Use of aeromagnetic data for structural mapping of the Tlemcen Mountains (northwestern Algeria)

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Abstract: In order to refine the geological mapping and to improve our knowledge of the Tlemcen Mountains structure (northwestern Algeria), the interpretation of aeromagnetic data using several processing techniques allowed us to map the Paleozoic basement of Rhar Roubane Mountains and the sedimentary cover constituted by geological formations of Mesozoic and Cenozoic age. Structurally, the Tlemcen Mountains are formed by several structures (e.g., Sebdou Graben), separated by three major transverse faults NNE-SSW (Tafna-Magoura, Oued Chouly and Ain Tellout transverse faults). We have also been able to highlight a set of deep and shallower structures, trending mainly in NE-SW, N-S, and E-W, and affect the western part of the Tlemcen Mountains (Rhar Roubane Horst) and the south-eastern part of the Tlemcen Mountains.

Key words: Aeromagnetic data, geological mapping, structure, Tlemcen Mountains, Algeria

1. Introduction
Magnetic prospection can be used to investigate geological structures (Hsu et al., 1996; Grauch, 2001; Sabaka et al., 2004; Munschy et al., 2007; Boukerbout et al., 2018; Bensefia et al., 2020; Ekinci et al., 2020). This method is applied for different purposes such as archeological studies or hydrocarbon exploration (Reynolds, 1997). Magnetic anomalies are frequently employed as a qualitative tool to support the regional geological interpretations (Ofoegbu and Mohan, 1990; Roest et al., 1992; Mohan, 1993; Abdelrahman et al., 2003). At present, magnetic survey finds application in a diverse range of fields, including geotechnical engineering, environmental and engineering studies, hydrological and geothermal investigation, archaeological exploration, mapping of unexploded military ordnance (UXO), and geotectonic research (Essa and Diab, 2022). Magnetic interpretations represent an important key to understanding the geological structures and their geometric forms and dimensions (Primdahl et al., 2002; Salem et al., 2002; Abdullahi et al., 2019). Established magnetic anomaly maps are usually examined using a variety of techniques, including linear transformations, such as the reduction to the pole or equator, as well as upward and downward continuation (Blakely, 1995). In order to accentuate the edges and delineate the boundaries of the magnetic sources, the gradients (horizontal and vertical), the analytic signal and their various combinations were applied (e.g., Ekinci and Yigitbas, 2012; Boukerbout et al., 2018; Abdullahi et al., 2019; Bensefia et al., 2020; Essa et al., 2022). For instance, the spectral analysis method, based on the energy spectrum of the magnetic anomalies, yields information about the depths of the main magnetic anomaly causative structures (e.g., Ekinci et al., 2013; Bouyahiaoui et al., 2017; Abdullahi et al., 2019; Bayou et al., 2022). Likewise, the continuous wavelet transform method can be utilized for the localization of the sources responsible of the anomalies, as described in the literature (e.g., Moreau et al., 1997; Hornby et al., 1999; Boukerbout et al., 2003; Fedi et al., 2004; Sailhac et al., 2009).

In this study, we investigate the Tlemcen and Rhar Roubane Mountains (NW Algeria) using aeromagnetic data. The region of interest is located between the Maghnia Depression in the north and the Oran High Plains in the south. The Tlemcen and Rhar Roubane Mountains have been the subject of several structural studies to show: (1) the important role of transverse faults (Tafna-Magoura, Oued...
Chouly, and Ain Tellout) whose directions are found at the scale of the Maghreb (Elmi, 1983), and (2) NNE-SSW, N-S, and E-W decoupling often accompanied by folding (Elmi, 1970, 1973; Benest, 1982, 1985). Moreover, the structural evolution of this part of the Oran Block shows the existence of several tectonic phases starting with the Eocretaceous phase until the recent Plio-quaternary phase (Benest, 1982, 1985). In this study, we use aeromagnetic data to refine the geological mapping and clarify the previous structural results. We analyzed the total field aeromagnetic anomalies of the Tlemcen and Rhar Roubane Mountains and performed linear transformations (Reduction to the pole), horizontal and vertical gradients, analytic signal, upward continuation, radially averaged power spectrum, 3D Euler Deconvolution and the complex continuous wavelet transform.

2. Geographical and geological setting
Located in northwestern Algeria (Figure 1a), the Tlemcen Mountains are bounded to the north by the Miocene trough (from west to east: Magnhia Plain, Hennaya Plain, and Sidi Bel Abbès Plain), to the south by the Oran High Plains, to the east by the Daïa Mountains and finally to the west by the Moroccan horsts (Figure 1b). The stratigraphy of the Tlemcen Mountains includes a Paleozoic bedrock outcropping at Rhar Roubane Horst (Figure 2). It is essentially made up of schists, microconglomerate (Carboniferous), quartzites and phanerites. In the Khemis region, granodioritic veins (Lucas, 1942; Marok and Reolid, 2012) intersect this ensemble of rocks. Furthermore, the thick Mesozoic and Cenozoic sedimentary cover has been studied stratigraphically, paleontologically, and sedimentologically (Lucas, 1942, 1952; Augier, 1967; Auclair and Biehler, 1967; Elmi, 1977, 1983, 1996; Elmi and Alméras, 1984; Elmi et al., 1974, 1998; Touahri, 1983; Benest, 1981, 1985; Mekahi, 1988; Benest et al., 1993, 1999; Mekahi et al., 1993; Kharroubi, 1987; Marok, 1989; Marok and Reolid, 2012; Reolid et al., 2014). The sedimentary cover is represented by the geological succession described below.

2.1. The Triassic succession
Triassic is represented by Keuper facies which form a diapiric complex with clayey, red, and greenish facies, rich in evaporites (both gypsum and halite). In certain localities (Beni Bahdel and Ain Tellout), these facies are associated with volcanic rocks of dolerite texture.

2.2. Lower and Middle Jurassic succession
The Lower and Middle Jurassic successions rest unconformably on the Paleozoic basement and commonly over the diapiric Triassic sediments. These materials, dated at lower Pliensbachian-Middle Jurassic, are found only in the western part of the Tlemcen Mountains (Rhar Roubane Horst). In the western part of the horst (Beni Bou Said region; Mekahli, 1988), the essentially carbonate deposits are made up of limestones and massive dolostones (Pliensbachian), alternating marls-limestones (Toarcian), oolitic limestones and crystalline dolostones (Aalenian-Bajocian), and finally Deglène ferruginous oolitic and silty limestones (lower and middle Bathonian). In the central part of the horst (Tissèddouâra and Khemis regions), the lithostratigraphic succession is formed by limestones with large bivalves (lower Pliensbachian), followed by limestones with brachiopods (upper Pliensbachian) and limestones with oncoliths (Toarcian). After a gap in the Aalenian and the lower middle Bajocian, the sedimentation begins with the deposition of a thin (centimetric) oolitic and oncolitic limestones rich in belemnites and ammonites (upper Bajocian), and thick silty limestones of the lower and middle Bathonian (Lucas, 1942; Elmi, 1977, 1983; Marok, 1989; Elmi et al., 1998; Marok and Reolid, 2012). In the eastern part (Beni Bahdel region), the sedimentary series is essentially represented by carbonates (lower Pliensbachian-lower Bajocian) passing to marls (upper Bajocian). Finally, in the southern part of the Rhar Roubane Horst (Mdrëba-Tenouchfi region), the deposits start with limestones (lower Pliensbachian-upper Pliensbachian) followed by the marls of the Aioun ben Mira (Toarcian; Atrops et al., 1970). The series ends with the Tenouchfi Dolomites (lower Aalenian-Bajocian) (Benest et al., 1978; Mekahi et al., 1993), the ammonite marls (upper Bajocian) and the silty limestones (lower and middle Bathonian; Marok, 1996).

2.3. Upper Jurassic succession
In the domain of the Tlemcen Mountains, a generalized sinking is recorded during the Callovian and continues until the early Oxfordian (Elmi, 1983). It is recorded by the thick deposits of the Saïda Clays Formation, followed by the Bou Médine Sandstones, the Zarifet Limestones, and the Tlemcen Dolomites. The Tithonian, is characterized by the deposition of marly-limestones, limestones and dolostones (Benest, 1985).

2.4. Cretaceous and Cenozoic succession
The sedimentary record of the Lower Cretaceous is composed of marls-limestones alternance, claystones, sandstones and limestones (Benest, 1985; Benest et al., 1999; Reolid et al., 2014). The Upper Cretaceous and Paleocene are not represented in the study area.

The Cenozoic series is represented by continental sedimentary rocks from the Eocene such as conglomerates, clays, marls and red silts. The Miocene is principally constituted by marine sedimentary rocks, includes (fine sandy green marls, conglomerates, red clays and sandstones).

Structurally, the Tlemcen Mountains form a long orographic barrier oriented roughly SW-NE. Their
Figure 1. Location of the studied area.
structure is marked by systems of (sinistral and dextral) detachments. Thus, the western part of the Tlemcen Mountains is dominated by a horst structure affected by two large boundary faults (N60° and N70°; Elmi, 1970, 1973; Marok, 1989). We should also note the presence of two families of unstreaking accidents (N10°–N30°) and N110°–N145° (Elmi, 1977). The presence of these faults indicates a crushing and a displacement towards the north (Elmi, 1977). On the other hand, the Tlemcen Mountains (sensu stricto) which develop between the Tafna-Magoura and Aïn Tellout transversals are cut into three segments, which are from west to east (Benest, 1982): the sigmoid zone of Sidi Yahia-Sebdou, the central arched panel of Terni and the sigmoid block of Lamoricière. According to Benest (1982), the general structure of the Tlemcen Mountains shows the presence of five main tectonic events (Eocretaceous phase, Atlasic phase, N-S to NW-SE compressional phase, distensive phase and Plio-Quaternary phase).

Figure 2. Geological map of the Tlemcen Mountains (extract from the geological map of Algeria).
3. Aeromagnetic data and methods

3.1. Aeromagnetic data
In the present study, aeromagnetic data were issued from survey conducted by Aero Service Corporation, between 1970–1974, at a constant altitude flight of 150 m along N20 W lines 2 km apart with perpendicular tie-lines at 5 km intervals; sampling distance along the profiles was about 46 m. The survey data were originally recorded in analogue form (Paterson et al., 1976). To image the deep structures of Tlemcen Mountains, we utilized filtering and enhancement techniques on the magnetic data, which derivatives, upward continuation and analytic signal analysis. In this work, we used the magnetic data from longitude of –2°00’ to -1°00’ W and from latitude of 34°25’ to 34°55’ N. The fracturing analysis was carried out by the softwares SPO2012 and Stereonet.

3.2. Magnetic transformations
Several filters and enhancements are applied in order to image the magnetic response of the Tlemcen Mountains. The incorporation of the interpretation of this specific set of filters has led to enhancements in the structural image of magnetic lineaments, as well as improvements in the understanding of the geometry and lithological composition of the Tlemcen Mountains. The magnetic anomaly map is plotted from a regular grid, of 100 × 60 km² (with 250 m spacing), using minimum curvature interpolation method. To remove the influence of the magnetic field’s inclination, which can cause anomalies to appear displaced from their source magnetized structures, we employed a reduction to pole filter (RTP). Once the reduction to pole process is applied, the magnetic anomalies become repositioned directly over the causative sources. Therefore, to identify geological bodies of interest, it is vital to apply various filters to the reduced map. Several techniques are used to determine magnetic lineaments, such as derivative method (Baranov, 1953; Aydogan, 2011) to highlight short wavelength anomalies. The sum of derivatives is illustrated by the analytic signal (AS) filter. This AS filter consists to delineate the bodies responsible for anomalies. The upward continuation at diverse altitudes (Bhattacharyya and Chan, 1977) technique is used to improve the long wavelength anomalies (Gilbert and Galdeano, 1985). To localize determine the structures responsible for the magnetic anomalies, we applied the 3D-Euler Deconvolution technique (Thompson, 1982; Reid et al., 1990; Mikhailov et al., 2003) and the 2-D Continuous Ridgelet Transform method (Boukerbout and Gibert, 2006).

4. Results and discussion
4.1. Magnetic anomalies
The magnetic anomaly map indicates values ranging from –60 to +130 nT (Figure 3). This map is characterized by significant anomalies of diverse shape, size, and orientation of very high intensity. The magnetic anomalies are elongated in NE-SW directions. In the central part of the map, positive anomalies are located north of Beni Snous and Sebdou areas (Figure 3). This is the Rhar Roubane Horst formed of Paleozoic metamorphic rocks (pink color) and Jurassic carbonate and detrital rocks (red color).

Likewise, in the southern part of the map, at the Sidi Djillali area, we note the presence of a strong positive anomaly which corresponds essentially to calcareous rocks (limestones and dolostones). The northern part of the study area is characterized by a strong positive anomaly. It consists of the Paleozoic basement of the Traras Mountains (pink color) and the sedimentary cover (limestones, dolostones, and claystones) of the Upper Jurassic-Lower Cretaceous (red color). Whereas the Maghnia Plain, the El Gor region, and the south of the Beni Snous area correspond to negative anomalies (Cenozoic and Quaternary detrital deposits) (blue color).

When the magnetization and ambient field are not aligned vertically, the observed magnetic anomalies tend to appear offset from their causative bodies, and may also exhibit distorted shapes due to phase enhancements (Blakely, 1995). These factors can create challenges when interpreting magnetic data. To mitigate these complications, an RTP process based on Baranov and Naudy’s (1964) method is commonly employed. This technique helps to remove the distortions and restore the original magnetic anomaly signal, allowing for a more accurate interpretation of the data.

4.2. Reduction to pole (RTP)
The RTP map consists in replacing anomalies above their causative structures, because of the inclination of the magnetic field. The main document in magnetic processing is the reduced map, which encompasses important features such as the analytic signal, gradients, upward continuation, and Euler Deconvolution. The processing sequence is applied to the reduction of the pole map. Derder et al., (2021), point out that the remnant magnetization in this area is negligible. So, to reduce the data, we used the values of –5.44° for declination, 48.72° for inclination and 41850 nT for the total magnetic field. By using the expression (1), the magnetic anomaly can be transformed (Blakely, 1995).

\[ \Delta T_{RTP} = f^{-1}[\omega_{RTP}f(\Delta T)] \] ........................(1)

Where, represents the RTP anomaly, f and \( f^{-1} \) represent the Fourier and inverse Fourier transforms, denotes the RTP filter in wave number domain and represents the observed magnetic anomaly.

Compared to the magnetic anomaly map, a slight shift of the anomalies to the north is observed on the RTP map.
This shift is related to the local magnetic remnant and the mathematical filter. The magnetic anomaly RTP map (Figure 4), shows three positive anomalies with values of the order of +10 nT, +5nT, and +140 nT. They represent a circular morphology that correspond to limestone sink (e.g., south of El Gor, south of Tlemcen, and northeast of Beni Snous area). A set of positive anomalies with +140 nT, is observed between Maghnia Plain and Beni Snous area. This is elongated in NE-SW to NNE-SSW direction. This is the Rhar Roubane Horst formed by the Paleozoic metamorphic basement (pink color) and the sedimentary cover (limestones, dolostones, and claystones) of the Jurassic (red color). This positive set is delimited by two main negatives anomalies, located at Maghnia Plain and south of Rhar Roubane Horst (blue color). At the south, the Sidi Djillali area is characterized by a positive anomaly corresponding probably to Jurassic deep basement. Finally, a large negative corridor is illustrated from the localities El Gor to Ouled Mimoun. These are the Cenozoic and Quaternary detrital deposits (blue color, Figure 4).

4.3. Vertical and horizontal gradients
In order to better understand the origin of magnetic anomalies and the abrupt lateral changes in the magnetization observed in the RTP map, we performed vertical and horizontal gradients filters.

The vertical gradient (Figure 5a) allows recognizing local and shallow features (Baranov, 1953; Aydogan, 2011; Bendali et al., 2022). The horizontal gradient map allows identifying the variation of the magnetic anomaly laterally (Figure 5b). The magnetic lineaments correspond to the maxima on a map of horizontal gradient magnitudes (Büyüksaraç, 2007) and to the passage negative to positive values on the vertical gradient map. The vertical gradient (VG) can be calculated using the relation below (2):

\[ VG = \frac{\partial F}{\partial z} = f^{-1}(|k| f(F)) \]  

The magnitude of the horizontal gradient (HG) can be calculated as (3):

\[ HG = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2} \]
Where $F$ is the magnetic field, $f$ and $f^{-1}$ are the Fourier and inverse Fourier transforms, respectively and $|k|$ is the radial wave number (see Blakely, 1995; Ekinci et al., 2013; Ekinci and Yigitbas, 2015).

A summary of these observations is shown on the magnetic lineaments and axes map of the Tlemcen Mountains (Figure 5c). From west to east, we observe three important magnetic lineaments assigned to different geological structures. The first one is the Tafna-Magoura transverse fault (FTM) that is oriented NNE-SSW and coincides with the eastern end of the Rhar Roubane Horst. The two others are related to the NNE-SSW strike-slip of the Tlemcen Mountains. These are mainly the Oued Chouly transverse fault (FOC) and the Aïn Tellout transverse fault (FAT).

In addition to these submeridian faults, the Rhar Roubane area is also characterized by a series of sinistral and dextral strike-slip faults (Elmi, 1970; Benest, 1982). The Sidi Djillali area is characterized by an N-S to NNE-SSW axes. Finally, to the south of the El Gor area, we observe a series of NE-SW magnetic lineaments. The identified axes and lineaments correspond to structural system or pattern. The imaged directions are well-matched with the Tellian Domain and, cut by oblique structures sometimes that mainly are of the submeridian direction.

4.4. Analytic signal

The amplitude of the analytic signal $AS(x,y)$ is defined as the sum of the potential field derivatives (vertical and horizontal) (Roest et al., 1992). The locations of maxima in the AS anomaly map along the grid plane are commonly utilized for identifying source bodies and enhancing their boundaries (Ekinci et al., 2013). The analytic signal of an anomaly magnetic is given by the following relationship (4):

\[ |AS(x,y)| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \]  

Where, $M$ is the magnetic anomaly and $\partial x, \partial y,$ and $\partial z$ are the directional derivatives.

The analytic signal map, calculated from RTP, shows an important geological body (B1, Figure 6). This body is located north of Beni Snous and extends from Algerian-Moroccan border to west of Tlemcen city. This is the Rhar Roubane Horst made up of metamorphic rocks (schists, quartzites, and phtanites) of Paleozoic age. The El Gor area

![Figure 4. Reduce to the pole aeromagnetic map of the study area.](image-url)
(Djebel El Arbi) is characterized by a rounded body (B2) associated to Triassic evaporitic rocks (Figure 6). At the northern and the southern edge of the map, appear a part of two geological structures. The first one located north of Maghnia Plain and is associated with volcanic materials (Miocene and Quaternary), in metamorphic rocks (Bensefia and al., 2020). The second geological structure is located around to Sidi Djillali area and corresponds to marls rich in gypsum (Triassic evaporitic rocks). The eastern part of the map is essentially marked by low values of magnetic anomaly according to the analytical signal.

4.5. Upward continuation

To distinguish between anomalies with long and short wavelengths, the upward continuation method is performed (Bhattacharyya and Chan, 1977; Jacobsen, 1987; Büyüksarac et al., 2005; Rozimant et al., 2009; Ates et al., 2012; Bouyahiaoui et al., 2017). The upward continuation method is often performed to eliminate and/or minimize the effects of superficial sources and noise on the grid. Upward continuations are executed at various heights (more than 20). We present in this work upward continuation, which highlight long wavelength anomalies, at different elevations: 1000 m, 5000 m, 10,000 m, 15,000 m, and 20,000 m (Figure 7). The maps resulting from the upward continuation illustrate a decrease in the magnitude of short wavelength anomalies to obtain a regular variation from 15,000 m to deeper. From this elevation a linear attenuation in the magnetic field from east to west, which is comparable to the regional form. At 1000 m elevation upward map, we find all the magnetic anomalies described previously (Figure 7a). The magnetic signature of the Maghnia Plain disappears along the upward continuation at 5000 m. This implies that the structure causing the anomaly is situated at a depth of less than 2 km. At this elevation, we have two distinguished compartments. A first-one with negative anomalies that reaches −40 nT at the east part and a second-one with positive anomalies at the west part that reaches +25nT (Figure 7b). However, the positive anomaly of El Gor area and the negative anomaly of Beni Snous persist. At higher elevations, the observed

Figure 5. (a). The vertical gradient map of RTP magnetic anomaly, (b) the horizontal gradient map of the RTP magnetic anomaly, and (c) map of magnetic lineaments from all the aeromagnetic anomaly derivatives.
Beni Snous negative anomaly is deeper and persists with an upward continuation at 10,000 m. We recommend that the structure responsible of this anomaly is located at depths that exceed 3.5 km. At 20 km elevation, the upward continuation map shows the regional tendency with a linear regression in the magnetic field from west to east (Figure 7e). This regression presents a slope of 0.37 nT/km.

5. Deep structures: Depth estimation, modeling, and discussion
To identify the sources generating the magnetic anomalies, we use the energy spectrum (Spector and Grant, 1970), Euler Deconvolution method (Thompson, 1982; Reid et al., 1990; Mikhailov et al., 2003) and the complex one-dimensional wavelet transform (Sailhac et al., 2000; Boukerbout et al., 2003).

5.1. Spectral analysis
We employed the energy spectrum method to estimate the depth of anomalous sources in the basement. Spector and Grant (1970) conventionally expressed the energy spectrum as the modulus squared of the Fourier transform of potential fields. Slopes of the logarithmic energy spectrum are directly proportional to the depth of the source. Different slopes indicate the quantization of the source energy by depth. The depth \( h \) for the structure is given by the following relationship (5):

\[
h = \Delta \log E / 4\pi \Delta l \quad \text{…………………. (5)}
\]

Where, \( \Delta \log E \) represents the log variation of the energy in the \( \Delta l \) frequency interval (measured in km\(^{-1}\)), and \( h \) represents the depth of the body causing the anomaly. In our case, we observe the presence of three energy packets that correspond to different wavelengths (Figure 8). A first packet (1) symbolizes the superficial structures, with depths of the order of 0.5 km. These short wavelengths are associated with the Cenozoic and Quaternary detrital deposits. A second energy packet (2) characterizes intermediate depths (~1.3 km) associated with the Cretaceous and Jurassic deposits (limestones, dolostones, and claystones). Finally, a third energy packet (3) showing the deepest generating sources, located at a depth of about 2.5 km, and corresponds to the Paleozoic basement (metamorphic rocks).

The energy spectrum technique was performed to segregate magnetic fields (residual and regional) and...
estimate the geological structures depths (shallow and deeper). Nevertheless, it gives us no information on geological contacts and accidents (nature, orientation, depth).

5.2. 3D-Euler deconvolution
We have applied the 3D-Euler deconvolution (Thompson, 1982; Reid et al., 1990; Mikhailov et al., 2003) to the RTP data to obtain a more detailed characterization of the magnetic anomalies and tectonic lineaments in the Tlemcen Mountains. By utilizing the Euler’s homogeneity equation, which employs the horizontal and vertical gradients derived from the data, the 3D-Euler deconvolution method enables automatic estimation of the source depth. The calculation is expressed as follows (equation 6):

\[
(x - x_0) \frac{\partial T}{\partial x} + (y - y_0) \frac{\partial T}{\partial y} + (z - z_0) \frac{\partial T}{\partial z} = N(B - T)
\]

\[\text{equation 6}\]

Where \(x_0, y_0, z_0\) are the position of anomaly source whose intensity of magnetic field \(T\) is measured at \(x, y, z\). \(N\) is the structural index and \(B\) is the regional value of magnetic field (Reid and Thurston, 2014). Apart from estimating the depth, the Euler deconvolution method also yields information about the type of source through the structural index. This structural index \(N\) is applied when performing Euler deconvolution analysis. In regional interpretation of magnetic data, structural indices are common for location of faults and contacts (\(N = 0-0.5\)), sills and dykes (\(N = 1\)), vertical and horizontal cylinders (\(N = 2\)), and sphere (\(N = 3\)). This work focuses on locations of lineaments, several tests were conducted by adjusting various parameters such as the structural index, window size, and tolerance. Various values of the structural index were tested, and we found that setting it to 0, along with a window size of 8 and a tolerance of 10%, resulted in well-organized Euler solutions. Using these parameters, we obtained Euler solutions with depths ranging from 0.20 to 4.5 km (Figure 9).
Figure 8. Energy spectrum of the RTP magnetic anomaly. (1) represents the superficial structures. (2) characterizes the intermediate depths, and (3) shows the deepest generating sources.

Figure 9. Superposition of Euler solutions SI = 0 and geological accidents of the Tlemcen Mountains on the RTP magnetic anomaly.
Qualitatively, the greatest depths recorded (2.07 km to 4.5 km) are equivalent to transverse faults of general NNE-SW direction. These are the Tafna-Magoura transverse fault (FTM), Oued Chouly transverse fault (FOC) and the Ain Tellout transverse fault (FAT) which mark their passage in the Tlemcen Mountains by the rise of the Triassic evaporitic rocks. They may also correspond to the strike-slip affecting the Rhar Roubane Horst, to the north-east and south of the El Gor area and the Terni Block (South of Tlemcen). Furthermore, from a quantitative point of view, the solutions of the shallow Euler deconvolution, which are relatively more numerous in the study area, are sometimes equivalent to sinistral and dextral strike-slip fault. In detail, the analysis of the fracturing of the Tlemcen Mountains by SPO2012 and Stereonet shows three predominant directions (NE-SW, N-S, and E-W) (Table).

5.3. Complex wavelet transforms
Several authors have described the continuous wavelet transform method that we use to pinpoint the sources generating the magnetic anomalies (such as Moreau et al., 1997; Hornby et al., 1999; Boukerbout et al., 2003; Fedi et al., 2004; Sailhac et al. 2009 and so on). In order to sketch out the shape of the magnetized substratum, we process a NNW-SSE profile extracted from the magnetic anomaly map, at coordinates (34.89°N, 1.56°W; 34.41°N, 1.46°W, ). This profile crosses the Miocene sedimentary basin of the Maghnia Plain in the north, passes through the Paleozoic basement of the Tlemcen Mountains and reaches the limestone massifs of the Mesozoic at Sidi Djillali area in the south. This magnetic anomaly profile is analyzed with the complex one-dimensional wavelet transform (Sailhac et al., 2000; Boukerbout et al., 2003). The modulus of the complex wavelet coefficients identifies the depth of the structures, while their phases give the dip of the identified structures. The inclination of an identified structure at (x_s, z_s), is extracted along the corresponding line phase on the phase map, of the complex wavelet transform. The results are presented in Figure 10. The top panel of Figure 10a, shows the magnetic anomaly profile whose intensity varies from –45 nT to 110 nT. The modulus of the continuous wavelet (Figure 10a, middle panel) shows a prismatic body with the signature of some contacts or faults. The depth of the magnetized structures is identified by the use of the maximum entropy criteria and, is shown in the bottom panel of Figure 10a. The depth is ranging between 4 and 30 km. The deepest structures are located in the North (East of Maghnia) and in the south (Sidi Djillali). From south to north, the first identified fault or contact is located at y = 3820 km latitude and 22 km depth. The phase of the wavelet (Figure 10b) identifies this contact with an inclination of 60°. It limits the Quaternary sedimentary basin (north Sidi Djillali) and the Mesozoic substratum of Sidi Djillali area. The second fault limiting Quaternary basin (north Sidi Djillali) and Jurassic substratum of Beni Snous area, is identified at latitude of y = 3836 km and 15 km depth with an inclination of 35°. The third contact or fault limiting Jurassic and Paleozoic substratum of the Beni Snous area, is identified at y = 3839 km latitude, 18 km depth with an inclination of 140°. The fourth identified contact is located at y = 3843 km of latitude and at depth of 8 km. Its inclination is 158°. The next contact is identified at latitude of y = 3849 km and 7 km depth with an inclination of –115°. These contacts sketch out the southern limits of the Jurassic substratum and Miocene sedimentary basin, south of Maghnia. The last identified contact is located at y = 3858 km latitude and 27 km depth, with an inclination of –80°. It represents the northern limit between Miocene sedimentary basin, south of Maghnia, and the Paleozoic substratum of the Maghnia Plain.

6. Conclusion
Based on the interpretation of the aeromagnetic data, in particular: Reduction to pole (RTP), analytic signal, horizontal and vertical gradient, upward continuation of the RTP, and Euler deconvolution, new details were

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</table>
Figure 10. Identification of deep magnetized structures causative anomalies. Figure 10a top: magnetic anomaly profile trending in NNW-SSE direction (see position in Figure 3). The magnetic anomalies intensity varies from –45 to 110 nT. Figure 10a middle shows the map of the complex continuous wavelet coefficients according the dilations. Maximum coefficients values are represented in red color while minimum coefficients values are represented in blue color. Figure 10a bottom represents the depth of the magnetized structures identified along the profile. The depth is ranging between 4 km and 30 km and six (06) contacts are identified at different depths and with different inclinations (see section 5.3 in the text). The Figure 10b represents the phase of the complex continuous wavelet which identified inclination of the contacts.
provided on the geology and structural lineaments of the Tlemcen Mountains. The geological mapping has made it possible to delimit the extension of the Paleozoic basement of Rhar Roubane Horst and to locate some Triassic formations. This mapping also shows the extension of the Mesozoic and Cenozoic deposits. On the structural level, we were able to determine three linear anomalies with strong magnetic responses that cross and differentiate the Tlemcen Mountains into three structural panels. They correspond to the transverse faults of Tafna-Magoura transverse fault (FTM), Oued Chouly transverse fault (FOC) and the Ain Tellout transverse fault (FAT) oriented NNE-SSW. The other lineaments correspond to strike-slip faults N-S, E-W, and NNE-SSW. Finally, through the interpretation of magnetic anomalies, we also determined other geological structures, such as the Rhar Roubane Horst, the Sebdou Graben, the Terni Block and the pseudocircular geometry corresponding to the Beni Snous Granite.

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