentioned genetic models for base–metal mineralization in the Zarigan–Chahmir basin, detailed information on the ore geology of its deposits is lacking in the international literature. The aim of this article is to provide an accurate description of the geology, ore facies, and sulphur isotope composition of the Koushk deposit. Our data constrain the origin of the mineralizing fluids in relation to the evolution of the Zarigan–Chahmir back-arc basin.

**Geological and tectonic setting**

The Bafq District lies in the central part of the Kashmar–Kerman structural zone (Ramezani and Tucker 2003), also known as the Posht-e-Badam Block (Alavi 1991), in the Central Iranian Microcontinent (Figure 1). This major metallogenic province hosts abundant iron oxide-apatite deposits (∼1.8 Gt distributed in 34 deposits; Stosch et al. 2011) and SEDEX mineralizations (Rajabi 2008). The Posht-e-Badam Block is located between the western Yazd Block and the central Tabas Block. These blocks together with the Lut Block further to the east form the crustal domain of the Central Iranian Microcontinent. The Posht-e-Badam Block is home to the oldest basement of the Iran plate, Precambrian in age, which is covered by Lower Cambrian to Mesozoic rocks (Foerster and Jafarzadeh 1994).

The Posht-e-Badam Block was thought to have been formed during the Pan-African intra-continental extension (Berberian and King 1981; Talbot and Alavi 1996; Samani 1998), but it was recently defined as a magmatic arc (Figure 1), developed along the Proto-Tethyan margin of the Gondwana supercontinent (Ramezani and Tucker 2003). Some authors have reported geological features, predominantly bimodal alkaline volcanism, suggestive of an extensional back-arc regime in the eastern portion...
of the area (Daliran et al. 2008; Rajabi 2008; Stosch et al. 2011). The SEDEX occurrences, as in the Kouash, Chahmir, and Zarigan deposits, formed in this tectono-sedimentary environment. The opening of the Zarigan–Chahmir basin in the Posht-e-Badam Block took place when the Central Iranian Microcontinent broke up in the Late Neoproterozoic—Lower Cambrian, due to the back-arc rifting of the continental margin, which occurred coeval with the convergence of the Proto-Tethys along the continental margin.

Regional faults divide the Posht-e-Badam Block into three lithotectonic domains: the Kalmard in the east, the Zarigan–Chahmir in the central part, and the Saqand in the west (Figure 1). The Zarigan–Chahmir basin is bounded by the Kuhbanan Fault to the east and the Posht-e-Badam Fault to the west (Figures 1 and 2). The basin is characterized by thick, fine-grained siliciclastic sediments and volcanics of the Lower Cambrian volcano-sedimentary sequence (LCVSS) and the rocks that are equivalent to the Rizu series or Esfordi Formation in the central part of the Zarigan–Chahmir lithotectonic domain (Figure 1).

In the Zarigan–Chahmir basin, Precambrian rocks of the Tashk Formation disconformably overlie the late Neoproterozoic metamorphic rocks of the Boneh-Shurow basement complex (Foerster and Jafarzadeh 1994). The Tashk Formation is a 2000 m-thick, well-stratified sequence of weakly metamorphosed to unmetamorphosed, sedimentary, and volcanic/volcaniclastic rocks (Figure 2). Age data delimit the overall deposition of the Tashk Formation between 627 and 533 Ma (207Pb/206Pb zircon ages, Ramezani and Tucker 2003), the latter being the intrusion age of the oldest Lower Cambrian arc-related granitic plutons emplaced into the Tashk Formation. The overlying 1500–2000 m-thick LCVSS consists of unmetamorphosed interlayered, intermediate to felsic, volcanic rocks and sedimentary rocks, including micro-conglomerates, sandstones, volcaniclastic rocks, pyritic black siltstones, shales, dolomitic limestones, and
dolomites (Haghipour 1974; Rajabi 2008). Although the LCVSS and their stratigraphic equivalents throughout the Central Iranian Microcontinent have been traditionally assigned to the Precambrian (Huckriede et al. 1962), recent geochronological findings show that the volcanic rocks of the area date from the Lower Cambrian (528.2 + 0.8 Ma) (Ramezani and Tucker 2003). The LCVSS is unconformably overlain by Lower Cambrian red sandstones and conglomerates (Lalun/Dahu Fm.) in the Zarigan and Chahmir areas, as well as in the Bafq region (Foerster and Jafarzadeh 1994; Rajabi 2008).

Geology of the Koushk deposit

The Koushk Zn–Pb deposit is hosted within the upper part of the LCVSS, in the centre of the Zarigan–Chahmir basin (Figure 2). In this area, two sequences have been identified (Figures 3 and 4): an ore-bearing sequence that comprises the upper part of the LCVSS at the base and an upper volcano-sedimentary sequence that includes lower Palaeozoic shales, limestones, and some tuffaceous rocks (Gibbs 1976). In the southeastern part of the deposit, the ore-bearing sequence trends northwestwards, with a steep dip to the southwest; in the northwestern part of the deposit,
however, it swings into a southwestward strike that gently dips to the southeast (Figure 4). The basal portion (of the ore-bearing sequence) consists of grey lithic crystal tuffs, rich in alkaline feldspars, quartz, and lithic fragments, overlain by dark-grey, locally dolomitized, sandy to silty limestones grading upwards to siltstones. The latter unit consists of calcareous siltstones in the lower part with conformable lenticular deposits of rhyolitic tuff in sharp contact with the enclosing sediments. The calcareous siltstones grade into the ore-bearing horizon, which includes organic matter-rich, fine-grained black siltstones. The top of this unit is overlain by interbedded tuffs, shales, and cherts (Figure 3). Limestones and massive cherty dolomites form the uppermost part of the LCVSS (Figure 3).

The ore-bearing sequence, from footwall limestones to hanging-wall dolomites, crops out in the Zardu syncline and is truncated by the Koushk Fault, which trends northwest–southeast with a steep dip to the southwest (Figure 4). The southwest block of this fault exposes shales, limestones, and tuffs (Figure 4). This volcano-sedimentary sequence is considered to be younger than the LCVSS, probably of lower Palaeozoic age (Gibbs 1976). However, in view of the occurrence of rhyolitic tuffs and horizons of iron oxides, this sequence could also be correlated with the lower part of the LCVSS in the Zarigan–Chahmir basin.

Within the host series, close to the mineralized beds of the Koushk deposit, sedimentary breccias and debris flow deposits (Figure 5) interfinger with the fine-grained ore-bearing sediments and abruptly increase in thickness towards the southeastern part of the deposit (Figure 6). These flow deposits are cemented by dolomite, calcite, and chalcedony quartz. According to Gibbs (1976), sedimentary breccias are common in the lower sandy- and silty-limestone series of the northeastern part of the deposit.
A rhyolitic dome intruded the ore-bearing sequence in the southeastern portion of the deposit and several diabase dikes cut the entire volcano-sedimentary sequence (Figure 4). Diabase sills occur in the lower part of the volcano-sedimentary sequence, just southwest of the Koushk Fault (Figure 4).

Sedimentation in the Central Iranian Microcontinent continued until the Triassic, when local epirogenic movements began (Aghanabati 2004). Late Triassic and Late Cretaceous orogenic events folded both the Cambrian basement and the Palaeozoic cover (Gibbs 1976). As a consequence, the ore-bearing sequence developed a succession of synclines and anticlines. The mineralized siltstone crops out in the northern limb of the Zardu synclinal (Figures 4 and 6). The southeastern end of the limb is cut by the NE−SW-striking Keel Fault (Figure 4). As a result, there are two separated outcrops, Keel (barren) and Old Koushk (with minor mineralization in the northwestern part). The Zardu and Pahnu mining zones include the main ore body (Figure 4).

Ore deposit morphology and mineralization
The geological structure of the Koushk deposit is schematically illustrated in Figure 6. The major sulphide mineralization is located northwest of the synsedimentary fault (Figure 6). It occurs as a stretched wedge within the black siltstone, attaining a maximum thickness, of about 111 m, in the southeastern deposit (Zardu) and decreasing to less than 60 m in the northwestern deposit (Pahnu). The trend of the Koushk ore body is SE−NW, with a southwesterly dip of 45°–48° (between the synsedimentary and Northern Pahnu faults), consistent with that of the host rock (Figure 6). In the SE portion of the deposit, the mineralization is massive, stratabound, and laterally discontinuous. But towards the NW portion, the mineralization forms a laterally continuous, tabular to stratiform lens that abruptly ends at the Koushk Fault (Figure 6).

The Koushk deposit encompasses four distinct ore facies: (1) stockwork zone, (2) massive ore, (3) bedded ore, and (4) distal facies (Figure 6).

Stockwork zone
The stockwork zone, which underlies the stratabound massive ore, consists of an irregular network of sulphide-bearing dolomite (quartz) veins cutting the footwall sedimentary rocks (Figure 7A). This facies occurs stratigraphically beneath the Zardu mining area (massive ore) but continues into the massive ore as large veins (up to 7 cm wide) (Figure 7B). The sedimentary host rocks are hydrothermally altered and intensely brecciated near the stockwork zone, either by hydro-fracturing or by syndepositional tectonic movement (Figures 7A and 7B). However, more recent tectonic events (e.g. Keel Fault) and igneous intrusions (Figure 4) obliterated the synsedimentary fault. The sulphide content of the stockwork zone is usually low, but pyrite, sphalerite, and minor galena are present in some veins and constitute up to 6 wt.% of the rock.

The prevalence of sulphide-bearing veins and sulphide-cemented breccias, along with the position of the stockwork mineralization systematically beneath the massive ore (Figure 6) and adjacent to the synsedimentary fault, is evidence that the stockwork ore facies represent the feeder zone for the SEDEX mineralization.

Massive ore
The massive ore consists of a high-grade ore body that forms the thickest portion of the deposit (Figure 6), principally in the Zardu and the southeastern part of the Pahnu mining areas and, to a lesser degree, in the northwestern margin of the Old Koushk. This facies comprises massive zones, replacement patches, brecciated sulphides, and irregular veins and veinlets of sulphides (Figure 8) and carbonates.

Based on its mineralogy and textures, the massive ore facies is divided into three sub-facies (Figures 6 and 8): (1) a galena-sphalerite-rich sub-facies (GSS) occurs in the central and lower part of the massive ore, mainly in the northern Zardu mining area; (2) a pyrite-sphalerite-rich sub-facies (PSS) lies above the GSS; and (3) a yellow-pyrite-rich sub-facies (YPS) is located in the upper part.

Figure 5. Hand specimen photograph of debris flow in the southeastern Koushk deposit, interfingered with fine-grained mineralized host rocks and increasing in thickness towards the southeastern portion of the deposit.
Figure 6. Plan view of the ore sequence and extension of ore facies in the Koushk deposit, 940 mining level. Solid grey circles show sulphide sample locations (listed in Table 1).

of the system. The massive ore facies shows mineralogical zonation from bottom to top with an upward decrease in galena and increase in sphalerite. The lower part of the massive ore (GSS) includes extremely high-grade Pb ores (15−25 wt.% Pb). The middle part (PSS) is characterized by massive pyrite, coarse-grained massive replacement sphalerite associated with dolomite, and minor galena (Figures 8D and 8E). This part has a lower Pb content (5−15 wt.%) but higher Zn content (13−27 wt.%). The upper part of this facies (YPS) has lower sphalerite content and includes massive pyrite only locally replaced by sphalerite and galena.

**Bedded ore facies**

The bedded ore facies, which is thinner (about 20−60 m thick) than the massive ore, is characterized by layered, low-grade ores in the northwestern part of the deposit (Figure 6). This facies occurs as stratiform, banded sulphide-rich bodies, concordant with the host rock. It is mainly composed of pyrite, sphalerite, and galena. The most characteristic textural feature is the regular, fine bedding (Figure 9), defined by sulphides on both the macro- and micro-scales. The lateral transition between the bedded ore and the massive ore facies is gradual and is recognized by increasing laminated sulphides. At the millimetre scale, the laminae consist of silt, organic matter, and sulphides. The sulphide-rich laminae are anchimonomineralic and consist of pyrite, sphalerite, or galena (Figure 9A). In the upper part of this facies, several massive pyrite bands, up to 15 cm wide, constitute the lowest grades of the entire mineralization (Figure 9B).

**Distal facies**

The bedded ore is overlain by the distal facies (Figure 6), which consist of interlayered pyrite-bearing silts and cherts with minor disseminated barite (Figure 10). This facies
lacks the economic value and its contact with the bedded ore is gradual (Figure 6). Banded cherts are a common feature of this facies.

Hydrothermal alteration
Although only 20% of SEDEX deposits are underlain by a hydrothermal stockwork zone (Sangster 2002), the hydrothermal alteration that develops around this zone has rarely been characterized in detail (Goodfellow and Lydon 2007). In the Koushk deposit, host rocks appear to be affected by sericitization and carbonatization. Sericitization, the most extensive alteration type, affects the coarse sedimentary fragmental rocks, which comprise the replacement of feldspars by sericite. The intensity of this alteration increases around the stockwork/feeder zone. Carbonatization has been developed around this zone and the massive ore, consisting of dolomite and calcite.

Mineralogy, textures, and paragenesis
The paragenetic sequence for the Koushk deposit (Figure 11) was deduced from a petrographic study conducted in over 50 polished thin and thick sections (Figures 7, 8, and 9). The sulphide mineralogy of the deposit is dominated by pyrite, sphalerite, and galena, with minor chalcopyrite and arsenopyrite. Dolomite, calcite, sericite, and quartz (chert), with minor barite and apatite, are the gangue minerals. Trace gypsum, epsomite, variscite, and melanterite occur as weathering products of the deposit.

Petrographic studies have shown that primary sulphide mineralization in the Koushk deposit was formed throughout two main stages (Figure 11). The first mineralization stage consists of laminated, colloform, and disseminated pyrites ($Py_1$), yellow-brown sphalerite ($Sp_1$), fine-grained disseminated and laminated galena ($Gn_1$), banded chert, and minor disseminated apatite and barite. At the microscopic scale, pyrite forms framboidal aggregates (Figures 9C, 9D, and 9E). Laminae of galena are less common than those of pyrite or sphalerite, occurring only in the northeastern end of the bedded ore facies. In addition, sulphides occur disseminated within the silty laminae (Figure 9D).

The second paragenetic stage is the main stage of development of the massive ore (Figure 8) and vein mineralization (Figure 7). This stage includes coarse-grained
Sulphur isotopes: results and discussion

Sulphur isotopes at the Koushk deposit were measured in 14 samples of pyrite, sphalerite, and galena collected from all ore facies except the distal facies. Samples were analysed by mass spectrometry using a Delta C Finnigan MAT continuous-flow isotope-ratio mass spectrometer with an elemental analyser, a TC-EA. These analyses were carried out at the facilities of Serveis Científico-Tècnics de la Universitat de Barcelona, Spain. The results are given as $\delta^{34}$S‰ values relative to the V-CDT (Vienna Canyon Diablo Troilite) standard. The analytical precision is within ±0.1‰ at 1 $\sigma$.

The $\delta^{34}$S in the Koushk deposit varies widely, from +6.5 to +36.7‰ (Table 1). The highest $\delta^{34}$S values correspond to the bedded ore, from +23.8 to +36.7‰. The $\delta^{34}$S values from the stockwork zone range from +21.8 to +25.1‰. The lowest $\delta^{34}$S values are those from the massive ore, which range from +6.5 to +17.8‰ (Table 1 and Figure 12). In the massive ore, $\delta^{34}$S is higher in galena than in sphalerite, suggesting isotopic disequilibrium.

The $\delta^{34}$S values are much higher than would be expected for sulphur of a magmatic source, thus precluding a magmatic origin of the mineralization, as previously proposed by Mehrabi (1991) and Yaghubpur and Mehrabi (1997). The ultimate source of the sulphur, therefore, is seawater sulphate. Sulphur isotopic composition of seawater sulphate in the Lower Cambrian ranged from +30 to +35‰, according to the curves of Claypool et al. (1980) and Bottrell and Newton (2006). The transformation of sulphate to sulphide either by bacteriogenic sulphate reduction (BSR) or by thermochemical sulphate reduction (TSR) implies isotopic fractionations greater than 20‰ (Ohmoto et al. 1990); the extent of fractionation depends principally on the temperature (as temperature increases, fractionation decreases). Nevertheless, TSR processes usually reach metastability and therefore little or no isotopic fractionation occurs between sulphur species (Cross and Bottrell 2000). The Koushk deposit is mineralogically and chemically zoned away from the feeder zone, reflecting steep temperature gradients. Sericite alteration found around the feeder zone suggests high-temperature conditions for this part of the deposit. However, the zonation, controlled mostly by zone refining in the massive ore (Goodfellow and Lydon 2007), along with the $\delta^{34}$S difference found between the bedded ore and the massive ore, implies that at the margins of the system (bedded ore and distal facies) temperatures would have been low enough to sustain BSR. If the temperature of ore-forming fluids is less than 150°C, microbial processes can play a significant role in sulphate reduction (Southam and Saunders 2005). The presence of frambooidal pyrite in the bedded ore facies and colloform pyrites within the lower part of the massive ore supports this interpretation. Although the development of pyrite frambooids can occasionally occur by means of abiotic...
processes (Berner 1969; Prol-Ledesma et al. 2010), laminated and framboidal pyrites are usually associated with biogenic deposition (Alfonso et al. 2005).

Sulphides from the bedded ore and the feeder zone have $\delta^{34}S$ values between +21 and +36‰. Those high values alone could account for a BSR process if it occurred in a closed or semi-closed system for sulphate, but open for sulphide following a Rayleigh distillation process (e.g. Canet et al. 2005). These conditions could occur in a framework of restricted environment, where BSR is limited by a restricted supply of sulphate from the open sea and a significant part of the sulphide produced is consumed continuously by the precipitation of sulphide minerals (Ohmoto and Rye 1979). Microbial-mediated sulphate reduction is known to have played a prominent in situ role in the formation of SEDEX deposits (Southam and Saunders 2005).
Colloform pyrite from the massive ore is replaced by galena and sphalerite with $\delta^{34}S$ values from +16.7 to +17.8 and from +6.5 to +6.7‰, respectively. These low isotopic values of late sulphides cannot be produced by BSR in the proposed closed system for sulphate and suggest at least a contribution of TSR to the sulphide sulphur that formed these minerals.

In other SEDEX deposits with similarly high $\delta^{34}S$ values, a dual source of fluids has been suggested (e.g. Dengjia Shan, China), with seawater TSR as the prevailing process for sulphur in the hydrothermal fluid prior to the discharge (Ma et al. 2007). There is textural evidence of the contribution of two fluids in the formation of the deposit. The fine-grained nature of the paragenetic stage I (Figures 9 and 11) and the presence of frambooidal and colloform pyrites reflect rapid crystallization on the seafloor caused by mixing of ascending hydrothermal fluids with cold ambient seawater (Herzig and Hannington 1995; Kelley et al. 2004; Xu and Scott 2005).

The formation of many SEDEX deposits elsewhere coincides with periods in the Earth’s history in which the oceans were stratified, with anoxic conditions prevailing near the seafloor (Goodfellow and Lydon 2007). Sedimentation of the organic matter-rich black siltstones...
A. Rajabi et al.

Table 1. The $\delta^{34}$S values for the Koushk deposit.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location index</th>
<th>Mineral</th>
<th>Ore facies</th>
<th>$\delta^{34}$S value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-Bg</td>
<td>1</td>
<td>Sphalerite I</td>
<td>Bedded ore</td>
<td>23.8</td>
</tr>
<tr>
<td>Zr-7</td>
<td>2</td>
<td>Sphalerite I</td>
<td>Bedded ore</td>
<td>23.95</td>
</tr>
<tr>
<td>K-P1</td>
<td>3</td>
<td>Pyrite I</td>
<td>Bedded ore</td>
<td>36.7</td>
</tr>
<tr>
<td>K-P2</td>
<td>4</td>
<td>Pyrite I</td>
<td>Bedded ore</td>
<td>34.5</td>
</tr>
<tr>
<td>K-BP</td>
<td>5</td>
<td>Pyrite I</td>
<td>Bedded ore</td>
<td>31.37</td>
</tr>
<tr>
<td>K-G2</td>
<td>6</td>
<td>Galena II</td>
<td>Vent complex</td>
<td>17.0</td>
</tr>
<tr>
<td>K-GV1</td>
<td>7</td>
<td>Galena II</td>
<td>Vent complex</td>
<td>16.7</td>
</tr>
<tr>
<td>K-GS1</td>
<td>8</td>
<td>Galena II</td>
<td>Vent complex</td>
<td>17.8</td>
</tr>
<tr>
<td>K-VS1</td>
<td>9</td>
<td>Sphalerite II</td>
<td>Vent complex</td>
<td>6.7</td>
</tr>
<tr>
<td>K-VS2</td>
<td>10</td>
<td>Sphalerite II</td>
<td>Vent complex</td>
<td>6.5</td>
</tr>
<tr>
<td>K-VP</td>
<td>11</td>
<td>Pyrite II</td>
<td>Vent complex</td>
<td>11.7</td>
</tr>
<tr>
<td>F-GL</td>
<td>12</td>
<td>Galena II</td>
<td>Feeder zone</td>
<td>21.84</td>
</tr>
<tr>
<td>F-SL</td>
<td>12</td>
<td>Sphalerite II</td>
<td>Feeder zone</td>
<td>25.14</td>
</tr>
<tr>
<td>F-S2</td>
<td>13</td>
<td>Sphalerite II</td>
<td>Feeder zone</td>
<td>24.23</td>
</tr>
</tbody>
</table>

Note: The ‘I’ and ‘II’ suffixes denote Stage I and Stage II, respectively, as in Figure 11. Location indexes show the situations of sulphide samples in Figure 6.

of the Zarigan–Chahmir basin, the high $\delta^{34}$S values in the bedded ore of the Koushk deposit, and the high V and U contents in the host siltstones (Rajabi 2008) are consistent with an anoxic sedimentary environment.

Genetic model of ore formation

Abrupt lateral changes in facies and thickness, along with the existence of synsedimentary breccias and debris flows within the ore sequence, suggest the proximity of synsedimentary faults (Lydon 1995; Large et al. 1998; 2005; Goodfellow 2004) and tectonic activity contemporaneous with the sedimentation in the Lower Cambrian, favourable to the formation of SEDEX deposits (Lydon 1995). Sedimentation, therefore, took place in a subsiding basin shaped by synsedimentary normal faults that promoted hydrothermal fluid circulation (Goodfellow and Lydon 2007). The abundance of carbonaceous and pyritic shales and sandstones, the scarcity of evaporites, and the absence of a basal oxidized (red bed) rifting sequence in the lower part of the LCVSS may have contributed to maintain the reducing conditions of basinal fluids (Cooke et al. 2000). These conditions, together with an acidic pH, gave the hydrothermal fluids the ability to leach metals from the rift-filling sediments and volcanic rocks. Based on fluid inclusion studies, Rajabi (2008) suggested that the Chahmir deposit formed from basinal, hydrothermal fluids rising through synsedimentary faults to the seafloor, which might be similar in the Koushk deposit. Base metals should have precipitated on the seafloor from these fluids by both (1) quenching due to contact with cool seawater and (2) combining with the sulphide sulphur produced mostly by BSR and in minor amounts by TSR.

The rather simple mineralogy of the Koushk deposit is similar to that of many shale/siltstone-hosted SEDEX Zn–Pb deposits worldwide (cf. Lydon 1995; Large et al. 2005; Goodfellow and Lydon 2007). However, the coarse-grained textures of the paragenetic stage II of the Koushk (in the massive ore and stockwork zone) are uncommon in the typical stratiform SEDEX deposits (Large et al. 2005; Saez et al. 2011), but have been commonly reported in volcanogenic massive sulphide deposits (Herzig and Hannington 1995).

Ore deposition in SEDEX deposits can occur below the seafloor surface, owing to different causes, such as fluid–rock interaction, a decrease of temperature, thermogenic reduction processes, and an increase of pH (Cooke et al. 2000). The sub-seafloor mineralizing processes (zone-refining stage) in the Koushk deposit caused the replacement of fine-grained, low-temperature mineral assemblages (i.e. framboidal and colloform pyrites) by coarse-grained sulphides (of the stage II). Rajabi (2008) reported a similar

![Figure 12. Histogram of $\delta^{34}$S values of sulphides from the Koushk deposit.](image-url)
Concluding remarks

The Koushk deposit has a prominent feeder zone (stockwork) overlain by a well-developed vent complex (massive ore) that laterally gives way to a bedded, stratiform ore body, as in the Chahmir deposit (Rajabi 2008). Thus, we regard this complex as a vent-proximal SEDEX deposit (i.e. Sangster 2002; Goodfellow 2004), in which sulphide minerals were deposited from hydrothermal fluids that were vented into a shallow marine basin affected by synsedimentary faulting (Figure 13).

$\delta^{34}$S values in analysed sulphides are much higher than those expected for magmatic sulphur. Their distribution in the bedded ore and vent-complex facies, along with the occurrence of colloform and frambooidal pyrites, suggests that the main sulphur source was seawater sulphate that underwent a BSR in a closed to semi-closed basin. The high $\delta^{34}$S values in the bedded ore support a bacterial process of reduction of seawater sulphate as the main source of sulphide sulphur. This process might prevail along the margins and external parts of the hydrothermal deposit, where mineralizing fluids were vented and thus mixed with seawater. On the other hand, TSR could have taken place at greater depths, during the deep circulation of hydrothermal fluids, resulting in the late sphalerite–galena assemblages that replace colloform pyrite in the vent complex.

Acknowledgements

Tarbiat Modares University of Tehran provided financial support for this research. In addition, the Serveis Científico-Tècnics de la Universitat de Barcelona provided support for the sulphur isotope analyses and the Catalan Government’s Department of Universities, Research and the Information Society provided assistance under research grant 2009SGR-00444 of the Departament d’Universitats, Recerca i Societat de la Informació (Generalitat de Catalunya). The authors thank the board of Lead-Zinc Bafq Mining Co. (Ali Mohammadi) and Heydari and Aghazadeh for allowing access to the deposit and their records. We also acknowledge D.F. Sangster for beneficial peer reviews of the manuscript. We thank R. Sáez Ramos and A. Cabral for providing helpful critical comments and suggestions that greatly improved this article.

References

Alavi, M., 1991, Tectonic map of the Middle East: Tehran, Geological Survey of Iran, scale 1:5,000,000.


