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Geodynamic, metallographic and geochemical characteristics of the Jbel Klakh copper deposit, Eastern High Atlas, Morocco

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Abstract

Purpose. This paper aims to make a metallographic and geochemical geological study of the Jbel Klakh copper deposit located in the northern part of the Eastern High Atlas of Morocco, and make a detailed inventory of the mining indices of this area and emphasizing their modes of formation, linking them to the different geological phenomena and specifying the kinematics of their placement.

Methods. To achieve our objectives, we have conducted a series of geological reconnaissance surveys in the Jbel Klakh area, and we have identified the former mining areas with strong copper mineralization. We have carried out a geological mapping of the main structures hosting the mineralization, with a detailed representation of the mineralization families. We carried out structural measurements and surveys to determine the tectonic regimes that led to the formation and development of the mineralization, to identify the relationship between fracturing and mineralization, and collected several samples that were subject of geochemical studies by ICP-MS, petrographic analyses, scanning electron microscopy (SEM).

Findings. The research proposes a new approach to mineral exploration based on fieldwork and laboratory work that aims to study the formation of copper mineralization in the Meso-Cenozoic cover, and to show the role of the geological texture and structural control in the migration and formation of this mineralization, and finally to give a new idea for the discovery of new deposits of supergene copper that can highlight the economic importance of this type of deposits.

Originality. The most economically exploitable copper deposits in Morocco are of the Basement porphyry type, there is no economically exploitable Jbel Klakh type deposit, recognized in Morocco, our paper therefore aims to highlight the deposits of the supergene sedimentary type, by giving a geological, structural, geochemical and geodynamic explanation of their occurrence.

Practical implications. This research therefore highlights the copper deposits of the supergene type and explains the link between the mineralization and the different geological, structural and geodynamic phenomena that contribute to the formation of this mineralization, and through this work opens the door for a future discovery of a large copper deposit of the same type around the world.

Keywords: *Jbel Klakh, copper mineralization, supergene copper, geochemical analysis, scanning electron microscopy*

1. Introduction

Research on the genetic models of mineralization systems has gradually evolved over time; these models that visualize the processes of mineralization formation mode in a hierarchical manner by taking into consideration the tectono-structural and mineralogical geodynamic framework. Mineral systems and their models require a fertile source of ore components in appropriate geodynamics with a lithological framework and crustal framework favorable for the migration of mineralizing fluid to a trap target, with appropriate syn and post-mineralizing tectonic processes to ensure the preservation of mineralization. This system is the multiplier effect of collecting the essential components of a mineral to determine whether an ore body has formed taking into account its size and economic value.

Morocco is located in the northern part of the African continent and is characterized by the diversity of its geological structures, as well as its mineral resource potential, which has led to the discovery of several mining deposits. It also occupies a prominent place at the global level for a number of mineral substances such as silver, gold, copper, lead, zinc, iron, manganese and barite, which has attracted the attention of geologists and prospectors and has placed great geological and economic value on Morocco's geological resources.

At the present time it is well known in the mining world that copper is a very important mineral and that the world demand for copper ore is increasing day after day. In Morocco, the most famous copper deposits are hydrothermal deposits of the basement type (Tizert, Tidili, Ighrem, Oumjrane Tiouyine and Ain chair...) [1]-[3]. This fact has oriented the

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strategy of copper research and mining exploration in the areas of the Proterozoic basement and Paleozoic areas of the Anti-Atlas and Middle Atlas, as well as distancing all mining activities from the High Atlas area (the subject of our paper).

The Eastern High Atlas of Morocco corresponds to the extension of the High Atlas chain, characterized by its geomorphology in a strongly eroded plain, revealing formations of the Neoproterozoic-Paleozoic basement in inlier sediments, very rich in copper (Ain Chair, Jbel Bousellam, Menhouhou, El Hamda, etc.). They are limited to the north by two major accidents that deform the Mezo-Cenozoic and Quaternary formations [2], [4]-[7].

The Jbel Klakh copper deposit is therefore located in the eastern High Atlas chain of Morocco on the North High Atlas accident formed by a set of thrusts, which reactivated in the Mezo-Cenozoic allowing the formation of strong copper mineralization. The amount of underground mining at Jbel Klakh is very large, more than 12 km of gallery and 600 m of shafts.

In this paper, we aim to highlight the relationship between basement and cover mineralization, allowing to define the heritable models of mineralization patterns in their geological contexts in order to highlight supergene-type copper deposits.

The objectives of this paper is to characterize the different copper occurrences as deposits and show the role of structural control and tectonic heritage in the formation of copper mineralization from basement to cover, and to establish the relationships and spatial evolution in the chronological order of events in order to develop deposits of this type to encourage investors and prospectors to give more importance to this type of mineralization.

To perform this work, we have conducted a systematic study based on field and laboratory work, which includes:

– field prospecting focused mainly on the monitoring of all mining occurrences and deposits that are in operation, in the process of prospecting or abandoned. It is an important source of information in the field, since the outcrops are exposed and allow work to be done on fresh rock, waste heaps and waste rocks. It is also an important source of information since prospectors search the entire study area which sometimes holds good clues, and also through the digging of trenches which opens the field to the possibility of studying new structures and their mapping, as well as taking structural measurements and sampling;

– surveying and detailed mapping for mineralized structures. During this phase, sampling is more targeted;

– sampling for petrographic analysis and ore characterization at the thin section and polished surface scale;

– ICP geochemical analyses and surface scanning electron microscopy for the measurement of major, trace and ultra-trace elements to quantify and identify chemical elements to fully understand the affinity of the elements analyzed and their geological contexts;

– structural analyses and tectonic measurements for brittle and vein structures, including the identification of rosettes and stereograms to determine stresses and their ages.

2. Geological setting

The Jbel Klakh copper deposit is located near the North Atlas Accident in the Highlands area. The North Atlas Accident is a multiple accident that extends over more than 500 km in an E-W direction; it bends to the NE at Bouarfa and continues into Algeria in a SW-NE direction (Fig. 1a). It is formed by a set of thrusts materializing the passage of the northern fault of the High Atlas, which underwent a reactivation in the Cenozoic.

The various Cu mineralization occurrences are hosted in the Dogger dolomites and the Infra-Cenomanian sandstones and conglomerates, which follow the North High Atlas Fault (Fig. 1b). The mineralization is deposited laterally in the dolomitic layers and is depleted at depth [2], [7]-[9].

It should be noted that the Jbel Klakh deposit does not only include the mineralized zone. There are several deposits with occurrences of hosted mineralization in the dogger formations, and there is not only one form of mineralization (Cu), but also Pb and Zn mineralization. From a geological point of view, the area corresponds to a large carbonate platform that extends from the Lower Lias to the Quaternary.

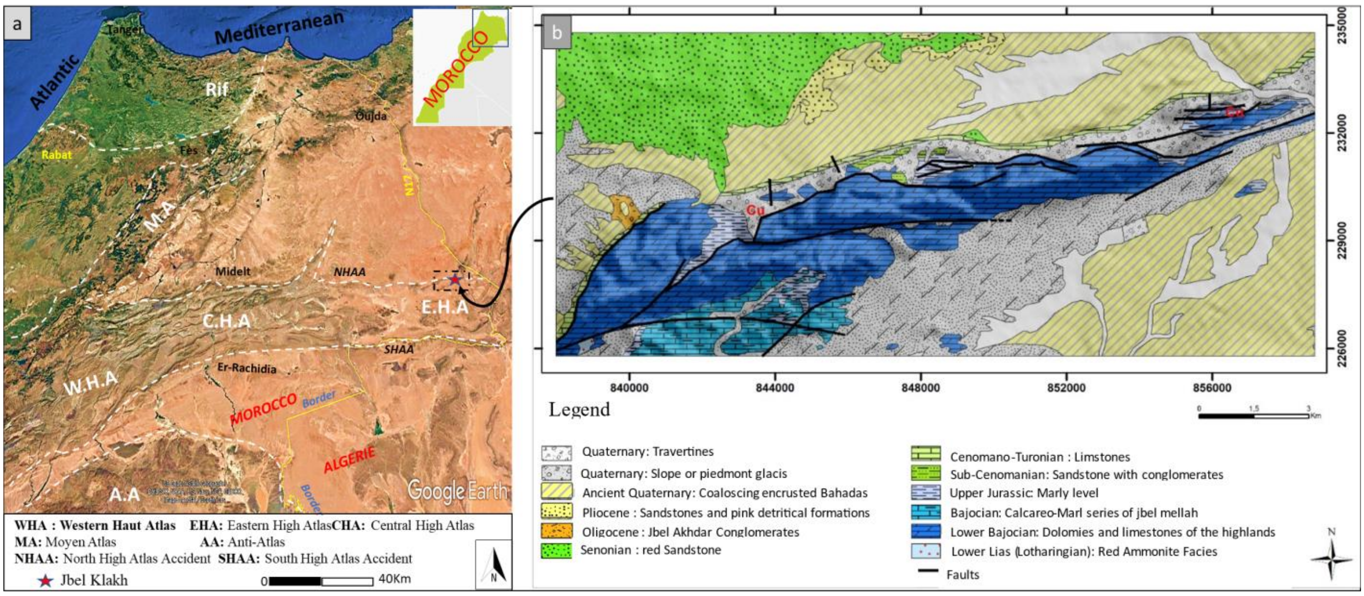


Figure 1. View of study area: (a) geographical location of Jbel Klakh in the Eastern High Atlas on the North High Atlas accident; (b) geological map of the Jbel Klakh region with representation of the main faults and mining occurrences

The base of the lower lias formed by two facies, one massive and the other bedded, the transition zone is marked by flinty layers and brachiopods with a change in sedimentation. The middle lias is represented by an alternation of limestone and marl banks, but this sedimentation passes to the upper lias and continues during the dogger [10]-[13].

The formation of the Jbel Klakh zone is predominantly carbonated and includes the series:

– the Lower Lias series is in direct contact with the red clays of the Trais, underlined by a brechification 10 m thick, resulting from the erosion of the underlying Triassic series and other polygenic elements of a carbonate nature. It has joints and calcite slits [9], [14], [15]. It is a syn-sedimentary breccia, reflecting the sliding of sediments consolidated under the action of tectonic movement. On this breach are massive dolomitic limestone deposits that form the high cliffs visible in the eastern high atlas, their thickness can reach 400 m. Finally, there are bedded limestones formed by black limestone in small banks with fine marl intercalations of light red color, ammonites are abundant, but difficult to detach from the rock;

– the series of the middle lias is concordant on the lower lias, which can reach up to 250 m thick. It is formed by light limestone in metric beds intercalated with pink marls, which also manifests itself in filling along the fracturing [2], [11], [13], [16], [17]. As you move up the series, the geological structure changes color and becomes more and more grayish, and the silica structures disappear;

– as for the formations of the lias, the lias-dogger boundary remains imprecise because the dogger retains marly facies with identical intercalated limestone banks of the upper lias. The only possible distinctions are of a paleontological nature, for which we have deliberately grouped both series under the same figure;

– the Cretaceous corresponds to a carbonate series with intercalation of sandstone and limestone, with conglomerates at the base;

– the Quaternary formations (Fig. 1b) are the most developed and clearly visible in the whole area. It is essentially composed of recent sedimentation in the dejection corners, as well as scree which is very abundant around the cliffs of the lias formed by accumulations of angular blocks of very variable size. Travertines are also present, consisting of vacuolar limestone tuff with vegetation stems.

3. Structural framework

Jbel Klakh is located in a tectonic node zone where several faults intersect. It is characterized by two major faults (Fig. 1a and 2a), the South Fault and the North Fault with a north dip of 60° and a rejection that increases to the east. In general, the faults are oriented ENE-WSW to E-W, parallel to the great North High Atlas fault, and following the trend of the Jbel Klakh North and South faults. The directional rosaces of these faults allowed us to characterize two families of faults, the first major is oriented E-W and the second minority – oriented NE-SW (Fig. 2b, d).

Jbel klakh is a set of overlaps materializing the passage of the northern High fault. In the study area, the dolomite is in the form of a stratoid lens, consisting of a tectonic breccia with polygenic elements with discontinuous and irregularly shaped high-grade ore bodies, cemented by large dolomite crystals. From the heart of the lens to its edge, the proportion of cement decreases.

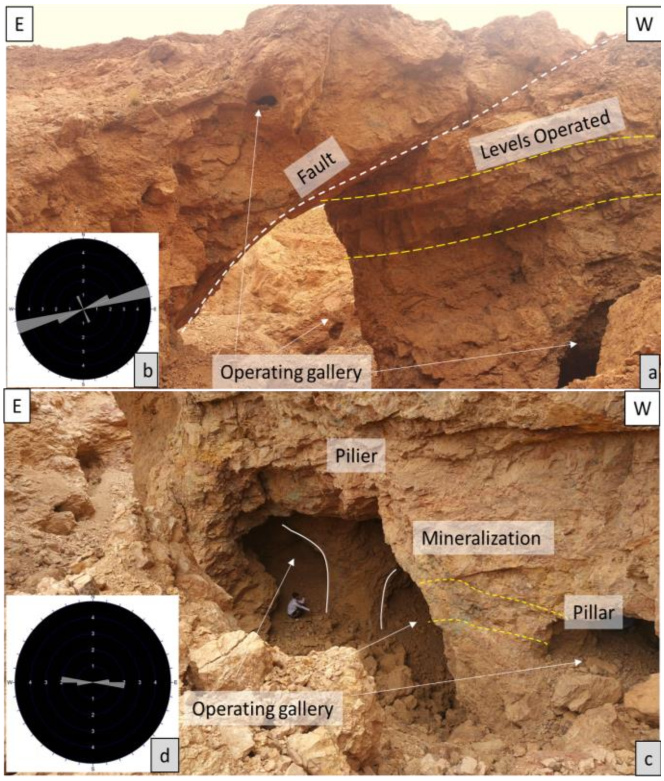


***Figure 2.** Area of former underground mining by gallery: (a) former mining zone in the passage of the fault; (b) directional rosace of the fault families affecting the zone; (c) zone of mineralization and Levels 2 of operating; (d) directional fracture rosace of the second exploitation level*

The micro-tectonic measurements, fault mirrors and striations observed in the Jurassic Jbel Klakh series, the treatment of these faults gives a paleo-field of extensive stresses originated NE-SE to NNW-SSE on normal faults N40, N80 and N120, and which becomes compressive NE-SW and NW-SE, reactivating the old fault (Fig. 3), but the reverse fault does not catch up with the first normal set.

These normal faults that intersect the Jurassico-Cretaceous series [2], [4], [5], [13], [18]-[21] testify to an extensive NW-SE to NNW-SSE regime giving rise to three fault families: a first NE-SW, a second NW-SE and a third E-W (Fig. 3), in which we identified the Jbel Klakh copper mineralization.

It is therefore a normal fault zone that activated and reactivated during the different phases and episodes of the Atlas orogeny, allowing the circulation of any mineral material from the depth (basement) to the surface, giving a favorable environment for the formation of mineralization.

Only one NNW-SSE compressive tectonic phase has been identified in the area that corresponds to the last reverse fault, in which the reverse fault did not catch up with the normal fault, so we are in a period of uprising in the High Atlas.

4. Mineralization

It is mineralization in fractured and crushed dolomites of the order of 5 to 10 cm in length; small stringers appear and occupy the joints between the fragments of dolomite whose filling consists of chalcocite and bornite transformed into a mixture of malachite and iron oxides (Fig. 4c, f).

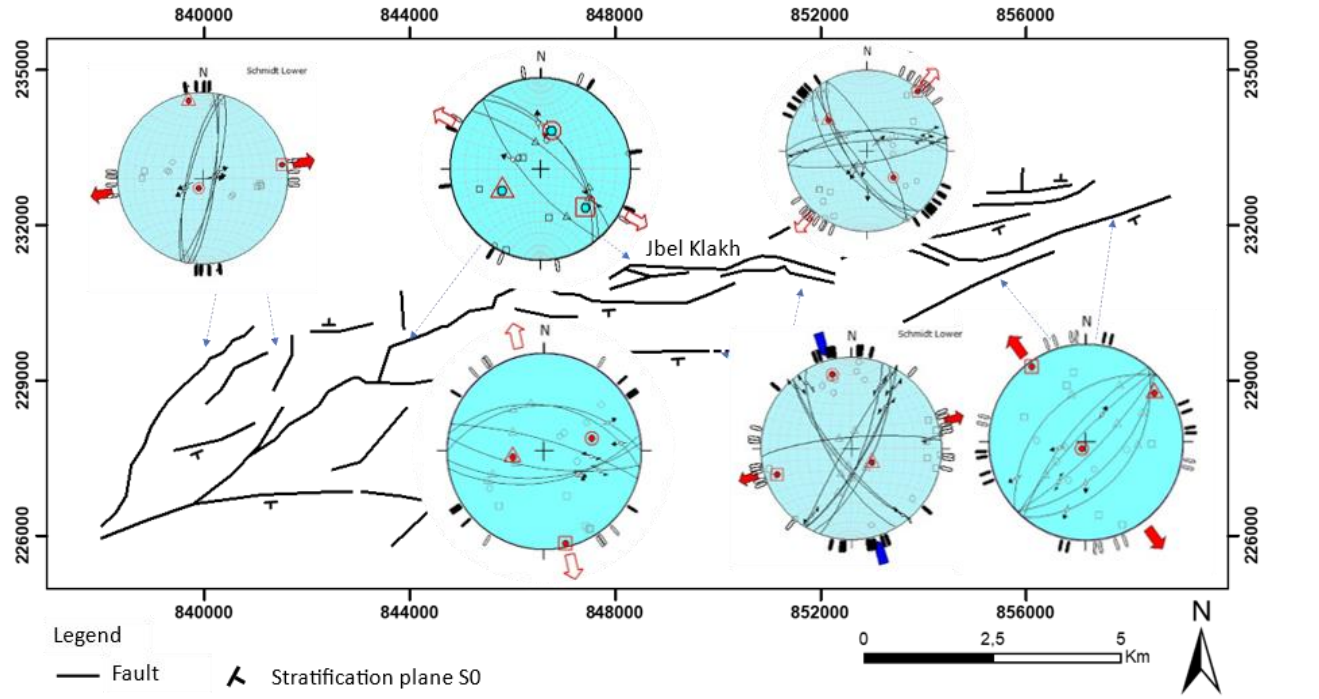


Figure 3. Jbel Klakh structural map with directional stereographic representation

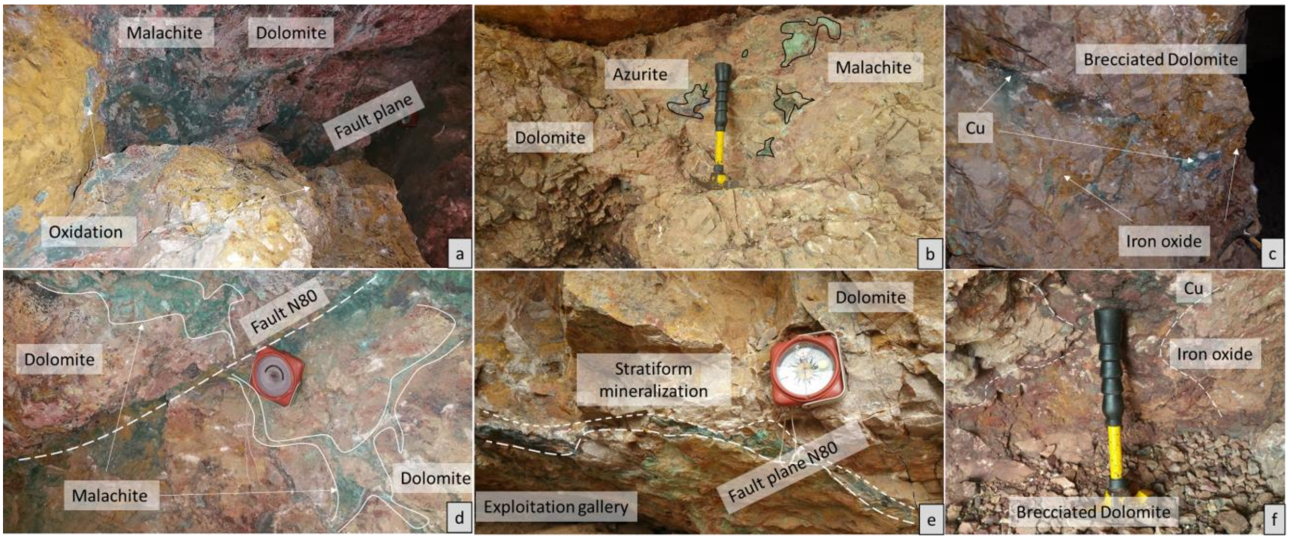


Figure 4. Malachite and azurite mineralization: (a) malachite mineralization following fault planes; (b) disseminated malachite and azurite mineralization; (c) copper and iron mineralization breccia; (d) copper mineralization in dolomites following N80 fracturing); (e) stratiform mineralization following the N80 fault plane (photo of the mining gallery); (f) dolomitic breccia with polygenic element rich in copper and iron

This mineralization consists of a deposit of azurite and malachite along the fault mirrors. This must be the result of sulfate solutions getting stuck in fracture planes at the contacts with clays. This type of mineralization is characterized by brecciated mineralization, with copper as a filler [5], [22]-[24]. It is presented in the form of a fault breccia, the elements of which are very rich in iron oxides with chalcocite or stratiform mineralization to malachite (Fig. 4a, c, e, f).

The copper mineralization consists of a layer, the strength of the strata of which varies from a few millimeters to 20 cm. Locally, the fractures produce clusters with a brecciated texture, formed by host elements cemented by marls and iron oxides (Fig. 4a, b, d).

The mineralization is distributed along the northern High Atlasic accident [2], [6], [25], [26]. The monocline fold with a northern view that forms the Klakh has undergone fracturing, which has given rise to a set of vertical faults, putting the Dogger in contact with the Cretaceous sandstone of the high plateau. This fault is a typical frontal ramp structure that allows for Jurassic thrust on the Cretaceous highlands, allowing for the placement of this mineralization.

5. Geochemical study

The known deposits are geochemically distributed over a distance of 13 km and designated as Klakh I, Klakh II, Klakh III, Klakh IV bis and IV East, Klakh V and Klakh VI (Table 1).

1. Klakh I. The Klakh I deposit is the largest deposit. It is located at the intersection of several faults, including a south-dipping southern fault, a 60°-N-dipping northern fault with satellite fractures and N-S fault. The mineralization, mainly

copper-rich and gangue-free, occurs in substitution, stockwork in crushed dolomites, in faults or clay breccias, in flies and stringers. The copper content varies from 1.5 to 2.0%.

2. Klakh II. Presence of old scrapes over 15 m and copper-bearing malachite stringers in the dolomitic spoil with a copper content ranging from 2.7 to 3.5% (Table 1).

3. Klakh III. Copper-bearing stringers in beige diaclath dolomites with marl interbeds were reported traces of malachite in crushed areas. The copper content is greater than 5%.

4. Klakh V. Essentially a little malachite and azurite in greenish marls and marly limestones under a Quaternary cover. The site is indicated by the presence of slag. In this area the copper content is less than or equal to 1%.

5. Klakh IV. An old trench of 10 m long and 1.5 m wide reveals a vein along a fault with a steep south dip. Mine-ralization has been recognized over 125 m in strike length, but does not continue at depth at a grade of 1.5% Cu at 2.75% (Table 1).

6. Klakh VI. Copper mineralization is present over 50 m in the vicinity of a fault that puts the Dogger dolomite in contact with the Bathonian marl-dolomitic series. In fact, there is a copper occurrence in the white sandstones of the Infra-Cenomanian with a steep dip to the north, which has been scraped over a length of about 30 m. The mineralization, mainly malachite and chalcocite, occurs in disseminations and fracture matings. The copper content is low.

7. Klakh IV Bis. It was the subject of underground mi-ning work with shafts and galleries on 2 levels, (-20 and -40 m). This paper reveals the presence of sulfides and copper carbonates in crushed dolomites and limestones with an ore content of 2% Cu) pressed against a south-dipping fault which brings crushed dolomites into contact with green marls.

Table 1. Geochemical analysis of the Jbel Klakh samples

Designation	Sample	Cu %	Pb %	$CaCO_3$ %	Ag, g/t	SIO_2 %	Zn ppm
Klakh I	JK1	1.5	0.6	20	1	0.89	113
	JK2	1.5	0.7	32	LD	0.78	940
	JK 3	2.75	LD	26	LD	0.97	534
Klakh II	JK 4	3.4	LD	45	LD	0.74	197
	JK 5	3.5	LD	56	LD	11.39	488
	JK 6	2.75	LD	44	LD	9.86	581
Klakh III	JK 7	8.23	LD	67	LD	2.44	355
	JK 8	9	LD	76	LD	0.65	LD
	JK 9	6.15	LD	65	LD	10.43	LD
Klakh V	JK 10	0.8	LD	25	10	8.19	LD
	JK 11	1.2	LD	18	LD	4.24	LD
	JK 12	1.12	LD	12	LD	0.95	LD
Klakh IV	JK 13	1.5	LD	67	10	0.50	LD
	JK 14	1.5	LD	76	LD	0.55	LD
	JK 15	2.75	LD	66	LD	0.21	LD
Klakh VI	JK 16	0.5	LD	80	10	0.25	LD
	JK 17	0.5	LD	82	LD	0.40	LD
	JK 18	0.75	LD	76	LD	0.32	LD
Klakh IV Bis	H1	2.5	LD	0.67	LD	0.45	LD
	H2	1.75	LD	0.76	LD	0.89	LD
	H3	2.12	LD	N/D	LD	0.78	LD

6. Petrographic and metallographic characterization

The mineralization encountered in the Jbel Klakh sector is malachite and azurite contained in Jurassic limestone karsts (Fig. 5a, e) The copper mineralization of Jbel Klakh is present without gangue, neglecting the secondary carbonates linked to the alteration of the dolomite and limestone (Fig. 5b).

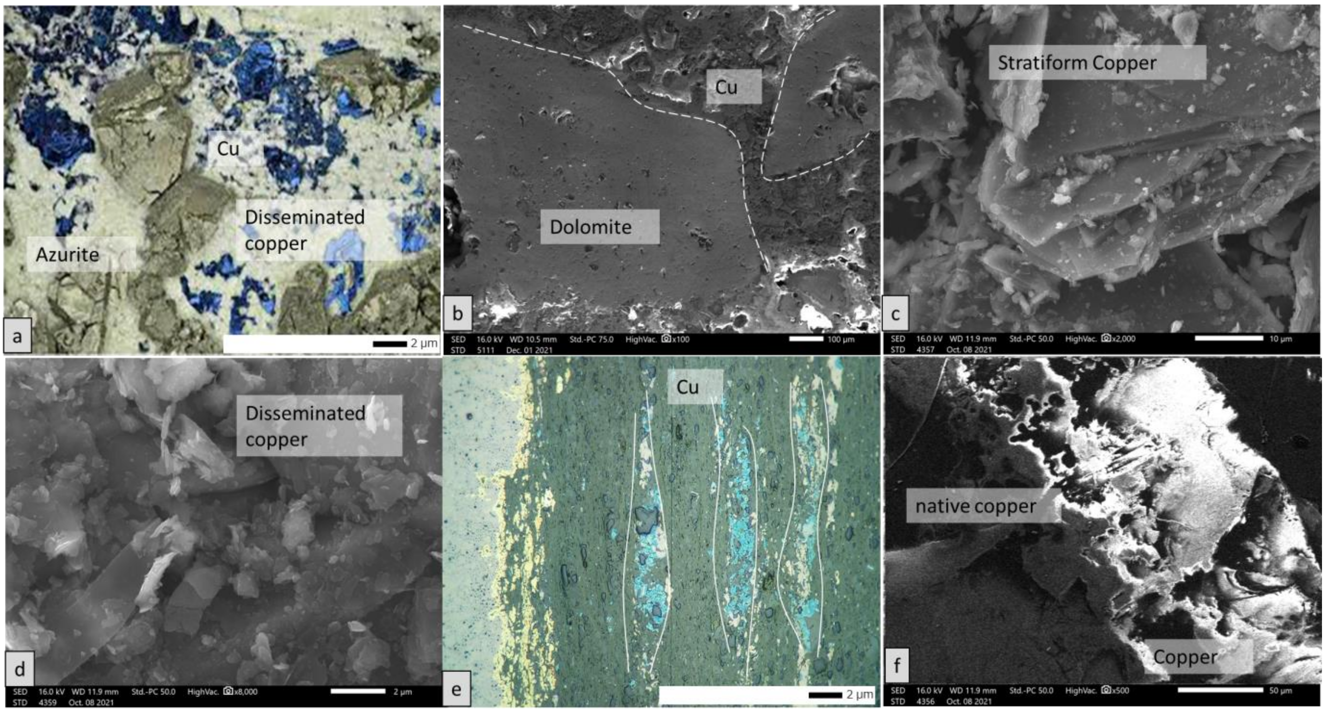
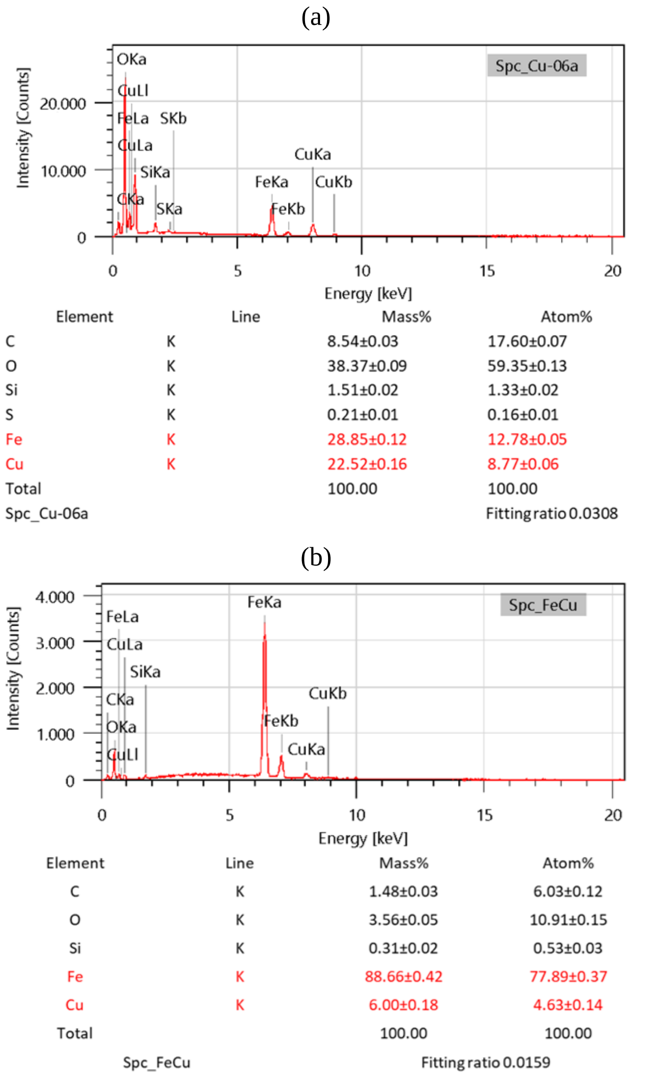


Figure 5. Microscopic observation of Jbel Klakh copper mineralization: (a) disseminated Azurite mineralization; (b) copper disseminated in the Dolomite; (c) stratiform mineralization; (d) disseminated copper; (e) chronology of Azurite and Malachite mineralization; (f) scanning electron microscopy image of native copper

The chemical composition of the ore is characterized by very low silica and iron contents that do not exceed 3%.

The copper mineralization also corresponds to lens-shaped strata bound with fragments of coarse-grained white dolomite (Fig. 5b, c, d, f). The amount of matrix decreases from the nucleus to the boundary of the body, with possibly a transition from brecciated texture to a stockwork of veinlets filled with white dolomite on the edges.

The results of SEM (scanning electron microscopy) correspond to a detailed analysis of mineralization at two levels – surface (Fig. 6b), and level – 10 m (Fig. 6a), which allows us, using this electronic scan, to know whether the mineralization is the same at all levels or it changes its characteristic at depth.



Element	Line	Mass%	Atom%
C	K	8.54±0.03	17.60±0.07
O	K	38.37±0.09	59.35±0.13
Si	K	1.51±0.02	1.33±0.02
S	K	0.21±0.01	0.16±0.01
Fe	K	28.85±0.12	12.78±0.05
Cu	K	22.52±0.16	8.77±0.06
Total		100.00	100.00
Spc_Cu-06a			Fitting ratio 0.0308

Element	Line	Mass%	Atom%
C	K	1.48±0.03	6.03±0.12
O	K	3.56±0.05	10.91±0.15
Si	K	0.31±0.02	0.53±0.03
Fe	K	88.66±0.42	77.89±0.37
Cu	K	6.00±0.18	4.63±0.14
Total		100.00	100.00
Spc_FeCu		Fitting ratio 0.0159	

Figure 6. SEM analyses of Jbel Klakh samples: (a) copper samples taken from a 10m deep drift; (b) copper samples taken at the surface following the E-W fault

SEM analysis clearly shows the presence of copper and iron mineralization in the carbonate formations (Fig. 6a, b), with indications of sulfide mineralization. The presence of these sulfides indicates that the buffering capacity of acidic rain fluids, through the dissolution of Jurassic-Cretaceous carbonate host rocks, was not sufficient to prevent these fluids from reaching the water table level [7], [27].

7. Discussion

On the basis of the various field and laboratory work, Jbel Klakh corresponds to an asymmetrical anticline limited to the north by the northern high atlasic accident characterized by a vertical or spilled movement towards the north, putting the Dogger in contact with the Cenomanian of the Highlands (Fig. 7). From a structural point of view this accident is composed of several fault branches alternating with each other. The mineralization is hosted in five roughly E-W trending fractures and in nearby fractures, affecting a Dogger dolomite bank. The fractures dip is 60 to 80° to the south.

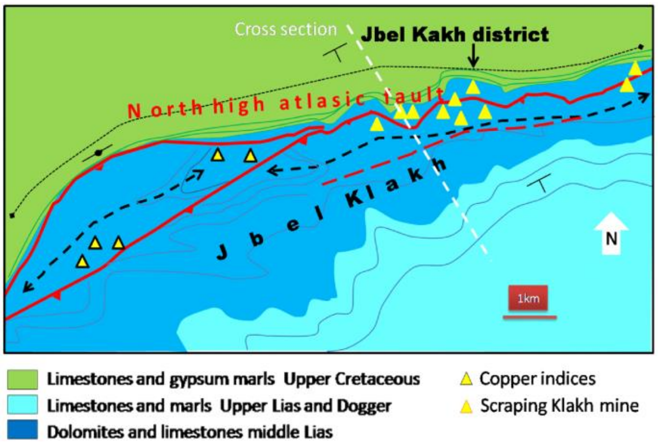


Figure 7. Simplified geological map of copper occurrences and thrusts of the northern High Atlasic accident

Based on the results of geochemical, petrographic and SEM analysis, we have proven that the mineralization contains traces of migration from the basement to the cover, and is explained by the amount of sulfide and iron identified in the mineralization. Thus, the karstification system occurred during the chemical alteration of the copper-bearing porphyries of the basement at depths large enough for meteoritic water circulation to dissolve and reprecipitate along the vertical and lateral alteration profiles.

Therefore, the oxidized copper mineralization of Jbel Klakh is of the supergene type. This mineralization is the result of the succession of extensive tectonic events of the Atlas orogeny, accompanied by a deposition of malachite-type copper mineralization. The last inverse set (compressive NW-SE) is responsible for the formation of white dolomite breccia, allowing the remobilization of hydrothermal solutions and then the deposition of azurite-type copper occurrences. The mineralization studied is therefore intimately linked to the Atlasic deformation event. The lithological control of the Copper is linked to the differential competence between coarse-grained white dolomite and the micritic limestone formations. Obviously, we are talking about a supergene oxidized copper mineralization. The second mineralization is irregularly hosted in fractures affecting dolomitic layers interbedded in green Bathonian (Dogger) marls on the northern Jbel Klakh flank (Fig. 7).

Therefore, Jbel Klakh is formed by a set of thrusts materializing the passage of the North High Atlas Fault (Very Deep Fault) (Fig. 7, 8) which reactivated during the Cenozoic, allowing the formation of copper mineralization in "Azurite and Malachite".

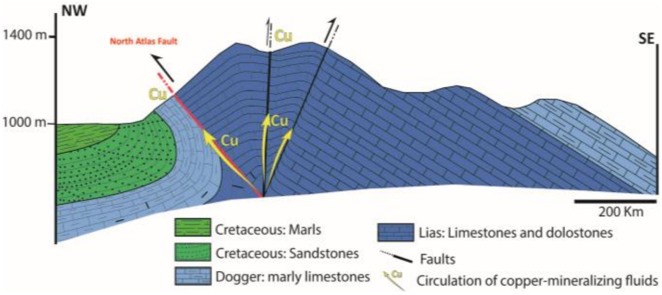


Figure 8. Geological section of the distribution of copper mineralization along the faults

The mineralization is distributed along the northern High Atlas accident, the monocline fold with a northern view that constitutes Klakh has undergone fracturing which has given rise to a set of vertical faults (Fig. 7), putting the Dogger in contact with the Cretaceous sandstone of the high plateau and allowing the mineralization to rise from the basement to the cover (Fig. 8), in filling vacuum and karstification.

The section shows that this is a ramp structure that allows for Jurassic thrust on the Cretaceous highlands and concentrates copper mineralization along its faults (Fig. 8). The copper mineralization of Jbel Klakh could be linked to the participation of water activity of meteoric origin and tectonic activity affecting the Eastern High Atlas during the Jurassic and Cretaceous periods. Such an evolution guided copper-rich fluids through faults affecting the region to dissolved and karstified carbonate formations. In this study, the genetic evolution of mineralization can help to better understand and enhance the origin of copper deposits hosted in carbonate sedimentary rocks.

8. Conclusions

The Jbel Klakh copper deposit is a very particular deposit model in Morocco. It corresponds to oxidized copper mineralization, which occurred during the chemical alteration of copper-bearing porphyries of the Neoproterozoic and Paleozoic inlier of the Eastern High Atlas at great depths, where meteorite water circulation dissolves and reprecipitates the so-called supergene copper.

This type of deposit corresponds to an attractive exploration and exploitation target, as even low-grade deposits have the potential to produce large amounts of copper in an environmentally friendly manner. Thus, the formation of this mineralization is the result of different phases of the Atlas cycle, resulting from the uplift of the High Atlas and the reactivations of the North High Atlas accident, allowing the remobilization of basement mineralization along the fault branches and its deposition in the Dogger dolomites, sandstones and Infra-Cenomanian conglomerates.

In conclusion, alteration of the primary basement sulfide mineralization has produced the establishment of a large high- and medium-grade copper prospect of malachite and azurite copper oxide. This paper suggests that the copper-bearing and supergene-type mineralization, resulting from the alteration and precipitation of karstification-filled copper in carbonate host rocks of the Dogger and Infra-Cenomanian, corresponds to the result of the desegregation and alteration of the basement copper deposits. It is characterized by the presence of primary sulfide copper deposits and their reworking by surface paleo-currents loaded with altered detrital materials. Due to a very particular tectonic regime, it is intimately linked to the atlasic deformation event caused by the uplift of the High Atlas. The lithological control of copper is linked to the differential competence between coarse-grained white dolomite and micritic limestone formations.

Author contributions

Conceptualization: JC; Data curation: JC; Formal analysis: JC; Investigation: JC, SM, HSM; Methodology: JC, SM, HSM; Project administration: JC, MC; Resources: JC, MC, AAA; Software: JC, HSM; Supervision: MC, NEM; Validation: JC, SM, MC, HSM, NS, NEM, AAA; Visualization: JC, SM, MC, HSM, NS, NEM, AAA; Writing – original draft: JC, SM, AAA; Writing – review & editing: SM, MC, NEM. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Геодинамічні, металографічні та геохімічні характеристики мідного родовища Джебель-Клах, Східний Високий Атлас, Марокко

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Мета. Металографічне, геохімічне та геологічне дослідження мідного родовища Джебель-Клах, розташованого в північній частині Східного Високого Атласу Марокко, а також детальна інвентаризація корисних копалин цієї території з виділенням режимів їх утворення, прив'язкою до різних геологічних явищ та уточненням кінематики їх розміщення.

Методика. Для досягнення поставлених цілей застосовано серію геологічних розвідувальних досліджень у районі Джебель-Клах і визначено колишні гірничодобувні ділянки з потужною мідною мінералізацією. Здійснено геологічне картування основних структур, що вміщують мінералізацію, з детальним представленням родин мінералізації. Проведено структурні вимірювання та зйомки для визначення тектонічних режимів, що призвели до формування і розвитку мінералізації, виявлення взаємозв'язку між тріщинуватістю та мінералізацією, а також відібрано декілька зразків, які були предметом геохімічних досліджень методом ICP-MS, петрографічних аналізів, растрової електронної мікроскопії (РЕМ).

Результати. Дослідження пропонує новий підхід до розвідки корисних копалин на основі польових і лабораторних робіт, який має на меті вивчити формування мідної мінералізації в мезо-кайнозойському чохлі, показати роль геологічної текстури і структурного контролю в міграції та формуванні цієї мінералізації, і, врешті решт, дати нову ідею для відкриття нових родовищ супергенної міді, що може підкреслити економічну важливість цього типу родовищ.

Наукова новизна. Встановлено, що найбільш економічно вигідними для розробки родовищами міді Марокко є родовища фундаментального порфірового типу. У Марокко не виявлено економічно вигідних родовищ типу Джбель-Клах, тому дослідження орієнтується на виявлення родовищ супергенного осадового типу шляхом надання геологічного, структурного, геохімічного та геодинамічного пояснення їх залягання.

Практична значимість. Дослідження висвітлює родовища міді супергенного типу і пояснює зв'язок між мінералізацією та різними геологічними, структурними і геодинамічними явищами, які сприяють утворенню цієї мінералізації, і завдяки цій роботі з'являється потенціал для майбутнього відкриття великого родовища міді того ж типу в усьому світі.

Ключові слова: *Джебель-Клах, мінералізація міді, супергенна мідь, геохімічний аналіз, растрова електронна мікроскопія*

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