Deposit-Type Characterization and Genetic Implications of the Albolaq Esfaryen Pb–Zn Mineralization, NE Iran

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ABSTRACT

The Albolaq Esfaryen deposite in Northeastern Iran represents a promising sediment-hosted Pb–Zn mineral system within Mesozoic carbonate sequences. Despite extensive exploration activities, the genetic classification of Pb–Zn mineralization in this area has remained debated. This study integrates field observations, ore petrography, mineragraphy, and alteration analysis to characterize the deposit type and clarify its genetic framework.

Pb–Zn mineralization is hosted by carbonate rocks and occurs as structurally controlled veins, veinlets, With mineralization locally developed within the host rocks along faults, fractures, and brecciated zones. The primary sulfide assemblage is dominated by sphalerite and galena with minor pyrite, supergene alteration has produced extensive secondary zinc and lead carbonates and iron oxides. Alteration patterns are characterized mainly by dolomitization, accompanied by silicification and late-stage calcitization, indicating multi-stage hydrothermal fluid evolution.

The strong structural control on ore distribution, dominance of carbonate host rocks, low abundance of iron sulfides, and widespread dolomitization collectively point to a Mississippi Valley–type (MVT) genetic affinity. the Albolaq Esfarayen lead and zinc deposit is probably of the MVT type, and the source rocks are also shale units. The host rocks of Tirgan limestone and brines also play a complex role. According to previous work [1].comparing the Albolaq Esfarayen lead and zinc deposit with the MVT deposits of Central Alborz and Tabas Posht Badam, the Albolaq Esfarayen lead and zinc deposit can be considered compatible with the MVT deposits of Central Alborz (the deposits of northeast Shahmirzad and the Pichmatou deposit of northwest Shahroud). Also, SEM-EDS analysis of selected galena samples confirms the presence of silver, whereas ICP-OES data from 56 samples generally low Ag concentrations, with only two samples (~3.6%) reaching 13 ppm, suggesting localized and sporadic enrichment.
The relationships observed in Thin sections indicate that the primary Pb–Zn sulfide system has undergone supergene processes involving oxidation, pseudomorphic replacement, phase transformations, and secondary metal enrichment.

Keywords: *Mississippi Valley–type (MVT),Sediment-hosted Pb–Zn deposit, Dolomitization Basinal brines,Structural control of mineralization, Albolaq Esfarayen, Carbonate-hosted, Ag*

1. *INTRODUCTION*

Sediment-hosted Pb–Zn deposits constitute one of the most economically significant groups of base-metal mineral systems worldwide. These deposits occur mainly within carbonate or clastic sedimentary successions and are genetically classified into several principal types, including Mississippi Valley–type (MVT), Irish-type, shale-hosted, and volcanogenic-related systems [1]. Discrimination among these deposit classes relies on integrated evaluation of geological setting, host lithology, mineral assemblages, ore textures, alteration patterns, and structural controls [2].

The Albolaq Esfarayen deposite in Northeastern Iran has recently emerged as a promising exploration target following regional metallogenic assessments and systematic exploration programs [2]. Nevertheless, the genetic classification of Pb–Zn mineralization in this area has remained uncertain, with competing interpretations invoking MVT, Irish-type, or tectono-magmatic hydrothermal origins [2].

This study aims to (i) document the ore geology, mineralogy, alteration, and structural framework of the Albolaq Esfarayen Pb–Zn occurrence, (ii) evaluate its deposit-type affinity through comparison with established Iranian analogues, and (iii) propose a coherent genetic model based on integrated field and petrographic evidence [2].

2. Geological Setting

The Albolaq Esfarayen Pb–Zn exploration area is located in Northeastern Iran and the southern part of the Kopet-Dagh structural zone and within the Binalud zone, northeastern Iran. The Binalud zone represents a highly dynamic tectonic domain that acted as a transitional region between the Turan Plate and the microcontinental blocks of Central East Iran and the eastern Alborz. This tectonic setting has recorded multiple rotational phases and repeated changes in kinematic regimes, resulting in intense deformation and additional fragmentation compared to adjacent zones. These tectonic processes strongly influenced the sedimentary basin architecture and led to rapid lateral facies variations within relatively short distances [3].

Regionally, the study area is characterized by the exposure of Jurassic, Cretaceous, and Paleogene sedimentary sequences, which are intensely affected by numerous faults. Pb–Zn mineralization occurs within different stratigraphic levels, mainly hosted by carbonate units. In addition to Upper Triassic and Jurassic units, several younger lithological units crop out in the mineralized area. The stratigraphic succession is described below from older to younger units [5].

The oldest exposed rocks in the study area belong to the Kashafrud Formation (Early Jurassic), which consists predominantly of dark-colored shale, sandstone, minor limestone, and conglomerate. Lithologically and facies-wise, this formation shows similarities to coal-bearing Jurassic sediments of the Alborz and Central Iran. The Kashafrud Formation represents a turbiditic flysch-type sequence deposited mainly in deep-marine environments, with minor contributions from non-turbiditic shallow-marine deposits. The formation is rich in organic matter, and its shale units are considered potential source rocks for hydrocarbons. Stratigraphically, the Kashafrud Formation overlies Upper Triassic sediments with an angular unconformity and is overlain by either the Chamanbid Formation or the Mozduran Limestone, depending on lateral facies variations [5].

Overlying the Kashafrud Formation, the Mozduran Limestone Formation (Upper Jurassic) represents the last major carbonate platform sequence of the Jurassic in the Kopet-Dagh region. This formation is composed mainly of thick-bedded micritic limestones with chert nodules, interbedded marl, and shale layers. Diagenetic features include early and late-stage dolomitization, evaporitic phases (gypsum), and both mechanical and chemical compaction. The Mozduran Formation was deposited on a shallow carbonate platform adjacent to deeper marine environments and exhibits significant lateral facies changes toward clastic-dominated equivalents in the eastern Kopet-Dagh [5]. Although the Mozduran Formation hosts Pb–Zn mineralization in nearby districts, petrographic investigations in the Albolaq Esfarayen deposite indicate that it is not the primary host rock for mineralization.

The Mozduran Formation is overlain by the Shurijeh Formation, which consists mainly of red-colored sandstones, conglomerates, siltstones, and mudstones with minor carbonate interlayers. This formation records a transition from shallow marine to coastal and fluvial depositional environments. The thickness of the Shurijeh Formation varies significantly across the region, reflecting syn-sedimentary tectonic activity and basin compartmentalization [5].

The Tirgan Formation (Lower Cretaceous) constitutes the most extensive and economically significant stratigraphic unit in the study area and represents the principal host rock for Pb–Zn mineralization. This

formation is composed predominantly of medium- to thick-bedded oolitic and bioclastic limestones with intercalations of marly limestone, marl, and calcareous shale. Orbitolinid-bearing limestone layers are ubiquitous throughout the formation. Field observations indicate that the Tirgan Formation locally contains rudist-rich horizons and chert nodules. The contact between the Tirgan and Shurijeh formations is commonly faulted and locally shows reverse fault mechanisms [5].

Petrographic analysis of limestone samples from mineralized zones confirms that the host rocks belong to the Tirgan Formation and consist mainly of orbitolinid-bearing bioclastic wackestone to packstone and oolitic grainstone textures. Skeletal components include large benthic foraminifera (Orbitolina), miliolids, bivalves, echinoderms, bryozoans, brachiopods, green algae, and gastropods, whereas non-skeletal components include ooids, peloids, intraclasts, and minor pellets within a sparry calcite cement. These petrographic characteristics confirm the attribution of the mineralized carbonate units to the Tirgan Formation [2].

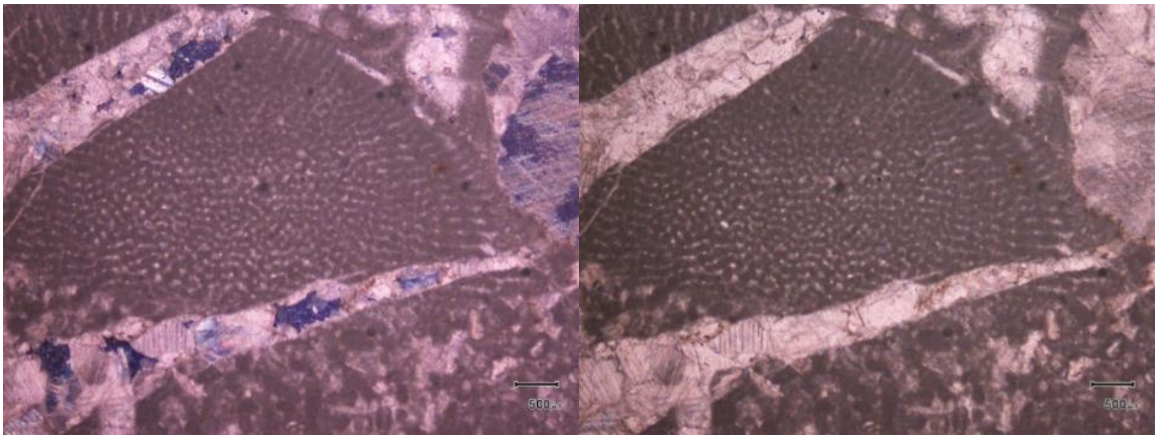


Fig. 1. *Photomicrograph of Orbitolina-bearing limestone with a micritic calcite matrix.Skeletal components: large benthic foraminifera (Orbitolina), small benthic foraminifera (miliolids), and bivalve fragments.Non-skeletal components: pellets observed under crossed-polarized light (XPL) and plane-polarized light (CPL) [6].*

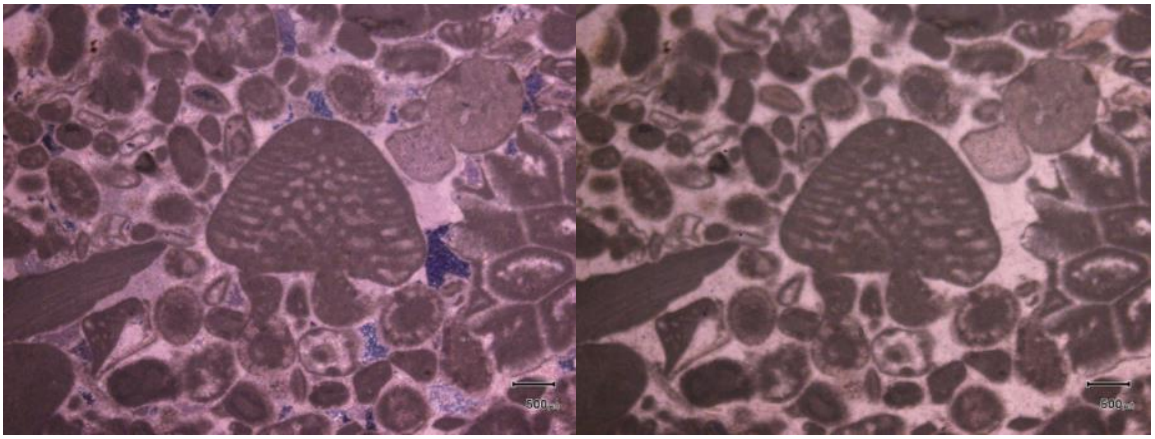


Fig. 2.*Photomicrograph of ovoid-bearing biocalcitic grainstone.Skeletal components: benthic foraminifera (Orbitolina and smaller forms), echinoderms, bryozoans, brachiopods, green algae, gastropods, and bivalves.Non-skeletal components: ooids, intraclasts, and minor pellets within sparry calcite cement, observed under plane-polarized light (CPL) and crossed-polarized light (XPL) [6].*

in The Albolaq Esfarayen deposite, shales can be considered as the source rock [2]. This interpretation is supported by several factors.
Shales are typically enriched in fine-grained minerals capable of storing metals such as lead and zinc through ionic bonding or surface adsorption. Moreover, many shales contain organic matter (kerogen) and sulfur-bearing compounds. Organic matter may act as a sulfur source or as a reducing agent in geochemical processes, thereby supplying the sulfur required for the formation of Pb–Zn sulfides such as galena and sphalerite.
Due to their specific chemical composition—including clay minerals, disseminated sulfides, and organic constituents—shales also possess a significant potential to release metals and sulfur during interaction with hydrothermal or diagenetic fluids [4].

3. Materials and Methods

This research integrates detailed field investigations with petrographic and mineragraphic laboratory analyses conducted during systematic exploration programs in The Albolaq Esfarayen deposite. Fieldwork involved geological mapping, documentation of ore geometries, and structural measurements within mineralized zones, followed by representative sampling of veins, replacement bodies, and altered host rocks [6].

Thin-section petrography was used to characterize host-rock lithologies and alteration features, whereas polished-section mineragraphy enabled identification of sulfide assemblages, textures, and paragenetic relationships. Selected samples were further examined by scanning electron microscopy (SEM) to confirm mineral compositions and recognize minor or supergene phases [8,10].

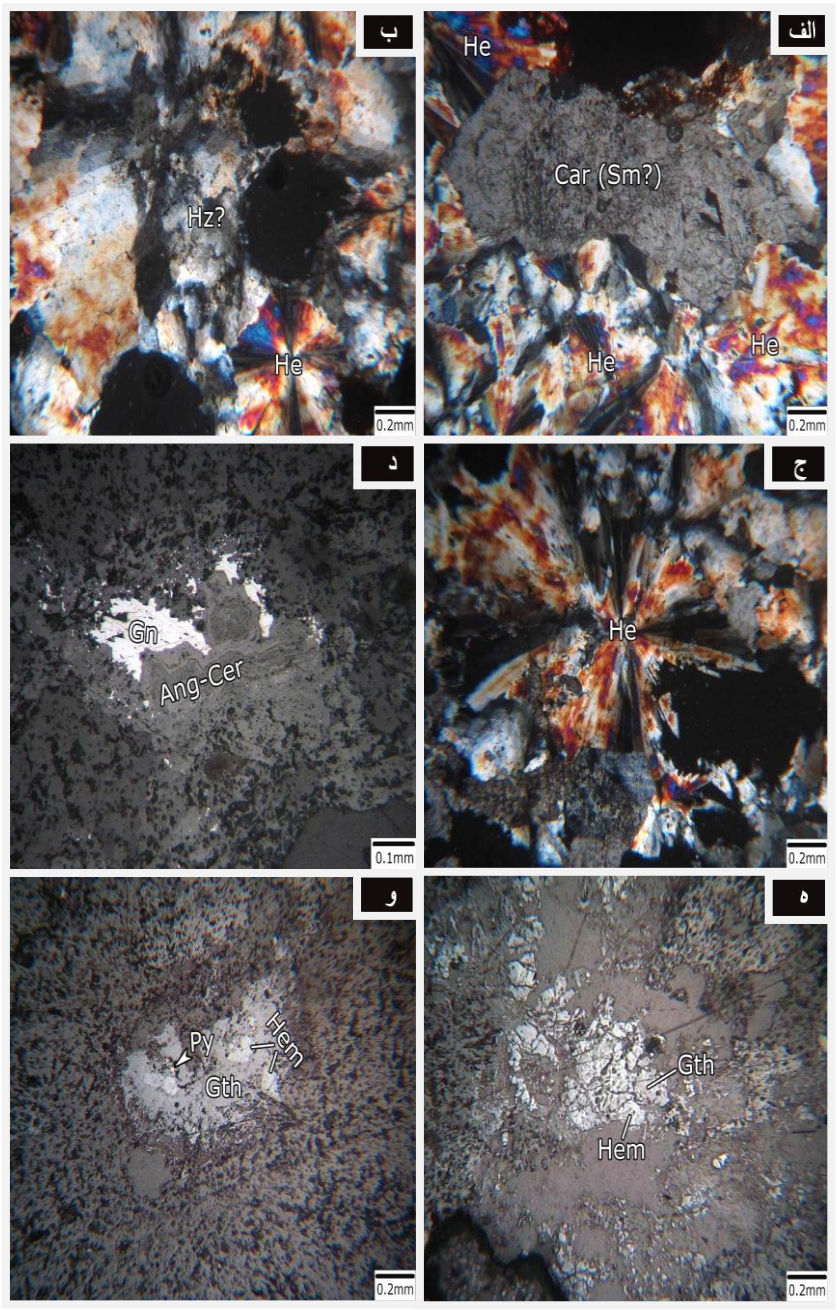


Fig. 3.*Mineralogical images of the sample:(a) carbonate patch (smithsonite) occurring among hemimorphite crystals;(b) hydrozincite between hemimorphite crystals;(c) hemimorphite crystal with a fan-shaped structure;(d) galena crystal partially altered along the rim to anglesite–cerussite;(e) hematite–goethite crystal;(f) relict pyrite crystals preserved within hematite–goethite [6].*

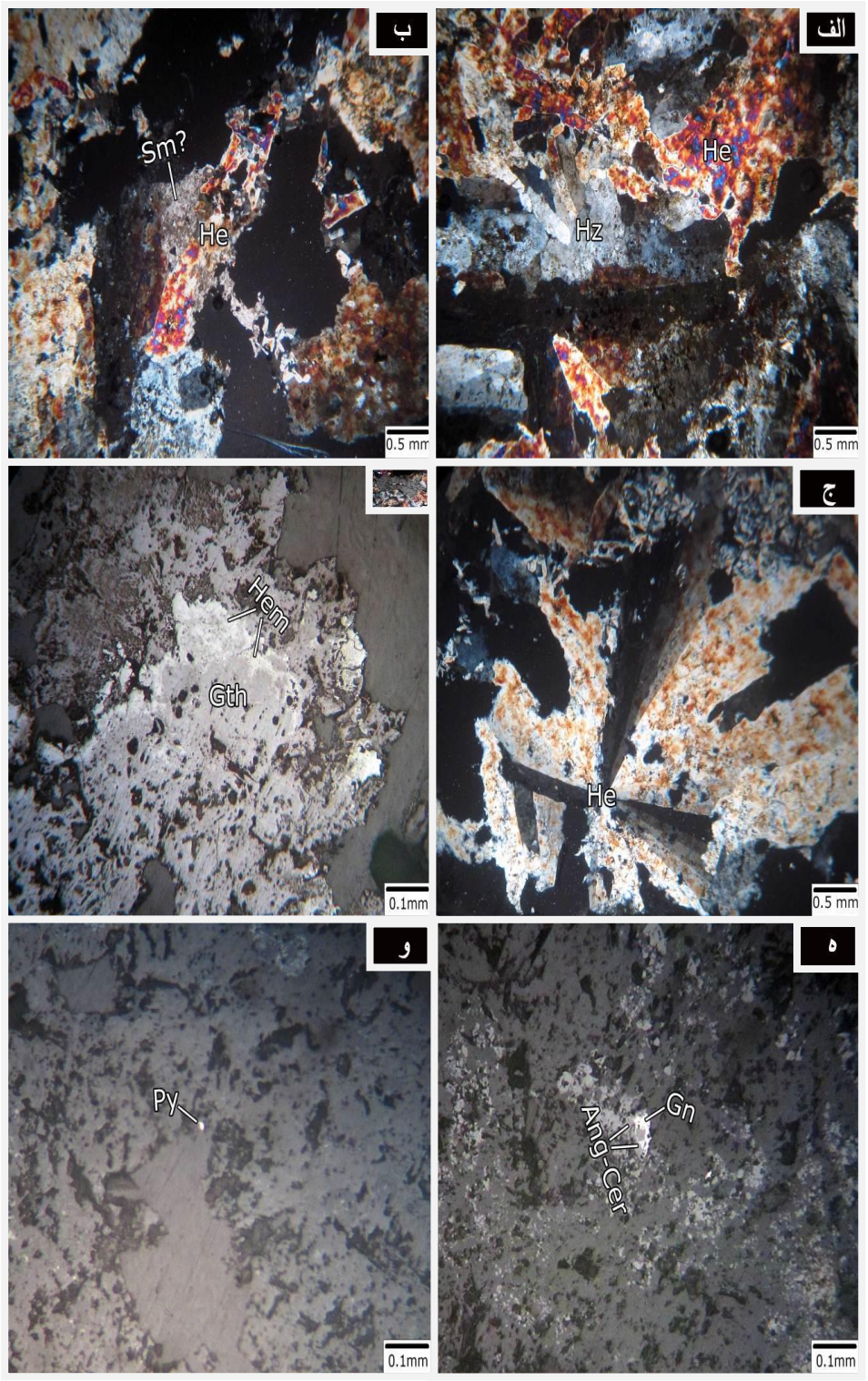


Fig. 4. *Mineralogical images of sample:(a) view of hemimorphite and hydrozincite crystals;(b) hemimorphite associated with zinc carbonate (smithsonite);(c) hemimorphite crystals displaying a fan-shaped arrangement;(d) hematite–goethite crystal;(e) galena crystal replaced by carbonate minerals (anglesite–cerussite);(f) very fine-grained pyrite crystal [6].*

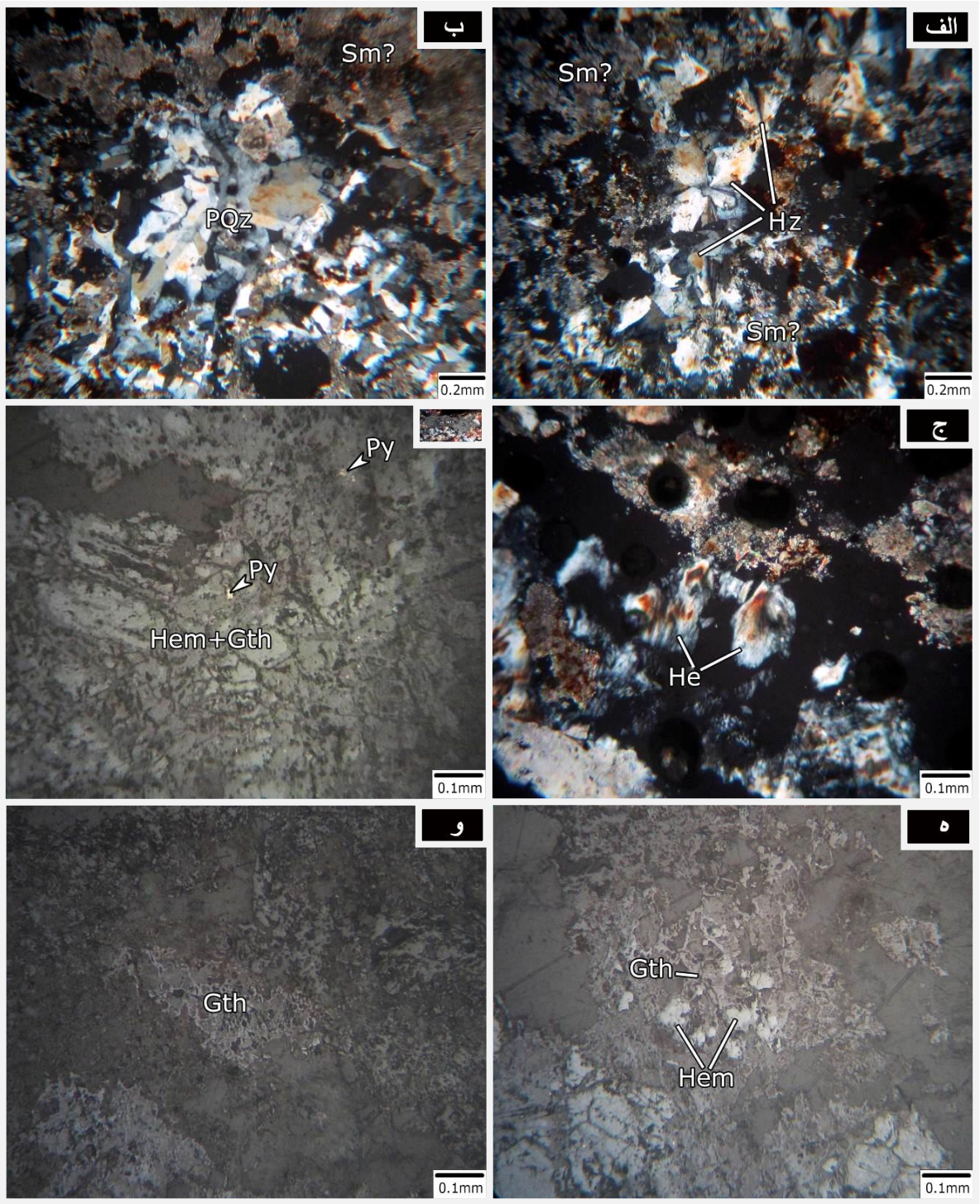


Fig. 5. *Mineralogical images of the sample:(a) hemimorphite crystals occurring among carbonate crystals (smithsonite);(b) patch of polycrystalline quartz;(c) general view of hemimorphite crystals;(d) fine relict .pyrite crystals preserved within hematite–goethite;(e) hematite–goethite crystals;(f) goethite crystal [6].*

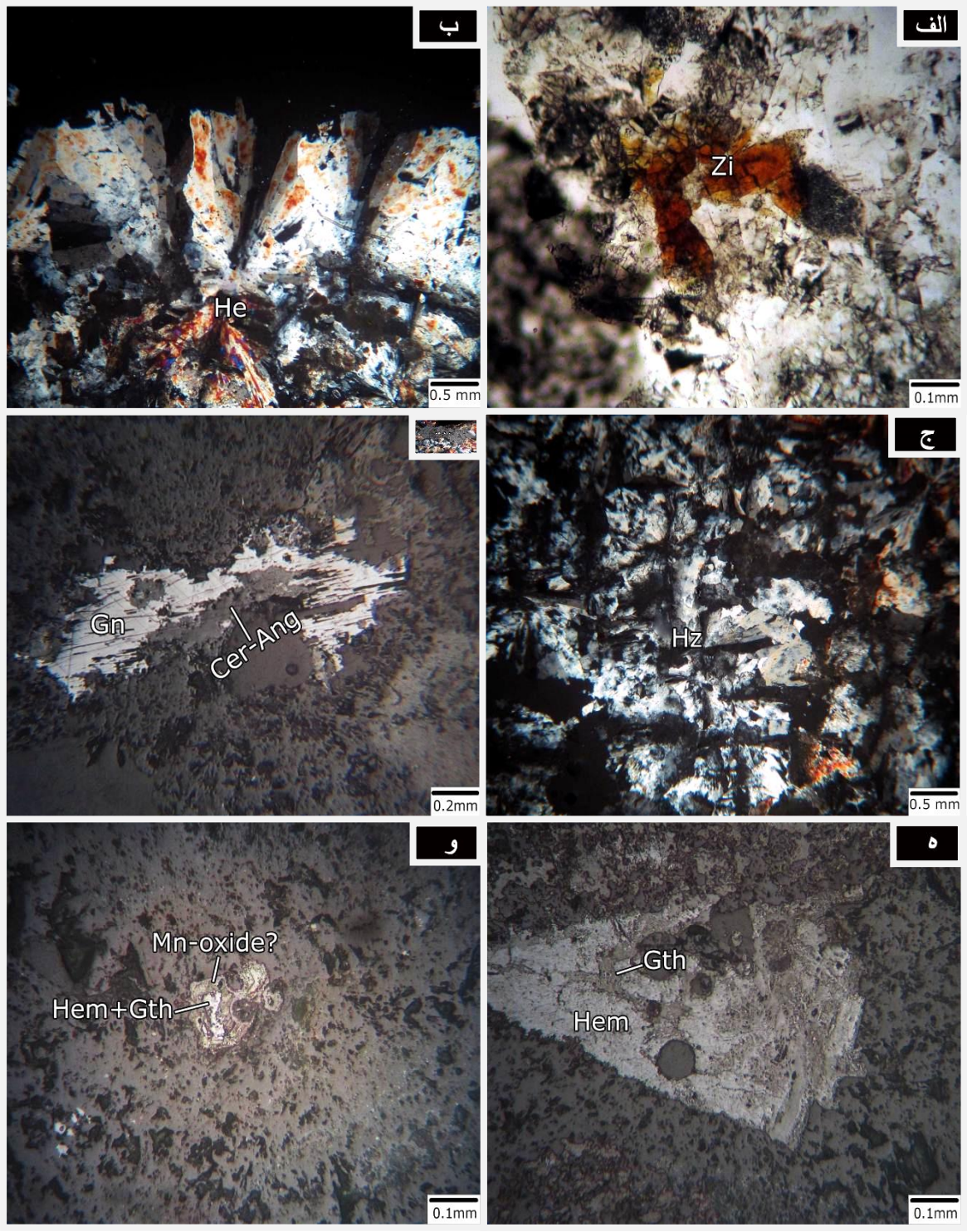


Fig. 6. *Mineralogical images of the sample:(a) view of zincite crystals;(b) hemimorphite;(c) hydrozincite;(d) galena crystal replaced by anglesite–cerussite;(e) hematite–goethite crystal;(f) manganese oxide associated with hematite–goethite [6].*

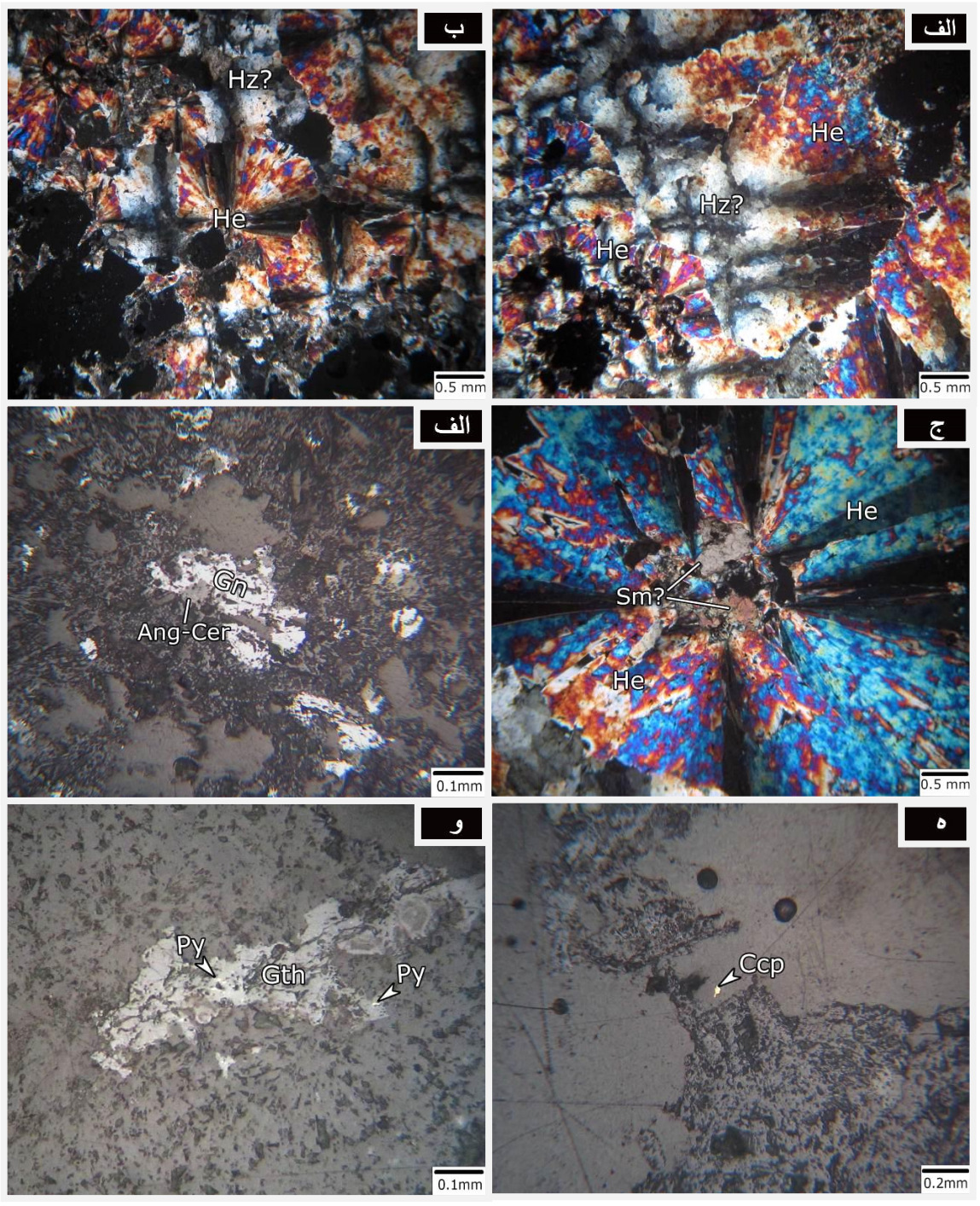


Fig. 7. *Mineralogical images of the sample:(a) hydrozincite occurring among hemimorphite crystals;(b) hemimorphite with fan-shaped arrangement accompanied by hydrozincite;(c) carbonate (smithsonite) within the center of a hemimorphite crystal;(d) galena crystal replaced by anglesite–cerussite;(e) chalcopyrite crystal;(f) relict pyrite crystals preserved within goethite [6].*

Interpretation of images:

a) Hydrozincite occurring among hemimorphite crystalsFrom a mineralogical perspective, hemimorphite is a zinc silicate that forms under oxidizing conditions and at a relatively neutral to slightly alkaline pH. The presence of hydrozincite in the intercrystalline spaces of hemimorphite indicates that supergene fluids, following hemimorphite formation, experienced an increase in CO_2 activity. Under such conditions, dissolved zinc tends to precipitate as carbonate rather than as a silicate phase.

The filling of intercrystalline spaces reflects secondary open-space filling deposition and suggests high mobility of Zn^{2+} ions during the oxidation stage. Therefore, hydrozincite is considered a late-stage mineral relative to hemimorphite.

b) Hemimorphite with fan-shaped arrangement accompanied by hydrozinciteThe fan-shaped crystal habit of hemimorphite indicates rapid crystal growth in a supersaturated environment and is influenced by the non-centrosymmetric crystal structure of hemimorphite, which causes asymmetric growth of crystal faces. The radial or fan-shaped arrangement in hemimorphite is characteristic of crystallization from dilute fluids within cavities or fractures. Crystal growth proceeds from the cavity walls toward the center.

This texture commonly forms in geode-like or vuggy environments with radial crystal growth and indicates precipitation from secondary fluids in open spaces. Based on field observations, it can be inferred that the Pb-Zn mineralization in the Albalagh Esfarayen deposite corresponds to a Mississippi Valley-Type (MVT) deposit hosted in karstified rocks [2].

The association with hydrozincite further suggests fluctuating geochemical conditions of the fluid, involving changes in SiO_2 and CO_3^{2-} activities

c) Smithsonite in the core of hemimorphite crystalsThis feature is mineralogically significant. The presence of smithsonite in the core of hemimorphite crystals indicates a pseudomorphic replacement process. Smithsonite is generally stable at higher pH and elevated CO_2 activity compared to hemimorphite.

The infiltration of mineralizing fluids through fractures and crystal discontinuities causes gradual dissolution of hemimorphite from the interior, concurrent with precipitation of smithsonite. This mechanism follows a dissolution–precipitation replacement process, preserving the external morphology of the original hemimorphite crystal.

d) Galena replaced by anglesite–cerussiteFrom a mineral stability perspective, galena is unstable under oxidizing conditions and undergoes rapid oxidation. In the presence of sulfate ions, anglesite initially forms as a transient, relatively more acidic phase.

With increasing pH and CO_2 influx, anglesite alters to cerussite. This sequence precisely reflects the classical supergene alteration model for lead and the pseudomorphic preservation of galena crystal shape confirms a pseudomorphic replacement.

e) Presence of chalcopyrite crystalsChalcopyrite is more resistant to oxidation than galena and sphalerite. Its occurrence indicates either a lower intensity of supergene alteration in this zone or limited fluid infiltration. The iron content in chalcopyrite's structure may form protective iron oxide layers, reducing oxidation rates.

Consequently, chalcopyrite is interpreted as a relict mineral from the primary mineralization stage.

f) Relict pyrite within goethitePyrite is highly unstable in oxidizing environments and transforms to goethite. The preservation of pyrite cores within a goethite matrix suggests progressive and incomplete oxidation. The replacement is volume-conservative, with liberated iron immediately converting to goethite.

This phenomenon commonly occurs in upper oxidation zones under acidic to neutral pH conditions.



Fig.7. *Pb–Zn mineralization of Albalagh Esfarayen in karstified zones.*



Fig.8. *Zinc-rich oxidized-silicate ore (left), and zinc–lead-rich ore containing residual galena within assemblages of cerussite, calamine, and others (right).*

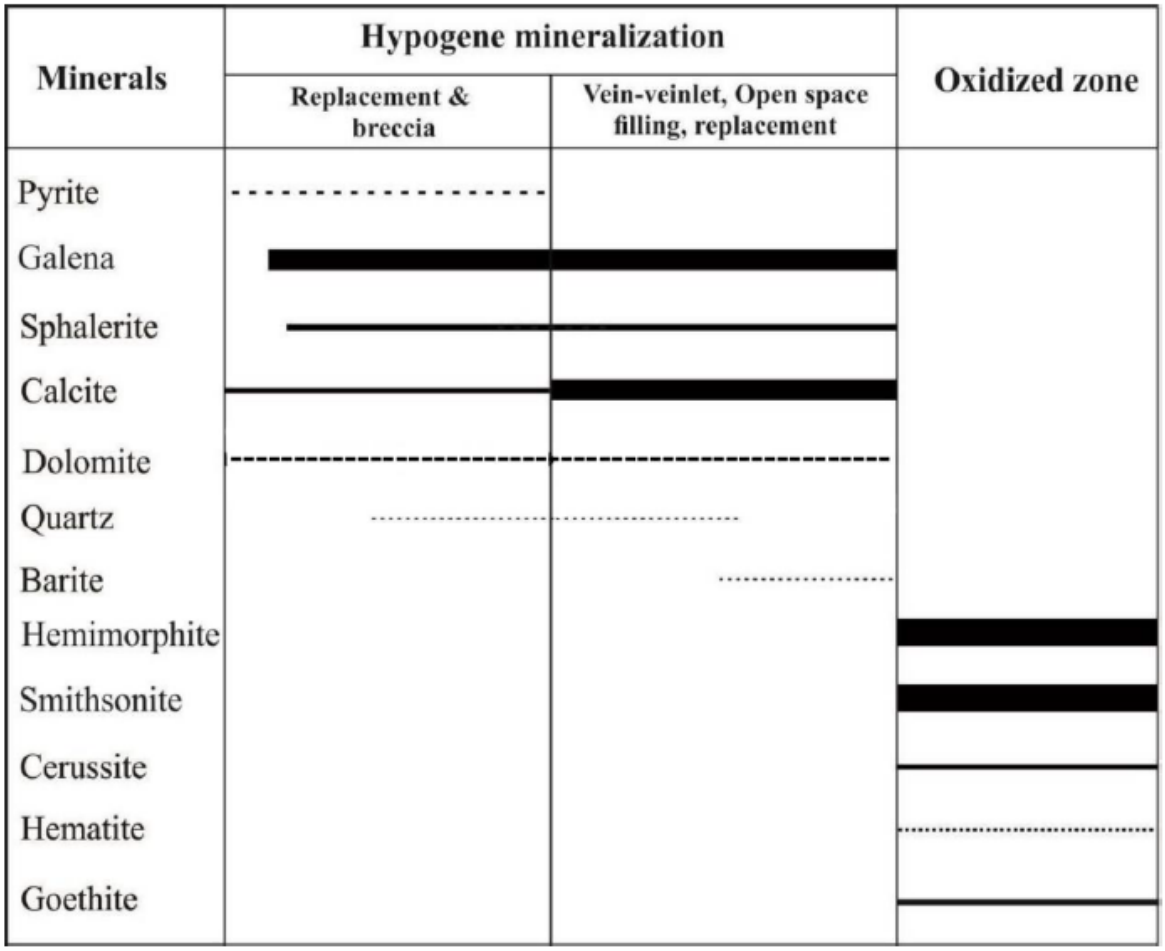


Fig.9. *Paragenetic sequence of mineralization in the Albolaq Esfarayen exploration deposite.*

3.1 Associated Elements in the Albolaq Esfarayen Deposit: Implications for Silver Distribution

Selected galena-bearing samples were examined using SEM-EDS.A polished section was prepared from a representative hand specimen of galena (Fig.10) for SEM-EDS analysis.In addition, 56 samples collected from different parts of the Albolaq Esfarayen deposit were analyzed for trace elements, including Ag, by ICP-OES



Fig.10.*Polished hand specimen of galena collected from the Albolaq Esfarayen deposit used for SEM-EDS analysis to investigate associated elements*

4. Results

4.1 Ore Geometry and Distribution

Pb–Zn mineralization occurs predominantly as structurally controlled veins, veinlets, and replacement bodies within carbonate host rocks. Ore zones are commonly localized along fault planes, fracture corridors, and brecciated horizons, although partial stratabound confinement within favorable carbonate layers is also observed. Crosscutting relationships indicate multi-stage mineralization linked to repeated fluid flow events [6].

4.2 Mineralogy

The primary sulfide assemblage is dominated by sphalerite and galena with subordinate pyrite. Sphalerite typically forms coarse- to medium-grained crystals displaying colloform, banded, and brecciated textures, whereas galena occurs as massive to disseminated grains commonly intergrown with sphalerite. Pyrite is minor and mainly disseminated within host rocks [6].
Supergene alteration is widespread, producing smithsonite, cerussite, anglesite, and iron oxides such as goethite and limonite that partially replace primary sulfides and fill fractures and cavities [6].

4.3 Alteration Characteristics

Alteration is dominated by carbonate-related processes, particularly dolomitization, silicification, and late calcitization. Dolomitization is spatially associated with ore zones and significantly enhances porosity and permeability, whereas silicification and calcitization locally overprint earlier mineralization stages [2].

4.3 *Associated Elements*

SEM-EDS observations qualitatively indicate the presence of silver associated with the galena phase.ICP-OES results show that silver concentrations are generally low and close to background values throughout the deposit.Only two samples (approximately 3.6% of the dataset) display elevated Ag contents, reaching up to 13 ppm.

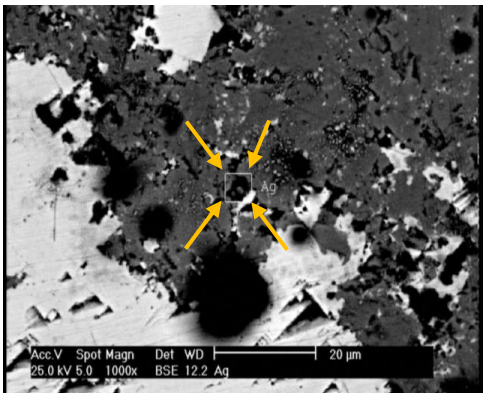


Fig.11.*SEM imaging of a polished section prepared from a galena sample collected from the Albolaq Esfarayen deposit.*

5. Discussion

5.1 Structural and Lithological Controls

Ore localization reflects the combined influence of structural permeability and reactive carbonate host rocks. Faults, fractures, and breccia zones served as principal conduits for metal-bearing fluids, while dolomitized limestone horizons provided optimal chemical and physical traps for sulfide precipitation [6].The close spatial association between dolomitization and mineralization suggests a syn- to pre-ore dolomitization event, a diagnostic feature of carbonate-hosted Pb–Zn systems [6].

Structurally, the study area is dissected by multiple fault systems that strongly control the distribution of lithological units and mineralization. Fault contacts between the Tirgan and Shurijeh formations are widespread and play a key role in localizing Pb–Zn mineralization by providing pathways for fluid migration. The combination of favorable carbonate host rocks, impermeable shale units, and fault-controlled fluid flow supports the interpretation of Pb–Zn mineralization in the Albolaq Esfarayen deposite as Mississippi Valley-Type (MVT).

5.2 Physicochemical Conditions of Ore Formation

- ✓ *Low to moderate formation temperatures (approximately 85–200 °C)*
- ✓ *High salinity of ore-forming fluids (~10–30 wt.% NaCl)*
- ✓ *Occurrence within carbonate sequences and a strong genetic relationship with basinal brines*
- ✓ *Mineralogical assemblage dominated by galena, sphalerite, and pyrite*
- ✓ *Lack of direct genetic association with magmatic sources, with mineralization controlled primarily by geochemical processes [1].*

Based on the last criterion, it can be concluded that the Albolaq lead–zinc deposit has no genetic relationship with the Eocene Shah Jahan volcanism [2].

5.3 Deposit-Type Evaluation

Comparison with global sediment-hosted Pb–Zn models strongly favors an MVT affinity.Irish-type characteristics—synsedimentary stratiform sulfides, feeder systems, and basin-scale exhalation—are absent, and VMS indicators such as volcanic host rocks and massive sulfide lenses are lacking [1].Conversely, The Albolaq Esfarayen exhibits the diagnostic MVT signature: carbonate host rocks, structural control, sphalerite–galena dominance, limited pyrite, and extensive dolomitizationclosely resembling the Central Alborz deposits (including the northeastern Shahmirzad and northwestern Pichmatu deposits) [2], while showing no geological or genetic affinity with the MVT-type deposits of the Tabas–Posht-e-Badam district[2].

5.4 Genetic Model and Fluid Evolution

The most plausible model involves migration of saline basinal brines through structurally prepared carbonate sequences during post-depositional tectonic activity. Metals were likely leached from adjacent shaly–clastic units and precipitated within dolomitized carbonate traps through fluid–rock interaction [4].Multiple hydrothermal pulses produced mineralogical overprinting, whereas later uplift and oxidation generated extensive supergene Zn–Pb carbonates and iron oxides[1].

5.5 Regional Metallogenic Implications

Recognition of an MVT genetic affinity places Albolaq Esfarayen within the broader framework of Iranian sediment-hosted Pb–Zn metallogeny. Similarities with Central Alborz deposits indicate a regionally

consistent basinal-brine mineral system and highlight fault-controlled dolomitized carbonates as prime exploration targets in Northeastern Iran.

5.5 Associated Elements

The SEM-EDS results suggest limited Ag incorporation into Pb-bearing sulfides and/or the occurrence of minor Ag-bearing phases at a micro-scale.This distribution pattern indicates localized and sporadic silver enrichment rather than pervasive Ag mineralization within the deposit.The combined interpretation of ICP-OES geochemical data and SEM-EDS mineralogical observations indicates that silver enrichment in the Albolaq Esfarayen deposit is limited in extent and likely controlled by localized mineralogical or physicochemical factors.Silver is interpreted to be hosted either through minor substitution within galena or by discrete, fine-grained Ag-bearing phases that are not volumetrically significant at the deposit scale.Such localized Ag enrichment may reflect specific stages of the mineralization process or restricted structural and fluid pathways.Further detailed micro-analytical investigations, particularly on anomalous samples, are required to better constrain the silver-hosting phases and to clarify the mechanisms responsible for silver enrichment in the Albolaq Esfarayen deposit.

6. Conclusions

The Albolaq Esfarayen Pb–Zn occurrence represents a structurally controlled, carbonate-hosted mineral system characterized by sphalerite–galena mineralization, extensive dolomitization, and supergene alteration. Metals were likely leached from adjacent shaly–clastic units and precipitated within dolomitized carbonate traps through fluid–rock interaction. Integrated geological, mineralogical, and alteration evidence indicates a Mississippi Valley–type genetic model involving basinal brine migration, structural focusing, and reactive carbonate host rocks.This interpretation aligns the deposit with Pb–Zn systems of the Central Alborz Central Alborz(including the northeastern Shahmirzad and northwestern Pichmatu deposits) [2].

metallogenic belts and provides important guidance for future regional exploration .

The relationships observed in Thin sections indicate that the primary Pb–Zn sulfide system has undergone supergene processes involving oxidation, pseudomorphic replacement, phase transformations, and secondary metal enrichment.

Silver enrichment in the Albolaq Esfarayen deposit is limited and localized, likely controlled by minor incorporation into galena or discrete Ag-bearing phases.

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