*International Journal of Engineering Science Invention (IJESI)*
*ISSN (Online): 2319-6734, ISSN (Print): 2319-6726*
*www.ijesi.org ||Volume 9 Issue 7 Series I || July 2020 || PP 06-17*

# Structural Control of Cu mineralizations hosted in Lower Cambrian formations of the Jbel Laassal deposit (Central Anti-Atlas, Morocco): Application of Sentinel-2A multispectral data for structural mapping

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***ABSTRACT:*** *Neoproterozoic to Cambrian formations form the cover of the Anti Atlas inliers. This cover deformed during the Hercynian orogeny. Many Cu occurrences are reported in this cover, whose origin and mode of emplacement is largely discussed. In order to understand copper enrichment in certain areas, Geological, Structural, Petrographic and Geochemical studies have been realized in the Jbel Laassal deposit. This deposit is located in the extreme NE of the Bou-Azzer El Graara inlier. The exploited zone with substantial copper mineralization is located along a SW-NE thrust fault with a SW-NE direction and verging to the SE. This thrust associated with an important folding of the cover. All of the mineralized bodies are associated with the folded and faulted zone, and are extended along the NW-SE direction, which is the same direction of faulted folds in this zone. The structural analysis of the studied area and the automatic extraction of lineaments using the Sentinel-2A image allows to identify two principal families of faults; the first with NW-SE direction, the second oriented NE-SW. The detailed study of the field as well as on a microscopic scale shows that mineralization is mainly hosted in the Lower Cambrian carbonate formations as stockwork and thin veinlets filling the reticulated fractures. These structures controlling the copper mineralization of the Jbel Laassal hardly correspond to the Hercynian shortening accompanied with the reactivation of pre-existing Proterozoic basement faults.*

***KEYWORDS*** *- Central Anti-Atlas, Cu-mineralization, Jbel Laassal, Sentinel-2A, structure*

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Date of Submission: 18-06-2020 Date of Acceptance: 04-07-2020

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## I. INTRODUCTION

The Central Anti-Atlas presents a large metallogenic province of Morocco, its location at the northern border of the West African Craton allowing to consider it as a typical zone to understand the geodynamic history of the anti-atlasic belt. Since 1938 to the present day a number of studies have been realized on the Anti-Atlas inliers ([1],[2],[3],[4]), Recent studies are numerous and provide a remarkable wealth across of structural, geochronological and geochemical research results. But the Neoproterozoic to Paleozoic formations which present the cover of all the Ant-Atlas inliers are less studied, especially in structural terms, despite their richness in mineralization. For this reason, we are starting our work to study certain copper deposits present within this cover.

This work focuses on the structural control of the hosted copper mineralization in the Lower Cambrian formations of the Jbel Laassal deposit, the discussion of the role of Hercynian shortening and reactivation of basement faults as the driving force behind the emplacement of the mineralization.

The Jbel Laassal deposit, in exploitation by SOMIFER (Managem Group) since 2012, is the most productive of the Bleida mine's (80% copper mining activity), with reserves of 7,500,000 t of Cu at an average content of around 1% [5].

## II. GEOLOGICAL SETTING

Geographically, the Jbel Laassal deposit is located to the west of the city of Zagora, in the Central Anti-Atlas of Morocco. Approximately 26 kilometres northeast of the Bleïda copper mine.

The Moroccan Anti-Atlas is a mountain range in central Morocco, located at the northern edge of the West African Craton (WAC) [6] (fig.1A).

Its general form as a WSW-ENE oriented anticline, with 720 km long, from the Atlantic Ocean to Algeria, limited to the North by the South Atlas Major Fault and to the South by the Sahara (fig.1B).

The Anti-Atlas characterized by the presence of more than 10 inliers where the Proterozoic terrains outcrop in the basement surmounted by a late Neoproterozoic to Paleozoic deformed cover during the Hercynian orogeny ([7],[8],[9];[10]). The Bou-Azzer El Grara inlier is one of these inliers located at the Central Anti-Atlas, and has a typical place in the understanding of the geological and geodynamic history of the Anti-Atlas, Thus the suture area along the Anti-Atlas Major accident. ([11], [12], [13], [5], [14], [15], [16], [17], [18]). Proterozoic basement composed of ophiolitic rocks and platform volcano-sedimentary complex of Lower to Middle Neoproterozoic age ([13], [19], [20], [21], [22]). These formations are surmounted in angular unconformity by a Late Neoproterozoic to Palaeozoic cover [23]. In the Bou-Azzer El Grara region, this cover begins with a transgressive platform carbonate formation known as the "Adoudou Formation" ([2], [24], [25]), with volcanic intercalations from Jbel Boho submarine volcanism dated between 532 ± 12 Ma [26] and 529 ± 3 Ma (U-Pb SIMS zircon) [9]. Synsedimentary deformations were found during the rifting phase in early Cambrian ([24], [27], [28], [29], [30], [31]). The second formation consists of the Tikirt Formation, which is a terrigenous series of clay-sandstone deposits. The boundary between these two formations is marked by a rapid disappearance of dolomitic layers in favour of clay-grit deposits. The second group corresponds to the "Tata Group" with four formations: Igoudine, Amouslek, Issafene dated to the Lower Cambrian as well as the Tazlaft Formation, attributed to the basal Middle Cambrian [32].

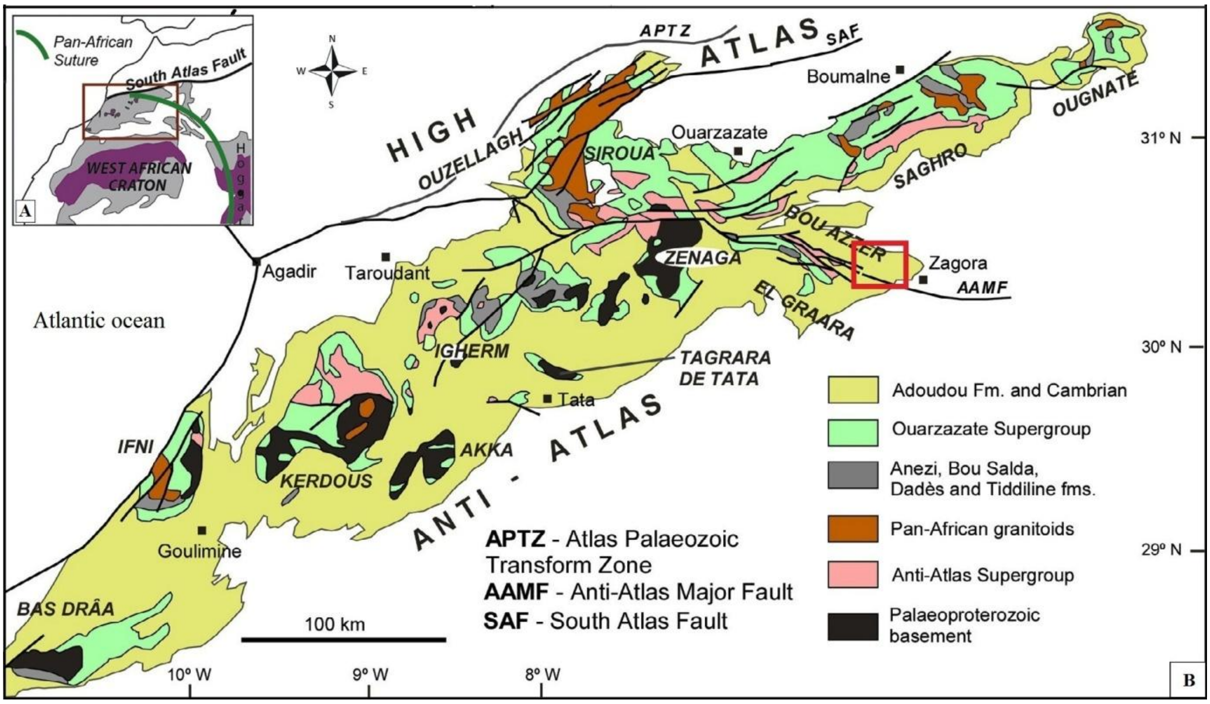

Figure 1: Geological setting of the entire Anti-Atlas with its location at the northern edge of West African Craton. Modified by Gasquet et al, 2005, the study area marked by the red circle

## III. METHODS

The first part of this work required the use of a Sentinel-2A satellite image covering the study area, acquired during a period characterized by the absence of clouds and before mining activities. For this reason we have chosen an image acquired on 28/06/2019. The image has been downloaded from the European Space Agency website https://scihub.copernicus.eu/dhus/#/home . It is composed of 13 spectral bands, with four bands (3,4,5 and 8) of 10m resolution, six bands (6,7,8A,9,11 and 12) of 20m resolution and three bands (1,2, and 10) of 60m resolution. The methodology to be used in this work for the automatic extraction of lineaments from the Sentinel-2A satellite image is summarized the flowchart in the figure (fig.2). The pre-processed image consists of atmospheric corrections and radiometric calibrations using the SNAP software (Sentinel Application Platform) downloaded from: http://step.esa.int/main/ . After pre-processed image, all the 20m and 60m resolution bands were resampled to 10m with nearest neighbour method. Than we calculated the principal component (PC) of seven bands (2,3,4,8,8A,11 and 12 ) (fig.3). Subsequently, the directional filters were applied to all bands and also on these principal component analysis (PCA) using the matrix 7-7 (N-S, NE-SW, E-W and NW-SE). Many tests of automatic extraction of the lineaments are applied out on the 7 bands and on the results of the PCA. Following these tests, we selected the band 8 and the PCA1 filtered with the directional filter 45, because they give the maximum information. The compilation of two lineament maps extracted from band 8 and PCA1 makes it possible to establish a synthetic study area map of the lineaments. Several corrections are made to eliminate the linear structures (roads, rivers, line of ridges, scrapings…).

The second part of this study consists of detailed mapping of the study area, as well as a structural analysis of different structures affecting the formations, mainly the Igoudine formation which hosts the Jbel Laassal copper mineralization. This study also consists of the comparison and verification of the results obtained from the automatic extraction of lineaments from the Sentinel-2A satellite image bands, and the Principal Component (PC) analysis data.

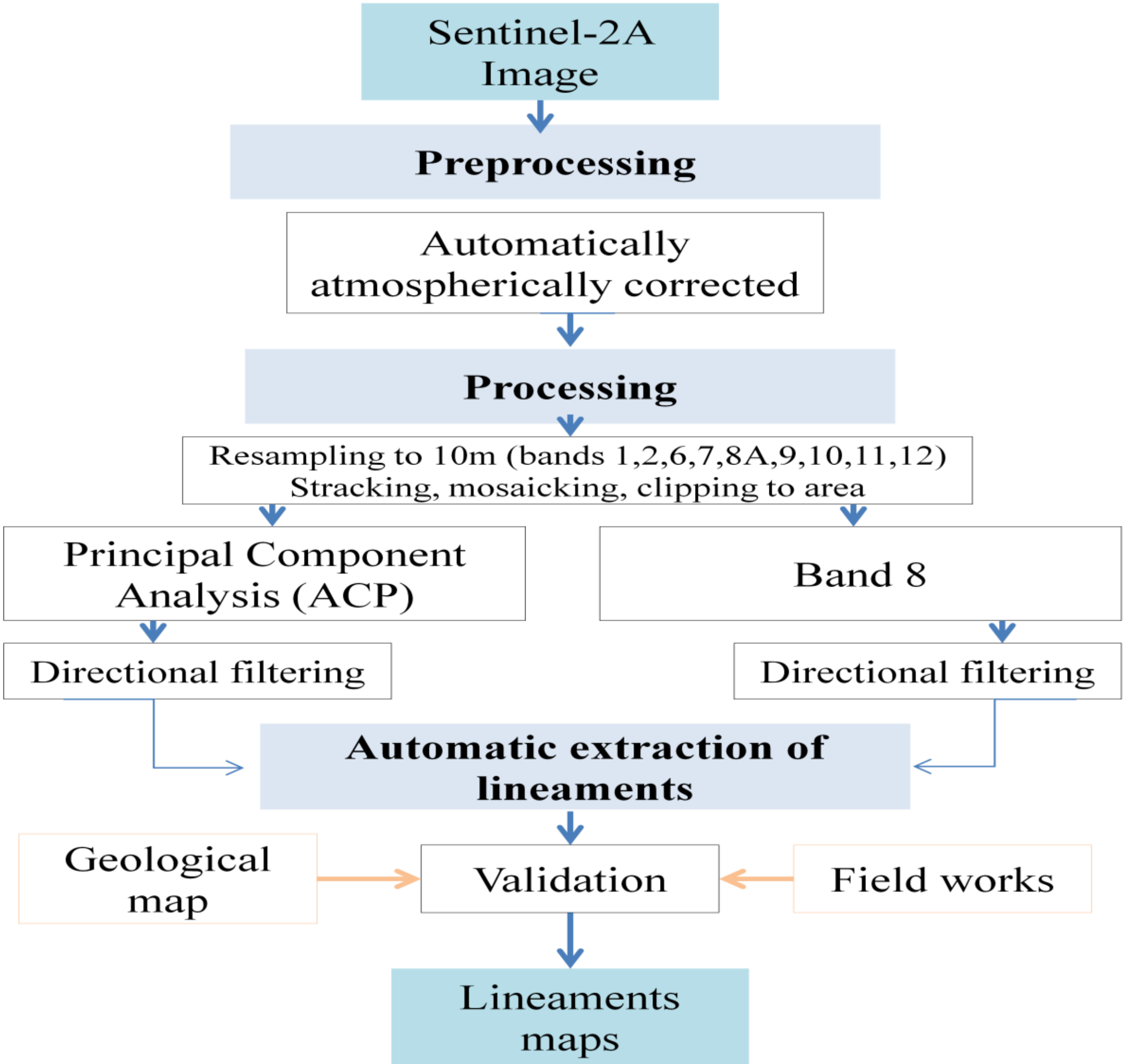


Figure 2: Methodology flowchart used in this study of lineaments extraction

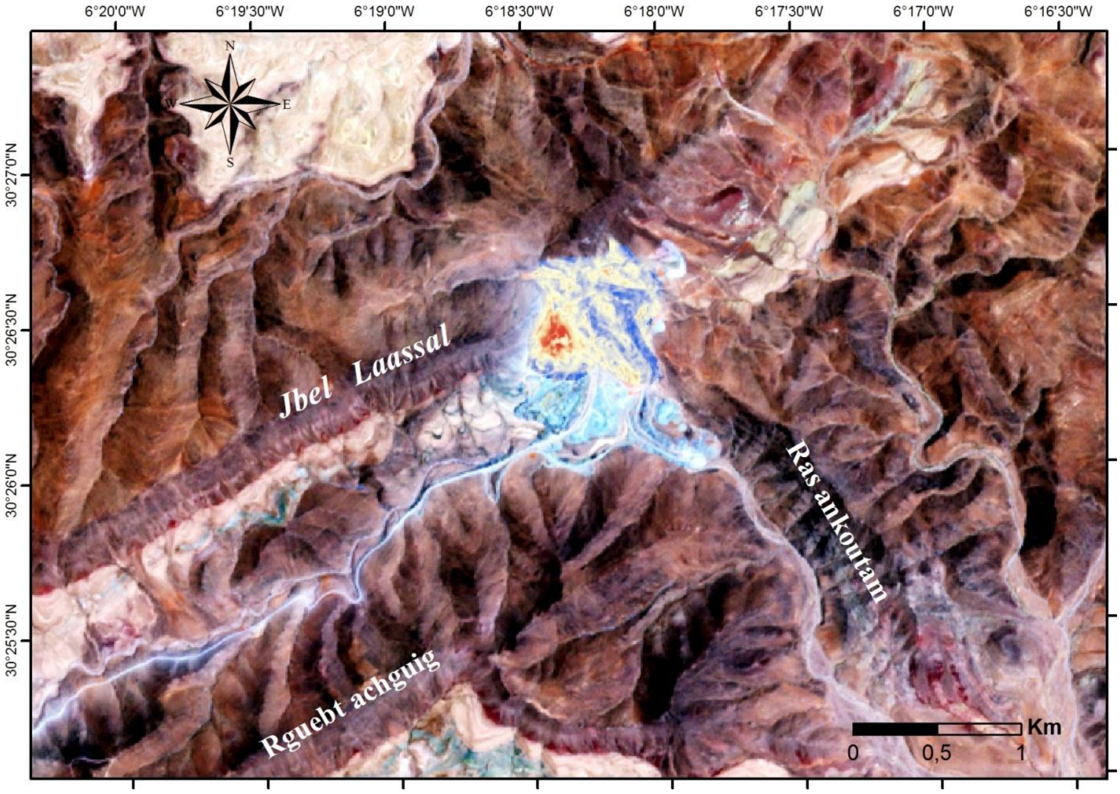


Figure 3: RGB (4,3,2) true color of Sentinel-2A image of study area

# IV. RESULTS

4.1. Extraction of structural lineaments from Sentinel-2A data

The compilation of the two lineament maps, Band 8 and PCA1, from Sentinel-2A satellite image data, provides a synthetic map of the lineaments in the study area (Fig.4). The correction of this map consists to eliminate the linear structures (River, Road, Ridge line...), to correct the geometry and to illuminate the lines duplicates. The validation of the results is made, in a first time by the pre-existing geological data and in a second time by the detailed mapping and structural study of the study area during field work.

The analysis of the final structural lineament map at allows to distinguish two main families of lineaments, a dominant family of NE-SW orientation and a second family of NW-SE to NNW-SSE orientation (fig.5).

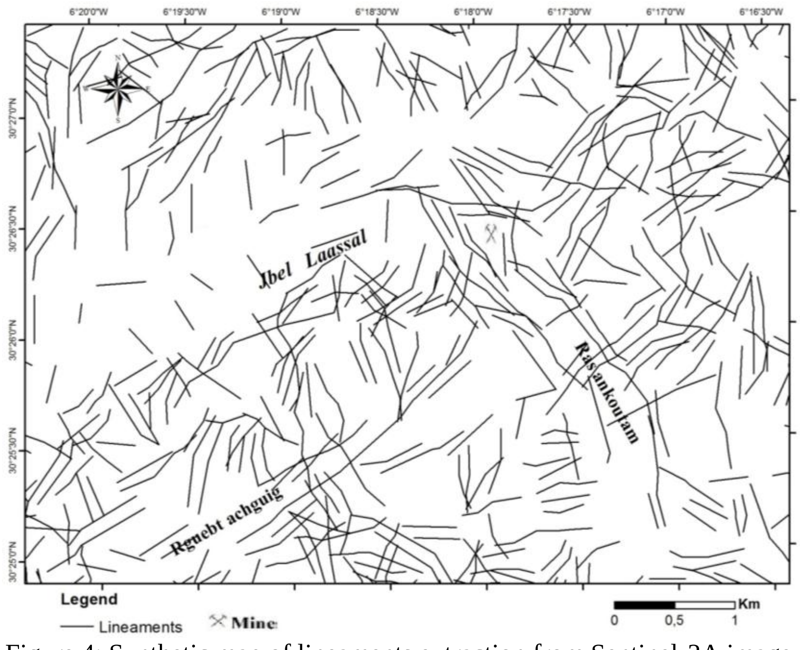


Figure 4: Synthetic map of lineaments extraction from Sentinel-2A image

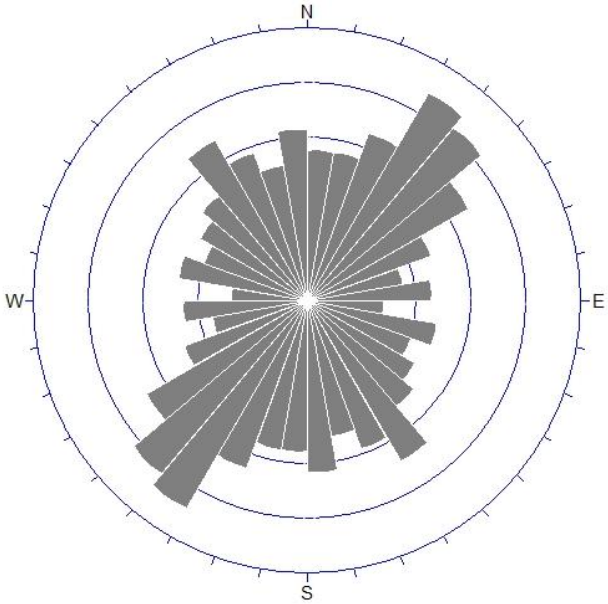


Figure 5 : Rose diagram of lineaments extract from Sentinel-2A image

The validation of the lineament extraction results is done by superimposing the lineaments extracted from the Sentinel-2A satellite image with the structures of the geological map. The results are a compliment to the geological map, and also a guide for mineral exploration (fig.6).

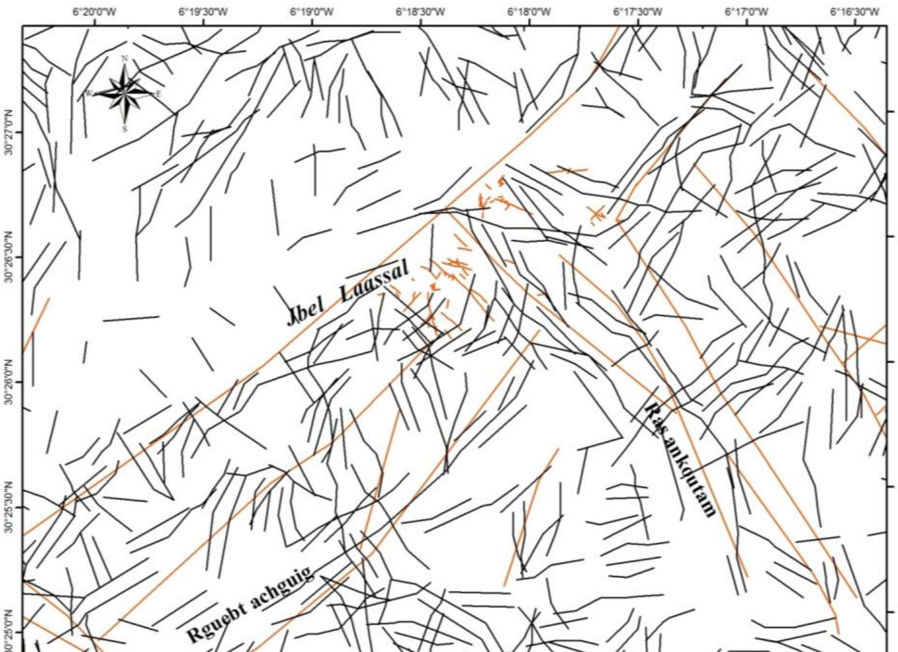


Figure 6: Superposition the lineament extraction from satellite image with geological map of the study area

4.2. Field study and structural analysis

4.2.1. Litho-stratigraphy:

Litho-stratigraphically, the study area consists of a thick succession of terrains of the terminal Neoproterozoic to Lower Cambrian cover, which can be seen from bottom to top: (Fig.7)

Adoudou formation: represented by a thick, predominantly carbonate-dominated series with a thickness of 150 to 250 m. This series is composed of a succession of dolomitic layers separated by more or less clay silt banks. Sometimes volcanic silts are observed in certain places.

Tikirt Formation: Occupies most of the map area, this formation is a terrigenous series of red to purplish hues about 250 to 300 m thick. It is represented by sandstone deposits with intercalations of silts and red pelites. On the surfaces of the sandstone massifs it is frequent to observe "ripples marks".

Igoudine and Amouslek Formation: corresponds to the host of copper mineralization in the Jbel Laassal deposit. It is a series of carbonates with facies comparable to those of the Adoudou formation. It is composed of a succession from 180 to 280 m of dolomitic limestones with intercalations of white and sometimes green silts.

Issafene Formation: means a unit less than fifty metres thick composed mainly of clay silt (red pelites) with thin sandstone beds.

Tazlaft Formation: This formation lies in continuity above the Issafene Formation. It constitutes a powerful sandstone bar separated by clay interlayers. These facies are comparable to those of the sandstone bars of the Tikirt Formation.

All of these formations are intersected by a network of basic dykes with dolerite nature of a post-Cambrian or Jurassic in age.

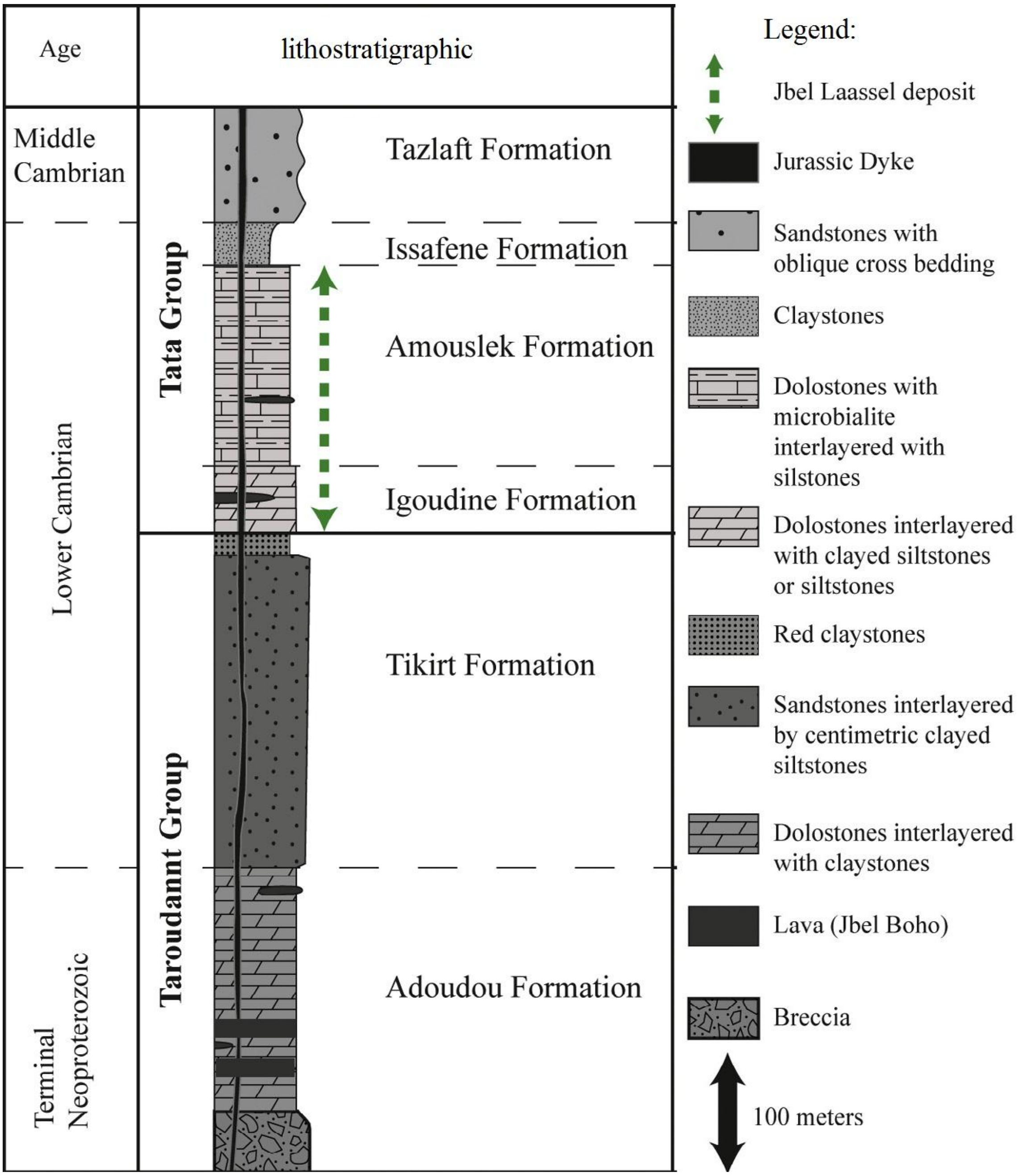


Figure 7: Lithostratigraphic column of the Jbel Laassel area

4.2.2. Structural analysis

At the Jbel laassal deposit the most important structure is the NE-SW thrust fault, which limits the deposit to the northwest. The analysis of different structures affecting the cover formations of the terminal Neoproterozoic to Lower Cambrian Neoproterozoic, has allowed to distinguish two types of deformation; the first one corresponds to the soft deformation with two families of folds. The first family presented by conical folds with NW-SE direction, and kneeling folds, with axis plunging 25° to NW associated with SW vergence faults. This fold developed mainly in the Igoudine formation in the central zone of the Jbel Laassal deposit. The second family of folds is almost orthogonal to the first one along a N70° direction slightly tilted to the south and with an axis plunging slightly to the ENE (fig.8). The second family of folds is almost orthogonal to the first in a N70° direction inclined to the south and with a plunging axis to the ENE (fig.9) (fig.10A).

For the second type of deformation which concerns the fracture deformation, geological field surveys show the dominance of three fault families (fig.10B): a) The N120° to N148° family corresponds to the most frequent direction. It shows a generally dextre movement, this type of fault is well represented in the western part of the deposit; b) The N50° to N70° faults, which are part of the major thrust fault at Jbel Laasel, located to the north and which puts the upper sandstones in contact with the series of carbonates and siltstones which are the main host of the mineralization (fig.11); c) The plate faults show a normal play and are parallel to the stratification.


Figure 8: Folds of the first NW-SE family


Figure 9: Folds of the second NE-SW family

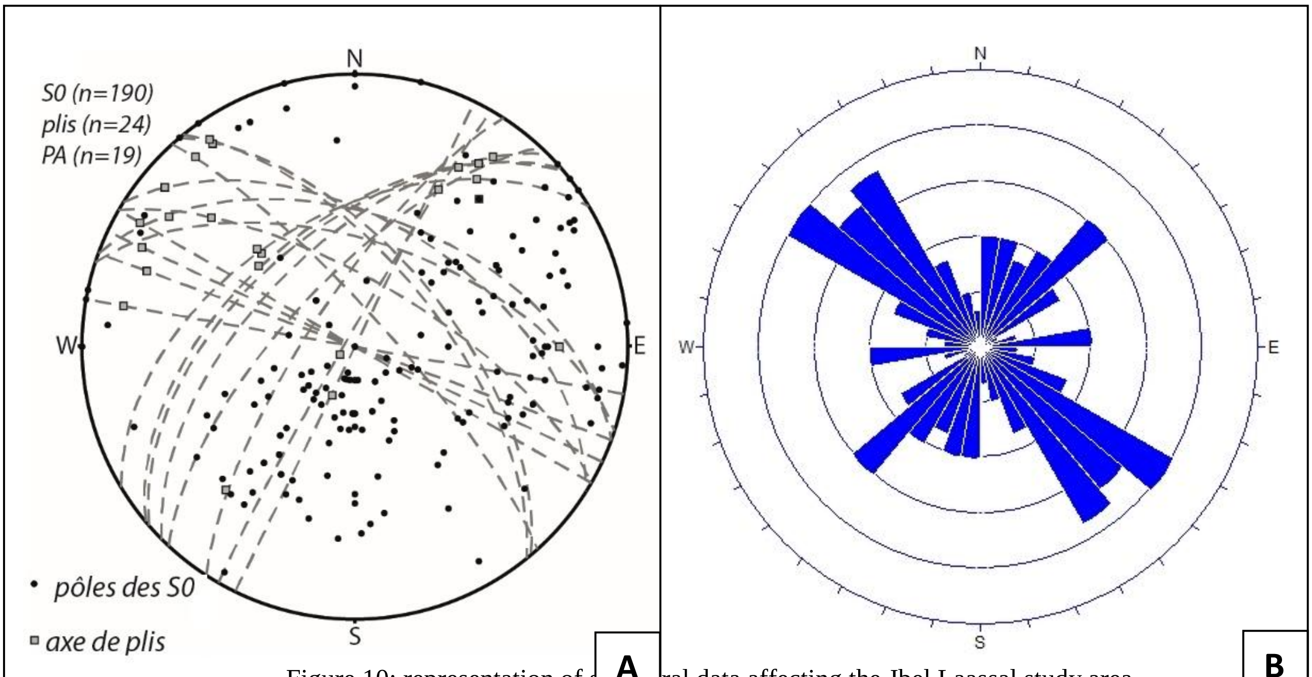


Figure 10: representation of s[illegible]ral data affecting the Jbel Laassal study area
A: Stereographic Projections of Fold Axial Planes
B: rosette diagram of different faults affecting the study area

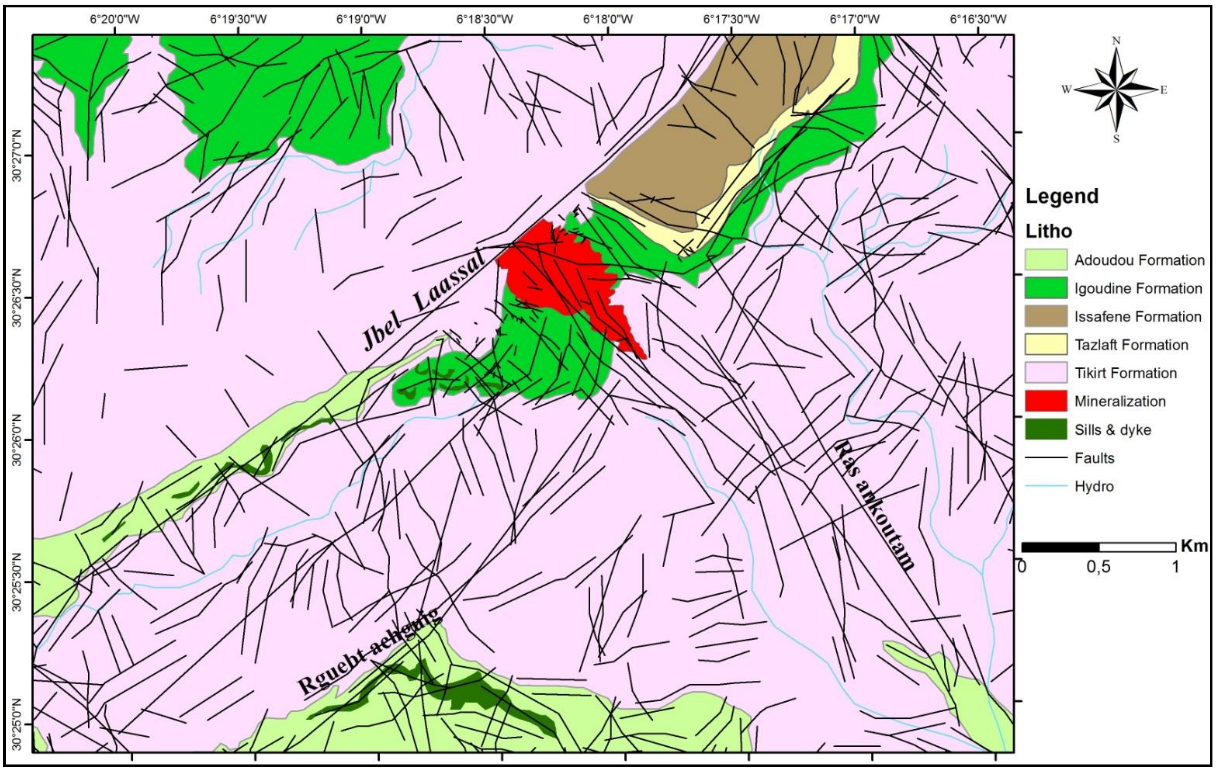

Figure 11: Geological and structural map of the Jbel Laassal study area

## V. DISCUSSION

This work is the first attempt to use the Sentinel-2A data for the extraction of lineaments and the production of a structural map of the study area, in order to highlight the structural control of copper mineralization in the cover formations of the Lower Neoproterozoic to Lower Cambrian terminal Neoproterozoic. A Sentinel-2A image covers the entire study area of the Jbel Laassal deposit, subjected to atmospheric corrections, then several tests of filtering directions from the different bands, as well as the results of Principal Component Analysis (PCA), for the extraction of maximum structural lineaments affecting the area, towards the end we came out of a structural map by adding the data collected in the field during our mission.

The results of the analysis of different lineaments as well as the detailed mapping and structural study of the study area provide important interpretations of the structural control of copper mineralization in the Igoudine Formation of the Jbel Laassal deposit.

The Jbel Laassal zone is one of the folded zones of the Central Anti-Atlas cover, two main families of folds have been observed in the study area; a first family of NW-SE conical and kneeling folds with an axis plunging 25° to the NW, associated with SW vergence faults. A fracture schistosity is frequently developed at the hinges of the folds. A second family of NE-SW direction slightly tilted to the south and with an axis plunging slightly to the ENE; these folds have a multi-metric to multi-kilometre amplitude spatially associated with overlaps in the same direction. The relations between the two types of folds could not be observed in the field.

In addition to the folded structures, the Jbel Laassal study area is affected by important fracture tectonics as shown by the presence of several faults of different types and orientations. The senestral- inverse faults are in the majority and have a mean N140°E direction with a dip between 90° and 60° to the SW or NE. The dextral-inverse faults have a mean direction N110° with a dip generally vertical to sub-vertical.

Based on macroscopic observation of some core drills that were drilled during the exploration work, the most dominant texture of the copper mineralization at the Jbel Laassal deposit is in the form of stockwork controlled by small fractures in the different sets (fig.12).

The copper mineralization at the Jbel Laassal is similar to the numerous copper occurrences and deposits in the Neoproterozoic to Lower Cambrian terminal Neoproterozoic cover recognized across the Moroccan Anti-Atlas. The interpretations of these mineralizations from the point of view of genetic model, age and driving force of the setting remains still under discussion. The first interpretations followed a similar evolution to those of the sulphides of the Bleida deposit and the arsenides of the Bou-azzer deposit, these two deposits are located in the basement of the Bou-azzer El Grara inlier. The first model was that of copper porphyres, linked to a hypothetical intrusion at depth [33]. [34] establishes the epigenetic character of the mineralization, the result of a post-tectonic migration of copper determined structurally by the junction of two families of faults.

The first family of NW-SE direction folds presented in the study area almost corresponds to the P1 folds described by [35] in the West and Central Anti-Atlas, observed mainly in the carbonate series (Adoudou and Igoudine formation). These folds are thus interpreted as the consequence of basement movements during the Hercynian shortening [35]. The second family of multi-kilometre NE-SW orientation folds has been described as disharmonic P2 phase folds ([36], [35]). [35] Conclude that these P1 folds are related to a first stage of block uplift from the basement, generating punctures and flexures in the base of the cover which, consequently, records structures oriented along the direction of accidents along which blocks are set in motion during Hercynian orogeny. In addition, they associate P2 folds with a more advanced stage of uplift of the basement blocks that would cause southward overlaps.

The most abundant NW-SE faults in the Jbel Laassal Study Area are probably inherited from Precambrian basement ([37], [23], [38]). In addition, there are in the basement of the Bou Azzer-El Graara buttonhole in the proximity of the Jbel Laassal deposit with a large and inverse NNW-SSE oriented, inherited tectonic structures [14], which could have entered into movement during the Hercynian orogeny and induced the P1 folds observed at the field. In addition, the overlapping structure and NE-SW direction faults, which may be the origin of the second phase of P2 folding, are interpreted as a result of the reactivation of pan-African structures during the compressive phase of Hercynian orogeny ([36], [39], [35], [40], [41]).

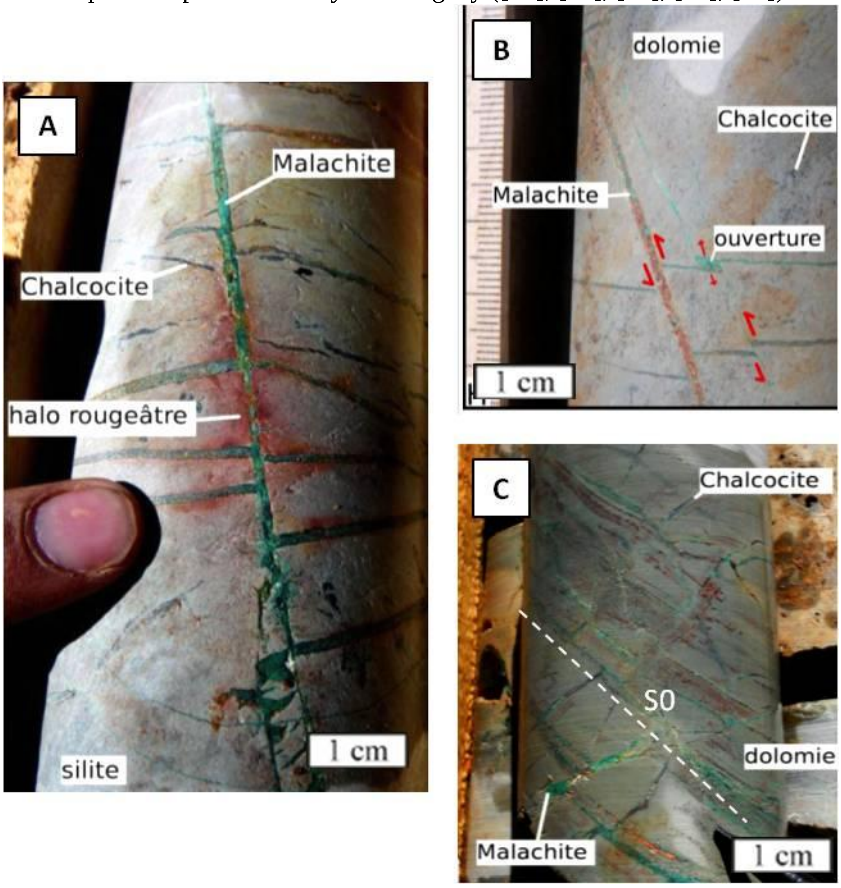


Figure 12: Photograph of drill core: A; Malachite-fill connected fractures, B; Malachite-fill fractures offset by a second reverse set fracture, C; mineralization in the form of Stockwork parallel and oblique to the stratification.

## VI. CONCLUSION

The copper deposit of Jbel Laassal, is one of the most important copper deposits in Morocco. The understanding of the structural control of the deposit is an important guide to the exploration work, but also a reference for the solutions of the exploitation problems. The Jbel Laassal mineralization is located in the structured zone of the Neoproterozoic to Lower Cambrian terminal Neoproterozoic cover, hosted mainly in the Igoudine and Amouselk carbonate formations. This complex Hercynian tectonic zone is characterized by the interference of two systems of structures associated with two folding phases. The NW-SE steering structures are parallel to the axes of the NW-SE to NNW-SSE folds, and the NE-SW steering structures are parallel to the axes of the NE-SW disharmonic folds. The mineralization develops mainly along the NW-SE main structure, with a high concentration in the hinges of the folds of the same direction of the main structure. The deposit is bounded to the NW-SW by the NE-SW straddling structure, but other copper showings are located in the NW extension of the main structure. All of these structures are confirmed by automatic lineament extraction by processing Sentinel-2A satellite image data. Macroscopic observation of the mineralization, which appears as a stockwork, indicates the role of structural control in the emplacement of the Jbel Laassal copper mineralization. During the compressive phase of the Hercynian orogeny, the Neoproterozoic to Paleozoic cover of the Central Anti-Atlas was deformed intensely into fracturing and folded structures.

These structures are not only inherited basement structures but are new structures resulting from Hercynian shortening, which can control the mineralization in the cover but also in the basement.

## Acknowledgements

This research was supported by LGCA Laboratory in the Faculty of Sciences Ben M'sick, Hassan II University Casablanca. The authors would like to thank the anonymous reviewers for their helpful and precious suggestions that largely improved the original version of the manuscript.

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