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New Insights from Gravity Data on the Geodynamic Evolution of Northern African Passive Margin, Case Study of the Tajerouine Area (Northern Tunisian Atlas)

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Abstract

In Northern Tunisia, geological structuring is very diverse. This diversification is due to its localization, which is situated within the convergence zone between Africa and Eurasia plates. This situation allows to a complicated geodynamic evolution from Permian Tethy's opening to the quaternary. Our study area is a key zone because we find several structures (Triassic extrusions, reefs, folds, grabens). The Surface studies (structural, sedimentology, etc.) leave controversies and many directions are only indicated as supposed faults. Thus, to understand geodynamic evolution is very important for petroleum and mining exploration. For this purpose geophysical method, which corresponds to a gravity data interpretation, is used to explore the subsurface structures. In this study, different techniques (regional-residual separation, Horizontal gradient magnitude, upward continuation, Euler DE convolution) were applied to the gravity anomaly map. The results obtained allowed to draw up a structural map showing faults system responsible for structuring the study area. The obtained structural map is consistent with several faults already identified in previous studies and shows new directions. This map leads to better understanding the geological structures and the geodynamic evolution of the region and is a very useful document to guide future mining and hydrocarbons operations research.

Keywords: Geological structures; Gravity data; MGH; Euler DE convolution; Tajerouine area; Northern African passive margin

Introduction

Gravity method is one of the oldest geophysical survey methods used by geophysicists. It was the first geophysical technique to be used in oil and gas exploration and despite being eclipsed by seismology, it has continued to be an important method in a number of exploration areas. Like magnetics, radioactivity and some electrical techniques, gravity method is a natural-source method. Local variations in densities of rocks near the surface cause minute changes in the gravity field. Gravity method is often regarded as a potential field method. Gravity is an inherent property of mass and the gravity effects of local masses are very small compared with the effect of the background field of the earth as a whole. Interpretation of gravity data can be carried out both quantitatively and qualitatively. It is aimed at mapping the surface and subsurface regional structures (intrusive bodies, syncline structures, anticline structures, contacts, faults, basement rocks, mineralization and thickness of sedimentations or depth to anomalous bodies). Moreover, gravity method is still widely used as an exploration tool to map subsurface geology and estimate ore reserves for some massive ore bodies [1-4]. Qualitative interpretation involves the description of the survey results and the explanation of the major features revealed by a survey in terms of the types of likely geological formations and structures (intrusive bodies, syncline structures, anticline structures, contacts, faults, basement rocks and mineralization). Quantitative interpretation involves making numerical estimates of the depth and dimensions of the sources of anomalies and this often takes the form of modelling of sources which could, in theory, replicate the anomalies recorded in the survey [5-8]. Several methods of interpretation in gravity prospecting include: the Euler-3D method, local wave number method, analytical signal method, source Parameter Imaging (SPI) method, forward and inverse modelling method [6,7]. The beginning stages of gravity data interpretation generally involve the application of mathematical filters to observed data after ensuring that the gravity data has been reduced (corrected). The specific goals of these filters vary, depending on the researcher's interest. The general purpose is to enhance anomalies of interest and/or to gain some preliminary information on location of the source anomalies.

Northern Tunisia is characterized by many geological structures which have been formed during the Atlas orogenic movements [9-12]. From north to south we found the alpine domain which characterizes by allochthonous formations, the Numidian and Tellian units.

In the southern part of the atlasic domain, we find the "*Diapiric Zone*", and the central Tunisian Atlas. The "*Diapiric Zone*" is characterized by NE-SW Triassic outcrops where we find the majority of ore mines in Tunisia and constitute a good target for petroleum exploration.

The area of Tajerouine is located in northern Tunisian Atlas (Figure 1) between latitude 36°00' and 35°50' and longitude 8°20' and 8°45'. Topographically, the mountains of this area are among the Algerian-Tunisian border (Figure 1). The massifs are limited to the west by the Algerian border named Tebessa area. The study area occupies the southwest portion of the province with Triassic extrusions which are strongly deformed and show the main direction NE-SW [10,12-15] The area is limited to the south by the central Tunisian atlas, which characterized by NE-SW atlasic folds truncated by NW-SE to E-W trends Graben.

The Litho-stratigraphic succession in our study area extends from the Triassic to the Quaternary with a lack of Jurassic series (Figures 2 & 3).The Jebel Slata anticline Located at the SW part of the Tajerouine region, is the most singular among the massifs that emerge

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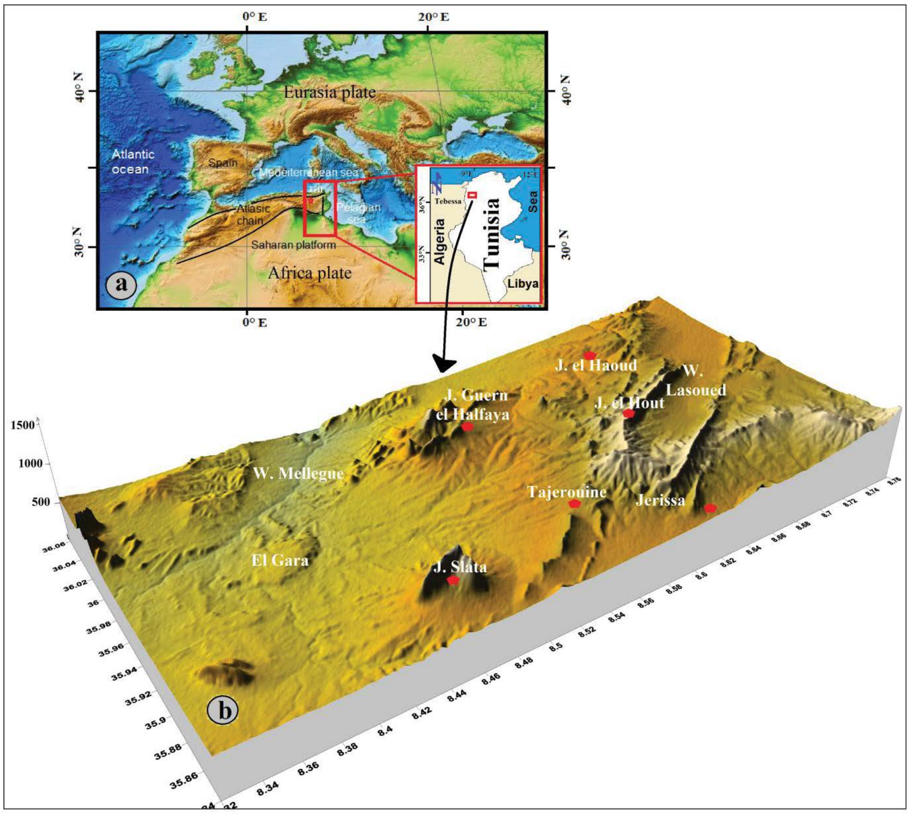

Figure 1: Digital Elevation Model in this region and location of Tajerouine area in Tunisia.

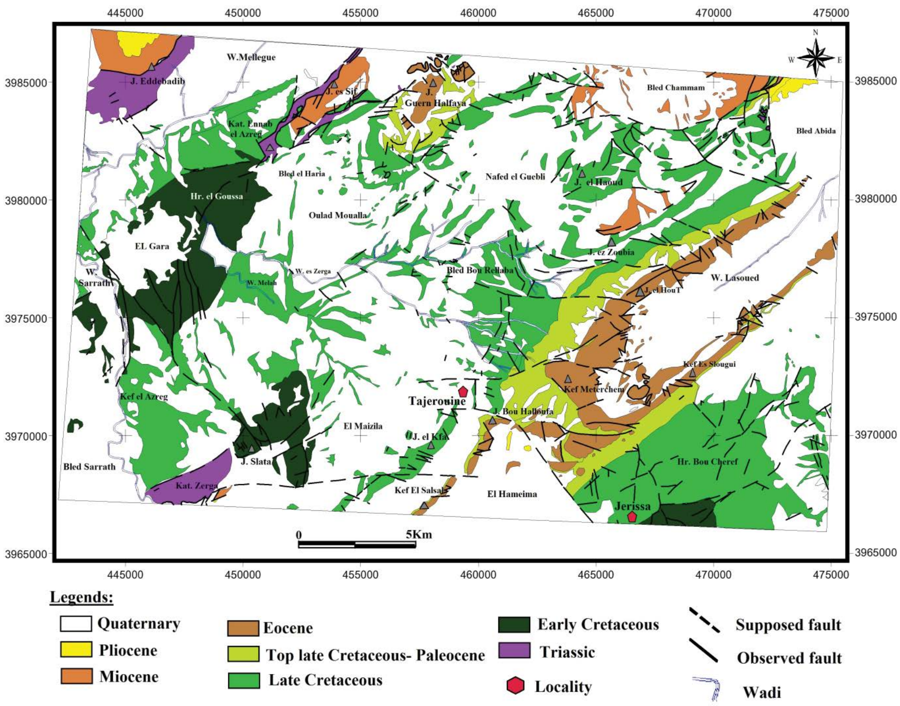

Figure 2: Geological map of Tajerouine (Northern Tunisian Atlas).

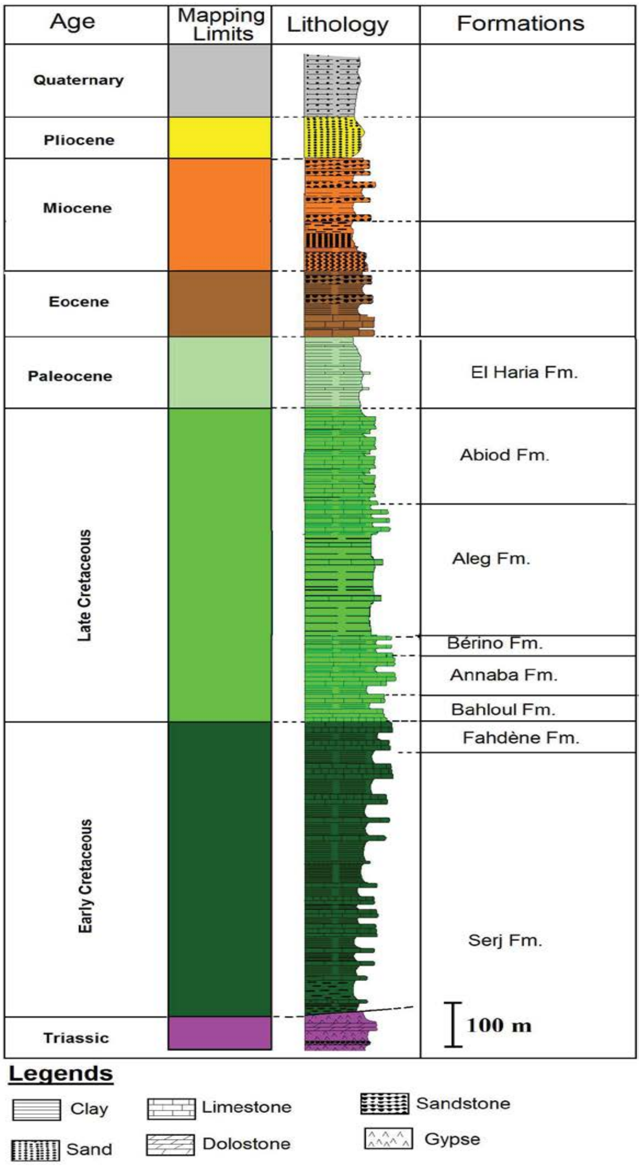

Figure 3: Synthetic logs of the Mesozoic and Cenozoic series in the Tajerouine area. Thickness was derived from outcrops and geological maps.

on the Algerian-Tunisian borders because it is characterized by a particular morphology and formed of two ridges, the one N-S, called Sidi Amor Ridge, culminating at 962 m, the second E-W, called Slata Ridge, culminating at 1023 m [16]. This massif has been the subject of numerous studies [12,17-19]. But these studies are not sufficient to understand the lineaments of the study region in detail and to explain the modality of Triassic ascension. In fact, this region shows a chaotic Triassic outcrops with a tectonic contact with the surrounding sediments. Besides, in the same locality we note interstratified Triassic bodies in the Albian series which can be explained as a salt extrusion on a passive continental margin which qualified "*Salt Glacier*". This last feature is mentioned in many locality in Tunisia [18-21]. The opening of NW-SE oriented Graben was explained as pull-apart basin. The reefs are explained as a top of diapiric sediments or a post-Aptian basculed bloc [12]. For this reasons, the Tajerouine area constitutes a key zone to understand the geodynamic evolution of northern Tunisia. The current study is concerned with the analysis of gravity data aiming to evaluate the subsurface structure to give some new insights into structural interpretations that were previously unnoticed and to provide an updated lineament map for the study area.

Gravimetric Data Analysis

The gravity data used in the current study is offered by the ONM "*Office National des Mines*". The studied area is covered by gravity station on a1×1 km^2.The density correction used to calculate Bouguer anomaly is 2.4. This density is very suitable with the lithology of the outcrops in this region. The complete Bouguer Anomaly map obtained in our study area (Figure 4) shows values between -10 mGal and -38 mGal. These values correspond to anomalies that reflect the heterogeneous densities in the subsurface, related to sources of different depths. So this map reflects not only the effect of the sedimentary cover but also the effect of all the heterogeneities under the topographic surface. The Bouguer anomalies map shows many positives and negatives anomalies: the axis of positive anomaly is called PA and the negative anomaly is called NA. In our study area we can find the last anomalies (Figures 4 & 5).

PA1: Towards the west of the study area, a positive anomaly NE-SW, is localized above the limestone of Early Cretaceous series (Serj Formation), and Late Cretaceous (Albian and the Cenomanian-Turonian) at Jebel El Gara.

PA2: A positive anomaly trending NE-SW, has a small amplitude and is superimposed on the Slata anticlinal which is formed mainly by Early cretaceous series.

PA3: The southeast of our study area shows a NE-SW trending anomaly, is which overlies the massif of Jerissa. This anomaly coincided with the Early Cretaceous (Aptian) outcrops which are characterized by alternating blocks of limestones, dolomites and, marls.

PA4: This positive anomaly of E-W to NE-SW trend, localized on J. el Haoud, coincides with Cretaceous series outcrops.

NA1: This negative anomaly of NE–SW direction reaches -34.5 mGal, and is located in Lassoued syncline, containing quaternary alluvium which is characterized by a low density.

NA2: This negative anomaly is located on the east of the area of El Kef el Salsal, with the continuity of the northern Graben Kalaat Khesba in the south. This anomaly on the map shows a value of -38 mGal.

NA3: The negative anomaly matches the syncline Guern Halfiya of NE-SW direction. A mass deficiency generated by Eocene series of Guern Halfiya structure.

NA4: This anomaly is at the northern limit of the map located above the mio-plio-quaternary outcrops of Bled Chammem. It reaches -26.5 mgal.

Anomalies gravity: Axis of Positive Anomalies (PA); Axis of Negative Anomalies (NA).

The complete Bouguer anomaly map shows a distribution of anomalies, which show the main Atlasic direction NE-SW. On (Figures 4 & 5) we have placed these axes superposed on the geological map of Tajerouine. This figure shows that all the positive anomalies are associated with Mesozoic outcrops which essentially formed by limestone's and aptian reef. This aptian reefs contains some mineralization in slata, Guaren el Halfaya and Jerissa area.

In order to highlight the gravity anomalies associated with the

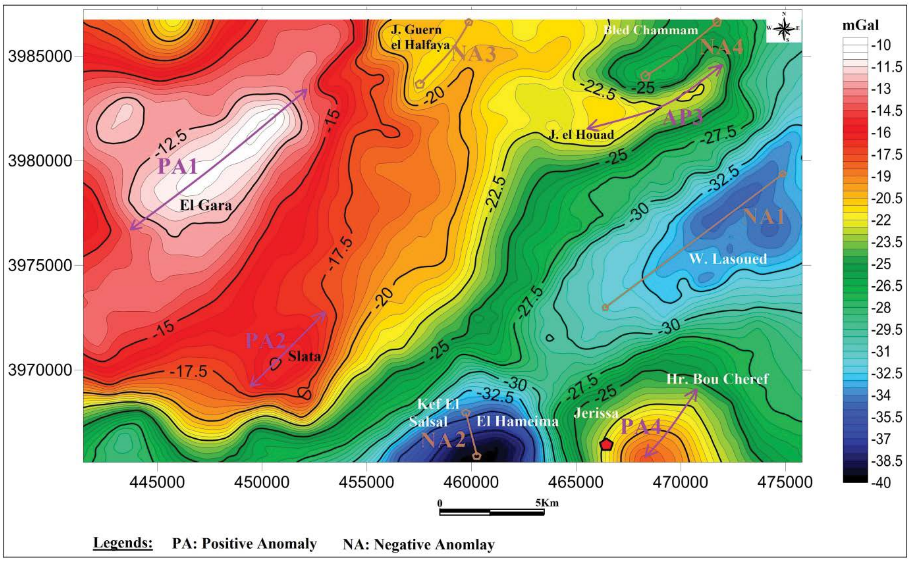

Figure 4: Bouguer gravity map of the study area. Contour interval=1.5 mGal.

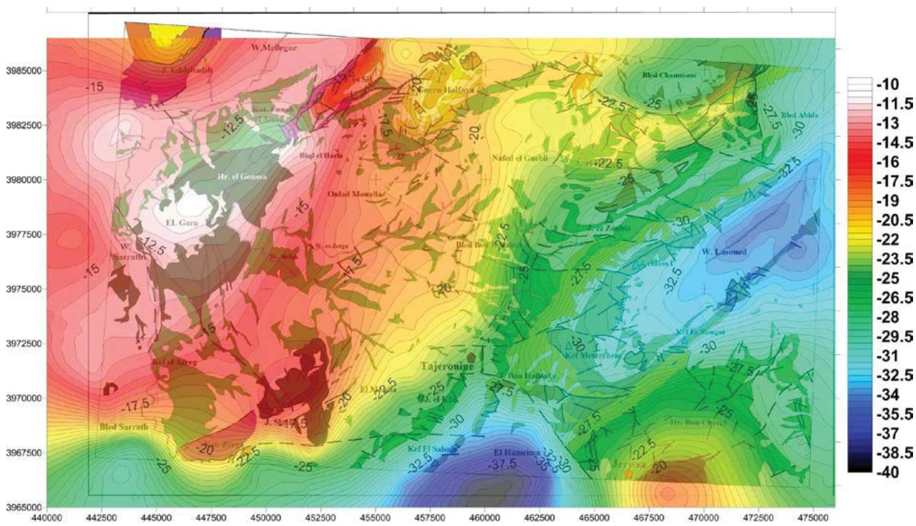

Figure 5: Superposed Bouguer anomalies map on the geological map.

sources located within the sedimentary over, a regional –residual separation of the Bouguer anomaly was performed.

The regional term remains rather subjective. Figure 6a-h shows the Bouguer anomaly and its upward continuation at several heights, from 500 m to 9000 m. The upward continuation of Bouguer gravity field at 9000 m map (Figure 6h) represents the regional gravity field of the study area because the gravity effect of the most prominent structure related to the El Gara. In northern Tunisia we highlight an increasing in Moho depth from north to south, which caused a gravity gradient near 0.9 mgal/km [22]. For this reason and taking into account the results of upward continuation, a regional trend corresponds to a 3-order polynomial surface is removed from the gravimetric field thus highlighting the local gravity anomalies (residual anomaly), which present best fitting with regional tectonic elements. The residual anomaly map obtained, represents the effect of the near surface sources (sedimentary cover). They are produced by heterogeneities, in the sedimentary cover. Indeed the elimination of regional anomalies promotes enhancement of responses sources of short wavelengths and the identification of sources directly responsible for the anomalies. The residual map obtained (Figure 7), shows that the amplitude of anomalies ranging from -10 to 12 mGal. The general amplitude decreased compared to the amplitude of the Bouguer anomalies map. On this map, it appears that the positive anomalies are related to cretaceous limestone outcrops and reefs. What can be deduced from this map is that positive gravity anomalies coincide with the Mesozoic outcrops (Cretaceous), while the Cenozoic basins and a graben structures are marked by negative anomalies.

Methodology

Magnitude of horizontal gradient

The Horizontal Gradient Magnitude (HGM) is a technique that used for measuring the rate of change of a potential field in the x and y directions in order to define subsurface structures [23].

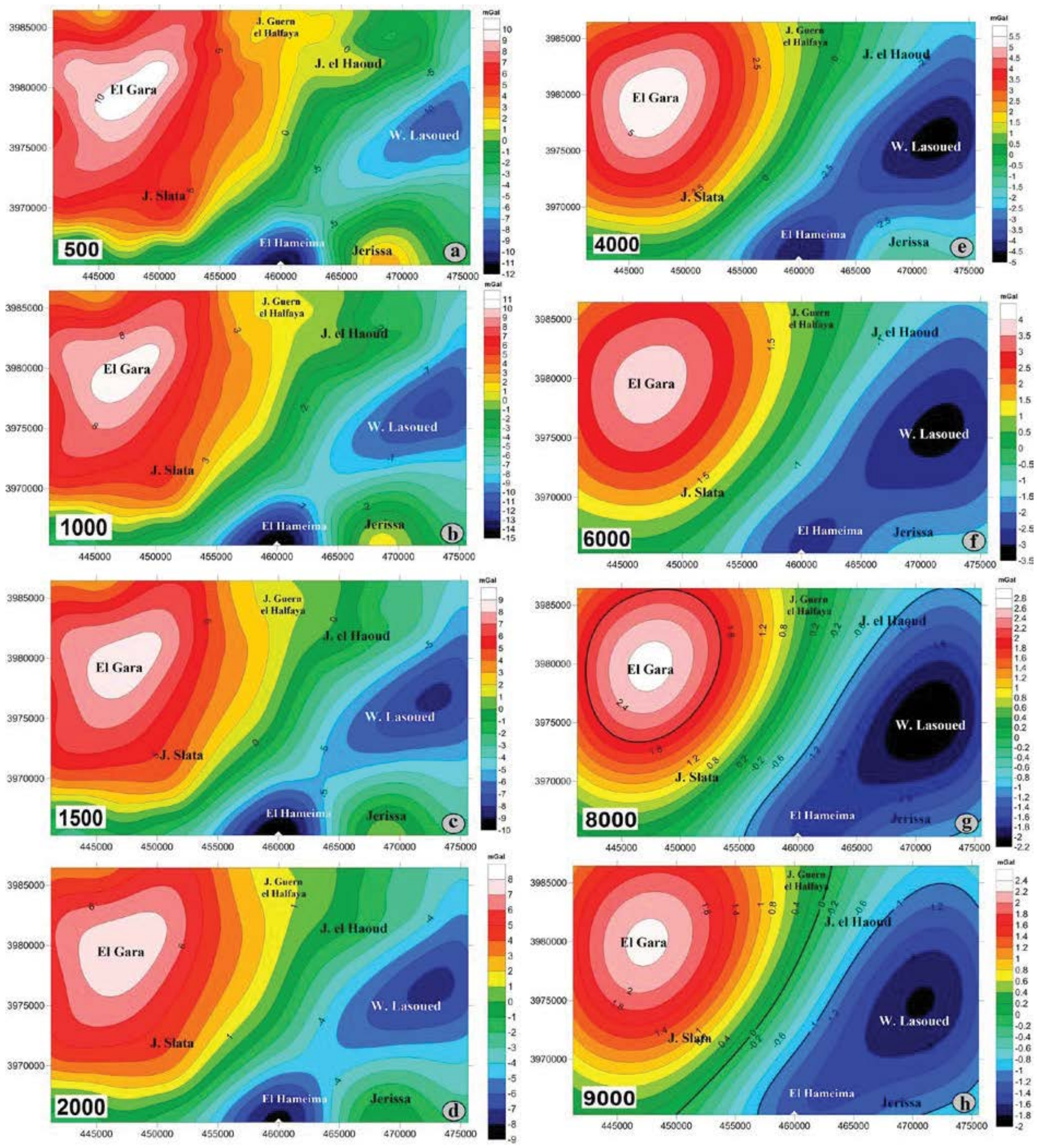

Figure 6 a-h: Upward continuation of the Bouguer anomaly maps at several heights: 500 m (a); 1000 m (b); 1500 m (c); 2000 m (d); 4000 m (e); 6000 m (f); 8000 m (g) and 9000 m (h).

$$HGM(x,y) = \sqrt{\left(\frac{\partial G}{\partial y}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2} \quad (1)$$

Where, G is the Bouguer gravity field.

In order to estimate the location of the lateral boundaries of the anomaly sources, we performed an edge enhancement analysis using the Horizontal Gravity Gradient Magnitude (HGM) method [23]. The HGM is calculated using north–south and East–West directional derivations (e.g., Bouguer or residual) of gravity anomaly value. The HGM tends to have its maxima located over edges of gravity sources corresponding to an abrupt change of density. Such a location of a lateral density contrast is useful in constraining the lateral location of the source body. The completion of the map of local maxima of the horizontal gradient is used to represent all the outlines that determine the tectonic lineaments responsible for the structuring of our study area. Figure 8 a-b shows the location of the local maxima of the horizontal gradient and highlights some lineaments which have no surface geological signature, reflecting the contribution of this geophysical method in the discovery of new lineaments. In order to estimate the lineament dip, we used the method of upward continuation to a series of high up to 4 km and at each level; the maxima of the horizontal gradient were located. The superposition of these maxima determined on the map of the Bouguer anomaly and its upward continuation underline the different contacts and indicate their dip. If the contact has a dip, the maximum horizontal gradient determined on upwards continuation maps move laterally to the direction of the dip. The vertical accident (vertical dip) is determined by the superposition of these maxima. The statistical treatment of contacts, interpreted as faults, revealed the existence of many directions NE-SW, NW-SE, E-W and N-S. These are

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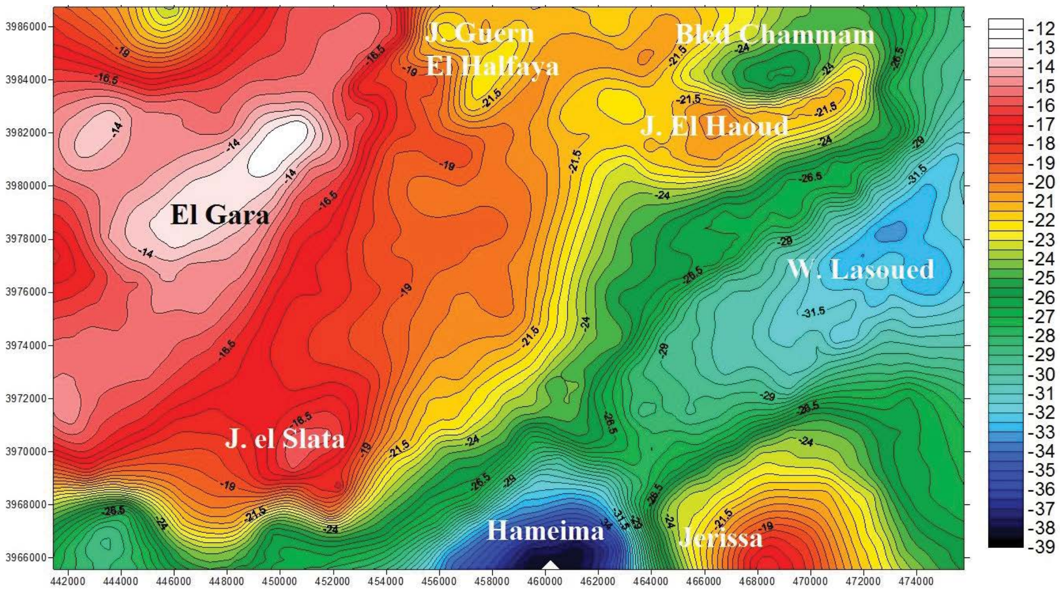

Figure 7: Map of residual anomalies (3rd degree polynomial).

regional faults that show the main Atlasic direction. The NE-SW faults boarded essentially the W. Massoued syncline. The N-S lineaments are only indicated as supposed faults after geological studies. These faults controlled the geodynamic evolution since the Triassic rifting [10] and it's responsible for the edification of the geological structures during the Cenozoic compression. The E-W dextral thrust dextral fault disposed relay, assuring the junction according to the Pull-Apart bassin of Kaâlet El Khesba and Bou Ghanem grabens which bordered by NW-SE faults.

Euler DE convolution

Euler differential equation which is well known in mathematics was used in potential field primarily by Hood [24]. The first successful application was realized by Thompson (1982) for magnetic anomalies along the profile. After that, study of Reid [25] was presented interpreted magnetic anomaly map by using Euler DE convolution. Finally, application of Euler DE convolution to first order vertical derivative of gravity data was applied by Klingele and Marson [26].

Any 3-D function f (x,y,z)is said to be homogenous of degree n if the function obeys the expression.

After that, the equation, which is known as Euler's equation, can be presented as the following is also satisfied;

$$f(tx, ty, tz)=t^n f(x, y ,z) \quad (2)$$

$$x\frac{\partial f}{\partial x}+y\frac{\partial f}{\partial y}+z\frac{\partial f}{\partial z}=nf \quad (3)$$

The treatment of Euler DE convolution applied on the residual map is a technique that allows us to detect the sources of anomalies and estimating their depths [27-29]. In order to assess the depth of the structures shown, the technique of Euler DE convolution was applied to gravity data by considering a contact model (structural index=0). The analysis of Euler DE convolution mapped over the residual map used to report structural discontinuities throughout the study area to understand the geodynamic evolution of the region (Figure 9). These results confirm the existence of the most structures determined by the previous treatment (maxima of horizontal gradient method). Some among these are deeply rooted, their depths exceeding 1000 m and can reach 4622 m. these deep accidents have a role in the geodynamic evolution of the studied area since the lower Cretaceous. Certainly, these accidents are responsible for the halotectonic activity and the reef edification and the graben opening during the different tectonic phases which affect northern Tunisia.

A structural map of the area is carried out following the superposition of these lineaments gravity on a background of the Tajerouine geological map (Figure 10). These lineaments are the result of the DE convolution Euler applied to the residual and MGH. This structural map exposes faults surface already known and faults in the subsurface set by gravimetric method.

Results

The Bouguer anomaly map was generated using a density stations repartition (1 point/km^2) which is useful for studying the geological structures. After separation of regional and residual anomalies, the residual map obtained has been superimposed over the geological map for understanding the correlation of the gravity anomalies and the geological structures of the study area. A positive anomaly coincides with cretaceous outcrops. While the Cenozoic outcrops, formed by sands and marls, and are expressed by negatives anomalies. To understand the sources of these anomalies and for identification of different geological features several treatments have been made to the residual anomaly maps (MGH calculation, Euler De convolution). The MGH map shows several NE-SW and NW-SE directional lineaments. This lineaments, mark a density contrast between different formations, are interpreted as a faults. These lineaments are well correlated with structural studies of northern Tunisia and we have determined new faults from the potential field data. Besides, the Euler De convolution map (Figure 9) shows deep faults which are controlled the geodynamic evolution of the study area and allows to the edification of ores deposits in the Jerissa and Slata area.

Discussion

Following the new established structural map (Figure 10), the NW-

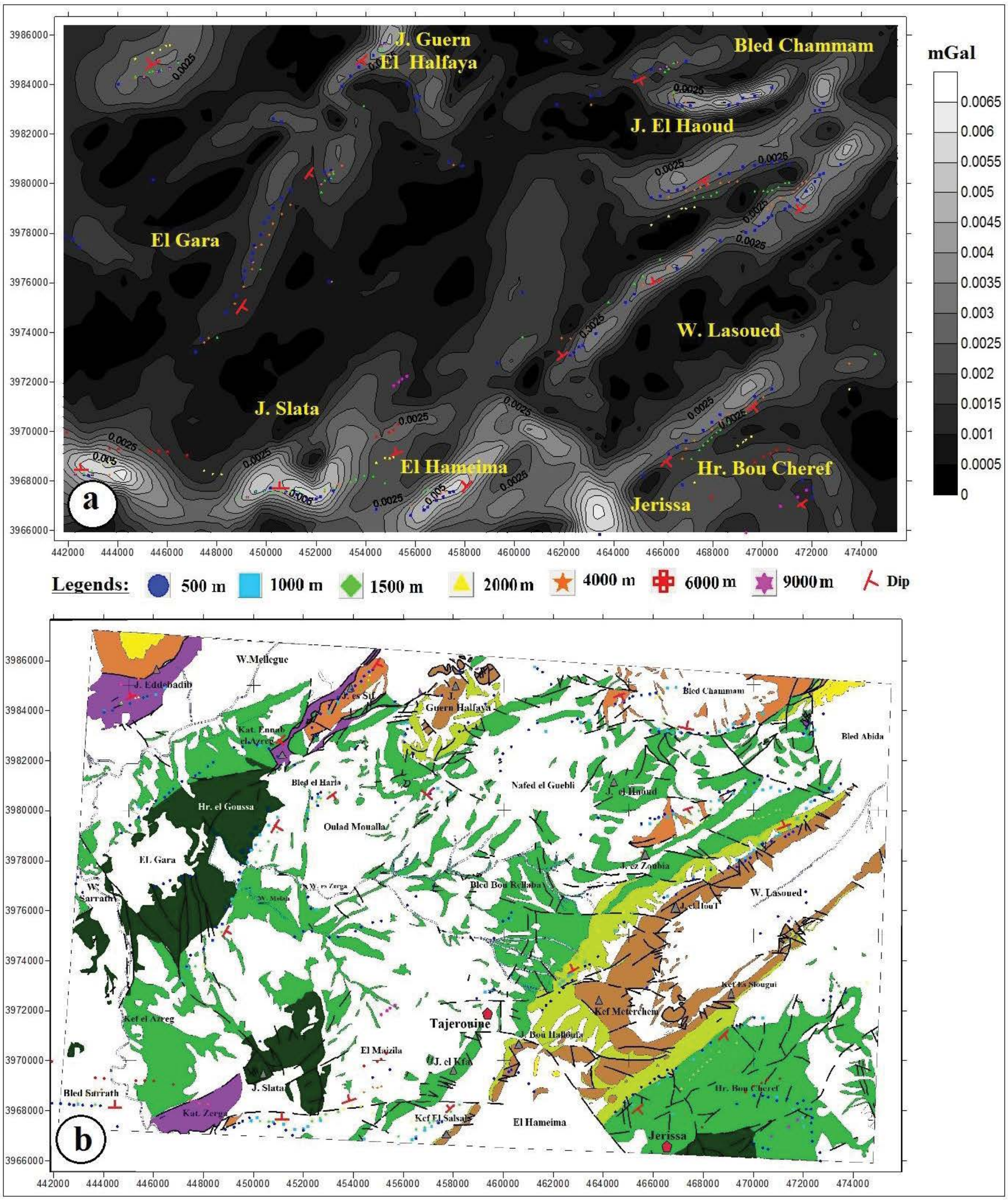

Figure 8 a-b: Superposition of the horizontal gradient map (gray background image) to the maxima of the same gradient obtained on the map of the residual anomaly (1) on its continuation upward at different altitudes: 500 m, 1000 m, 1500 m 2000 m, 4000m, 6000 m and 9000 m.

SE and NE-SW are the most significant tectonic faults responsible to the edification and geodynamic evolution of the northern Tunisian atlas. These faults have a great deep, which can affect the basement structure. Taking into account the result of numerique modelling, the stress which affect northern African margin from Triassic rifting to actual [9,11,12,27,28] and a results of similar geological structures in Tunisia and in the world which shows a salt diapiric structure, Graben structures and folding we can explain the mechanism of edification and the geodynamic evolution of the geological structures in study area: -During the Jurassic and lower cretaceous the Northern African margin is affected by an extensive regime, which is characterized by the activation of the NE-SW lineaments as normal faults [30-33]. The thick-skinned allows in this period, to the establishment of depo-center and a salt pillow structures. This latter is confirmed by aptian reef in the uplifted zone near the actual Triassic outcrops. The diapiric salt structure is preferentially located above a deep faults which is in is in good agreement; with the results of analogical modelling of the initial stage of salt diapiric structures.

In the Albian the extension persists and the Triassic body reaches the surface and formed small overhangs in the Albian layer. This latter phase as evidenced by the interstratifications of Triassic rocks in Albian sediments which could match lateral overlaps of diapiric "*Rooted*" structure [34-36].

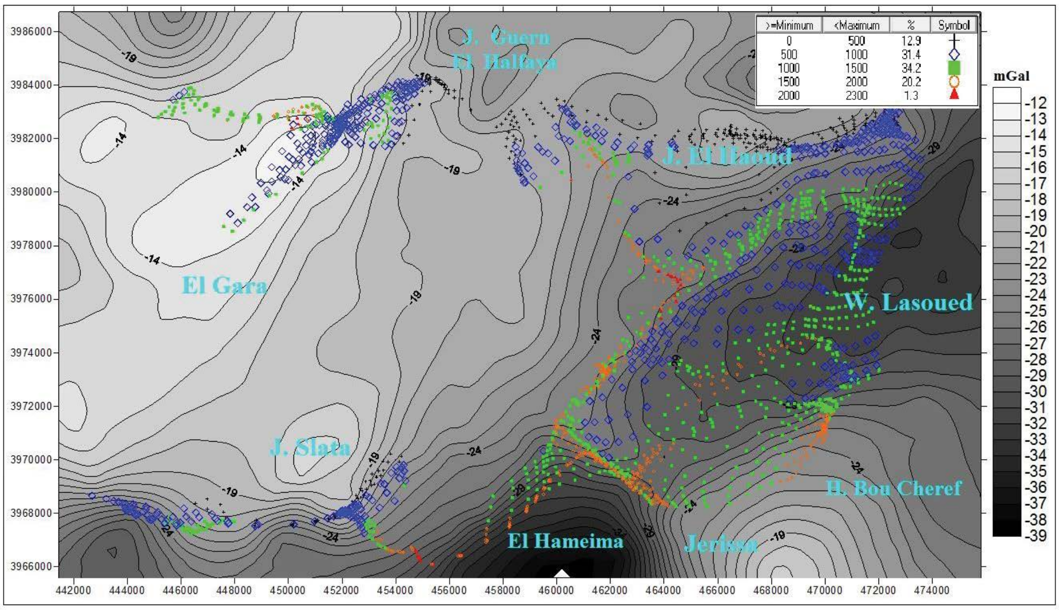

Figure 9: Euler deconvolution over the residual map.

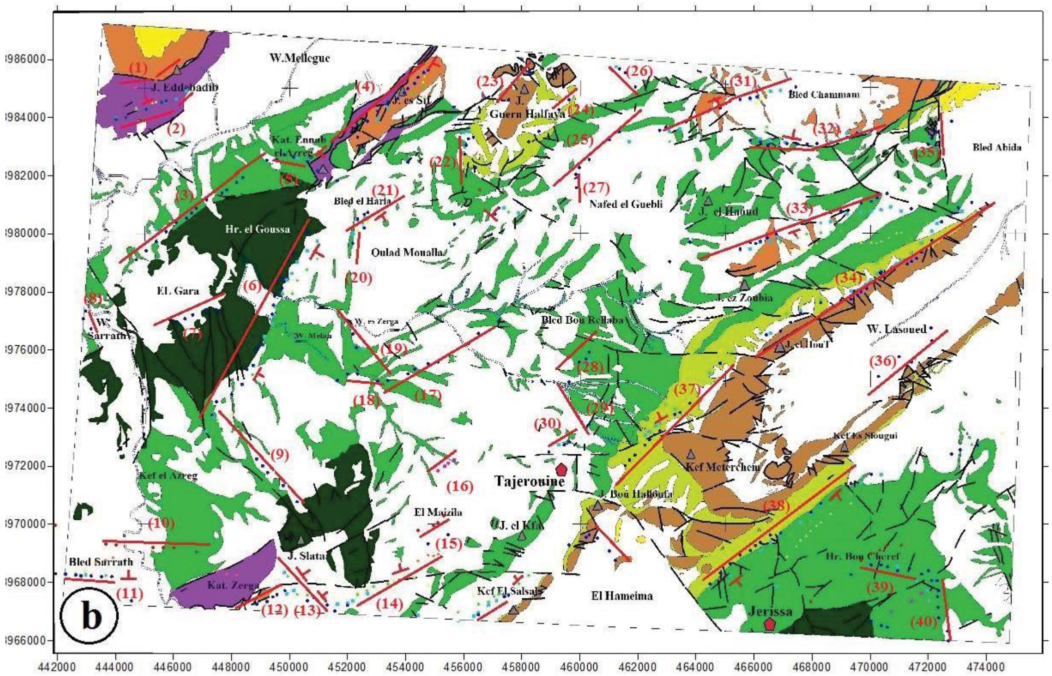

Figure 10: Structural map of the region having Tajerouine gravimetric lineaments in red lines.

During the compressive phase at the end of the Cretaceous and Tertiary, The NE-SW faults were re-activated and inverted. This allows to the structuring and folding of the study area (anticlinal and synclinal oriented NE-SW). At Jebel Slata (Figure 10), we were able to confirm the existence of a fault rooted as mentioned by Tandia [19]. This structure is edified in the junction of NE-SW (lineament (14)) and NW-SE (lineament (13)) faults (Figure 10). While, the NW-SE are reactivated as a dextral strike slip faults and contribute to the Graben opening as a "*Pull Apart*" basin [37].

Conclusion

Considering the different results generated by the processing of gravity data of the study area, this allowed providing input to the Geological Survey in central and northern Tunisia. Indeed, this study allowed plotting the structural map of the study area. Taking into account these results, geological observations and tectonic stress which affect northern Tunisia from Triassic to actual, we can explain the mechanism of edification of some particular structures in this area (Triassic extrusion, graben opening, and folds) and contribute to understand the geodynamic evolution of the region. The structure of the region is the combined result of events responsible of folding, opening the graben, the establishment of the Triassic extrusions and fractures. The structures building, in this area was controlled especially by a deep faults (NE-SW and NW-SE oriented faults). The activation of these faults during the extensive period allows to the beginning of the mobilization of Triassic rocks and the edification of salt pillow. The extension persists and the Triassic rocks reach the surface, this stage is well-fitting with geological observations. During early, cretaceous to actual, these faults are reactivated and inverted to contribute the genesis of many NE-SW folds and the opening of the NW-SE graben. This geodynamic evolution is suitable to ore genesis and hydrocarbons traps edification. In this way the new structural map established in this study area is very interesting and constitute a document to guide the hydrocarbons and mining exploration.

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