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**Sustainable Earth Trends**

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# Structural and tectonic aspects of the Kuh-e Surmeh Pb-Zn deposit, a rare case of metallic mineralization in the Zagros Fold-Thrust Belt

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**ABSTRACT**

The Surmeh deposit is a rare case of metallic mineralization in the Zagros FT-Belt. The regional structures with geological conditions from Paleozoic sequences to Late Paleozoic-Early Mesozoic extensional faulting, Cenozoic continental convergence and collision, thrust tectonic, reactivation of inherited and basement faults, basinal-atmospheric fluids interactions and salt diapirism have crucial role in MVT-type Surmeh deposit formation. The Surmeh anticline is double plunging and its southern limb is cut by thrust faults, which formed at the southern termination of the Mengharak segment of the Karehbas fault. New field data highlights three fault trends. The first trend is thrust faults parallel to the Zagros trend cutting the southern limb of Surmeh anticline and pushed the older units over the younger units from NE to SW. The second is normal faults mainly in the Permian and Triassic rocks and their strike varies from NW-SE to N_S. The third trend is ~N-S surface manifestations of the Karehbas basement strike-slip fault. Some of them can be easily mapped in satellite images. Small strike-slip faults have caused displacement and destruction of mineralized zones. Normal faults were important structures in ore-formation process. These findings can be utilized as an exploratory sign for similar ore deposits in the Zagros Range, where the Paleozoic rocks are intensely folded, faulted and uplifted within the cores of anticlines near the intersection of salt domes and basement faults. This case is an interesting metallic mineralization in a foreland area, where is affected by basement and thrust faults, folding and salt tectonics.

**ARTICLE INFO**

**Keywords:**
Mississippi Valley Type Deposits
Faulting and Mineralization
Karehbas
Paleozoic
Jahani salt dome

**Article history:**
Received: 08 Jul 2024
Accepted: 15 Sep 2024

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**Citation:**
Ehteshami-Moinabadi, M. et al., (2024). Structural and tectonic aspects of the Kuh-e Surmeh Pb-Zn deposit, a rare case of metallic mineralization in the Zagros Fold-Thrust Belt, *Sustainable Earth Trends:* 4(4), (56-72).

**DOI**: 10.48308/set.2024.236848.1066

## 1. Introduction

The Zagros Fold-Thrust Belt, especially south of the High Zagros Fault, is renowned for its hydrocarbon resources (Ala, 1982; Beydoun et al., 1992; Kordi, 2019; Alipour, 2024; Sajedi et al., 2024), but the presence of metallic ore deposits remains relatively unexplored. There is no good estimate of metallic mineralization potential of the Zagros Fold-Thrust Belt. The region's extensive Mesozoic-Cenozoic geological history, characterized by thick sedimentary cover (Figs 1 and 2), coupled with the predominant economic focus on hydrocarbon extraction, has historically diverted attention away from prospecting for metallic ores. Nevertheless, in the past decade, several intriguing instances of metallic mineralization within the belt have emerged. One notable example is the Kuh Surmeh Pb-Zn Mine, henceforth referred to as the Surmeh mine, which holds significant importance in the Fars region firstly studied by Tavana (1993) and then Pousti et al. (2005) and Pousti (2005). Additionally, upper Cretaceous karst bauxite deposits have been identified at various locations (Zarasvandi et al., 2012; Ahmadnejad and Mongelli, 2023) alongside phosphate deposits (Zarasvandi et al., 2021). Pousti et al. (2005) conducted facies analysis and stable isotopes studies, utilizing these findings to elucidate the genesis of the deposit. Based on field observation, ore body texture and structure, carbonate facies types, paragenetic sequences, fluid inclusions and oxygen and carbon isotopes, the Surmeh Pb-Zn deposits is similar to MVT type deposits (Pousti et al., 2005). This classification was corroborated by Eskandari (2013) and Taghipour and Eskandari (2014) who further investigated the mineralogical, geochemical, and genetic aspects of the Surmeh deposit. Taghipour and Eskandari (2014) highlighted the role of thermochemical sulfate reduction processes in supplying the necessary reduced sulfur for ore deposition within the Dalan host rock, likely facilitated by sulfate reduction in the Jahani salt dome. Furthermore, they proposed that dolomitization was influenced by two distinct fluid sources: one originating from deeper hydrothermal or basinal reservoirs associated with Precambrian rock units, and the other from meteoric water. Subsequent studies, such as those conducted by Fazli et al. (2018) and (2019), provided further insights into the structural aspects of the Surmeh Pb-Zn mine. This study aims to delve into the structural characteristics of the Surmeh Pb-Zn mine, situated within the Surmeh anticline of the Zagros Fold-Thrust Belt. This deposit is an interesting case in a foreland area where metal mineralization is affected by transversal basement faulting, thrust faulting, folding and salt tectonics. The Kuh-e Surmeh anticline is located 33 km south of Firouzabad (Fig. 1).

## 2. Material and Methods

The data on regional strucutres including Jahani salt dome and Karehbas fault achived and revised from older studies. Field strcutral data gathered in this study using convensional geological compass, GPS and photography. Photo lineaments of the study area were also mapped using Landsat 8 image data processed in the PCI geomatica software. Th e rose diagram of these lineaments were prepared using general strucutral softwares and compared with measured faults in the fields in this study and faults in the mine tunnel measured by Pousti (2005). This section includes geological setting, major regional strucutres and local structures especially important faults.

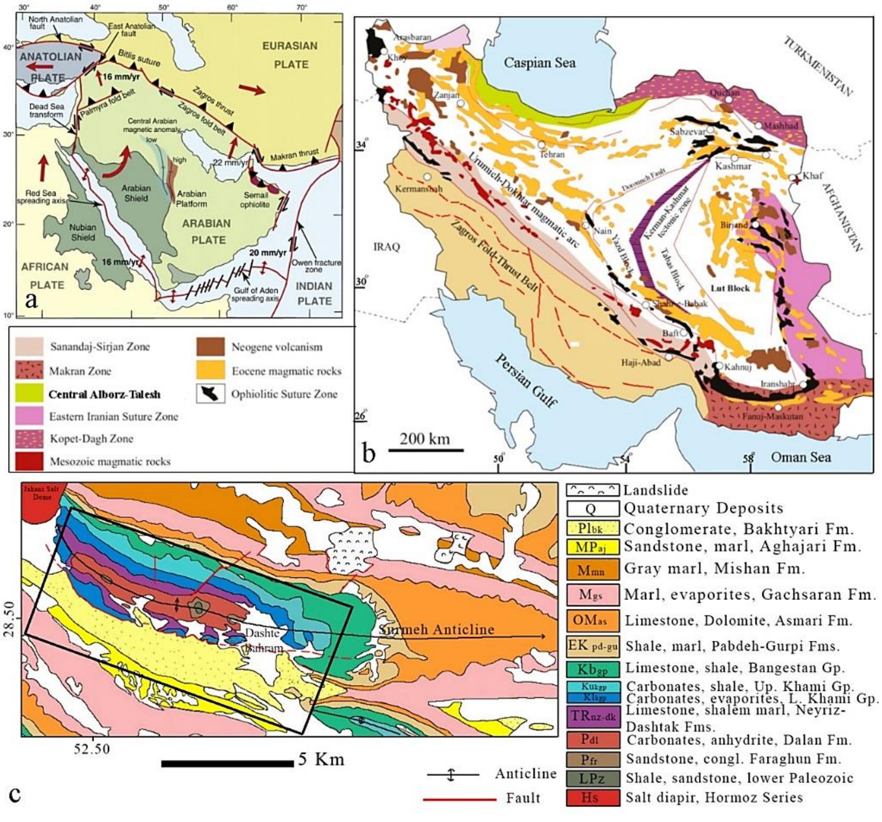


**Fig. 1.** a: General tectonic framwork of the SW Asia showing the location of tectonic plates and major tectonic boundaries as well as Zagros collision (Stern and Johnson, 2010) b: the map showing major structural zones of Iran modified after Almasi et al. (2019), the white quadrangle in the Zagros Fold-Thrust Belt marks the boundary of Fig c. c: Geological map of Kuh-e Surmeh anticline modified after Fakhari et al. (1994a) and (1994b). The black rectange shows the location of Fig. 5.

*2.1. Geological setting*

The study area is located in the Zagros Fold-Thrust Belt, an integral part of the Zagros orogenic sequence. The evolution of the Zagros orogeny includes a sequence of magmatic, metamorphic, and deformational events arising from the subduction of the Neotethys oceanic plate northwards, spanning from the late Triassic to the end of the Cretaceous, followed by the Miocene era. This culminated in the collision between the Arabian plate and Eurasia, giving rise to a significant and relatively youthful example of continental-continental collisional orogens with the Zagros Fold-Thrust Belt as the foreland of this collisonwithin the Alpine-Himalayan belt (Berberian and King, 1981; Alavi, 1994, 2004, 2007; Agard et al., 2011; Mohajjel and Fergusson, 2014; Sheikholeslami et al., 2019). The northward subduction of the Paleo-Tethys oceanic plate below the Eurasia triggered the opening of the Neo-Tethys ocean along the boundary between the Cimmerian Terrane and Gondwana and finally the separation of the Iranian Terrane from the Arabian margin of Gondwana (Alavi, 2004; Jamei et al., 2021, Jafari et al., 2023). Madani-Kivi and Zualf (2015) modeled and dicussed the tectono-sedimentological evolution of development of continental rift basin in the Zagros region and its environmental changes from a siliciclastic basin to a carbonate platform setting. They studied well-log data to specify the distribution of synrift deposits in the Zagros and have related this information to the modelling. Evidences of Late Devonian-Early Permian rifting and related rocks, subsidence and then Triassic marine sedimentation that led to normal faulting and development of a passive margin in the Late Paleozoic were reviewed Jafari et al., (2023). However in relation to the rifting and formation of the Neothetys Ocean many authors belive in a Late Permian to Triassic normal faulting that somewhere continued to the Early Jurassic as syn-sedimentry normal faults (e.g. Navabpour et al., 2010 and 2011; Mohajjel and Fergusson, 2014; Tavani et al., 2018; Alipour et al., 2021).

The Zagros Fold-Thrust belt includes a wide area of unexposed thrust structures and related folds that have affected the lithological units deposited on the margin of the Arabian plate (e.g. Berberian, 1995; Alavi, 2007). Most of these thrusts and folds have been active in the Cenozoic, although evidence of tectonic activity has also been reported in the Cretaceous (e.g. Farahpour and Hessami, 2012). Most of the folding trend is from northwest to southeast, but the change in the axis of the folds is influenced by various phenomena, especially the old and transverse faults of Zagros, the salt tectonic activity of the Hormuz series as the main detachment horizon along with the intermediate detachment horizons in the Mesozoic formations have played an important role in the local changes in the geometry of folds in the Zagros Fold-Thrust belt (Sepehr and Cosgrove, 2004; Sherkati et al., 2006; Sepehr et al., 2006). Meanwhile, large thrust faults play an important role in the deformation distribution in this belt. The seismic activity and deformation observed along the Zagros Fold-Thrust belt primarily result from deep crustal stresses associated with the convergence of the Arabian and Iranian plates (Paul et al., 2006; Nissen et al., 2011; Palano et al., 2018; Zamani, 2023); in the case wihch the Zagros Fold-Thrust belt is still shortening and is considered the most seismic part of the Iranian plateau (Hessami et al., 2001).

Fig. 2 shows a simplified stratigraphic column of the Zagros Fold-Thrust Belt. From a stratigraphic standpoint, the Surmeh anticline is considered as a rare example of the structures in the Zagros thrust belt, where part of the Paleozoic formations of Zagros are outcropped. The oldest exposed unit in the region belong to the Hormuz series in the Jahani salt done, which is one of the largest active salt outcrops in the Zagros mountains (Talbot et al., 2000). In addition to halite and basic igneous rocks, black massive limestone with traces of stromatolites, thin bedded limestone, low quantity of oligist-bearing marls and red shale are exposed in this dome, which show lithological similarities with Barut and Mila formations (Zamin Kav Gostar, 1995).

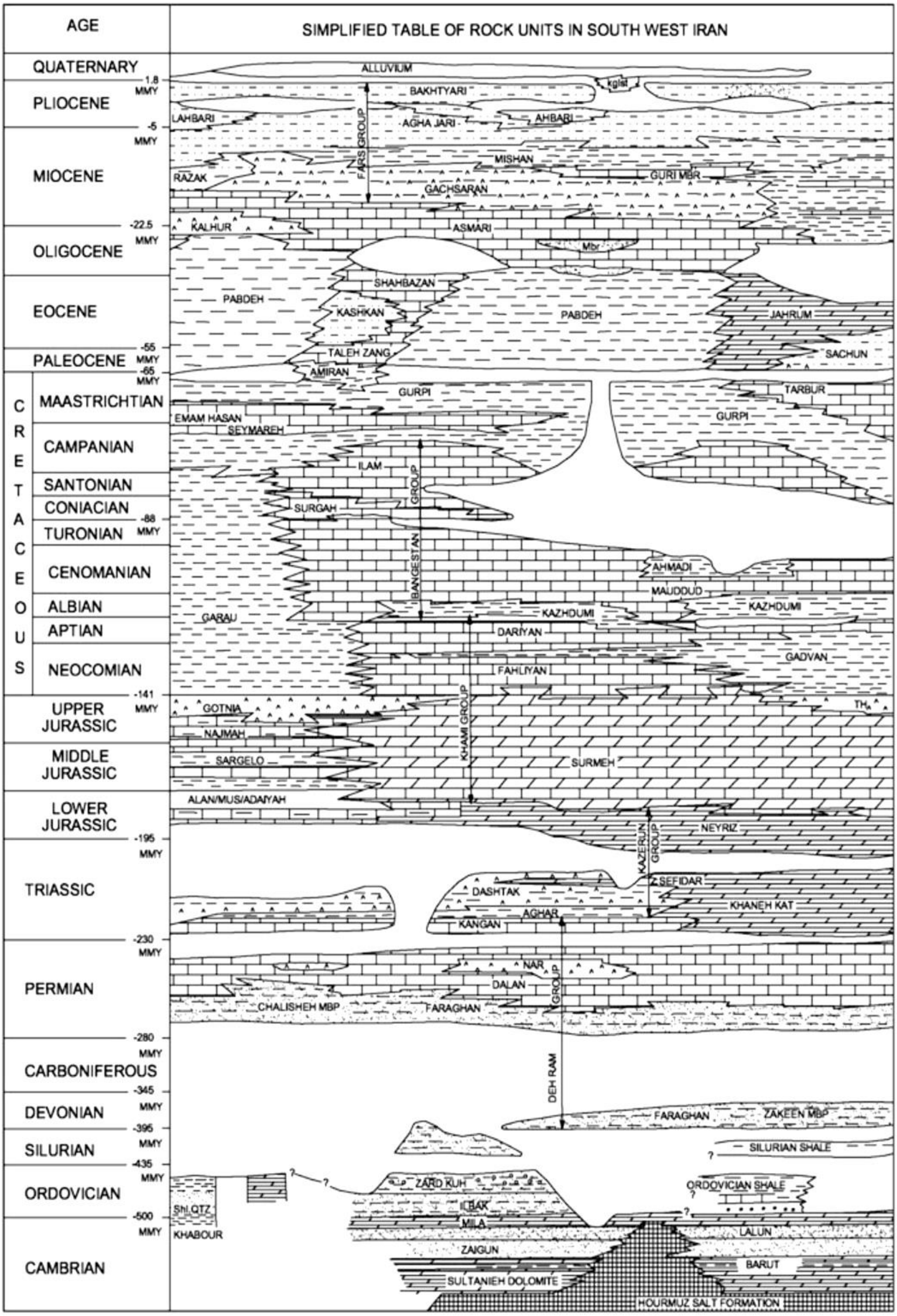


**Fig. 2.** Simplified stratigraphy of the Zagros Fold-Thrust Belt (after Motiei, 1993).

It seems that the alternation of sandstone and shale belonging to the Ordovician Siahou Formation is exposed in parts of the anticline core, but no detailed study has been done on them so far (Fig. 3). Dehram group including sandstones of Faraghan Formation (Devonian to Permian), carbonate rocks and evaporites of Dalan Formation (Permian) and carbonate rocks of Kangan Formation (Early Triassic) form the next lithological units in this anticline. Next, in this anticline, the Kazeroun group includes Dashtak formations (Triassic shale, evaporite and dolomite) and the clastic rocks of the Neyriz Formation (Jurassic), the Khami group with Surmeh Formation (Jurassic dolomite and dolomitic limestone), Heath anhydrite (mostly has been eroded in the anticline), Fahlian Formation (massive olitic limestones and gray to brown dolomites of Lower Cretaceous age), Gadvan Formation (alternation of gray limestones with colored marls of Late Neocomian-Apsian age) and Darian (orbitulin-bearing limestone of Aptian age) are placed. Gurpi Formation with known lithological units in Kuh-e Surmeh is about 130 meters thick. From the collection of Cenozoic formations in Kuh-e Surmeh anticline, we can mention Mishan, Aghajari and Bakhtiari formations.


**Fig. 3**. Core of the Surmeh anticline in the eastern part of the Bahram Plain, where the units related to the Dalan, Faraghan and possibly Sihao formations are outcropped.

Kuh-e Surmeh lead-zinc deposit is one of the few active metal mines in the Zagros Fold-Thrust belt. The mine has ancinet evidence of mining. In an earleir modern working preiod, before its closure in 1979, underground mining produced more than 150,000 tonnes of ore over a period of about 8 years (Liaghat et al., 2000). The deposit is divided into three parts: Choubandeh, Cheshme Surmeh and Dasht-e Bahram. Currently, the Choubandeh section is in operation and the Dasht-e Bahram section is in the exploration phase. Earleir estimated reserve of the Kuh-e Surmeh orebody was more than 990,000 tonnes of ore grading 12.1 wt% Zn and 5.4 wt% Pb (Liaghat et al., 2000). The ore-body has a semi-tabular shape that lies within the northern limb of Kuhsurmeh anticline (Fazli et al., 2018). Absolute reserve of the Kuh Surmeh is 1200000 tons ore with 4 and 6% Pb and Zn, respectively. based on their observatioins, Liaghat et al. (2000) indicate that ore deposition took place asas open-space fillings in brecciated carbonate rock and as internal sediments consisting of fne-grained ore minerals interlayered with carbonates. From the point of view of economic geology, the host rock in this deposit is the lower part of the Dalan Formation, which has been affected by the dolomitization process. Scattered mineralization of lead-zinc can be observed in the holes and fractures in this unit (Poosti 2004). The studied samples from the lower corridor of dolomicrosparite to dolo-sparite cotian ore minerals such as sphalerite, galena, and pyrite, and minor minerals including marcasite, cerusite, anglesite, chalcopyrite, cavelite, hematite, and magnetite. Gange minerals are generally calcite, dolomite, barite, quartz and gypsum. Pyrite is one of the dominant minerals that is observed together with galena and sphalerite in most cases. Sphalerite is the main sulphide ore in this deposit. Galena is the second most abundant metal mineral after sphalerite, and it is mostly amorphous in the form of disseminated, massive, veinlet, and matrix between the rock forming crystals or filling the voids. Silver is also substituted only in the galen network. (Tavana, 1993; Poosti, 2005). Pousti and Safari (2014) measured the thickness of Dalan Formation in the Surmeh Mountain to be 836 meters, with four mineralization horizons in lower part.

*2.2. Structures of the area*

*2.2.1. Karehbas Fault*

Karehbas fault is one of the important basement transversal faults in the Zagros, which starts near the southeastern end of the Dena fault and continues towards south oblique to the regional trends of folds (Bachmanov et al., 2004) (Fig. 4-a and b). This fault was first introduced with a length of about 160 km by Tchalenko and Berberian (1976). Sahabi-Fard et al. (2015) estimated the length of the fault to be 200 km. Most of the transverse faults in the Zagros, due to the significant thickness of the Hormuz series and soft intermediate horizons in the sedimentary cover (Fig. 4-c and d), do not have a complete surface manifestation, but are seen as separate faults with different patterns, especially en-echelon. This feature is also found in the Karehbas fault, of which six fault segments have been identified so far (Fig. 4-b) (Berberian, 1995; Sahabi-Fard et al., 2015). In the south of Firouzabad, there are two important fault segments of it, called Mengharak and Kalagh, which have a right-lateral movement, although at their terminations, due to rotation their kinematic change and act in the form of thrusts in the anticlines of the Firouzabad region, including the Surmeh anticline (Fig. 4-b) (Sahabi-Fard et al., 2015). Some studies in this area consider about 6 to 10 km strike slip displacement for these segments of Karehbas fault, based on the offset of the axis of the anticlines (Berberian, 1995; Bachmanov et al., 2004). A well-exposed segment of the Mengharak fault on the satellite images, cut and displcaced the Asmari Formation in the western portion of Siakh Anticline, more than two kilometers right laterally (Fig. 4-e). The Kuh-e Surmeh thrust fault at termination of Karehbas segment in the study area is an important structure in the scope of the study. According to Berberian (1995), this thrust can be the cause of earthquakes with magnitudes of 5.9 and 5.2 in 1976.

*2.2.2. Jahani salt dome*

The Jahani salt dome is the largest active salt structure in the Zagros Mountains, where salt moves up from a depth of approximately 4.5 km below sea level and forms a dome with a height of nearly one and a half kilometers and then spreads around (Talbot et al., 2000). This salt dome is located near the Surmeh anticline (Figs 1, 4-a, and 4-b). Using ground surveying operations and installation of markers, Talbot et al. (2000) investigated and modeled the activity status of this salt dome. By measuring over a period of four and a half years, they measured the rate of salt rise between 2 and 3 cm per year. The annual surface dissolution of this salt dome is about the same amount. The current outcrop of this salt dome is considered to be the third generation of salt activity, which takes place at the intersection of strike-slip faults or their overlapping parts (Fig 4-d) (branches of the Karehbas fault) (Talbot and Alavi, 1996). Salty mylonites with clear gneissic foliations, recumbent folds and overthrust nappes are important structures in this dome. Based on the interpretation of Talbot et al. (2000), the rise and release of salt in this dome first began with the release of Cambrian salts, and then Neoproterozoic salts were released, which are separated from the Cambrian salt with red layers and cover it (Talbot et al., 2000). Figs 4-c and 4-d shows the map and cross-section of the Jahani salt dome. Talbot and Alavi (1996) discussed and emphasized the importance of the Kazeroun and Mengharak systems (Karehbas) in the placement of salt domes in this part of the Zagros range.

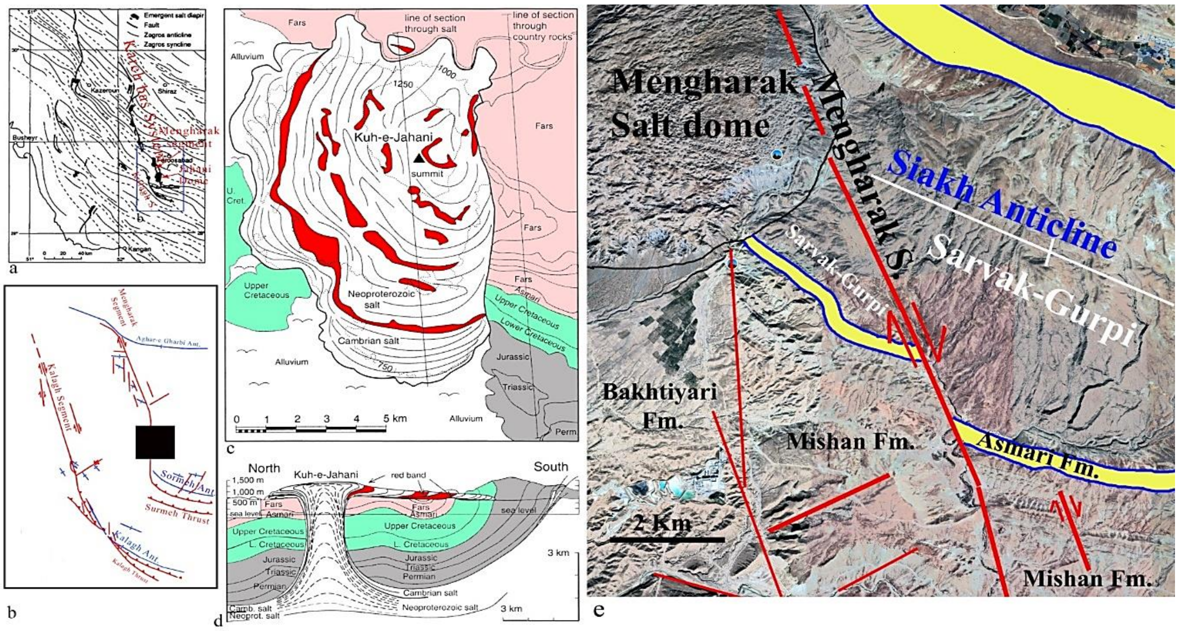


**Fig. 4.** a: structural elements of southeast Iran highlighting the Karehbas fault; b- segments of Karehbas fault based on Sahabi-Fard et al. (2015); c: Jahani salt dome and its cross section. d: modified after Talbot and Alavi (1996) and Talbot et al. (2000). e: interpreted satellite image showing the right-lateral displacement of Asmari Formation in the limbs of Siakh anticline, by the Mengharak segment of the Karehbas fault. The location of the image is marked on Fig. 4-b by black rectangle.

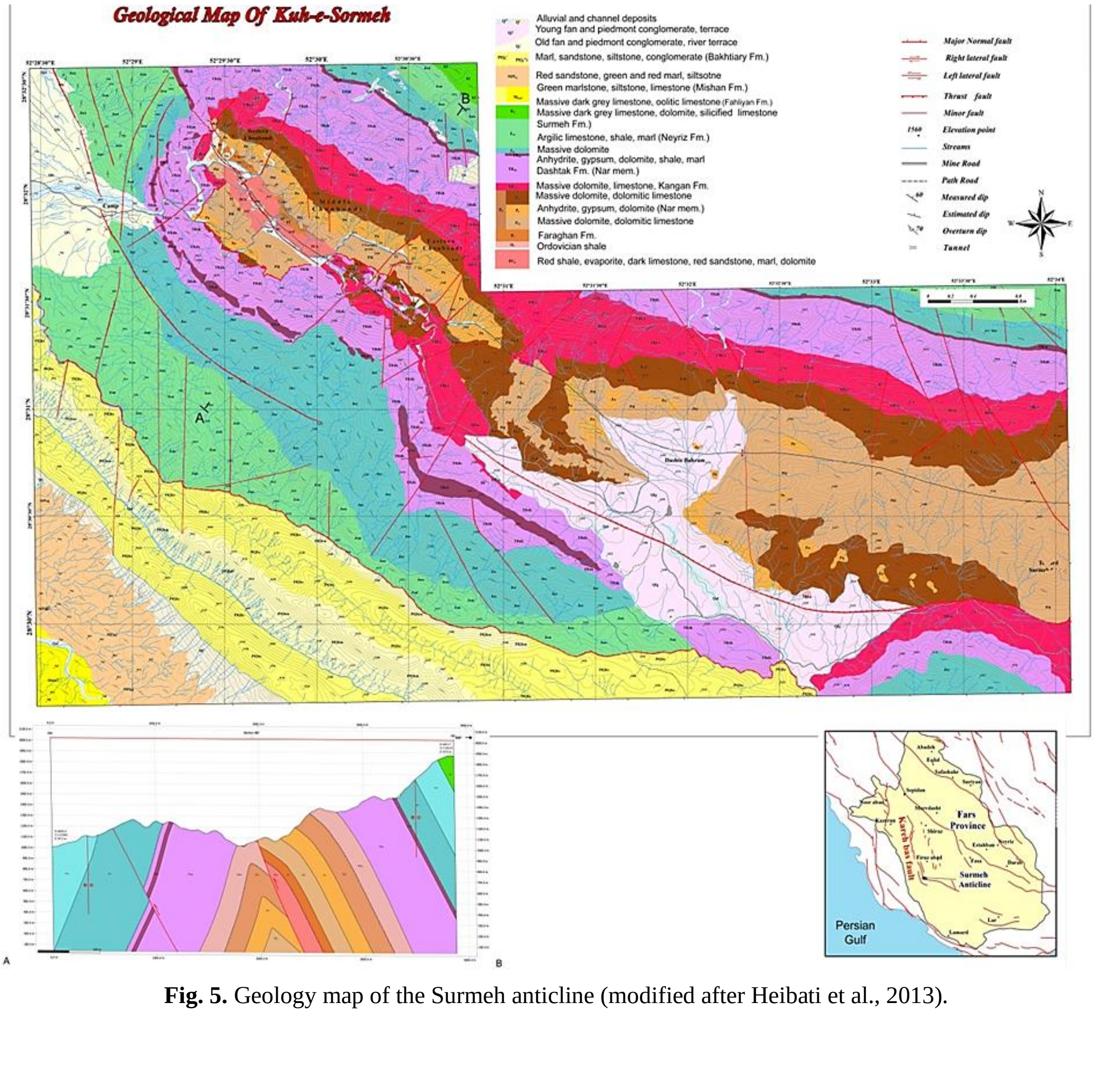


**Fig. 5.** Geology map of the Surmeh anticline (modified after Heibati et al., 2013).

*2.2.3. Structures of the Surmeh Pb-Zn mineral area*

The Surmeh anticline is a double plunging anticline that its southern limb is cut and displaced by the thrust faults, which are probably formed as the southern termination of the Mengharak segment of the Karehbas fault system (Figs 1 and 5). The axial trace of the anticline changes between N290 and N305. This anticline is an important structure in the Zagros belt, in the core of which the old formations of the Zagros up to the Ordovician age are also exposed, and in this sense, it is one of the few cases in this belt. The core of the anticline is highly disturbed and many parts of it have been affected by erosion. The northern limb of anticline has a high slope of about 70 degrees and the southern limb is overturned and of course under the influence of several thrust fault that are almost parallel to the anticline. Evidence of salt tectonic exists in some places of the Surmeh anticline, especially near middle part of the Dalan Formation near the core of anticline, where a series of evaporites attributed to the Nar member with fragments of Permian carbonate rocks have flowed in ~E-W zone (Fig 6-a). In the hand samples of the wall stones, the presence of tensile fibrous veins can be seen in different directions (Fig. 6-b). There is no information about the timing of this salt activity. The section of the zone is not very good for shear sense, but it seems that the upper wall rocks show a normal component.

Interpretation of new field data in the study area highlights three main fault trends with different mechanisms. The first trend is parallel to the trends of the Zagros structures and includes thrust faults that cut the southern limb of the Surmeh anticline and caused the older units to slide over the younger units. The evidence of these thrust can be seen both in cross-sections (Fig. 5) and in the field (Figs 7 and 8). An example of cutting the anticline by the thrust fault can be seen in the cross-section drawn in the Fig 5, where the Permian and younger units from the central part of the anticline were pushed onto the Faraghan Formation. Fig 8 shows another form of thrusting in the southern limb, where the Permian units of the Dalan Formation are thrust over the Triassic deposits of Kangan. In the field observations, the footwall of the thrust fault in the central part of the anticline includes sandstone and shale deposits related to the Faragan formations with mesoscopic scale chevron folds with the axial surface dipping towards the northeast (Fig. 9).

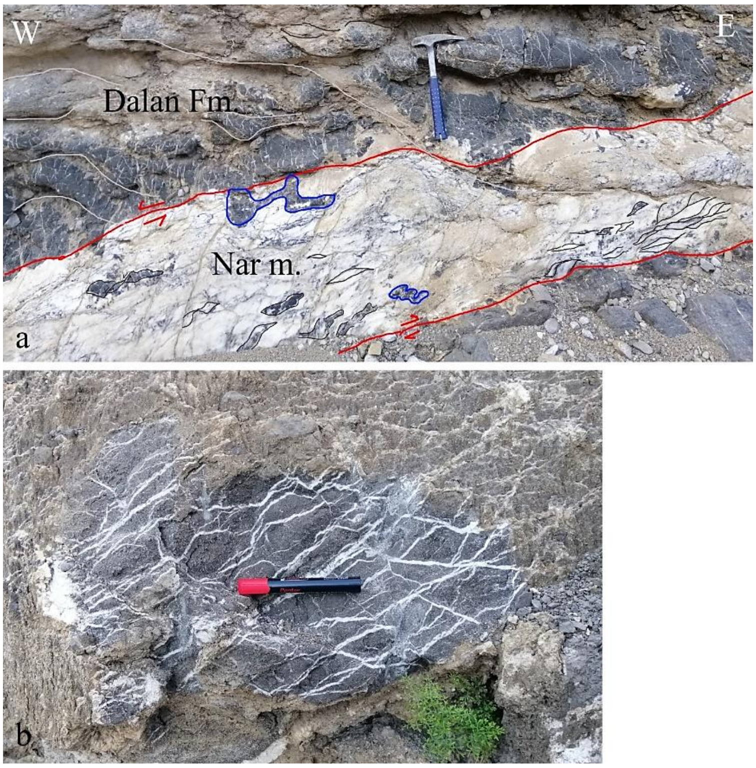


**Fig. 6.** a: salt flow zone in the Nar member, central portion of Surmeh anticline with fragments of carbonate rocks in the matrix. b: A view of wall rock with network of filled fibrous tensile veins.

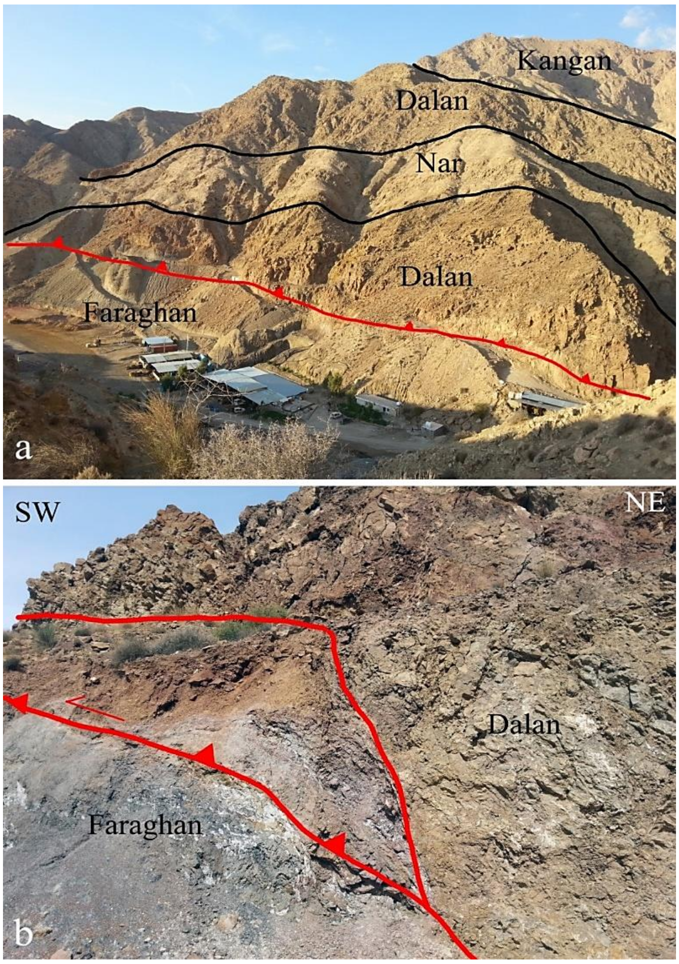


**Fig. 7.** a: general exposure of the formations in the northern limb of Surmeh anticline that thrust over the Faraghan Formation in the core of anticline from north to south. b: The thrust zone showing the emplacement of Dalan Formation over the Faraghan Formation.

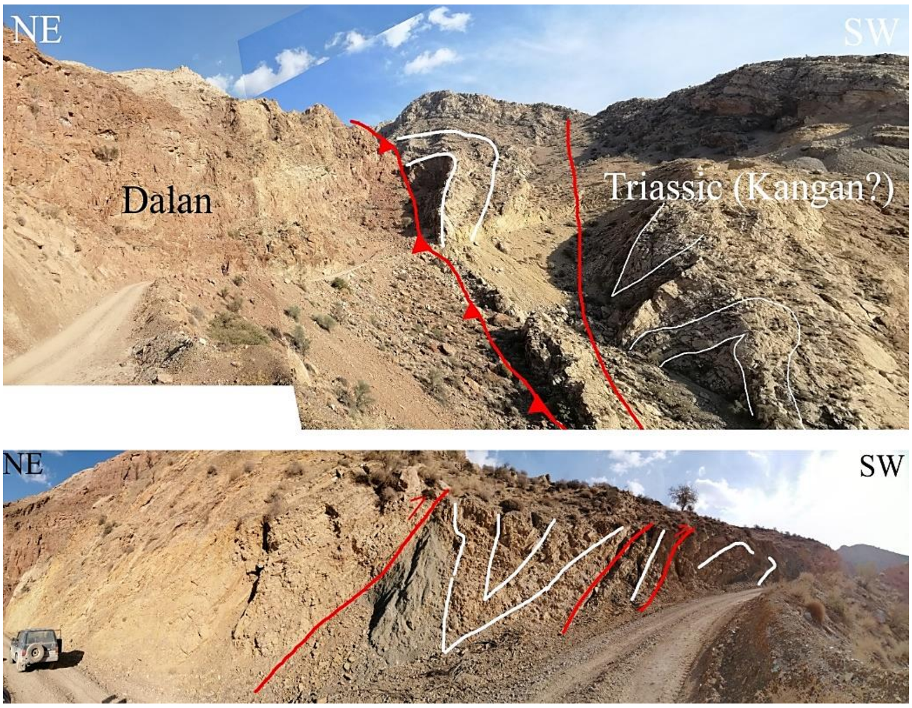


**Fig. 8.** Up and down are two field photos showing the thrusting of Permian Dalan Formation over the Triassic Kangan Formation in the southern limb of Surmeh anticline.


**Fig. 9.** Paleozoic rocks in the core of Surmeh anticline are intensely folded as northeast dipping mesoscopic chevron folds in sandstones and shales of Faraghan Formation.

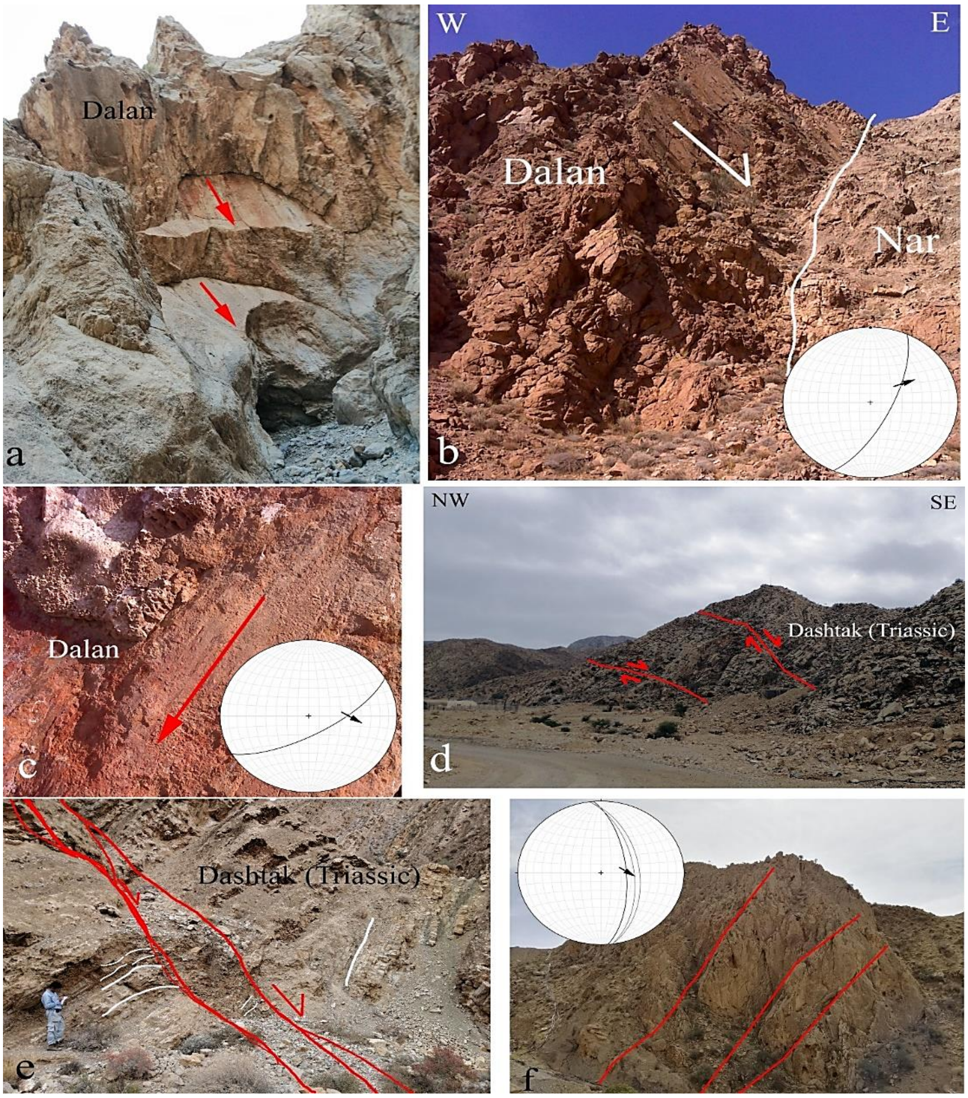


**Fig. 10.** Examples of normal faulting in the study area which has been observed in mainly Permian and Triassic units. a: NW-SE striking slickenside in Dalan Formation, west of the northern limb of the Surmeh anticline. b: Normal fault boundary between the Nar member and the carbonate rocks of the Dalan formation in the central parts of the anticline. c: Another slickenside with normal slip from the same area, d: the old normal fault with a strike-slip component in the carbonate units of the Triassic Dashtak formation, southwest of the Surmeh anticline. e: Normal fault with a significant width in the Dashtak formation, northwest of the anticline. f: normal faults with strike slip component in the Triassic Dashtak Formation.

The second category of faults in the study area, are normal faults that were visible in mainly Permian and Triassic rocks their strike varies from northwest-southeast to almost north-south (Fig. 5). There are different opinions about the origin of normal faults in the range (Fig. 10). The normal slickensides in Fig. 10-a to c are samples measures in the Dalan Formation, and their slip rake is between 70 and 90 degrees. In Fig 10-d to f, there are three examples of normal faults in the Dashtak formation with fault zones width of more than 30 cm. previously; it was explained about the Jahani salt dome in the scope of the study. The origin of the normal fault in the range may be related to the activity of this salt dome. However, the presence of normal faults in the Permian units can be related to old extensional tectonics and intra-basin faults. With this preliminary explanation, examples of more important structures are presented in this section. Based on the studies and field observations, it was found that minor faults, especially normal faults, had an effective role in mineralization in the region. It was also found that the geometry and kinematics of the thrust faults follow the main trend of the Zagros, but the normal faults are probably related to the time of the formation of the sedimentary basin. In order to better investigate the state of fracture structures in the study area, photo lineaments were drawn using Landsat 8 satellite data with Geomatica software, then their rose diagram were compared with rose diagram of faults that measured during field investigation and also faults that were measured inside the tunnels of Surmeh Pb-Zn mine by Pousti (2005) (Fig. 11). From the comparison of the data obtained from the photo lineaments with the faults measured in the field and mine tunnels, two dominant trends are observed in the region, one of which is parallel to the main direction of the anticline, i.e. northwest-southeast, and the other is perpendicular to it, i.e. the northeast-Southwest. On the other hand, there are strike-slip faults with a north-south trend, which are the surface effects of the Karehbas basement fault system (the Mengharak and the Kalagh segment), and some of them can be easily recognized in satellite images. In field outcrops, small strike-slip faults have caused displacement and destruction of mineralized zones (Fig. 12). The normal fault (N080, 70E) with Pb-Zn mineralization along fault zone and wall rock is show in Fig. 13.

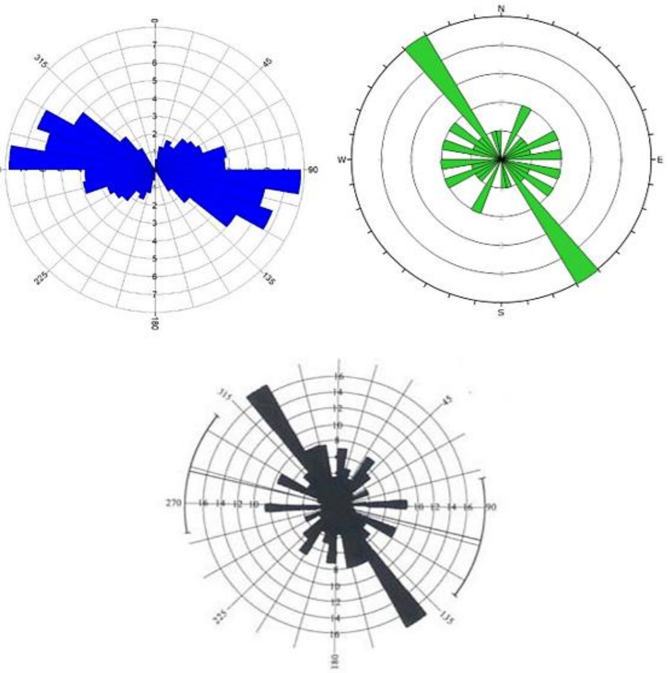


**Fig. 11.** Rose diagrams of photo lineaments (blue), measured faults in the field (green) and measured faults in the mine tunnels (black, from Pousti, 2004) within Surmeh Pb-Zn mineral area.

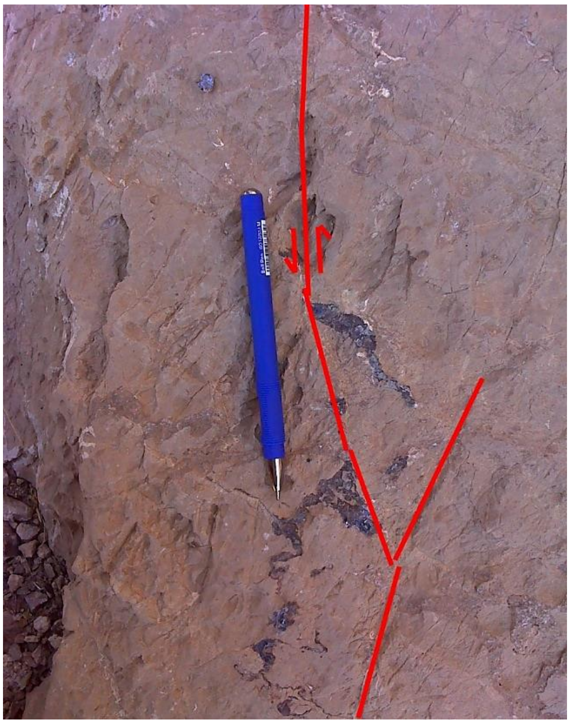

**Fig. 12.** A small strike slip fault (N340) that displaced the galena bearing vein left laterally.

**Fig. 13.** A normal fault (N080, 70E) with Pb-Zn mineralization along fault zone and wall rock.

## 3. Results and discussion

Kuh Surmeh anticline hosts a rare case of metallic mineralization in the Zagros Fold-Thrust Belt with Pb-Zn as the major products. Several studies conducted so far to investigate the type of this ore deposits as well as the effective factors in economic concentration of Pb-Zn ores in this area. Based on fluid inclusion studies, Taghipour and Eskandari (2014) suggested that mixing of deep fluids and atmospheric fluids has critical role in the formation of Surmeh deposit. They claim that the main fluid is related to deeper hydrothermal vents or basinal sources related to Precambrian salt formations that ascended through faults during the intrusion of the Jahani salt dome, and the other fluid is related to atmospheric waters. According to the comparison of sulfur values of Surmeh deposit with base metal deposits with carbonate hostrock, this deposit can be of Mississippi Valley type (MVT) (Taghipour and Eskandari, 2014). Other influencing factors in the formation of Surmeh deposit are the presence of fractures and faults that played the role of the path for the flow of water, the mixing of basin water with atmospheric waters, the existence of the Jahani salt dome and its diapirism, compressional tectonics in the Neogene, which is the engine of movement. It has provided concentration and enrichment of mineralization. In the meantime, the role of faults and fractures has been very important both in guiding the flows and in providing a suitable place for the concentration of mineralization. Although there is fault with normal, thrust and strike-slip mechanism in the region, but it seems that normal and strike-slip processes have played a decisive role. The origin of normal faults can be related to the diapirism activity of the Jahani salt dome or can be from the inherited normal faults created during Zagros basin development and rifting of Paleozoic rocks that led to Neotethys Ocean (e.g. Tavana, 1993, Pousti, 2005; Jafari et al., 2023). The role of faults in the formation and evolution of MVT and SEDEX type lead and zinc deposits has been proven (e.g. Maghfouri & Flavien, 2021; Song et al., 2023). The similarities between MVT deposits and Surmeh deposit include: the host rock of Surmeh deposit is dolomite, the deposit is epigenetic in which the ore minerals formed as a filling of voids and replacement in the veins and veinlets, or small to large lenses along fault zones or parallel to the axis of the anticline. Also, the lateral extension of the deposit is 12 Km, the mineralization depth is about 100 meters including the oxide zone. The Surmeh deposit is also stratiband and is placed in folded Permian rocks; similar to Mississippi Valley type deposits which are usually found in platform carbonate or folded sequences from Proterozoic to Cretaceous (Evans, 1980). In the formation of Mississippi Valley type deposits (MVT), large faults and fault cuts have played a role (Ramdohr 1980; Kendrick et al. 2002) and in Surmeh Mountain, the deposit is formed by a deep and long fault parallel to the anticline axis and the sedimentary construction of oolitic limestone. It is heavily dolomitized and controlled. In the Mississippi Valley type deposits, the ores are located at a little depth compared to the current surface (Symons et al. 1998; Marie and Kesler, 2000). In Surmeh deposit, some of the minerals are located on the surface of the ground and most of them are located at a small depth. Considering the comparison of this deposit with the mentioned types of lead and zinc deposits with carbonate hosts, it seems that the studied deposit is more similar to Mississippi Valley deposits.

Fazli et al. (2019) have described the tectonic model of the development of Surmeh Pd-Zn mine during the structural evolution of Zagros in three stages that modified slightly as follows: (1) the subduction of Neotethys plate under the Iranian plate and the closing of the ocean and the formation of the Zagros Mountains until early Miocene; (2) continuation of compressional tectonics and folding from Miocene to Pliocene and diapirism of the Jahani salt dome and also salt tectonic in younger evaporate units such as Nar member; (3) the reactivation of the Surmeh thrust fault and regional uplift during the Neogene, circulation of metal-bearing brines of basin origin with atmospheric fluids, which were mixed to form deposits during compressional tectonic activity.

Most recently, Song et al. (2023) examined MVT deposits in the late Mesozoic–Cenozoic Tethyan and Cordilleran orogenic thrust belts in which some deposits predated regional thrusting, but most deposits formed during regional transpression or extension after early stages of thrusting during orogeny. They found that extensional faults control the distribution of ore zones at the deposit through which post-thrusting MVT mineralization occurs due to stress transition from compression to transpression/extension, favoring for development of new extensional faults or reactivation of pre-existing structures, dilation sites or other mechanisms. They pointed out that exploration for MVT ores in thrust belts should focus on extensional zones and faults at deposit scale. Similar conclusions made on the importance of secondary normal faults and evaporate-related activities in the MVT Zn–Pb deposits in Pucará Group, northern central Peru by de Oliveira et al. (2020) and other studies (e.g. Wei et al., 2020; Maghfouri & Choulet, 2021). In several cases the earlier normal faults act as the nearly vertical pathways for the fluid (e.g. Yucai et al., 2017; Yue et al., 2024) or the mineralization increases near the normal faults (e.g. Maghfouri and Choulet, 2021, Cheng et al., 2024). Accordingly, we think the normal faults in the Surmeh deposits are more important than thrust faults in ore-formation process. The attitude of normal faults in the study area varies from NE-SW to NNW-SSE (Figs 5 and 10). Inherited normal faults from the Paleozoic–Mesozoic rifting related extension trends E–W and NNW–SSE (e.g. Navabpour et al., 2011; 2014; Carminati et al., 2016); so it is meaningful to consider larger normal faults in the Kuh Surmeh anticline with E-W to NNW-SSE trends in the Permian rocks as the inherited faults from Late-Paleozoic to early Mesozoic times, but normal faulting in relation to the salt diapirism is also important especially at the western side of the Surmeh anticline. Vatandoust et al., (2023) suggested that the intersection of NW-SE and N-S trending fault sets are promising areas for Pb-Zn-related mineral exploration in the regional scale. These sets are likely associated with the main Karebas tear fault and its horsetail splay terminal. Exposed evidences of salt tectonics along the Karehbas Fault indicate that salt diapirs such as Jahani and Mengharak were rising at least since the Late Jurassic, long before the Zagros Fold-Thrust Belt formed by shortened during the Late Cenozoic and the earliest salt activities has most likely been started in the Earlier Paleozoic shortly after their deposition (Hassanpour et al., 2018). Hassanpour et al. (2018) described how the long-term pre-folding salt tectonic activities influence and control the stress pattern and downbuilding of lateral minibasins, preferential weakness of the diapirs on one hand and greater stiffness of the minibasins on the other hand. They added that deformation advance was therefore irregular during Cenozoic because strain is localized at the diapirs and squeezes them whereas tends to avoid folding the thick, and hence stronger, minibasins into anticlines. This view might also consider a role for slat tectonics for the localization of folds such as Kuh-e Surmeh Anticline and hence the formation of Kuh-Surmeh deposit. So we propose that salt tectonics and the intersection of Karehbas transverse fault with folded lower Paleozoic rocks that contains inherited faults facilitated growth of Kuh-e Surmeh anticline and thrust faulting by providing basal and medium level detachments.

## 4. Conclusion

Kuh-e Surmeh deposit is a lead-zinc deposit with precious metals, which is very similar to MVT deposits. Diapirism of the Jahani salt dome and the presence of the Karehbas basement fault played a key role in the formation of this deposit. The existence of fractures and faults with different trends has played an important role in conducting fluids and were necessary for deposit formation. Among these, normal faults have played a more important role. The origin of these normal faults can be traced back to the faults inherited from the rifting before Neotethys development in the Late Paleozoic, and some of them were probably formed during the Jahani salt dome diapirism. Kuh Surmeh anticline is one of the rare cases in the Zagros thrust belt, where Mesozoic-Paleozoic units are outcropped, and from the point of view of stratigraphic studies, it is a suitable place for further studies. The mixing of basinal fluids with atmospheric waters from the path of fractures and faults has been the main factor in the economic enrichment of metal sulfides in the veins. The compressional tectonics caused by collisional orogeny in the Miocene is the driving engine of the evolution of this deposit and has facilitated and accelerated the metal enrichment. Although the surface evidence of similar deposits in the Zagros belt has not been reported so far, since the Zagros anticlines mainly have Paleozoic formations, it is possible that in the same structural positions as the Surmeh anticline, i.e., at the intersection of salt domes with basement faults in similar sequences of mineralization have taken place that can be identified and studied by subsurface exploratory surveys and drilling, as considered in some recent studies. The findings of this paper can be utilized as an exploratory sign for similar ore deposits in the Zagros Range as well as other foreland basins where the intersection of salt domes with transverse basement faults interacted with common deformation features of the forelands; i.e. folding and thrust faulting.

**Acknowledgments**

We thank Professor Nosrati and Dr. Salehi for their efficient editorial handling of this paper. We are grateful to two anonymous reviewers for their constructive comments and suggestions. The administration of Kuh-e Surmeh Mine is greatly thanked for helps and supports during field visitation.

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