Gravity Data from the Teboursouk Area ("Diapirs Zone", Northern Tunisia): Characterization of Deep Structures and Updated Tectonic Pattern

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A b s t r a c t

Located between eastern segments of the Atlas and Tell-Rif orogenic belts, the "Dome zone" of northern Tunisia is characterized by the juxtaposition of various structures that mainly controlled the long geodynamic history of this part of the south-Tethyan Margin. To better understand the organization and deep extension of these structures, gravity data from the Teboursouk key area are proposed. These data include the plotting of Bouguer anomaly map and related parameters such as vertical and horizontal gradients, upward continuation and Euler solution. Compared to geological and structural maps available, they allow the identification of new deep structures and greater precision regarding the characteristics and organization of known ones; consequently, an updated structural pattern is proposed.

Key words: Northern Tunisia, Teboursouk, gravity data, deep structure, diapir, faults.

1. INTRODUCTION

Northern Tunisia is an extension of the Tell-Rif eastern segments and the north-Atlantic domain (Fig. 1A). It is considered as one of the important sectors where the complex geological history of the Maghrebian south-Tethyan Margin can be reconstructed. In fact, at least since the Triassic period, this area has undergone many tectonic episodes that alternated through time. Edi-

Fig. 1: (A) Tectonic pattern of the western Mediterranean domain (modified from Doglioni *et al.* 1999), (B) geological map of the study area (extracted from geological map of Teboursook, 1:50 000). 1 – Jebel Ech Cheid, 2 – plain of El Aroussa, 3 – plain of Khalled, 4 – jebel Strassif, 5 – jebel Chetlou, 6 – Koudiat el Mahjbia, 7 – Knana, 8 – Tabet Ech Cherif, 9 – Ain Tounga Khalled, 10 – Ain Jemala, 11 – Oued Hermoucha, 12 – Oued Arkou, 13 – Thibar, 14 – Jebel Goraa, 15 – Ain Hamra-Dougga, 16 – Draa el Kantra.

fied structures were repeatedly affected by successive phases leading to the present-day structure. A set of various structures at different scales can record signatures of the main steps of this geodynamic evolution. The Tebour-souk area belongs to the “Diapirs zone” of northern Tunisia which is adjacent to the northernmost Atlasic domain. Since the 1920s, particular attention has been paid to this key sector by many geologists interested in thematic investigations aiming at the reconstruction of geodynamic evolution of the Tunisian Tethys Margin and its controlling factors (Biely *et al.* 1974, Ben Ayed 1994, Chihi 1995, Gueguen *et al.* 1998, Guiraud *et al.* 2005, Rigane and Gourmelen 2011). The stratigraphical succession disturbance, the tectonic style, and the onset mode of the characteristic Triassic material are still a matter of debate; the drowning or burial of many structures makes it difficult to follow the continuation of structural units. In the gravimetric study, the subject of this paper, we propose to follow the distribution of density contrasts due to depressions and faults aiming to increase our understanding of the deep geological structure using unpublished gravity data (Hachani 2006). Interpretation of the Bouguer anomaly map and related derivative compilations serve as a base for deep structures’ characterization; an updated tectonic pattern is proposed for the area replaced in its broader geodynamic context.

2. GEOLOGICAL AND PALAEOGEOGRAPHICAL CONTEXT

In northeastern Tunisia, the Tebour-souk area (672 km²) is located one hundred kilometres to the NW of Tunis (Fig. 1B), between Lambert coordinate lines: $X = 430$ km and $X = 462$ km; $Y = 338$ km and $Y = 359$ km).

As a part of the “Diapirs zone”, it records many stratigraphic and structural signatures of the geodynamic evolution of the eastern Maghreb Tethyan margin. By Middle to Upper Triassic, the northern Tunisia passive margin registered the first echoes of a distensive phase, better expressed after the fragmentation of the Liassic initial carbonate platform (Solignac 1927, Bolze 1950, Rouvier 1985, Ben Ayed 1986). Consequent subsidence reached its maximum during Middle Jurassic and continued until Lower Cretaceous, all in a Tethyan rifting context related to Africa–Eurasia relative movement. As a result, a mosaic of high blocks and adjacent depressions, separated by reactivated Hercynian faults, characterizes the main palaeogeographical features of the area. A northward more subsiding area, the “Tunisian Trough”, developed in a tilted-block-structural pattern allowing progressive ascensional movement of Triassic material. This material has pierced its sedimentary cover since the Albian times (Chitta 1979, Perthuisot 1979, Rouvier 1985, Dali 1997) and underlined NE-SW-trending major faults.

Table 1

Lithological synthesis of Teboursouk

Age	Stages	Formations	Lithostratigraphic descriptions	Densities [g/cm ³]	
Quaternary (40 to 50 m)			limestone, clay, silt et conglomerates	1.7< <i>d</i> <2.38	
Neogene	Pliocene (20 m)		conglomerates		
	Miocene (1300 m)	Kechabta-Oued el Khedim	sandstone, clay, rare conglomerates		
		Oued Mellah	marl and gypsum		
		Hakima	sandstone, breccia, conglomerates, marls		
Paleogene	Oligocene (75 m)	Fortuna	sandstone	1.7< <i>d</i> <1.95	
	Upper Eocene (35 m)	Souar	marls, nummulitic limestones		<i>d</i> > 2.4
	Ypresien-lower Lut (150 m)	Metlaoui	limestones and et nummulitic limestones		
	Paleocene (300 m)	el Haria	marls		
Upper Cretaceous	Campanian-Maastrichtian (365 m)	Abiod	limestones, marls et marly calcareous	<i>d</i> ≈ 1.9	
		el Kef	marl and clay with rare intercalations of limestone and marly limestone		
	Santonian (500 m)				
	Coniacian (50 m)				
	Turonian (130 m)	Bahloul	black limestones finely bedded	<i>d</i> ≈ 2.4	
	Cenomanian (> 250 m)				
Lower Cretaceous	Albian (500 m)	Fahdene	marl and platy limestone	2.38< <i>d</i> <2.41	
	Aptian (500 m)	M'Cherga	marl, marly calcareous limestone, sandstone		
	Barremian (≈200 m)		marl, marly calcareous		
Trias			gypsum, carbonates	1.75< <i>d</i> <2.6	

In relation to Africa–Europe collision, northern Tunisia underwent several compressional tectonic events. A first episode, recently attributed to the Middle Eocene (Perthuisot 1974, Adil 1993), is still a matter of discussion; however, a consensus is reached on the occurrence of three major phases dated as Middle Miocene, Late Miocene, and earliest Pliocene. The most important one, referred to as the “Atlasic phase”, was responsible for important folding and reactivated diapiric movement of Triassic deposits also interpreted as salt glaciers by some authors (Vila 1995). These NE-SW trending Triassic chaotic material as well as a set of curved axis folds mainly characterize the present “Diapirs zone” of northern Tunisia. In this area, anticlines are narrow and asymmetrical with faulted south-eastern flanks; synclines are wide and infilled by Neogene deposits. Four major fault types can be identified considering their general trends: N-S, NE-SW, SE-NW, and E-W (Perthuisot and Jauzein 1972, Perthuisot 1978, 1979; Hammami 1999, Kadri and Ben Haj Ali 1999, El Ouardi 2002, Chikhaoui 2002, Balti *et al.* 2014). The stratigraphic data (Table 1) includes various successions of Triassic-to-Quaternary ages with the lack of Jurassic series.

3. GRAVITY DATA

Gravity data were gathered by the Val d’Or Sagax company for the Tunisian geological survey (ONM 2000). They concern 648 regularly distributed stations covering the map section of the Teboursouk area. The approximately mean density is one observation per square kilometer. A Lambert North projection using the Clark ellipsoid 1880 and Carthage datum was adopted. Free-air and Bouguer gravity corrections were performed using sea level datum and a reduction density of 2.4 g/cm^3 . This value results from the comparison of several methods: direct measurement of densities over several samples, and using the indirect Nettleton’s method.

3.1 Bouguer anomaly map

The Bouguer gravity anomaly map ($d = 2.4 \text{ g/cm}^3$) of the study area shows a variation of 34 mGals. Three anomaly groups bounded by strong gravity gradients can be identified (Fig. 2) considering their trends.

- **NW-SE:** these anomalies consist of B_1^+ (Tabet Ech Cherif syncline), B_1 (along Khaled-Ain el Hamra-Dougga), B_3^- (Teboursouk), and B_7^- (El Aroussa plain);
- **NE-SW:** following this direction, the anomalies B_2^+ , B_3^+ , B_4^- , and B_5^+ are of weak gradients and coincide with the Triassic outcrops of Ain Jamela, Jebel Ech Cheid, Ain Tounga-Khaled, and Thibar, respectively. B_8^- characterizes the Ain el Hamra-Dougga syncline, B_5^- and B_6^- correspond to the plains of Khaled and El Aroussa;

Fig. 2. Bouguer anomaly map of Teboursouk ($d = 2.4$).

- **E-W:** B_4^+ and B_5^- overprint the Oued Arkou anticline and the Oued Hermoucha syncline, respectively.

3.2 Methods and results of interpretation of gravity anomalies

Various techniques, such as vertical and horizontal derivatives, Euler deconvolution, and upward continuation, were used to interpret the gravity map. The programs used for the gravity data interpretation in this study are the Geosoft and keating programs (Keating 1998).

Vertical derivative $\left(\frac{\partial g}{\partial z} \right)$

Vertical derivatives of anomalies provide a powerful technique for enhancing anomalies of smaller and near surface geological features (Evjen 1936, Baranov 1953, Marson and Klingele 1993). This derivative allows to identify the structures in the subsurface from the Bouguer anomaly. Indeed, the transformation reduces the regional element (low-frequency anomalies) which may distort or even hide the relationships near surface geological features (high-frequency anomalies) and the shape of the anomalies. Positive zones indicate rock densities exceeding the average and *vice versa*. Consequently a vision on sub-outcropping lithologies is possible and distinguished raised zones are characterized by positive anomalies where heavier platform

Fig. 3. First vertical derivative of the Bouguer anomaly.

is either closer to the surface or showing a light and thin cover. On the other hand, depression zones are characterized by negative anomalies indicating a light and thick cover.

Figure 3 shows that, in our case study, the raised zones are related to the Triassic outcrops (**H₁** – J. Ech Cheid; **H₂** – Knana; **H₃** – Ain Jamela; **H₄** – Thibar), to the Cretaceous series of Tabet Ech Cherif (**H₅**) and to the Neogene outcrops of the Oued Arkou anticline (**H₆**).

These raised zones strongly contrast with depressive ones filled in by light and thick series which are, from north to south: **D₁** (Pliocene deposits of Oued Hermoucha), **D₂** (NE the study area), **D₃** (between Jebel Ech Cheid and Knana), **D₄** (Ain el Hamra-Dougga), **D₅** (the plain of Khalled), **D₆** (two distinct subdepressions in El Aroussa), and **D₇** (southern J. Ech Cheid).

The association of horizontal gradient $\left(\frac{\delta g}{\delta(x,y)} \right)$ and the upward continuation

The association of horizontal gradient and the upward continuation is used for the identification of the deep faults' limits and their dips (Cordell and Grauch 1985, Blakely and Simpson 1986, Blakely 1996, Phillips 1998, Archibald *et al.* 1999, Everaerts and Mansy 2001, Khattach *et al.* 2004, Najine *et al.* 2006, Chennouf *et al.* 2007, Abderbi and Khattach 2010). The Bouguer anomalies were prolonged to heights up to 4000 m with a step of 250 m. For each level, the maxima of the horizontal gradient were localized.

Fig. 4. Horizontal gradient map.

If the structures are vertical, all maxima are overprinting. On the other hand, the shifting of maxima for the upward extension indicates the direction of the dip.

Zones with strong gradients as shown by Fig. 4 are:

- **G1** (0.01 mGal/m): trending NW-SE, this zone marks a rooted and sub-outcropping fault (loose iso-anomalous contours) between Cretaceous series (north to the rift: high zone) and those of El Aroussa basin: low zones. This limit would correspond to the NE edge of El Aroussa;
- **G2** (0.008 mGal/m) and **G3** (0.007 mGal/m) on both sides of Jebel Ech Cheid are of a ENE-WSW and NE-SW trend;
- **G4** (0.007 mGal/m) trending E-W, overprints Oued Siliana and indicates a vertical deep fault separating Tabet Ech Cherif from a basin located to the NE of the study area. This fault underlines the contact between Triassic outcrops and Cretaceous series of Tabet Ech Cherif.

Other zones with weaker horizontal gradients (< 0.006 mGal/m) are also shown in Fig. 4. These consist of: **G5** (south-eastern Thibar, trending NE-SW); **G6** and **G7** (Tabet Ech Cherif; NW-SE and NNE-WSW, respectively); **G8** (south to El Aroussa, NNE-SSW); **G12** (Ech Cheid, E-W); **G11** (plain of Khalled, flexure), **G9** (North Ain Jamela, NE-SW), and **G10** (NW flank and the periclinal termination of Ain el Hamra-Dougga syncline).

The superposition of the maxima of horizontal gradients (Fig. 5) shows that some faults are sub-vertical: **F1**, **F2**, **F3**, and **F4** delimiting the Jebel

Fig. 5. Superposition of horizontal gradient maxima obtained from the Bouguer anomaly and from upward continuation map at different altitudes: (2) 250 m, (3) 500 m, (4) 750 m, (5) 1000 m, (6) 1250 m, (7) 1500 m, (8) 1750 m, (9) 2000 m, (10) 2500 m, (11) 3000 m, (12) 3500 m, (13) 4000 m, and (14) dip direction.

Ech Cheid; **F5** and **F17** affecting the plains of El Aroussa and Khalled, respectively; **F16** close to the Oued Arkou anticline; **F8** crossing the Tabet Ech Cherif syncline, and **F11** in Oued Hermoucha. The other faults show various dipping trends; from east to west they are: **F9** (N-dipping, located to the north-eastern extremity of the sector); **F7** (SW-dipping, NE J. Ech Cheid nearby Ragoubet el Mahjbia); **F6** (S-dipping, north to J. Strassif); **F18** and **F19** (NW-dipping, plain of Khalled), **F12** (SW-dipping, Oued Hermoucha); **F13** (SE-dipping, SW J. Thibar); **F14** (NE-dipping, Jebel Thibar), **F15** (SE-dipping, NW J. Goraa), and **F22** (east-dipping, Ain el Hamra-Dougga syncline).

The digitization and statistic processing of the gravimetric contacts (Fig. 6: Map 1 and panel A) reveal four fault trending groups: N-S, E-W, N30 to N70, and N120 to N150. This is in line with the geological map structures where the N40, E-W, N140, and N-S trends predominate (Fig. 6: Map 2 and panel B). The outline length of structures is nevertheless different.

Fig. 6. Statistical analysis of accident directions obtained on the various maps: (a) rose and histogram of cumulated lengths in meter, (b) rose and histogram of frequencies.

As far as frequencies are concerned (Fig. 6: panels A and B), the identified trends are ordered from high to low as follows: E-W, N40, N135, and N-S. The final structural map obtained shows a predominance of the trends E-W, N30 to N60, N130 and N-S (in number) and of the N40, E-W, N140, and N-S trends (for the length outlines) (Fig. 6: Map 3 and panel C).

Among the identified structures, some fault outlines obtained from the processed gravimetric data and those plotted on the geological map of Teboursouk (Fig. 6: Map 1) are identical (*e.g.*, NE-SW-trending ones of southern J. Chehid Triassic outcrops) or complementary (Fig. 6: Maps 2 and 3).

The Euler deconvolution

The Euler deconvolution allows the horizontal location and the depth estimation of contacts (Thompson 1982, Reid *et al.* 1990, Keating 1998, Asfirane-Haddadj and Galdeano 2000, Mushayandebvu *et al.* 2004, Khattach *et al.* 2004, Chennouf *et al.* 2007, Saibi *et al.* 2012). It depends essentially on grid spacing, size of the deconvolution windows, and structural index (Barbosa *et al.* 2002, Stavrev and Reid 2007, Melo *et al.* 2013). Based on the calculation

of horizontal gradient $\left(\frac{\partial g}{\partial(x,y)}\right)$, and the vertical gradient $\left(\frac{\partial g}{\partial z}\right)$, the Euler equation is written as follows:

$$(x-x_0)\frac{\partial g}{\partial x} + (y-y_0)\frac{\partial g}{\partial y} + (z-z_0)\frac{\partial g}{\partial z} = -NT(x,y),$$

Fig. 7. Euler solution map (structural index of 0.25, 10×10 windows, maximum relative error of 15%).

where (x_0, y_0, z_0) are the coordinates of a gravimetric source, g is the intensity of the measured field to (x, y, z) , N is the structural index and refers to the source geometry.

For good horizontal localization and source alignment we chose a structural index (SI) of 0.25.

In our case study (Fig. 7), the Euler deconvolution highlights the presence of some faults reaching 3141 m depth. The dominating faults in this area are ranging between 500 and 1500 m. The Euler solution highlights also that the Khalled basin is limited by a deep faults raging from 1500 to 2000 m.

However, several faults previously identified are absent in the Euler solution.

This is may be due to the fact that densities do not contrast enough with depths; the interference of close source responses is also a potential cause.

4. DISCUSSION

As a synthesis, the results obtained from the Euler solution, correlated to the geological data, allow to propose a new structural map for the Teboursouk area (Fig. 8a) which shows:

- NE-SW trending faults of important depths around J. Ech Cheid (**F1**, **F2**, and **F3**), Fej Lahdoum (**F21**), and Thibar (**F13**). Their depth varies from 500 to 1500 m, sometimes reaching 2000 m. These faults are controlling the upward movement of Triassic material. Elsewhere, the NE-SW trending faults are less deep. For the Teboursouk major fault (**F10**), the gravity data show an insignificant depth in the study area; however, the seismic reflection data have shown an important depth exceeding 1500 m (TOTAL 1978, Gasmi 2002).
- E-W trending major faults are less numerous; however, they have an important role in the structure of the area, such as from north to south: (i) in the north-eastern the study area, the fault **F9** is north-dipping with a depth exceeding 1000 m. It coincides with Oued Siliana and may explain its sudden change in flow direction. The relationship of the fault **F9** with the Triassic outcrop on this site is more than probable; (ii) on the eastern edge of J. Ech Cheid, along the Koudiat Tellilet-Koudiat Guella alignment, the 1500 m deep fault **F23** could be responsible for the arched aspect of Jebel Ech Cheid. The Lakhouat NS-trending fault, well individualized to the south of the study area, may have also played the common role. To the south, from Koudiat Mejemba to Koudiat Bazina Serira, the 500 to 2000 m deep fault **F4**, would be the extension of the fault **F5** of northern J. Strassif; (iii) both **F19** and **F17** faults, with depths up to 1500 m, affect the plain of Khalled and the syncline of Ain el

Hamra-Dougga, respectively, and are interpreted as responsible for the torsion of this structure.

- **N-S-trending faults** are either hidden by Quaternary deposits of El Aroussa (depth = 500 to 2000 m (**F5**)); or delimited to the east and to the west, the Eocene series of Ain Tounga (**F7** and **F8**, depth = 1500 m).
- **NW-SE-trending faults** are the deepest and show high dipping angles. The vertical **F9** affects Tabet Ech Cherif and is considered to be at the origin of the important gradient (Fig. 3). The SW-dipping fault **F7** corresponds to the north-eastern limit of El Aroussa graben. **F24** constitutes the northern extension of this graben, bordering to the south of the Triassic outcrop of Knana. In this latter locality, major measured depths are from 2000 to 3141 m. Indeed, oil exploration works revealed important Tertiary series (1800 m) overlying the 1200 m thick Aptian–Maastrichtian successions. Eventually, in the Oued Hermoucha syncline, the faults **F12** and **F25** have depths of about 1500 m.

Fig. 8: (a) Synthetic structural map of Teboursouk area, (b) synthetic structure of el Aroussa graben.

The principal directions described above can be integrated into the local geodynamic context controlled mainly by the NW-SE Atlasic phase of upper Miocene (Tortonian). This compression leads to the individualization of NE-SW reverse faults and to the reactivation of old normal faults during the Tertiary. During the Aptian, the upward movement of the diapiric structures was activated. As shown in the gravity data, faults bordering the Triassic outcrops can reach 2000 m. This pleads in favor of a deep origin of the Triassic outcrop and defends its diapiric character.

In the south-eastern region, two subparallel normal faults NW-SE limit the graben of El Aroussa. The opening of this graben as a pull apart structure is guided by the E-W dextral strike-slip fault of Dougga and Bou Arada (Fig. 8b). The strike-slip fault of Dougga is linked to Fej Lahdoun one in the east. The N-S sinister strike-slip fault of Fej Lahdoun is the cause of the local derivation of the diapiric structure of Ech Cheid. This tectonics style is typical in the Tunisian Atlas (Jauzein 1967, Ben Ayed 1975, Chihi 1995).

In the western Mediterranean context, the occurrence of graben in northern and central Tunisia is related to the geodynamic evolution of the Maghreb eastern part (Algeria and Tunisia) and the Pelagian Block expansion, from Miocene to actual. This expansion integrates as part of the general geodynamic evolution of the central and western Mediterranean by the subduction-collision systems of African and Eurasian plates (Chihi 1995).

5. CONCLUSION

The qualitative and quantitative analyses of the gravity data have a great interest in the structural studies. Thus, these techniques allowed specifying the structure and highlighting the fault system affecting the Teboursouk area. First of all we deduct the diapiric character of the J. Ech Cheid Triassic and probably the Thibar one, mainly explained by the major deep faults delimiting it (2000 m). In this study, a deep E-W fault network (1500 m), going from Fej Lahdoun (no. 18, 19) to J. Ech Cheid (no. 2, 23, 4, and 5) was also highlighted. During the upper Miocene, where the Atlas compressive phase is oriented NW-SE, and the old Quaternary (post villafranchienne), the Dougga E-W faults are dextral strike-slip and affected the architecture of Teboursouk area. Thereby, the megafold axes in Ain Hamra-Dougga, Kern el Kebch, and the J. Ech Cheid anticline are curved and vary from NE-SW to E-W direction in the neighbourhood of the E-W faults.

In Teboursouk area, the NW-SE faults are usually buried. This fault network highlighted in this study by the gravity data, affects the substratum and locally appear at the surface when it is reactivated. The fault **F10** (Fig. 8a) representing the NE edge of El Aroussa graben seems to be active in the Miocene and delimits a subsiding zone where the Tertiary series reaches

1800 m (TOTAL 1978). The El Aroussa graben is an extensional relay between the E-W Dougga fault and the E-W Bou Arada fault located in the SE of the study area.

Finally, the architecture of this study area has been controlled by the re-activation of the pre-existing deep faults. Thereby, several tectonic structures have been implemented. Gravity data processing is useful in delineating these structures (rootedness and amplitudes) and in mapping, with greater precision (depth and dip), lineations, intrusive and faults within basement rocks that are covered by sedimentary strata. These basement features tend to localize zones of weakness and, therefore, are important to the siting of man-made structure (*i.e.*, dams, water drilling, boreholes).

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