



Islamic Azad University  
Mashhad Branch

# Determination of a Conceptual Model for the Structural Features and Pb–Zn Mineralization in the North of Behabad Fault Zone, Central Iran

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Received 17 November 2016; accepted 4 April 2017

## Abstract

The Behabad region is located within a tectono–sedimentary zone in southeast Yazd province, Central Iran. The tectonic activities have deformed and faulted the Mesozoic and Quaternary formations in this area. The faults in Kuhbanan and Behabad have played a key role in the evolution of geological events, mineralization, and the formation of Behabad–Kuhbanan horst. These faults have separated the Posht-e-Badam block from the Tabas block and the Behabad zone from the Abdoghi–Ravar tectonic zone, respectively. Remote-sensing techniques and field observations show that the Pb–Zn veins share similar trends with the structures. The compressional system induced by the activities of the Behabad-1 and 2 fault systems have caused the formation of thrusts, drag, and sigmoidal folds, the North Behabad horst, and shear zones containing Pb–Zn mineralization. The Mississippi Valley-type (MVT) deposits and strata band mineralization types are present in the study area. In terms of the temporal phase controller, it is consistent with the tectonic–magmatic model of the Late Paleozoic–Triassic period; in terms of the spatial controller, mineralization is situated in the tectonic–metallogeny province of Central Iran and the ore deposits that mainly follow the geometry of the thrust faults' crushed zones. The thrust fault that drives the dolomite unit over the limestone is the main cause of the ore solutions migration. According to the MVT mineralization and the correlation between structures and mineralization, the sulfide deposits can be potentially found at the base of the Permo–Triassic units in the studied area. There are several active and non-active Zn–Pb mines such as Abheydar, Rikalaghi, and Tapesorkh.

**Keywords:** Conceptual model; non-sulfide mineralization; Behabad fault; Kuhbanan fault.

## 1. Introduction

The study area is located in the southeast of the Yazd province and the northeast of the Behabad city in the tectono-sedimentary zone of the Tabas block, Central Iran (Fig 1). The Kuhbanan and Behabad-1 and 2 faults have played a major role in the geological and mineralization processes of this area, and have resulted in the formation of various structural zones in this region, such as the Kuhbanan and Behabad-1 faults, the Posht-e-Badam block, the Tabas block, the Behabad zone, and the Abdoghi–Ravar tectonic zone, respectively (Kargaran Bafghi et al. 2012; Adib et al. 2017). Geological processes such as igneous and metamorphic activities and ore deposits occur within the plate boundaries (such as thrusts), which are often identified by fault zones (Alavi 1991; Leach et al. 2001; Robb 2005). These mineralizations are very similar to the Mississippi Valley-type (MVT) in which mineralizations like barite, lead, and zinc deposits occur within the carbonate host rock. In the Behabad and

Mehdiabad regions (~70 Km SW of Behabad fault), minerals are formed in the continental rifts and margins (Evans 2000; Piri and Asghari 2012). Thus, it can be stated that the mineral deposits in the Behabad region are MVT with various geological units, such as shale, sandstone, conglomerate, gypsum, limestone, and dolomite.

In this research, the main tectonic characteristics of the area are counted among the important controlling factors in the mineralization processes. Hence, the structural parameters in relation with mineralization are described by a structural–mineralization conceptual model. Deformations of the study area are consistent with the recent activities of the faults (Mahdavi 1996; Walker and Jackson 2004), while the active faulting is affected by a N–S dextral strike-slip shearing between the Iranian plate and Western Afghanistan with a movement rate of 15 mm y<sup>-1</sup> (Vernant et al. 2004a).

The recent activities of the major NW–SE regional structures are mostly in form of a strike-slip fault, and are consistent with the trend of folds and faults of the study area.

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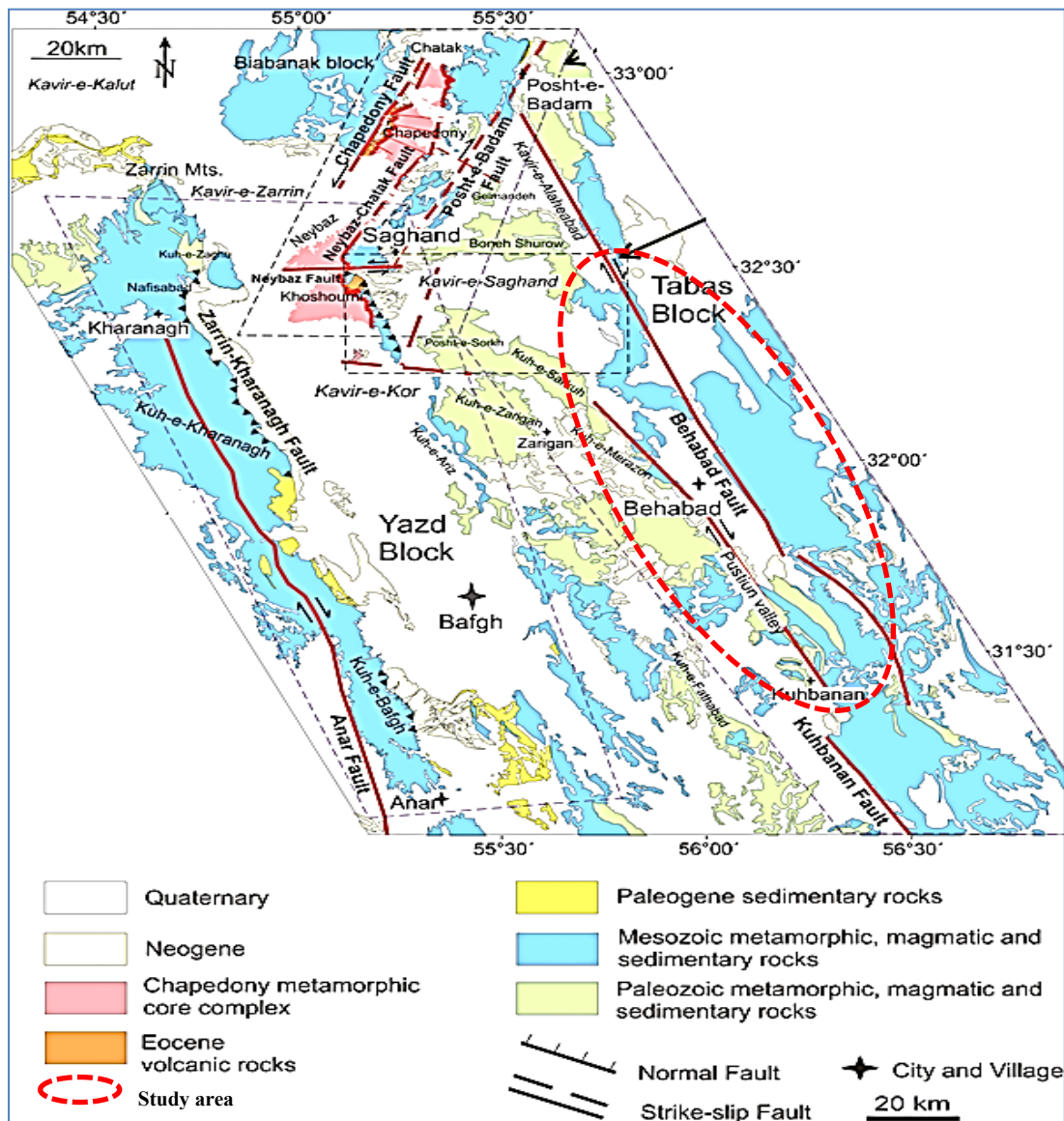


Fig 1. Location of the studied area and the simplified geological map of Southwestern Central Iran, showing major Eocene and Neogene to the recent faults (Kargaran Bafghi et al. 2012).

The density of lineaments depends on the extent of the tectonic uplift and represents its active tectonic features (Walker 2006). Migration of the solutions along the rock joints results in the hydrothermal alteration of the rocks. Metallic prospects can be discovered by tracing this phenomenon (Kearey et al. 2009).

The leaching and enrichment processes depicted in Gilbert and Park's (Guilbert and Park 1997) schematic diagram might be used to illustrate the location of Pb-Zn mineralization in the supergene environments. Based on this diagram, lead, anglesite, and cerussite are formed above the water level table (Bateman 1950). Smithsonite, hydrozincite, and hemimorphite are formed near the surface, while smithsonite and gypsum emerge below the water level. Iron oxide and lead

sulfate are relatively insoluble and remain at the surface. Galena is soluble in a solution containing ferric sulfate, whereas the stable lead carbonate is formed in the veins, in which the other sulfides are altered or washed away. Silver and zinc sulfides are soluble in the presence of ferric sulfate fluids (Guilbert and Park 1997). Because of the solubility of zinc sulfate, the zinc containing the most oxidized bodies is scattered in the groundwater and can be presented as smithsonite, hydrozincite, and hemimorphite or in form of other carbonate minerals and silicate above the surface. This process may occur in semi-arid climates, such as that of Behabad, in carbonate rocks. The main aim of this study is to propose a conceptual model for the MVT Pb-Zn

mineralization in the Behabad faulting zone based on geology, field observations, and known mines/deposits.

## 2. Geology and tectonic setting

The Infra Cambrian to Quaternary rock units of Central Iran are affected by orogenic phases, magmatism, and metamorphism. The Central Iran micro-continent is surrounded by the ophiolitic sutures of Sistan, Nain-Baft, the Darouneh fault, and the ophiolites of Kashmar-Sabzevar. The activities of the faults with the strike-slip component are found in the Shotori, Tabas, Kalmard, Posht-e-Badam, Bayazeh-Bardsir, and Yazd blocks (Bateman 1950; Takin 1972; Berberian 1981; Jackson and McKenzie 1984; Kargaran Bafghi et al, 2012). Based on the structural sub-stages, magmatism, metamorphism, mineralization, stratigraphic sequences, and the deformation of the basement, the study area is located in the middle part of Central Iran in the Tabas block (Fig 1).

The Permian outcrops in the study area consist of siliceous clastic rocks impregnated with iron compounds located on the Shotori formation by a normal overlap (Nadimi 2007). In the eastern region of Behabad, the Triassic carbonate rock sequences are covered by Jurassic gypsum units. The rocks of the Upper Triassic to the Lower Jurassic (Lias) are covered by tectonic boundaries of the Shotori formation. The sequence of a thin layer of limestone with mid-layers of green shale covers the Hojedk formation (Mahdavi 1996). The geological units in RGB color composite (7-4-2 bands of Landsat image) are presented in Fig 2a and alterations of ancrite and iron oxides by a band ratio of 5/7, 4/3, and 3/2 are presented in Fig 2b (Mirzaee 2012).

At present, the convergence rate of 22–25 mm y<sup>-1</sup> (Vernant et al. 2004a) has led to the development of deformed structures in the area. There is clear evidence of Quaternary fault activity in the region and it appears that the Anar fault plays a significant role in the distribution of the right strike-slip displacement in the study area (Walker 2006). The Behabad and Kuhbanan faults affect the tectonics and mineralization of the study area (Fig 3). There is an abundance of historical and instrumental earthquake reports in this region (Walker 2009). The relatively dispersed pattern of faults in the study area indicates a deformation rate of several millimeters per year (Mahdavi 1996; Vernant et al. 2004a; Walker et al. 2010). The study area rose above the water level around the late Mesozoic period due to the convergent tectonic stresses (Ramezani and Tucker 2003).

## 3. Methodology

This research is conducted through four different steps; analysis of satellite imagery, field study, tectonic evidence gathering, and mine data. The lineaments reflect the sub-surface phenomena and satellite imagery is a valuable tool for the detection of these lineaments (Casas et al. 2000). To validate the interpretation of the sub-surface structural effects, it is required to confirm the origin of the lineaments by investigating the geological structures such as faults and fractures. An accurate mapping of the lineaments and faults plays a key role in the research concerning the relationship between mineralization, faulting, and mineral exploration.

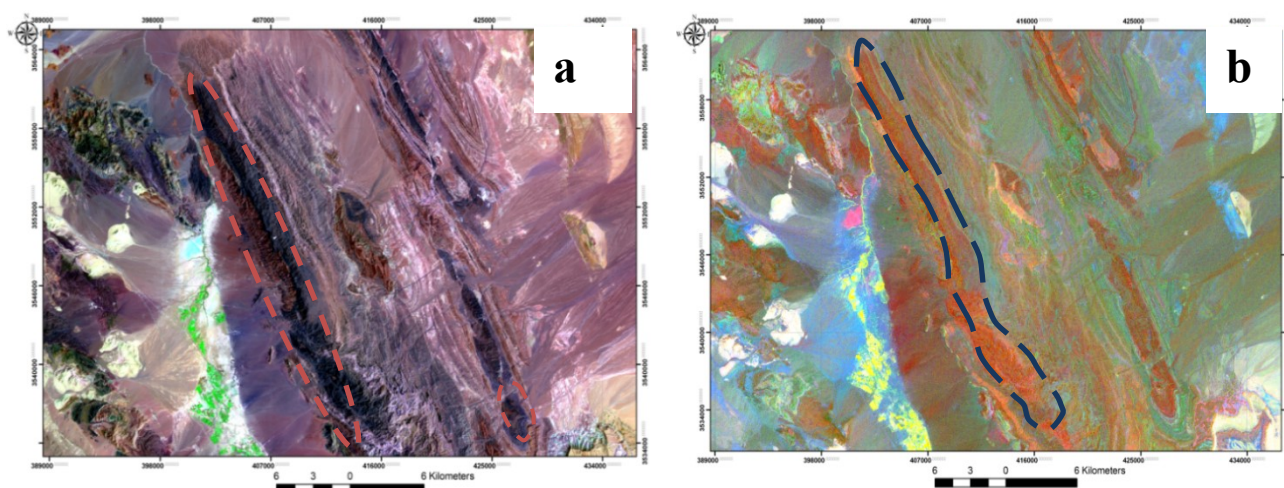


Fig2 (a) Geological units in RGB color composite (7-4-2 bands): light brown: red sandstone; Dark blue: shale and green sandstones; Green to yellow: Permo-Triassic limestone and dolomites; (b) Band ratio: 5/7, 4/3, and 3/2 Pink to amethystine-yellow inside the dashed ring: alterations of ancrite and iron oxides (Mirzaee 2012).

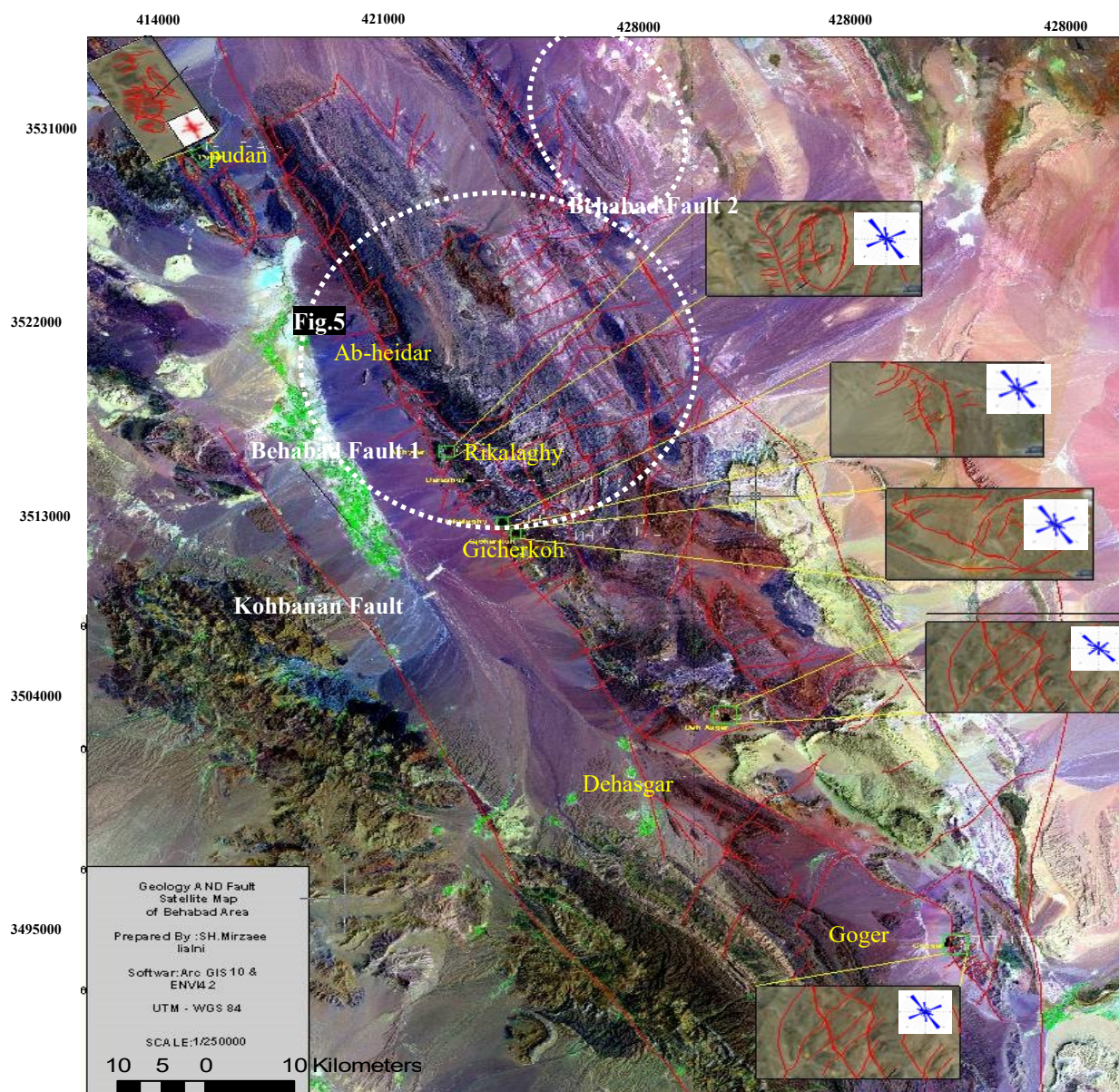


Fig 3. The fault system, geological units, and the location of the studied mines (The NE–SW faults are mainly tensional with the strike-slip component).

Lineaments and zones of alteration are extracted from the ETM multispectral images using PCI Geomatica software (PCI 2012) by applying various filters like the Envi Software. To confirm the fault lineaments and provide information on the distribution of active faulting, the extraction is validated through a series of field surveys (e.g. Sarp and Toprak 2005). Then, to identify the major and minor fault trends, their rose diagrams are compared with mineralization and alteration evidences in these zones. To construct a conceptual model in this area, mineralization-controlling indexes at the regional scale, the stratigraphic evolution, structures, and regional mineralization, as well as the spatial and temporal controllers are investigated.

## 4. Result and discussion

### 4-1. Faulting and alteration

Most alterations are used as a guideline to find the relationship with the other structural factors (Shahabpour 2005). The study area mainly consists of limestone, dolomitic limestone, shale, and sandstone (Fig. 2A). The hydrothermal solutions cause the alteration in the limestone (Fig.2B). The hydrothermal solutions are directed by fractures toward the ground surface. At the intersection between the faults and fractures with the dolomites, mineralization is likely to occur (Kearey et al. 2009). The studies indicated that mineralization and alteration areas are mostly located in the dolomites and the limestone near or along the thrust faults. The northwest, north, and central parts of the

region have the largest diversity and number of structural fractures (Fig.2 and Fig.4). Thus, these areas might have the greatest mineralization potential.

The structures of the area are affected by the movement of the Tabas block toward its adjacent blocks (Posht-e-Badam, and Yazd). Transpressional deformation, drag and sigmoidal folds, and the direction of thrusting in oblique-slip tear faults are the obvious reasons for the dextral component of the Behabad strike-slip faults (Adib 1998). The Kuhbanan and Behabad dextral strike-slip faults converge around the west of Ravar to Gojer mine (Fig.3), where the tension system between these faults results in the formation of the Behabad depression. The compressional fault system between Behabad-1 and 2 has caused the formation of the circular structures (Fig.4), drag folds (Fig.5), thrusts, and the horst system (Fig.6,7) in the north and northeast of Behabad.

The fault system of Behabad and Kuhbanan has a direct impact on the uplifting, folding, magmatism, and mineralization in the area. There is a large number of lead and zinc ore deposits from the north of Kuhbanan to the north of Behabad. Most of these deposits have a carbonate host rock (Mirzaee 2012). Over 90 percent of these deposits are located at the base and within the Triassic units (limestone and dolomite), contain non-sulfide minerals, and Pb-Zn sulfides, in rare cases.

Some of these minerals are associated with molybdenite minerals. Gojer, Tappeh Sorkh, Gicher Kuh, Ri-Kalaghi, Ab-Heidar, Ahmad-Abad, and Poodan relate to the Behabad fault in the north and northeast, and Taj-Kuh, Kuh-Ghaleh, Jalal-abad, Zard-Kuh, Dar-Tangol, and Zar-kuieh are associated with the Kuhbanan fault (Fig. 3). The main host rock of the ore deposits in this area is the dolomitic-ancritic limestone of the Shotori formation. Because of the thrust faulting, the Shotori formation is driven on the younger units and minerals are formed in the shear zone (Figs. 4, 5,8 and 14).

#### 4.2. Petrography and Mineralization

The ore minerals in the study area are carbonate-oxide including smithsonite, hemimorphite, hydrozincite, calamine, and serussite; as well as galena in Ab-Heidar and Gojer deposits. However, the association of copper carbonates minerals in Poodan, Gicher kouh, and Gojer occurred consisting of malachite and azurite. Lead concentration in Dare-e-Shur, Ri-kalaghi, and Gicher-kouh mines is less than %1,(Figs 9,10,11 and Table.1). Thin-polished sections indicate the relationship between minerals and filling cavities in the number of mines in the area (Figs. 10-11). Several thin-polished sections were prepared and studied for determination of petrographical and mineralogical particulars.

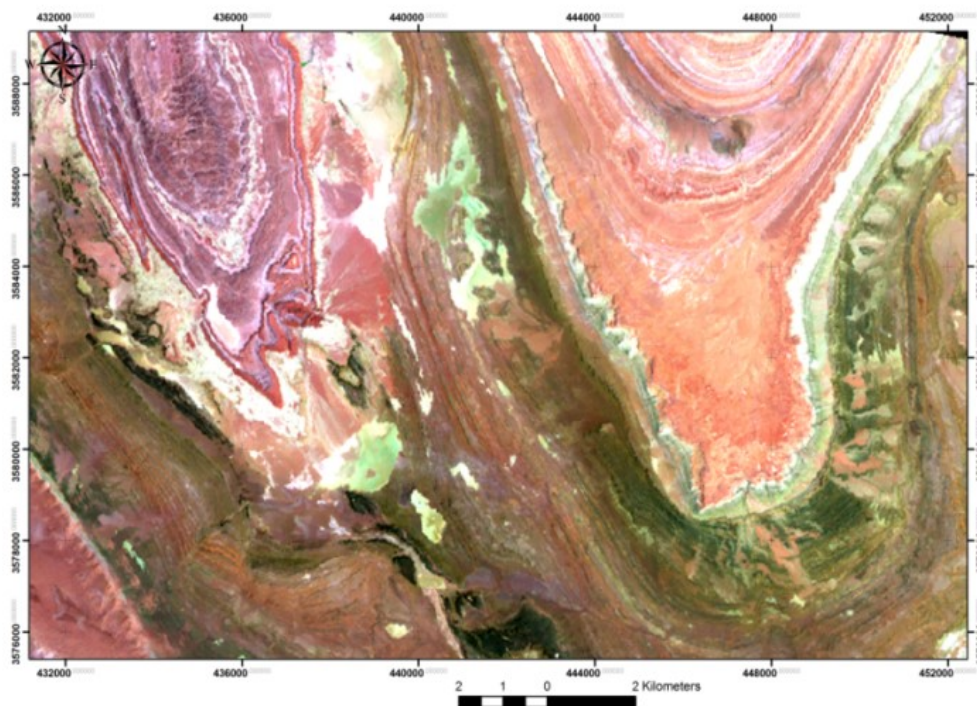


Fig 4. Circular structure; Eastern Behabad, between the Behabad-1 and 2 faults.

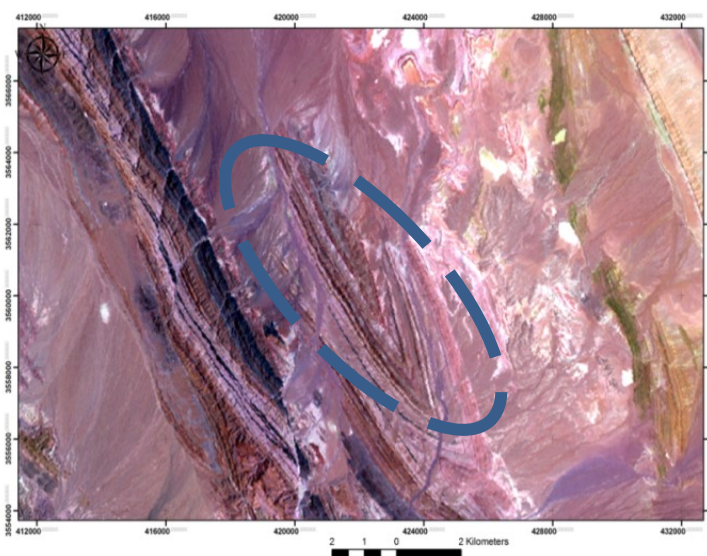


Fig 5. Circular structure, drag folds; Eastern Behabad, between the Behabad-1 and 2 faults (the important geological points in the map should be marked) (The location was shown in Figure 3).

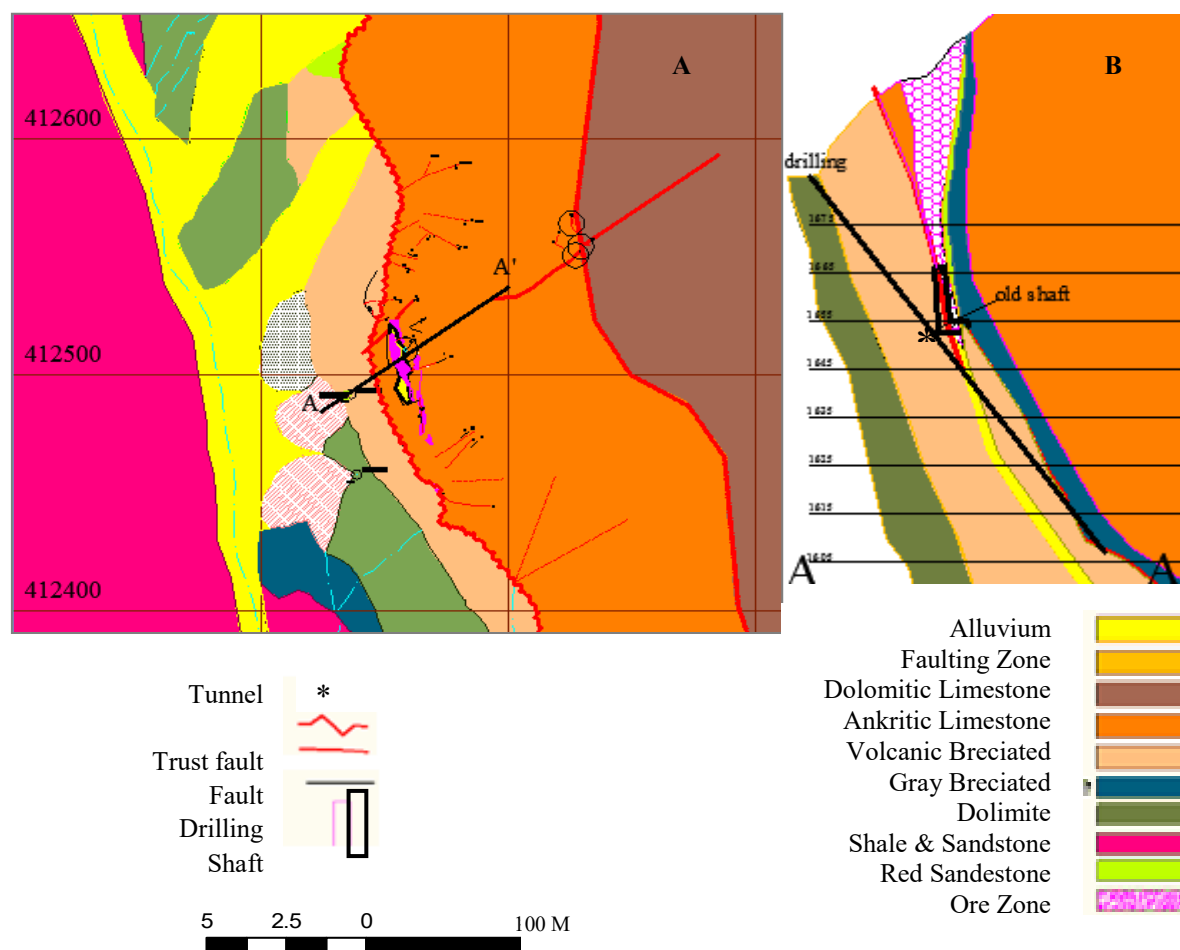


Fig 6. Geological map of Ab-Heidar mine; A. A typical profile of the geological units; B. The relation between mineralization and the thrust fault is shown in the map. In the cross-section, the vein of wulfenite and galena in the brecciated zones along the fault to a depth of 60 m is traceable (Mirzaee 2012).

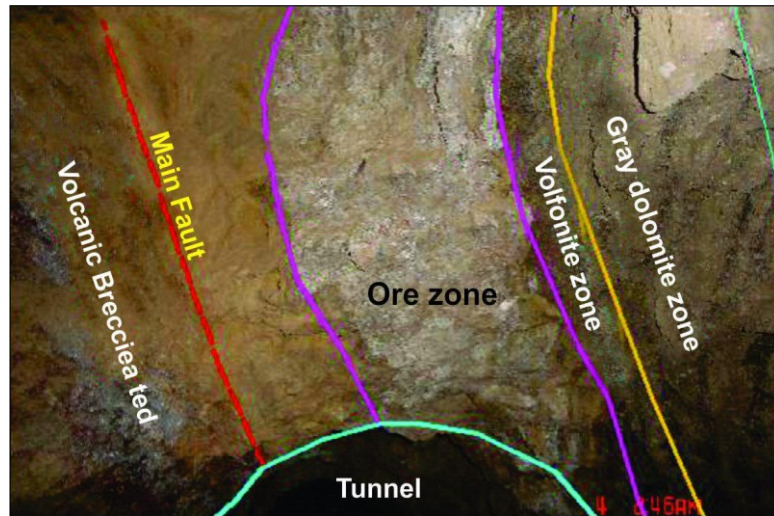


Fig7. Zonation of Ab-Heidar deposit that viewed in tunnel in fig 6(\*) .

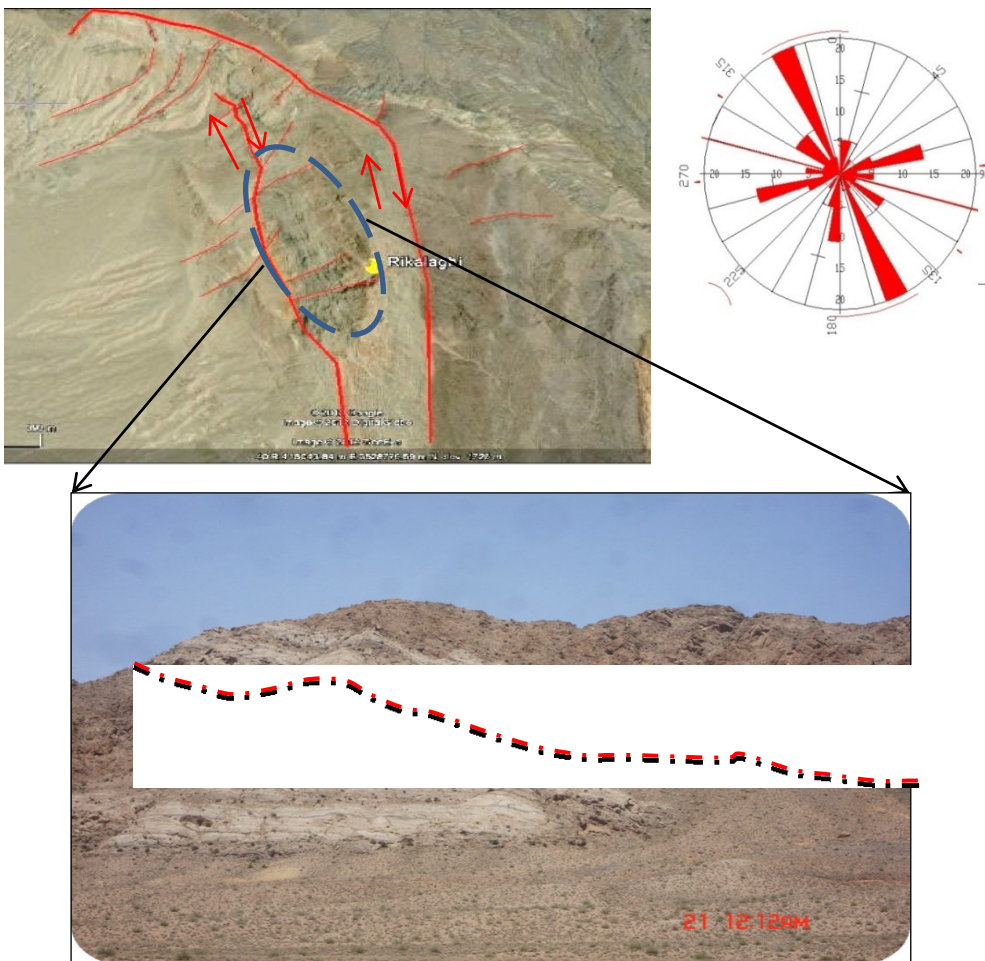


Fig 8. Thrust system, the Shotori formation is driven on the younger units and minerals are formed in the shear zone; southwest of the Behabad area (view to the north).

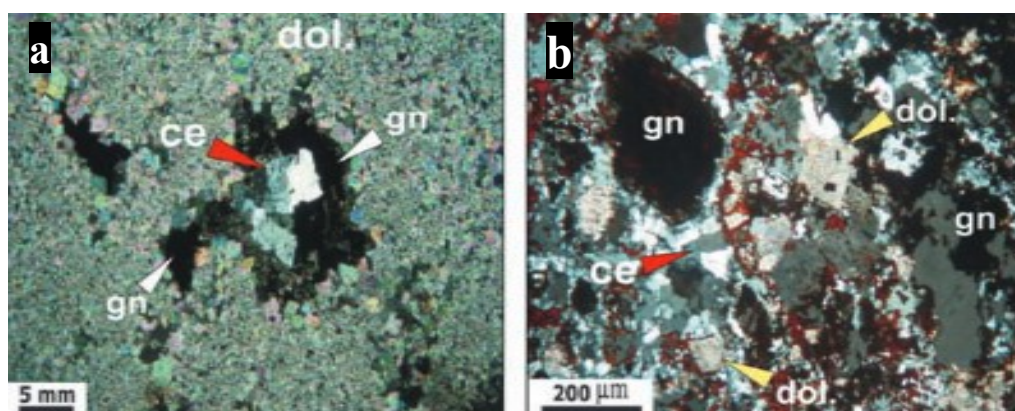


Fig 9. Abhydar Pb-Zn Mine; (a) The relationship between dolomite rocks (dol) and the conversion of minerals (gallons [gn] to cerussite [ce]); (b) Gallons (gn) to fill cavities and dolomites also seen between gallons (gn) and Cerussite(ce).

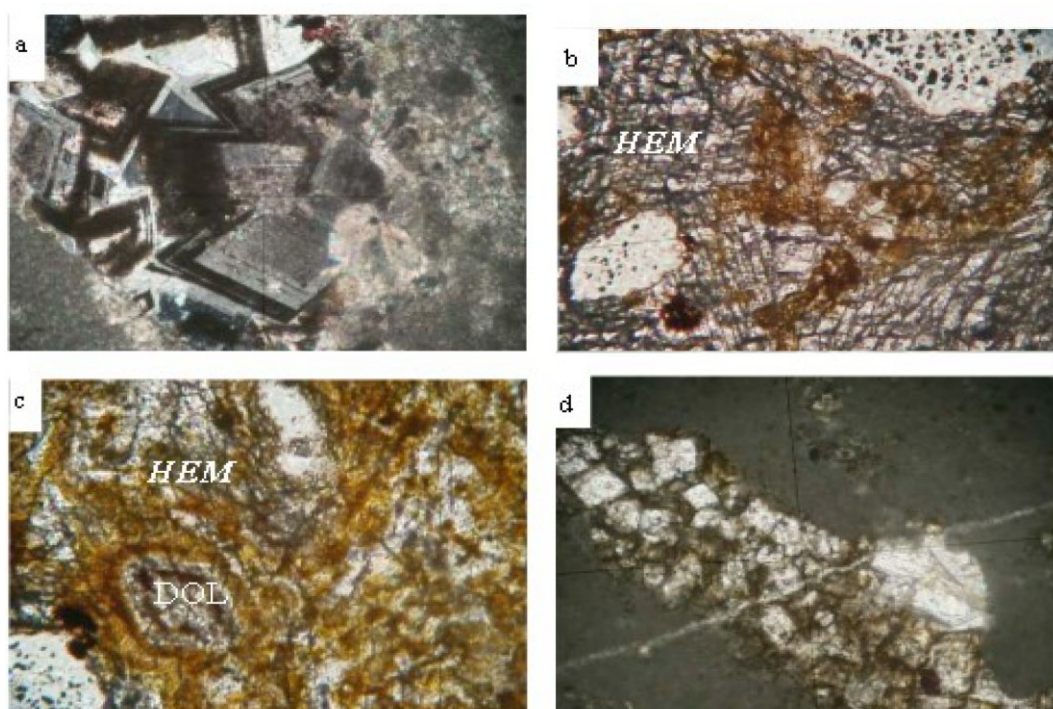


Fig 10. Gujer Mine; (a) Coarse crystalline dolomite epigenetic in micrite; (b) and (c) Hemimorphite with iron oxide minerals from pyrite in the early sulfur ore; (d) Dolomitization along fractures in micritic background.

Table 1 presents the mineralogical composition and abundance of Fe, Zn, Pb, Cu elements in some of these mines. In the carbonate host rock, the concentration of Zn is more than the lead. During the process of non-sulfide minerals, sphalerite is formed as secondary mineral, while galena is brecciated and changes in to the cerussite (Cer) and anglesite. In Ab-Heidar and Gojer

mines, mineralization is observed in the form of veins and lenses with variable length and thickness. Mineralogical composition represents the primary Mississippi Valley Type (MVT) mineralization/deposits and secondary non sulfide supergene enriched by the mines.



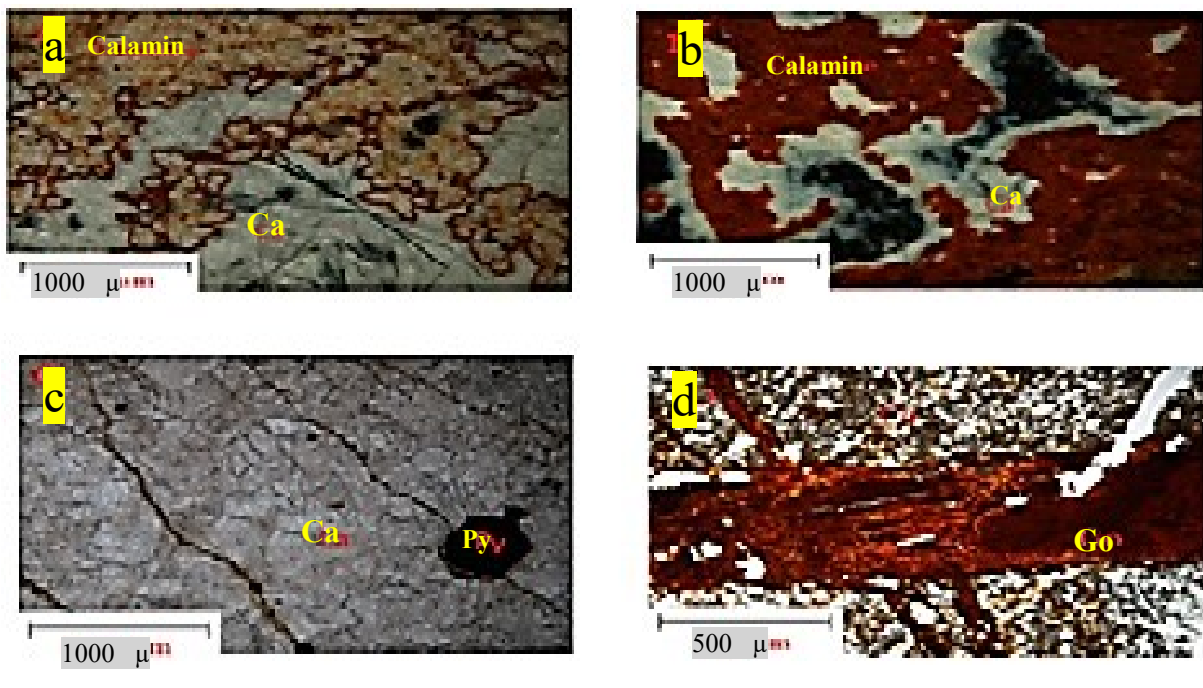


Fig 11. Gicher Kuh Mine; (a) Calamine (Zn Co<sub>3</sub>) with chloroform texture; (b) Calamine with Calcite; (c) Fractures filled with pyrite; d. Goethite and calamine in carbonate rocks.

Table1. Characteristics of the Pb-Zn min the study area

Mine Name	Gange	Ore Mineral	Length (m)	Width(m)	Cu%	Pb%	Zn%	Fe%
Ab Heidar	Dol+Cal+Iron Oxide+Gyp	Gal+Cer+Hem+Smit+Wolf	65	0.5-3	>1	3_5	16_19	2_3
Dahaneh Shur	Dol+Cal+Iron Oxide	Hem+Smit	30	0.5-5	>1	>1	15_25	8_10
Luk-e-Siah	Dol+Cal+Iron Oxide	Hem+Smit	15	0.2-5	>1	>1	15_23	8_10
Rig-e-Kalaghi	Dol+Cal+Iron Oxide	Hem+Smit+Cer	90	0.2-10	>1	>1	29_31	8_10
Gijjar Kuh	Dol+Cal+Iron Oxide	Hem+Smit+Cer+Hzin	250	0.1-8	>1	>1	20_35	2_3
Deh-e-Asghar	Dol+Cal+Iron Oxide	Gal+Cer+Hem+Smit	120	0.1-7	>1	>1	20_30	8_11
Tapeh Sorkh	Dol+Cal+Iron Oxide	Hem+Smit+Cer+Hzin	150	0.1-10	>1	>1	25_35	5_15
Gujar	Dol+Cal+Iron Oxide	Hem+Smit+Cer+Hzin	300	0.5-15	>1	>1	25_35	3_5

In these mines, a temperature of 200 to 250°C was likely the cause of sulfides dissolution from the probable organic shale containing lead, zinc, and iron sulfides, and mineralization in carbonate host rock what

is the evidences for this state. Colloform texture in the secondary minerals implies presence of low to medium temperature in this area (Leach et al. 2001 and 2010). Permeation of mineral fluids is more obvious in the

deeper host rocks, where non sulfide Zn mineralization like (calamine, smithsonite, hemimorphite, hydrozincite, and olegiste) contain small percent of lead (Mirzaee 2012). Thus, these deposits provide very interesting examples of non-sulfide lead-zinc mineralization. In the Ab-Heidar mine (Figs.12 and 13), the mineral veins containing galena are exposed in the east of the non-sulfide main vein. The main oxide and carbonate minerals in this area are hematite, goethite, cerussite, smithsonite, and hemimorphite. There are sulfide minerals in some deposits in Taj-Kuh, Ab-Heidar, and Senjedu ores. In Gojer and Gicher-kuh ores, presence of iron oxide, hydrozincite, cerussite, anglesite, hemimorphite, malecite, and azurite non-sulfide ores are

detected. Nevertheless, sulfide mineralization is also expected at depths below groundwater level.

**4.3. Ore deposit related to the faults system**

In the Behabad area, thrust faults trigger migration of mineral solutions from depth to surface, resulting in the displacement of high concentration minerals at depth with NW-SE trend, while the faults with NE-SW and NS trending cause formation of low concentration minerals with a brecciated texture at surface. Main mineralization occurred based on thrust and strike slip fault activation by NW-SE trending in the dolomitic rocks. In addition, this faulting occurred breccias and fluid flow approach from depth to surface. Next, normal faults generated further brecciation and creation of concentrated ore veins with NE-SW trend (Fig.13).

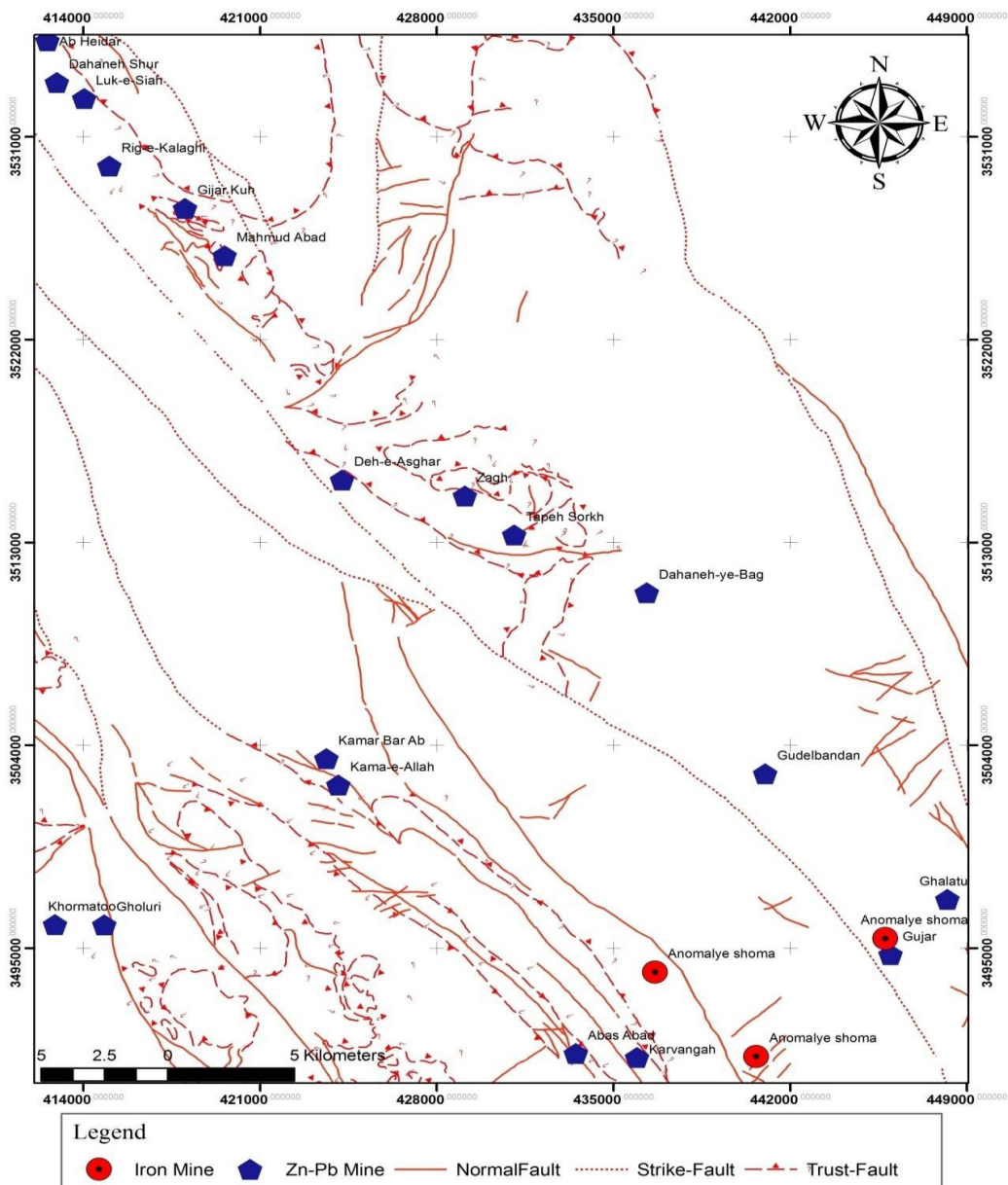


Fig 12. Faults and metallic mines map of the area.

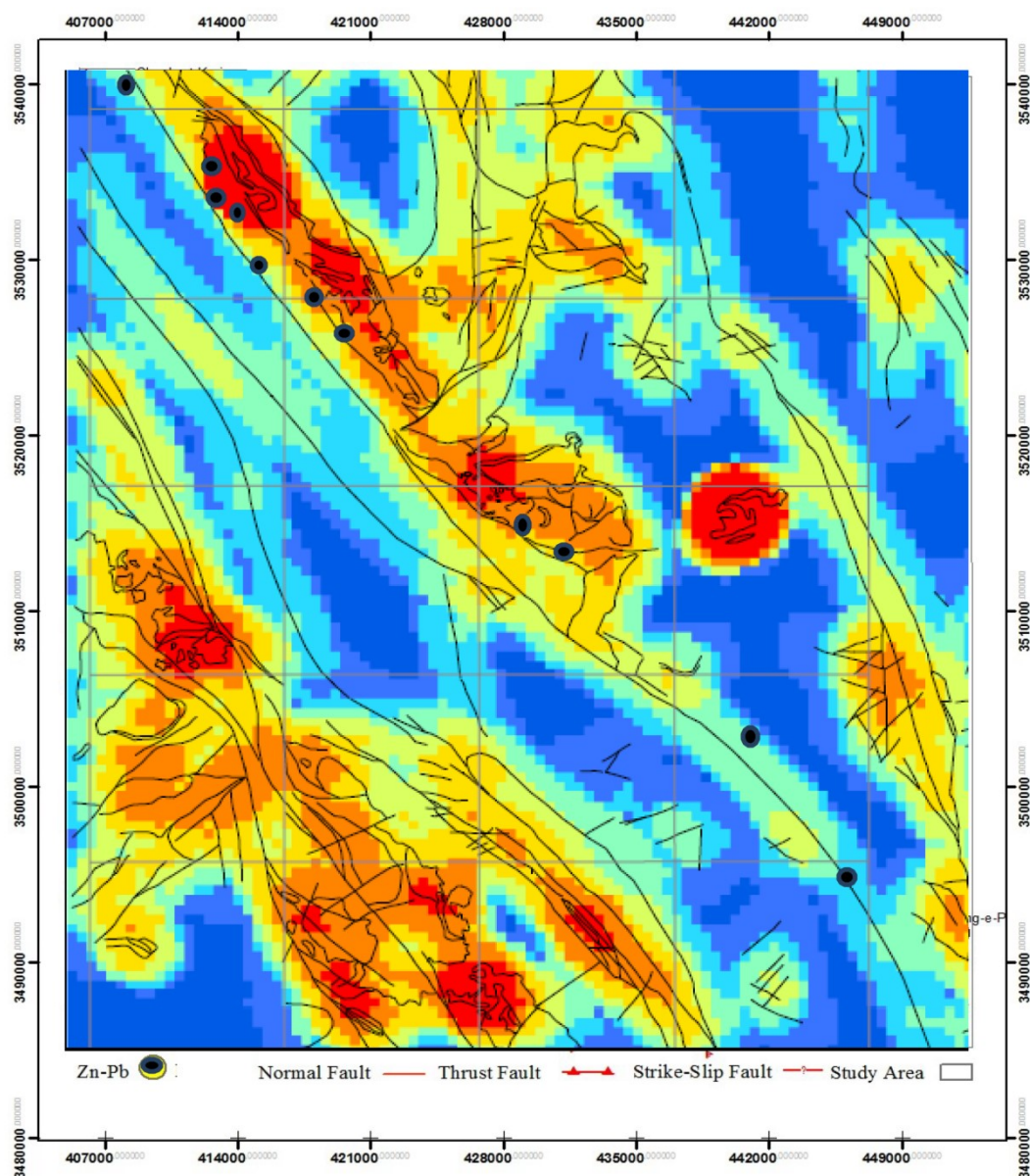


Fig 13. Fault density map of the area.

Presence of hemimorphite, hydrozincite, and calamine in brecciated dolomite indicates the effect of faulting in mineralization process in the form of cavity filling in the brecciated zones.

This process is associated with shallow faults and in steep thrust belts in the vein and epigenetic forms.

Most of the high concentration mineralized veins following the Behabad fault trend. Because of the remobility of supergene hydrothermal fluids, Zinc mineralization (*i.e.* calamine) are reformed and the high concentration calamine veins are developed around the karstic and dissolution areas. Extent of breccia is mainly limited to the zones around the veins, implying genesis of breccia with of tectonic activities.

In the eastern and western Behabad subsidence, the fault system has controlled the trend of mineralization. In Figure 12 faults map and their location relative to the

iron, lead and zinc mines in the Behabad-Kuhbanan shown, distance between faults and Pb, Zn and Fe mines are 200 and 1,200 meters. Most mineral evidences have relationship with Behabad 1 and 2 thrust faults. Furthermore, the rose diagram and fault densities' map were prepared which show the association of mineralized faults (Figs 12,13 and 14).

The dominant veins are with 300-330 degrees azimuth, which are very good agreement with the NW-SE faults. Most of the faults have NW-SE trend in the area with intense intersection of thrust and normal faults and ore vines are formed in the NW and SE of the Behabad area. The overlap between the faults map and mineralized veins shows that the association of between ore veins and fault zones. Most metallic mines are situated in 200 to 1500 meters' distances from the main fault line within the zone of Behabad 1.

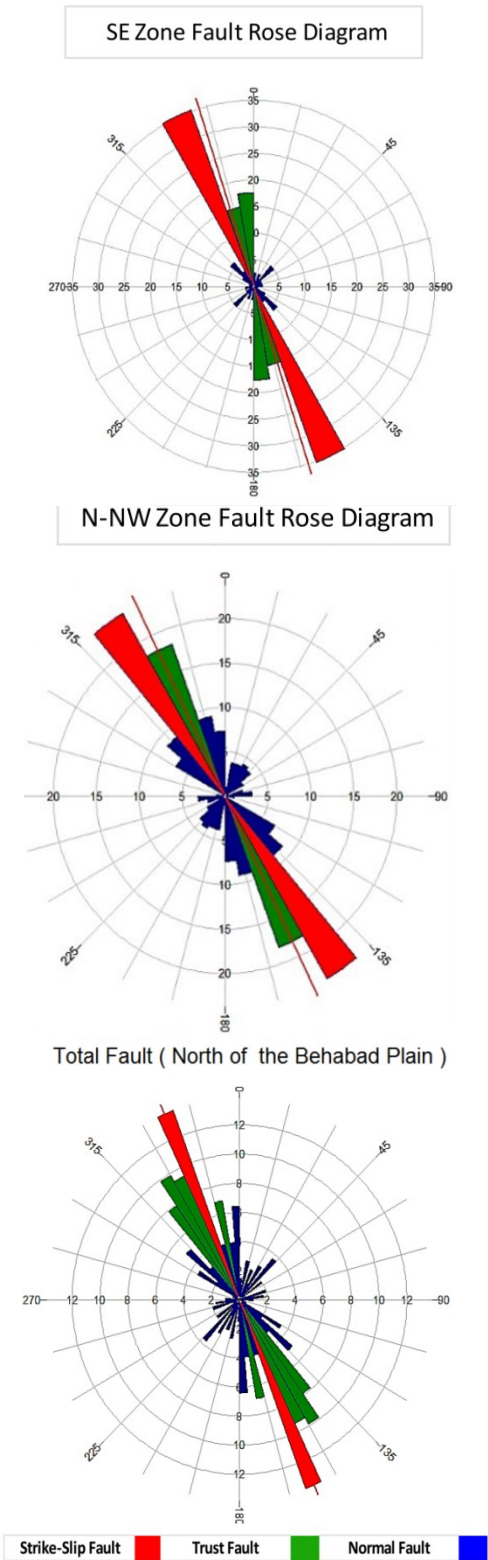


Fig 14. The rose diagram shows the main strike of faults (N–NW and SE). The predominant strike-slip faults with a reverse component are marked with a red color (NW–SE), the thrust fault with a green color (NW–SE) and the normal faults are shown striking NE–SW.

#### 4.4 Structure–Mineralization Conceptual Model

Statistical analysis shows that most of the folds have strikes extended from N65W to N35W (Fig.15).

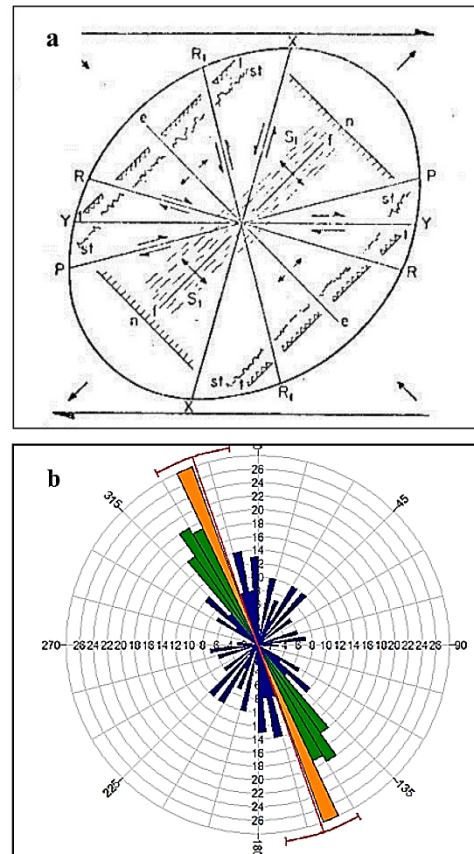


Fig 15 (a). Regional pattern of the strike-slip shear zone in Kuhbanan and Behabad compared with the rose diagram of the area; R1 and R2 are riddle and conjugate faults, N and F represent the normal and trust faults, respectively and F is the axis of folding (Adib 1998); (b). The rose diagram of the faults in the N–NW and SE.

Since the folds always have a strike that is perpendicular to the axis of the principal compressive stress, the direction of the tectonic force is N30E (Adib 1998). The rose diagrams of the joints in most deposits reveal the effect of structure on ore accumulation. The spatial distribution of non-sulfide mines such as Tarz, Gojer, Tap-e-Sorkh, Gicher-kuh, Ri-kalaghi, Dar-e-Shur, and Ab-Heidar in the east of the Behabad-1 fault in the Abdoghi tectonic zone shows that the faults control the mineralization processes. All evaluated deposits and mineralization signs have the dolomitic host rock and are controlled by the faults, particularly the Behabad fault. The tectonic-mineralization conceptual models are presented in Figs.16–18 based on the field results and studies. The schematic model of the thrust fault development, brecciation of dolomite, influence of hydrothermal solutions (mainly lead and zinc rich fluids), and vein formation are shown in Fig.17 (Steps 1 to 3).

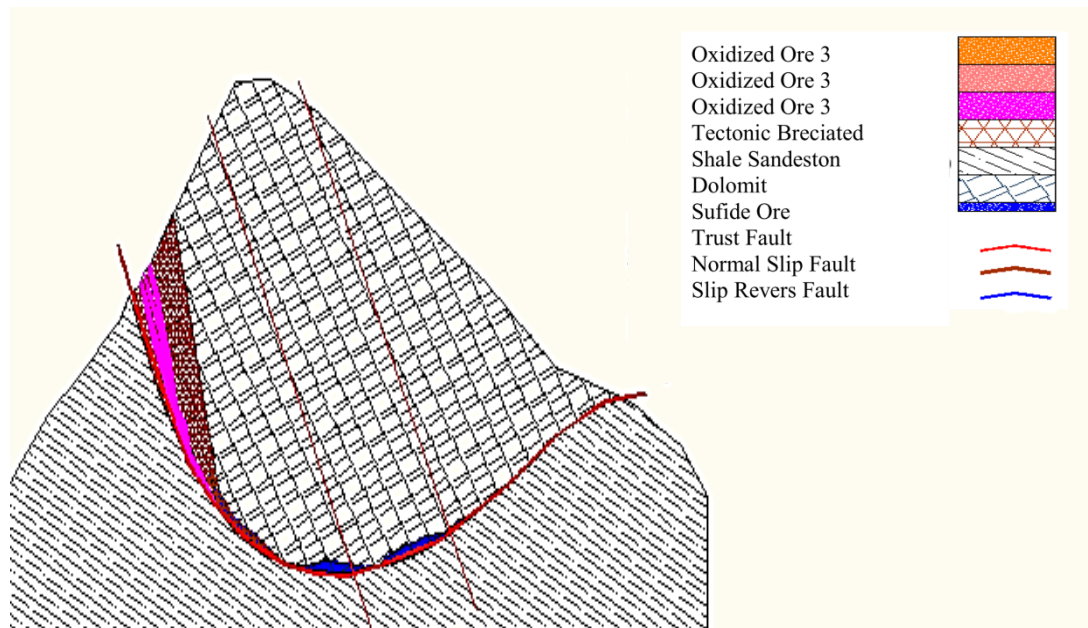


Fig 16. The schematic cross section of the tectonic-mineralization conceptual model for the epigenetic non-sulfide Pb-Zn mineral veins of the Permo-Triassic dolomites in Northern Behabad.

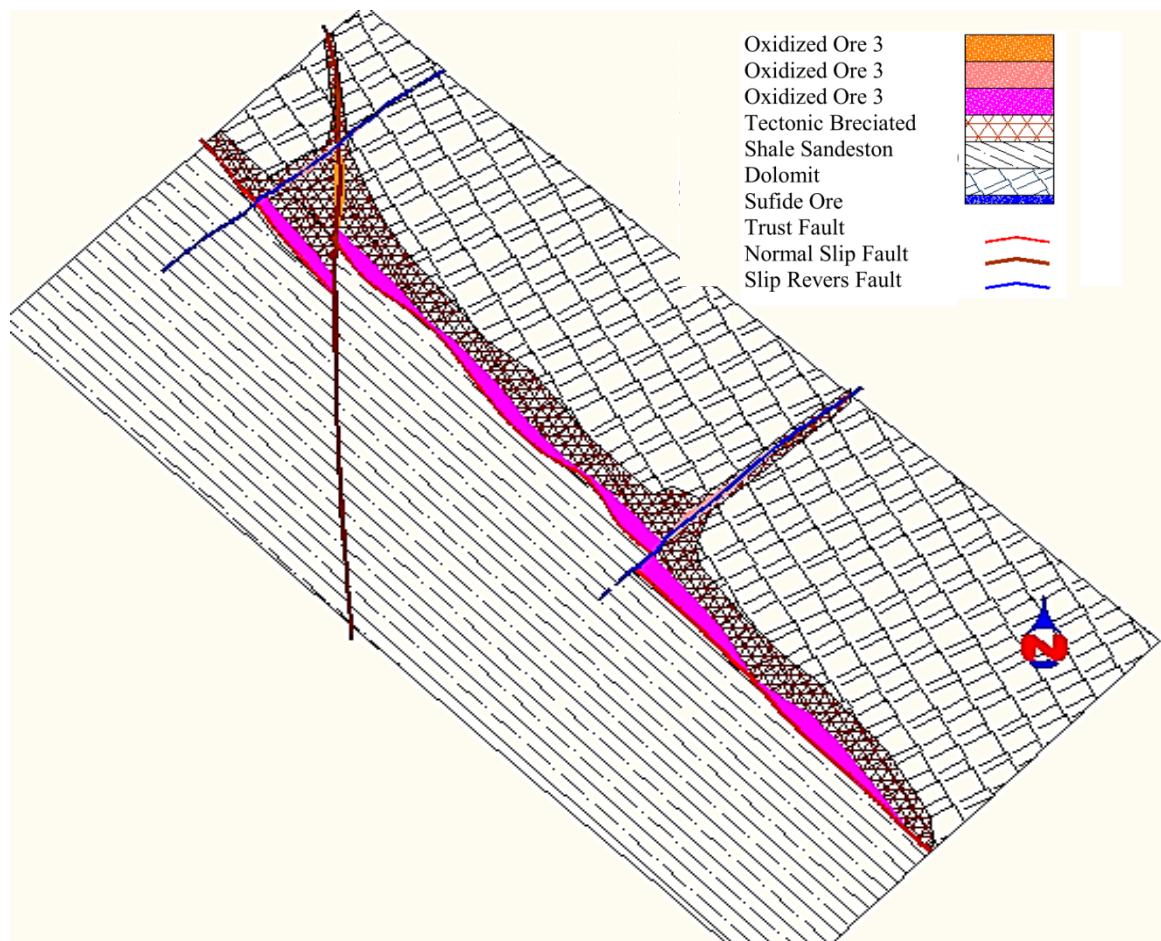


Fig 17. The schematic map of the tectonic-mineralization conceptual model for the Pb-Zn non-sulfide mineral veins of the Permo-Triassic dolomites in Northern Behabad.

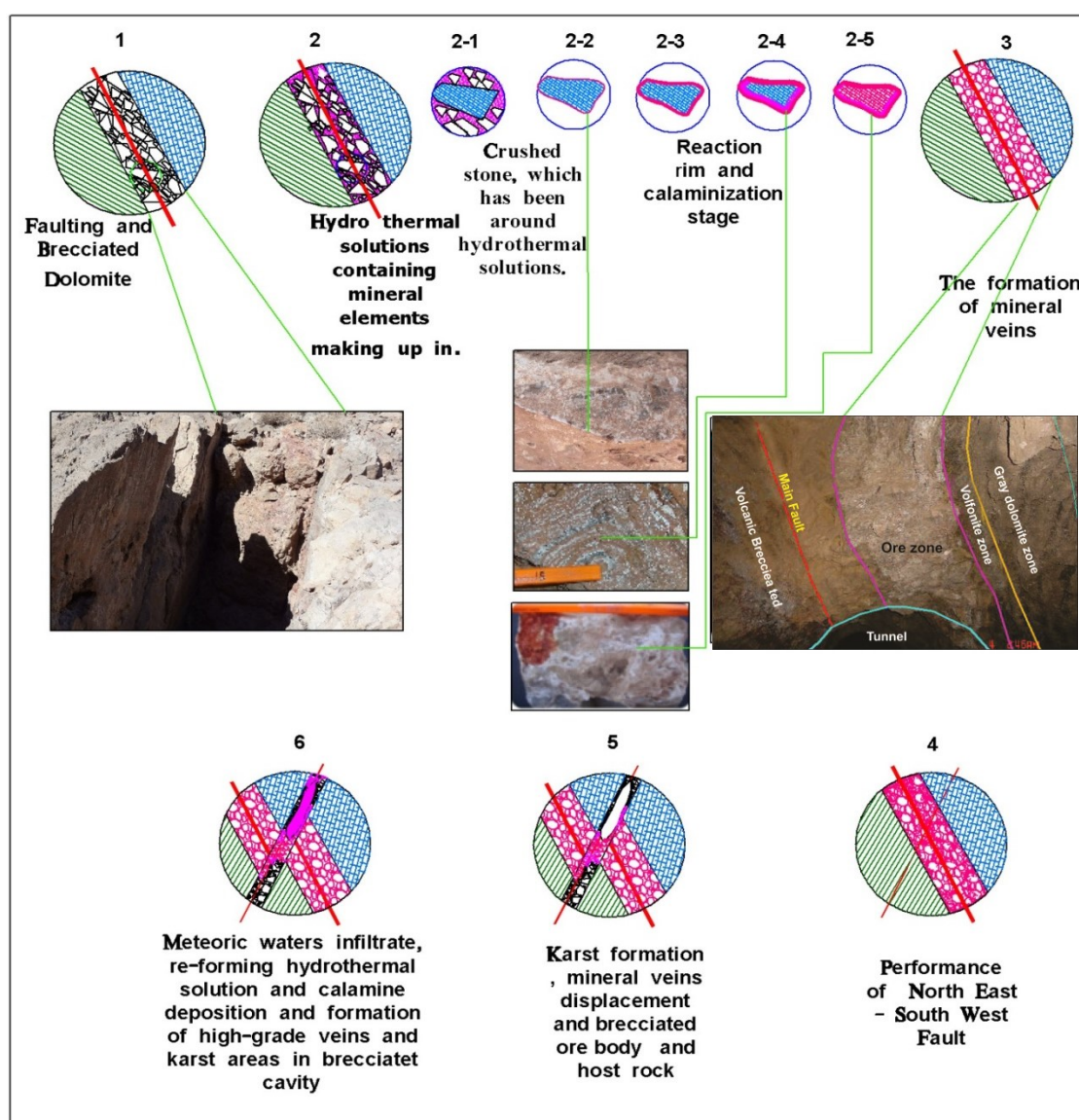


Fig 18. The schematic model indicating the steps involved in the formation of the normal fault with the strike-slip component, brecciating of dolomites and veins, re-mobility of the zinc-containing hydrothermal solution. The mineralization process occurs in the fault plane, joints and fractures and everywhere that the hydrothermal solution containing zinc and iron is distributed in different parts of the brecciated rocks.

## 5. Conclusions

There is a significant relation between the mineralization and structural system in the north of Behabad. This relation is provided by the number of lead and zinc vein outcrops along the Behabad-1 fault. In terms of the tectonic-mineralization formation setting, the area presents an inter-continental and continental margin region with carbonate host rocks similar to the MVT lead and zinc deposits. Based on the temporal control factors, the area is a part of the Late Paleozoic-Triassic mineralization phase and, according to the spatial control factors, it is a part of the Central Iran and Bafq-Behabad tectonic-metallogeny

provinces. The Behabad fault system is the main controller of the deformation of the northern Behabad structural zone, where the mineral resources of the area follow the fault geometry. Firstly, the Behabad-1 and Behabad-2 faults were formed in the west and east of the area, respectively. Secondly, the compression system of the strike-slip movements between these two faults has caused the thrusts, sigmoidal and drag folds, and the bulge of the northern Behabad. In the final stages, normal faulting with the strike-slip component is the governing phenomenon in the northern part of the region. The thrust fault, with the northwest-to-southeast trend, is probably the main pathway for the movement

of the ore solution from the depth to the surface (faults can provide a way or channel for ore fluid movements). The performance of the faults has caused a displacement of the veins, the formation of high-concentration mineral patches at the bottom, and low-grade mineralization with the brecciated texture in the surface. The mineralization in this area is mostly controlled by these faults and related structures. Additionally, dolomites are brecciated due to the faulting processes that host the ore minerals, including hemimorphite, hydrozincite, and calamine associated with oligest. According to the MVT mineralization in the structural–mineralization conceptual model, sulfide deposits are emplaced at the base of the Permo–Triassic dolomitic units.

### Acknowledgement

The authors would like to thank the research deputy of the Islamic Azad University, South Tehran branch for supporting this research.

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