Mapping lineaments using Landsat 8 OLI and SRTM in the Boumalne-Imiter regions of the southern Central High Atlas. Morocco

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Research Article

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Abstract

This work presents the results of the automatic extraction of lineaments in the region of Boumalne-Imter, which is located on the southern front of the Central High Atlas. These lineaments are extracted by remote sensing and Geographic Information System (GIS) approaches. These approaches are based on the first principal component (PC1) and the panchromatic band (B8), which are derived from a Landsat 8 OLI satellite image. These data underwent a 3x3 matrix directional filtering, with the addition of a shading effect on the digital terrain module STRM. These treatments allowed us to establish a synthetic lineament map of the study area. It consists of 1251 lineaments whose length varies between 407.75 m and 8.7 km and whose distribution is dominated by the class with lengths varying between 400 m and 1422 m. The direction of the lineaments is dominated by three families respectively, NE-SW, ENE-WSW and E-W. The density map shows a high intensity in the Saghro Massif (Eastern Anti-Atlas) and in the area that extends between the village of Ait Ibrirne and Arg-n-Sidi Ali Oubourk. Validation of these results is based on comparison of the synthetic map with the geological maps, the high-resolution satellite image (ESRI), in addition to two factors for validation. The first of these is the lithological factor, which shows us that the lineaments are often focused in the competent rocks, as is the case of the magmatic rocks of Saghro Massif in the south-east and also the limestones of the Jurassic and Paleocene-Eocene in the north. However, the second factor is the superimposition of the lineaments on the map of the slopes. This reflects that the concentration of lineaments is quite marked in places where the slopes are steep by steep, while the abrupt change of slopes is probably generated by the play of faults. The correlation of these results with previous work allows us to say that the area is made up of two domains. The first corresponds to the poly-orogenic Anti-Atlas with a very important tectonic heritage. The second is attached to the Atlasic domain, influenced by the southern Atlasic accident which is expressed by overlaps that occurred during the Atlasic uplift. The method of automatic extraction of structural lineaments is considered a useful reference technique due to its validity and accuracy in the selection of structural lineaments, and is considered as having an additional value in this type of study.

Introduction

Remote sensing and the Geographic Information System (GIS) are among the means commonly used in geological studies in most of its disciplines (hydrogeology, hydrology, lithological mapping, geomorphology, structural ...). Both means with their several techniques provide opportunities to conduct studies and analyses on large areas without direct contact with the land, and to obtain statistical information in each type of study. This work is focused on the automatic extraction of tectonic lineaments on the southern slope of the Central High Atlas and the northern front of the Eastern Anti-Atlas (Saghro Massif), and specifically in the Boumalne syncline, which constitutes the eastern part of the Ouarzazate Basin. Furthermore, the lineaments are linear or curvilinear discontinuities in direct connection, with faults and fractures of composite character; they are associated with varied geomorphological features and tectonic structures (El Hadani 1997). While this method can detect all objects that have linear or slightly curved shapes, among them we must discriminate the lineaments that
have a relationship with the study objective, which in this work is interested in lineaments of tectonic origin (faults, fractures, tectonic accidents ...) and in eliminating the non-geological lineaments (ridge lines, talwegs, cliffs ...). The effectiveness of the automatic technique for the extraction of lineaments by processing satellite images is well recognized for its speed and coverage of large areas to enable the addition of geostatistical information (lengths, numbers, directions, density ...), unlike traditional field work which is relatively slow compared to this approach, and where statistics are often very rare. The method of lineament extraction has shown its validity and accuracy through its use in numerous studies by several authors. For example, we can cite the mapping of structural lineaments in the regions of Bou Azzer-Ouarzazate (Idrissi 1999), a hydrogeological study of the Ziz Basin (Nouayti, Khattach, and Hilali 2017), automatic extraction of lineaments in Sidi Felah-Bouskour by (Jellouli et al. 2021), a recent study that was also obtained at the level of Iknouin Eastern Anti-Atlas (Farah Abdelouhed, Algouti Ahmed, Algouti Abdellah 2021), as well as the use by the same author of the automatic extraction of lineaments in the regions of Imini-Ounilla-Asfalou (Farah et al. 2022) while a study of lineament extraction in the regions of Imilchil-Tounfite (the High Central Atlas) was carried out by (El Moujahid et al. 2016). In the side of Morocco countries, as Nvogayong massif south of Cameroon (Ndong et al. 2014), the semi-automatic extraction of lineaments at the El Kseibat region in the south of Algeria by the Landsat-7 ETM + image was performed by (Hammad, Djidel, and Maabedi 2016). These previous works based on remote sensing approaches in combination with the GIS system show the validity of these types of studies based on lineament mapping by satellite images.

The realization of this work is based on the use of the satellite sensor Landsat 8 OLI (Operational Land Imager) and the digital terrain module SRTM (Shuttle Radar Topography Mission) that covers our study area. The choice of the Landsat 8 OLI sensor was based on its resolution and sharpness and also its spatial extension, and in addition its use in many works by several authors (Khadouja Nedjraoui et al., 2021; Danold, 2021; Bentahar, 2020; Es Sabbar, 2020; Hamdani, 2019; Ling Han, 2018; Adhab, 2014; Imikaltouma Ibrahim, 2012) has yielded very effective results, reflecting the success of the Landsat 8 OLI image in this category of study. Several steps and techniques were undertaken concerning the preprocessing and processing of all these data, ranging from radiometric, atmospheric and geometric corrections applied on the Landsat 8 OLI image, the application of directional filtering to a 3*3 matrix by ENVI Classic software on the first principal component analysis (PCA1), and shading on SRTM under ArcGis 10.3, then finally the extraction of lineaments using the algorithmic module LINE EXTRACTION of PCI Geomatica 2013.

The main objective of this work is to map the most possible structural lineaments through the automatic extraction of lineaments on the southern front of the Central High Atlas, using several methods based on remote sensing, and to combine the results from different sources of information, such as the first principal component, the panchromatic band and SRTM, in order to obtain a synthetic lineament map, and also to establish the relationship between the distribution of the lineaments and that of major faults, in order to enrich the structural side of this sector, and to better clarify the geodynamic evolution.
The study area is located in the western end of the southern slope of the Central High Atlas, and on the northern edge of the Saghro Massif (Anti-Atlas). It corresponds to the central part of the pre-African furrow, and more precisely to the eastern part of the Ouarzazate Basin. In administrative terms, the study area is located in the regions of Draa Tafilalet and exactly in the province of Tinghir. It is accessible by the national road N°10 which connects Ouarzazate and Errachidia, via Boumalne Dades, Imiter, Timadrouine and Tinghir. This area is bounded to the south by the northern front of the Saghro Massif (Eastern Anti-Atlas), to the north by the southern slopes of the Central High Atlas, and the city of Tinghir to the east, whose western boundary corresponds to the region of Boumalne and Oued Dades (Fig. 1). The coordinates of the four corners of the area are given in Table 1. In geomorphological terms, the study area is characterized by altitudes that vary between 1300 m and 3500 m, increasing from south to north. The center of the area is occupied, by an intermontane plain between the Anti-Atlas and the Central High Atlas, with very little to no vegetation cover. The climate is arid to semi-arid with irregular rainfall (Agoussine et al. 2008). Oued Dades is the only valley that crosses the area, and has its source in the Central High Atlas, so that it flows south to southwest.

Table 1
coordinates of four corners of the study area.

<table>
<thead>
<tr>
<th>Points</th>
<th>Coordinate système : WGS1984 UTM zone 29N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Projection: Transverse Mercator / Units: Degree minuts seconds</td>
</tr>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>5° 34'26,4&quot; W</td>
</tr>
<tr>
<td>2</td>
<td>6° 3’ 3,8 “ W</td>
</tr>
<tr>
<td>3</td>
<td>5° 34'27 “ W</td>
</tr>
<tr>
<td>4</td>
<td>6° 2’ 58 “ W</td>
</tr>
</tbody>
</table>

Geological setting

From the geological point of view, the area is constituted by the Precambrian basement, and is formed essentially of volcanic and volcanic series, testifying to a predominantly explosive volcanism, which are intruded by diorites and granites (Saquaque 1992). The Paleozoic cover in the Saghro Massif (Eastern Anti-Atlas) begins directly with formations attributed to the Cambrian, and on the latter (Cambrian) we have the carbonate and sandstone-pelitic sequences of the Ordovician, Silurian, Devonian and Carboniferous. They have a general weak to medium dip towards the North (Ouguir, Macaudiere, and Dagallier 1996)(TUDURI Johann 2005)(BAİDDER-2007 2007)(Eddine et al. 2007). The Meso-Cenozoic begins with the Jurassic deposits which are in the form of two facies; the carbonate Jurassic corresponds to the Lower and Middle Liassic with a thickness of up to 1500 m, and the other facies corresponds to the detrital continental Jurassic formed by sandstones, and conglomerates (Jossen and Filali Moutei 1988). The facies that are formed by massive or bedded limestone and dolomite correspond to the formation of the ouchbis (M Ettaki 2003). The Cretaceous starts with the infra-Cenomanian formed
by sandstones and conglomerates with fluvial type bedding (Rhalmi et al. 2000). It is surmounted by a limestone to marly beige limestone, in layers that are generally massive with nodules of selix, belonging to the Cenoman-Turonian (Eddine et al. 2007)(Massironi et al. 2007). Then, the Senonian is constituted at the base by conglomerates, surmounted by alternating red pelitic layers, that are often intercalated by levels of gypsum, whose top is formed by conglomeratic reddish sandstones (Eddine et al. 2007). The Paleocene-Eocene is named the subatlas group by (Herbig 1994), and is formed by a transgressive-regressive megacycle which is mainly constituted by phosphate and carbonate sediments, marl, siltstone and sandstone. The center of the Ouarzazate Basin is filled by continental detrital sediments of Miocene-Quaternary age (Boummane, Jaffal, and Khikach 2009).

Structurally, the study area is part of the Ouarzazate watershed, which corresponds to a tectonic depression located between the mobile zone in surrection, of the High Atlas and the stable domain of the Anti-Atlas (EL HARFI, Lang, and Salomon 1996). This place is limited to the north by the South Atlastic accident, whose southern limit, is marked by the Anti-Atlas terrain (Rhalmi et al. 2000). This basin is characterized by two major tectonic phases, the Triassic-Jurassic extension and the Atlas compression to Oligocene. The legacy of this tectonic phase is well observed, in the northern part of the Ouarzazate basin (Boummane, Jaffal, and Khikach 2009)(Laville, Lesage, and Seguret 1977). The Anti-Atlas has a very important and ancient tectonic legacy ranging from the Eburnian orogeny, to the Hercynian to Alpine (BAIDDER-2007 2007)(Robert-Charrue 2006). This succession of tectonic events makes the Anti-Atlas domain very faulted and fractured. Our area is overlain by the Sagho massif limited to the north by the South-Atlastic accident, and to the south by the major accident of the Anti-Atlas (Alansari, Mouguina, and Maacha 2011).

**Methodology And Work Data**

**Data of the work**

The database of this work is constituted mainly by a Landsat 8 OLI satellite image comprising 11 bands (Table 2), of which the panchromatic band 8 has a spatial resolution of 15 m, while 8 bands (OLI 1, 2, 3,4, 5, 6, 7, 9) have a spatial resolution of 30 m and the bands TIRS 10 and TIRS 11 are up to 100 m. This scene covers the area of Boumalne-Tinghir with Path 201 ROW 38 and a date of acquisition of 2021-06-05, which characterizes the summer season to avoid cloud cover. In this work, only bands 2, 3, 4, 5, 6, 7 and 8 are used. Also used is a digital terrain module SRTM having a resolution of 30 m. All these data are downloaded from the site (), in addition to which we use geological maps of different scales covering the study area, namely the geological map of Boumalne 1/50 000 (Massironi et al. 2007), the geological map of Imiter 1/50 000 (A.SCHIAVO 2007) and the map of Jbel Saghro Dades 1/ 200 000 (Hindermeyer et al. 1977). Using these geological maps, we digitized the major lineaments that affect the study area (Fig. 3) to obtain a general idea of the distribution of the tectonic structures in the area. All these data are projected in the WGS 1984 UTM zone 29 coordination system.
Table 2
Landsat Oli8 bands used in this work.

<table>
<thead>
<tr>
<th>Bands</th>
<th>Wavelength (µm)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 - Blue</td>
<td>0.45–0.51</td>
<td>30</td>
</tr>
<tr>
<td>B3 - Green</td>
<td>0.53 - 0.59</td>
<td>30</td>
</tr>
<tr>
<td>B4 - Red</td>
<td>0.64–0.67</td>
<td>30</td>
</tr>
<tr>
<td>B5 - Near Infrared NIR</td>
<td>0.85–0.88</td>
<td>30</td>
</tr>
<tr>
<td>B6 - SWIR 1</td>
<td>1.57–1.65</td>
<td>30</td>
</tr>
<tr>
<td>B7 - SWIR2</td>
<td>2.11–2.29</td>
<td>30</td>
</tr>
<tr>
<td>B8 - Panchromatic</td>
<td>0.50–0.68</td>
<td>15</td>
</tr>
</tbody>
</table>

Methodology

The extraction of the lineaments was performed by an automatic method from many remote sensing steps that were applied on the satellite data (Landsat 8 OLI and SRTM image). Before starting the processing, these data must undergo some preprocessing steps for the spectral bands of the usable satellite image (Landsat 8 OLI). This preprocessing includes radiometric, geometric and atmospheric correction that serves to reduce the impact of distortions during the recording of the scene by the satellite. In addition, other steps consist of increasing the sharpness of the image by changing the pixel dimensions from 30 m to 15 m, using the panchromatic band (Band 8) and the algorithmic function pansharpening, then the extraction of the area that interests us. Finally, we have a scene that will be processed through several steps that are summarized in diagrams for the automatic extraction of lineaments (Fig. 5). After the application of directional filtering with the 3*3 matrix on the panchromatic band and the first principal component (PC1), the effect of shading on SRTM is analyzed. Then, the automatic extraction of the lineaments was applied on the set by the "line extraction" function in the Geomatica 2013 software, using some basic parameters of this software which are mentioned in the table (Table 3). Confirmation of the results obtained was based on a more detailed verification, to remove the linear forms that are not structural (ravines, ridge cloths, cliffs ...) and eliminate anthropic interventions (walls, tracks, roads ...), and also based on high-resolution satellite images (ESRI, MAXAR, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, AeroGRID, IGN and the GIS User Community) and geological maps of the study area in addition to the field works.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Signification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter radius (Pixels)</td>
<td>5</td>
<td>Specifies the radius of the edge detection filter, in pixels. This parameter roughly determines the smallest-detail level in the input image to be detected. A large RADI (Filter Radius) value indicates that less detail can be detected, and also less noise.</td>
</tr>
<tr>
<td>Edg Gradient Threshold</td>
<td>20</td>
<td>Specifies the threshold, in pixels, for the minimum gradient level for an edge pixel. This value must be in the range of 0 to 255.</td>
</tr>
<tr>
<td>Cuvre Length Threshold (Pixels)</td>
<td>80</td>
<td>Specifies the minimum length of curve, in pixels, to be considered as lineament or for further consideration; for example, linking with other curves.</td>
</tr>
<tr>
<td>Line Fitting Error Threshold</td>
<td>3</td>
<td>Specifies the maximum error, in pixels, allowed when fitting a polyline to a pixel curve. Lower values provide better fitting, but also shorter segments in the polyline.</td>
</tr>
<tr>
<td>Angular Difference Threshold (Degrees)</td>
<td>30</td>
<td>Specifies the maximum angle, in degrees, between segments of a polyline. If the angle exceeds the specified maximum, the polyline is segmented into two or more vectors. This angle also defines the maximum angle between two vectors for them to be linked.</td>
</tr>
<tr>
<td>Linking Distance Threshold (Pixels)</td>
<td>50</td>
<td>Specifies the minimum distance, in pixels, between the end points of two vectors for them to be linked.</td>
</tr>
</tbody>
</table>

**Processing**

**Principal component analysis**

The principal component analysis technique is a statistical method widely used in geological studies (Gabr, Ghulam, and Kusky 2010) (Amin Beiranvand Pour and Hashim 2011) (Amin Beiranvand Pour and Hashim 2012) (Adiri et al. 2017). This method allows the assembly of the information contained in the initial bands in the form of neo-bands called principal components (PC) (Gabr, Ghulam, and Kusky 2010) (Adiri et al. 2017). Therefore, PCA is used to enhance and separate certain types of spectral signatures from the background (Gabr, Ghulam, and Kusky 2010). In this work we are interested in the first component (PC1) because of its sharpness, and because the percentage of variance that the PCA1 axis contains is greater than that of the PCA2 axis which is, in turn, greater than that of the PCA3 axis (Himyari et al. 2001).

**Directional filtering**

Directional filtering is among the treatments used, and consists in the enhancement of an image. The main objective of directional filters is to detect all linear shapes in order to reduce the blurring and smoothing of the image (Farah Abdelouhed, Algouti Ahmed, Algouti Abdellah 2021). According to (Bonn
and Rochon 1992), in the case of applications in geology, these filters are used to detect fractures with large spatial frequencies, and wavelengths of the order of 10 to 100 m on the ground. The directional filter used in this study is a 3*3 matrix, in order to generate the finest structures (Coulibaly 1996). This is applied to the first principal component PC1 (Fig. 7) and the OLI panchromatic band 8 (Fig. 9), in four different directions (N0°, N45°, N90° and N135°) (Figs. 8 and 10).

**Shading:**

Analytical hillshading, is a technique for generating shaded topographic images of the Earth's surface elevations. It simulates the reflection of artificial light arriving from a point source of illumination from a given altitude (tilt) and azimuth (declination) (Masoud and Koike 2006) In this study, the application of shading is done on the SRTM digital terrain module that covers our study area. Then, the choice of angles 0°, 45°, 90°, 135° (Fig. 11). The boundaries between shaded and unshaded areas can indicate the presence of lineaments (Masoud and Koike 2006)(Abarca et al. 2006)(Saadi et al. 2011).

**Results And Discussion**

Following the previous processing techniques, and after the elimination of all the linear shapes that do not correspond to lineaments of geological, or structural origin, we obtain the lineament maps from the automatic lineament extraction method. These are applied on all four directional filters of the panchromatic band (B8), and those of the first principal component (PC1); also on the four shadings of the digital modulus of the SRTM terrain. These maps are accompanied by statistics that reflect the numbers of lineaments, their lengths and the frequency of their distribution as a function of length in the study space and the directional roses that are created from the proportion of the cumulative lengths of the lineaments. The results of the first principal component (PC1) show a map that consists of 286 lineaments (Fig. 12-A), whose minimum length is 408.04 m and maximum length is almost 8655 m, with an average of 1781.91 m. The total distribution of the lineaments is dominated by classes with lengths that vary between 408 m and 1675.1 m with percentages that range between 80% and 100% (Fig. 12-C). The directional roses of the lineaments for the first component (PCA1) show that the NE-SW to ENE-WSW direction is the most dominant (Fig. 12-D). For the OLI 8 panchromatic band, 436 lineaments were extracted (Fig. 13-A) with a minimum length of 299.7 m and maximum length of 5.906 km, and an average length of 1.537 km. The lineamentary direction of the panchromatic band is generally closer to that of the (PC1), being dominated by NE-SW with a minority that approaches the E-W direction (Fig. 13-D), with the frequency of the distribution reaching 100% for the class that varied between 500 m and 1000 m. The lineaments that are extracted from SRTM number 341 (Fig. 14-A), have different lengths ranging from 981.43 m to 4.988 km, with an average length of 1759.9 m. The lineament population is dominated by the class that has lengths varying between 981 m and 1.5 km (60–80%) (Fig. 14-C). The directional diagram (Fig. 14-D) shows two major directions, one running ENE-WSW to E-W while the other is almost N-S.
The directional roses of all the lineament maps from PCA1, the panchromatic band and STRM show common points that reflect the dominance of the NE-SW to ENE-WSW direction. These two directions are identical to the direction of the major faults that are digitized from the geological maps of the study area (Fig. 3).

The density maps show the areas most populated by lineaments according to their spatial distributions. At the level of the study area, the lineament density maps (Fig. 15) reflect that the highest densities are focused in the southern to southeastern part that corresponds to the Anti-Atlas domain. This domain is one of the terrains that witnessed several orogenic cycles, inheriting highly fractured terrains. Another strong intensity is located in the northern part, forming a belt located in areas that are characterized by the overlap of the Liassic formations on the Cenozoic terrains. However, the center of the area is sparsely populated. The three density maps obtained from PC1, the panchromatic band and STRM (Fig. 15, B, C, and D respectively) show a close approximation to the density map of major faults (Fig. 15-A).

After superimposing the results of the first principal component, the panchromatic band and STRM, we obtain a synthetic map of the lineaments (Fig. 16-A). It groups 1251 lineaments with metric to kilometer lengths that vary between 400 m and 8.7 km, with the average length of 1331 m, and whose sum of lengths is 166538.02 m. The frequency of the distribution is dominated by the class that has a length that varies between 407 m and 1422 m (Fig. 16-C). The majority of the lineaments are located in the Saghro Massif (eastern Anti-Atlas), and in the northern zone of the Boumalne syncline, from the village of Ayt Ibrirene to the village of Arg Ali Oubork. The direction of these lineaments is dominated by two major families, NE-SW to ENE-WSW with a minority that has an E-W direction (Fig. 16-D).

In the same context, there are many previous works based on the extraction of lineaments in the same area or else in its surroundings. According to (Aaggad et al. 2016), the distribution of lineaments in this area is dominated by three families, of which the most important family has a direction that varies between N50° (NE-SW) and N80° (ENE-WSW to E-W), a direction that corresponds to the overall direction of the major High Atlasic accident. In the Imiter regions,(Abdelouhed et al. 2021) shows a dominance of the NE-SW direction based on the extraction of Landsat OLI 8 and STRM lineaments. The same author, Farah et al. (2021) (Farah Abdelouhed, Algouti Ahmed, Algouti Abdellah 2021) concludes that the distribution of lineaments in the vicinity of the Iknouin region is dominated by two major directions, NE-SW and E-W. Another study carried out in the Boumalne (Ait Ibrirn) area by (Konty et al. 2021) shows a dominance of two directions, which are NE-SW and E-W. The correlation of our results with previous geoscientific studies concerns the tectonic and structural sides in the study area. As concerns the Todgha-Dades region, (Mohammed Ettaki et al. 2000) shows that the structuring of this region is governed by a set of faults whose map axes show curved trends with a NE-SW direction, and which straighten towards the NNE. Meanwhile, (TUDURI Johann 2005) shows that the terrains of the Anti-Atlas (Saghro Massif) are constituted by three families, the most dominant of which is characterized by plurikilometric structures, with horizontal dexterous discharges, oriented N60° (NE-SW to ENE-WSW) and N90° (E-W), where the second family is kilometerized with directions that vary between N-S and N150°. The last family is composed of fractures oriented N20° to N40° with a weak extension. They are well
marked in the Paleozoic cover. Similarly, (CHAKER 1997) describes that the NE-SW fault system is the most dense compared to the two NW-SE and N-S systems. In the same area (Anti-Atlas), analyzing the Imiter buttonhole, which belongs to the Saghro Massif, (Saquaque 1992) (State Thesis) shows that this area is characterized by two families of faults, with orientations NE-SW and E-W. Dykes are associated with these faults. This association between faults and veins and dykes can be expressed in this work by a high population of lineaments, which is of course the case in this part of the study area. (Benammi, M., Toto, E.A. et Chakiri 2005) shows that the axes of the major structures (folds, fold-faults and intrusions) in the Central High Atlas are generally distributed along three preferred directions, in order of frequency: NE-SW, WNW-ESE, E-W.

From the correlation of our results and previous works, whether geological and geoscientific studies or works based on remote sensing, we notice that all the datasets show results that are similar or identical. In order to validate our results, we will compare the synthetic lineaments maps with the geological maps that show the distribution of major faults in the targeted area. In addition, we draw on two other factors that will intervene in the confirmation of these results, the first factor corresponding to the lithological map, and the second corresponding to the comparison of the lineaments with the map of the slopes. Moreover, field investigation is also very helpful in this study.

**The lithological factor**

The lithological nature of the formations that constitute the area is among the factors that intervene in the recording of faults and structural lineaments. This intervention is well marked in the differentiation of the hardness of the rocks, knowing that the competent rocks can keep the movement of the faults, and the offsets of the bars, veins and dykes, while the rocks that are less hard to fragile cannot preserve these traces. That is why we examine the integration of the lithological factor in order to understand its impact on the spatial distribution of the lineaments. The study area is generally constituted by two parts that differ from the lithological point of view. The superposition of the lineaments on the lithological map of the study area shows us that almost the totality of the lineaments are concentrated in the parts that are constituted of competent rocks, while there is impoverishment of the lineaments in the formations that are less hard and fragile. In our case study, the concentration of lineaments is well marked in the Precambrian basement of the Saghro Massif, which is generally formed of magmatic rocks. In the north, the lineaments are very concentrated in the Paleocene-Eocene limestone formations, and some parts in the Jurassic dolomitic limestone, while in the fragile formations (silt, sandstone silt, marl and scree) of the Cretaceous to Quaternary, the geological lineamentary structures are weakly detected.

**The slopes factor:**

The comparison of the lineaments with the maps of slopes is among a number of validation approaches, where the morphology and geomorphology of the current landscapes are probably generated by tectonic activities that result in the inclination and depressions generated by the movement of faults. The superposition of the lineaments from the PC1, the panchromatic band and STRM on the map of slopes drawn from the digital terrain module (Figure 18) shows that the majority of lineaments are focused in
areas of steep slopes, and where there are sharp variations in the topographic profile, specifically in the southeast (Saghro Massif), but also in the northern part (the southern front of the Central High Atlas), while the areas of low slope (the central area) show an impoverishment of lineaments.

**Fields investigations**

Our field mission consisted mainly in validating our results, which are distributed throughout the study area, including some places having difficult access and others that are moderately accessible. For this reason and to understand the influence of remote sensing in digital mapping, several places were visited in order to confirm the presence or not of some of the linear structures detected previously. In Figures 19 and 20, we provide some places with the structures detected. Although other details see even their location on maps well selected, just for precision, our study area is divided into two large geomorphological parts, the first corresponding to Jbel Saghrou with the dominance of the moderate north and south-western slopes (Figure 19, a-3, a-4, a-5 and a-6). The second zone is formed by the Ait Sedrat mountain (Figure 19, a-1, b-2, b-3 and b-4). This area generally corresponds to the southern slopes of the Atlas Mountains, which have the sharpest slopes. The distribution of slopes is dominated by those facing north and southwest, with some slopes exposed to the southeast. The intermediate area between these two chains (Saghrou and Ait Sedrat) corresponds to an intermontane plain in which the slope is more or less low, i.e., the exposure of the slopes is low and very variable except for the bank of the Dades valley, which is exposed to the south-west (Figure 19. Photo a and b). Some lineament structures have been eliminated during the realization of the final lineament map (Figure 19. a-5), but other structures are considered true lineaments, as shown in the photo (Figure 19, a-4). This network of metric or even kilometer fractures affects the Saghrou Massif, which partially explains the high concentration of lineaments in all the maps made prior to our visit in the other part of the study area. The southern border of the Central High Atlas is much more confirmatory in terms of the lineaments and non-lineaments detected. In (Figure 19, a-1) at the level of Sidi Ali Oubork, we can observe a panoramic view, grouping the two geological formations of the upper Cretaceous and the Paleocene over a thickness of more than 130 m, a precise observation of the contacts, although a comparison of some facies already existing on the earlier geological map has been updated. In this way, several non-lineamentary structures have been located. This field mission was coupled with the use of new structural maps produced in the same places of study by several authors to validate some of the lineaments, namely faults in several places (Figure 19, a-3, a-4 and a-5, b-3, b-4). In Figure 18, we summarize, with legend, all the probable non-linear structures that will negatively influence the accuracy of the numerical mapping that we review in the following study.

**Conclusion**

The automatic extraction of lineaments is considered a very important and positive method in geological studies. This technique of lineament extraction serves to reduce the time spent on field missions, and also has informational importance from the geodynamic point of view, and the tectonic heritage of the study area. This work is based on the Landsat 8 OLI sensor, which is commonly used in this type of study
because of its spectral potential and its spatial extension. According to it, we have derived the first principal component and the panchromatic band, with the addition of the digital field module STRM, with a resolution of 30 m. All these data are processed through a specific method in order to extract the most possible structural lineaments constituting the study area.

The synthetic map of lineaments obtained as the final result is validated by high-resolution satellite images (ESRI) and geological maps that cover the same area and field missions. The statistical and spatial analyses show that the area is constituted by 1251 lineaments with lengths that vary between 400 m and 8760 m, with the average length of 1331 m. The frequency of the lineament distribution is dominated by lineaments that have lengths of 400 m and 1500 m. The highest populations of lineaments are well concentrated, always around the major faults and thrust faults known in these places, while the highest densities are focused in the Saghro Massif (Eastern Anti-Atlas) and in the thrust zones (the southern front of the Central High Atlas).

The introduction of remote sensing and the Geographic Information System into structural lineament mapping in an automatic way enables efficient and precise definition of the lineaments and speed in the discovery of the fractured zones, and this technique also enables the generation of statistics concerning the length, density, and frequency of the distribution. Moreover, this study is useful as a reference for other studies, potentially such as hydrogeological studies, mining research and so on.

**Declarations**

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**Authors’ contributions**

Moujane said: investigation, methodology, writing—original draft. Farah Abdelouhed: investigation, methodology, writing—original draft, Ahmed Algouti and Abdellah Algouti: Validation, writing— review and editing, supervision. The authors read and approved the final manuscript.

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Abbreviations

N
North
S
South
E
East
W
West
X
Latitude
Y
Longitude

OLI
Operational Land Imager

PC1
Principal component 1

SRTM
Shuttle Radar Topography Mission

UTM
Universal Transverse Mercator projection

ESRI
Environmental Systems Research Institute

ENVI
Environment for Visualizing Images

WGS
World Geodetic System

References


Figures
Figure 1

Geographical location of the study area: A: National scale. B: At the regional scale. C: The digital field module.
Figure 2

Structural scheme of the Boumalne syncline, the eastern part of the Ouarzazate basin (based on the geological map of Boumalne 1/50 000 (MASSIRONI et al 2007) and the geological map of Imiter 1/50 000 (SCHIAVO et al 2007).
**Figure 3**

Figure 4

3D representation of a view to the east of: A: the RGB 652 Landsat 8 OLI combination. B: The digital terrain module. C: The North-South topographic profile, Section A-B.
Figure 5

Flowchart of the automatic lineament extraction methodology.
Figure 6

the natural color composition RGB 432.
Figure 7

The first principal component (PC1).
Figure 8

Figure 9

The panchromatic band (B8), Landsat 8 OLI.
Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

The density map of: A: major faults in the study area. B: lineaments of the PC1. C: lineaments of the panchromatic band. D: lineaments of the digital terrain modulus STRM.
Figure 16

A: synthetic map of the lineaments with the high resolution satellite image background (ESRI). B: table of statistics. C: frequency diagram of the distribution of lineaments as a function of length. D: directional diagram.
**Figure 17**

The superposition of the lineaments on the lithological map of the study area.
Figure 18

Figure 19

Plate showing the different areas visited, a) Structural diagram of the Boumalne syncline, eastern part of the Ouarzazate basin (based on the geological map of Boumalne 1/50 000 (MASSIRONI et al 2007) and the geological map of Imiter 1/50 000 (SCHIAVO et al 2007), a-1) Southern edge of the High Atlas, Sidi Ali Oubork area, with a detailed section of the area on the right of the picture above, a-2 a-3) Structural map of the Saghro massif, interpreted from Hindermeyer et al. [1977], Tuduri et al. [2018], Hejja et al. [2020],
Aabi et al. [2020], and this work, b) 3D representation of a view of the RGB 652 landsat 8 Oli combination, a-4, a-5) some lineaments and non-lineaments detected and considered in this work in the Anti Atlas part, b-3, b-4) some lineaments and non-lineaments detected and considered in this work in the central High Atlas part.

Figure 20
Plate showing non-linear structures in the study area, on RGB 432 natural color composition (A, B, C, D and F) showing the following features (stream, talweg, cliffs, road, railroad, border, vertical beds, cliffs, rivers) as mentioned in the Methodolog section to remove linear forms that were not structural.