

A new emergent alpine front chain in central Tunisia (Maktar area): filtering gravimetric data contribution

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Abstract A residual anomaly gravity map of the Maktar area has been processed via several methods including horizontal gradient, upward continuation, and Euler deconvolution to highlight structures hidden by sedimentary cover. These methods reinforce the existence of several faults inferred from geologic studies. This work outlines deep or near-surface faults that had remained hidden until now. The most important set of these faults is NE–SW trending, with depths in excess of 3,000 m. These faults limit the Northwestern limb of Balouta massif and restrain the Northwestern side of Oued Ousafa syncline. This last fault presents a thrust front which constituted the western continuity of a southern Tunisian thetys margin and a western Zaghouan scar prolongation. E–W striking faults refer to an arched beam of faults limiting Kessera plateau and others situated in the northern part of the Maktar plateau. N–S and NW–SE directions correspond to branches of less-apparent importance. Superposition of local maxima specifies dipping vergence of different

proven structures. Results from this work show the importance of gravimetric data analysis in Maktar area and provide new insight into Central Atlas Tunisia structure such as new emergent segment front Alpine chain. The proposed map could be a basis for planning future hydrogeological and petroleum research in this region.

Keywords Central Tunisia · Maktar · Gravity · Horizontal gradient · Upward continuation · Euler deconvolution · Zaghouan scar · Alpine front chain · Structural map

Introduction

The Atlas Mountains is a major orogenic belt which have significant effects on the development of basins along the North African margin. It extends from Morocco in the West to Tunisia in the East (Bracène et al. 1998). In Morocco, it is composed of the High Anti- and Middle Atlas Mountains; in Algeria, it is known as the Tellian and Sharian Atlas which are separated by High Plateau; and in Tunisia, it is called the Oriental Atlas (Fig. 1a). In this last zone, the emergence and mapping of this Alpine front chain leads to many interpretations (Burolet 1973; Turki 1975, 1980, 1988; Morgan et al. 1998). Various studies have attempted to determine the western terminus of this Alpine thrust front (Jauzein 1967; Ghanmi 2003; Fig. 1b). This paper uses gravity data to improve knowledge of the Central Northern Atlas structures in Tunisia and to delineate west Zaghouan scar prolongation, which has been called T2 by (Jauzein 1967), and continues into Serj massif (Burolet 1973; Turki 1975, 1980, 1988). The interpretation is based on various filtered maps (horizontal derivative, upward continuation, superposition of maxima, and Euler deconvolution; Archibald et al. 1999; Keating 1998; Khattach et al.

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2005) to highlight various major geological structures and to indicate their dip.

Geological setting

The Atlas Mountain Range is formed by the convergence of the African and European Plates. This corresponds to a North African Alpine chain or the Maghreb Range. The evolution primarily occurred during the Tertiary as the collision of Africa and Europe was most prevalent (Dercourt et al. 1978). The Atlas system is situated between the Sahara platform to the south and the Tell–Ref system to the north (Fig. 1). In Tunisia, the Atlas Mountains correspond to the NE–SW “Tunisian dorsal” that was reviewed in several papers (Salaj 1978; Zargouni and Abbas 1985; Bocaletti et al. 1990; Ben Ferjani et al. 1990). The overall structural style is dominated by SE trending folds and thrusts. However, north Tunisia can be subdivided into major zones based on structure and stratigraphy (Fig. 1): (1) Tell Atlas zone, which corresponds to vertical and lateral successive allochthonous units made up of Oligocene–Miocene Numidian flysch and Cretaceous–Eocene shales and limestones “El” (Euchi et al.

2004); (2) To the southeast of the Tell is the Saliforous Province (Ghanmi 2003), which is characterized by Triassic rocks; (3) Central Atlas zone; formed by a NW–SE pull-apart basin (Boukadi 1994) opening associated with a NE–SW atlasic fold (Jauzein 1967; Ben Ayed 1986; Chihi 1995; Dlala 2002). Maktar region constitutes a transition zone between the Tunisian furrow, Oriental Atlas, and Central Northern Atlas (Fig. 2). Structural studies in this region have been based on outcrops through direct observation. However, this method remains insufficient over structures that are totally or partially hidden by Cenozoic and Quaternary cover. Many major deep features are not expressed at the surface by folds or flexures due to sedimentary cover, and thus remain difficult to observe.

Gravimetric and geological data

Data and methodology

The gravity data used in this study is a Maktar Bouguer anomaly map at 1:50,000. This map was calculated with 2.35 g/cm^3 density reduction (Fig. 3). It was affected by a weak regional gradient estimated at 0.35 mGal/km .

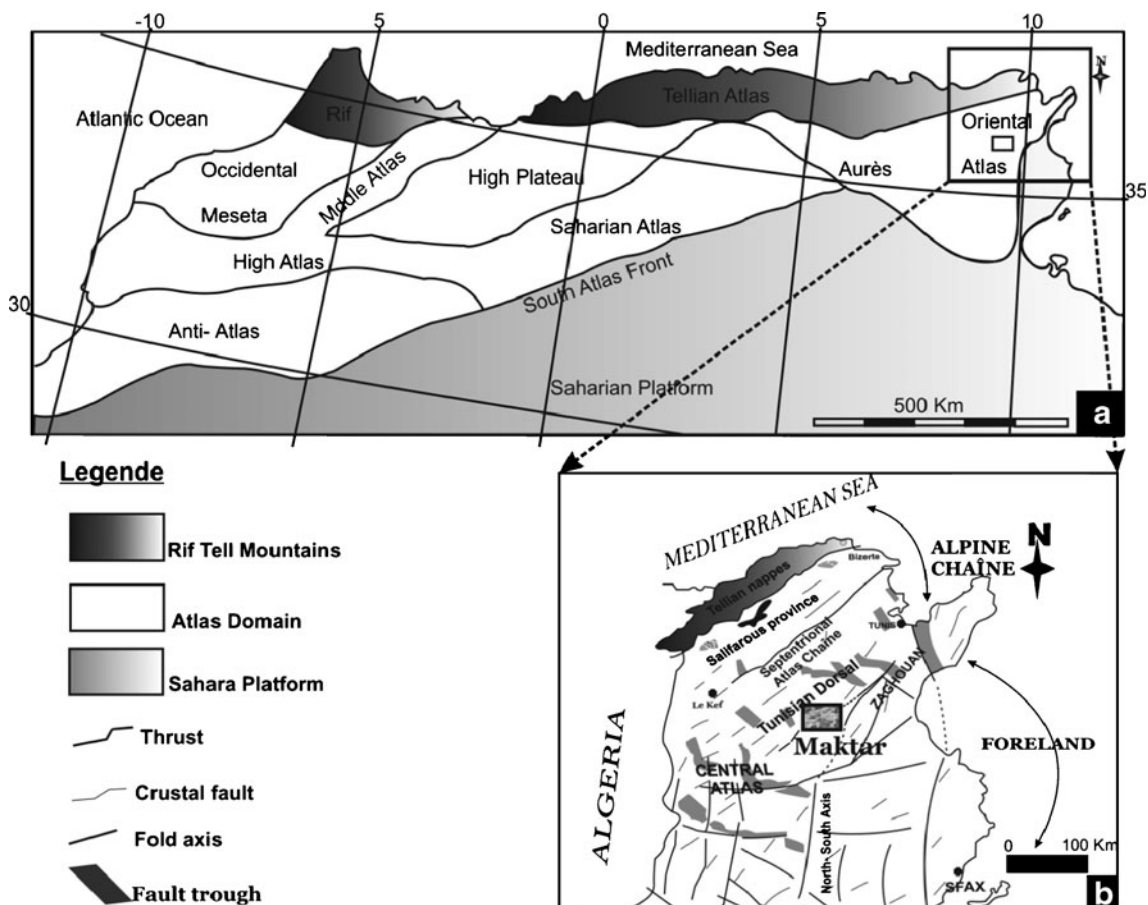


Fig. 1 a A schematic map of North Africa showing the main structural domains; b the structural map of Tunisia (Ghanmi 2003)

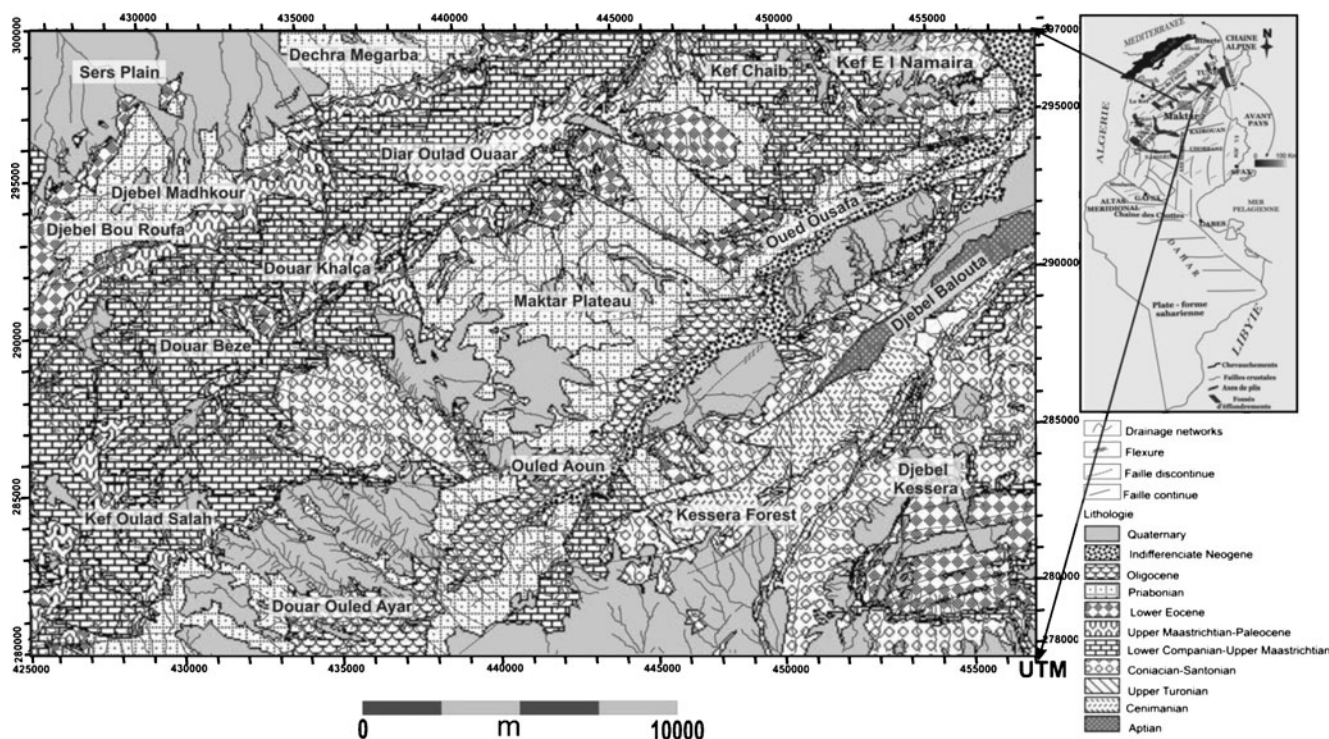


Fig. 2 Geologic map of Maktar region, scale:1:50,000 (Redrawn from Jauzein 1959). The structural map of Tunisia (Ghanmi 2003)

For a better interpretation of the data, a residual map was calculated (Fig. 4a). A 2D filter in the frequency domain was applied to isolate features of various spatial wavelengths. Thus Fourier transformation was used to calculate the horizontal gradient and the upward continuation of the gravity signal. Both techniques have shown success in other

studies (Debeglia et Weber 1985; Everaerts and Mansy 2001; Khattach et al. 2004; Najine et al. 2006).

These procedures have been undertaken to delineate contacts between blocks of contrasting density and to analyze their dip (Blakely and Simpson 1986; Chennouf et al. 2004; Cordell and Grauch 1982; Everaerts and Mansy,

Fig. 3 Bouguer anomaly map of Maktar region (milli-Galileo)

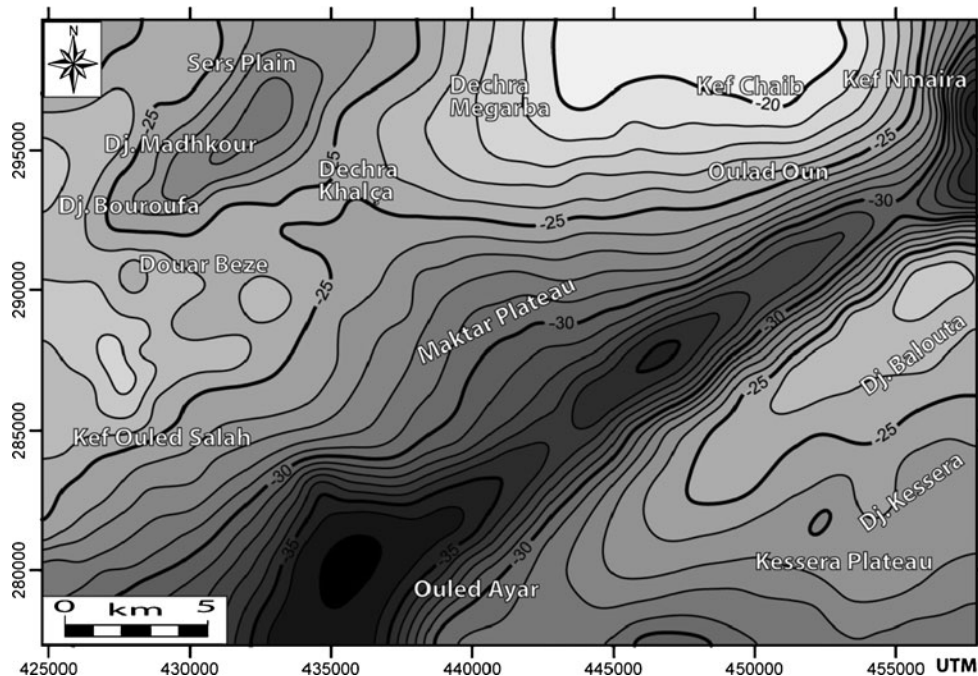
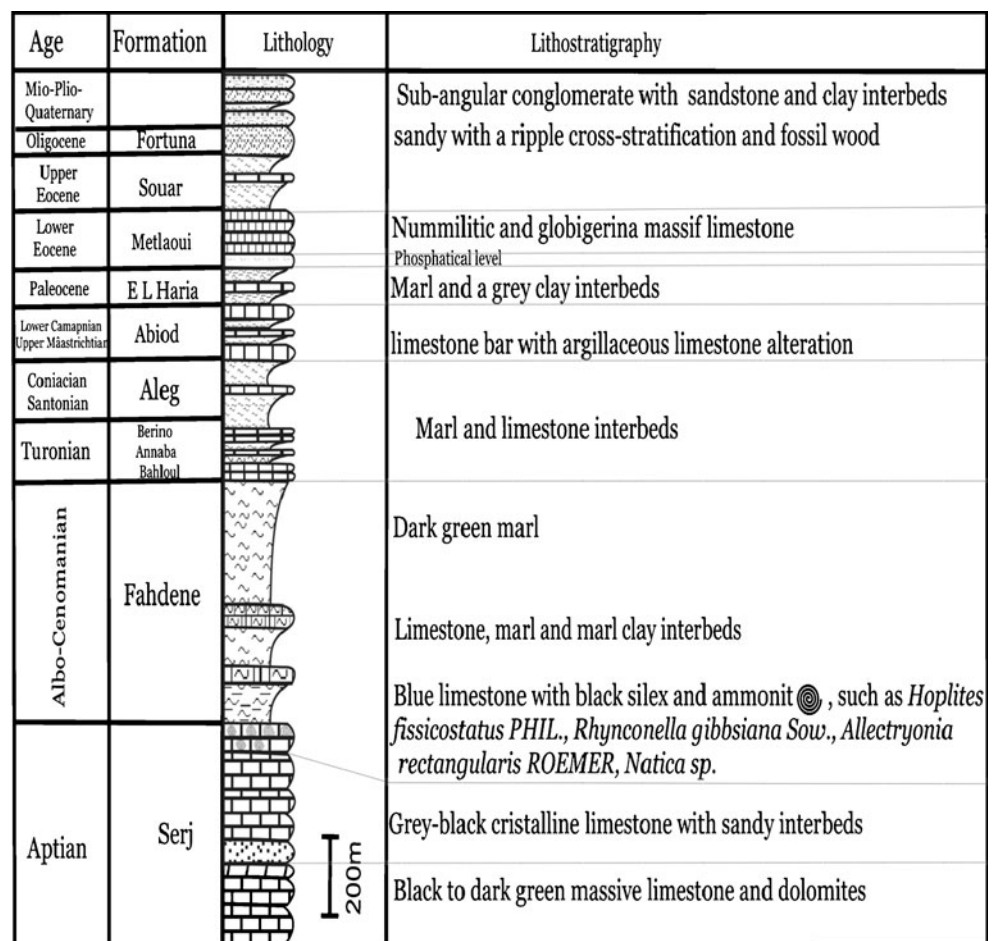


Fig. 4 Synthetic stratigraphic column of Maktar area



2001; Khattach et al. 2004). A vertical contact separates two formations of different densities, showing a low signal on the side of low-density rocks and a high signal on the side of high-density rocks. The inflection point is located just above the contact. The location of maximum horizontal gradient outlines the geologic contacts. In the case of a dipping contact, the maximum stays close to the contact but moves in the down-dip direction (Reid et al. 1990) with increasing depths (Blakely and Simpson 1986; Cordell and Grauch 1982; Everaest et Mansy, 2001). Euler's deconvolution was applied on the gravimetric data to determine the three-dimensional location of the anomalies. (Thompson 1982; Keating 1998). This method uses the gravity field values and its gradients in the X, Y, and Z vector directions. The Euler approach uses a convolution window (square grid cells) and a structural indice (SI) imposed by geologic constraints to characterize many sources. SI can be interpreted as integer exponent in a power law expressing the fall-off of field strength versus distance from source. For real data, physically plausible (SI) values range from "0" (contact for infinite depth extent) to "3" (point dipole; Fitz Gerald et al. 2004). Using wrong values of the SI index leads to misleading depth calculation. A good structural

indice estimation of value is crucial for this method's success (Reid 1995) and leads to an Euler solution with a good grouping (Keating and Pilkington 2004).

Regional geology

In the northern African margin, Tunisia is a key region, both because it is located at the junction between the eastern and western Mediterranean domains and because it straddles the orogenic domain and the stable platform. The studied area is situated in Central Northern Tunisia, in Maktar region, which includes a lithostratigraphic succession started by Aptian series of the Serj formation. This facies was localized only on Balouta massif. Maktar area outcrops correspond to the upper Cretaceous and Eocene series. Oligocene formations are only found in the Oued Ousafa syncline. The Quaternary facies consists of conglomerate and alluvial deposits (Figs. 4 and 2). This area can be subdivided into six parallel structural zones (Fig. 2).

(1) Elles syncline structure corresponds to prey-syncline termination of Messouge syncline with nummilitic facies in its SE limb and a globigerines facies in its NW limb; (2) Siliana–Maktar anticline is composed of a series Santonian

layers. This dissymmetric structure is characterized by a lower dipping NW limb (10° to 20°), associated with higher dipping SE limb (50° to 70°); (3) Maktar anticline is characterized by priabonian clay associated with a Quaternary cover; (4) Oued Ousafa syncline shows a narrow structure widened by many NE–SW

fractures in a zone between El Ksour and Maktar–Kairouan road; (5) Balouta NE–SW anticline is characterized by a limestone–dolomite facies of the Serj formation. Its NW limb is altered by faulting; (6) Kessera syncline is essentially represented by lower Eocene nummulitic limestone.

Fig. 5 **a** Residual anomaly map of Maktar region (milli-Galileo). (1) Positive gravimetric axis. (2) Negative gravimetric axis. **b** Superposition of the gravimetric axis to the geological map of the study area

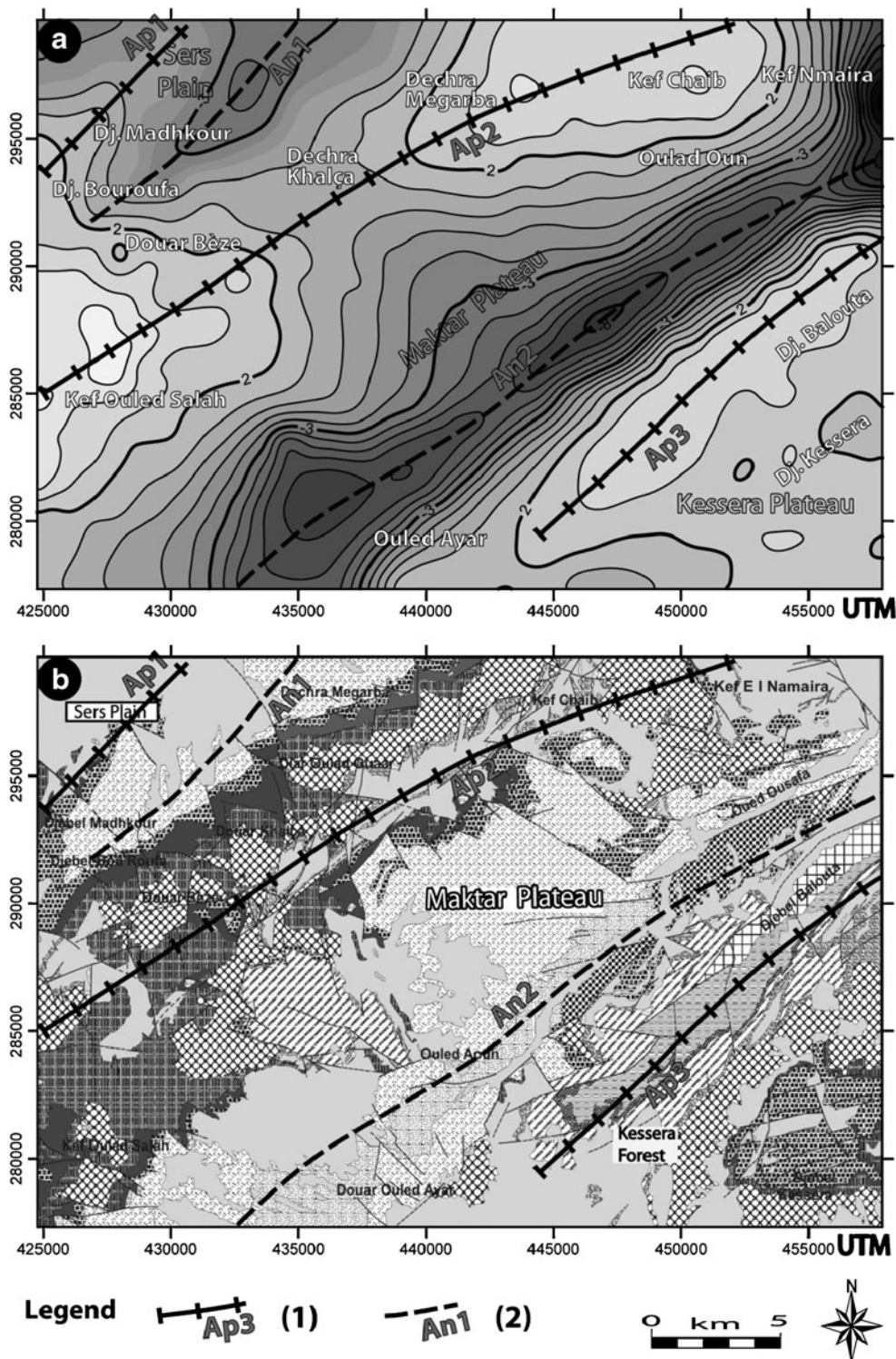


Fig. 6 Superposition of the horizontal gradient gravity map (gray background) to the maxima of the same gradient of the residual gravity map (1) and its upward continuations to different heights: 500 m (2), 1,000 m (3), and 2,000 m (4). (5) Dipping direction

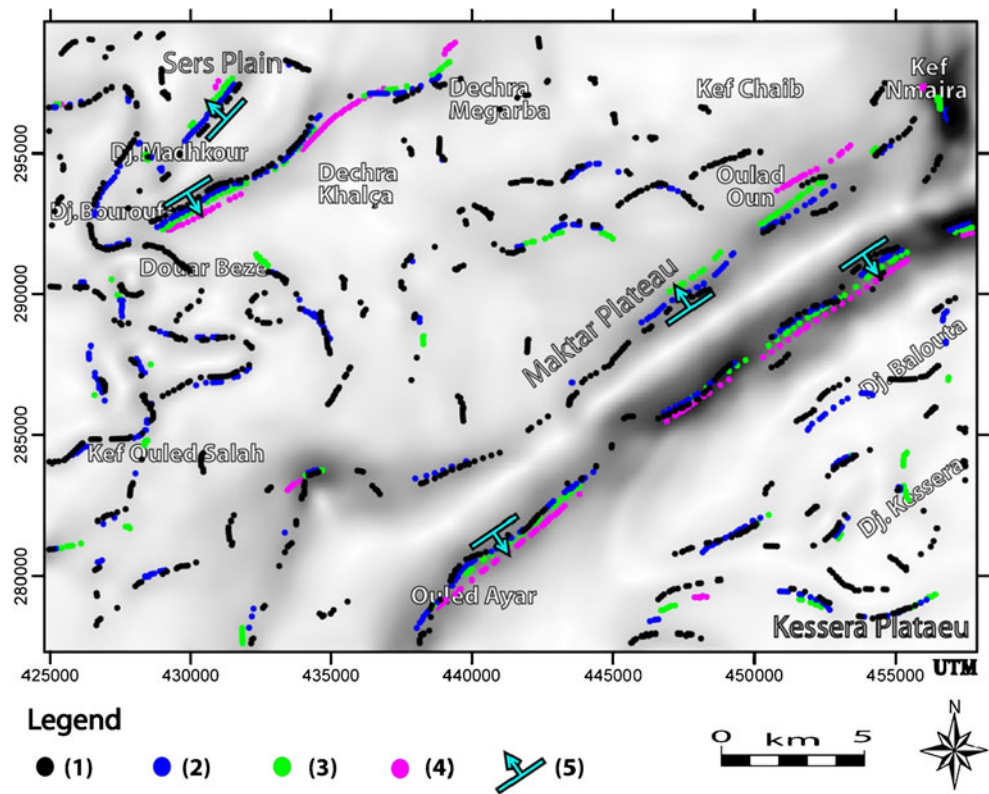
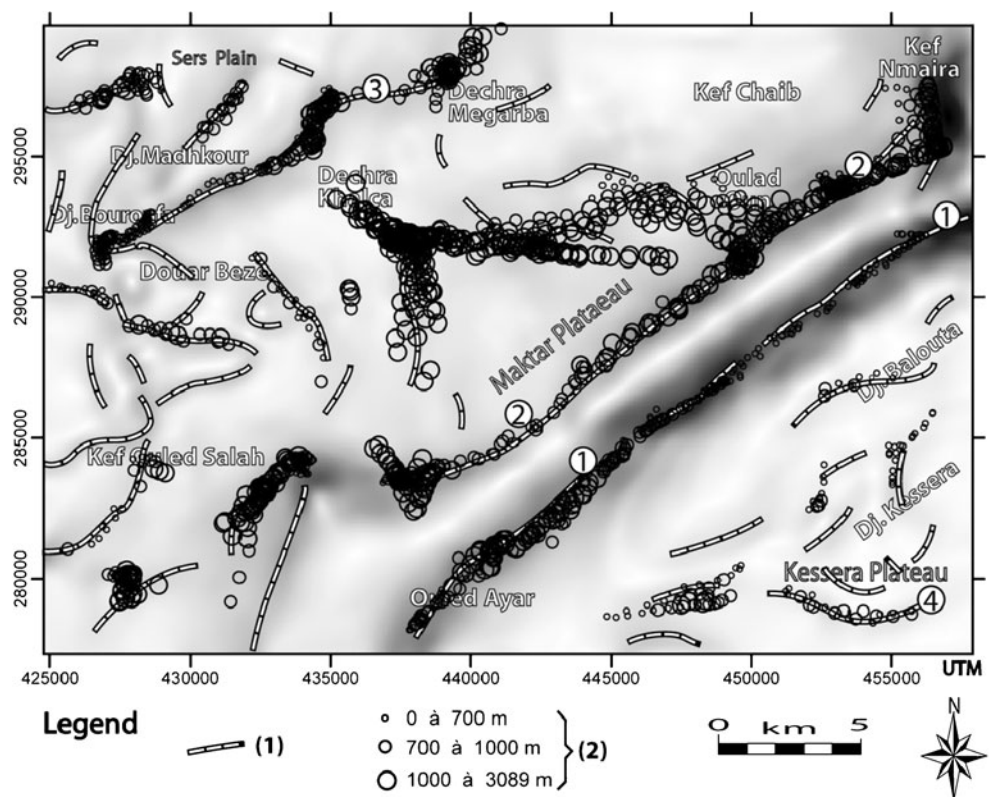


Fig. 7 Euler solutions computed for a structural index $IS=0$, a 10×10 moving window and a maximum relative error of 15%. (1) Horizontal gradient maxima. (2) Euler depth



Results

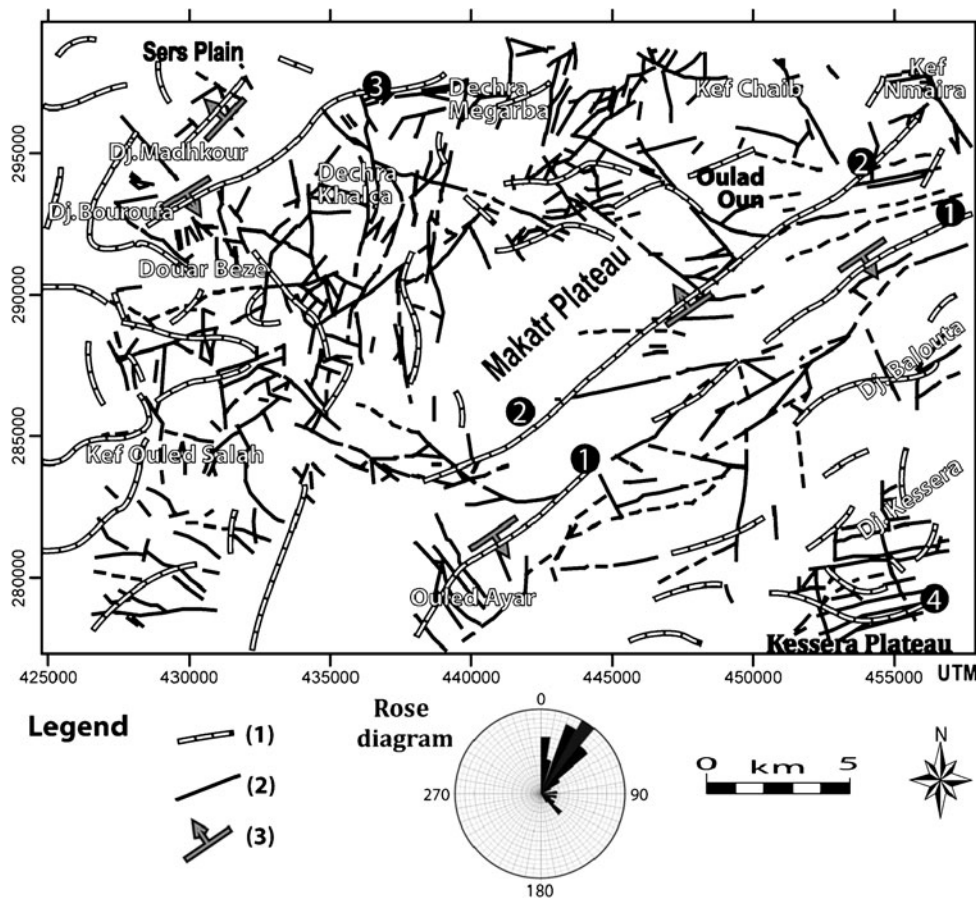
Residual anomaly map analysis of the studied area reveals several positive (PA 1 to PA 3) and negative (NA1 and NA2) gravity anomalies (Fig. 5a). These gravimetric anomalies are well correlated with geological and structural features (Fig. 5b). (PA1) positive anomaly, situated in the Western region, coincides with an Eocene series; (NA1) negative anomaly reflects a mass deficiency generated by clay and alluvial sedimentary Elles syncline series; (PA2), positive axis coincides with Siliana–Maktar anticline. These anomalies are characterized by a lower variation of the residual, which are explained by a sub-tabular Eocene cover feature that constitutes this plateau; (NA2) anomalies superposed to Neogene and Quaternary series of Oued Ousafa syncline. In the Eastern Maktar residual map, Balouta anticline massif is characterized by a NE–SW positive anomaly (PA3), which coincides with the high-density limestone and dolomite Aptian facies of the Serj formation.

Superposition of horizontal gradient maxima is computed from residual gravity map and its upward continuation at different altitudes allows us to highlight the different contacts and converging dips (Fig. 6). Statistical treatment of fault lineaments shows primary features in the NE–SW direction

with secondary features in other principle directions. Faults striking NE–SW correspond to structures tens of kilometers in scale crossing the Maktar geologic map with lengths greater than 50 km. These fault azimuths are well represented in Elles plain and Kessera syncline. NE–SW faults restrain the Oued Ousafa syncline and Balouta anticline Northwestern limbs. E–W, NS, and NW–SE directions are observed on various scales and their lengths are typically less than 20 km. E–W striking faults are situated in northern Maktar plateau and correspond to arched beams of faults limiting the southern Kessera plateau. N–S and NW–SW directions are scattered heterogeneously over the Maktar region.

Euler deconvolution was used to locate the source of anomalous structures. We proceeded by applying the structural indice (SI=0), a window of 10×10 and a relative maximum error of 15%. The Euler deconvolved features are shown in Fig. 7. The size of the circular symbols of the Euler solution is proportional to anomaly depth. These solutions are well grouped and correlated with various contact faults previously deduced from horizontal derivative maxima. From this analysis we can see their depth can reach 3,000 m. The deepest contacts are mainly directed along NE–SW azimuth in accordance with results obtained from the upward extension analysis.

Fig. 8 Structural map of Maktar area. (1) Major geological contacts inferred from gravity data interpretation. (2) Observed fault. (3) Dip vergence



Integration of gravimetric analysis results and interpreted faults permits us to draw a Maktar structural map. Further integration with classic structural studies results in (Fig. 8) and underlines the importance of using gravity data filtering for geological contacts mapping. The principal faults that affected the studied area are: (1) NE–SW fault limiting the Northwestern side of Oued Ousafa syncline. This fault corresponds to the west continuation of Zaghouna overlap. (2) NE–SW fault lining the Northwestern side of Balouta massif. (3) NE–SW fault bordered southern Elles syncline. (4) E–W directions correspond to an arched beam of faults limiting Kessera plateau and others are situated in northern Maktar plateau.

Discussion and conclusion

Results of this study show the importance of using various filtering and interpretation techniques in gravity data analysis. They also provide a spatial organization of major faults affecting Tunisian Atlas region, particularly the central Atlas. The main results are summarized the following principal points: There is a high correlation between gravity and geological data. The filtered operations define NW–SE, E–W NS, and NE–SW directions with predominance of the latter and their depth can reach 3,000 m.

The superposition of horizontal derivative maxima from residual anomaly map and from upward continuation at several heights up to 2,000 m shows alignments outlining contacts and indicates their vergence.

- The confirmed faults: (1) The fault limiting the northwestern side of Oued Ousafa syncline that represents the western prolongation of the Zaghouna thrust. (2) The fault restraining the Northwestern limb of Dj. Balouta anticline. This fault limits the NW limb of the Serj anticline.
- A newly determined fault: (1) NE–SW fault limiting the Northwestern Oued Ousafa syncline side reveals a NW deep and a SE vergence. It defines the west prolongation of Zaghouna scar. This fault delineates an emergent alpine chain and southern Tunisian tectonic margin. (2) NE–SW fault limiting the NW limb of the Balouta anticline structure shows a SE deep and a SE vergence. Its map trace is terminated in the Serj massif. (3) NE–SW fault borders southern Elles syncline part. (4) E–W arched beam of faults limiting Kessera plateau.

The application of Euler deconvolution determines anomaly source depth and spatial location. The source depth in the study region can reach 3,000 m. Deepest contacts are mainly directed along NE–SW direction in

accordance with results obtained from upward extension. This direction was expressed by northwestern faults limiting (1) Oued Ousafa syncline structure and (2) the Balouta anticline.

The elaborated structural map, integrates surface data with filtered gravimetric data results. This document highlights new structures, while confirming the existence of several faults, and finding their extension and their dip. This map could also be, a very useful document in hydrogeological and petroleum planning research over the study area.

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References

- Archibald N, Gow P, Bochetti F (1999) Multiscale edge analysis of potential field data. *Explor J Geophys* 30:38–44
- Ben Ayed, N. (1986). Evolution tectonique de l'avant-pays de la chaîne alpine de Tunisie du début du Mésozoïque à l'actuel. Thèse d'Etat, Université de Paris, Sud-centre d'Orsay
- Ben Ferjani A, Burolet PF, Mejeri F (1990) Petroleum geology of Tunisia. *Entreprise Tunisienne d'Activités Pétrolières*, Tunis
- Blakely RJ, Simpson RW (1986) Approximating edges of source bodies from magnetic or gravity anomalies. *J Geophysics* 51:1494–1499
- Bocchetti M, Cello G, Tortorici L (1990) First order kinematic element in Tunisia and Pelagian Block. *Tectonophysics* 176:215–228
- Boukadi N (1994) Structuration de l'Atlas de la Tunisie: signification géométrique et cinématique des nœuds et des zones d'interférences structurales au contact des grands couloirs tectoniques, *thèse d'Etat*. *Ann Mines Géol Tunis* 18(1956):1–350
- Bracène R, Bellahcène A, Bekkouche D, Mercier E, De Frizon Lamotte D (1998) The thin-skinned style of South Atlas front in Central Algeria. *Petroleum geology of North Africa*. *Geol Soc London Spec Pub* 133:391–400
- Burolet PF (1973) Importance des structures salifères dans la tectonique Tunisienne. *Livre Jubilaire M. Solignac*. *Ann Minn Et Géol n°26*:110–120, Tunis
- Chennouf T, Khattach D, Mlihi A, Andrieux P and Keting P (2004). Détermination de la structure du bassin de Triffa par interprétation conjointe des données gravimétriques et sismiques: Implications hydrogéologiques (résumé étendu). *Actes du 2e Colloque de géophysique appliquée*, pp.30–32
- Chihi, L. (1995). Les fossés néogènes à quaternaires de la Tunisie et de la mer pelagienne: Etude structurale et leur signification dans le cadre géodynamique de la méditerranée centrale. Thèse de Doctorat d'Université, Tunis. El Mannar II
- Cordell, L., and V.J.S. Grauch, (1982). Mapping basement magnetization zones from aeromagnetic data, The San Juan Basin, New Mexico, 52nd Ann. Int. Meet. Soc. Explor. Geophys, Dallas., pp. 246–247
- Debeglia, N., and C. Weber (1985). Geologic mapping of the basement of the Paris basin (France) by gravity and magnetic data interpretation. *The Utility of regional gravity and Magnetic Anomaly Maps*, SEG Publication, pp.154–163
- Dercourt J, Zenenshaain LP, Ricou LE, Kazmin VG, Le Pichon X, Knipper AC, Grandjaquet C, Ssbortchikov IM, Geysand J, Lepunier C, Westphal M, Bazhenov M, Lauer JP, Biju-Duval B

- (1978) Geological evolution of tethys from the atlantic to the Pamirs since the Lias. *Tectonophysics* 123:241–315
- Dlala M (2002) La tectonique distensive synsédimentaire d'âge campanien maâstrichtien en Tunisie: implication sur l'évolution géodynamique de la marge nord africaine. *Compte Rendus de l'Académie des Sciences, Paris* t 334:135–140
- El Euch H, Saidi M, Fourati L, El Mahessi C (2004) Northern Tunisia thrust belt: deformation models and hydrocarbon systems. *AAPG Hedberg Series* n° 1:371–390
- Everaerts M, Mansy JL (2001) Le filtrage des anomalies gravimétriques, une clé pour la compréhension des structures tectoniques du Boulonnais et de l'Artois (France). *Bull Soc Géol Fr* 172 (3):267–274
- Fitz Gerald D, Reid A, Mc Inerney P (2004) New discrimination techniques for Euler deconvolution. *Computers & Geosciences* 30:461–469
- Ghanmi M (2003) Géodynamique de la plateforme saharienne et sa marge septentrionale au Crétacé, son évolution vers l'Atlas septentrional, interférences du rifting et de l'halocinèse. *Université Tunis El Mannar II*, 347p
- Jauzein A (1959) Carte géologique no. 59 du Makar à 1:50 000
- Jauzein A (1967) Contribution à l'étude géologique des confins de la dorsale tunisienne (Tunisie-septentrionale). *Ann Mines Géol Tunisie* 22:475
- Keating BP (1998) Weighted Euler deconvolution of gravity data. *J Geophysics* 63:1595–1603
- Keating P, Pilkington M (2004) Euler deconvolution of the analytic signal and its application to magnetic interpretation. *Geophys Prospect* 52:165–182
- Khattach D, Mraoui H, Sbibih D, Chennouf T, Andrieux P, Milhi A (2004) Apport de la gravimétrie à l'étude de la structure du bassin de Triffa (Maroc nord-oriental): implications hydrogéologiques. *C R Geoscience* 336:1427–1432
- Khattach D, Mraoui H, Sbibih D, Chennouf T (2005) Analyse multi-échelle par ondelettes des contacts géologiques: application à la carte gravimétrique du Maroc nord-oriental. *C R Geoscience* 338:521–526
- Morgan, MA, Grocott, and TJ Moody (1998). The structural evolution of the Zaghoan-Ressas Structural Belt, northern Tunisia. In MACGREGODR, DS Moody, TJ & Clark-Ildwde, DD (eds) 1998. *Petroleum Geology of North Africa*. Geological Society, London. Special Publication No. 132.405–422
- Najine A, Jaffal M, ElKhammari K, Aifa T, Khattach D, Himi M, Casas A, Badrane S, Aqil H (2006) Contribution de la gravimétrie à l'étude de la structure du bassin de Tadla (Maroc): implications hydrogéologiques. *C R Geoscience* 338:676–682
- Reid, A (1995). Euler deconvolution: Past, present and future—A review. 65th SEG meeting, Houston, USA, Expanded Abstracts, 272–273
- Reid AB, Allsop JM, Granser H, Millett HAJ, Somerton IW (1990) Magnetic interpretation in three dimensions using Euler deconvolution. *J Geophys* 55:80–91
- Salaj J (1978) The geology of the pelagian block: the eastern Tunisian platform. *The Ocean Bassins and Margins*, vol 4B. Plenum Press, New York, pp 361–416
- Thompson DT (1982) EULDPATH—A technique for making computer-assisted depth estimates from magnetic data. *J Geophys* 47:31–37
- Turki M.M. (1975). Etude géologique du massif Serj-Bargou (Atlas Tunisein central) Thèse 3 ème cycle, Univ. Paris VI
- Turki MM (1980) La "Faille du Zaghouan" est la résultante des structures superposées (Atlas Tunisein central). *Bull Soc Géol Fr* (7) t XXII 3:321–325
- Turki MM (1988) Polycinématique et contrôle sédimentaire associée sur la cicatrice Zaghouan- Nebhana. *Mémoire*, Vol. 7, Centre des sciences de la terre. Institut National de Recherche Scientifique et Technique- Tunisie
- Zargouni F, Abbes C (1985) The structural zonation of Tunisia. *European Foundation*, Strasbourg, pp 249–253