

Geological and geochemical assessment of precious metal mineralization in the Jbel Houanite region (Eastern High Atlas, Morocco): Implications for resource and environmental management

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ABSTRACT

Located within the Eastern High Atlas Mountain Range of Morocco, the Jbel Houanite mining district represents a polymetallic hydrothermal system with a structurally controlled genetic origin associated with a Paleozoic tectonic heritage followed by Atlasic reactivation. The results of the litho-structural studies suggest that mineralization is preferentially localized along E–W and NE–SW fault systems and subvertical foliation associated with inherited Hercynian shear zones. The occurrence of quartz stockwork veins and extensive fracturing suggests prolonged hydrothermal circulation through these highly permeable structural corridors. Geochemical data also reveal a distinction between a Fe–Zn sulfide assemblage typical of a volcano-sedimentary environment, and an Au–Sb–Ag–Pb assemblage related to a hydrothermal event associated with tectonic remobilization. Antimony was found to be the most reliable indicator element for gold mineralization. Hydrothermal alteration is dominated by phyllic assemblages characterized by enrichment in K–Rb–Cs and depletion in Ca, reflecting intense sericitization associated with fluid flow along deformation zones. Ag/Au ratios, together with the mineralogical and geochemical characteristics, suggest mesothermal to epithermal conditions and hydrothermal activity at intermediate crustal depths. Mineralogical mapping and trace-element analyses show that Au, As, Fe, and Sb are strongly spatially associated, with arsenopyrite and stibnite representing the principal As- and Sb-bearing sulfide phases associated with Au-bearing mineralized zones. No geochemical evidence for porphyry, volcanogenic massive sulfide (VMS), or Ni–Cu mineralization was identified, arguing against a direct magmatic or submarine volcanogenic origin and supporting a tectonically driven orogenic setting for the mineralization. The combined structural, mineralogical, and geochemical evidence indicates a polygenic mineralization process, with an early syngenetic sulfide phase followed by tectonically driven hydrothermal remobilization and concentration of Au within shear zones. There are also geological similarities between the Jbel Houanite mining district and major orogenic gold provinces within North Africa, and indicate how important inherited crustal structures are in determining the circulation of fluids and their mineralization.

Keywords: orogenic gold deposit, Sb–Au mineralization, shear zones, hydrothermal alteration, Moroccan High Atlas.

INTRODUCTION

Due to the worldwide increase in demand for mineral resources, particularly precious and strategic metals, metallogeny is now viewed as a major scientific and economic concern. Gold, in particular, is in high demand of its high economic value and widespread use in industry and finance. Furthermore, significant gold-antimony (Au-Sb) mining regions exist throughout the world, where gold and other metal elements have concentrated as a result of hydrothermal circulation and the effects of tectonic structures in different metallogenic provinces (André-Mayer et al., 2024). Understanding the relationships between hydrothermal alteration, lithology, tectonic deformation, and geochemical distribution is thus an essential step toward better constraining the mechanisms responsible for the genesis of gold mineralization. The Eastern High Atlas region of Morocco is characterized by a diversity of mineral deposits (Figure 1), resulting from a multi-phase geodynamic evolution marked by several tectonic, magmatic, and hydrothermal episodes that affected both the Paleozoic basement and the Mesozoic cover (Adil et al., 2004; Pelleter et al., 2007; Frizon de Lamotte et al., 2009; Rddad and Bouhlef, 2016; Verhaert et al., 2017; Allouban et al., 2021; Lafforgue et al., 2021; Rddad and Mouguina, 2021). These events facilitated the formation of numerous polymetallic mineralizations controlled by major tectonic events and by

fluid circulation rich in metallic elements. Fractured structures and shear zones thus served as preferred pathways for the hydrothermal fluids responsible for the precipitation of sulfides and metal-bearing phases.

The Jbel Houanite mine is situated within the Tamlelt massif, on the eastern side of the High Atlas) and is of metallogenic interest primarily because it contains gold and antimony ores. Previous investigations have identified that mineralization, predominantly located in highly fractured and altered formations of Paleozoic age, has also been influenced by large quantities of hydrothermal fluid that has passed through them (Bouladon, 1940; Emberger, 1970; Blanc, 1972; Vasquez Lopez, 1974; Rajlich and Lomoz, 1977; Azza and Boushaba, 2006; Choukrad et al., 2026). Recent work by Choukrad et al. (2026) established the main geodynamic and paragenetic framework of the Jbel Houanite mineralization, including the role of tectonic reactivation and the development of the Sb-Au and Pb-Zn mineralizing stages. However, the spatial organization of the Au-Sb mineralization and its relationships with multivariate geochemical signatures and hydrothermal alteration require further investigation. In particular, the geochemical relationships between ore-related elements and alteration-related elements have not been sufficiently constrained at the district scale. The mineralization occurs either in quartz-carbonate veins or within alteration zones associated with arsenic-rich sulphide minerals,

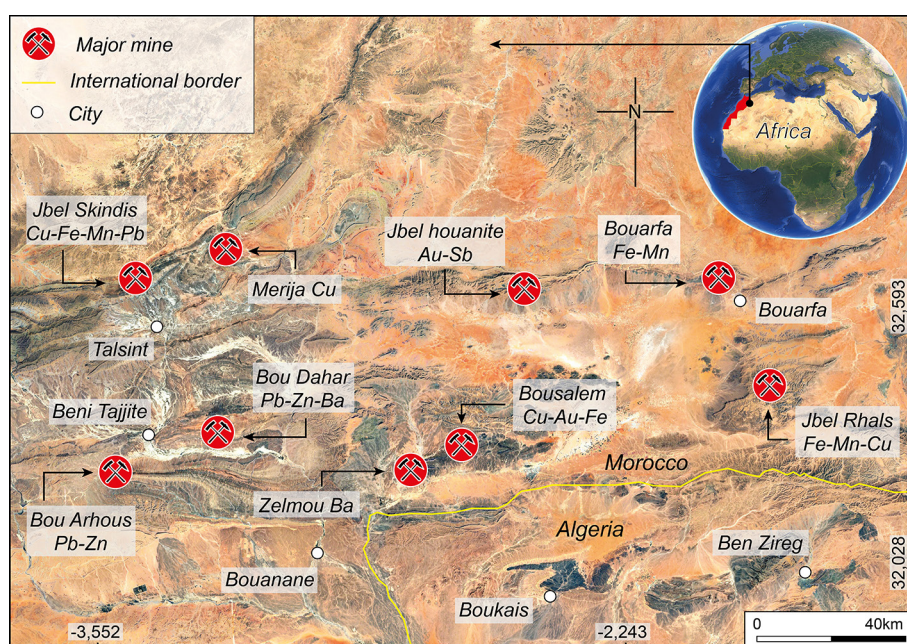


Figure 1. Main deposits of the Eastern High Atlas

thus providing evidence for a polyphasic hydrothermal system.

Although the structural and paragenetic evolution of the Jbel Houanite mineralization has recently been documented, the integration of structural observations with quantitative geochemical relationships remains limited. In particular, the extent to which ore-related elements are coupled with hydrothermal alteration signatures, and how these relationships vary spatially within the mineralized system, requires further clarification. A detailed petrographic and multivariate geochemical characterization is therefore needed to complement the existing geodynamic and paragenetic framework and to better constrain the processes governing metal enrichment and the spatial distribution of Au-Sb mineralization.

Accordingly, the present study aims to complement the geodynamic and paragenetic framework established by Choukrad et al. (2026) through an integrated structural, petrographic, mineralogical, and multivariate geochemical investigation of the Jbel Houanite Au-Sb mineralization. Particular emphasis is placed on identifying the statistical relationships among ore-related elements, hydrothermal alteration indicators, and host-rock components, and on evaluating their spatial organization within the mineralized structures. The objective is not to propose a fundamentally different genetic model, but rather to refine the existing interpretation by providing additional geochemical constraints on metal enrichment, hydrothermal alteration, and structural localization. These results are further used to assess their implications for mineral exploration, resource evaluation, and environmental considerations in the Jbel Houanite district.

GEOLOGICAL BACKGROUND

The Jbel Houanite mining district is located in the northern part of the Tamlelt Massif, which belongs to the structural domain of the Eastern Moroccan High Atlas (Figure 2A–B). The latter constitutes a major intracontinental mountain range in Morocco, characterized by a folded Mesozoic–Cenozoic cover resting unconformably on a Paleozoic basement consolidated during the Variscan orogeny (Mattauer et al., 1977; Piqué and Michard, 1989; Frizon de Lamotte et al., 2008; El Hassani, 2023). The Tamlelt Massif exhibits a distinctive structural organization,

with its northern part showing affinities with the Variscan Atlas-Meseta Belt, while the central and southern sectors are linked to the Anti-Atlas domain (Hoepffner et al., 2005; Baïdier et al., 2008; Michard et al., 2010; Ouanaimi et al., 2018). To the north, it is bounded by the North Atlas Fault (NAF) (Figure 2B). To the south, it is bounded by the South Meseta Fault Zone (SMFZ) (Figure 2B), which is well exposed within the central High Atlas in the western buttresses of Aït Tamlil and Skoura (Becker et al., 2021; Karaoui et al., 2022; Gibb et al., 2025), and extending further east along the northern fringe of the Anti-Atlas, south of Tinghir (Michard et al., 2010; Hejja et al., 2020; Talih et al., 2022a, b; Talih et al., 2025; Ousaid et al., 2026) all the way to the northeast of Béchar in Algeria (Benyoucef et al., 2015; Ab-bache et al., 2022; Leprêtre et al., 2024).

The Paleozoic basement of the Jbel Houanite region (Figure 2C) mainly consists of Cambrian to Devonian formations. The oldest formation is Hamda Formation, which developed during the Cambrian/Ordovician (Milhi et al., 2003) and composed of greywacke-bearing quartz phyllite, quartzitic sandstone, phyllite, green quartzitic sandstone, siltstone, and interbedded sandstone and pelitic rocks, with locally developed volcano-sedimentary units (El Kochri et al., 1992; Bolata, 1995). These facies reflect marine detrital sedimentation and have been influenced by tectonic activity during the process of early Paleozoic basin formation (Geyer and Landing 2020). The Silurian unit is represented by the Aïn L'Orak Formation (Du Dresnay and Wilfert 1960; Milhi et al. 2010), ranging in age from the Llandovery to Ludlow. This formation consists mainly of graptolitic chert, green to purple shale, and green quartzite. These lithological and paleontological features suggest a generally deep-marine environment in which fine-grained siliceous and clay-rich sediments accumulated under relatively low-energy conditions (Choubert et al. 1950; Negroni 1964; Kergomard 1973; Bolata 1995).

The Mesozoic-Cenozoic succession unconformably overlies the Paleozoic basement. This unconformity records a prolonged period of erosion and subaerial exposure prior to renewed sedimentation (Frizon de Lamotte et al. 2008; El Kochri, 1996). During the Early Triassic, continental red claystones and conglomerates were deposited in a semi-arid fluvial system (Beauchamp, 1988). Most of these deposits are early evidence of the first episodes of extension associated with the

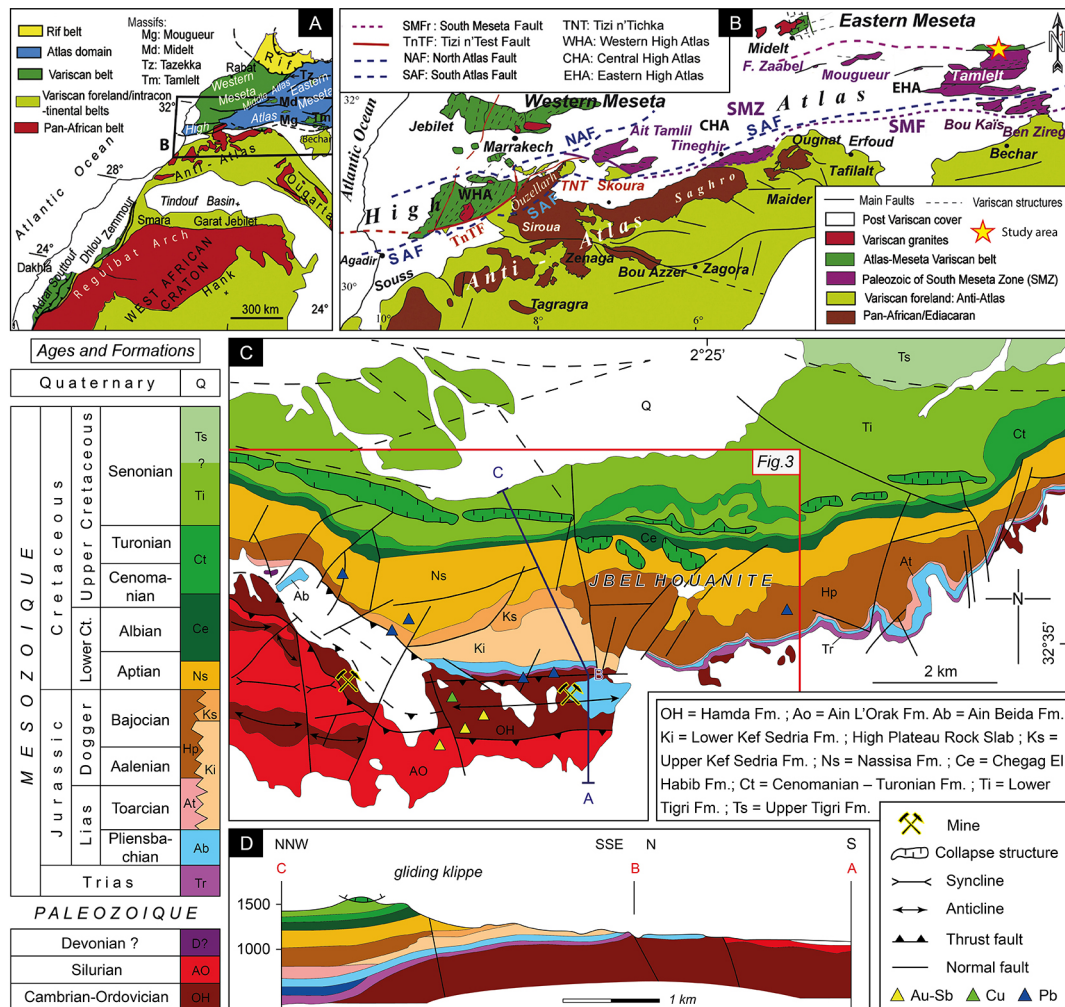


Figure 2. (A) Structural map of northwestern Africa showing the northern part of the West African craton as well as the adjacent Atlas and Mesetian domains (Hoepffner et al., 2005; Michard et al., 2010); (B) Enlarged view of the regional setting of the study area, showing the location of the sector in the Tamlelt region (Ouanaimi et al., 2018); (C) Detailed geological map of the study area (modified from Milhi et al., 2003); (D) Cross-section highlighting the complex structure of Jbel Houanite

creation of the Central Atlantic and evolution of the Atlas basins (Milhi et al. 2010).

The Jurassic Period begins with the Aïn Beida Formation assigned to the Pliensbachian. This formation consists of limestones arranged in beds of ecimeter-thick limestone beds with some localized evidence of emersion and small coral reefs. The facies of this formation suggest shallow water carbonate platform environments that experience eustatic fluctuations. The Toarcian is represented by the Achachab Torach Formation, which represents open marine conditions that favored biogenic carbonate production that includes bioclastic limestones. The Dogger consists of alternating marl and limestone beds that form the Lower Kaf Sedria Formation. The Lower Kaf Sedria Formation ends with layers of continental deposits (red claystones) and gradually transitions

through carbonate and dolomitic deposits into the final unit of the sequence (marlstone). The vertical facies evolution indicates a gradual transition from shallow marine environments to confined and eventually continental environments. These changes were due to regional paleogeographic and tectonic changes (e.g. El Bchari and Souhel, 2008; Charrière and Haddoumi, 2016; El Ouali et al., 2021; Jaydawi et al., 2024).

The Cretaceous succession comprises several superposed formations. The first of these is the Nassissa Formation, which contains fluvial-deltaic sediments reflecting the interaction between continental and coastal environments interacted. After that comes the Chegag El Habib Formation, which is made up of marl and gypsum beds; this formation indicates that the sediments were deposited in a lagoon and/or evaporitic environment

under an arid climate. After the end of the Cenomanian-Turonian, marine carbonate sedimentation resumed. The Lower and Upper Tigri Senonian formations record continued sedimentation within the basin during the Late Cretaceous.

In terms of structure, the Hercynian tectonics created a significant amount of deformation in the existing Paleozoic strata through the process of folding and faulting. The folding and faulting occurred in two phases (Hoepffner, 1987; Houari and Hoepffner, 2003). The first deformation, or Eo-variscan phase, occurred in two episodes, D1 and D2. In the west part of Jbel Houanite, these episodes primarily affected the Aïn Lorak Formation. These deformation episodes occurred under tectono-metamorphic conditions that were less intense than those observed in the east (Hoepffner, 1987; Houari et al., 2000; Houari and Hoepffner, 2003). However, the structures associated with these episodes (P1 and P2 folds and S0-1 schistosity) were disrupted by the succession of Hercynian and Atlasian events. The post-Westphalian D3 deformation phase, which was responsible for detachment and thrusting, produced P3 folds and affected all Paleozoic strata and their structures (P1 and P2 folds and S0-1 planes). The P3 folds are relatively upright and gently inclined northward have large radii of curvature and are associated with weak schistosity. During the Alpine orogeny, the Jbel Houanite zone was affected by the poly-phase reactivation of the North Atlas fault system, which resulted in the thrusting of Paleozoic strata over the Mesozoic succession. The northward-dipping folds are interpreted to have developed in association with this E–W-trending fault zone.

MATERIALS AND METHODS

The comprehensive methodology used in this study includes fieldwork, petrographic and mineralogical examinations, and geochemical investigations backed by statistical analysis.

Fieldwork, sampling, and structural analysis

Geological series were identified during fieldwork, with an emphasis on the Paleozoic basement formations. Nodes of interest were units of mineralization. Detailed geological surveys and cross-sections were completed along profiles crossing the mineralized structures. All information was inputted to geographic information

systems (ArcGIS 10.8) So that the spatial distribution of the mineralization could be compared to the host structures. Tectonic structural data were also processed through WinTensor software (Delvaux and Sperner, 2003) to constrain the stress fields and understand the structural control on mineralization.

Petrographic and mineralogical analyses

Petrographic thin sections were made from representative samples from the study area, which were carried out at the Science and Engineering Research Laboratory of Sidi Mohamed Ben Abdellah University in Fez (Morocco). Mineral phases were identified based on their petrographic characteristics and SEM/EDX observations, considering their morphology, textural relationships, and elemental composition obtained from semi-quantitative EDX analyses. Particular attention was given to ore-related phases occurring within quartz-carbonate veins and altered zones. Mineral phases were identified primarily from their petrographic characteristics, including morphology, optical properties, textural relationships, and their association with the surrounding mineral assemblage. SEM/EDX observations were then used as complementary evidence based on the elemental composition of individual analyzed spots. The identification of Au-, Sb-, and As-bearing phases was therefore based on the combined interpretation of morphology, textural relationships, elemental peaks, and consistency with the whole-rock geochemical and petrographic data. Because the available EDX analyses were semi-quantitative and were not designed as a systematic quantitative mineral-chemical dataset, they were used to support phase identification rather than to establish precise mineral compositions or proportions. Consequently, the SEM/EDX observations are considered complementary evidence and are not used alone to establish the genetic interpretation of the mineralization.

Geochemical analyses and modeling

A total of 30 representative rock samples were systematically collected across the Jbel Houanite district (Supplementary Table 1). Major element sampling was conducted using a commercial X-ray fluorescence spectrometer (Axios) on fused glass beads. Trace element and precious metal analyses were conducted using inductively coupled plasma

mass spectrometry (ICP-MS) following a multi-acid digestion, as per NF EN ISO 11885.

To ensure data reliability and strictly comply with NI 43-101 quality control guidelines, the analytical sequences systematically included certified reference materials (CRMs), field duplicates, and analytical preparation blanks. Detailed analytical performance, including limits of detection (LOD) for each element, duplicate precision, and CRM recovery rates, are provided in Supplementary Table 2.

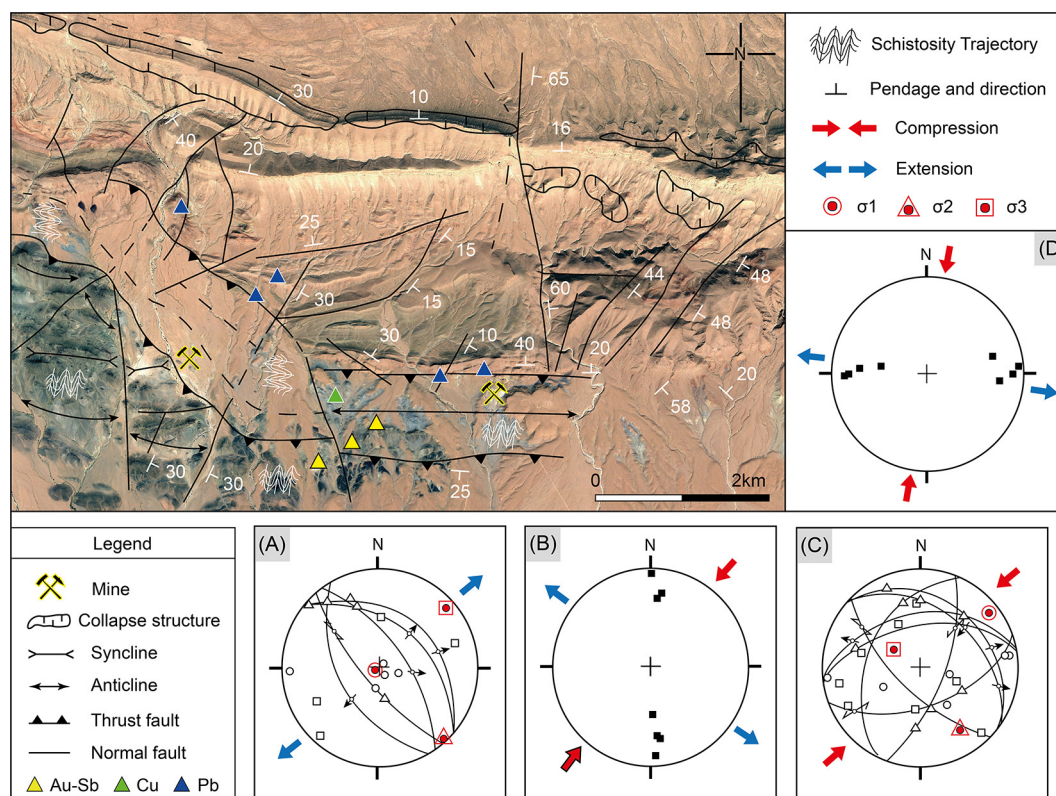
The complete dataset of 30 samples was used for statistical analysis focusing specifically on the Au-Sb system. Data preprocessing and multivariate analysis were conducted using Python (v3.10) with the Pandas and Scikit-learn (v1.2) libraries. To properly handle left-censored data, values strictly below the analytical LOD were substituted with half the detection limit (LOD/2). Given the compositional nature of geochemical data (constant sum constraint), a centered log-ratio (CLR) transformation was systematically applied prior to principal component analysis (PCA) to avoid spurious correlations (Aitchison geometry). PCA was then computed on the centered CLR-transformed data to extract the main

factors controlling the spatial distribution of the elements. No independent geochronological or isotopic analyses were performed in the present study. Consequently, the relative sequence of mineralizing events is interpreted from the combined structural, petrographic, mineralogical, and geochemical relationships observed in the studied samples and from comparison with the previously established geological framework of the Jbel Houanite district.

RESULTS AND DISCUSSION

Structural kinematics and petrographic study

Extensional and compressional tectonic regimes predominate in the complex structural setting of the Houanite District (Figure 3). These are primarily linked to the Hercynian orogeny and were partially reactivated during phases of Atlasian compression in the Cenozoic. This structural framework directly controls the formation of mineralization. Indeed, the preferential location



of the veins and the concentration of geochemical anomalies bear witness to this.

Field studies, combined with microtectonic measurements, have led us to identify four phases of brittle and ductile deformation (Figure 3). The first stage is N60 extension, giving rise to a set of normal faults trending N140 (Figure 3A). The second is marked by N100 ductile deformation with schistosity and folding trending from N40 to N60. This stage can be equated with phase D1 (Figure 3B). The third stage is represented by N40 compressional deformation characterized by N-S folds observable in many places and especially in

the southern units. This deformation stage is well known in the eastern Meseta as phase D2 (Figure 3C). Finally, the fourth deformation stage is characterized by submeridional shortening, which induces the large E-W folds (Figure 3D), the interfering folds in the quartzites, the dome of the central unit, and the eastern synform. This phase is also characterized by northward thrusts.

From a lithostructural perspective, the mineralization is primarily controlled by E-W and NE-SW trending fault structures (Figure 4A). These are associated with subvertical foliation (Figure 4B), which plays a fundamental role in

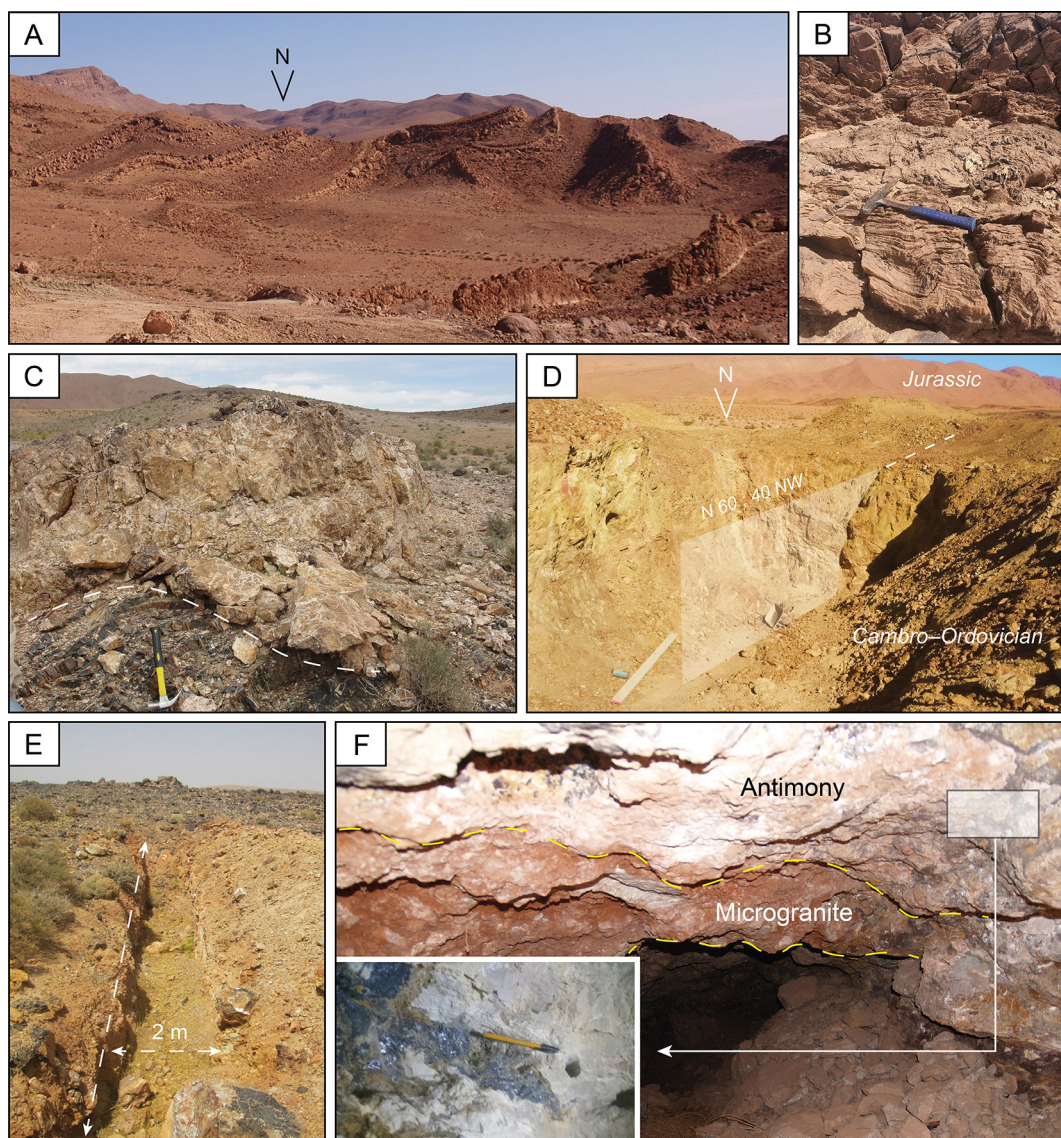


Figure 4. Field photos of Jbel Houanite. (A) Contact between the basement and the overlying strata, showing ductile deformations and brittle structures oriented E-W to NE-SW. (B) Subvertical foliation in the Cambrian-Ordovician Hamda Formation. (C) Stockworks in the Silurian cherts of the Aïn L'Orak Formation. (D)

Mineralized trench cut by an N60 fault at the Jbel Houanite mine. (E) Mineralized vein mined within a shear zone. (F) View from an underground tunnel showing the contact between the microgranite and the antimony-bearing mineralization

channeling hydrothermal fluids. The development of Sb-Au mineralization within stockwork quartz veins reflects an intense fracturing regime (Figure 4C). This now allows for high permeability, which is conducive to the prolonged circulation of mineralizing fluids. The orientation of the mineralized structures along ENE-WSW directions, in relation to Paleozoic shear zones, confirms structural control inherited from the Hercynian tectonics.

Mineralized structures exhibit an interaction of deformation with hydrothermal alteration, demonstrating that shear zones can be considered primary conduits for the migration of fluids. Therefore, both structural and geochemical elements contribute to the distribution of metal and the mineral association of the components of the gold system, indicating a dual control over the geochemistry of this gold system. The majority of the mineralisation in the area occurs in NE-SW aligned lenses with a

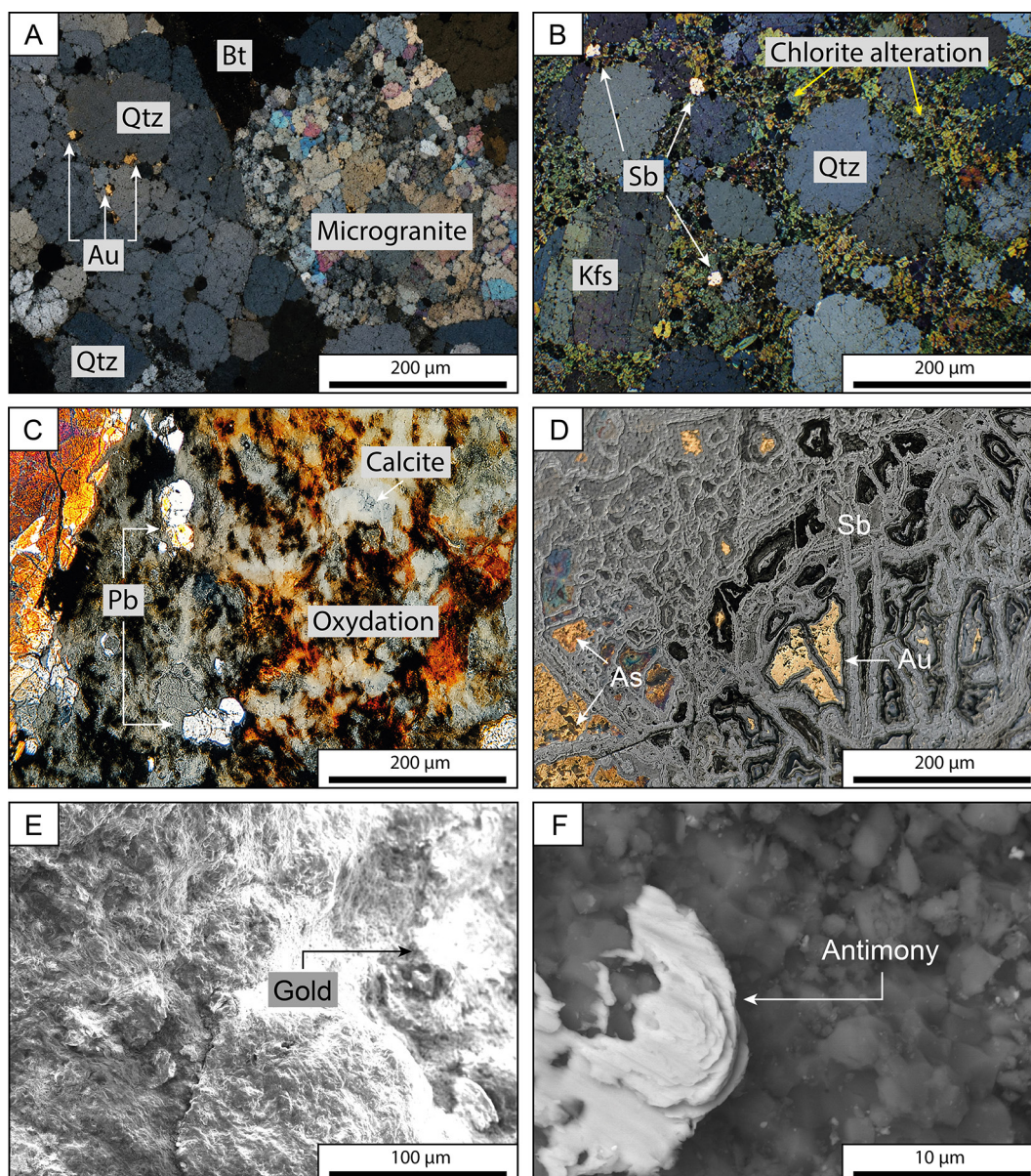


Figure 5. Photographs of thin sections and SEM images illustrating the mineral associations and mineralized textures at Jbel Houanite. (A) Flakes of native gold (Au) disseminated in quartz (Qtz) at the contact with a biotite (Bt) microgranite. (B) Stibnite (Sb) crystals associated with quartz (Qtz) and potassium feldspar (Kfs), accompanied by chlorite alteration. (C) Lead (Pb) mineralization associated with calcite formation and oxidation phenomena. (D) Polished rock showing native gold (Au) embedded in stibnite (Sb), with the presence of arsenic (As). (E) SEM image detailing a native gold particle disseminated in the host matrix. (F) SEM image showing an antimony phase associated with the mineralization

predominance of stibnite, arsenopyrite, and pyrrhotite in the overall mineral assemblages, while the gold occurs as both free gold and within the sulphide bodies through a combination of structural and chemical means of precipitation.

A mineral assemblage consisting of quartz, carbonate, sulfide minerals, and Au-bearing phases was identified from petrographic observations and SEM/EDX analyses (Figure 5A–F). Stibnite and As-bearing sulfide phases were observed within the quartz-rich gangue and altered domains, while fine-grained Au-bearing phases were detected in association with sulfide-bearing areas. The SEM/EDX results provide complementary evidence for the occurrence of Au-, Sb-, and As-bearing mineral phases within the mineralized zones. However, the available SEM/EDX dataset is semi-quantitative and was not designed to provide a systematic census of mineral grains or statistically representative quantitative mineral compositions. In particular, the available observations do not allow the relative abundance of individual phases or their complete compositional variability to be quantified. Therefore, the mineralogical observations are used here primarily to document the mineral assemblage and its textural relationships, while the genetic interpretation is based on the integration of mineralogical, structural, petrographic, and whole-rock geochemical evidence. It appears that this paragenetic assemblage of Au-Sb-Pb-Fe may represent a tectonically driven hydrothermal system. In addition, the secondary elements (Mg, Al, Si, Fe, Cr, Ti) are representative of silicate gangue mineral and accessory phase mineral formation as a result of alteration processes on mafic minerals and suggest that both chromite and ilmenite may be present.

Multivariate geochemical analysis

The geochemical data (Supplementary Table 1) indicate there is a strong relationship connecting deformation to the distribution of metallic elements; but precious metals show spatially variable concentrations and can be systematically enriched in shear zones; therefore, it appears that the effective structural trapping occurring in zones of high permeability is related to the dramatic concentration of precious metals.

The multivariate geochemical analysis performed on the CLR-transformed data (Supplementary Table 3) (Figure 6) shows an isolated gold-bearing event, with the correlation matrix

(Figure 6A) showing a very strong statistical cluster between gold and both antimony and arsenic (gold-antimony, correlation coefficient of 0.60). On the correlation circle plot (Figure 6B), the principal component (PC1) accounts for 53.2% of the variance and is predominantly defined by this pair ($Sb = 0.987$; $Au = 0.753$; Supplementary Table 4-a); in contrast, gold is negatively correlated to both tungsten (Tung) (-0.754) and molybdenum (Mo) (-0.683). Furthermore, base metals (Cu, Pb, Zn) are visually separated from gold, indicating a geochemical antagonism among these elements. The Individual Plot (Figure 6C) also illustrates the alignment of all samples along this principal component 1 (PC1) vector. The richest samples (S29, S28, and S25) fall at the positive end of the PC1 axis, which strongly suggests there is a close association between gold and the antimony-arsenic fluid.

PCA 2 (Supplementary Table 4-b) identifies the ion substitution process associated with hydrothermal fluid circulation (Figure 7). The alteration heatmap (Figure 7A) shows an extremely strong positive correlation among mobile lithophile elements, particularly between potassium and rubidium ($r_{Rb-K} = 0.91$). The correlation circle (Figure 7B) illustrates dramatic substitution dynamics along the principal component PC1 (51.6% of variance); a direct opposition is observed between the mobile elements of weathering (K: 0.985; Rb: 1.003; Cs: 0.949) and the primary constituents of the calcic host rock (Ca: -0.555 ; Mg: -0.124). On the individual sample plot (Figure 7C), the alignment of the samples along the PC1 axis serves as a reliable statistical proxy for the intensity of phyllic alteration undergone by the rock in contact with shear zones.

The analytical combination of the 21 geochemical characterizations into the complete principal component analysis (PCA) of Jbel Houanite (Figure 8A and Supplementary Table 4-c) strongly supports the genetic model for Jbel Houanite from a statistical viewpoint. Principal component 1 (PC1), being responsible for 42.1% of the variance, provides a robust statistical representation of the most significant hydrothermal process associated with the shear zones. The relation circle (Figure 8B) illustrates the high degree of collinearity between the gold mineralization vector (Au, Sb) and the potassium-rich phyllic alteration vector (K, Rb, Cs).

The elements Sb (atomic number = 51), K (19), Rb (37), Cs (55), and Au (79) have very high and

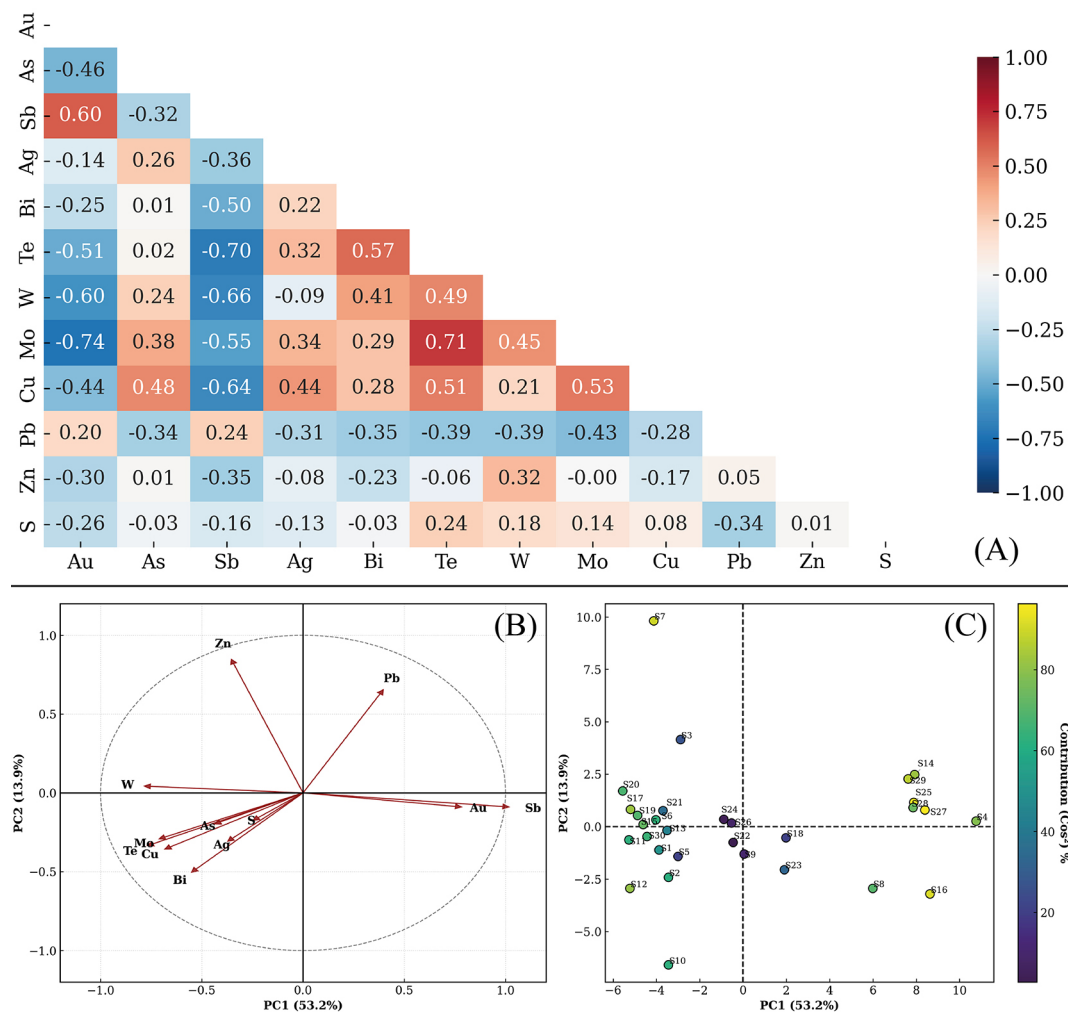


Figure 6. Principal Component Analysis (PCA1) applied to the metallogenic cluster of the Jbel Houanite hydrothermal system. (A) Pearson correlation matrix (heatmap) highlighting the Au-Sb-As cluster. (B) Correlation plot of variables in the PC1-PC2 space illustrating the dominance of the orogenic fluid and its independence from base metals. (C) Projection of samples colored according to their contribution to the overall variability in the PC1-PC2 space; the graph highlights the alignment of highly mineralized samples along the orogenic deposit vector

positive loadings on the PC1 axis of this study, and Sb and Au are tightly correlated. Arsenic is also present in the system but shows a more dispersed distribution throughout the samples. This analysis demonstrates the prominent role of the Au-Sb pair. At the opposite end of the Au-Sb loading, which represents a powerful hydrothermal plume, we find the host rock elements (Ca = -0.527; Mg = -0.622) have strong negative correlations with the PC1 axis. Additionally, Cu (-0.294) and Zn (-0.145) base metals are not correlated with PC1, indicating that these metals are probably not genetically linked to the main orogenic (or “nerdy”) gold-bearing phase. The Au-Sb pole and K-Rb-Cs pole on the PC1 axis are strongly tied together mathematically and suggest a very tight relationship between tectonic and

hydrothermal processes during mineralization (e.g., the metasomatic crystallization of sericite [trapping K, Rb, Cs] and the coprecipitation of stibnite and gold). This statistical association is consistent with a model where the same shear fluid responsible for the intense leaching of ferromagnesian minerals and host rock carbonates is responsible for the metasomatic crystallization of sericite and the coprecipitation of stibnite and gold.

The spatial arrangement of each sample (Figure 8C) is highly consistent with the structural model, as the most highly mineralized samples (as indicated by very high yellow Cos^2 values) occur along the alteration gradient with the direction of travel away from sterile carbonates. This supports the hypothesis that the amount of

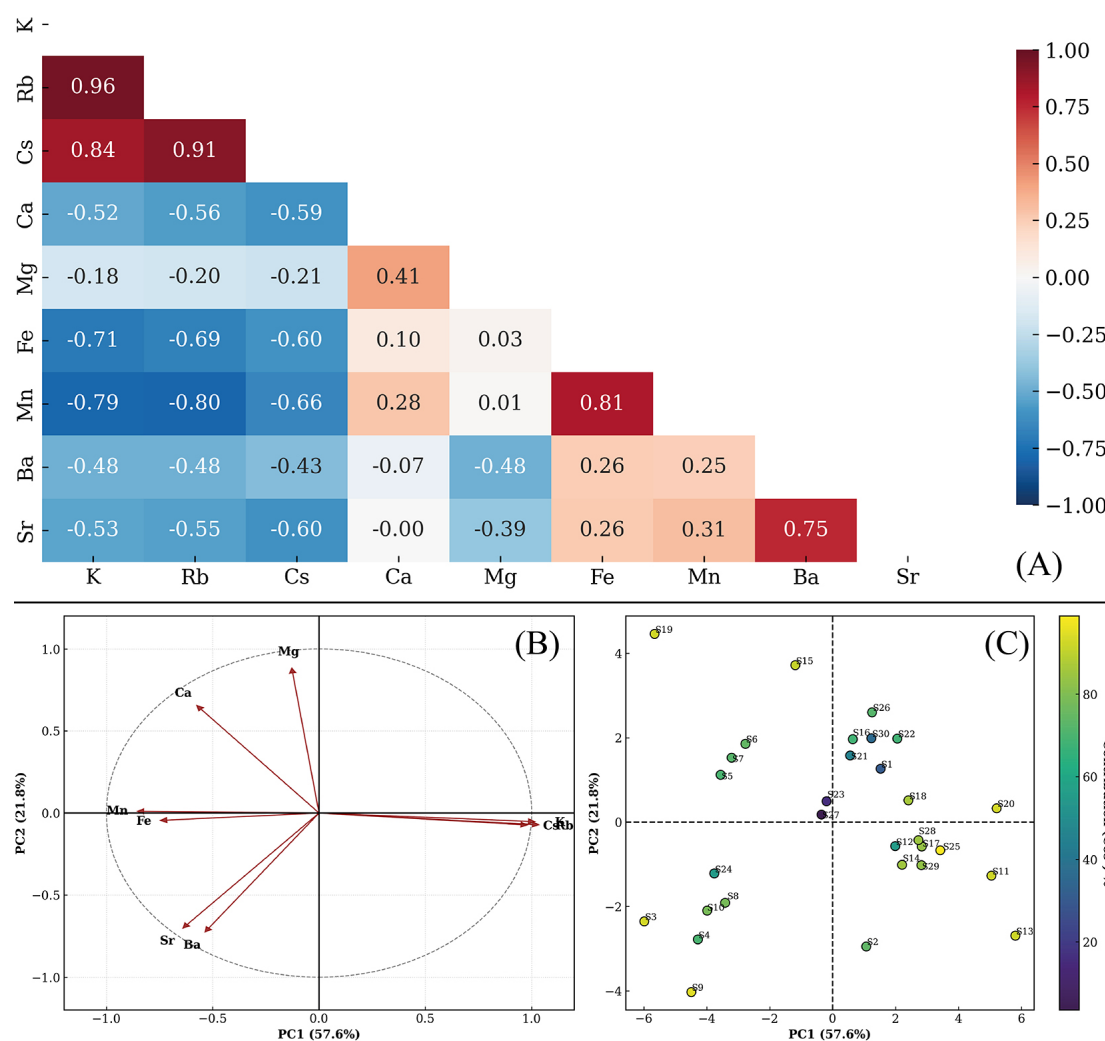


Figure 7. Principal Component Analysis (PCA2) applied to the metasomatism zone and hydrothermal alteration halos. (A) Pearson correlation matrix (heatmap) showing the extreme co-mobility of alkaline lithophile elements (K, Rb, Cs) during fluid circulation. (B) Correlation plot (PC1-PC2) illustrating potassium metasomatism as a strict opposition to host rock elements (Ca, Mg). (C) Spatial distribution of data points in the PC1-PC2 space tracing the gradient of phyllic alteration intensity

shear deformation and the corresponding metasomatism both directly control the distribution and concentration of precious metals in the study area, and therefore affect precious metal grades.

Ore-forming processes and mineral system modeling

Mineralization has a close association with lithological contact zones and faults, as illustrated by geochemical and geological data. The contact zones of these lithologies are pervious areas where hydrothermal fluids may circulate. The precipitation of metals, especially gold, arsenic, and antimony (Au, Sb, As), appears to be directly related to favorable structural environments.

Additionally, the strong correlation of Au, Sb, and As suggests that they were deposited from a metallogenic source, and supports the hypothesis that gold may have been co-precipitated with sulfide minerals such as stibnite and arsenopyrite. This also implies that the movement of gold is closely associated with the chemical evolution of sulfide fluids. The concentrations of Fe and S suggest that sulfides (pyrite and pyrrhotite) are the dominant hosts of mineralization, particularly in the form of disseminated submicroscopic gold. The petrographic and SEM/EDX observations are consistent with the occurrence of Au-bearing phases and Sb- and As-bearing sulfide minerals and provide complementary support for the proposed hydrothermal interpretation. Elemental

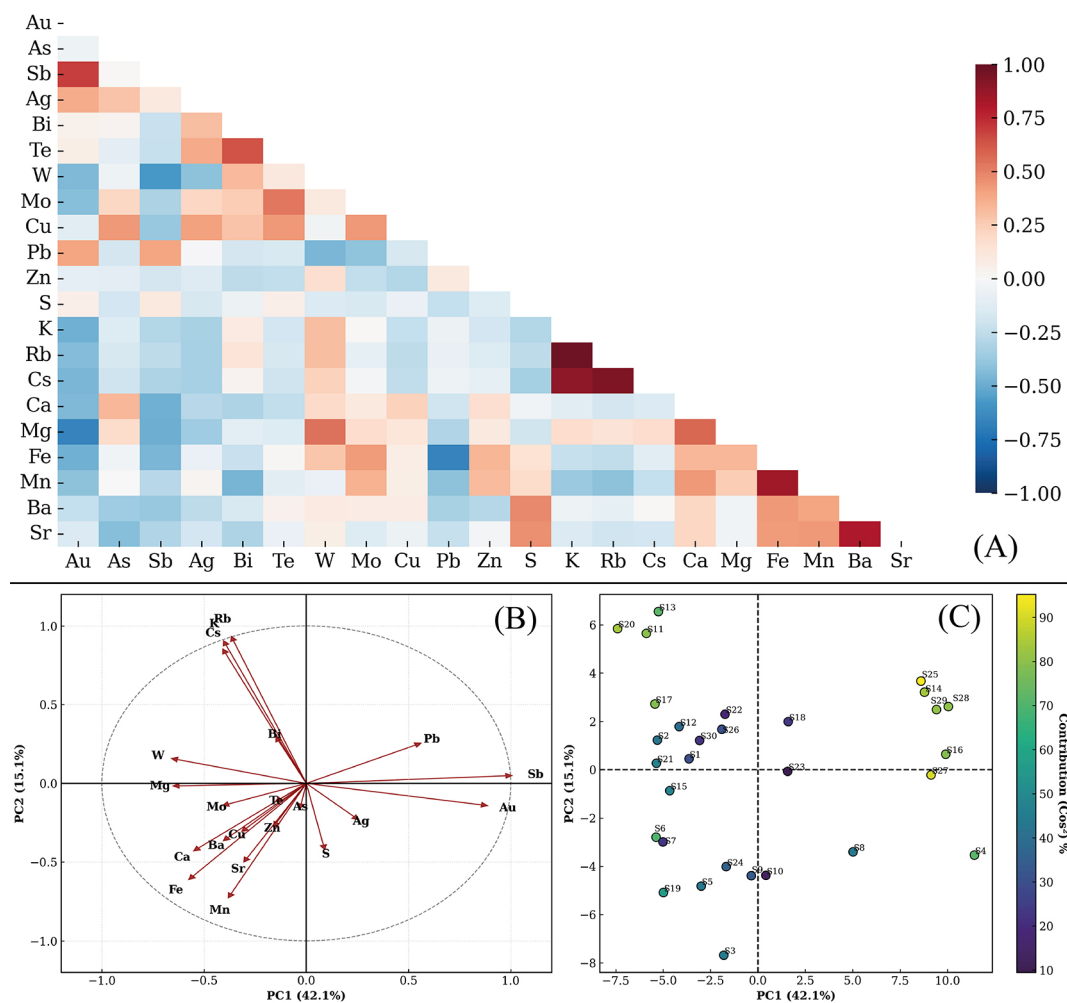


Figure 8. Global PCA-based tectono-hydrothermal synthesis demonstrating the synchrony of the deposit's genetic processes. (A) Global correlation matrix (heatmap) of the system validating the interdependence of metallic and lithological tracers. (B) Correlation plot (PC1-PC2) geometrically demonstrating the synchrony between the metal deposit (Au-Sb) and potassic alteration (K-Rb). (C) Scatter plot validating the proportional relationship between mineralization and shear

mapping further illustrates the localized distribution of Au-, Sb-, and As-associated signals within the analyzed mineralized domains (Figure 9). However, because the available SEM/EDX data are semi-quantitative and do not include systematic grain counts, representative quantitative mineral compositions, or a complete set of phase-specific spectra and elemental maps, these observations alone are insufficient to establish a specific ore-forming mechanism. The genetic interpretation is therefore based on the integration of mineralogical observations with structural relationships, petrographic textures, alteration patterns, and whole-rock geochemical data. The lower concentrations of Pb and Ag suggest either multiple hydrothermal pulses or a slow evolution of the fluid-rock system over time. This geochemical evolution documents an evolving hydrothermal

system consisting of several episodes of fracturing, circulation, and the precipitation of metals.

Ag/Au ratio distribution shows a geochemical signature primarily dominated by mid-range ratios (between 1:1 and 10:1; Figure 10). Poulsen et al. (2000) say this trend is indicative of a significant hydrothermal contribution to the geochemical signature associated with mesothermal-type orogenic systems. Given that the sample locations are very close to the boundary between the mesothermal and epithermal domains, it suggests that the system is heterogeneous. In contrast, the variation seen in the samples indicates a gradual change in the physicochemical conditions, or that several successive hydrothermal events have overlapped one another. The variability seen in the samples is also likely the result of very complex tectono-hydrothermal

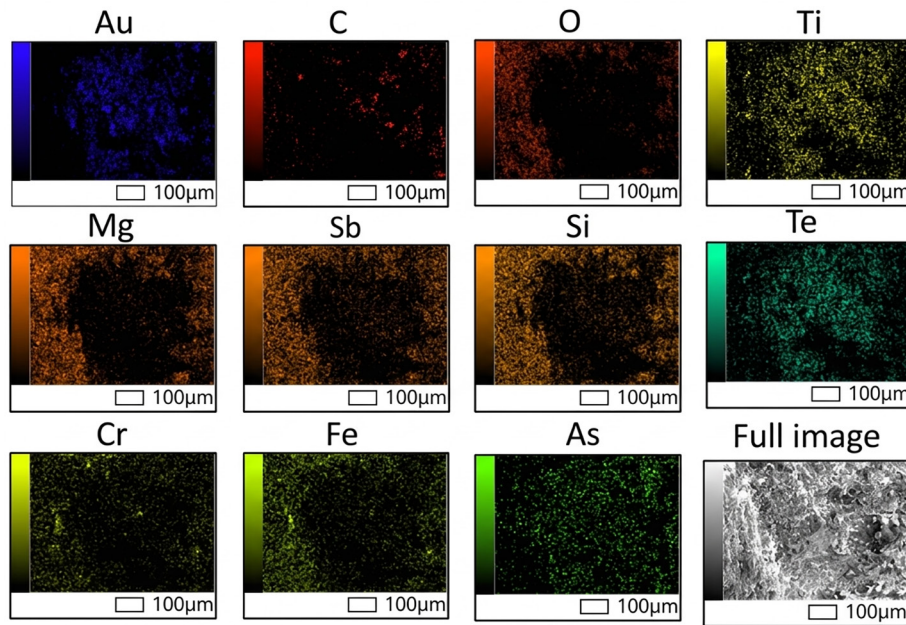


Figure 9. Mineralogical observations derived from elemental mapping, highlighting localized concentrations and their spatial distribution

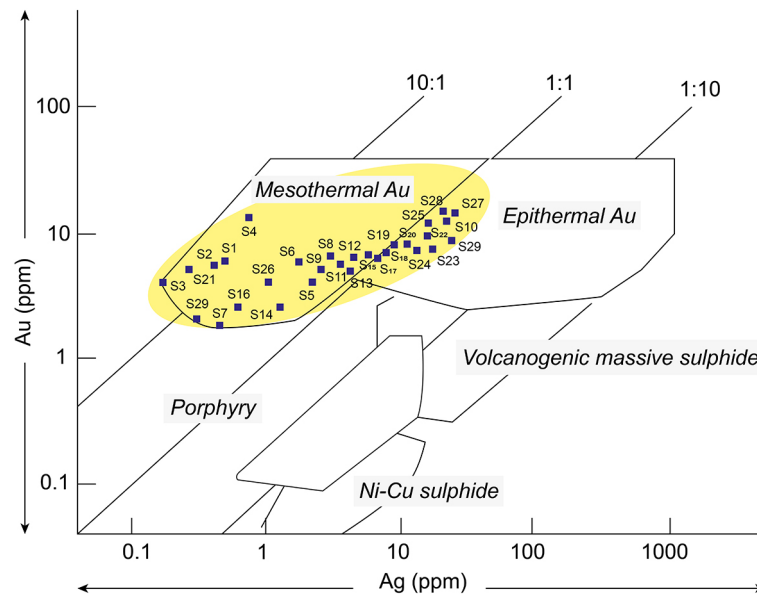


Figure 10. Location of gold (Au) and silver (Ag) samples from the Jbel Houanite deposit in the diagram by Poulsen et al. (2000)

dynamics in which there have been multiple re-activation events of the structures.

Mineral systems do not exhibit the usual signs (signatures) seen in porphyry-type systems, VMS and Ni-Cu mineral systems, which also suggests that these systems are neither directly formed by magmatic volcanic eruptions nor from explosive underwater volcanism. The combination of low abundance of metallic elements in addition to the absence of the typical porphyry / VMS / Ni-Cu

type signature strongly suggests that the development of these systems is controlled by tectonic processes, where the play of regional tectonic structures has had a major influence on the location of fluids. Thus, there is very strong evidence to suggest that these systems have characteristics of a mesothermal hydrothermal (metamorphic) system dominated by gold. Specifically, silver is a secondary metal that has the same occurrence in these systems as gold, and both are associated but not

dominantly associated (typically found together in orogenic mineral systems) with other elements (gold) that are common to these types of systems (Arsenic, Iron, Antimony) as a result of their association with sulfide minerals (specifically, arsenopyrite and stibnite), which have played an essential role in the retention of gold. The observed correlation between these elements confirms that mineralization occurred in a reduced, sulfur-rich hydrothermal environment where physicochemical conditions were favorable for metal precipitation.

Taken together, these results support a working genetic model in which mineralization is closely linked to the inherited Paleozoic structural framework and its subsequent reactivation. The inherited structures provided pathways for hydrothermal fluid circulation and influenced the distribution of mineralized zones. Subsequent tectonic reactivation is interpreted to have promoted fluid focusing, metal redistribution, and reconcentration within shear zones. However, the relative timing of these processes is inferred from structural and mineralogical relationships and is not independently constrained by geochronological or isotopic data in the present study.

At the regional level, the Houanite district is part of a setting comparable to that of the western and central Hoggar in Algeria (Ferkous and Leblanc, 1995; Saad, et al., 2018), the Reguibat Shield in Mauritania (Key et al., 2008; Heron et al., 2016) and the Eastern Egyptian Desert (Zohair and Akawy, 2010; Groves et al., 2021). This analogy combines ancient basement that has experienced significant deformation, complex transgressive structural features, as well as multiple phases of hydrothermal activity.

The evidence indicates a polyphase polymetallic mineralization system. The observed structural, petrographic, mineralogical, and geochemical relationships are consistent with an earlier Fe–Zn sulfide assemblage followed by a later Au–Sb–Ag–Pb hydrothermal stage associated with tectonic reactivation and metal redistribution. However, this relative sequence is inferred from cross-cutting relationships, mineral associations, alteration patterns, and geochemical signatures rather than from independent geochronological or isotopic constraints. Therefore, the proposed temporal sequence should be regarded as a working genetic interpretation that requires future confirmation through appropriate geochronological and isotopic investigations. This evolution reflects a dynamic system in which tectonic

processes played a decisive role in the genesis and redistribution of the mineralization.

Resource and environmental implications

The results obtained from the Jbel Houanite district provide important insights into its mineral potential and the direction of future exploration activities. The integration of geological and geochemical data allows the mineralized occurrences to be considered not as isolated showings, but as expressions of a coherent hydrothermal system. This integrated approach provides a useful basis for prioritizing areas with greater exploration potential and for optimizing future exploration programs. Areas characterized by a favorable combination of geological features, hydrothermal alteration, and geochemical anomalies could therefore be prioritized for detailed geological mapping, systematic sampling, trenching, and, at a later stage, drilling. Although the available data do not allow a quantitative mineral resource estimate to be established, they provide a relevant exploration-level framework for further evaluating the mineral potential of the district.

From a resource assessment perspective, future investigations should focus particularly on determining the continuity of the mineralized structures, their thickness, and the spatial distribution of metal grades. More closely spaced sampling, combined with detailed structural mapping, would help better constrain the extent of the mineralized zones and distinguish higher-grade domains from more diffuse mineralization. Such information will be essential for improving the understanding of the spatial variability of the Au–Sb mineralization and, ultimately, for developing a robust resource model. In this regard, the results presented in this study should be considered as an initial framework for assessing the mineral potential of the district rather than as a formal mineral resource estimate.

The mineralogical and geochemical characteristics of the mineralization also highlight environmental aspects that should be considered during future investigations. The occurrence of arsenic and antimony, together with sulfide minerals such as arsenopyrite and stibnite, identifies elements and mineral phases that may warrant particular attention in the environmental characterization of the district. However, the present study does not include specific environmental investigations of soils, surface waters, groundwater, stream

sediments, element mobility, or baseline geochemistry. Consequently, no direct assessment of element migration, dispersion, or environmental impact can be made from the current dataset. The environmental implications discussed here should therefore be considered preliminary and conceptual, based on the mineralogical and geochemical characteristics of the mineralized rocks rather than on direct environmental measurements.

Future environmental studies should establish a site-specific geochemical baseline through systematic sampling of soils, stream sediments, surface waters, and, where appropriate, groundwater. Such investigations should determine the concentrations and spatial distribution of potentially sensitive elements, particularly As and Sb, and evaluate their relationship with the mineralized zones and weathering processes. Additional studies of element mobility and natural geochemical dispersion would also be required to assess whether these elements are being released or transported from the mineralized areas. Establishing such a baseline would provide a reference framework for distinguishing natural geochemical variability from any changes that could potentially result from future exploration or mining activities. Thus, the present geological and geochemical characterization provides a preliminary basis for identifying environmental priorities associated with the mineralized system, while dedicated environmental baseline studies will be necessary to evaluate element mobility, natural dispersion, and potential environmental impacts.

CONCLUSIONS

The integrated study of the litho-structural framework, mineralogy, and geochemistry of the Jbel Houanite mining district led to the following conclusions:

Mineralization within the Jbel Houanite district is predominantly controlled by inherited structural features, notably E–W to NE–SW-trending faults, subvertical foliations, and reactivated Hercynian shear zones. These structures provided favorable pathways for hydrothermal fluid circulation and played a key role in the localization of ore mineralization.

The development of stockwork quartz veins and pervasive fracturing reflects prolonged hydrothermal activity within highly permeable structural corridors. Such conditions facilitated efficient fluid flow and promoted the transport,

remobilization, and subsequent concentration of metals during multiple hydrothermal episodes.

Geochemical evidence supports a polyphase metallogenic history comprising an early Fe–Zn sulfide stage and a subsequent Au–Sb–Ag–Pb hydrothermal event related to tectonic reactivation. This evolution emphasizes the key role of metal remobilization and reconcentration processes in the development of the gold mineralization.

Hydrothermal alteration is predominantly characterized by intense sericitization, accompanied by K–Rb–Cs enrichment and Ca depletion. This alteration signature indicates prolonged hydrothermal fluid circulation and sustained fluid–rock interaction along major deformation corridors.

Mineralogical and geochemical data show a strong association between Au, As, Fe, and Sb, indicating that arsenopyrite and stibnite were the main mineral phases controlling gold precipitation. Antimony is identified as a key pathfinder element, and Ag/Au ratios suggest mesothermal to epithermal depositional conditions.

The absence of diagnostic signatures of porphyry, VMS, and Ni–Cu systems, together with the integrated structural, mineralogical, and geochemical evidence, supports a tectonically controlled orogenic-style model involving hydrothermal remobilization and concentration of metals along inherited and reactivated crustal structures. The present results complement the geodynamic and paragenetic framework previously established for the Jbel Houanite mineralization by providing additional constraints on the spatial and geochemical organization of the Au–Sb system. Nevertheless, the temporal relationships among the identified mineralizing stages remain to be independently constrained by future geochronological and isotopic investigations.

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