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GEOLOGY

Quantifying Morphostructural Evolution of the Eastern Algerian Saharan Atlas (NE, Algeria) Using GIS-based Surface Envelope Technique, Drainage Network Analysis, and Geological Features

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ABSTRACT

This research work focuses on the morphostructural evolution of the eastern end of the Algerian Saharan atlas. The study employs a comprehensive methodology involving the utilization of the surface envelope technique, combined with an analysis of the hydrographic network and geological context. These techniques are integrated within a GIS framework to decipher the current relief characteristics. To interpret the current relief features, two ASTGTM v2 tiles were processed to extract morphometric data. The reconstruction of the original relief requires the generation of the summit level surface, the base level surface and the relief amount maps for 3 different grid sizes (4000m, 1000m and 250m). The respective different grid size maps has allowed determining the initial surface of the reliefs; first before any major vertical erosion, then after a phase of dismantling and finally the recent and sub current morphological aspect. The extraction of the hydrographic network and the elimination of lower than order 5 streams revealed the harmony of the latter with a raised shaped form (mega-horst) which represents the main morphostructural unit. This morphostructure is particularly characterized by outcrops from the Lower Cretaceous outcrops. The ramification of the hydrographic network along the main tectonic accidents has allowed the digging of wide valleys, often described as graben.

Keywords: Morphostructural evolution; envelope surface; horst; GIS; Saharan atlas; Algeria

Determinación de la evolución morfoestructural del extremo oriental del atlas sahariano argelino a través de la técnica envolvente superficial, el análisis de la red hidrográfica y las características geológicas

RESUMEN

Este trabajo de investigación se centra en la evolución morfoestructural del extremo oriental del atlas sahariano argelino. El estudio emplea una metodología global que implica la utilización de la técnica de la envolvente superficial, combinada con un análisis de la red hidrográfica y del contexto geológico. Estas técnicas se integran en el marco de un Sistema de Información Geográfica (SIG) para descifrar las características actuales del relieve. Para interpretar las características actuales del relieve se procesaron dos mosaicos ASTGTM v2 para extraer datos morfométricos. La reconstrucción del relieve original requiere la generación de la superficie del nivel de la cumbre, la superficie del nivel de la base y los mapas de la cantidad de relieve para 3 tamaños de cuadrícula diferentes (4000m, 1000m y 250m). Los respectivos mapas de diferentes tamaños de cuadrícula han permitido determinar la superficie inicial de los relieves; primero antes de cualquier erosión vertical importante, después tras una fase de desmantelamiento y finalmente el aspecto morfológico reciente y subactual. La extracción de la red hidrográfica y la eliminación de los arroyos de orden inferior a 5 han revelado la armonía de estos últimos con una forma elevada (megahorst) que representa la principal unidad morfoestructural. Esta morfoestructura se caracteriza especialmente por los afloramientos del Cretácico Inferior. La ramificación de la red hidrográfica a lo largo de los principales accidentes tectónicos ha permitido la excavación de amplios valles, a menudo descritos como fosas tectónicas.

Palabras Clave: Evolución morfoestructural; superficie envolvente; horst; SIG; atlas sahariano; Argelia

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1. Introduction

Over the past few decades, the "eastern end of the Saharan Atlas" has been the subject of several research works. They were carried out mainly for academic purposes in the form of theses (Dubourdieu, 1956; Madre, 1969; Othmanine, 1987; Bouzenoune, 1993; Manchar et al., 2022), and applied research work for mineral exploration (Betier et al., 1952; Rouvier et al., 1985; Perthuisot et al., 1987; Bouzenoune et al., 1995; Bouzenoune and Lecolle, 1997; Perthuisot et al., 1998; Perthuisot et al., 1999; Bouzenoune et al., 2006; Kerbati et al., 2020; Boulemia et al., 2021; Zerzour et al., 2021; Benyoucef et al., 2022) and for the preparation of geological surveys maps (Dubourdieu, 1949, 1951; Durozoy, 1956; Blès and Fleury, 1971; Sonatrach, 1977a, 1977b, 1977c; Sonatrach., 1977d; Dozer et al., 1985; Kuscer et al., 1985; Tamani et al., 2019; Chibani, 2022). These works are often limited in space and objective and hence they fall short of giving a global vision that leads to a structural scheme integrating all the elements at the origin of the morphostructural evolution of the region.

This situation has stimulated us, with the development of new tools (remote sensing and GIS), to resume work in this region with the aim of elaborating a synthesis that proposes an integrated vision based essentially on the analysis of morphostructural aspects and taking into account the results obtained in previous studies. Nevertheless, the lack of necessary information required for the elaboration of a global structural scheme, prompted us to propose a morphostructural evolution scheme. This proposal, while drawing partially from previously published geophysical data (Zerdazi, 1990; Asfirane and Galdeano, 1995; Boubaya, 2013) it is based essentially on the concept of envelope surfaces (De La Noé and De Margerie, 1888; Prud'homme, 1972) and their integration in a geographic information system. This method was largely enhanced by the analysis and interpretation of the drainage network which allowed us to reconstruct the dismantling stages of the paleo-relief resulting from the succession of tertiary and quaternary tectonic phases mentioned in the works cited above.

Hence, this study employs methods and tools that are centered on the landscape characteristics, in order to establish a comprehensive view of the evolution of the relief. This comprehensive view admits that the topographic landscape is the result of the interplay between internal and external geodynamic processes. In tectonically active regions, the shape of the relief is in itself a witness of this activity. The topographic surface is regularly shaped by erosion, deposition and the continuous evolution of structures (Deffontaines, 1990; Deffontaines and Chorowicz, 1991; Jackson and Leeder, 1994; Jackson et al., 1996; Burbank and Anderson, 2001; Chen et al., 2003; Delcaillau, 2004; Delcaillau et al., 2006; Ribolini and Spagnolo, 2008; Champagnac et al., 2009). Thus, the current topographic configuration is an outcome of the modification of an initial surface (paleo-surface) that predates the influence of neotectonic forces, either in isolation or in tandem with erosion. This surface can be reconstructed by applying cartographic techniques related to the surface envelope method.

The concept of "Summit Level Surface" (SLS), was introduced as early as the late 19th century (De La Noé and De Margerie, 1888). It was defined as "a virtual surface joining the topographic peaks". The term envelope was introduced and described as the surface contained in the envelope of the actual highest topographic points (Argand, 1912). As for the Base Level Surface (BLS), it is constituted by joining the lowest topographic points (Filosofov, 1960). Since then, these two concepts are generally combined and their use is widely adopted in morphostructural and morphometric analysis (Prud'homme, 1972; Howard, 1973; Ait Brahim and Rosanov, 1986). Several works such as those in Zaïr basin, have employed these concepts to characterize ancient deep-seated structures and their subsequent rejuvenation (Deffontaines and Chorowicz, 1991). Other authors have used this method and combined it with the drainage network to study recent neotectonics activity (Deffontaines et al., 1992).

It has been established that anomalies in the drainage network, including atypical stream patterns or unanticipated behaviors, are frequently associated with underlying tectonic phenomena. In fact, tectonic processes can induce shifts in the Earth's crust through sliding, uplifting, or subsidence, thereby changing the courses of water streams from their original paths. These modifications, coupled with erosional influences, can occasionally result in significant modification in the landscape, creating conditions for a river to divert and redirect the flow of another.

The analysis of the surface envelope has yielded valuable insights into the dynamic evolution of the relief. Indeed, it consists in determining the remains of the initial surface in the form of flats located on isolated ridges and summits (Ait Brahim and Rosanov, 1986). Thus, to measure neotectonics deformations, it is essential to define a horizontal reference surface that corresponds to the initial surface. Today, with the development of digital tools and spatial imagery, their extraction is performed from the digital elevation model (DEM).

However, for large cells of the considered grid, the SLS and BLS correspond respectively to the paleo-morphology and its evolutionary trend. Also, these two surfaces when jointly reconstructed and superimposed, reflect the Relief Amount (RA) and give an overview of the distribution of the areas of slope breaks (Motoki et al., 2015b; Motoki et al., 2015a).

Furthermore, the drainage network complying the underlying structure and particularly the one conditioned by fracturing, allows eventually to highlight the neotectonics activity.

The primary objective of this research work is to define and reconstruct the evolution of the morphostructural entities that have been eroded or covered by other formations. This is achieved through a combination of elements including:

1. Segmenting the relief as determined by calculations, a pattern confirmed by its staircase-like morphology.
2. Analyzing the surface envelope (SLS) and studying the distribution of the Relief Amount to determine the original topography.
3. Classification of the drainage network and its configuration to detect significant orientations.
4. Conducting a spatial distribution analysis concerning some specific geological formations, particularly those from the Triassic and lower Cretaceous periods.
5. The combination of these elements of analysis has allowed us to envision the morphostructural evolution of this part of the Eastern Saharan Atlas in harmony with the current configuration of the relief.

2. Geographical and geological context

The study area is located in northeastern Algeria near the Algerian-Tunisian borders, in the extreme east of the Atlas Mountains. It corresponds to a rectangular area that stretches over 200 km from east to west and 100 km from north to south. It is located between latitudes 35°00'00"N and 35°59'00"N and longitudes 7°00'00E and 8°59'00"E covering an area of about 20.000 km^2 between Ouenza and the Saharan plains (Fig.1).

The uplift of the Atlas Mountains during the Cenozoic era, as documented by Laffitte in 1939, was succeeded by a phase of vigorous erosion (Mahleb and Hadji, 2022). This erosional process is characterized by the establishment of an extensively developed drainage network. The current relief configuration is attributed to the combination of the flow pattern and the lithological composition of geological formations. Indeed, we note the juxtaposition of high and low areas where the level difference exceeds 700 m in some parts (Dj Bou Roumane, Dj Anoual and Dj Bou Rbaia, Khenchela Mountains); this morphology is typical in the study area.

Generally, the orographic units which correspond to the Eocene folded structures are obtained by the inversion of the Mesozoic sedimentary basin which received thick series of marl, marlstone and limestone (Laffitte, 1939; Dubourdieu, 1956; Guiraud, 1973) (Fig. 2). This global Tertiary inversion is responsible for the formation of typical folded structures such as large synclines with flat bottoms and large radius of curvature with relatively narrow anticlines. The commonly encountered large plains are underlined by folds plunging flanks.

Towards the north of Tebessa region, a noticeable shift in morphology is distinguished. It is marked by the gradual transformation of anticlines and synclines into narrower and more tightly compressed formations. This transformation is particularly evident in regions intersected by diapiric domes containing Triassic evaporitic materials, as observed in locations such as (Dj Ouenza, Dj Boukhadra, Dj Mesloula, Belekfif and Dj Djebissa) (Dubourdieu, 1951, 1956; Durozoy, 1956; Blès and Fleury, 1971; Bouzenoune, 1993) (fig.2). This material is considered by some authors to be re-deposited during the Albian and not diapiric (Vila and Charrière, 1993; Vila et al., 1994b; Vila et al., 1994a; Vila, 1995).

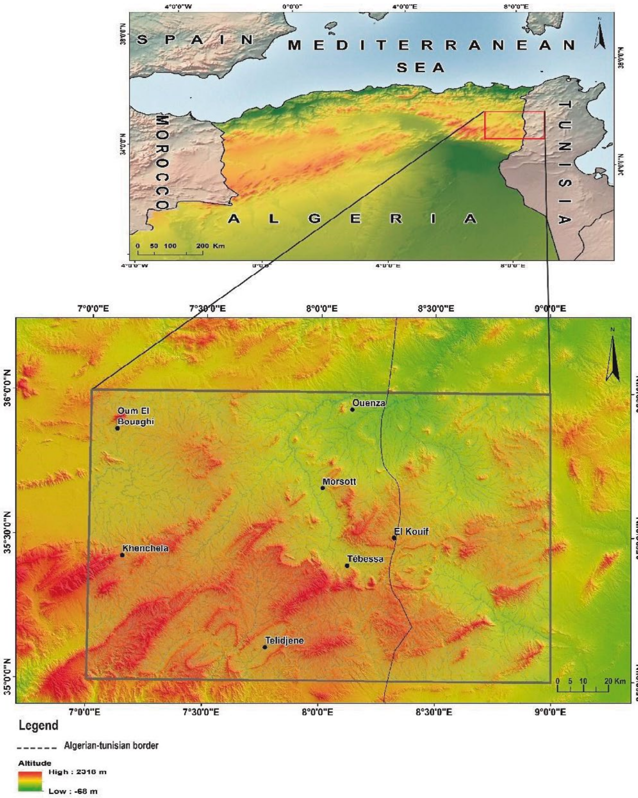


Figure 1. Study area represented by an area covered by two tiles: ASTGTM2_N35E007_dem and ASTGTM2_N35E008_dem.

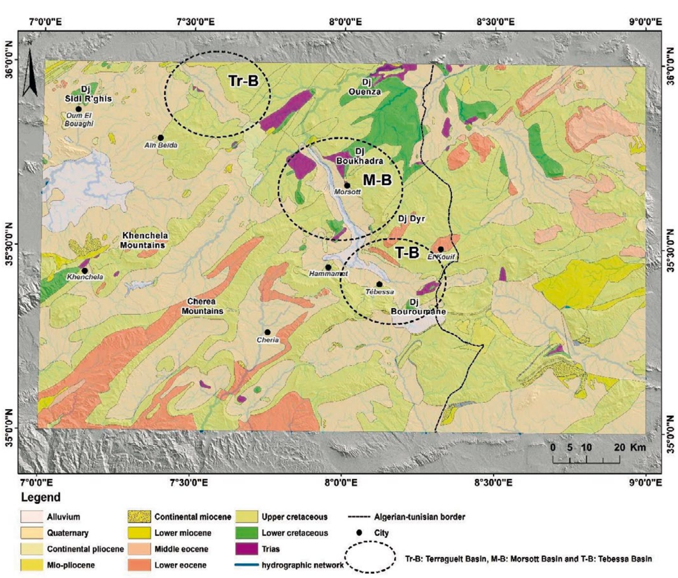


Figure 2. Geological map of eastern end of the Algerian Saharan Atlas (Deleau and Laffitte, 1951) and north of Tunisia (Castany, 1951)

Moreover, the rising of these structures is followed by subsequent dismantling and erosion phases. Also, this region is characterized by the existence of many Tertiary basins called "Neogene basins" that characterize the entire Saharan Atlas of eastern Algeria (Dubourdieu, 1956; Durozoy, 1956; Blès, 1969; Blès and Fleury, 1971; Guiraud, 1973; Vila, 1980; Wildi, 1983; Taib et al., 2023) and central Tunisia (Castany, 1948; Zargouni, 1975, 1985; Ben Ayed, 1986). Among these basins, Morsott graben which is oriented NNW-SSE gets linked towards the South East with that of Tebessa whose orientation is WNW-ESE. To the North, it is the basin of Ouled Boughanem (NNW-SSE) and those of Tunisia oriented along the same direction. To the northwest of the study area, we encounter the Terraguelt basin, oriented NNW-SSE (Fig. 2).

The genesis and evolution of the aforementioned basins are the result of the combined effect of neotectonics and erosion. The latter is well materialized by a dense drainage network. But to what extent does the work of the hydrographic network contribute to the current shape? And what is the part of neotectonics in the exacerbation of erosion? The answer to this question refers us to the use of morphometric analysis methods of the surface envelope and the drainage network analysis.

3. Materials and Methods

The present research necessitated the use of both classical cartographic resources, such as geological maps, and digital data sources, such as Digital Elevation Models (DEMs).

Since the advent of satellite technology, the production of topographic maps has increasingly relied on satellite data. The two main used data sources are the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) products. These data sources provide comprehensive coverage of terrestrial surfaces in the form of digital surface models (DSMs), making them a pragmatic choice for topographic map creation (Riegler et al., 2006; Wang, 2008; Hadji et al., 2013; Hadji et al., 2014). Their use, is a good compromise in the preparation of topographic maps. This work requires the use of conventional cartographic documents (geological maps) and others in digital format (Digital Elevation Model).

The conventional cartographic documents used are the medium-scale geological maps (1/50,000) covering the study area published by the geological survey of Algeria (Dubourdieu, 1951; Durozoy, 1956; Blès and Fleury, 1971; Sonatrach, 1977c, 1977b, 1977a; Sonatrach., 1977d; Dozer et al., 1985; Kuscer et al., 1985), as well as the small-scale geological maps (1/500,000) of northern-east Algeria (Deleau and Laffitte, 1951) and north of Tunisia (Castany, 1951). In the context of the Algerian part, this map stands as the best comprehensive cartographic document available at this scale for the entire study area. It adeptly demarcates the facies and prominently displays the principal fault lines. However, it's noteworthy that this earlier edition does not make any allusion to the concept of "thrust sheets."

The used spatial documents are the ASTER GDEM (ASTER Global Digital Elevation Model) version 2 satellite images. The GDEM product provides a global digital elevation model (DEM) of land areas at a spatial resolution of 1 arc second (horizontal display of about 30 meters at the equator). This product is freely available at the USGS website (https://earthexplorer.usgs.gov/). Each tile is distributed in GeoTIFF format. The two tiles used to cover the study area are: ASTGTM2_N35E007_dem and ASTGTM2_N35E008_dem. Given the nature of the work conducted combining DEM processing, geostatistical processing, cartographic restitution and structural data processing, ArcGis 10.7 (ESRI®) software package was used for these purposes.

The approach we adopt in this article consists in creating a mosaic of DEM tiles as a first step and then, the pixels of the latter are converted into a "shape file of points" where each point is located at the center of the pixel and provides the elevation value.

The second step consists in dividing the study area into three categories of grids, with different cell sizes (4000m X 4000m, 1000m X 1000m and 250m X 250m). For each grid, three points are selected, representing the highest altitude (Z_{max}), the lowest altitude (Z_{min}), and the Relief Amount (RA) denoting the difference between Z_{max} and Zmin. This operation yields three grids for each mesh size (Zmax, Zmin, and RA), culminating in a total of nine grids. Finally, we construct graphs expressing Zmin = f1 (Zmax), RA = f2 (Zmax) and RA = f3 (Zmin) for each mesh. The objective is to proceed to a segmentation of the relief based on the average values of these altimetric variables.

The third step consists in drawing maps of the Summit Level Surface (SLS), the Base Level Surface (BLS) and the Relief Amount (RA) respectively. To accomplish this task, a universal kriging interpolation method is employed for the grids specifying that the local average is different from the global average for each population of points (Matheron, 1963; Gratton, 2002). Nevertheless, the use of these techniques requires a test to validate the normal distribution of the data, otherwise we proceed to a transformation.

The drainage network was automatiquelly extracted from the DEM using ArcHydro tools algorithm and it was classified according to the Strahler method of orders (Strahler, 1952). We opted for the elimination of orders lower than 5 in order to highlight the reliefs that potentially influenced the initial organization of the network.

The above work is achieved by the digitization of a part of the geological map covering the north of Algeria and Tunisia at the scale of 1/500 000 (for algerian part: Deleau and Laffitte , 1951) and Tunisian part (Castany, 1951).

Ultimately, through the integration of SLS, BLS, RA maps, hydrographic network data, and geological characteristics, we can elucidate the arrangement and development of diverse morphostructural units.

4. Results

Within this section, we provide a comprehensive examination of the data gathered specifically for this study. The outcomes derived from processing these data through the aforementioned methodology yield crucial insights into the initial topography and its subsequent evolution due to the interplay of tectonic forces and erosional processes.

4.1 Correlations between altitudinal factors

In our approach, the altitudinal variables are cross-correlated in order to search for possible correlations between them (Figure.3). This procedure allowed us to show that Zmax as a function of Zmin is a quasi-linear relationship for all cell sizes. This linear relationship is even stronger as the cell size is reduced. The correlation observed between the variables (Zmax, RA) seems to decrease as compared to the couple (Zmax, Zmin). This decrease becomes more pronounced for the couple (Zmin, RA). These relationships are valid for all mesh sizes.

Concerning the couple (Zmax, RA) for the cell size 4 km X 4 km, the correlation is more or less pronounced, where the graph corresponds to a polynomial curve of the second order (Fig. 3).

This correlation remains weak compared to the value of the index $R^2 = 0.48356$ but acceptable with regard to the other dimensions of cell. It is thus retained for the segmentation of the relief. It is clear from this curve that RA, which represents the difference in altitude, increases significantly with the increase in altitude.

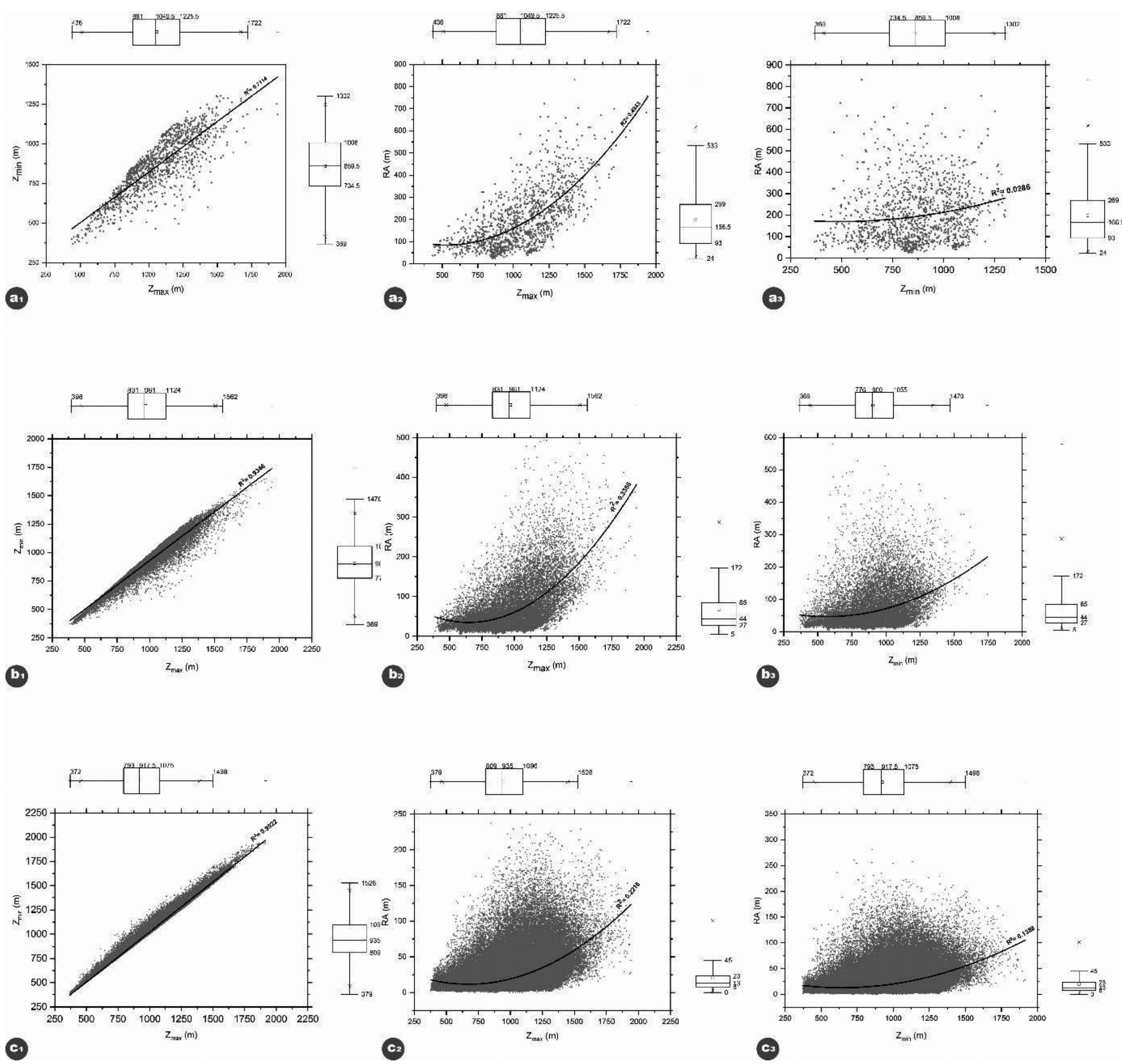


Figure 3. Cross-correlation between altimeter parameters Zmax, Zmin and RA. a1, a2 and a3: 4km X 4km grid; b1, b2 and b3: 1km X 1km grid; c1, c2 and c3: 0.25km X 0.25km grid.

4.2 Relief segmentation

The approach consists in dividing the cloud of points of the graph a_2 of figure 3 based on the averages of the two variables Zmax and RA, noted respectively MZmax and MRA (Fig. 4).

Consider the point P whose coordinates are (MZmax, MRA) and draw the lines Y = MRA and X = MZmax. Thus, the point cloud is divided into four classes of points contained in four rectangles corresponding to 04 types of relief.

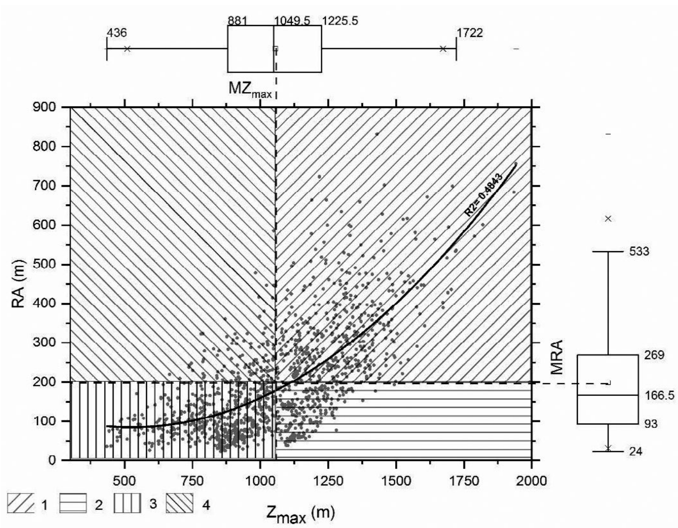


Figure 4. Relief segmentation using mean values of Zmax and RA for cell size 4km X 4km. 1 : MZ, 2 : PZ, 3 : PLZ et 4 : WZ

Consider: (Zmax - MZmax) * (RA-MRA) = a

- For a> 0 (Zmax> MZmax and RA> MRA): This class is delimited by a higher level altitude than the average and a difference in altitude also higher than the average, which corresponds to a relief named mountain zone noted MZ.
- For a> 0 (Zmax <MZmax and RA <MRA): this class is the opposite of the previous class on the graph. It is delimited by a lower-than-average altitude and lower difference in altitude and corresponds to the zone of plains noted PZ. Its lower limit constitutes the average base level of the study area.
- For a<0 (Zmax> MZmax and RA <MRA): this class is intermediate, it is characterized by a lower than average difference in level and higher than average altitude. Thus, it corresponds to a slightly perched space compared to the base and constitutes a transition zone between the mountainous zone and the plain zone noted PLZ.
- For a<0 (Zmax <MZmax and RA> MRA): this class, which is characterized by an above-average difference in height and a below-average altitude, corresponds to a residual relief which is the area spared from the destructive action of erosion and therefore corresponds to the "Witness Hills" noted WZ.

Thus, the cross-referencing of morphometric data, i.e., vertical drop (RA) and maximum altitude (Zmax), allows the discrimination of the relief that characterizes the study area.

The limits of the zones resulting from this segmentation clearly coincide with the limits of the physiographic units shown on the topographic and geological maps (Figure.2). Indeed, the main features of the atlas structures are well underlined by the limits of these zones and the SW-NE and NW-SE profiles, longitudinal to these structures, confirm well this morphological distribution and organization. Therefore, the results show the suitability of this simple treatment, based on the averages of the variables described above, to establish a classification of landforms or landform segments at different levels of Zmax and RA. Indeed, it appears that at high altitude, the relief is relatively young and is subject to strong erosion, resulting in a strong difference in altitude within the grid.

4.3 Summit Level Surface and Relief Amount maps

We need to remind that the study area's topography exhibits a notable interplay between elevated and depressed regions, highlighting a discernible structural element. This variability in local trends across different locations led us to opt for universal kriging as our interpolation method (table. 1). To meet the requirement of a normal distribution, we transformed the data using a logarithmic function. Universal Kriging assumes the following model

$$Z(s) = \mu(s) + \varepsilon(s).$$

where μ(s) is a second order deterministic function representing the trend and ε(s) the error. The trend is subtracted from the equation and the obtained error is assumed to be random with a mean of ε(s) zero. Conceptually, the autocorrelation is modelled on the basis of these random errors ε(s).

To interpolate the values needed to estimate the variability of relief, we applied semi-variograms. The results showed significant variability in the RA (relief amount) values in the study area, with a nugget effect of 0.058 for a record dataset of 1288 (Table. 1).

Table 1. Kriging interpolation model characteristics

Method	Data set (Records)	Transformation	Neighborhood	Neighbors to include	Include at least	Variogram	Nugget	Model
Universal Kriging	1288	Log	Standard	5	2	semivariogram	0.05896	stable

The SLS obtained from the Zmax altitudes for a 4000m X 4000m cell size, is inclined towards the NE. It is globally consistent with the current surface. Indeed, the high altitudes are located much more to the SW and the low altitudes to the NE (Fig. 5).

The SW-NE topographic profiles made on this SLS map (Fig. 6), show a staircase like relief similar to the one resulting from the segmentation. We can therefore admit that despite the strong erosion that has affected this region, it still retains its initial general appearance with slight changes.

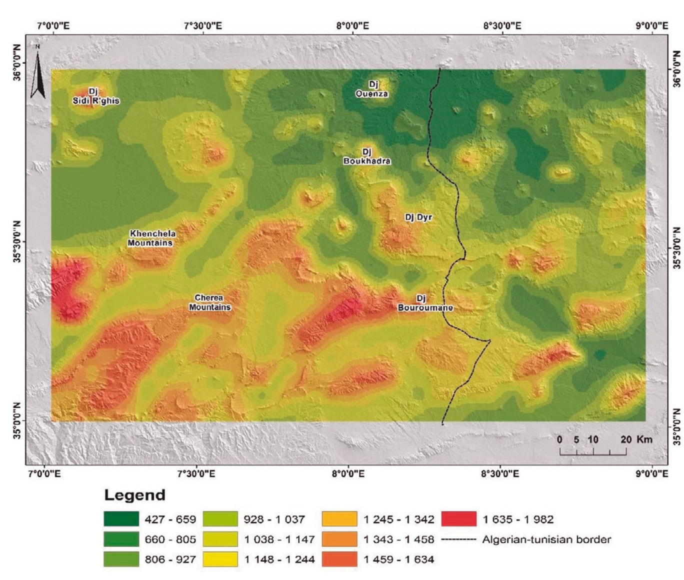


Figure 5. Summit Level Surface map for 4000m X 4000m cell size.

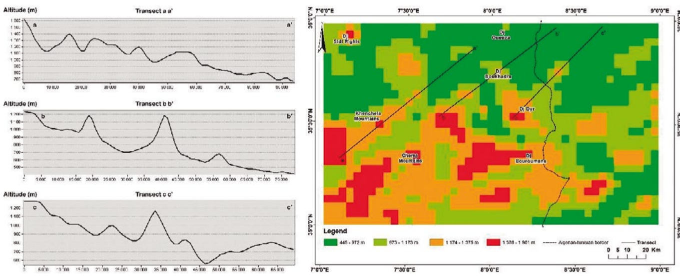


Figure 6. Transects a a', b b' and c c' carried out on the segmented SLS map of 4000m x4000m cell size.

The Relief Amount (RA) map (fig.7) shows areas of steep slopes that generally follow the limits of Lower Cretaceous limestone massifs. The latter which corresponds to disjoint geological units appear grouped around Djebel Dyr. They appear to underline a megastructure of subcircular shape.

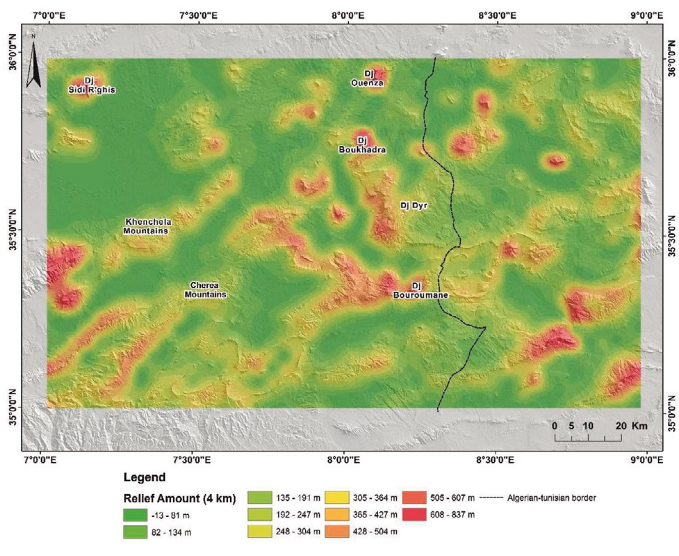


Figure 7. Relief Amount map for 4000m X 4000m cell size.

The NE-SW and NW-SE transects carried out on the RA map (fig.8), show a topographic elevation located in the center of the profiles.

Moreover, in the southwestern part of the study area, in Khenchela and Cheréa mountains, these surfaces of ruptures highlighting the Atlas structures do not reach this sub-circular shaped megastructure described above and are disconnected from it revealing the posteriority of this morphostructure to the Atlas structures.

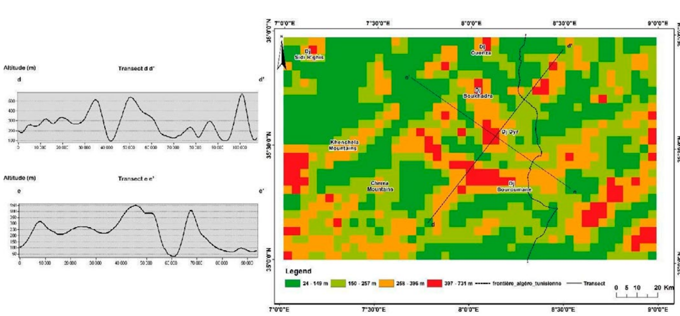


Figure 8. Transects a a', b b' and c c' carried out on the segmented RA map of 4000m x 4000m cell size.

4.4. Drainage network analysis

The drainage network (Fig. 9) was automatically extracted from the 30m resolution DEM using ArcHydro tools module in ArcGis 10.7.

This tool is used to derive several data sets that collectively describe the drainage patterns of catchments. Raster analysis is performed to generate data on flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation. These data are then used to develop a vector representation of catchments and lines corresponding to drainage network. The choice of "stream definition" is a decisive parameter in the extraction of the drainage network, which allows us to obtain the 1st order stream. The product is then imported into Arcmap for processing and analysis.

The drainage network is of dendritic type. This implies a globally homogeneous drained surface made of more or less impermeable formations. This impermeability is revealed by a high drainage density due to a predominance of marl and marl-limestone. In the study area, the classification of the drainage network according to Strahler's method (Strahler, 1952) highlights rivers and streams of up to order 7. In order to highlight the paleo-morpho-structures and to overcome the difficulty of masking the higher orders of the drainage network by the low order streams, we opted for the elimination of lower than order 5 streams of the drainage network. Thus, we obtain a certain harmony between the configuration of the RA map (Fig. 7) and the organization of the retained orders of the drainage network (Fig. 9).

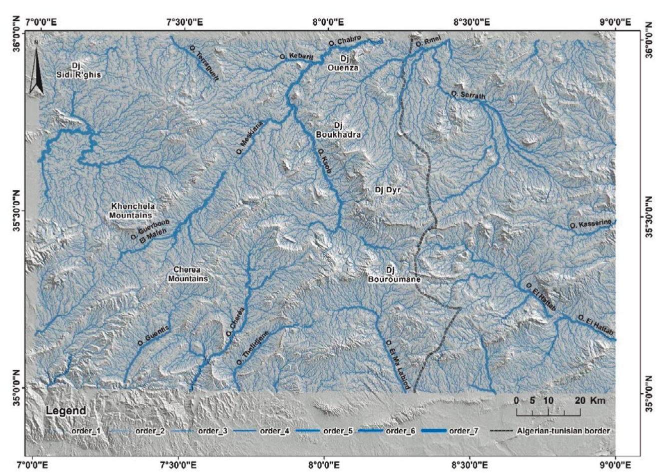


Figure 9. Drainage network map showing the radial pattern of order 5, 6 and 7 streams.

At the scale of the selected orders, we note that the main rivers and their tributaries are arranged in a more or less radial manner in relation to a subcircular physiographic unit. Indeed, oued Cheréa drains in a southern direction, oued El Ma Labiod and oued El Hatab flows in a SE direction, oued Serrath is oriented in a NE direction and then takes a NW direction to finally resume its initial NE direction and joins oued R'mel southeast of Kef. Oued Terraguelt follows the basin and flows in NW direction.

This arrangement can only illustrate the idea of the existence of a mega-morphostructure that has controlled this drainage network in such a way that the flows are from the center to its periphery. It should be noted that some segments of this network present particular situations. Indeed, oued Guergoub El Melah of order 6 runs along the gutter of the eroded Meskiana anticline in SW-NE direction and stops abruptly. This anomaly can be explained either by the fact that the width of the river bed at this point are smaller than the pixel dimension of the DEM so that this watercourse cannot be detected; or, this watercourse which usually flows into Sebkha of Garaat el Tarf and which is in the continuity of Oued Meskiana is captured by the latter (order 5). The segment of order 6 of oued Serrath which runs along the eastern limit of this morphostructure, is captured by a segment of order 5 located much further upstream from its initial confluence and this happens after the dismantling of the obstacle related to the above mentioned morphostructure.

4.5 The Atlas structures under multiple influences

The fold structures dominated by a NE-SW orientation (Figure.2) acquired during the Eocene phase in the Saharan Atlas are characteristics. The hinges of the anticlines are in many areas occupied by saliferous Trias formations, and are generally in contact with the lower cretaceous formations, i.e (Dj Ouenza, Dj Boukhadra, Dj Mesloula, Dj Djebissa ... etc.). These Trias formations can also be found as small outcrops rising along longitudinal and transverse fault structures (Djebels Hamaimet, Dj Belekfif, SE of the peak of Dj Boukhadra and Argoub Ezitoune).

Many authors have interpreted the structural setup of these Triassic evaporite masses to be diapirs (Dubourdieu, 1956; Durozoy, 1956; Perthuisot, 1991; Aoudjehane et al., 1992; Bouzenoune, 1993; Perthuisot et al., 1999) while others have attributed them to salt glaciers (Vila et al., 1994a; Vila et al., 1994b; Vila, 1995; Vila et al., 1996). Concerning the diapirs, the main remobilization is predominantly Eocene in the Saharan Atlas. Other upward activities of these Triassic evaporites with surface extrusions are also known at least since the Aptian (Dubourdieu, 1956; Madre M, 1969). They are also known in the Vraconian (terminal Albian), Turonian, Eocene and Miocene (Dubourdieu, 1956; Madre, 1969; Perthuisot, 1991; Aoudjehane et al., 1992; Bouzenoune, 1993; Perthuisot et al., 1998; Kowalski and Hamimed, 2000). These upward movement persist even during the Quaternary where we observe present terraces straightened up to the vertical at Dj Djebissa. This position within the anticlines is sometimes exaggerated with the initiation of planes of detachment with an overall southward convergence and sometimes northward leading to shoulders as at Ouenza (Bouzenoune, 1993) and elsewhere at Kt Delaa (Perthuisot et al., 1999). This diachronic remobilization of evaporite masses is of various origins, halokinetic, diapiric, or by faulting related to deep vertical movements of the basement. The surface forms and the state of the outcrops mentioned above are the effect of deep processes that are obviously interpreted differently with their advantages and disadvantages but remain key formations for the understanding of the regional structure.

Indeed, it is easy to see on the geological map (Fig. 10), the existence of an area of subcircular shape centered around the Jebel Dyr, and this, on a radius of 50 km. This area includes various limestone massifs of lower Cretaceous age in contact with the Triassic or not (Dj Bouroumane, Dj Hamaimat, Dj Boukhadra, Dj Mesloula, Dj Boudjaber ... etc.). In our opinion, this area corresponds to a raised megastructure.

This elevation allowed the total or partial erosion or dismantling of the post-lower Cretaceous cover. Outside this area, the geological formations of the different massifs become more recent (massifs south and west of Tebessa). The limits of this area coincide with those highlighted by the Relief Amount (RA) map (Figure 8) which also attest to this geometry. The interposition of this megastructure, intersecting the typical NE-SW trending structures of the Atlas, suggests a post-Eocene genesis age, very probably even more recent than the Lower Miocene. This hypothesis is supported by the presence of remnants of formations of Middle to Lower Miocene age, located at the heart of the perched syncline of Djebel Dyr.

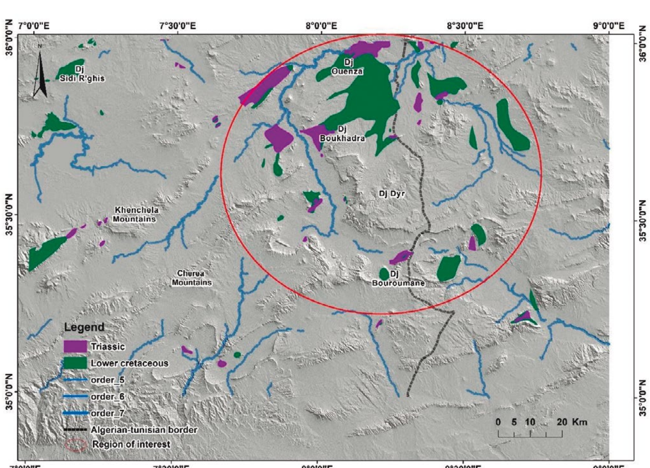


Figure 10. Extract from the geological map showing the subcircular distribution of Triassic and Lower Cretaceous outcrops.

Furthermore, the regional depth morphology of the evaporitic material, which is concentrated in outcrop in a band 300 km long and about 80 km wide, is not well defined by previous work. However, the exploitation of some bibliographic data from geophysical work, helped us to support our interpretation. Indeed, the Bouguer anomaly is characterized by a regional gradient that increases gradually from Hodna basin (SW) to the Algerian-Tunisian borders (NE) where the hypothetical megastructure is located (Zerdazi, 1990). This long wavelength variation is probably caused by the topography of the MOHO (Zerdazi, 1990), this hypothesis is supported by the interpretation of the aeromagnetic map of northern Algeria (Asfirane and Galdeano, 1995). The relative maximum of the Bouguer anomaly recorded at the Algerian-Tunisian borders is very difficult to explain by surface data (Boubaya, 2013), Zerdazi attributes it to a rise of the basement (Zerdazi, 1990). This maximum is present on the upper levels of the upward extension of the anomaly which confers a deep origin combined with a semi deep origin (Boubaya, 2013). The latter is related to short wavelength magnetic anomalies linked to structures due to Triassic magmatism (Asfirane and Galdeano, 1995), keeping portions of the crust in an elevated position, remobilized during a post-Eocene period, probably Miocene. This interpretation is attested by the location of large metal deposits in the area bounded by this maximum (Asfirane and Galdeano, 1995).

The wide geographical extent of the diapirs is only very weakly marked gravimetrically (Zerdazi, 1990), which supports the interpretation by the attenuation of their effects by the rise of a denser substratum and not only in their situations at the edge of the Neogene basins with recent fillings as stipulated by this same author. This observation concerns all the most important diapiric apparatuses of the region (Ouenza, Mesloula, Boukhadra and Tebessa).

In the northeast of the Aurès, the rise of the Moho which implies a thinning of the crust and consequently the initiation of the “Uplift” is well documented by the interpretation of seismic refraction profiles (Buness H & al, 1992) and the gravimetric study (Jallouli and Mickus, 2000; Guidara et al., 2010) showing also a crust which thins going from SW to NE.

To confirm the validity of the findings presented in this research, it is crucial to integrate mechanical drilling alongside the existing geophysical data. It’s worth mentioning that the interpretation is based on the limited and fragmented data currently accessible. Obtaining fresh data has the potential to become a central aspect of future research endeavors.

4.6 Tebessa-Morsott and Terraguelt Neogene basins

The previously described megastructure is crossed by Neogene basins such as Tebessa-Morsott (T-B and M-B) and Terraguelt (Tr-B) basins (Fig. 2). They are filled in by clastic silico-carbonate sediments that come from the dismantling of the surrounding relief. This vigorous erosion is demonstrated by the existence of perched synclines such as the syncline of Dj Dyr which culminates at more than 1200m altitude. The Tebessa-Morsott neogene basin has two segments, T-B and M-B, both of which has sub-rectangular elongated form, characteristic of this region, hence its qualification of “area of diapirs and ditches”. They are considered by several authors (Castany, 1951; Dubourdieu, 1956; Durozoy, 1956; Blès and Fleury, 1971) to be graben structures. However, according to our observations, we note the very low frequency of fractures with tectoglyphs at their edges, which for a structure in stepped collapse trenches is a fundamental criterion, which leads us to remain cautious about this interpretation, which we consider questionable, for the following reasons

- It is generally accepted that a collapse under the effect of extension and subsidence leads to the appearance of normal fault planes striated at the edge of the collapsed area. Indeed, on the south bank of the basin southeast of the city of Tebessa (Dj Djoua), the density of faults as shown on the geological map of Tebessa No. 206 is remarkable but we note that open fractures affecting the Turonian which slides in panels under the effect of gravity. This is also observed at the level of Bir Salem and Kef Labiod west of Tebessa, where the panels of the Emsherian, Campanian and Maestrichtian are tilted with different directions in a very limited area; this observation, leads us to assume the dominance of the gravity phenomenon.
- On the north bank of the ditch, if we consider the area of Koudiat Nassela as a panel slipped under the effect of tectonic collapse, it would have had a tilting antithetical to the rim faults of the ditch,

but the panel is synthetic to the plane of rupture, to this effect, the imprint of gravity is present.

- Southeast of the town of Morsott on the north side of the basin, Turonian panels show relative scissor movements that exhibit both clockwise and counterclockwise movement over a very restricted area. This attitude may be due to gravity-induced movements caused by erosion.
- Gravity profiles (Fig. 11) carried out in the M-B (profile 9), in T-B basin (profile 10) and in Tr-B (profile 7) (in Zerdazi, 1990), show a "V" shaped incision for Tebessa basin located upstream of Morsott basin where the carbonate bedrock is at more than 5000 m depth. This "V" shape, which is relatively closed in Tebessa basin, tends to open in "U" shape in profile 9 of the Morsott basin and profile 7 of Terraguelt basin with a decrease in the depth of the carbonate basement, indicates a filling and a probable resumption of subsidence downstream (Morsott basin and Terraguelt basin). The deep incision upstream in Tebessa basin bears witness to the uplift of its substrate. Thus, the NW limit of the raised block would be located at the junction of the two basins (Morsott basin and Tebessa basin) and the SE limit would correspond to the relics of the horst represented in part by the Bouroumane massif. Such observations cannot, in our opinion, be the product of tectonic effects alone, but rather a process initiated by a major tectonic accident in which erosion followed its direction and played a predominant role.

It is very likely that this megastructure would correspond to the relics of a large post middle or post lower Miocene horst, which maintained atlasic structures in elevation, thus exposing them to further erosion (Fig. 12). The accidents of NE-SW, NW-SE and E-W orientations having affected this megastructure would have guided the orientation of the drains which served as evacuators of eroded material. Thus, by lateral progression, this process led the widening these V shaped incisions to form the actual wide valleys. In our opinion, the tectonics has controlled the orientation and erosion has taken care of the rest. This scenario is in harmony with the "V" shape of the substrate and then incised by erosion. It is less likely to get developped to the present form of the landscape if we assume the development of a depression of about 5000 m (Zerdazi, 1990) whose width is of the same magnitude.

This pattern is similar to what is currently taking place in the Youkous valley, where the N-S oriented fault has controlled the N-S orientation of the valley: The current intense regressive erosion affecting marly and marl-limestone formations is constantly widening the valley. The longitudinal progression towards the south of this erosion, would give a relief where the plateau of Cheréa would be equivalent to the now a days Djebel Dyr.

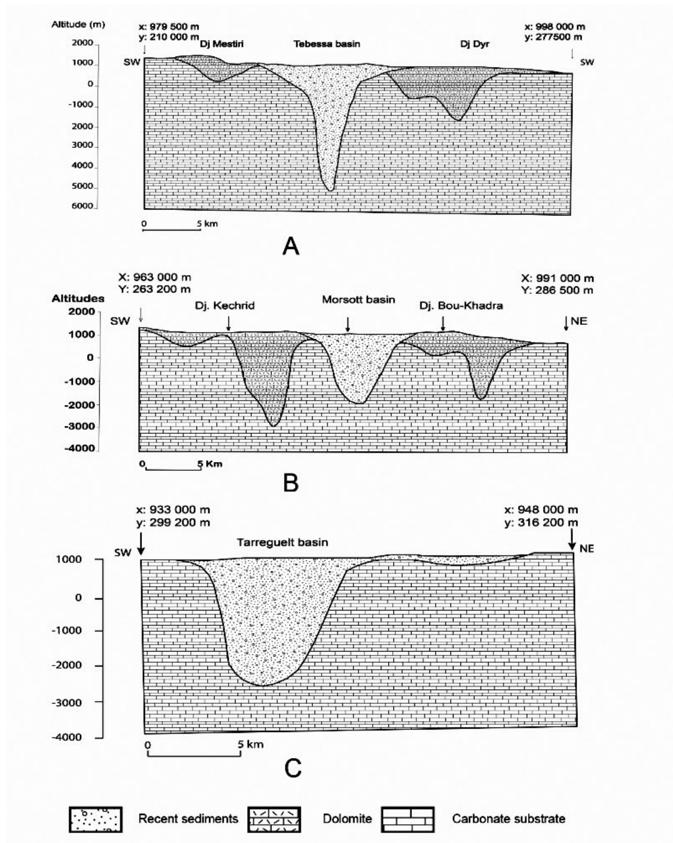
5. Discussion

It is undeniable that our approach which is essentially based on the use of digital terrain models (ASTGTM) and applying the surface envelope technique, remains an effective asset to enhance the data necessary for the interpretation of the structures recognized by previous works. The use of more geophysical data, in particular gravimetric data (Zerdazi, 1990; Asfirane and Galdeano, 1995; Boubaya, 2013) and geological maps covering the study area and mentioned above constitutes an effective mean in strengthening the interpretation. This adopted methodology has a definite ability in reconstructing the paleo-relief and foresee its likely future evolution and contributes to the conception of a global structural scheme of the region.

The determination of the altitudinal factors Zmax, Zmin and RA and their cross correlations allows making a significant segmentation of the relief. This approach is partly inspired by the work of Motoki (2014; 2015) who illustrates graphically the Relief Amount (RA) as a function of Zmax in order to explain the role of external geodynamics in the elaboration of the shapes of a magmatic landscape.

The acquisition of new data from geophysical surveys and boreholes will allow us to validate and/or differentiate the proposed interpretations, which are mainly based on the use of free radar images available at the various sites. In this way, the eastern end of the Saharan Atlas will remain a "test zone" from which it will be possible to generalize the approach to all the bare areas of north-eastern Algeria.

Figure 11. Gravimetric profiles carried perpendicular to the basins.



A: Tebessa basin B: Morsott basin C: Terraguelt basin

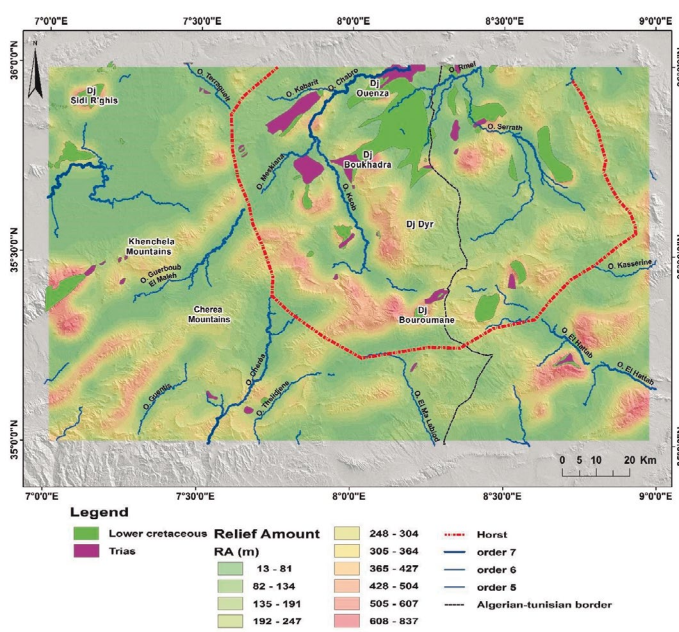


Figure 12. Map showing the location and extent of the probably megastructure of horst.

6. Conclusion

The approach adopted, which combines the use of the surface envelope technique, the analysis of the hydrographic network and the geological characteristics of the region, has enabled us to reconstruct the palaeo-relief before the action of the erosional processes that led to the present relief. The technique of the summit and basal envelope surfaces has allowed us to characterize the state of the relief through the elaboration of a map called "Relief Amount" which corresponds to the subtraction of the basal surface from the summit surface. This approach required the use of several grids. Indeed, the largest cell size (4000m X 4000m) has allowed us to obtain a map that materializes the initial topography. The medium cell size (1000m X 1000m) has shown an intermediate state, while the small cell size (250m X 250m) has shown the most recent state, close to the current configuration of the relief.

The reading of these different maps has revealed a sub-circular shaped structure, bounded by areas of slope breaks, which correspond to the dismantled physiographic unit. Being more conservative, these observations cannot prevent us from considering this megastructure as a "vast regional horst", which has controlled the configuration of the relief and consequently the drainage network.

On the other hand, the use of different grids has helped us to identify the stages of evolution where erosion played a preponderant role. Thus, the establishment of the "Horst" promoted the exacerbation of erosion. The rapid progress of the dismantling was conditioned both by the dissolution of the triturated calcareous walls and a digging along the main accidents which leads to the development of low areas of elongated forms assimilated by the majority of the previous published works to a graben structure. This situation is represented by the basins of Morsott and Tebessa. Thus, our interpretation is that Morsott basin is chronologically setup first, which is showed by the RA map deduced from the 4000m X 4000m grid, followed by that of Tebessa highlighted by the 1000m X 1000m grid. This succession in the set ups seems to respect an order from downstream to upstream and can only translate a regressive erosion since the regional base level is located in the NE of our study area.

The gravimetric data and the resulting interpretations support a relatively strong uplift of the southern and south-eastern part of the hypothetical horst, allowing a consequent channeling in the substratum of Tebessa basin, leaving an imposing carbonate massif of more than 1400 meters height on the southern side of the basin .

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