Lithostructural Mapping Using Landsat OLI images and Field Investigations in the Oumjrane–Boukerzia Mining District, Eastern Anti-Atlas, Morocco

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Abstract
The application of remote sensing is considered to be highly efficient in the field of geology, particularly for mapping and discrimination between lithological units, as well as the identification of different surface minerals which enable the acquisition of all the optical and radar data needed to obtain more reliable and particular information, especially in inaccessible areas. Landsat 8 (Operational Land Imager) image bands, which include color compositions 7, 4, and 1, band ratios 7/5, 4/2, 3/1, and 6/3, 6/1, 5/2, Principal Component Analyses PC1, PC4, and PC3, and directional filtering at 0° (NS), 45° (NE–SW), and 90° (EW), were used to analyze the spectral characteristics of the lithological units of the study area and delineate the alteration zones which may contain significant concentrations of base metals. Combined with geological field observations, these data were integrated and analyzed in a geographic information system to establish a multi-criteria characterization of mineralized zones. Hence, the use of remote sensing contributed to the improvement and updating of available geological maps of the Oumjrane–Boukerzia area. Lineament extraction allowed for performed analyses of the structural elements that play a crucial role in the mineral distribution in the study area. Several of the targeted areas were examined in the field by selective sampling. Consequently, the results helped identify new mineralized zones with important mining potential which could be evaluated in the future through detailed geophysical and geochemical work.

Keywords: Oumjrane-Boukerzia; Landsat 8 OLI; Remote sensing; Lineaments; Eastern Anti-Atlas

1. Introduction

Geological mapping is fundamental for geologists, and thus all of the current methods and tools for making geological maps should be used. Recently, remote sensing has become a powerful tool for geological mapping (Siamak et al., 2016) and mining geology for the exploration of mineral resources. Indeed, remote sensing reduces the costs and time requirements of exploration in areas which are difficult to access. This technique provides effective approaches for separating tectonic lineaments.

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The Oumjrane–Boukerzria region is located at the southwestern end of the Eastern Moroccan Anti-Atlas (Fig. 1). It is well known for its significant mining potential hosted in the sandstones of the second Bani of the Upper Ordovician which contain an abundance of mineralized veins such as those of Bounhas (Cu, Pb), Afilou n’Khou (Cu), and Rich Marzoug (Cu, Ba) (Boissavy, 1979; Kharis, 2015). There has been no updated work of the study area which also lacks detailed geological maps; moreover, some lithological units and mineralized structures are missing from the Todgha-Maider geological map (Du Dresnay et al., 1988) due to its small scale (1/200000), preventing the detection of small structures with fillings of Cu, Pb, and barite. Therefore, a detailed geological map covering the entire study area was produced by remote sensing techniques and allowed us to obtain additional geological information of use to geologists. This method is based on tracing the continuity of mineralized faults and deducing lithological limits in inaccessible areas based on the interpretation of the geomorphological signatures resulting from the processing of an Operational Land Imager Landsat 8 (OLI) image.

This research aimed to use remote sensing tools for the geological exploration of the Oumjrane-Boukerzria mining district, focusing on the mineral prospecting approach for the vein mineralisations consisting of copper–galena–barite. The multi-processing of Landsat 8 OLI satellite images allows geological and fracturing maps to be produced. The data derived from this processing were integrated into a geographic information system (GIS) as a multi-criteria analysis method for establishing exploration guides for potentially mineralized sites in the studied area. This research was also supported by fieldwork, which helped us improve the pre-existing geological map in order to understand the structural patterns of the area. This workflow can be considered as a direct exploration tool for base metal (Cu, Pb) and barite prospecting primarily by helping define potentially resource-rich areas for mining exploration.

2. Geological Setting

The Eastern Anti-Atlas consists of a Precambrian basement and a Paleozoic cover, thus forming two inliers: Sahro and Ougnat. It is separated from the High Atlas by Cretaceous basins. The two Precambrian inliers are surrounded by 4.5 km thick Paleozoic sedimentary layers, which form, on the southern and eastern sides of the Sahro-Ougnat axis, the Maider and Tafilalet basins, respectively.

The Eastern Anti-Atlas is characterised by a superposition of tectonic events resulting in major-oriented structures trending in the Anti-Atlasic E-W and the Ougartien NW-SE directions (Baidder, 2007; Robert–Charrue, 2006). These two tectonic events affected the Tazzarine, Maider, and Tafilalet basins. The Precambrian basement underwent shortening during the Variscan orogeny resulting in the folding of the Paleozoic cover folding (disharmony during the Adoudounian which led to the formation of a plastic layer providing a favourable surface for detachment folds). Subsequently, the folds were only rarely refolded during the Alpine orogeny. As in the High Atlas, the Anti-Atlas foreland belt was uplifted in response to the NS-trending Alpine compression (Robert-Charrue, 2006; Boissavy, 1979).

The Paleozoic sedimentary pile was deposited in shallow water and contains reduced Lower Cambrian shales and conglomerates, superimposed by Middle Cambrian, Ordovician, and Silurian alternating shales and sandstone. This monotonous terrigenous succession is overlain by a Devonian Carbonates platform containing a detrital Carboniferous succession. This thick series was subjected to an extensional event during the Middle-Upper Devonian era (Baidder et al., 2008), and was later deformed by Variscan shortening, which was mostly NE-SW-directed and suggests the reactivation of the normal faults (Baidder et al., 2016).

The Oumjrane-Boukerzria mining district is located in the eastern Anti-Atlas, 50 km south of the town of Alnif and 90 km northeast of Zagora city. The mining area has 40 km long and 10 km broad.
This huge territory (400 km²) is situated in the western part of the Maider basin, in the southeast of Jbel Saghro. It is part of the Maider and Tafilotalet vein fields and is made up of Lower and Upper Paleozoic units. This Paleozoic cover is sub-horizontal and heavily faulted, with a large radius of curvature folds situated along fault corridors. These terranes are locally intersected by a set of basic dikes with three directions; E-W, NE-SW, and NW-SE (Boissavy, 1979).

The Bounhas deposit is the most economically significant deposit in the whole Oumjrane-Boukerzia mining district, containing large metals stocks. The south-dipping Bounhas deposit has a lenticular vein-type mineralized structure, extending about 3 km in an E-W direction. The mineralisation associated with this deposit is hosted in sandstones and quartzites of the second Bani formation of the Upper Ordovician (Fig.1) (Boissavy, 1979; Charrue, 2006; Baidder, 2007; Kharis, 2015).

![Map of the study area and the Oumjrane-Boukerzia mining district.](image)

**Fig.1.** (a) Location of the study area; (b) Location of the Oumjrane-Boukerzia mining district in the eastern Anti-Atlas map adapted from (Baidder et al. 2008).
3. Data and Methods

3.1. Satellite Imagery and Reference Maps

Several data sources were used in this work, including a Landsat 8 OLI satellite image (July-August 2020) whose characteristics are indicated in Table 1.

Many workers have shown the potential of using Landsat 8 OLI images in the same context for Paleozoic units (Es-Sabbar et al., 2020). The processing of the Landsat 8 OLI image allowed the analysis of bands 1, 2, 3, 4, 5, 6, and 7 which contain spectral information useful for copper exploration. In addition, the Landsat 8 thermal infrared bands have significantly improved the quality and the availability of thermal infrared remote sensing data for lithologic mapping. These results are of great use for the exploration of porphyry copper deposits in similar contexts. The topographic and geological maps of Taghbalt Maider (Destombes and Hollard, 1986; Du Dresnay et al., 1988) were used as reference maps during the first validation process of the results obtained in this work.

Table 1. Spectral bands of the Landsat 8 OLI image

<table>
<thead>
<tr>
<th>Bands</th>
<th>Wavelengths (μm)</th>
<th>Spatial resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Land Imager (OLI)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 1– Coastal aerosol</td>
<td>0.43 to 0.45</td>
<td>30</td>
</tr>
<tr>
<td>Band 2– Blue</td>
<td>0.45 to 0.51</td>
<td>30</td>
</tr>
<tr>
<td>Band 3– Green</td>
<td>0.53 to 0.59</td>
<td>30</td>
</tr>
<tr>
<td>Band 4– Red</td>
<td>0.64 to 0.67</td>
<td>30</td>
</tr>
<tr>
<td>Band 5– NIR</td>
<td>0.85 to 0.88</td>
<td>30</td>
</tr>
<tr>
<td>Band 6– SWIR 1</td>
<td>1.57 to 1.65</td>
<td>30</td>
</tr>
<tr>
<td>Band 7– SWIR2</td>
<td>2.11 to 2.29</td>
<td>30</td>
</tr>
<tr>
<td>Band 8– Panchromatic</td>
<td>0.50 to 0.68</td>
<td>15</td>
</tr>
<tr>
<td>Band 9– Cirrus</td>
<td>1.36 to 1.38</td>
<td>30</td>
</tr>
</tbody>
</table>

3.2. Image Preprocessing and Processing

Depending on the quality of the image, the first phase of image preprocessing involves radiometric and atmospheric corrections to remove atmospheric noise, followed by the dark object subtraction technique to decrease shadows caused by strong relief (Adiri et al., 2016). The Landsat 8 OLI image processing consists of several techniques, such as: (i) lithological mapping, which includes the best results of color composites, band ratios, and principal component analysis (PCA), and (ii) structural lineament mapping, which includes automated lineament extraction through directional filtering applied to the first principal component of bands 1–7 (PC1). To adequately detect these lineaments, we used the "Gram-Schmidt Pan-Sharpening" method to improve the image's spatial resolution and resample the spectral bands using the panchromatic band (resolution = 15 m) (Amer et al., 2012). Considering the perimeter, we kept a window of 5 * 5 for the larger lineaments and 3 * 3 for the finer structures in our investigation. To obtain effective results, directional filters were first applied to the near infrared band (Band 4) and to the first principal component (PC1). Then, automated extraction was performed using the algorithm line extraction of the Geomatica 2015 software with the settings listed in Table 2.
Table 2. Parameters values applied for automatic lineaments extraction.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Applied Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADI (filter radius)</td>
<td>15</td>
</tr>
<tr>
<td>GTHR (Edge Gradient Threshold)</td>
<td>55</td>
</tr>
<tr>
<td>LTHR (Curve Length Threshold)</td>
<td>10</td>
</tr>
<tr>
<td>FTHR (Line Fitting Threshold)</td>
<td>4</td>
</tr>
<tr>
<td>ATHR (Angular Difference Threshold)</td>
<td>20</td>
</tr>
<tr>
<td>DTHR (Linking Distance Threshold)</td>
<td>20</td>
</tr>
</tbody>
</table>

The processing of the Landsat 8 OLI satellite image by ENVI 5.1, ARCGIS 10.8, and Geomatica 2015 allowed us to draw a lithostructural map of the study area. The main steps of the adopted methodology are summarized in the flowchart of Fig.2.

4. Results

4.1. Lithological Mapping

Geological maps are an essential tool in any mining prospecting approach. There has been no updated work or recent regional geological mapping in the study area. Therefore, a detailed geological map covering the entire study area was produced. This new map is based on the compilation of
preexisting geological data, data from the field, and the interpretation of remote sensing and data images. The lithostructural map obtained from the combination of the results of the processing carried out on the Landsat 8 OLI image, such as the colored composition, band ratio, and PCA allowed us to clearly differentiate the lithological units and draw the continuity of mineralized structures of Cu, Pb, and barite in the study area.

4.1.1. Color composites

The RGB color composition of the band combinations (7, 4, and 1) provided excellent results for discriminating the main lithological units of the Oumjrane–Boukerzia region. The color composites precisely indicate the contact between the Upper Ordovician sandstones (malachite green color) which occupy a considerable area in the northwest, the Middle Ordovician pelitic rocks (dark amethyst color), and the Middle Devonian limestones (raw umber color) (Fig. 3).

![Color composite of lithological units](image)

**Legend**
- Location
- Lithological limit
- Quaternary
- Upper Devonian
- Lower Devonian
- Upper Ordovician
- Middle Devonian
- Middle Ordovician

**Fig. 3.** Lithological units detected in the Color composite (741 in RGB respectively)

4.1.2. Band ratio

This technique is based on differentiation analysis, which aims to improve the discrimination between lithological units using spectral bands to establish band ratios (Mars and Rowan, 2006). The
band ratios were used to identify and categorise various lithological units in the study area. Multiple tests were conducted on the band ratios used in the literature (Table 3).

<table>
<thead>
<tr>
<th>RGB scale</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>4/2</td>
<td>6/5</td>
<td>6/7</td>
<td>(Ali and Pour, 2014)</td>
</tr>
<tr>
<td>combinations</td>
<td>5/4</td>
<td>6/5</td>
<td>7/6</td>
<td>(Adiri et al. 2016b)</td>
</tr>
<tr>
<td></td>
<td>6/5</td>
<td>7/6</td>
<td>4/7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5/4</td>
<td>6/7</td>
<td>7/2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6/5</td>
<td>7/6</td>
<td>4/7</td>
<td></td>
</tr>
</tbody>
</table>

When the 7/5, 4/2 and 3/1; 6/3, 6/1 and 5/2 band ratios were processed along with their RGB combinations, we obtained a net discrimination between the different geological units of the study region. The first results of band ratio processing (7/5, 4/2, and 3/1) allowed us to detect Upper Devonian limestones (UD) with a dark navy color in the northeastern part of the area, as well as Lower Devonian limestones (fern green color) occurring in the upper part of Jbel Ighf N’Tslit. Thereafter, the Jbel Boukerzia North and Jbel Boukerzia South were marked by an alternation of Middle Ordovician pelitic rocks (spruce green color) and Upper Ordovician sandstones (deep forest color). The beryl green color represents the Visean shales (V) that occupy a large area in the eastern part of the Oumjrane-Boukerzia region (Fig.4).

**Fig.4.** Color composite of 7/5, 4/2 and 3/1 as RGB images obtained from band ratio technique

The second results obtained from the combination of the 6/3, 6/1, and 5/2 band ratios were used to discriminate between the Upper Ordovician sandstones (ultra-blue color), Middle Ordovician sandy pelitic rocks (medium lilac color), and Lower Devonian limestones (Seville orange color) which occupy most of the northern part of the area. The peridot green color represents the Quaternary cover developed
in the southeast of Oumjrane towards Tafraout Sidi Ali, while the Yogo blue color represents the alluvium deposited around the Oumjrane valley, Rich Marzoug, and Fezzou (Fig.5).

**Fig.5.** Color composite of 6/3, 6/1 and 5/2 band ratios (in RGB, respectively)

4.1.3. **Principal component analysis (PCA)**

The combination of the major components allowed us to discriminate the lithological units based on the nature of each unit's spectral reflectance; units with extremely high spectral reflectance were clearly distinguishable, subsequently represented by bright pixels. The color composite PC1, PC4, and PC3 yielded effective results; the Upper Ordovician (UO) sandstones appear in a fire red color and the Upper Devonian limestones in a spruce green color. The Visean (V) sandy pelitic rocks, which cover the south-eastern part of the study area, are characterised by a fuchsia pink color. The Middle Ordovician pelitic rocks, which are always interposed with Upper Ordovician sandstones and sometimes with Devonian limestones, are marked by a light medium coral color. The alluvium occupies a large area in the southern part of the study area, following the direction of the valley; this is shown by the lichen green color in the processed image (Fig.6).
4.1.4. Control and validation of lithological units

The obtained results were validated through their comparison with a Google Earth image and the geological map of Todgha–Maider (Destombes and Hollard, 1986), as well as by conducting multiple field excursions. A good correlation between the data of the Landsat 8 OLI image and the geological map of the studied area can be observed when they are superimposed. The second Bani (Upper Ordovician) sandstones are well developed in the southern part, particularly in Jbel Bounhas, Oumjrane North, El Fecht, and Jbel Boukerzia. Alternating series of sandstones and pelitic rocks (Middle Ordovician) dominate the northern part of the region, particularly at the foot of Jbel Ighir Oungal and Gara Tibert, while Devonian limestones, represented by Jbel Ighf N'Tsslit and Jbel Issimour, are very developed in the eastern part of the study area.

The study area mainly consists of Ordovician formations which constitute the main elements of the Paleozoic cover of the Eastern Anti-Atlas. These formations are well represented on the southern flank of the latter and can be subdivided into four large groups defined in the region of the Dra (Choubert, 1943). Two pelitic groups can also be found: the schists of the so-called “Feijas extern formation” and the schists in Ktaoua, which are topped by two sandstones barres of the first and the second Bani formations, respectively (Fig.7).
4.2. Structural Lineament Mapping

The purpose of the application of the directional filters is to facilitate the identification and tracking of lineaments corresponding to lithological or structural discontinuities in the images. Directional filters improve the perception of lineaments by improving the visibility of the multispectral image. Moreover, this type of filter can enhance the lineaments which are not favored by the lighting source. In this work, lineament enhancement was achieved with the following directional filters: N-S, E-W, NE-SW, and NW-SE (Fig.8).
4.2.1. Synthetic map analysis

A structural map was produced using both manual and digital interpretations of images and field measurements (Fig. 9a). The results highlighted a total of about 250 fractures spread heterogeneously over the study area. The rose diagram shows fracture networks in two major directions (E-W and NE-SW) (Fig. 9b): (i) the E-W system developed exclusively in the southwestern part of the study area, which constitutes the fractured zone of the Oumjrane copper-bearing mine; this system of fractures affects the second Bani sandstones of the Oumjrane; (ii) the NE-SW system, which is remarkably pronounced within the northern part of the image (Oumjrane North) and the northeastern part of the Oumjrane zone (Rich Merzoug-Boukerzia).

The lineament analysis of the obtained map in conjunction with field findings enabled us to determine the relative chronology of these two families of fracture. The NE-SW-trending fractures appeared to be the most recent, as they intersected the longest and oldest E-W fractures. We could distinguish, for example, the Rich Merzoug (FRM) and Boukerzia (FBK) faults to the northeast of Oumjrane and the Gara Tibert (FGT) fault to the north. This later mineralized Gara Tibert fault can be up to 15 km long, and in some places, it has a width exceeding 4 m (Fig. 9). The rose diagram revealed that the E-W oriented fractures are dominant in the southwestern part of the study area, particularly in Jbel Bounhas, where copper ore mining is currently taking place. The Rich Marzoug and Jbel Boukerzia areas are characterised by a predominance of NE-SW-trending faults.
Fig. 9. (a) Lineament’s map extracted from PC1 and Landsat 8 OLI Image; (b) Rose diagram of the extracted lineaments (J. Jbel; S. Sidi)

4.2.2. Lineament density

The lineament density technique determines the frequency of lineaments per area unit (Hung et al., 2005). The generated map revealed a high lineament density in the southern part of the study area (Jbel Bounhas and Jbel Ighir Oungal) and in its eastern part (Sidi Ali and Fezzou), while the northeastern (Ighf n’Tslit) and northern (Gara Tibert and El Fecht) parts of the Oumjrane mining district were characterized by a regular density (Fig.10). Based on the results of the lineament density map and preexisting data (geological map of the area, field measurements), we deduced that the outcrops of competent lithological units (sandstones and limestone) are characterized by a large fracture network. Thus, in contrast to the incompetent formations, the competent formations favored the development of fractures which created space for the circulation of mineralized fluids. As a result, copper, galena, and barite vein-type mineralization are concentrated in the second Bani sandstones and quartzites.
4.2.3. Control and validation of structural lineaments

The extracted lineaments were based on preexisting geological and topographic maps of the study area and validated by various field trips. The principal aim was to remove the lineaments with no geological significance (roads, ridge lines, rivers, etc.).

The final map produced after validation represents only the geological lineaments (faults and fractures) (Fig.11). Therefore, the analysis of the obtained structural map showed that E-W faults were generally dominant in the southwestern part of the area; these included the major faults of Bounhas (BNF) and Gara Tibert where the veins are filled with barite and iron oxides (1 m to 3 m of thickness). The NE-SW fractures filled with quartz and occasionally copper ores (malachite and azurite) were exclusively pronounced in northeast, inside the Afilou N’Khou (AKF), Rich Marzoug (RMF), and Boukerzia (SBKF; NBKF) fault zones, with thicknesses ranging from 1 m to 1.5 m. It is worth noting that, in the Oumjrane–Boukerzia mining district, the EW mineralized fractures are longer and wider than the NE-trending ones.

Fig.10. Lineament’s density map of study area, showing the spatial distribution of fractured zones (I.: Ighir, J.: Jbel; R.: Rich; S.: Sidi).
5. Field Investigations

We acquired lithostructural data through several field missions. Investigations at the outcrop scale subsequently allowed us to recognize particular fractures which were discovered using remote sensing and to determine their relative directions (Fig.12). In detail, the southern and western parts of the study area were mainly affected by N70° to N115° striking faults. Dipping at 40° to 75° southwards, these faults show a dextral strike-slip movement. In addition, these faults host the main copper and barite mineralization of the study area. The Bounhas mineralized fault is a conspicuous example of these mineralized faults; it corresponds to a large EW-trending mineralized structure which is currently being mined by the MANAGEM GROUP (Fig.12a).

The Bounhas mineralized fault extends over 6 km in a N70° to N115° direction, dipping from 40° to 75° southward (Figs.12b). Structural analyses carried out on this fault showed a polyphase movement; (i) the first movement corresponded to an early dextral slip displacement, marked by the presence of 40° pitch striae and tearing steps; (ii) the second movement likely occurred later as a left–lateral slip motion, confirmed by the presence of other generations of horizontal striae and slicken lines. This sinistral slip motion is probably a response to the NE-SW oriented late Variscan shortening, known to have affected the Eastern Anti-Atlas during the Stephano-Autonian period (Baidder, 2007). Another example of mineralized fault is represented by the steeply dipping and EW-oriented South Bounhas mineralized fault with a length of 400 m and width of 5 m (Fig.12d). The Oumjrane north fault is a N100° to N120°-trending steeply dipping mineralized fault; it shows in some places a width of 2 m, and is filled by iron oxides, quartz, and malachite (Figs.12c and 12e).
Fig. 12. East–West faults in the study area: (a) Google Earth image showing the orientation of the faults with the position of the geological section of (f); (b) Bounhas Fault (BF); (c–e) The Oumjrane North Fault (NOF); (d) South Bounhas Fault (SBF); (f) NE–SW geological section, see (a) for her position.

The N60° to N75° fault system with a sub-vertical dip is related to a second generation of veins defined by sinistral slip motion. There are two main veins in this system: Vein I exhibit variable dip angles ranging from 70° to 90° and is oriented N60° to N75° (Figs. 13a and b). A normal throw with a slight horizontal component point to a dextral motion, which is manifested by the presence of striated planes along this vein.

The N45°- to N60°-oriented mineralized Vein II about 3.5 km long with southeastward subvertical dips with angles ranging from 70° to 90°. In the northeastern part of the study area, its corresponding fault deflects to join Vein III within the sandstone host rock. Vein II has a significant width of up to 10 m in some places, but when it crosses pelitic rocks, it branches out into several veins of lesser strength, which can be explained by the rheological contrast between the politic rocks (incompetent) and sandstones (competent). A late lozenge structure filled with barite and iron oxides is assumed to occur
within this mineralized structure. The barite veins were likely formed late as they intersect the early quartz ones (Figs. 13c and e).

**Fig. 13.** NE–SW Mineralized veins of Jbel Boukerzia: (a) Google Earth image showing mineralized veins (I, II and III) of Jbel Boukerzia; (b) Mineralized vein (I) in the south of Jbel Boukerzia; (c) Mineralized vein (II) of Jbel Boukerzia; (d) NW–SE cross-section passing through the mineralized veins of Jbel Boukerzia; (e) Mineralized vein (III) in the north of Jbel Boukerzia.

### 6. Discussion

#### 6.1. Lithostructural Map

The analysis of the results obtained from the processing of the Landsat8 OLI image, validated by fieldwork, enabled the identification of lithological units which are not mapped in the old map (Destombes and Hollard, 1986), including the second Bani sandstones in the southern part of the Zagora Graben (X = -5.2°; Y = 30.6°), the Lower Devonian limestones to the north of El Fecht (X = -5.3°; Y = 30.8°), and the Viséan shales in the southeast of Fezzou (X = -4.9°; Y = 30.8°). Consequently, the results of this work also allowed the detection of new mineralized structures (Cu, barite, and Pb) having an extension of 30 m to 200 m, especially the southwestern zone of Jbel Bounhas (X = -5.2°; Y = 30.65°) and the northern part of Jbel Boukerzia (X = -5°; Y = 30.75°). The combination of these results helped update the old geological map of the area and produce a well-detailed lithostructural map of the Oumjrane–Boukerzia region. This map will be used as an important reference for future Cu, barite, and Pb mining exploration in this area as it allowed us to trace the continuity of the mineralized faults having an economic importance in the valuation of the mining potential of the Oumjrane-Boukerzia deposit (Fig. 14).
6.2. Structural Model

Compared to the other mineralized fractures in the Oumjrane mining district, the Bounhas fault is the most important copper-bearing structure, representing thus, at the district scale, the main copper deposit in the study area. The Bounhas fault is hosted in sandstone-pelitic sedimentary series of the upper formation of the second Bani. The EW-oriented Bounhas large mineralized structure contains lenticular-type veins reaching about 3 km in length with dips ranging from 45° to 50° to the south (Fig. 15a). The EW-trending fault that hosts the Aflou n’Khou vein is subparallel to the Bounhas fault, dipping 60° to 70° towards the NNW. This fault has a vertical throw of up to 100 m, placing Ordovician sandstones from the second Bani formation that is overlain by the black pelitic rocks of Silurian age. The fault generally hosts Cu, Pb, and barite mineralization with a lenticular shape, similar to those of Bounhas (Fig. 15b).
7. Conclusions

The use of different techniques such as colored composition determination and PCA with band ratios to analyze images from Landsat 8 OLI allowed us to clearly distinguish between the numerous geological units of the Oumjrane–Boukerzia mining district. We were able to establish the directional families of fractures by analyzing the lineament map. In comparison to the northeastern section of the Oumjrane–Boukerzia mining area where NE-SW-oriented fractures are dominant, the southwestern part of the mining district is characterized by a dominance of EW-trending fractures. In turn, the northern section of the area is only rarely transected by NS-trending fractures. The structural analysis of the various faults enabled us to identify the area's polyphase tectonic and structural events. The results of the field investigations suggest that the late Variscan shortening was in fact the main tectonic event to have affected the study area. The superimposition of the structural data with the linear density map helped identify the zones with a high density of fractures corresponding to zones with competent sedimentary series.
The combination of field investigations and image processing findings allowed us to identify the main zones of mineralized fractures in the Oumjrane–Boukerzia area. These mineralized fracture zones are hosted in the sedimentary formations of the second Bani group. The proposed method provided clearly effective results for lithological discrimination and structural lineament mapping, and it could be used in geological mapping particularly in arid areas. It should be noted that these faults and mineralized veins do not exceed a few metres in width, hence the need for using high-resolution or airborne images. Future work will also involve hyperspectral and radar imaging to efficiently evaluate the mining potential of these features, particularly when combined with other geophysical and geochemical data.

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