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Geological, fluid inclusion and isotopic characteristics of the Gardaneshir Zn–Pb deposit, Central Iran

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Abstract

The Gardaneshir Pb–Zn deposit is hosted by dolomitic carbonate of the Shotori formation which is located in the SW Ardestan in Isfahan province. Ore body in this deposit is dominated by stratabound type. Primary ores in this type are composed of sphalerite, galena, barite and quartz with massive, banded, veined and disseminated structures. Evaluation of ore-grade at Gardaneshir Pb-Zn deposit, based on chemical analysis indicates average values of 4.35% Pb, 0.17% Zn, 20 ppm Ag in the form of galena, sphalerite, minor cerussite and smithsonite occurred along brecciated and silicified fractures mainly by NW-SE trending. Physico-chemical information of ore-solutions under chemical control, performed by entrapped fluid inclusion studies in gangue minerals. Through this way, liquid-rich two phase (L+V) inclusions as predominant types were recognized. These types of inclusions are homogenized into liquid state with a range of TH and related salinities ranges: 78-183 and 216-283 °C, respectively. Salinity ranges vary 3.5-5.86 and 9.7-25 wt% NaCl eq. The above microthermometric data reflect the nature of two populations of fluid inclusions originating from different source. The source materials would have provided by basinal brines, derived during compaction of sediments in shallow sea environment and then by upward movement into sediments, the stratabound dolomitized carbonate hosted Pb-Zn deposit will be formed. Furthermore; the range δ^{34}S from -0.6 ‰ to -20.4‰ that have been extracted by galena can be an evidence of bacterial sulfate reduction in a subsidence sedimentary basin. This study suggests that the Gardeneshir Pb–Zn deposit is an epigenetic, thrust fold-controlled and stratabound deposit with fluids and metals derived from the Triassic sedimentary strata.

Keywords: *Fluid Inclusions, Sulfur Isotope, Stratabound Deposit, Gardaneshir, Ardestan.*

Introduction

This paper discusses the genesis of the Gardaneshir carbonate-hosted lead-zinc deposit located in Central Iran and Uromieh-Dokhtar Magmatic Arc (Fig. 1). There is association between Pb-Zn mineralization and dolomitization in this deposit. Dolomitization occurs as a result of various geological processes involving evaporitic, normal marine and meteoric water (Morrow, 1998), including diagenesis of limestone, and hydrothermal alteration (Wilkinson *et al*., 2005; Zentmyer *et al*., 2011; Bouabdellah *et al*., 2012; Gomez-Rivas *et al*., 2014) and the role of faulting in the formation of dolomites within carbonate sequences as noted that fluids moving along the faults, to cause extensive hydrothermal alterations (Davies and Smith, 2006).

Many researchers have been showen the nature of diagenetic or hydrothermal of dolomitization with respect to associated sulphide mineralization in order to define the type of ore deposit (e.g. Wilkinson, 2003; Wilkinson *et al*., 2005; Leach *et al*., 2006; Johnson *et al*., 2009; Bouabdellah *et al*., 2012; Wilkinson, 2014). These studies also resulted in the recognition of chemical composition of ore fluids and the different types of fluids involved in the formation of sulphide mineralization worldwide (cf. Grandia *et al*., 2003; Nagy *et al*., 2004; Wright *et al*., 2004; Wilkinson *et al*., 2005; Johnson *et al*., 2009; Wilkinson, 2010; Hendry *et al*., 2015). Dolomite-hosted Zn-Pb deposits have been widely reported from different localities of the world (Hitzman *et al*., 2002; Wilkinson *et al*., 2005; Leach *et al*., 2010; Bouabdellah *et al*., 2012). They genetically belong to three major groups of deposits: Irish-type (syngenetic-diagenetic; Hitzman *et al*., 2002; Wilkinson *et al*., 2005; Wilkinson, 2014), SEDEX-type (syngenetic-early diagenetic; Kelley *et al.,* 2004a, 2004b; Wilkinson, 2014) and MVT-type deposits (epigenetic; Leach *et al*., 2010; Bouabdellah *et al*., 2012; Konari *et al*., 2016).

The present study emphasizes on field and petrographic observations, textures and structural features of the sulfide ore minerals and their associated carbonate host rocks. Microthermometrical analyses of fluid inclusions in coexisting transparent gangue minerals and galena are also included. Finally, its geological characteristics were corolated with Mississippi Valley-Type (MVT) deposits.

Materials and Methods

The samples analyzed for this study were taken from drillcores, mineralized outcrops and the carbonate host rocks. Minerals were characterized by optical microscopy and X-Ray powder diffraction (XRD) analysis. Fluid inclusion microthermometry was performed at the Iranian Mineral Processing Research Center (IMPRC) and employing standard procedures (Shepherd *et al*., 1985) using a Linkam THM600 heating-freezing stage, fitted with a thermal control unit TMS-93 and equipped with Ziess microscope. Drillcore and outcrop samples (n=12) were collected from all host rocks. For understanding the relationships between dolomitization and sulphide mineralization, thin and thin-polished sections were studied which using transmitted and reflected light microscopy to establish the paragenetic sequence. Four samples selected for isotope analyses (S) and then sulfur isotope ratios were determined at the G.G. Hatch Stable Isotope Laboratory of the University of Ottawa, Ontario, Canada.

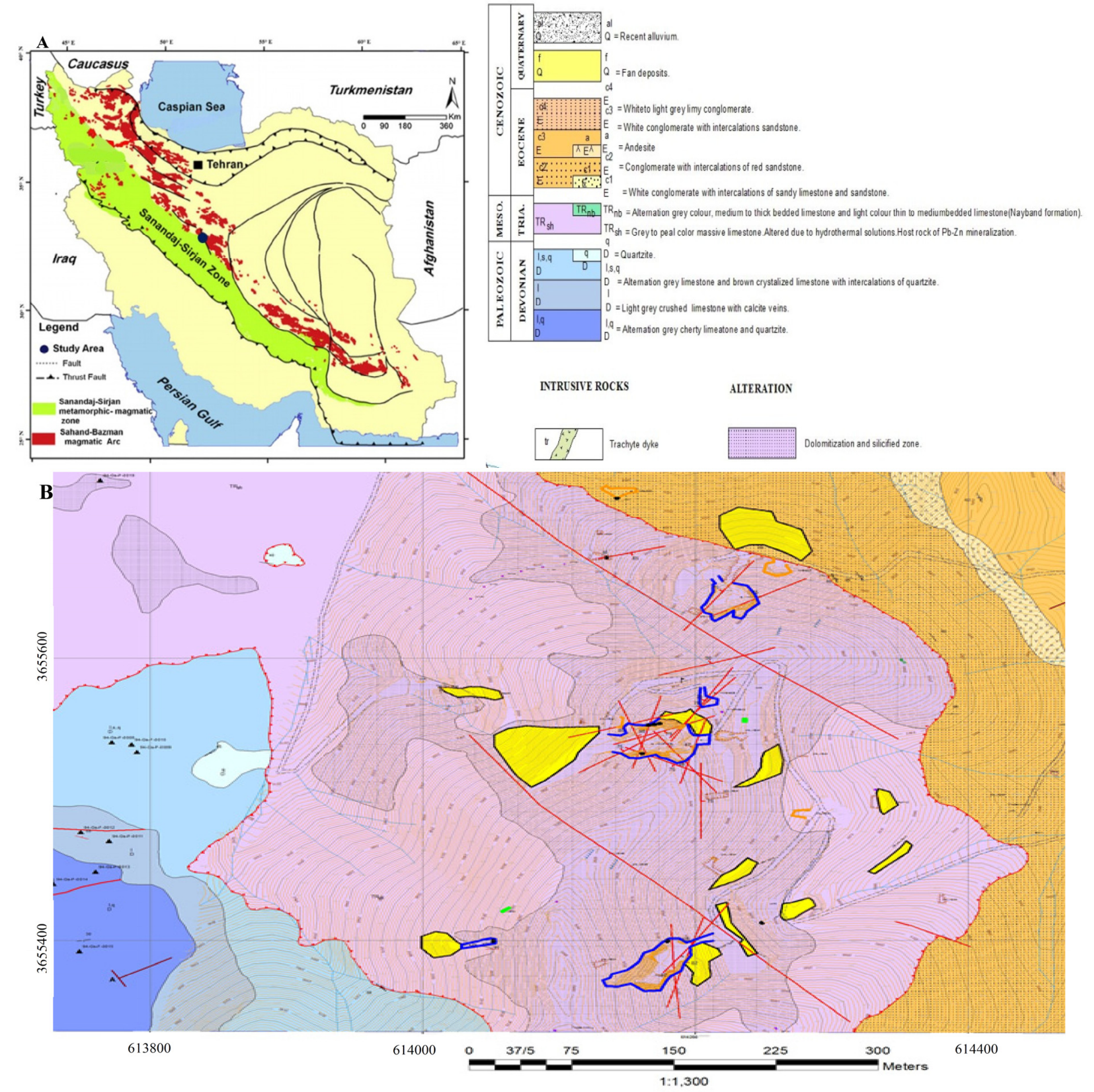

Figure 1. A: Location of the Gardaneshir deposit in the Uromieh-Dokhtar Magmatic Arc, B: Local geological map of the study area.

Geological setting and Host rock petrography

The Gardaneshir carbonate-hosted Pb-Zn deposit on the ground of study area located in the SW of Ardestan, Central Iran. Main structure; besides the small outcrops of Jurassic shales, has been made up of carbonate and detrital rock materials depending on Paleozoic, Triassic and Cretaceous time stages (Fig. 2). This sequence of geological rock units were placed adjacent to Eocene volcano-sedimentary succession in the area.

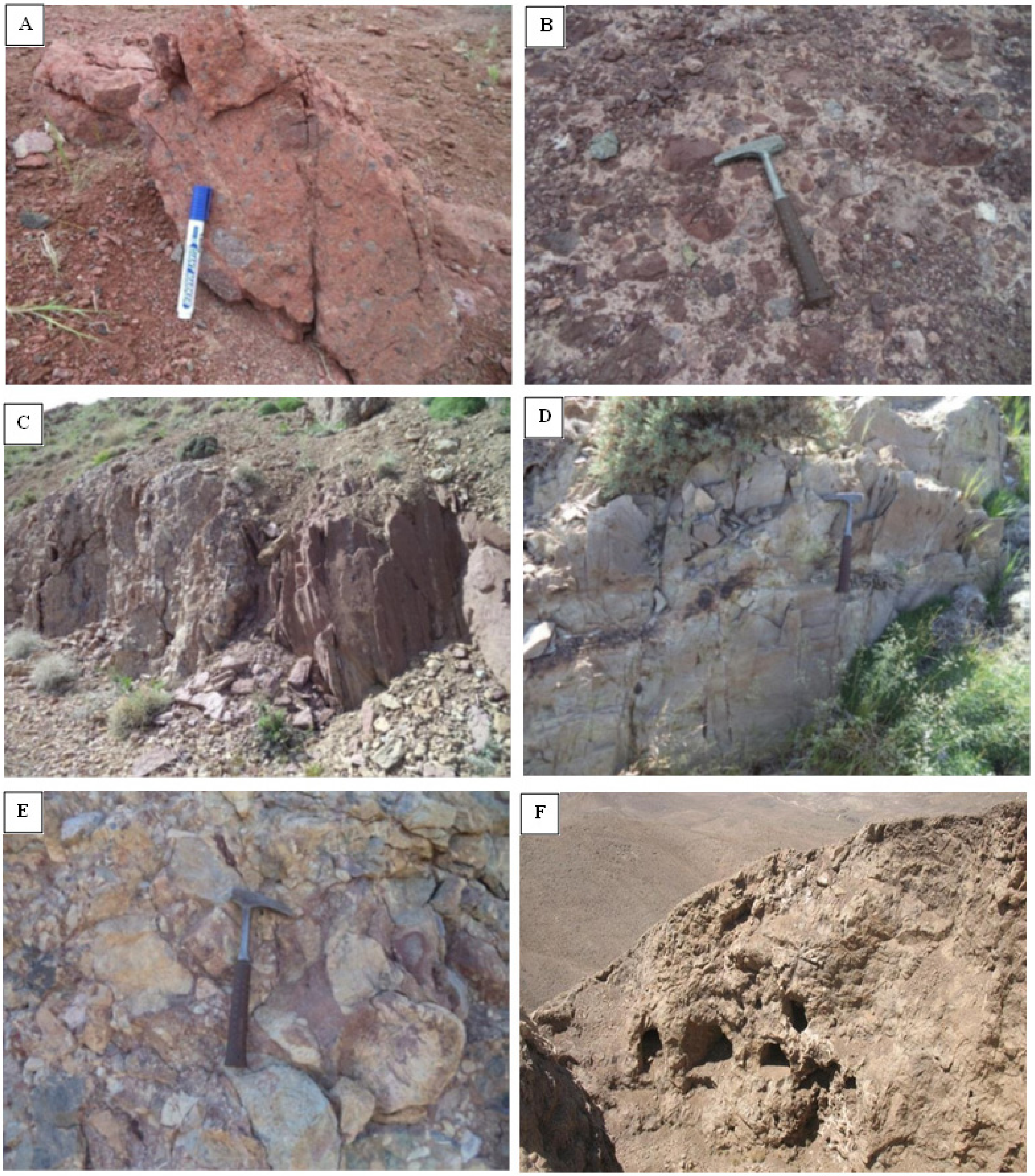

Figure 2. Field images of the Gardaneshir deposit. A) Lithic tuff in the volcano-sedimentary unit. B) Brecciated tuff in the volcanic unit. C) Outcrop image of the Eocene sandstone. D) Photograph of ore-bearing breccia, the main lithology is dolomite, limestone and minor siltstone. E) Fe-oxides alteration in the Lower Eocene conglomerate. F) Cave and karstic part in the carbonate host rock.

In special case, the Triassic system composed of dolomitic carbonate which in aspect of geology is attributed to the Shotori formation. Mineralization is hosted by middle Triassic dolomitized limestone of the Shotori formation. The dolomite is overlain by Late Triassic shale. Mineralization is epigenetic and controlled by lithology and structures. Silicification generally follows dolomite which was replaced original limestone. This phenomenon leads to ground preparation in the host rock for mineralization. The ores occur as bedded stratabound replacement sheets, veins and the solution-collapse breccias. Because of ore deposition by replacement as well as by open-space fillings, ore structures are variable and the minerals vary from fine to very coarse-grained. Evidence of solution activity is common, and it appears that replacement preceded open-space fillings which occur as veins along faults and breccia cements or as solution cavity fillings. Stratabound-replacement mineralization occurs as massive or laminated ores parallel to host rock bedding. Ore layers are discontinuous, and their thickness is variable even at short distances.

It is notable the Shotori formation also showed a strongly brecciated zone of kinetic fracture features of low pressure environment, favorable for moving the ore solutions into distributed fissures and subsequent production of fracture filling of vein-type mineralization. The Quaternary strata consist of gravel fans, and recent alluvium. Ore-mineral description carried out on 40 sample polished thin sections obtained from the studied mineralized zone and its compilation with other laboratory data, caused the following ore-paragenesis in ascending order of: pyrite, chalcopyrite, galena, sphalerite (hypogene phases), malachite, azurite, cerussite, smithsonite, iron oxides (supergene phases) and gangues of barite, quartz and calcite (Table 1, Fig. 3). Barite appears in massive or laminated shapes with white and milky colors.

Dolomitization and silicification

Based on field data and microscopic observations on thin and thin-polished sections of the carbonate strata containing disseminated sulfide minerals, two types of dolomites were distinguished in the Gardaneshir deposit; the first one is regional, and the other is uplifted-related dolomites.

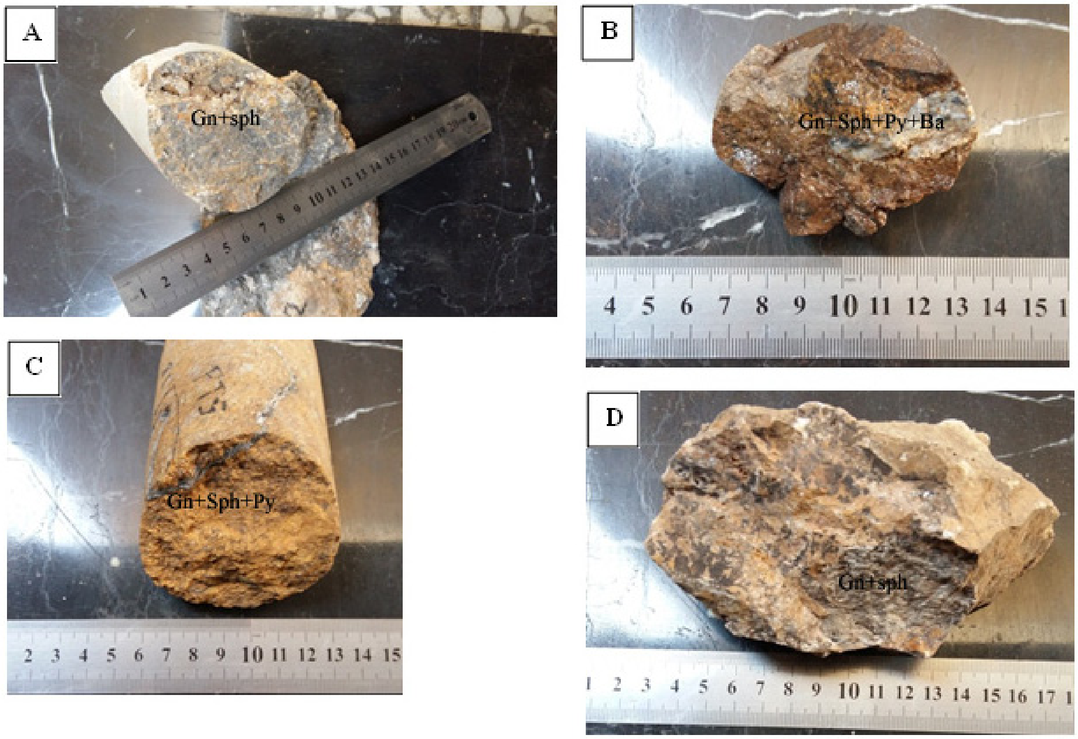

Figure 3. Hand specimen from the different sulphide mineralization in the study area. (A) Massive galena and sphalerite replaces the quartz, dolomite and barite. (B, C) Core samples which include vein-veinlets of sulphides (sphalerite, pyrite and galena) which cross-cut the host rock (D) Hand specimen from massive texture of the ores. (Sph: sphalerite, Gn: galena, Py: pyrite, Ba: barite).

Table 1. Paragenetic sequence ore and gangue minerals in Gardaneshir deposit

Ore Minerals	Stage of ore-mineralization	
	Early →	Late
Pyrite(Ⅰ)	▬	
Chalcopyrite	▬	
Sphalerite	▬	
Galena	▬	
Pyrite(Ⅱ)		▬
Barite	▬	
Cerussite		▬
Fe-Oxides &Hydroxides		▬
Dolomite	▬	
Quartz	▬	▬
Calcite	▬	▬

The dolomite precipitated from hot hydrothermal solutions circulating in fissures and fractures, suggesting that the Ca+2 content of the fluids changed during crystal growth and fine to medium grained subhedral dolomite occurred as a replacement in the limestone and the micritic matrix in regional dolomite (Fig.4 A, B). The uplift-related dolomite is related to faulting that caused brecciation in host rock and the brecciated clasts have been cemented by dolomite (Fig. 3D, E). Silicification generally favors dolomite that has replaced original limestone. It occurs as veinlets and nodules of fine-grained quartz predating mineralization, and as disseminated coarse grained euhedral quartz during mineralization.

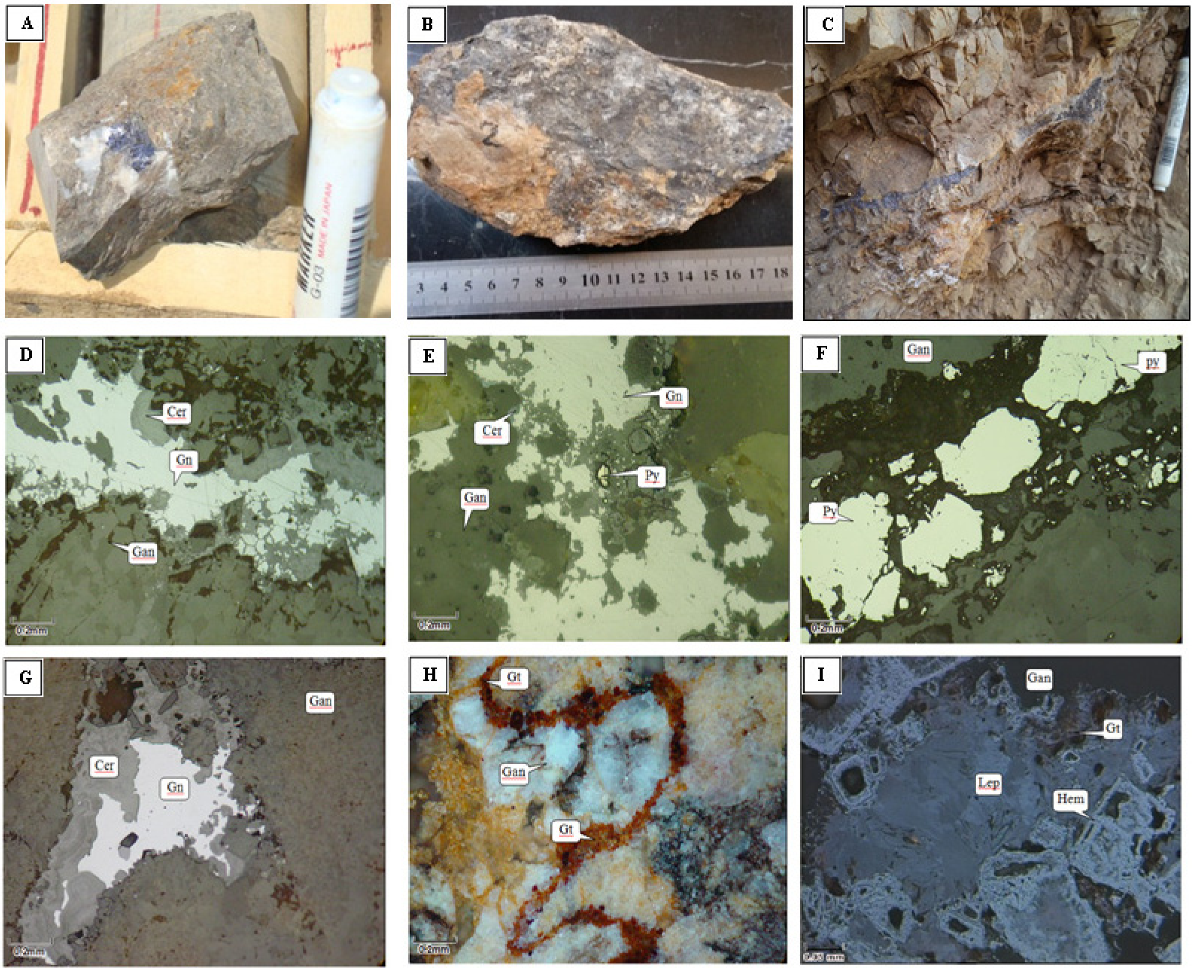

Figure 4. Microphotographs of sulfide ores from Gardaneshir.A,B) Hand specimen of host rock with sulphide mineralization. C) Sulphide mineralization in carbonate strata. D&E) Reflected light microphotograph of sulfide ore with galena (Ga), Cerussite(Cer) and gangue (Gan).Galena altered to cerussite. F) Pyrite (py) crystals as vein-fillings (XPL).G) Galena contains a pyrite inclusion H) Transmitted light microphotograph of Fe-oxides,pyrite replaced by geotite. I) Replacement of geotite(Gt) and hematite (Hem) in pyrite crystals ,formation of lepidocrusite(Lep) in open space.

Fluid Inclusions

Fluid inclusion microthermometry was carried out on inclusions in calcite using a Linkam THM600 heating-freezing stage, fitted with a thermal control unit TMS-93 and equipped with Ziess microscope at the Iranian Mineral Processing Research Center (IMPRC) and employing standard procedures (Shepherd *et al*., 1985). The inclusions contain two phases, a colorless aqueous liquid and small vapor bubble, at room temperature and have a consistent degree of fill [VLIQ/(VLIQ+VVAP)=0.7].

They range in size from less than 5 up to 28 µm, often display negative crystal or rounded isometric shapes, and occur mostly as isolated inclusions, often along growth zones but rarely in clusters. They are mainly primary in origin, with only a few considered as pseudosecondary or secondary. The homogenization temperatures into the liquid phase scatter between 78 and 283°C (Fig. 5 and Table 2). These microthermometric data indicate a fluid composition in the system $CaCl_2$-NaCl-H_2O with salinities between 3.5 to 25 wt.% total dissolved salts (Fig.6). There are two populations of fluid inclusions originating from different sources. The first, source materials would have provided by basinal brines, derived during compaction of sediments in shallow sea environment and then by upward movement into sediments, the stratabound dolomitized carbonate hosted Pb-Zn deposit will be formed.

Table2. Summary of studied fluid-inclusion assemblages

Sample	**n**	**Size(µm)**	**Type**	**Origin**	**Te (°C)**	**Tmice (°C)**	**wt% NaCl**	**Thv-l (°C)**	**Degree of Fill**	**Host Mineral**
sgs-18BH	1	10	L+V	Primary	-21	-3.5	15.86	178	0.8	Carbonate
	2	12				-	19.1	130		
sgs-12	1	10	L+V	Primary	-	-	20	167	0.7	Carbonate
	2	11				-	15	128		
sgs-7	1	11	L+V	Primary	19-	-1.1	10.2	137	0.9	Carbonate
	2	12			23-	-0.9	18	179		
sgs-9BH	1	15	L+V	Primary	16-	-1.2	17	141	0.6	Carbonate
	2	18			20-	-3.8	13.2	157		
	3	12			18-	-4.8	11.2	165		
sgs-15BH	1	8	L+V	Primary	17-	-2.1	15.7	134	0.7	Carbonate
	2	17			-19.5	-1.8	17.6	127		
	3	12			24-	-1.9	12.8	126		
sgs-11BH	1	16	L+V	Primary	-21.3	-0.5	15.3	173	0.8	Carbonate
	2	25			18-	-6.2	10.3	157		
sgs-12BH	1	19	L+V	Primary	20-	-4.1	18.8	134	0.6	Carbonate
	2	20			-15.3	-	9.7	168		
	3	23			19-	-3.1	15.1	116		
	4	9			-22.1	-2.1	20.2	131		
	5	14			21-	-2.5	23.1	179		
	6	6			-20.1	-0.8	21.1	183		
	7	28			23-	-1.2	17.7	173		
sgs-11	1	11	L+V	Primary	19-	-0.8	13.9	160	0.8	Carbonate
	2	15			20-	-1.3	22	145		
	3	5			-18.2	-0.6	15.4	170		
	4	8			-12.9	-0.4	10.7	149		
	5	14			21-	-0.9	19	159		
Sgs-17	1	7	L+V	Primary	-13.2	-4.2	16.2	110	0.6	Carbonate
	2	11			-16	-8.1	18.5	112		
	3	6			-17.1	-0.9	17.3	85		
Sgs-5BH	1	23	L+V	Primary	-19	-3.1	4.2	216	0.7	Carbonate
	2	33			-20	-0.8	3.6	283		
Sgs-2	1	20	L+V	Primary	-15	0.0	3.5	268	0.6	Carbonate
	2	10			-21	-3.5	5.86	278		
Sgs-24BH	1	9	L+V	Primary	-11.1	-7	16.2	78	0.7	Carbonate
	2	5			-9.3	-2.2	19.1	91		
	3	11			-12.5	-0.9	25	83		
	4	13			-21	-4.5	13.6	92		
	5	5			-16.1	-6.8	17.9	81		
	6	14			-12.2	-1.5	22	102		

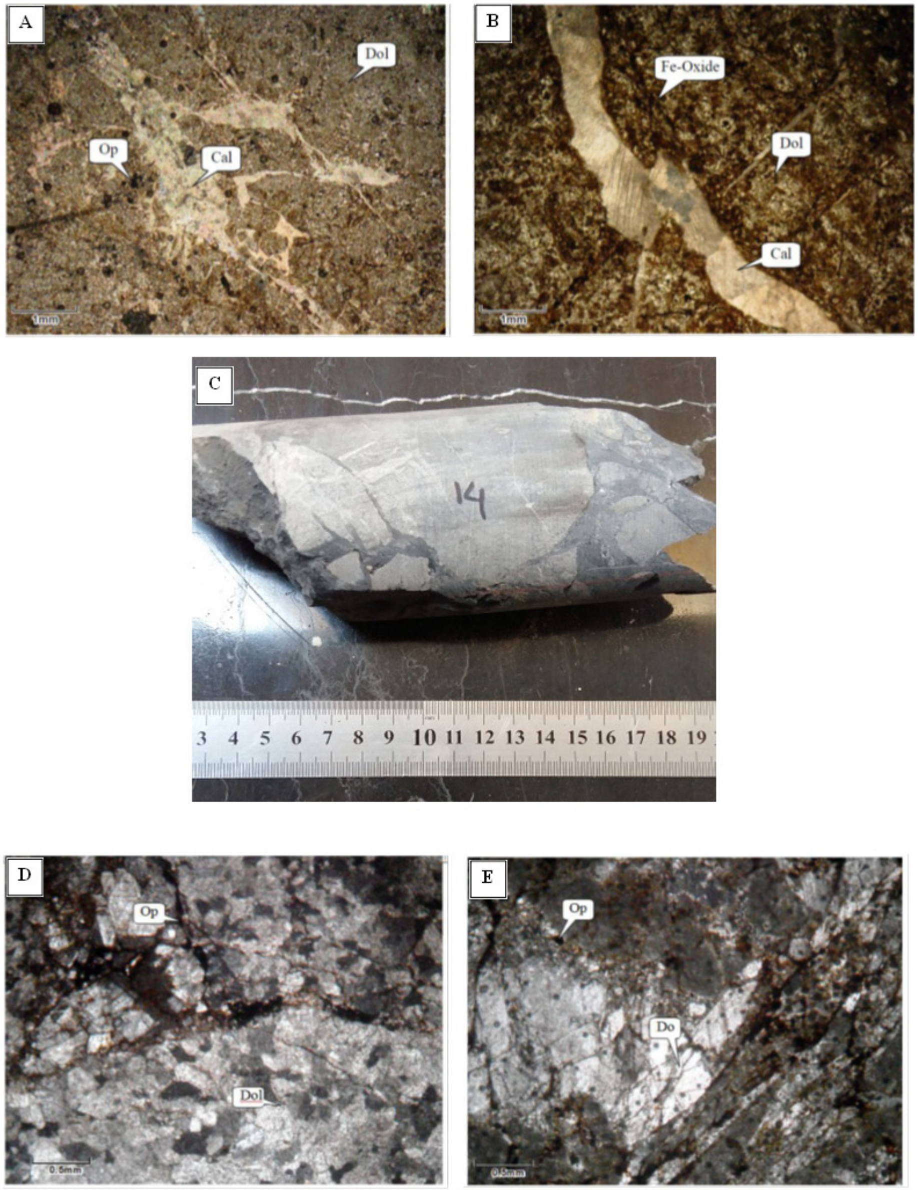

Figure 5. Photomicrographs of dolomite in study area: (A&B) Microscopic image from fine-grained selectively regional dolomitization of micritic matrix.C) Hand specimen from uplift-related dolomite. (D&E) Microscopic image from faulting-related dolomite.

These inclusions (n=35) indicate high salinity (9.7-25 wt.% NaCl) and low temperature (78 to 183 °C). The graph of the salinity versus the homogenisation temperature (Fig. 7) (Kesler, 2005) of the fluid inclusions shows the highest concentration of fluid inclusions in hydrothermal-type water. In a few cases, the inclusions were large and clear enough to measure the homogenization temperature varies between 216 to 283 °C (n=4). This type of inclusions have high temperature and low salinity (average salinity 4.29 wt.% NaCl). This suggests mixing between highly saline brine and low-salinity fluid (meteoric water, seawater, or a mixture of both) at the site of mineralization, subsequent to the formation of the calcite.

Sulfur isotope

Sulfur isotope analyses from the Gardaneshir deposit were carried out on galena in order to determine the physicochemical characteristics of the mineralizing fluid. Samples selected for isotope analyses were first grinded and sieved to a mesh size of 2 mm. Individual minerals were then separated in heavy liquids. Finally, individual grains were handpicked under the binocular microscope. The $\delta^{34}S$ values were measured in SO_2 gas using a continuous-flow gas-ratio mass spectrometer (ThermoQuest Finnigan Delta PlusXL). The samples were analyzed by G.G. Hatch Stable Isotope Laboratory in the advanced research complex of Ottawa University, Canada. The results are expressed as $\delta^{34}S$ values in parts per mil, where the standard is the troilite sulfur from the Canon Diablo meteorite. The $\delta^{34}S$ values for sulfide minerals Gardaneshir vary from -0.6 to -20.4 ‰, with an average value of -9.2‰ (Table 3). The isotopic values from the Gardaneshir deposit plot in the sedimentary Environments (Figs. 8, 9).

Table 3. Sulfur isotope ($\delta^{34}S$) values of the study area.

Sample No	**Mineral**	**$\delta^{34}S$**	**%S**	**$\delta^{34}S_{H2S(T:78)}$**	**$\delta^{34}S_{H2S(T:283)}$**
Gs-15	Galena	-14.0	12.3	-7.8	-10.9
Gs-17	Galena	-20.4	12.4	-15.2	-17.3
Gs-2	Galena	-1.8	0.6	-3.4	-1.3
Gs-24bh	Galena	-0.6	12.1	-4.6	-2.5

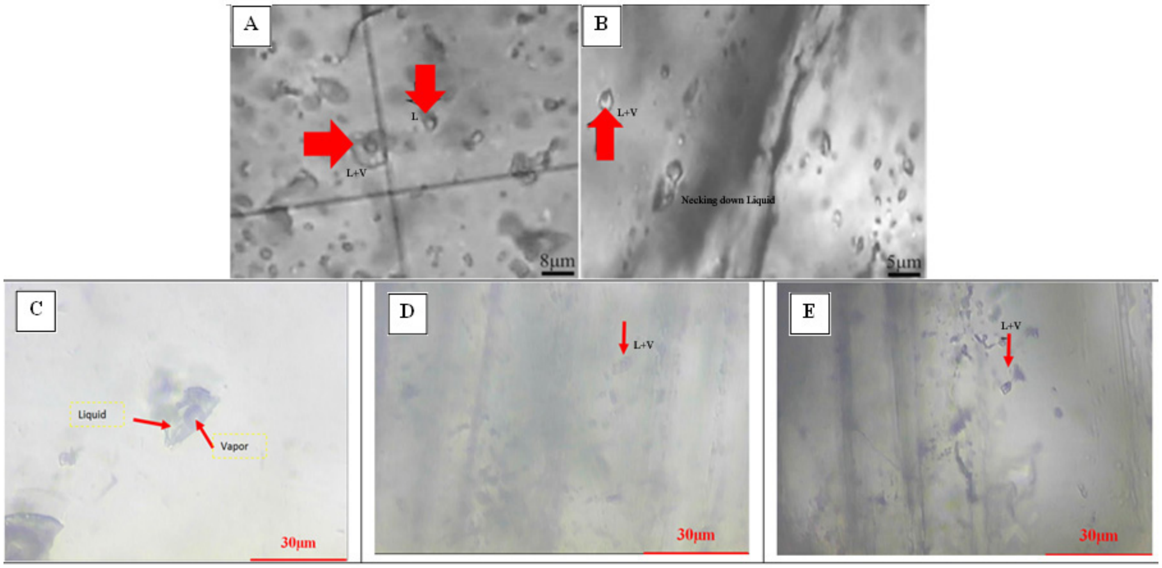

Figure 6. Microphotographs of fluid inclusions. A, B, C) Group of liquid-rich two-phase primary fluid inclusions in calcite from Gardaneshir, D & E) Group of primary mono-phase (L=liquid or V=vapor) inclusions in calcite.

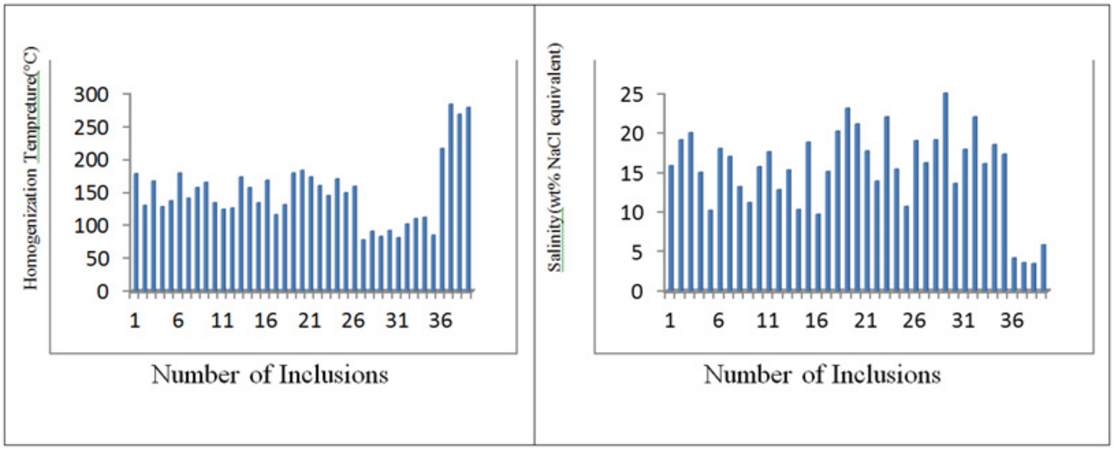

Figure 7. Fluid inclusion microthermometric results (histogram of the homogenization tempreture and salinity) versus frequency from the Garaneshir deposit.

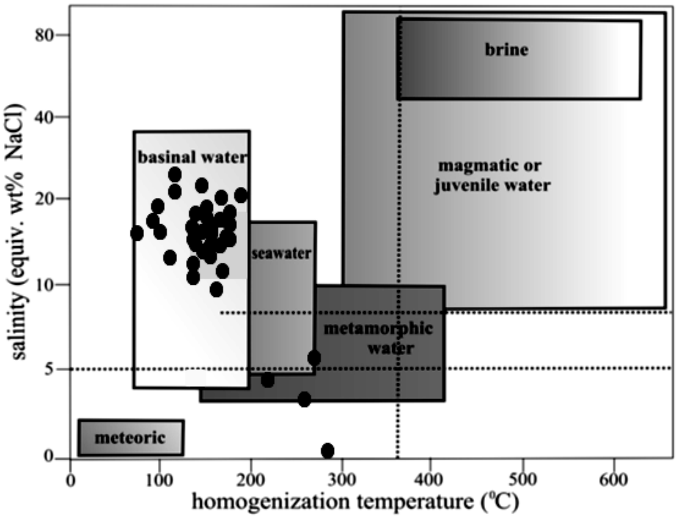

Figure 8. Detection of the mineralized fluid in the Gardaneshir deposit using the salinity vs. homogeneous temperature histogram (Kesler, 2005).

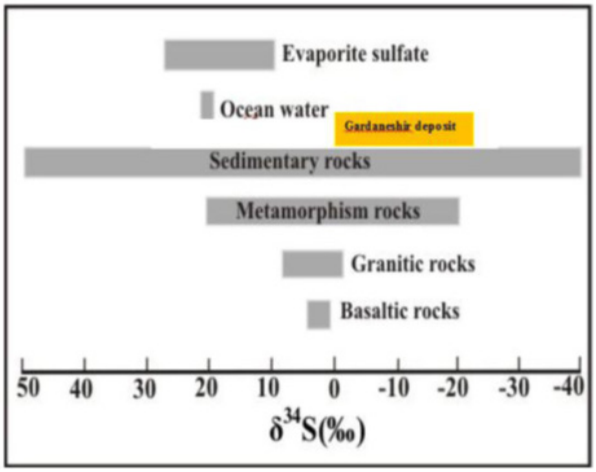

Figure 9. Isotopic composition of Galena from Gardaneshir deposit as compared with some geologically important materials (note text from Hoefs 1997).

The sulfur isotope values are similar to those from the MVT-type deposit of Reocín, Spain (Velasco *et al*. 2003). The sulfur isotope data of Gardaneshir contrast with the sulfur isotope compositions of sphalerite from the Irankuh deposit (−9.6 to −3.6‰) reported by Ghazban *et al*. 1994.

Discussion

Fluid inclusion studies illustrate the presence of two different types of hydrothermal fluids in the Gardaneshir deposit. The earliest hydrothermal fluid with high salinity (9.7 to 25 wt % NaCl equiv) and low temperature (mean-137°C) had a basinal origin. This salty fluid was moved upward to shallower levels, and its temperature subsequently decreased. The meteoric water circulated in the peripheral parts and portion of this water moved toward the center of the stock and after interaction with basinal water, the fluid gradient decreased and then produced a mixture of basinal and meteoric fluid with salinity of 3.5 to 5.86 wt % NaCl equiv. This fluid caused alteration in peripheral parts and carbonate wall rocks. Late fractures or reopened veins provided pathways for this fluid to circulate in the system. This fluid, when circulated, progressively increased in temperature, causing destabilization in wall rock and produced alteration zones, and leached away early formed lead and zinc sulfide minerals to upper levels of system and precipitated limited proportion of galena, sphalerite and chalcopyrite in some of the shallower parts. These hydrothermal processes are caused dolomitization (Zentmyer *et al*., 2011; Gomez-Rivas *et al*., 2014, Konari, 2016). Hydrothermal dolomitization results from the circulation of fluids with higher temperature than the ambient host rocks (Davies and Smith, 2006). This fluid is generally rich in Mg, and able to precipitate dolomite within limestone in the cooler and shallower parts of the sedimentary basin (Hardie, 1991). Mg can be originate from Mg-rich rocks such as Jurassic shale. This process is generally characterized by an outflow of hydrothermal waters along normal faults; such fluids can also transport base metals to form sediment-hosted mineralizing systems (Grandia *et al*., 2003; Wilkinson *et al*., 2005; Leach *et al*., 2006; Shelton *et al*., 2011; Hendry *et al*., 2015). Many hydrothermal dolomites in sediment-hosted deposits form during faulting, while dolomitization along thrust faults is rarely extensive (Morrow, 1998). In the Gardaneshir deposit, occurrence two types of dolomites associated with sulphide minerals could support hydrothermal dolomitization coeval with sulphide mineralization in a hydrothermal ore system.

The Gardaneshir fluid inclusion data, sulfur isotope and other characteristics compared with Nakhlak deposit in Centarl Iran (Jazi and Shahabpour, 2010, Jazi *et al*., 2015), illustrate a similarity in both deposits that suggest; these deposits formed from a similar composition fluid. Finally, the geological setting of the area and the observed petrographic fabrics suggest a possible orogeny-related Mississippi Valley-Type (MVT) mineralization.

Conclusions

Mineralization at the Gardaneshir deposit in the Ardestan region is hosted by Triassic dolomitized limestone. The paragenetic sequence indicates that the mineralization is entirely epigenetic. Based on petrography and mineralography of drill cores and outcrop samples, important hydrothermal alteration types are recognized at Gardaneshir like silicification and dolomitization. Fluid inclusion studies show the presence of two hydrothermal fluids at Gardaneshir deposit. The fluid I, originated from low temperature and high salinity that has basinal source. The fluid II, is a mixture of seawater fluid with meteoric water which has low temperature and salinity, was responsible for occurrence types of alteration in the wall rocks. The $\delta^{34}S$ values of sulfide minerals in the Gardaneshir are between -0.6 and -20.4‰ that suggest basinal origin for sulfur. All of these factors and camparison with Nakhlak deposit led the Gardaneshir Pb-Zn deposit is a MVT stratabound carbonate hosted.

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