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Mineralization-tectonic Relationship in the JbelTirremi Fluorite Mine (Taourirt Region - Eastern Morocco): Contribution of Remote Sensing for Geological Exploration

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Abstract

The Tirremi fluorite deposit, located in the Taourirt region (Eastern Morocco), morphologically constitutes a mainly carbonate dome of the Jurassic age, crossed by numerous dykes of lamprophyric rocks of Eocene age. The tectonic study coupled with the study of lineaments extracted from band 2 of the sentinel-2 image shows that the main directions, in terms of frequency and size, are NE-SW and E-W to ENE-WSW. The other directions, N-S and NNW-SSE, are satellite faults with respect to the potential faults; but they are economically important since they give rise to fluorite-rich veins. Similarly, analysis of fracturing (faults, tension cracks, dykes, etc.) allows us to identify the Palaeostresses of stress responsible for the structuring of the Tirremi region. These phases, classified in chronological order based on field observations, are perfectly compatible and correlatable with previous work done in the area.

Keywords: *Eastern Morocco, Fluorite Veins, Lineaments, Sentinel-2 image, Tirremi Mine*

1. Introduction

Faults are zones of weakness in the brittle part of the lithosphere, along which movement can take place in response to stress. When faults undergo displacement, depending on geological and structural conditions, deformation markers can be formed on the fault surface (Dehandschutter, 2001). The presence of faults in any is based on the displacement of rock layers. But also, most faults are represented by certain geological features such as drainage patterns, lineaments (linear features) and lithological contacts between rock units within the rocks of the region. The term lineament was first introduced by (Hobbs, 1904 and 1911) who recognized the existence of linear geomorphic features and interpreted them as superficial expressions of zones of structural weakness or displacement of the earth's crust. Lineaments are linear features at the Earth's surface, generally related to subsurface phenomena. Generally, lineaments are related to large fractures and faults where their orientation and number give an idea of the fracture pattern of the rocks (Arlegui and Soriano, 1998). In recent years, lineaments

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have been defined as natural crusts structures that may represent a zone of structural weakness (Walker, 2006).

The JbelTirremi district, located in the Horsts chain, is about 12 km northwest of the town of Taourirt. Fluorite mineralization, hosted in dolomitic limestones and liasic dolomites, occurs in different morphological types (stratabound, disseminated, karstic and in veins). Topographically, these Jurassic carbonates occupy a relief of subcircular shape, known as the dome of JbelTirremi. The latter, 2.7 km long and 1.5 km wide, shows a sub-meridian direction; its maximum altitude is about 580m. These calcareous-dolomitic platform facies are surrounded by yellow to green Toarcian marls.

In this work, we will use the Tirremi sentinel-2 image to extract linear structures. These lineaments will be compared with the field and geological map data to identify the paleostress and their relationship to the mineralization. Exploration of the sentinel-2 archive has made it possible to follow the directions of mineralized fractures.

2. Lithostratigraphy of JbelTirremi

In the JbelTirremi area, the geological outcrops are represented by lithostratigraphic units ranging in age from Triassic to Quaternary. The description of the Jurassic facies is partly due to the work of Moussa (1999) (Figure 1). The Triassic outcrops to the south of our study area; it is mainly represented by red mudstones with centimetric beds of gypsum. The Carixian outcrops in the form of a succession of massive dolomite beds of a beige or yellowish hue, with fragments of brachiopods and echinoderms. The thickness of this dolomitic formation is about 50m. The Domerian, about 80m thick, is dated by ammonites within the dolomite and limestone beds (Russo, 1930; Giret, 1985). The Toarcian, an epiphyseal of about 100 m, is represented by marly-calcareous terrain, showing greenish marls with thin intercalations of grey-black clayey limestones at the base. The top of the Toarcian is characterized by an accumulation of black limestone banks and greenish marls with radiolarians, echinoderms and ammonites. The Aalenian Thick of the order of 35m, the series of the Aalenian shows a succession of marly and marly-limestone banks with ammonites and cancellophycus. The Bajocian is organized in a formation of green marls, known regionally as the Saka marls. This formation, which outcrops north of JbelTirremi, shows green marls with echinoderms and lamellibranchs tests, surmounted by an alternation of black marls and regular marly-limestone banks. The Bathonian and Callovian outcrop in the vicinity of JbelTirremi, in the valley of OuedZa in the form of alternating sandstone limestones and marls at the base and essentially sandstone formation, oolitic limestone formation and marls with ferruginous oolites at the top (Giret, 1985) The Miocene outcrops widely south of JbelTirremi where it overlies in angular discordance the Jurassic terrains. It appears as a lithological complex composed from the base to the top by polygenic conglomeratic facies with calcareous cement and angular elements formed by the sandstones of the Upper Jurassic, marly of the Bajocian and Toarcian and the alkaline magmatic rocks of the Eocene, carbonates with oysters, marly sandstones which locally pass to sandstones and carbonates with conglomeratic pebbles. The Quaternary is widely developed at the level of OuedZa and in the vicinity of JbelTirremi, in the form of terraces of silts, pebbles, conglomeratic terraces and lacustrine clays.

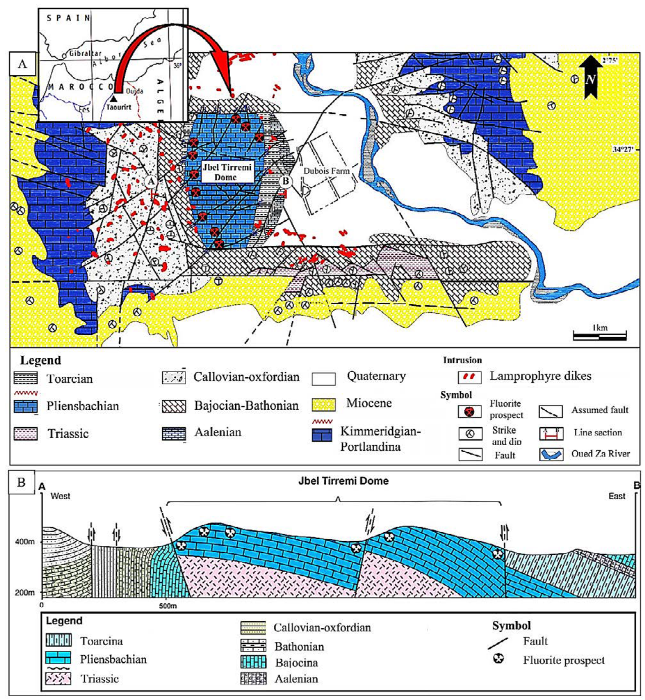

Figure 1. **(A).** District-scale geologic setting of the JbelTirremi fluorite-barite hydrothermal deposit (modified after Giret, 1985 and Bouabdellah et al., 2014) showing the main lithostratigraphic units, the extent of structural styles, and the relative position of known fluorite-barite prospects, and their relationships to the Eocene lamprophyre dike swarms. (B). Representative E-W cross section through the JbelTirremi fluorite-barite hydrothermal deposit showing the major lithostratigraphic units and the location of the main fluorite-barite (F-Ba) prospects relative to the JbelTirremi dome (See map for location of section line A-B).

3. Tectonic Evolution

The Starat of JbelTirremi region have undergone a polyphase tectonic deformation during the Hercynian and Alpine cycle giving a variety of tectonic structures brittle (faults and fractures) and sometimes ductile (folds) (Torbi and Gélard, 2000). The faults can be divided into several directions, NE-SW, ENE-WSW, NW-SE, E-W and NS (Figure 2). These faults have structured the region into a series of elevated and subsided compartments (horsts and (horsts and grabens). The variations in stratigraphy and thickness of the layers, which are crossed by numerous faults, are generated by synsedimentary normal faults, which will undergo atectonic inversion. During Neogeneperiod, most normal faults were reversed as a result of Cenozoic time due to convergence between the African and Eurasian plates (Jacobshagen *et al.*, 1988, Sani *et al.*, 2000; Torbi and Gélard, 1994; Torbi, 1996; Torbi and Gélard, 2000).

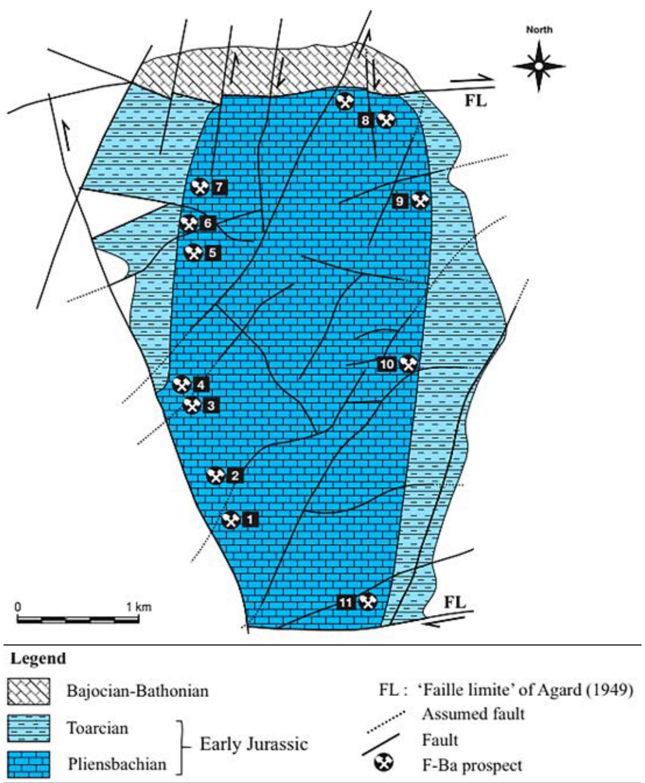

Figure 2. Local structural geology of the JbelTirremifluorite-barite hydrothermal deposit, illustrating the closely spaced ENE-WSW–, NW-SE–, and N-S–trending faults relative to the dome (Bouabdellah et al., 2013).

4. Magmatisme

At the level of JbelTirremi, outcrops a series of magmatic rocks in the form of dykes and intrusive stocks intersecting the Jurassic calcareous-marl formations. These rocks are known regionally as lamprophyres (Aiounites old name) and mestigmerites (Figure 3).

Macroscopically, these dykes occur in faults of variable direction but are most often oriented NW and NE. The power of these magma bodies varies from 0.5 to 3m. They extend over hundreds of meters (Moussa, 1999). They correspond to black or light grey rocks, intersecting the carbonate formations of the Lias. Petrographically, these lamprophyres consist of phenocrysts of biotite, pyroxene. Recent geochemical studies (Mokhtari *et al.* 1996) show that these Eocene magmatic rocks of the Taourirt region correspond to alkaline rocks saturated in silica. The accepted age of these rocks is Eocene following geochronological analyses on biotites from an aïounite dyke affecting the Bajocian and Bathonian formations of Mdaouer (South of Taourirt), delivering an age of 57±3 Ma (Eocene) (Robert-Charrue, 1964).

Figure 3. Lamprophyre dyke, with phenocrysts of biotite, crossing the Jurassic carbonates (Bi: biotite).

5. Mineralization and Nature of Deposit

Geological investigations based on the observation and study of the mineralized bodies both in outcrops and in trenches and boreholes, on the one hand, and the careful examination of the relationship between mineralization, host rocks and gangue minerals, on the other hand, allow us to distinguish three main distinct morphological types of mineralization: i) open space-filling ii) epigenetic replacement iii) and fluorite in collapse breccias.

The first style of mineralization, substitution type, shows mainly two modalities. The progressive substitution of limestones and dolomites of the Lias by fluorite or the more or less total replacement of fragments or tests of fossils.

The second type, the most widespread, results in the filling of karsts or open spaces by mineralization, giving it a strata-bound or vein-like aspect.

Karst mineralization, relatively abundant in the Tirremi dome, seems to be concentrated at the boundary between the Toarcian and the Pliensbachian or along with certain anomalous contacts in the form of strings. These discontinuity zones are conducive to the circulation of both the meteoric waters responsible for the dissolution and the mineralized hydrothermal fluids. The mineralized pockets are either massive fluorite alone or dominant or in the form of aggregates of fluorite, barite and calcite.

The fluorite filling open spaces, forming the main part of the economically exploitable mineralization in the Tirremi mine, is sometimes in veins of small extension, of the order of a few meters, arranged in a network (vein mineralization); sometimes in the form of levels parallel to the stratification of the host rock.

A third style corresponds to fluoride mineralization associated with collapse breccias. This type, less frequent and of the local extension, is characterized by carbonate blocks in the form of collapse breccias often associated with normal faults. These collapsed blocks, of variable size and irregular shape, are cemented by an association of fluorite, barite and calcite.

Generally, The fluorite bearing veins are hosted in an anastomosing complex fracture system with a mean orientation of NNW-SSE (N18W-S18E) and dip to the west at shallow (<10 to 15^0) to steep angle (55 to 75^0) in the western part of the hill. Orebody orientation and structural information are furnished in geological maps (Figure 4). So far, two sub-parallel lodes with fluorite have been defined. The carbonate rocks are dated as Domerian in age (Lower to Middle Liass). The main cracks/fissures are along NE–SW direction has fragmented the dome into three blocks. Such cracks also caused the development of other smaller cracks along with NNW, EW, ENE and WNW directions. Such a mode of occurrence ensures depth continuity of the structure and the contained mineralization as well. Mineralization is associated with areas of crushing and fractures on the edges of the carbonate dome. In the west zone of the deposit, mineralization took place as clusters of fracture filling of karst cavities and veins of substitution in the dolomitic limestone and the northern, north-eastern and south-eastern areas, fluorite occurs either in the form of veins or fracture fillings. The CaF_2 content of minable portions of veins normally range from 15 to 80%, although grades above 80% also occur in limited areas. Similarly, in some zones, CaF_2 content varies between 1 to 15%. The borehole sections show continuity of mineralization down to about 200m vertically below the surface outcrop level.

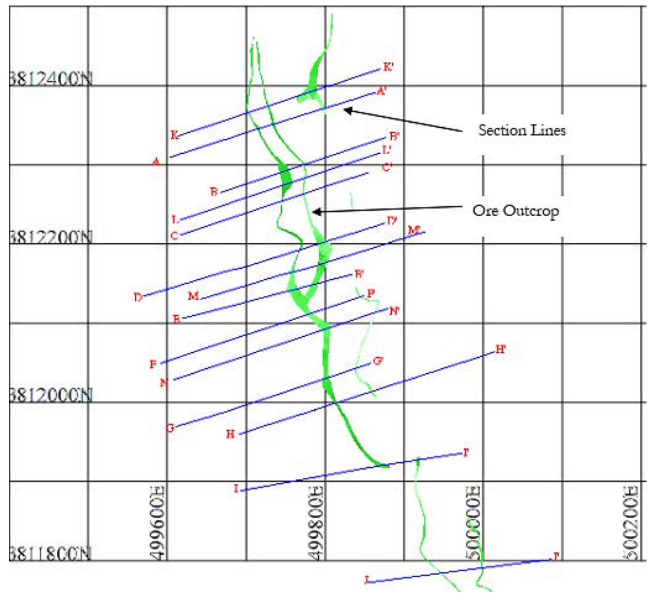

Figure 4. Mineralized fractures in the exploration phase.

The mineralization is controlled primarily by tectonic activities. The western mineralized zone is slightly tilted towards the SE direction. The mineralized zone consists of fluorite mainly of white mass, sometimes also as purple, automorphic crystals together with calcite, quartz and rarely with barite. These veins show zoning with barite at vein margin, followed by fluorite and calcite. At places, ankerite occupies the vein margin followed by massive fluorite. The fluorine content in the surface samples and drill-core samples from traces to as high as 96% CaF_2. The presence of silica and calcite is often quite high. Chemical analysis of samples indicates that there is a direct relation between calcite ($CaCO_3$) and fluorite (CaF_2). In the veins, an increase of calcite crystallization is indicative of less mineralization of fluorite and vice versa. Fluorite appears to have filled open spaces left from the dissolving of limestone by the ore-bearing solutions or their precursors. The Fluorspar mineralization is not of contact metamorphic origin, but formed later, following the contact zone as a conduit replacing the limestone outward from the contact, either massively or selectively along certain planes.

6. Materials and Methods

The sentinel-2 scene of the Tirremi area is acquired for this study (Figure 5), it is 2.7 km by 2.7 km and covers the whole study area. The techniques used to develop this study are (Figure 6):

1. The extraction of band 2 of the sentinel-2 image, since its spatial resolution of 10m is favorable to this study with respect to the dimensions of the scene.
2. Application of the LINE algorithm which allows the automatic extraction of linear structures and export of these structures in vector format Shapefile.
3. Filtering of the lineaments by excluding man-made structures (roads, agricultural fields, etc.).
4. Implementation of these data in a GIS with geological map data and field data for analysis and interpretation.

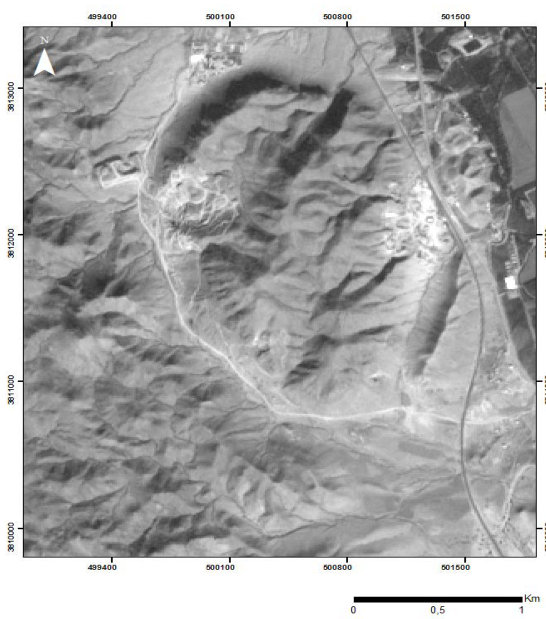

Figure 5. Sentinel-2 scene of JbelTirremi.

7. Results and Discussion

The cartographic study of the Tirremi region, completed by field data, allowed us to determine the networks of magmatic dykes (Figure 7a), mineralized veins (Figure 7b) and faults (Figure 4c) that affect the region. The rosette shows the main directions of the faults highlighted; these are NE-SW, NW-SE, E-W to ENE-WSW, N-S to NNW-SSE. Furthermore, the structural map (Figure 8) from the sentinel-2 satellite image gives an overall view of the main orientations of the lineaments affecting the study area (Figure 7d). The fluorite vein mineralization is largely controlled by preferred tectonic directions. Indeed, the vast majority of the mineralized veins are located on fractures N-S to N10, N70-N90 and N110-150 (Figure 9).

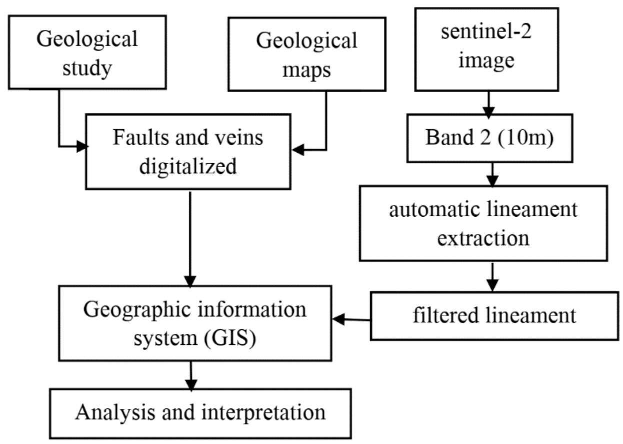

Figure 6. The techniques used to develop this study.

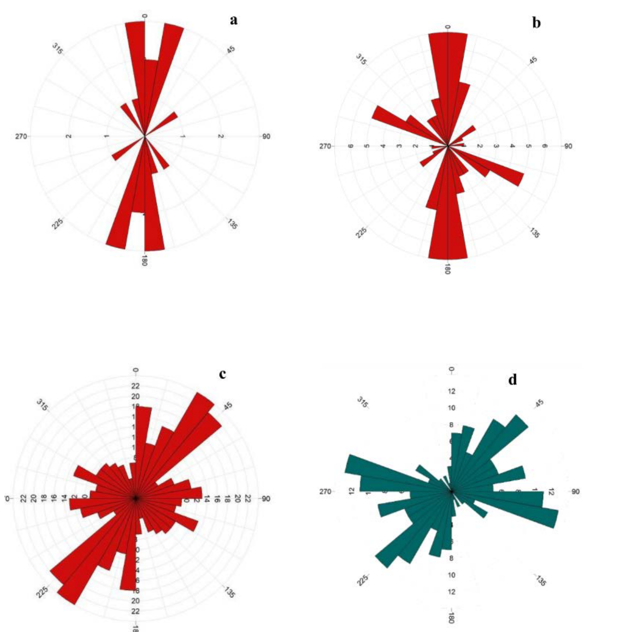

Figure 7. Directional rosettes: a. Magmatic dykes; b. Mineralized veins; c. Faults; d. Lineaments.

The results obtained are consistent with previous work (Torbi and Gérald, 2000), carried out in eastern Morocco.

They also allowed us to highlight the Palaeostresses responsible for the structuring of the study area. These Palaeostresses are :

- NNW-SSE to N-S extension phase: Upper Tortonian to Messinian
- E-W extension phase: Messinian to Lower Pliocene
- NW-SE to NNW-SSE compression phase: Late Pliocene to Middle Quaternary
- NE-SW to NNE-SSW compression phase: Recent Quaternary

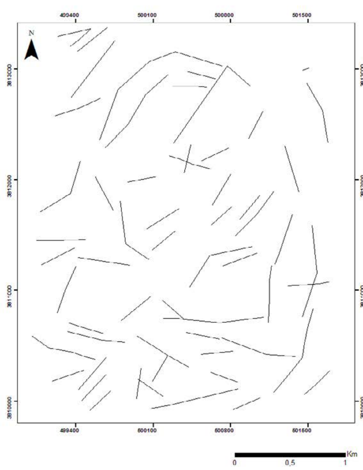

Figure 8. Map of lineaments extracted from the Sentinel-2 image.

Figure 9. Photos showing the found veins of fluorite in a different direction. (A). vein oriented N75. (B). vein oriented N110. (C). vein oriented N10.

8. Conclusions

This study allowed the evaluation of Band 2 from the Sentinel-2 image in the mapping of linear structures. These structures are generally comparable to field data. Based on the remote sensing and the sentinel-2 image we quickly extracted geological lineaments in the study area.

The extracted lineaments are presented as discontinuities corresponding either to fractures showing an offset between geological formations or to extensions of already mapped faults; or to anomalous contacts between two different geological outcrops without apparent offset.

Finally, it is the secondary and satellite faults that are the richest in fluorite and not the major faults.

From the point of view of the relationship between mineralization, Eocene alkaline magmatism and tectonics we showing that: a) the mineralization of fluorite and associated base metals in the J. Tirremi area is polyphase and is intimately linked to brittle tectonics. It is itself polyphase and would be attached essentially to the periods in compression (p2), (p5) and (p6) of respective Eocene-Oligocene age. Terminal Pliocene-Early Quaternary and Quaternary; b) the Eocene alkaline magmatism would also be Related to the Eocene-Oligocene tectonic period (p2) and would also be contemporary to the first phase of mineralization.

Finally, the application and importance of multi-source remote sensing data with different resolutions in the extraction of geological lineaments will be a top priority in the future for geological study and mineral exploration.

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