Contribution of Remote Sensing to the Mapping of Lineaments and Ore-Mineral Occurrences in the Taghbalet Region, Moroccan Eastern Anti-Atlas

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Abstract

The Taghbalet region is a part of the Paleozoic cover of the Moroccan Anti-Atlas, known by a rich mineral potential of vein type. This paper presents the results of a field investigation and processing of Landsat 8oli and Aster satellite images. The pre-processing allows for improving the image quality by applying a radiometric calibration, atmosphere correction and a pansharpening correction. Landsat-8 oli data is used to map structural lineaments including fracture and/or vein. C compositions ( RGB: 2, 5 and 7) and band ratios (5/7, 3/1, 4/3 and 5/7, 5/4, 3/1) were applied, both of which showed the lithological contrast between formations. Then directional filters (N-S, NE-SW, E-W and NW-SE) were applied on the spectral bands and principal component analysis to map the different lineaments. Validation and correction of lineaments obtained by automatic extraction are based on visual interpretation and field verification. The mining prospecting is performed usingASTER multispectral images. Therefore the results obtained show that we have two main directions; one E-W and the other NE-SW. The majority of these lineaments are concentrated in the south of the area. The results of mapping the hydrothermal alteration zones show us that these zones have a clear relationship with the fault.

Keywords: Taghbalet; Eastern Anti-Atlas; Lineaments; Hydrothermal zone; Landsat 8oli; Aster.

1. Introduction

Geologists rely on geological mapping as a primary method to comprehend the features and properties of geological formations in a particular location. Nonetheless, conventional geological mapping approaches tend to be cost-intensive, time-consuming, and limited by geographical barriers. The emergence of remote sensing technology has transformed geological mapping and mineral exploration into a more efficient and cost-effective process. This technique offers numerous benefits,
such as reduced exploration time and costs, especially in remote and hard-to-access areas, making it a powerful tool for the mining industry.

Remote sensing utilizes multi-spectral and hyperspectral satellite imagery to identify geological features on the earth’s surface. This technique provides effective approaches for separating tectonic lineaments, such as faults and joints, from lineaments with geomorphological implications, such as ridgelines and rivers.

The Eastern Anti-Atlas is considered as an important metallogenic province in the northern fringe of the West African Craton (Tuduri et al., 2018, Bouabdellah and Slack, 2016, Levresse et al., 2018, Aabi et al., 2021, 2022b; Sassioui et al., 2022).

The Taghbalt region is located in the southern part of the eastern Anti-Atlas, the area is characterized by its richness in polymetallic mineralization, mainly base metals (Cu, Pb, Zn) which is hosted mainly in sedimentary terrains of sandstone-pelitic nature of Ordovician age such as, those of Bounhas (Cu, Pb), Afilou n’Khou (Cu) and Rich Marzoug (Cu, Ba) (Boissavy, 1979).

The objectives of the study are multiple. Structural mapping was applied to Landsat-8 Oli images. It is based on the automatic extraction of lineaments after an improvement of the clarity and visibility of the lineaments. Radiometric and atmospheric corrections, color compositions, directional filters applied on spectral bands and principal component analysis (PCA) (Argialas et al., 2004; Thannoun, 2013; Mah et al. 1995; Si Mhamdi et al. 2017; Saidi et al. 2020; Bentahar et al. 2020; Es-Sabbar et al. 2020; Ouhoussa et al. 2022). Mining is carried out using ASTER multispectral images, after preprocessing and processing using band ratios, while delineating iron caps and altered areas (Abrams et al., 1983; Peyghambari and Zhang, 2021; Rajendran and Nasir, 2017; Rowan and Mars, 2003).

2. Geological Setting

The Anti-Atlas is located at the northwestern limit of the West African Craton (Fig.1a) and consists of mountainous relief arranged in a WNW-ENE direction. The precambrian rocks that compose it outcrop in the form of inliers, overlain by more recent units ranging from late Precambrian to Paleozoic sedimentary cover (Choubert, 1947; Gasquet et al. 2005). Stratigraphically, the oldest outcrops in the eastern Anti-Atlas correspond to the Saghro and Ouarzazate groups, formed mainly by volcanic and volcaniclastic rocks deformed during the Pan-African orogeny (Walsh et al., 2012). The basement is unconformably overlain by an important Paleozoic sedimentary cover of calcic and carbonate nature and exhibits thicknesses that can locally reach 4 Km (Fig.2) (Raddi et al., 2007; Baiddar et al., 2008, 2016). In the Eastern Anti-Atlas the two inliers labeled Saghro and Ougnat (Fig.1b) are known by the superposition of tectonic events that controlled E-W and NW-SE major tectonic structures (Baiddar et al. 2008, 2016; Raddi et al. 2007; Robert-charrue, 2006; Hejja et al., 2020; Aabi et al., 2022a). These two tectonic events affected the Tazarine, Maider and Tafilalet basins. According to Michard et al., 2008; Soulaymani et al., 2014; Hejja et al., 2020 and Aabi et al., 2022b, the Hercynian orogeny is responsible for shortening and faulting of the Precambrian basement and folding of the Paleozoic cover.
Fig. 1: a: Location of the Anti-Atlas at the northern limit of the West African Craton (Ennih & Liégeois, 2008; Fabre, 2005; Liégeois et al., 2005), b: Main geological units and mining districts of the Moroccan Anti-Atlas belt (Hollard et al. 1985; Thomas et al. 2004a; Mouttaqi et al. 2011; Tuduri et al. 2018).

Fig. 2: Lithostratigraphic log of the Eastern Anti-Atlas (Raddi et al., 2007)
The taghbalt region is formed by Paleozoic sedimentary cover presented by Ordovician sandstone and shale (1ere and 2 Bani, shals of Ktaoua) (Fig. 3). These formations recorded tectonic evidence of the Hercynian orogeny. In the eastern Anti-Atlas, the Hercynian orogeny allows us to differentiate two structural sub-zones. The structures are oriented NW-SE to NE-SW, and are governed by a NW-SE to E-W tightening (Fig. 4) (Boissavy, 1979; Robert-Charrue, 2006; Baiddar, 2007; Kharis, 2015).

Fig. 3. A: simplified geological map of the High Atlas and Anti-Atlas (Fekkak et al. 2003). B: Geological map of the Taghbalet region (Destombes et al. 1988)

Fig. 4. Tectonic sketch showing polyphase tectonic fault systems deforming the Eastern North slope of Saghro and the Western North slope of Ougnat (after, Baiddar et al., 2007).
3. Data and Methods

In this work, we used as data two types of satellite images: the first one corresponds to the Landsat 8-oli image (Operational land images which is an American satellite for observation of the earth launched in 2013) (Table.1), whereas the second is the ASTER LT1 image (Advanced space borne thermal Emission and reflection Radiometer) Table.2. These images are downleaded from the Earth explorer of the United States web site (USGS).

**Table 1. Spectral characteristics of Landsat 8 OLI (USGS site)**

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (μm)</th>
<th>Resolution</th>
<th>common name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>0.433- 0.453</td>
<td>30</td>
<td>Aerosol / Coastal</td>
</tr>
<tr>
<td>Band 2</td>
<td>0.450-0.515</td>
<td>30</td>
<td>Bleu</td>
</tr>
<tr>
<td>Band 3</td>
<td>0.525-0.600</td>
<td>30</td>
<td>Green</td>
</tr>
<tr>
<td>Band 4</td>
<td>0.630-0.680</td>
<td>30</td>
<td>Red</td>
</tr>
<tr>
<td>Band 5</td>
<td>0.845-0.885</td>
<td>30</td>
<td>NIR</td>
</tr>
<tr>
<td>Band 6</td>
<td>1.560-1.660</td>
<td>30</td>
<td>SWIR 1</td>
</tr>
<tr>
<td>Band 7</td>
<td>2.100-2.300</td>
<td>30</td>
<td>SWIR 2</td>
</tr>
<tr>
<td>Band 8</td>
<td>0.500-0.6800</td>
<td>15</td>
<td>Panchromatic</td>
</tr>
<tr>
<td>Band 9</td>
<td>1.360-1.390</td>
<td>30</td>
<td>Cirrus</td>
</tr>
<tr>
<td>Band 10</td>
<td>10.30-11.30</td>
<td>100</td>
<td>TIR.1</td>
</tr>
<tr>
<td>Band 11</td>
<td>11.50-12.50</td>
<td>100</td>
<td>TIR.2</td>
</tr>
</tbody>
</table>

**Table 2. Spectral bands of the ASTER image**

<table>
<thead>
<tr>
<th>Sybsystem</th>
<th>Band no</th>
<th>Spectral range (μm)</th>
<th>Spatial Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIR</td>
<td>1</td>
<td>0.52 - 0.60</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.63 – 0.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3N</td>
<td>0.76 – 0.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.40 – 1.70</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.145 – 2.185</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.185 – 2.225</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.235 – 2.285</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.295 – 2.365</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.360 – 2.430</td>
<td></td>
</tr>
<tr>
<td>SWIR</td>
<td>10</td>
<td>8.125 – 8.475</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>8.475 – 8.825</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>8.925 – 9.275</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>10.25 – 10.95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>10.95 - 11.65</td>
<td></td>
</tr>
</tbody>
</table>

In this work Landsat 8-oli is used for lineaments extraction and lithological mapping, known for it high potential in fracturing mapping and tectonic investigation especially in arid areas which is the case of the Anti-Atlas belt (Jellouli et al., 2021; Tobi et al., 2022 ; Courba et al., 2023). On the other hand, Aster is used for mining exploration because of its properties and it is recommended for this type of investigation (El-mimouni et al., 2020; Lamrani et al., 2021). The results are checked, verified from field missions and calibrated based on the geological map of Todgha-Maïder. (Destombes et al, 1988).

Fig. 5 shows the strategy followed in the extraction of lineaments and mining using high resolution satellite images.
3.1. Pre-Processing

Before the processing, we have preprocessed and prepared the data of both images (Landsat 8oli and ASTER). These correspond to Radiometric and atmospheric corrections which led to eliminating the atmospheric noise either seasonal or climatic. We note that another preprocessing named “Gram-Schmidt Pan-Sharpening” was applied to the Landsat 8oli image using the panchromatic band (Resolution 15 m). This technique consists to improve the spatial resolution of data which is very useful for structural mapping (Amer et al., 2012).

3.2. Colors Composites

The colors composites technique allows to produce color images with a spectral signature of spatial data. Thus, the optimal index factor (OIF) was used to determine the combination of RGB bands (Red, Green, Blue) that presents the maximum information with less noise (Abrams et al., 1983; Si Mhamdi et al., 2017) Table 3 presents some combinations for geological studies.

<table>
<thead>
<tr>
<th>Colors composites (RGB)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-3-2</td>
<td>Real color of the image.</td>
</tr>
<tr>
<td>2-4-6</td>
<td>Interesting to discern the lithological limits between rocks.</td>
</tr>
<tr>
<td>7-6-5</td>
<td>Best result to use for geological analysis, band 5 is concerned with the presence of iron, band 6 characterizes the general albedo of materials and band 7 is that of hydroxyl minerals.</td>
</tr>
<tr>
<td>7-5-2</td>
<td>Provided the minimum data redundancy, the best result to differentiate between different rock units.</td>
</tr>
</tbody>
</table>
3.3. Band Ratio

Band ratios are used in geology to discriminate rock or mineral indexes. For ASTER images Fig. 4 shows that iron oxides (hematite, geothite) are detectable by using bands 1 and 3; the Al-OH group of clay minerals can be detected by using bands 5 and 6; whereas band 7 and band 8 detects Fe-OH (jarosite, muscovite) and Mg-OH (chlorite, epidote, carbonates), successively (Rajendran and Nasir, 2017). For Landsat 8oli table 4 shows some ratio of bands used.

Table 4. Some combinations of band ratios used in the literature.

<table>
<thead>
<tr>
<th>R</th>
<th>V</th>
<th>B</th>
<th>Référence</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/2</td>
<td>6/5</td>
<td>6/7</td>
<td>(Ali and Pour, 2014)</td>
</tr>
<tr>
<td>5/4</td>
<td>6/5</td>
<td>7/6</td>
<td></td>
</tr>
<tr>
<td>6/5</td>
<td>7/6</td>
<td>4/7</td>
<td>(Adiri et al., 2016)</td>
</tr>
<tr>
<td>5/4</td>
<td>6.5</td>
<td>7/2</td>
<td></td>
</tr>
<tr>
<td>5/7</td>
<td>4/2</td>
<td>3/1</td>
<td>(Ouhoussa et al., 2022)</td>
</tr>
<tr>
<td>6.3</td>
<td>6/1</td>
<td>5/2</td>
<td></td>
</tr>
</tbody>
</table>

3.4. Principal Component Analysis

The PCA technique is a multivariate statistical decomposition technique, which allows the analysis of the variability and dispersion of data from different spectral bands. It is a descriptive method that is built on a geometric model. It is widely used in geological mapping (Abdelouhed et al., 2021; Adiri et al., 2016; Es-Sabbar et al., 2020; Jellouli et al., 2021; Saidi et al., 2020; Zafaty et al., 2023).

3.5. Directional Filtering

It is a tool on ENVI-Classic to remove continuous noise from the satellite image, and it allows to improve the visual quality of the image (Drury, 1986). This digital processing of the image facilitates the identification and extraction which is done using Geomatching 2015 software.

4. Results

4.1. Colors Composites

During processing, several combinations were tested according to spectral sign. In fact the combination that gives the best result and contains the maximum information according to the optimal factor index (OIF) is the blue band, the infrared band (NIR) and mid-infrared 2 (SWIR2) in RGB (RGB: 257). The result of this combination makes it possible to discern the lithology of the Taghbalt sector; it shows the sandstones of 2nd Bani in dark blue to black color and the Sandstones of the first Bani in light blue. It also shows the hydrographic networks in light green color (Fig.6).

4.2. Bands Ratio

In this work we have examined the band ratios of Landsat 8oli in RGB; 5/7, 3/1, 4/3 and 5/7, 5/4, 3/1. The first result Fig.7 allows us to detect the Devonian formation in black color and the sandstone of the first Bani in blue, the formation of Silurian age in orange. Fig.8 shows the Quaternary formation in purple and the sandstone formation in light green.
**Fig. 6**: Landsat 8oli bands in RGB 2-5-7. q: Quaternary; dh: Devonian sandstone and shale; S2: Silurian shale; Ord4: Lower Ordovician 1 Bani sandstone; Or5-b: Upper Ordovician sandstone; Or6-b: Upper Ordovician 2 Bani sandstone.

**Fig. 7**: Ratio of Landsat 8oli bands in RGB 5/7-3/1-4/3. q: Quaternary; dh: Devonian sandstone and shale; S2: Silurian shale; Ord4: Lower Ordovician 1 Bani sandstone; Or5-b: Upper Ordovician sandstone; Or6-b: Upper Ordovician 2 Bani sandstone.
Fig. 8. Ratio of Landsat 8oli bands in RGB 5/7-5/4-3/1. q: Quaternary; dh: Devonian sandstone and shale; S2: Silurian shale; Ord4: Lower Ordovician 1 Bani sandstone; Or5-b: Upper Ordovician sandstone; Or6-b: Upper Ordovician 2 Bani sandstone

4.3. Lineaments Mapping

After extracting automatically lineaments using Geomatica software from bands 1,2,3,4,5,6 and 7, ACP1 to ACP7, applying the directional filters according to 4 directions N-S, NE-SW, E-W and SE-NW in order to map all the lineaments existing in the study area, (fractures, veins, ..). We have chosen band 5 and ACP1. These two gave us the best results.

Fig. 9 shows the automatically extracted lineaments along the 4 directions (N00, N45, N90 and N130). The compilation of the two lineament maps from band 5 and PCA1 allows establishing a synthetic lineament map of the study area Fig.10. The correction of this map consists in eliminating the linear structures (Road, River, Ridge line...), correcting the geometry and illuminating the lineament redundancies. The validation of the result is done in a first time by the images of Google Earth, and in a second time by the pre-existing data and the missions of the ground.

The rose digram of the lineaments shown in Fig.11a, shows main directions; N-E and NE-SW. These two directions are comparable with the data of our area Fig.11b pre-existing in the Todgha-Maider map. The E-W direction is located mainly in the Jbel amghorfi and in the north of the study area, while the NE-SW direction is developed mainly in the southwest and in the west in general.
Fig. 9. Extracted lineaments from spatial filtering of the ACP1 Landsat 8oli. A Filter N-S. B Filter NE-SW. C Filter E-W. D Filter NW-SE.

Fig. 10. Synthetic map of ACP1 and band5 lineaments in the study area.
Fig. 11. a: Directional rose of automatically extracted lineaments. b: Directional rose of existing faults in the study area.

4.4. Mineralogical Indices

In this part we used the ASTER image to detect the areas of mineralization. In this purpose Rajendran and Nasir 2017 made a study on laboratory gives the properties of spectral bands of ASTER image. Iron oxides (hematite, geothite) are detectable by bands 1 and 3, the Al-OH group of clay minerals by bands 5 and 6, band 7 detects Fe-OH (jarosite, muscovite) and band 8 detects Mg-OH (chlorite, epidote, carbonates) Fig. 12.

In our work we used the reports proposed by Rowan and Mars 2003; Hewson et al. 2005.

- Clay zone (Allunite, Kaolinite and Pyrophylite): Band4+Band6 / Band5
- Prophylactic Zone (Carbonates, Chlorite and Episode): Band7+Band9 / Band8
- Oxidation Zone (Fe2+): Band5/Band3 + Band1/Band2
- Phyllic Zone (Sericite, Muscovite and Ellite): Band5+Band7 / Band6

Fig. 12. Laboratory spectra of minerals from hydrothermal alteration zones stacked from the USGS Spectral Library for Minerals. (Rajendran and Nasir, 2017).
Fig. 13. Hydrothermal alteration map of the study area

The combination of the different results obtained by processing satellite images allowed us to produce a synthetic map Fig. 14. The validation of the data was made based on the pre-existing geological map and field missions. The field work shows that the area is occupied mainly by Ordovician formations with outcrops of carbonates of Devonian limestone to orthoceras Fig15a, and green shales of Silurian. The dominant formations in the area are the sandstone formations of the first and second Bani between them we have the shale formations Fzeouata and Ktaoua respectively. (Fig.15b, c)

Structurally, the lineament map shows the existence of two main directions; E-W and NE-SW. The E-W direction, this family of faults shows an early normal movement and a stalling play due to their reactivation during the Hercynian deformation phase (Baidder, 2007).

Locally we have defined normal faults N80, 65NW (Fig.15d) and dislocations with directions N40 to N90. Thus the region experienced a significant ductile deformation, in this sense folds have been mapped (Fig.15e) exhibiting axes oriented N80 to N130. It is important to note that these faults have a metallogenic significance (Sassioui et al., 2022). About the NE-SW direction, this family of faults represents in Taghbalt receptacles of barite-rich vein-type mineralization. These results are the same in the whole region, Maider Basin and Tafilalet. For example at Jbek Tijekht (Saidi et al., 2020), and Jbel Ras Kammouna (Es-Sabbar et al., 2020) in the Southeast of the area. The structures are oriented NE-SW and E-W.

The zone is characterized by a vein-type mineralization, where barite veins are of a small thickness directed N90-120, 85S (Fig.16a). Moreover, there are showings of iron and malachite. At the level of the upper Ordovician formation, barite veins with lead sulphides were discovered (Fig. 16b, c).
Fig. 14. Synthetic map of the area

Fig. 15. Field photographs showing different lithological units and structures of study area
5. Conclusions

The present paper constitutes a contribution of remote sensing in the structural and mineralogical study using two types of satellite images; Landsat 8 Oli and Aster, with multiple processing in area known by its full mining potential of artisanal type. In conclusion, the structural study of the Taghbalet area gives two main directions: E-W and NE-SW, the exploitable mineralized fractures are mainly hosted in the second Bani sandstone formations. The results of the hydrothermal maps extracted from the spectral bands show that the zone is rich in phytic, prophylic, clay minerals and iron oxides, these zones have an excellent relationship with the fault system. Through the analysis and interpretation of the data we have gathered, we have obtained valuable geological documentation that has greatly enhanced our understanding of the area. This knowledge has played a pivotal role in shaping our approach to exploration and executing mining operations, with a particular focus on promoting local development. The insights derived from the data have provided us with a solid foundation upon which to make informed decisions and drive progress towards achieving our goals.

References


