Introduction

Lineaments are natural and linear terrestrial surface features interpreted directly from satellite images and geophysical maps, called fracture traces (O’leary et al., 1976; Moore and Waltz, 1983). Mapping and lineament analysis from remote sensing data is an important approach for regional structural and tectonic studies (Solomon and Ghebreab, 2006). The aim of this work is to analyse the lineaments of the Ouaouizaght syncline in terms of their structural and tectonic significance, processing image satellite data and the geological map.

Geological setting

The study area is part of the northern edge of the Moroccan Central High Atlas. The structure of the Central High Atlas is characterized by the occurrence of several anticlines oriented NE-SW (longitudinal ridges) and NW-SE (transverse ridges) delimiting synclines formed by Jurassic-Cretaceous deposits (Laville, 1985). The Ouaouizoght syncline constitutes one of these NE-SW synclines (Fig. 1) with a slight curvature in its western part. It is an asymmetrical syncline whose NW limb presents a more complete stratigraphic succession than that of the SE limb, which becomes thinner toward the Lower Jurassic ridge of Jbel el Abbadine (Haddoumi et al., 2010). The anticlinal ridges, developed from the basinal stage, have played a major role controlling the Jurassic-Cretaceous sedimentation in the High Atlas area and its structure during the subsequent tectonic inversion. Several authors point to a diapiric origin for these structures (Michard et al., 2011; Saura et al., 2014; Moragas et al., 2017; Torres-López et al., 2018). The study area comprises the Ouaouizaght syncline and the area delimited between the Aghbala-Afourer fault zone in the north and the Jbel Abbadine anticline in the south (see Fig. 1).
The Aghbala-Afourer fault zone, in the north, permits the limestones and dolomites of the Lower Jurassic platform series to overlap and thrust over the Cretaceous series of the northern part of the syncline. To the south, the Ouaouizaght syncline is bounded by the diapiric Jbel Abbadine anticline with its southwestern extension, which separates the former from the Tilouguit basin to the south and Aït Attab to the west. In addition to these two atlasic structures, the Ouaouizaght basin is separated to the east from the Taguelft basin by the NW-SE trending diapiric ridge of Tansrift.

Methodology

Processing:

The methodology consists of satellite image processing by means of principal component analysis (PCA). We used a Landsat 8 OLI satellite image, already corrected geometrically, consisting of eleven bands, from which the first seven were analyzed in this work. This image has undergone atmospheric preprocessing based essentially on dark objects subtraction in order to have reflectance at the soil level, to obtain a maximum of information on different spectra (Moore and Waltz, 1983; Van der Werff and van der Meer, 2016).

Principal Components Analysis

Principal components analysis (PCA) allowed us to compress all the information contained in the different bands with one, two or three components. This operation shows a considerable spectral enrichment, providing improvement and precision of the geological discontinuities. It also shows contrasts between different outcrops (Fig. 2), which facilitated the determination of the lineaments. The PCA synthesized 96.15% of the information contained in the original multispectral image. It shows a clear correlation between some bands (Table I).

The directional filtering of the resulting image of the PCA permits to highlight and classify the contrasts following each direction.

Directional filtering

In geology, we are interested in lineaments of natural origin, which most often correspond to topographic ridges, contacts between different lithologies, fracture lines and/or faults (Nicolini, 1980; Scanvic, 1983).

The application of the 7x7 sobel filter in the four directions N-S, E-W, NW-SE and NE-SW (Table II) had the following goals: i) to produce a specific map for each direction (Fig. 3), ii) to extract the lineaments of each map and iii) to combine the four results on a global map.

Table I. Correlation matrix of landsat TM bands.

<table>
<thead>
<tr>
<th>Band</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
<th>PC6</th>
<th>PC7</th>
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<tr>
<td>1</td>
<td>-0.375</td>
<td>-0.378</td>
<td>-0.383</td>
<td>-0.381</td>
<td>-0.375</td>
<td>-0.378</td>
<td>-0.375</td>
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<tr>
<td>2</td>
<td>-0.539</td>
<td>0.449</td>
<td>0.172</td>
<td>-0.129</td>
<td>-0.080</td>
<td>-0.458</td>
<td>-0.495</td>
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<tr>
<td>3</td>
<td>-0.020</td>
<td>0.102</td>
<td>0.233</td>
<td>0.337</td>
<td>-0.860</td>
<td>-0.078</td>
<td>0.276</td>
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<tr>
<td>4</td>
<td>0.413</td>
<td>0.127</td>
<td>0.329</td>
<td>0.642</td>
<td>0.248</td>
<td>0.222</td>
<td>0.365</td>
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<tr>
<td>5</td>
<td>-0.346</td>
<td>0.150</td>
<td>0.588</td>
<td>-0.401</td>
<td>-0.125</td>
<td>0.471</td>
<td>0.343</td>
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<tr>
<td>6</td>
<td>-0.203</td>
<td>0.021</td>
<td>0.412</td>
<td>-0.387</td>
<td>0.189</td>
<td>-0.565</td>
<td>0.533</td>
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<tr>
<td>7</td>
<td>-0.487</td>
<td>0.778</td>
<td>-0.387</td>
<td>0.038</td>
<td>0.036</td>
<td>-0.037</td>
<td>0.060</td>
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Table II. Sobel filters in four principal directions.

<table>
<thead>
<tr>
<th>A) N-S</th>
<th>B) E-W</th>
<th>C) NW-SE</th>
<th>D) NE-SW</th>
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Fig. 2. First component principal (CP1) issue the PCA.

Fig. 2.- Primer componente principal (CP1) emite el PCA.
Most lineaments show more than one direction. Therefore, variable direction lineaments were divided to obtain the direction of each rectilinear segment. This produced an automatic lineament map with 5527 straight segments or structures. The classification of these segments, based on their lengths, shows a dominance of two classes (2-3 km and 3-4 km), which represent 79.28%. The other classes (5, 6, 7, 8, 9, 10, 11 and 12 km) are less frequent as the longest lineaments are generally rare.

To obtain an idea about the distribution of linear structures extracted automatically, a rose diagram with all directions was produced (Fig. 4).

**Results and discussion**

The automatic extraction of lineaments gave 1420 lines, with lengths between 0.9 and 11.922 km. The total cumulative length is 9533.44 km. A selection based on the length of the lineaments allowed us to eliminate all segments whose lengths are less than 2 km, in order to target the larger structures such as anticline axes and kilometric scale faults (Fig. 3).

Sobel’s directional filtering allowed us to highlight all lineaments of different sizes and directions.

The rose diagram (Fig. 4) evidences the predominance of a NE-SW trend with two relative maxima oriented N0 and N90. Generally, the fracturing density is higher in the competent formations, such as limestone and sandstone, in comparison with soft formations such as clays. On limestone outcrops, the spatial distribution of fracturing is not uniform, with the higher lineament densities following the main structures, showing a striking geometric shape (Fig. 5).

The lineament density map (Fig. 5) highlights higher density of lineaments located around the Ouaouizaght syncline, and coinciding with i) the Jbel Abbadine anticline, which bypasses the Ouaouizaght syncline from the SE with an extension to the SW; ii) the Tansrift ridge separating the Ouaouizaght syncline from that of Tagoulet to the east and iii) the Aghbala-Afourer faulting zone. An additional concentration of lineaments is observed along a NW-SE trending area, separating Ouaouizaght from Ait Attab to the west.

This distribution of fractures defines a rhomboid shape giving a pull apart map view of the Ouaouizaght syncline. This kind of structures is widely observed in the field at small scale, in Jurassic limestones of the Central High Atlas northern border. This distribution of fault zones around the Ouaouizaght syncline and the WNW-trending magnetic lineation (obtained from Bathonian series; Moussaid et al., 2013) are oblique. We interpret this disposition as resulting from stretching of this area under a strike-slip component, dominant in the activation of the Abbadine fault in the south and the major Aghbala-Afourer fault in the north.

As mentioned above, the map of figure 5 shows a higher density of lineaments along four linear zones surrounding the Ouaouizaght syncline. These zones show...
different geological features. i) Two of these zones (Jbol Abbadiine and Tansrift ridge) show outcrops of Triassic diapiric material, Jurassic gabbroic rocks and unconformities. These structures indicate the synsedimentary activity of these two ridges developed along two major faults controlling sedimentation during the Mesozoic in the Ouauiz zaght basin. ii) The Aghbala-Afourer fault is considered as a major paleo-geographic lineament controlling the sedimentation in this area from Jurassic to Mio-Pliocene time (Laville, 1978). iii) The NW-SSE segment located between Ouauiz zaght and Ait Attab synclines does not show any synsedimentary structures in the field or diapiric evidence.

The concentration of brittle structures along the major faults; which coincide with the current anticlines cores of Jbol Abbadiine in the south, the Tansrift ridge to east and the Aghbala-Afourer fault in the northern boundary; can lead to explain the high density of lineaments along the western part separating Ouauiz zaght from Ait Attab as linked to a synsedimentary ridge developed on a deep basinal fault. The presence of a NW-SE trending syn-sedimentary ridge (ridge “R”, 4 in the map of figure 5, between Ait Attab and Ouauiz zaght), is consistent with the presence of similar structures (non-diapiric ridges in outcrops) evidenced in the axial part of the central High Atlas using paleomagnetic data (Torres-López et al., 2018).

The frame of synsedimentary ridges around the Ouauiz zaght syncline, during the basinal stage, reveals its behavior as a confined area more or less separated from surrounding areas. This gives for the northern boundary of the Central High Atlas an aspect of NE-SW en-échelon mini-basins. These mini-basins were linked to a range of syncline during Cenozoic mini-basins. These mini-basins were inverted to a synsedimentary ridge developed during the Mesozoic stage. The higher density areas of lineaments are located along the four borders of the Ouauiz zaght syncline, probably highlighting the importance of diapirc processes (e.g., movement of salt towards the anticline cores delimiting the Ouauiz zaght syncline) during the extensional stage and the relevance of these previous discontinuities in the subsequent tectonic inversion. Almost all of the extracted lineaments are concentrated in the ridge areas surrounding the Ouauiz zaght syncline. The directional analysis reveals the dominance of three directions: N0, N90 and N45, conferring a rhomboidal appearance to the synclines of the northern edge of the Central High Atlas.

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References


