Tectonophysics 608 (2013) 149–160

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Evidence for an east–west regional gravity trend in northern Tunisia: Insight into the structural evolution of northern Tunisian Atlas

Chokri Jallouli [a,b,*], Saad Mogren [a], Kevin Mickus [c], Mohamed Moncef Turki [b]

[a] Department of Geology and Geophysics, College of Sciences, King Saud University, P.O. Box. 2455, Riyadh 11451, Kingdom of Saudi Arabia
[b] Geological Department, Faculty of Sciences, University Tunis El Manar, Campus Universitaire, 2092 Manar 2, Tunis, Tunisia
[c] Department of Geosciences, Missouri State University, Springfield, MO 65897, USA

ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form 2 October 2013
Accepted 4 October 2013
Available online 12 October 2013

Keywords:
Gravity analysis
Crustal structure
Plate boundary
Convergent continental margin
North Africa
Tunisian Atlas

ABSTRACT

The Atlas orogeny in northern Algeria and Tunisia led to the destruction of Tethys oceanic lithosphere and cumulated in a collision of microplates rifted off the European margin with the North African continental margin. The location of the boundary between African plate and Kabylian microplate is expressed in northern Algeria by a crustal wedge with double vergence of thrust sheets, whereas in northern Tunisia the geologic environment is more complex and the location of the plate boundary is ambiguous. In this study, we analyzed gravity data to constrain the crustal structure along the northern margin of Tunisia. The analysis includes a separation of regional and residual gravity anomalies and the application of gradient operators to locate density contrast boundaries. The horizontal gradient magnitude and directional gradient highlight a prominent regional E–W gravity gradient in the northern Tunisian Atlas interpreted as a deep fault (active since at least the Early Mesozoic) having a variable kinematic activity depending on the tectonic regime in the region. The main E–W gravity gradient separates two blocks having different gravitational and seismic responses. The southern block has numerous gravity lineaments trending in different directions implying several density variations within the crust, whereas the northern block shows a long-wavelength negative gravity anomaly with a few lineaments. Taking into account the geologic context of the Western Mediterranean region, we consider the E–W prominent feature as the boundary between African plate and Kabylian microplate in northern Tunisia that rifted off Europe. This hypothesis fits most previous geological and geophysical studies and has an important impact on the petroleum and mineral resource prospection as these two blocks were separated by an ocean and they did not belong to the same margin.

1. Introduction

The crustal structure of northern Tunisia (Fig. 1) is thought to be the result of the tectonic interaction between the Eurasian and African plates and is considered to be part of a broad boundary plate zone in northern Africa (Billi et al., 2011; Bouaziz et al., 2002; Capitanio and Goes, 2006; Carminati et al., 1998; Faccenna et al., 2001; Frizon De Lamotte et al., 2000, 2009; Gueguen et al., 1998; Mauffret, 2007; Meghraoui and Pondrelli, 2012; Morgan et al., 1998; Piqué et al., 1998; Rosenbaum et al., 2002; Wortel and Spakman, 2000). The general sequence of tectonic events within the western Mediterranean region includes: 1) Early Mesozoic rifting forming the Tethys Sea where a passive margin sequence was developed; and 2) northward convergence of the African plate relative to Eurasia since the Late Cretaceous. This convergence evolved into Cenozoic subduction and formed the Western Mediterranean back-arc basin known as the Algero-Provencale basin (Fig. 1). However, the structure of the Cenozoic subduction in northern Africa was not similar to a Pacific-style subduction, as it was more complex. This Cenozoic subduction zone may have produced a slab detachment with the subduction zone migrating toward the east over time (Capitanio and Goes, 2006; Carminati et al., 1998; Faccenna et al., 2001, 2004; Frizon De Lamotte et al., 2000, 2009; Goes et al., 2004; Mauffret, 2007; Morgan et al., 1998; Piqué et al., 1998; Spakman and Wortel, 2004; Wortel and Spakman, 2000).

As consequence of the above convergence, thrust faults and folds were developed in northern Africa with a southward vergence (Fig. 1). Even though northward vergence of thrust faults is not observed at the surface, Mauffret (2007) proposed a wedge model with double directional vergence with a northern vergence occurring over a much narrower zone than the southern region. This wedge is related to transpressional forces that formed within the Maghreb margin in Algeria and Tunisia. Although the convergence eventually evolved into

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* Corresponding author at: Geological Department, College of Sciences, King Saud University, P.O. Box. 2455, Riyadh 11451, Kingdom of Saudi Arabia. Fax: +966 11 4673662.
E-mail address: cjallouli@gmail.com (C. Jallouli).

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http://dx.doi.org/10.1016/j.tecto.2013.10.003

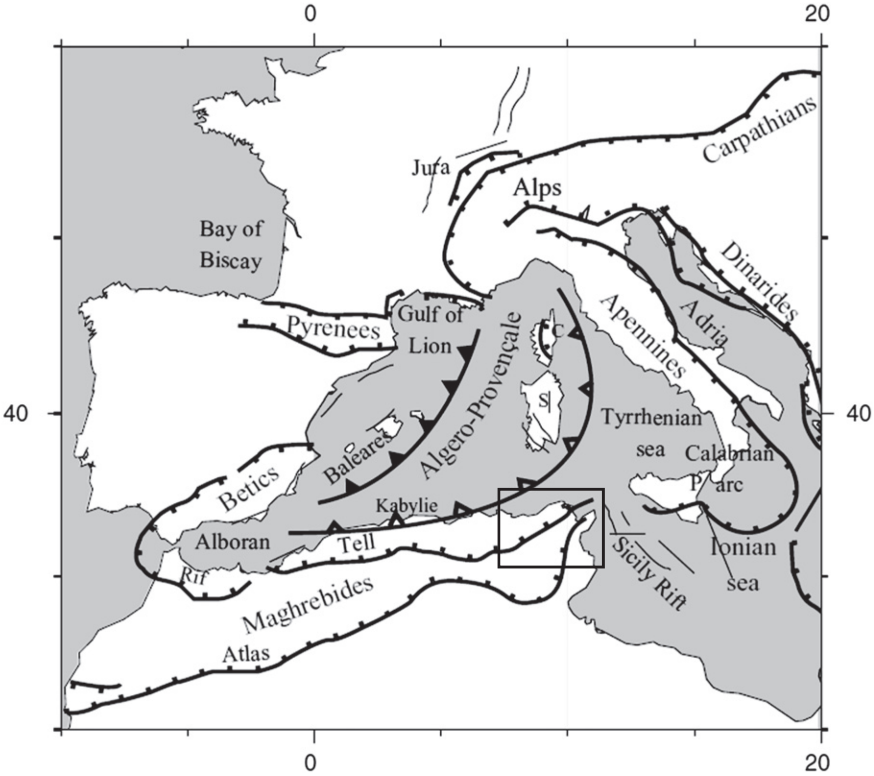

Fig. 1. Location of the study area on a map showing the tectonic setting of the western Mediterranean (from Capitanio and Goes (2006), based on reconstructions by Gueguen et al., 1998; Frizon de Lamotte et al., 2000; Faccenna et al., 2001). Lines with small squares show current position of the Maghrebian–Apenninic–Alpine convergence front. Thin lines mark extensional faults. Lines with triangles mark Cenozoic migration of the Maghrebian–Apenninic trench (solid triangle: 35 Ma, open triangles: 16 Ma). P—Peloritani block, S—Sardinia, C—Corsica.

a collision between the Kabylian block and the African plate, the crust beneath the Sardinia Channel and northern Tunisia and Algeria is thin (Blundell et al., 1992; Jallouli and Mickus, 2000; Mickus and Jallouli, 1999). However, Tricart et al. (1994) considered that a thickening of the crust as a result of collision during the Miocene is probable and after this collision, the crust was thinned by the collapse of the orogen. There is evidence of thinning crust related to the opening of the Tyrrhenian Sea during the Late Miocene (Mascle et al., 2004). Also, a thinning of the crust since the Middle Miocene related to the opening of the Algerian basin has been imaged by seismic reflection profiles (Catalano et al., 2000), whereas, the mechanism that caused crustal thinning within northern Tunisia remains unclear.

Northern Tunisia contains a variety of complex tectonic features. Based on surface geological observations, the simplified geological map of northern Tunisia (Fig. 2) shows in addition to southward verging thrust faults, Neogene volcanic activity, Triassic rocks (including evaporites) which intrude younger sedimentary layers and trend in a SW–NE direction, SW–NE trending folds, SE–NW trending grabens and a variety of faults striking in different directions.

Within the above complex geological environment, a gravity data analysis was attempted by Jallouli and Mickus (2000) and Jallouli et al. (2002). These gravity analyses revealed a regional E–W trending anomaly. Given its potential significance and importance in the understanding of the geological evolution of northern Africa, the E–W trending gravity anomaly has to be better defined through appropriate data enhancement methods (e.g., horizontal gradient) allowing one to emphasize such anomalies. Such trends will help in providing insights into the regional structure and geodynamic evolution of the Alpine chain in northern Africa.

Our analysis involves separating the observed complete Bouguer gravity anomalies into regional and residual gravity anomalies, and by applying enhancement methods to locate and highlight principal density heterogeneities that could be related to major density variations. The results are then discussed within the context of the western Mediterranean tectonic evolution.

2. Structural overview and previous work

Northern Tunisia is located at the eastern edge of the Cenozoic Alpine orogenic belt of northern Africa known as the Tell Atlas and the Maghrebides Atlas. This belt is the result of the convergence between Africa and Europe and has been subject to numerous investigations (e.g., Amiri et al., 2011; Ben Ayed, 1993; Ben Ferjani et al., 1990; Bouaziz et al., 2002; Boukadi, 1994; Burollet, 1991; Chihi, 1995; Cohen et al., 1980; Dewey et al., 1989; Dlala, 1995; Frizon De Lamotte et al., 2009; Jallouli and Mickus, 2000; Jallouli et al., 2002, 2003; Jolivet and Faccenna, 2000; Khomsi et al., 2009; Mauffret, 2007; Meghraoui and Pondrelli, 2012; Morgan et al., 1998; Piqué et al., 1998; Rouvier, 1977; Serpelloni et al., 2007; Slim, 2010; Turki, 1985; Zargouni, 1985).

Based on surface observations, the uppermost crust in northern Tunisia is composed of Mesozoic and Cenozoic sedimentary rocks (Ben Haj Ali et al., 1985). Previous analyses of the structural features led workers to divide northern Tunisia into two structural zones: 1) the Tell, located in northernmost Tunisia (Rouvier, 1977) and 2) the northern Tunisian Atlas (Fig. 2) (Burollet, 1991).

The major structural features within the Tell Atlas are thrust faults within the Oligo-Miocene Numidian flysch deposits and SW–NE trending folds (Ben Ferjani et al., 1990; Cohen et al., 1980; Rouvier, 1977). The Northern Atlas is characterized by numerous northeast-trending exposures of Triassic rocks intruded into younger Cenozoic and Mesozoic sedimentary rocks (Fig. 2). The Triassic rocks which consist mainly of evaporites are thought to have been emplaced by diapirism during the Atlas and the Alpine orogeny (Benassi et al., 2006; Chikhaoui et al., 2002; Jallouli et al., 2005; Perthuisot, 1981;

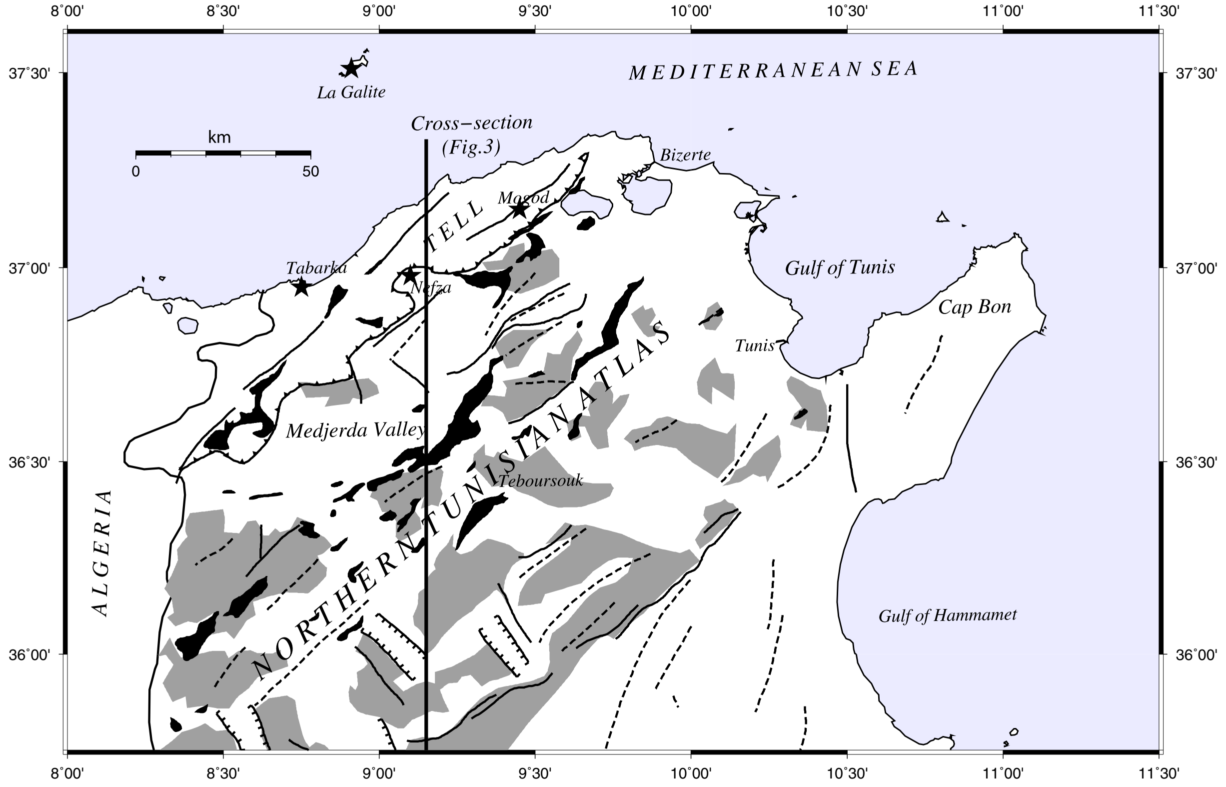

Fig. 2. Main features in northern Tunisia based on the geological map of Tunisia (Ben Haj Ali et al., 1985). Bold lines represent faults, bold lines with triangles represent thrust faults and dashed lines represent the traces of fold axes. Black regions represent Triassic outcrops. Gray regions represent Mesozoic outcrops. White regions represent Cenozoic outcrops. Stars represent locations of Miocene volcanic outcrops. The bolded N–S line represents the location of the cross-section shown in Fig. 3.

Perthuisot et al., 1999). In addition to the Triassic formations, the northern Atlas has numerous northeast-trending faults and folds dissected by northwest-trending normal faults and grabens (Fig. 2). These structures are thought to have formed during the Cenozoic under regional compression related to the convergence between Africa (northern margin of Tunisia) and the southern margin of Europe (Corsica–Sardinia–Petite Kabylie plate).

In northern Tunisia, evidence of Miocene volcanism within the northern Tell area is also found. This volcanism is essentially calco-alkaline associated with shoshonitic and rhyolitic lavas (Girod and Girod, 1977; Laridhi Ouazaa, 1994; Mauduit, 1978).

An additional important tectonic element near northern Tunisia is the Cenozoic-aged Algerian basin, known also as Algero-Provencale Basin, which is located offshore of northern Tunisia and Algeria (Fig. 1). This basin is comparable to an active back-arc basin (Billi et al., 2011) and contains numerous volcanic rocks and a steep bathymetric gradient (Girod and Girod, 1977).

The general sequence of tectonic events affecting northern Tunisian and northern Africa in general may be outlined as follows:

- Early Mesozoic rifting which formed a passive continental margin. This margin was associated with strike-slip faults that developed a system of sedimentary basins with deposition of Triassic evaporites and Jurassic carbonate platform sequences and turbidites.
- Post rifting sequence as a result of a convergence between microplates rifted off the European margin (Corsica–Sardinia–Petite Kabylie plate) and Tunisian continental margin from the Late Cretaceous to the present. The post rift sequences are associated with a dextral transpression event that reversed the displacement along the boundary zone at the northern Tunisian margin and developed fault inversions.
- While the convergence was occurring during the Cenozoic, the Algerian basin (northern offshore of Algeria and Tunisia) was formed as a back-arc basin.

Regional geophysical studies have provided useful information on the deep crustal structure of northern Tunisia based on the analysis of seismic refraction data (Boccaletti et al., 1990; Buness et al., 1992) and regional gravity analyses (Jallouli et al., 2002); Jallouli and Mickus, 2000; Mickus and Jallouli, 1999. These studies show how the physical parameters vary within the crust of northern Tunisia. There is evidence of an abrupt thinning of the crust from 35 to 22 km and increasing seismic velocity from 6.0 to 6.6 km/s toward the Mediterranean Sea. Northern Tunisia is characterized by a thin crust with low P-wave velocity. Fig. 3 shows the shape and thickness variation of the Paleozoic, Mesozoic and Cenozoic basins along a N–S cross-section within the studied area. This cross-section is derived from the model presented by Jallouli et al. (2002) based on the available geological and geophysical data. We note that there is a general decrease in the sediment thickness toward the north and there is a particular crustal structure within the Medjerda Valley implying that there is an abrupt thickness change of the Paleozoic and Early Mesozoic basins. Recently, based on a detailed gravity data analysis in the Medjerda region (northwestern Tunisia), Amiri et al. (2011) highlighted the complex geological architecture in this region and evoked the contribution of inherited E–W and N–S faults in the geodynamic evolution of Medjerda basin.

Geological and geophysical studies have roughly agreed on the general characteristics and tectonic events that controlled the formation of the northern Atlas Mountains in northern Africa and on the general crustal structure; however, there is considerable ambiguity on the location of major continental margin structures and the major faults that have an important role on the sedimentary environment and on the deformation affecting the margin. Even though the origin of the northern Tunisian Atlas has been modeled as the result of a long period

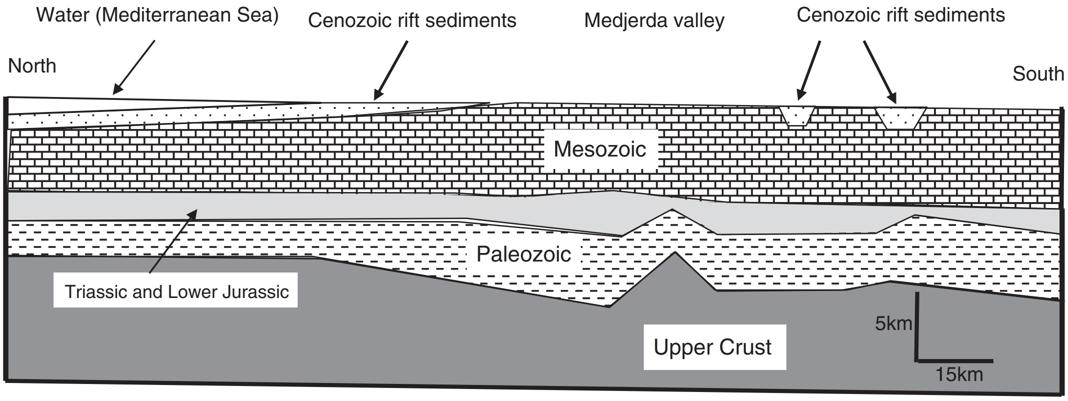

Fig. 3. North–south geological cross-section derived from the model presented by Jallouli et al. (2002) based on the available geological and geophysical data with the location shown in Fig. 2. Note the general decrease of the thickness of the sedimentary cover toward the north and the particular crustal structure within the Medjerda Valley implying a basement uplift and an abrupt thickness change of Paleozoic and Early Mesozoic basin. This crustal structure coincides with the E–W gravity trend.

of convergent plate interactions, the observed geological features based on outcrops are in general dominated by the last tectonic events and therefore they may hide other important geological features. In these cases, geophysical data provide further information and allow one to emphasize the principal regional geological features that could be hidden or not well expressed by outcrops.

In this study, through the analysis of gravity data, we will try to locate the main structural features in northern Tunisia that would infer different structural or tectonic boundaries and provide more insights into the structural pattern of the region and its geodynamic evolution.

3. Gravity data and processing

The gravity data used in this study were obtained from the Department of Geological Sciences at the University of Texas at El Paso and the Entreprise Tunisienne des Activités Pétrolières (ETAP). The data were tied to the 1971 International Gravity Standardization Net and reduced using the 1967 International Gravity Formula. Bouguer gravity corrections were made using sea level as datum and 2.67 g/cm^3 as a reduction density. Terrain corrections were applied using 5 minute topography grid (US National Geophysical Data Center, 1995). The complete Bouguer gravity anomalies were gridded and

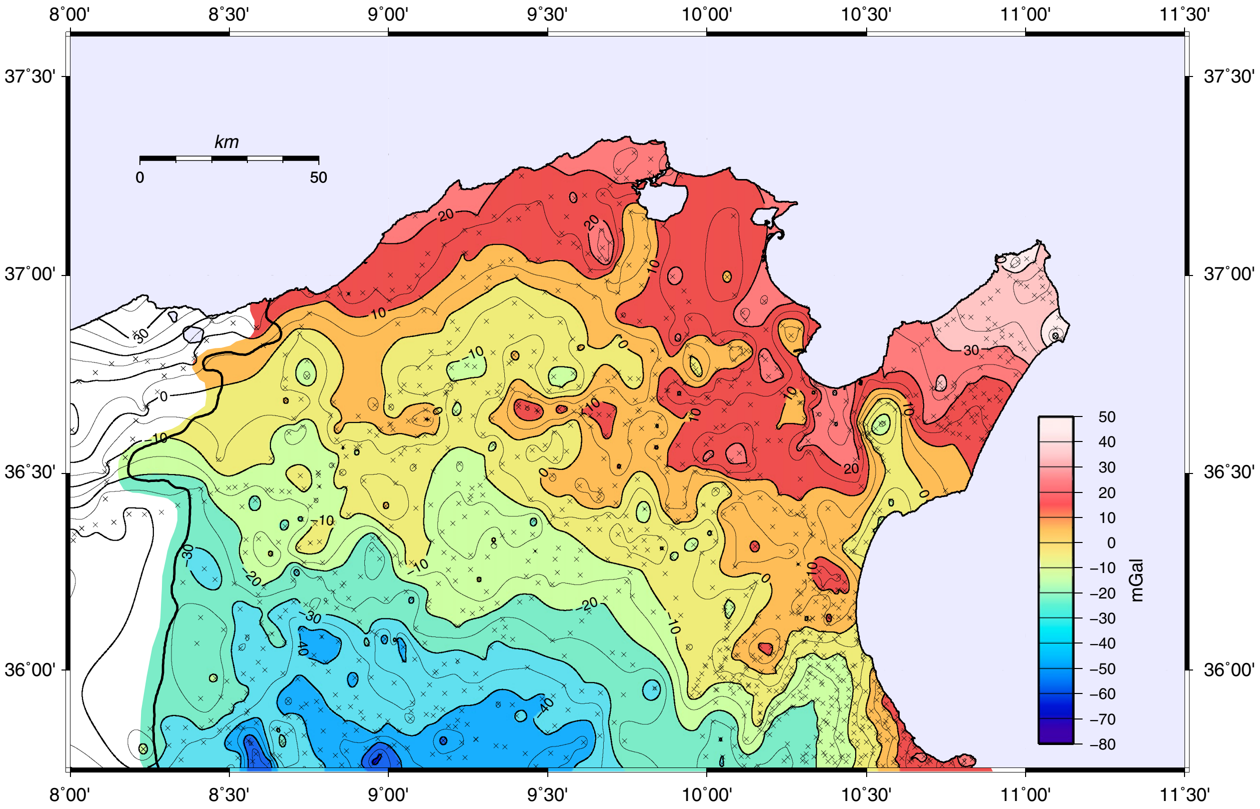

Fig. 4. Complete Bouguer gravity anomaly map of Northern Tunisia. Station locations are indicated by +. Contour interval is 5 mGal.

contoured to produce a complete Bouguer gravity anomaly map (Fig. 4). The distribution of the gravity stations in the study area is not homogenous. The gravity station coverage is relatively poor in northern Tunisia with an average station spacing of 10 km, whereas in the rest of the study area the average station spacing is less than 5 km. Such a distribution may filter out short wavelength anomalies in northern Tunisia, however our objective is not to investigate small density bodies or short wavelength anomalies that may express responses of density heterogeneities at shallow depths. Our objective is to emphasize major deep structures which usually cause long wavelength anomalies.

4. Regional and residual gravity anomalies

The Bouguer gravity anomaly values (Fig. 4) show a general increase between −50 and +40 mGal toward the north. The long wavelength component of the Bouguer gravity field can be explained by the depth variations of the crust/mantle boundary which mainly involves thinning of the crust toward the north (Jallouli et al., 2002). To emphasize shorter wavelength anomalies due to density variations of the uppermost crust including basement topography and density heterogeneities within the sediment cover (Paleozoic, Mesozoic and Cenozoic basins), a regional gravity anomaly representing the density contrast caused by the crust–mantle boundary variations must be removed. This operation was accomplished by removing a regional gravity anomaly determined by Jallouli et al. (2002) based on three-dimensional (3-D) modeling of the geometry of the crust–mantle boundary as imaged by the European Geotraverse seismic refraction model (Buness et al., 1992).

Normally, the obtained residual gravity anomalies (Fig. 5) that range from −95 to −35 mGal, represent the gravity effect of all upper crustal density changes including the basement topography and variation in densities of sedimentary rocks. Such density variations could be caused by different features (e.g., faults, grabens, folds, basin thickness variations, salt intrusions) induced by all tectonic events that have occurred within northern Tunisia. However, we note that a long wavelength gravity anomaly still remains in the residual gravity anomaly obtained by only removing the effect of crust–mantle boundary. This residual gravity anomaly, as described by Jallouli et al. (2002), shows a general decrease in the gravity values toward the north. Modeling of this regional gravity anomaly shows that it can be explained either by a large sedimentary basin thickening toward the north in Tunisia or by the presence of continental crust that is a piece of remnant subducted African plate within the upper mantle under northern Tunisia (Jallouli et al., 2002). Taking into account other geological and geophysical results (Buness et al., 1992) which indicate that a sedimentary basin thins northward, Jallouli et al. (2002) favored the second scenario. In this case, extracting the effect of the crustal thickness variations imaged by the seismic refraction data to obtain the residual gravity anomalies is not sufficient to determine the true residual gravity anomaly. To obtain a more reliable gravity residual anomaly, the gravity effect of the continental crust within the upper mantle should be removed.

The geometry and the dip of the slab due to the remnant subduction zone are known only in general terms but to model its gravity response one can use the crust–mantle boundary imaged by seismic tomographic models (Carminati et al., 1998; Hoernle et al., 1995). These models showed that any density contrast within the upper mantle due to probable remnant subduction in northern Africa would be expressed by a trend decreasing toward the north. As the remnant crustal material within the upper mantle is deep, its gravity response should be a simple polynomial surface. To calculate this surface representing the signature of a deep source, we used two methods: 1) a two-dimensional (2-D) polynomial surface where different polynomial orders were tried and 2) upward continuation which attenuates the shorter wavelength anomalies and the degree of attenuation which increases with altitude. Using polynomial surfaces, it was found that a third-order polynomial surface adequately fits the long wavelength anomaly. Additionally, a

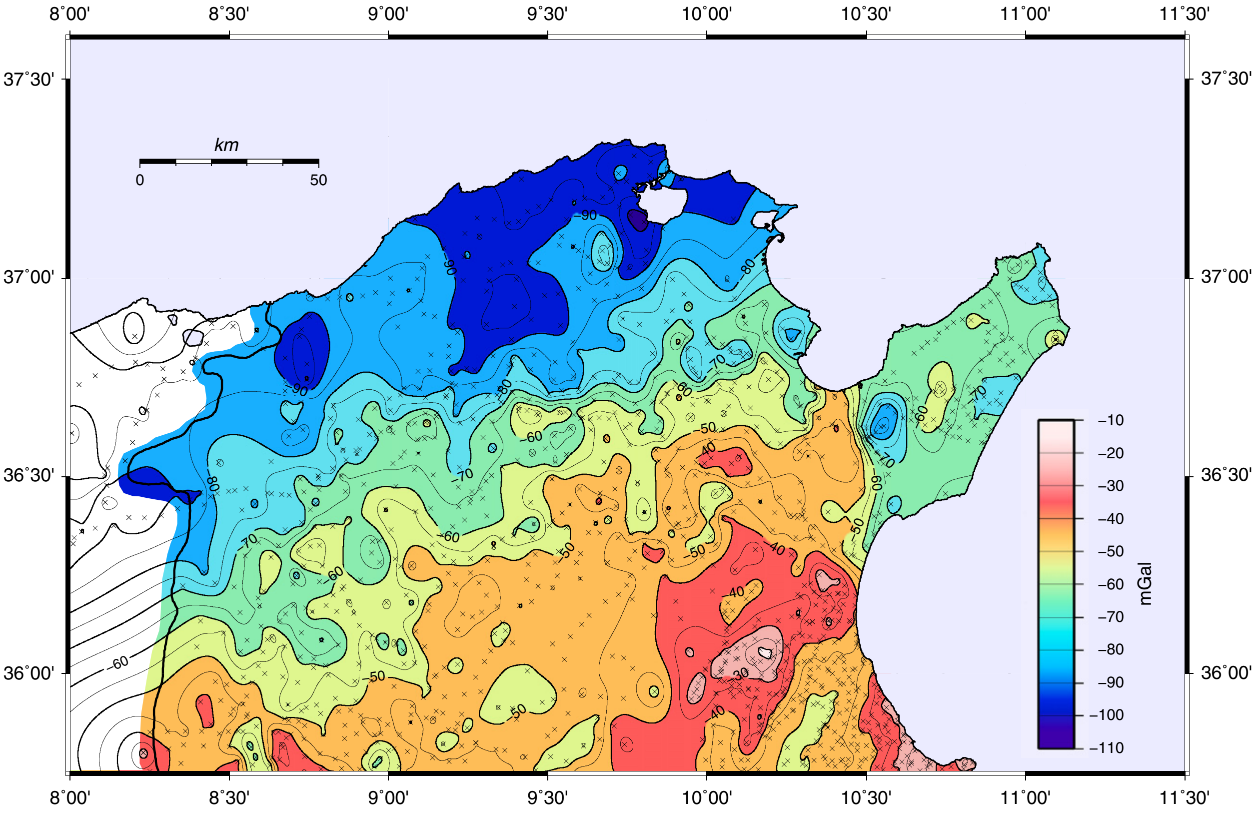

Fig. 5. Residual gravity anomaly map obtained by removing from the complete Bouguer gravity anomalies the effect of crust–mantle boundary imaged by seismic refraction data (Buness et al., 1992). Contour interval is 5 mGal. Note that there appears a general northward decrease in the gravity values.

number of different continuation distances ranging between 10 and 50 km were calculated. It was found that the residual gravity anomaly that adequately represents the known geologic features was obtained by subtracting a long wavelength anomaly represented by an upward continuation surface of 15 km. Such an altitude is reasonable as the depth of the Mesozoic and Cenozoic basins, where there are densities heterogeneities, does not exceed 7 km in northern Tunisia based on seismic refraction (Buness et al., 1992) and gravity modeling (Jallouli and Mickus, 2000). The upward continued gravity anomaly adequately attenuates the effect of upper crustal sources within Mesozoic and Cenozoic basins. Additionally, the final residual gravity anomaly obtained using this approach is similar in amplitude and shape to the residual gravity anomaly obtained by subtraction of a third-order polynomial surface from the regional gravity anomaly. The final residual gravity anomalies (Fig. 6) correlate with several known surface features such as folds and grabens.

4.1. Analysis of the residual gravity anomaly

As described above, we attempted to remove the gravitational effect of the crust–mantle boundary modeled by seismic refraction data and the effect of a piece of deep continental crust remaining after subduction ceased. The resultant residual gravity anomaly represents the gravity anomalies due to the Precambrian basement geometry and density variations in the Paleozoic, Mesozoic and Cenozoic basins due to thickness variations and structural features (e.g., faults, folds, diapirs). Therefore, the residual gravity anomaly can be used to locate upper crustal density variations.

By examining the residual gravity anomaly map one can distinguish two regions corresponding to two different large blocks separated by an east–west trend (Fig. 6). The northern region has low amplitude negative anomalies that cover a large area, whereas the southern region has numerous negative and positive anomalies composed of different wavelengths. The dominance of large-scale negative anomalies in the northern block can be explained by the abundance of thick Cenozoic sedimentary formations composed mainly of sands and shales, whereas the southern block is mainly composed of Cretaceous limestone that has been intensely deformed as evidenced by numerous folds, faults and grabens. Such structures can explain the existence of the shorter wavelength positive and negative anomalies in the southern block. Based on the above description stating that the study region includes two different blocks having different gravity response, an analysis of the residual gravity anomalies can be useful to locate the boundary between these two blocks and to help to determine its nature.

To locate the gravity anomaly lineaments that correspond to density contrast boundaries, we used the horizontal gradient magnitude (HGM (x,y)) as an edge detector function as defined by Cordell and Grauch (1985):

$$\mathrm{HGM}(x,y) = \left((\mathrm{d}g/\mathrm{d}x)^2 + (\mathrm{d}g/\mathrm{d}y)^2\right)^{1/2}.$$

This is one of the many suitable edge detector functions (Blakely, 1996; Debeglia et al., 2006), other functions including the Laplace operator (Pitas, 2000), analytic signal (Roest et al., 1992), enhanced analytic signal (Hsu et al., 1996), and enhanced horizontal gradient (Fedi and Florio, 2001). However, the HGM function is the most frequently used method and is suitable for the analysis of potential field data. As the edge detector function is based on horizontal gradients, the maxima of the HGM indicate the locations of density contrasts (Cordell and Grauch, 1985). In our study area, the maxima of

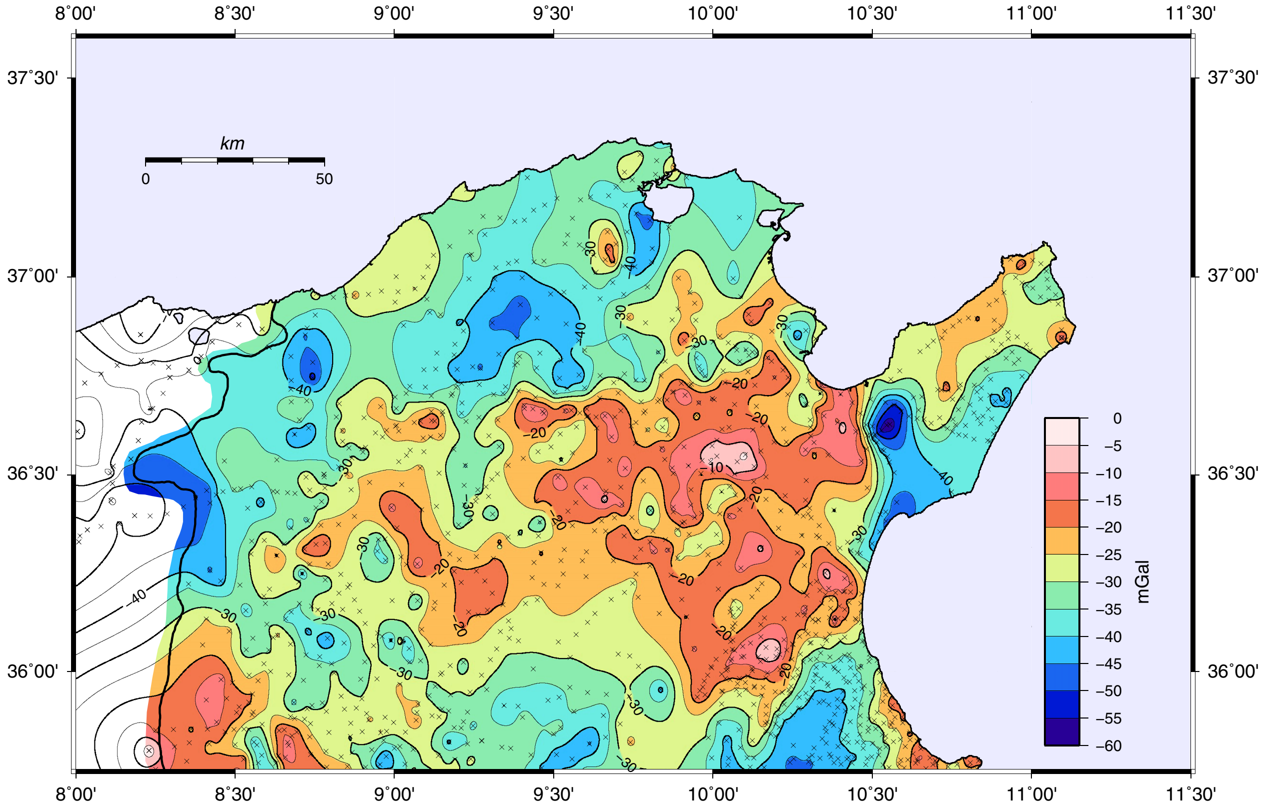

Fig. 6. Residual gravity anomaly map obtained by removing from the complete Bouguer gravity anomalies: 1) the effect of crust–mantle boundary as imaged by seismic refraction data (Buness et al., 1992), and 2) a third-order polynomial surface representing the effect of remnant subducted slab beneath northern Tunisia as proposed by Jallouli et al. (2002). Contour interval is 5 mGal.

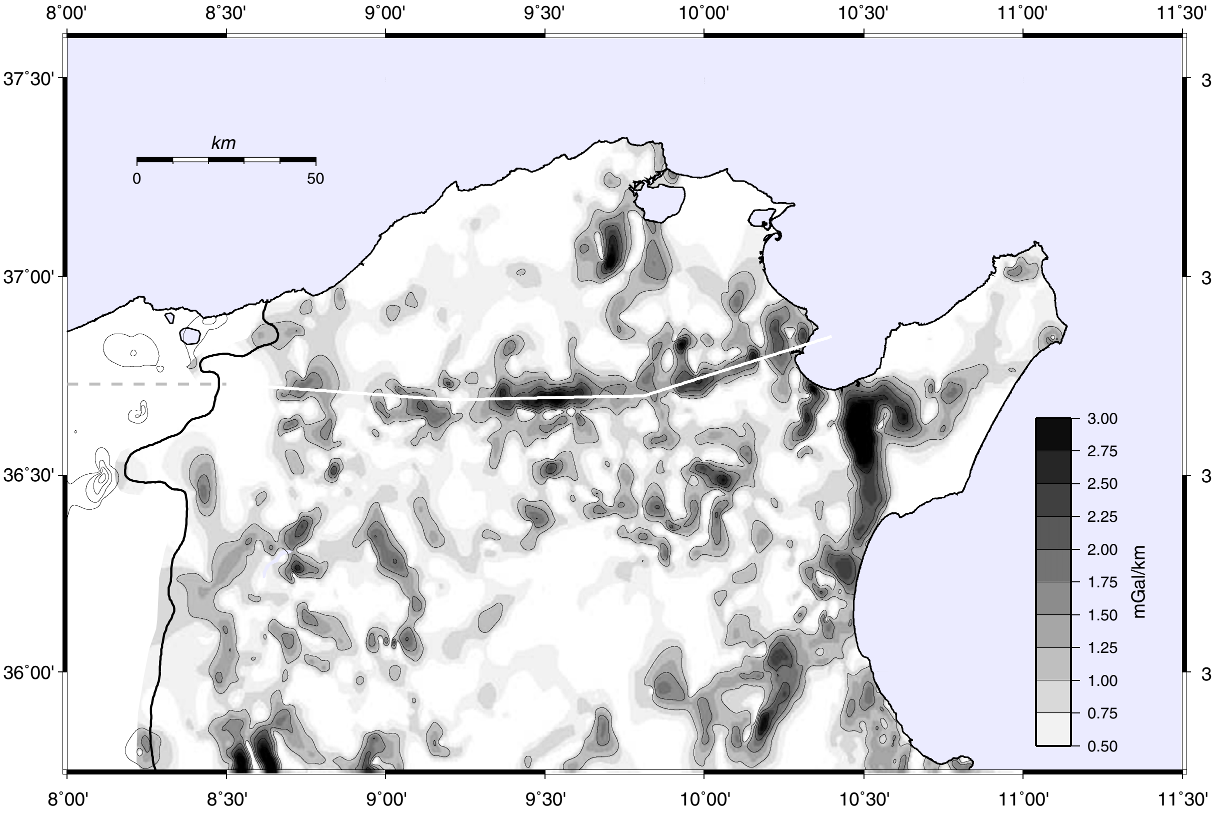

Fig. 7. Gray-scale image of the horizontal gradient magnitude of gravity residual anomalies. High values indicate location of density contrasts representing boundary edges of density contrasts. Note the prominent E–W trend as indicated by the solid white and black lines from Algeria to Gulf of Tunis. Bold lines represent faults, bold lines with triangles represent thrust faults and dashed lines represent the traces of fold axes.

the HGM may indicate the location of faults, grabens, and the boundary between the two blocks described above.

An examination of the HGM map of northern Tunisia (Fig. 7) shows a prominent E–W trend crossing Tunisia from Algeria to the Gulf of Tunis. To enhance this E–W trend, a directional gradient was calculated. As the trend is E–W, the gradient was calculated along a N–S direction (from north to south). The maxima and minima shown on the N–S directional gradient map highlight in particular the locations of E–W lineaments (Fig. 8) and represent geological features associated with density contrasts. They may represent faults, grabens boundaries, or any other geological structure that induce lateral density variation. Fig. 9 shows the location of the maxima and minima of the largest amplitude gradients which basically outlines a main E–W corridor crossing the Medjerda Valley. As this corridor is clearly outlined, this implies that in northern Tunisian Atlas, there is evidence of a previously unknown regional E–W geological feature separating two blocks. These different blocks separated by the prominent E–W feature contain numerous other trends that are characterized by smaller amplitudes and directions. The southern block has lineaments trending in a variety of directions implying a highly deformed geology, whereas the northern block has fewer lineaments that trend roughly in E–W direction, except the eastern area (from latitude 9°30 to the Gulf of Tunis) where we have other lineaments trending in N–S direction and more seismic activity. This observation suggests that the two blocks have not undergone the same structural deformation or they do not have the same mechanical properties.

In addition to the observed geological features and the gravity lineaments derived from horizontal gradient operators, there are numerous moderate magnitude earthquakes in northern Tunisia. Fig. 9 shows the epicenters of earthquakes with magnitude greater than 3. The distribution of earthquakes indicates that northern Tunisia is under active deformation and that many of the earthquakes coincide with the main gravity derived E–W corridors, in particular in the Medjerda zone. Additionally, there is an asymmetrical repartition of earthquakes and the majority of these events are located in the southern block relative to the E–W feature implying that the current deformation is more active in the southern block. This observation implies that the E–W lineament separates two blocks that do not have the same mechanical behavior.

5. Discussion

The above analysis highlighted a prominent E–W trending gravity anomaly that crosses the Tunisian Atlas from Algeria to the Gulf of Tunis. In addition, there is evidence that the southern block consists of more gravity lineaments than the northern block (Figs. 7, 8 and 9). The question what is the geological significance of this E–W feature and its geodynamic implications arises.

When interpreting this feature, one has to remember that it is expressed by the residual gravity anomalies as enhanced by a derivative analysis. Therefore its source may be a geological feature in the upper crust that may include density contrasts in either the basement and/or the sedimentary cover. Additionally, this region is under active deformation as evidenced by the current seismic activity. As the region is still tectonically active and has been affected by multiple tectonic events since the early Mesozoic, these geological features could be faults, folds, thickness variations of basins or basement density contrasts.

Surface observations of outcrops agree with the results of this gravity analysis. The geologic map shows an abundance of Mesozoic outcrops in the southern part whereas in the northern part, there is abundance of Cenozoic outcrops (Fig. 2). In addition, the northern block shows fewer lineaments and faults than the southern block.

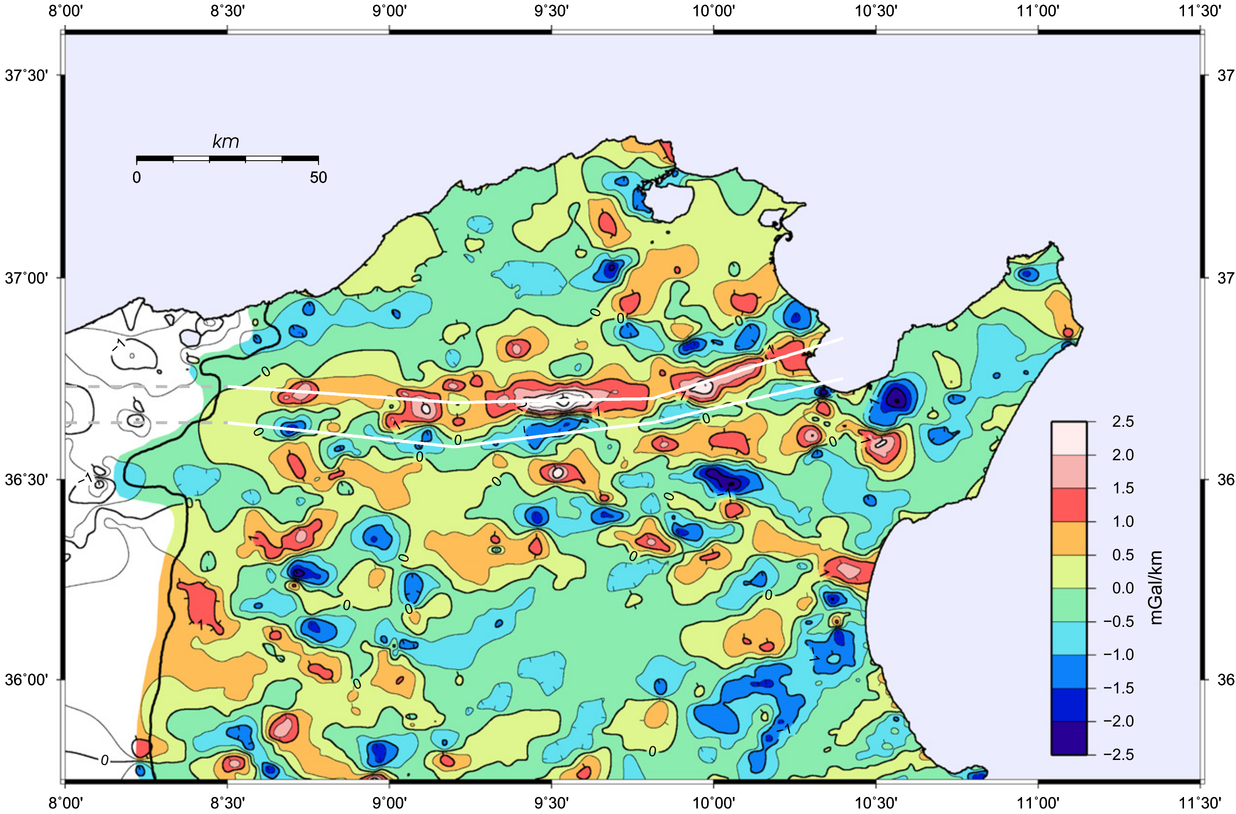

Fig. 8. Directional horizontal gradient (N–S gradient) of the gravity residual anomalies that enhances E–W gravity trends (Fig. 6). Maximum and minimum gradients indicate the location of density contrasts that represent boundary edges of density contrasts. The E–W prominent trend as indicated by the solid white lines is more clearly defined on this map.

However, it is difficult to draw a boundary between them based on surface geological observations. Even though there is no regional E–W fault drawn on the geological map (Medjerda Valley), all the observations mentioned above lead to distinguish two geologically different blocks in northern Tunisia with an E–W boundary expressed by the E–W gravity trend seen in Fig. 8.

The E–W corridor crosses the Medjerda Valley (Fig. 9). In this region, the cross-section derived from geological and geophysical data (Fig. 3) shows an uplift of the basement and evidence of thickness changes of Paleozoic and Early Mesozoic basins implying the presence of a particular structure in this region. The main E–W gravity trend coincides with this deep structure. Such a feature implies the role of ancient and deep faults that controlled the sedimentary environment causing either a thickening or thinning of sediments. These faults would be normal in case of extensional regime and they would be inverted in case of compressional event. It is known that E–W striking faults (strike slip and normal faults) were developed during the Early Mesozoic rifting event within a transtensional stress regime and which formed a system of sedimentary basins. Later, during the post rift period (Latest Cretaceous and Early Cenozoic), these features were reactivated as strike-slip or inverse faults under a transpressive tectonic regime due to the convergence between Africa and Europe. Indeed, based on surface observations and structural studies, many authors imply that the observed structures in the Tunisian Atlas were caused by the reactivation of inherited E–W faults (Ben Ayed, 1994; Saïd et al., 2011; Zouari et al., 2004). The major folds in the Tunisian Atlas are considered to have been at least partly formed by strike slip movement (Ben Ayed, 1993; Rouvier, 1977). The observed NW–SE trending grabens are considered to be pull apart structures associated to E–W dextral faults as a result of a masked regional compression (Ben Ayed, 1994; Bouaziz et al., 2002; Chihi, 1995; Guiraud et al., 2005). The compressive and extensive structures developed during Cenozoic in northern Tunisia were formed by E–W and N–S convergent strike slip faults (Ben Ayed, 1994). Similar tectonic style is observed in northeastern Algeria. Indeed, based on geological observations, Marmi and Guiraud (2006) describe the E–W folds, reverse faults and strike slip faults developed during Early Quaternary in the “Mole Constantinois” located at the southern edge of Petite Kabylie. The lateral strike slip tectonic regime is confirmed recently in the same region based on focal mechanisms and stress tensors deduced from the Constantine seismic sequence of 27 October 1985 (Ousadou et al., 2013). The focal mechanism of this earthquake indicates a strike slip fault with small inverse component. These authors show also that faults associated to this seismic sequence are deep. The depth of the main rupture reaches 15 km. Other geological studies evoke the role of deep E–W strike slip faults to explain the complex geological architecture of the Tunisian Atlas (Amiri et al., 2011; El Ghali et al., 2003; Gabtni et al., 2011; Meghraoui and Pondrelli, 2012; Zouari et al., 2004). Additionally, based on seismic deformation studies along the boundary between Africa and Europe, Pondrelli (1999) and Meghraoui and Pondrelli (2012) showed that the boundary between northern Africa to Sicily have the characteristics of a transpressional regime. In this context, one can interpret the major E–W corridor in Fig. 9 to be due to the response of a major deep fault that was reactivated during the Cenozoic as transpressive fault and it may be extended toward the West (Algeria) as we have similar tectonic regime observed in the Constantinois high, southern edge of Petite Kabylie. We note that this E–W fault in northern Tunisia is not unique, but it can be considered a major fault that controlled the observed geological architecture. These kind of inherited faults are not directly observed at the surface, however, their expression under the sedimentary cover can be indirectly observed and they have an import role in the geodynamic evolution.

Based on the structural and geodynamic studies mentioned above, this kind of ancient fault (developed at least during the Early Mesozoic

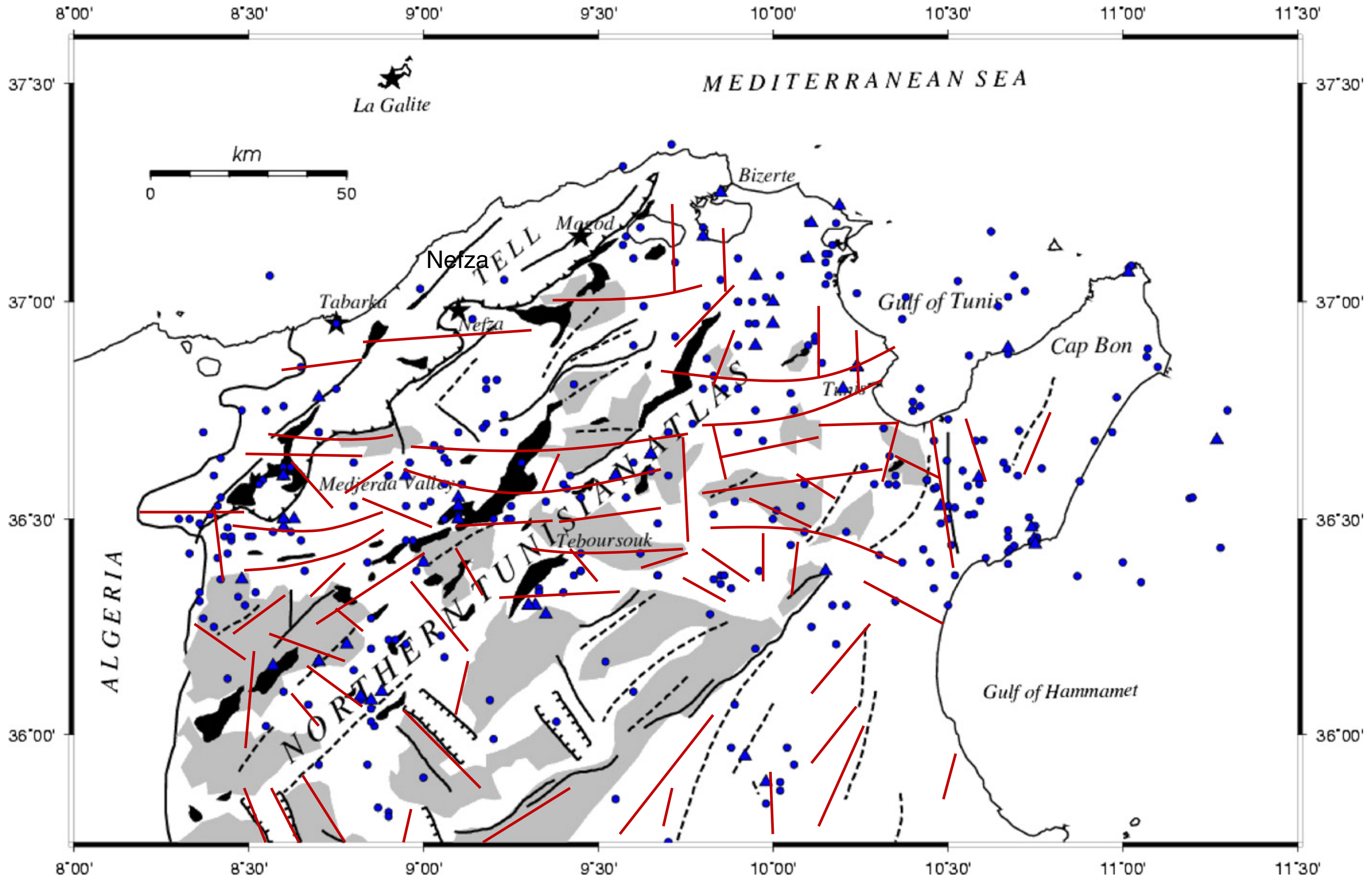

Fig. 9. Map showing the gravity lineaments deduced from the gravity analysis and the earthquake epicenters (Institut National de Meteorology, Tunisia) in relation to the main observed geological features (Fig. 2). Thick red lines represent gravity lineaments, small blue circles represent the earthquake epicenters with magnitudes between 2 and 3, and blue triangles represent earthquake epicenters with magnitudes greater than 3. Note that most gravity lineaments and many of the earthquakes are located within the inferred E–W corridor that separates two different crustal blocks. Bold lines represent faults, bold lines with triangles represent thrust faults and dashed lines represent the traces of fold axes.

rifting) are deep and affect the basement. In this context, we may wonder "is the major E–W fault described above lithospheric in nature?". Knowing the kinematic scenario that built the Atlas orogeny in northern Tunisia, one has to take into account that a subduction zone was active in the region and led to the destruction of Tethys oceanic lithosphere. Then a collision of microplates that were rifted off the European margin occurred with the North African margin (Morgan et al., 1998). In northern Algeria, based on seismic reflection data of the TRANSMED project, Roca et al. (2004) proposed that transitional crust exists between oceanic crust of the Algero-Provencale basin (Fig. 1) and the continental crust of Africa. This transitional crust corresponds to the Kabylie blocks that collided with the African margin. The lithospheric section of the Algero-Provencale basin and Nubia (Africa) presented by Roca et al. (2004) and Mauffret (2007) shows that the Kabylie blocks are regions inherent to the African crust but they have a specific characteristics. Such a situation is comparable to our gravity data observations in northern Tunisia.

Mauffret (2007) defined a microplate that consists of the Calabro-Peloritan–Kabylian blocks that includes the Petite Kabylie (northern Algeria), La Galite Island (northern Tunisia) and Sicily. Mauffret considers that this microplate was accreted to northern Africa. This observation raises a question on the location of the southern boundary of the microplate or block that has been accreted to Africa. In this context, the E–W corridor expressed by the gravity lineaments (Fig. 9) and which can be explained by a major deep fault may be the southern edge of the microplate. In other words, the prominent E–W corridor could be the boundary between the African plate and the microplate that rifted off Europe. Taking into account the geological context of western Mediterranean Sea, the northern block is named the Kabylian block because it is equivalent to the Kabylie blocks in northern Algeria that formed during a collision with the African plate. This scenario is supported by observations implying differences between the two blocks separated by the E–W trending gravity anomaly (Fig. 9). Among these observations:

- The boundary defined by the gravity trend is characterized by lateral density contrast, it corresponds to a regional geological feature and it is over a hundred kilometers long.
- There is a geophysical difference between northern and southern block. The gravity response of the northern block has relatively low amplitude and uncomplicated anomaly patterns, whereas the southern block contains numerous positive and negative gravity anomalies implying numerous changes in the subsurface densities. Based on the results of a seismic refraction survey (Boccaletti et al., 1990), the P-wave velocity of the Tunisian crust is not constant. It varies from 6.0 to 6.6 km/s and the highest values are within the northernmost crust of Tunisia.
- The location of the E–W corridor (Fig. 9) coincides with the active boundary between the Africa and Eurasia plates defined by Pondrelli (1999) and Meghraoui and Pondrelli (2012) based on a seismic deformation studies of western Mediterranean region.
- There is a seismic activity in the entire northern Tunisian Atlas and the majority of the epicenters are located within the E–W corridor (Fig. 9) implying that the E–W feature is currently active.

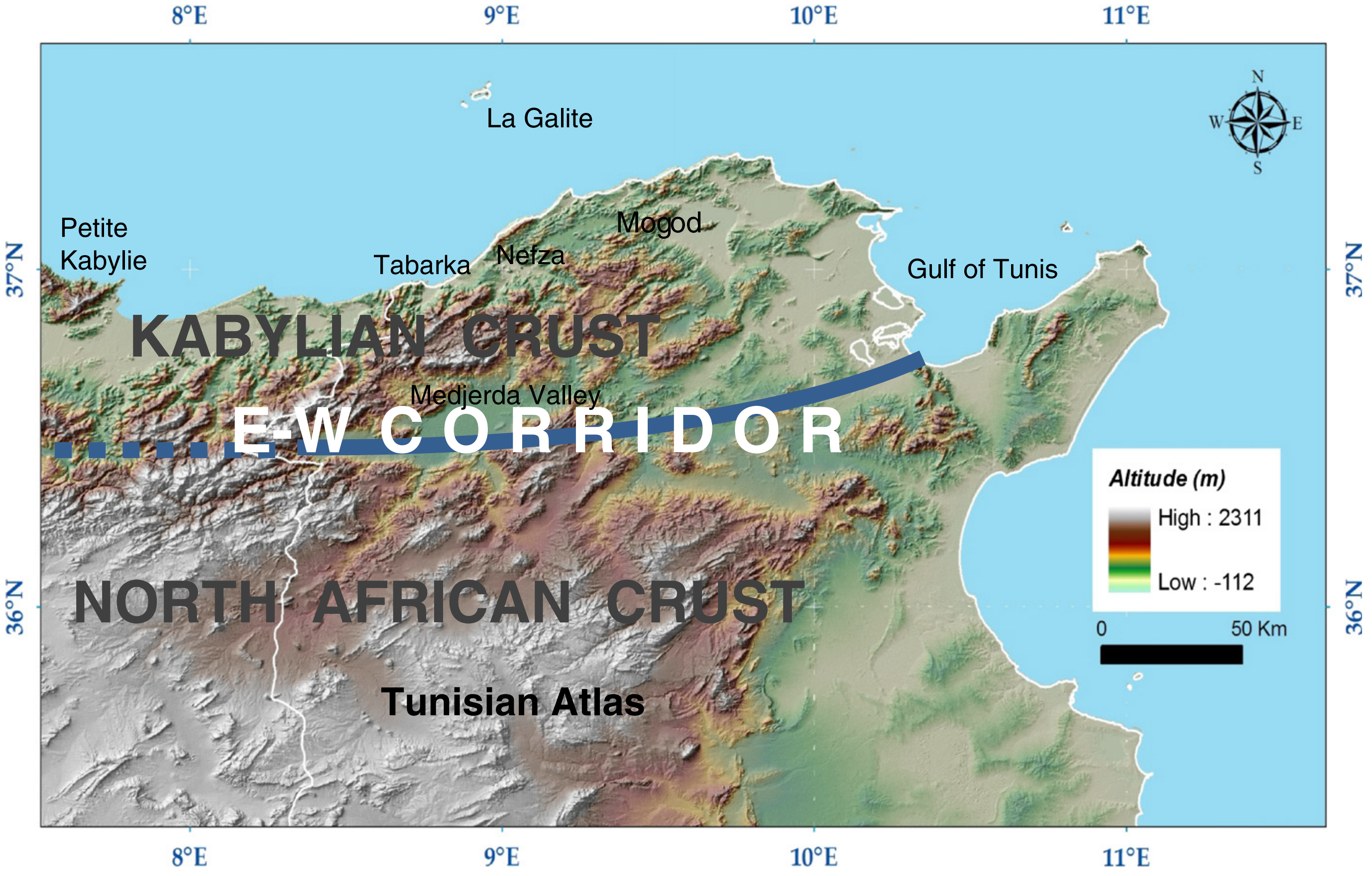

Fig. 10. Digital elevation map showing the tectonic setting of northern Tunisia in the context of the western Mediterranean Sea region. The thick blue line represents the regional geological feature derived from the gravity data analysis that is interpreted as a deep inherited fault that controlled the geological architecture structures in the region and is considered to be a boundary separating two different blocks. The southern block belongs to the African plate, whereas the northern block (here named the Kabylian plate) is considered a part of the Corsica–Sardinia–Petite Kabylie microplate that rifted off Europe.

- An examination of the geologic map of Tunisia (Ben Haj Ali et al., 1985) shows that the southern block has an abundance of Mesozoic outcrops with numerous faults, folds and grabens (Fig. 9), whereas the northern block shows mainly Cenozoic outcrops. We can state that the two blocks have not been controlled by the same tectonic events or they do not have the same mechanical responses to tectonic events that controlled the region.
- And the northern block includes Miocene volcanic rocks. At least four localities contain outcrops of igneous rocks: Tabarka, Nefza, Mogod and La Galite Island (Fig. 9). These volcanic outcrops are small in areal size (a few hundred meters in width) whereas, based on a gravity and magnetic analysis, Jallouli et al. (2003) showed that igneous bodies occur over a much wider region in the subsurface and are interpreted to be related to the subduction of the African plate that occurred during the Early and Middle Miocene in northern Tunisia.

From seismic and gravity studies, one notes that the Kabylian block has a thin crust (Buness et al., 1992; Jallouli and Mickus, 2000) and this observation is not normally found in collision zones. The thickness of the crust in northern Tunisia ranges from 22 to 25 km, however the crust should be thicker due to the collision with the African plate. However, this observation is not in contradiction with our observations that northern Tunisia (the equivalent of Kabylian block in Tunisia) is a part of microplate rifted off of Europe. A similar situation exists in northern Algeria where the depth to the Moho beneath the Kabylies is less than 25 km (Mickus and Jallouli, 1999). It is probable that the northern Algerian and Tunisian crust was thickened and then thinned after it was accreted to the Africa plate as suggested by Mauffret (2007) and Mascle et al. (2004). Additionally, a slab tear may have occurred in the Tunisian margin and the subduction zone migrated toward the East (Argnani, 2009; Faccenna et al., 2001; Frizon de Lamotte et al., 2009; Goes et al., 2004; Panza et al., 2007). In such a scenario, the collision may have initiated and then stopped. In this case, the shortening of the crust would have been small. Besides, many thrusts and inverted faults are found on both sides of the prominent E–W gravity trend and such features are observed in different localities in the Tunisian Atlas up to southern Atlas (Saïd et al., 2011). This tectonic scenario could explain the energy dissipation of the compressional events due to plate convergent between Africa and micro-plates rifted off of Europe.

6. Conclusions

A gravity data analysis of the northern Tunisian Atlas highlights a regional E–W corridor of E–W trending gravity lineaments interpreted to be the result of a major deep fault developed at least since Early Mesozoic rifting (Tethyan rifting). This fault is still active and controls the geological architecture observed in northern Tunisia. Additionally, this regional E–W feature separates two blocks having different gravitational and seismic responses. The southern block has numerous gravity lineaments trending in different directions implying density variations within the crust and numerous geological structures, whereas the northern block has a longer wavelength negative anomaly with few lineaments. Taking into account the geological context of the western Mediterranean region, the E–W corridor can be interpreted as the boundary between African plate and Kabylian microplate in northern Tunisia. This feature seems to extend into northern Algeria and it joins the southern edge of the Petite Kabylie (Fig. 10). This scenario suggests that northern Tunisia is part of the Corsica–Sardinia–Petite Kabylie microplate that rifted off the Europe to be in collision with the African plate. This result has an important impact on mineral and energetic resource prospection as these two blocks are supposed to be separated by an ocean and they did not belong to the same margin.

Acknowledgments

We thank the Editor Professor L. Jolivet and two anonymous reviewers for their constructive comments and discussion that led to improvements of the paper. This work was supported by King Saud University, Deanship of Scientific Research, Research Centre. Maps were produced using Generic Mapping Tools (GMT).

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