

Structural and geodynamic study in central Tunisia using field and geophysical data: new structural interpretation of the N–S axis and associated Atlassic structures

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Abstract A structural and geodynamic evolution of central Tunisia is constructed from field studies and geophysical data within the Tunisian Atlassic domain. Bouguer gravity and horizontal gradient magnitude (HGM) maps indicate that computed anomalies are related to subsurface structures and are in accordance with the general structural trends of central Tunisia. Near Cherichira fault, the strike is ENE–WSW, whereas it is N–S along the N–S axis, a major discontinuity between the Pelagian shelf to the east and Central Atlas Mountains to the west. E–W-oriented HGM profiles on the north side of the Cherichira fault show moderate HGM variations, which correspond to the NE–SW fault system of the Ousselet–Bou Dabous. This trend is also expressed by the second-order vertical derivative map of this area. However, on the south side of the fault, a dominant peak is indicated rather than the anomalies characteristic of the north side of the fault. This anomaly is associated with the N–S axis discontinuity. Seismic reflection data are also used to elucidate the structural configuration and style north and south of the Cherichira fault. The seismic lines demonstrate that

faulting and associate halokinesis in Ousselet–Bou Dabous area are not comparable to the paleogeographic fault system of the N–S axis southward. To the south of Cherichira fault, the seismic lines show massive Triassic evaporates piercing along the major paleogeographic faults associated with thickness variations of Mesozoic and Cenozoic stratigraphic units and a reverse slip of western structural elements. It seems that the N–S axis corresponds to a steeply dipping major zone of weakness in the Tunisian Atlassic Mountains and indicates evidence of several stages of activity, including the rise of Triassic evaporates rise up which outcrop at several localities such as Rheouis and Mezzouna. The loading and upward rise of Triassic evaporites along this weak zone are a key factor in the thinning of the Mesozoic–Cenozoic sedimentary cover along this paleogeographic discontinuity. These new data indicate the northeast extrapolation of fold and grabens of the Central Atlas of Tunisia to the northeast of Kairouan, whereas the northern extent of the N–S axis is limited to south of the Cherichira fault. The Cherichira fault is NE–SW oriented and parallels the Ballouta–Zaghuan fault system, which reflects the regional strike of the Tellian orogeny and the associated nappes to the north. The geometry and kinematics of these Tellian features are linked to the tectonic evolution of the northern African margin, including Mesozoic extension separating the African and European plates to the inversion of these structures since the Late Cretaceous. The N–S axis is correlated in its direction and tectonic framework to the strike-slip fault system of the African craton, which is present to the south in the Algerian Saharan domain of Hoggar.

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Introduction

The complex structural pattern of Tunisia is attributed to major Mesozoic–Cenozoic orogenies recognized at the North African plate margin scale. In the Saharan platform in southern Tunisia, the Pan-African orogeny is well recorded through inherited deep faults network, N–S-trending folds and metamorphism affecting the Precambrian series (Burolet 1956; Fabre 1976; Jauzein and Perthuisot 1985; Abbes 2004). Subsequent major orogenic events include a Mesozoic extensional phase and a Cenozoic shortening phase that reactivated preexisting structures and led to generalized tectonic inversion of the preceding Mesozoic extensional structures (Boukadi et al. 1992; Morgan et al. 1992; Brunet and Cloetingh 2003; Masrouhi et al. 2008; Dhahri and Boukadi 2010). Reconstruction of the kinematic/tectonic evolution of Tunisia from the present-day structures and basin distribution reveal an early multi-stage tectonic heritage (Boukadi 1994; Bouaziz et al. 2002; Dhahri and Boukadi 2010). The tectonic inheritance controlled subsequent deposition and kinematic responses of structures to the Neogene shortening events.

In fact, the Tunisian chain constitutes the eastern extend of the Maghrebic orogenic belt which comprises the Tell–Rif interpreted as an Alpine-type orogen resulting from the closure of the Maghrebic Tethys (Bouillin 1986) and the Atlas systems regarded as an intra-continental active fold-thrust belt (Frizon de Lamotte et al. 2006; Roure et al. 2012). The Saharan Atlas extends between the Tellian thrust front in the north and the South Atlasic front in the south (Fig. 1) (Guiraud 1998; Vially et al. 1994; Frizon de Lamotte et al. 2006; Bracène and Frizon de Lamotte 2002; Benaouali-Mebarek et al. 2006). To the south of the South Atlasic front, the African craton seems to be stable and makes up the deep basement of the Algerian Saharan domain of Hoggar.

Structural interpretations of Tunisia began during the twentieth century with Pervinquière (1903) and Burolet (1956) followed by several studies which divide the Tunisian realm into several structural domains exclusively based on morpho-structural aspects. Figure 1 displays these different domains: (1) The intensely deformed Tellian domain in northwest Tunisia is composed of the allochthonous Tellian flysch nappes constituting the eastern extension of the Algerian Tellian Atlas. This domain is limited by the ENE-trending Tellian thrust front to the south. To the southeast, thrust features occur with a progressive decrease in the intensity of thrusting and are bordered by the Tebousouk fault (Perthuisot 1978; Burolet 1973). The amount of displacement to the southeast of the allochthonous nappes is still controversial. (2) The Tunisian Atlas is the eastern extension of the Algerian Saharan Atlas (Fig. 1). It is limited by the Tellian domain to the north and the Saharan flexure (also called

South Atlasic front) to the south; it shows NE–SW-oriented anticlines separated by large synclines and NW–SE to E–W-trending grabens (Dlala 1984, 1995; Dlala and Rebai 1994; Boukadi 1994; Ben Ayed 1986; Chihi 1995). This domain is conventionally divided into northern, central and southern Atlas. (3) The Pelagian shelf or Pelagian platform located to the east of the N–S axis of Tunisia (a major domain-bounding thrust fault) and the Zaghuan thrust. This domain extends to the east to the Pelagian Block (Fig. 1) and encloses subsurface structures recording Cretaceous to Quaternary deformations (Haller 1983; Touati 1985; Gabtni 2005). (4) The Tunisian Saharan platform constitutes the domain situated to the south of the SW-trending South Atlasic front and is part of the African craton (Fig. 1). It is tectonically stable compared to the northern domains and adjoining the Algerian stable Saharan Platform (Busson 1967; Haller 1983; Ellouz 1984; Gabtni et al. 2005).

The N–S axis is a north-trending mountain range separating the central Atlas with the NE–SW Atlasic folded structures to the west from the Pelagian shelf to the east. According to previous literature, this axis extends from the Gulf of Tunis to the north, to the Gulf of Gabes to the south and constitutes a paleogeographic complex structure of the Alpine orogeny (Burolet 1956; Ouali 1984; Abbes and Boukadi 1988; Boukadi 1994; Rabhi 1999; Abbes 2004).

In this work, we perform gravity and seismic reflection analysis to determine the deep structures and the geodynamic character of the N–S axis in the building of the central Tunisian Atlas. The regional gravity and seismic reflection data used for this study were obtained from the Entreprise Tunisienne d'Activités Pétrolières (ETAP) after geophysical surveys performed by petroleum companies. New gravity terrestrial stations were obtained from the Office national des Mines (ONM). Some petroleum well reports are also consulted to correlate seismic data to the regional geological cross section.

This paper focuses on the central Tunisian Atlas matching mostly the paleogeographic domain known as the “Central Tunisia Island” that has been emerging since the Late Cretaceous to the southwest of Kairouan area located in the Pelagian Shelf (Fig. 1) (Burolet 1956; M'rabet 1981; Marie et al. 1984). We investigate its relations with the adjoining structural domains especially these located between Kairouan and the Ballouta–Zaghuan thrust. In this area, the trend of the folded structures is intermediate between the NE–SW Atlasic direction and the N–S direction of the N–S axis in the south. In that, these structures are positioned north of the N–S axis, *sensu stricto* and south of the Zaghuan thrust makes them important in understanding the junction between the two main paleogeographic structural trends (NE–SW to the north and N–S to the south). The fundamental question is: For which structural domain can the structures northwest of Kairouan be attributed?



Fig. 1 Simplified structural sketch of the eastern Maghrebian area showing the deformed Atlasic domain to the north of the South Atlasic front, the African Craton to the south with the Hoggar fault system and the location of the study area. Tunisian features are especially delineated

Geological setting

The study area is located in the northeastern part of the paleogeographic domain “Central Tunisia Island” (Buroillet 1956; M’rabet 1981; Marie et al. 1984). It comprises NE–SW-oriented anticline structures separated by large syncline basins and lowlands occupied by Tertiary–Quaternary

sediments (Figs. 2, 3). These structures record normal faulting during the Upper Cretaceous that is subsequently inverted during the Cenozoic shortening by the Atlas orogeny (Dahri 2009; Masrouhi et al. 2008; Dahri and Boukadi 2007, 2010; Roure et al. 2012). To the north of the study area, structures are stacked against the “Tunisian Dorsale” trending almost N060 and extending southwest

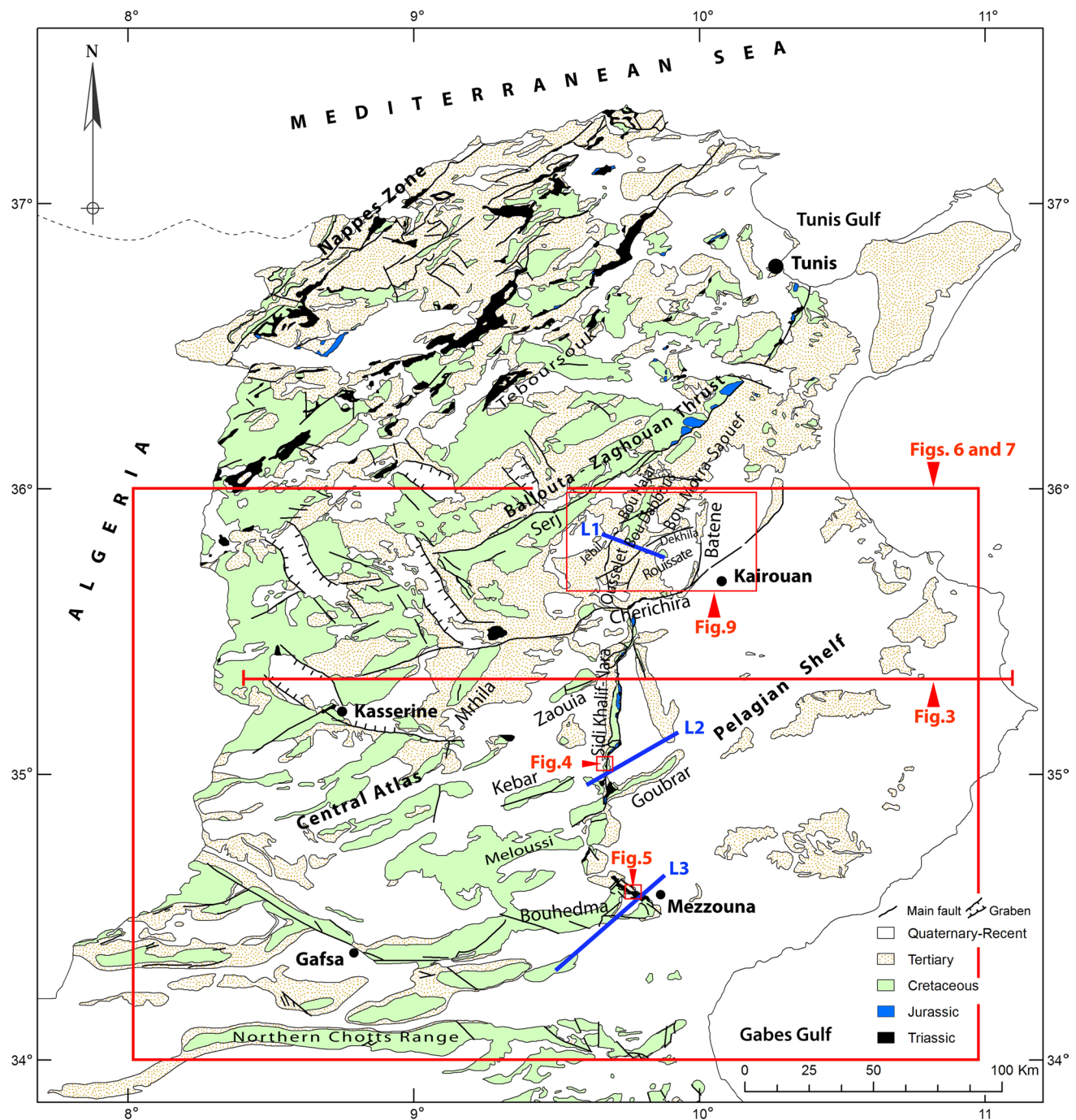


Fig. 2 Simplified geological map of north-central Tunisia with location of main studied structural features, seismic profile of Fig. 11, gravity data of Figs. 6 and 9, cross section of Fig. 3 and the locations of Figs. 4 and 5

to the Tebessa highlands in Algeria (Fig. 1). About 50 km southward, the study area is affected by the main paleogeographic fault system of Mrhila–Cherichira parallel to the “Tunisian Dorsale” and intersecting the N–S axis at the Cherichira structure level.

Folded structures mainly consist of Triassic to Neogene rocks. The stratigraphy is characterized by incompetent

levels such as argillaceous and marly rocks alternating with competent levels such as limestone. The outcropping stratigraphic succession comprises the evaporitic Triassic rocks (Rheouis formation), the Nara formation Jurassic in age and composed of two carbonate members separated by an irregular marly and oolitic middle member (Burolet 1956). The Neocomian series are composed of the open

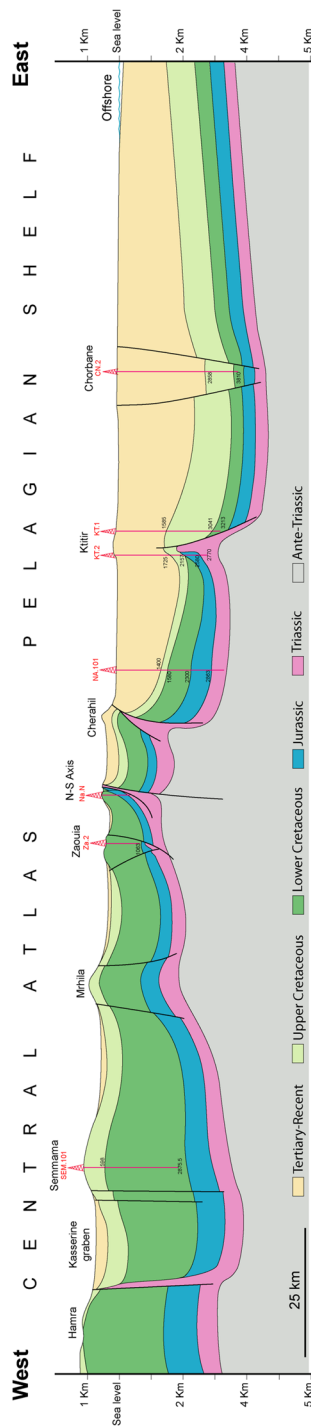


Fig. 3 E–W-oriented regional geological cross section across central Tunisia calibrated with available petroleum wells (in red). This section shows especially the main structural features of the central Atlas to the west and of the Pelagian Shelf to the east, and the inversion of subsidence since the Late Cretaceous: Ante-Upper Cretaceous series are thicker to the west of the N–S axis (in the Central Atlas basin), but Upper Cretaceous–Neogene series are clearly thicker to the east (in the Pelagian Shelf basin)

marine shaly Sidi Khalif formation and the deltaic regressive detritic body of Meloussi and Boudinar formations (M'rabet 1987). From Late Hauterivian to Late Aptian, transgressive depositions occur and give three formations: the Bou Hedma formation with transgressive composite lithology, the sandy Sidi Aich formation and the carbonated Orbata formation (Buroillet 1956; M'rabet et al. 1995). The Cenomanian–Turonian series are composed of two dolomitic members separated by clay and gypsum middle member and acknowledged as the Zebbag formation that overlay unconformably the Orbata formation in central Tunisia (Buroillet 1956). The marly Aleg formation, Santonian in age and contains micritic carbonate layers, the Abiod formation, Campanian–Maastrichtian in age is composed of two limestone members separated by an intermediate marly member. The Haria formation, Paleocene in age is composed of green marls with intercalations of carbonate layers. The Eocene series are made of the Ypresian limestones with two corresponding facies; the Nummulitic Garia formation and the bioclastic and Globigerina Bou Dabbous formation, and the Souar formation, Lutetian–Priabonian in age, composed of chalky deposition with a condensed lumachellic level (Castany 1951; Buroillet 1956). The Mio-Plio-Quaternary deposition constitutes a mixture of detritic and siliciclastic sediment facies and occupies lowlands and synclinal basins (Buroillet 1956). Triassic evaporate outcrops are commonly associated with major faults such as the N–S axis, Mrhila–Cherichira fault, Zaghuan thrust and Bou Dabbous fault (Dhahri and Boukadi 2007, 2010). Some thickness variations are stated for several series in many subsiding basins: The northern blocks of the Mrhila–Cherichira and Ballouta–Zaghuan faults subsided during the Upper Cretaceous (Boukadi et al. 1992; Zghal et al. 1998; Haji et al. 2013), and the area east of the N–S axis constituted a subsiding basin during the Neogene (Fig. 3) (Haller 1983; Ellouz 1984; Touati 1985; Rabhi 1999; Gabtni 2005). Other restricted subsided basins are described in the graben structures such as the one of Ousselet–Bou Dabbous (Dhahri 2009; Dhahri and Boukadi 2007, 2011). In addition, some thickness variations are documented around paleohighs such as the central Tunisia and the Serj and Rouissate anticlinal highs.

The Zaghuan thrust is a major regional fault, which occurs in the northern part of the study area (Fig. 2). This regional fault was fundamental in controlling deformation and deposition distribution since Mesozoic time. Petroleum wells drilled on both sides of the Ballouta fault which constitute the southwestern extend of the Zaghuan thrust (Fig. 2) show that the subsidence of the Cretaceous series is clearly increased to the north due to the normal slip of its northwestern block and show mainly open marine facies. This can be explained by the subsidence of the northwestern blocks of Ballouta fault system during the Cretaceous

extensional phase (Dhahri and Boukadi 2010; Haji et al. 2013). However, this fault was thrust to the southeast during the Neogene leading to the outcropping of the Jurassic series (Morgan et al. 1992). The Mrhila–Cherichira fault evolved in similar fashion to the Ballouta fault during the Cretaceous time. This fault is characterized by a subsided block to the northwest and a shallow marine domain to the southeast with successive marine regression episodes subsequent to the emersion of central Tunisia. These structural–stratigraphic relationships are responsible for many unconformities and partial erosion of various series (Marco et al. 2014).

The domain between the Zaghouan thrust and the Mrhila–Cherichira fault system is affected by N10–20-oriented faults that cut longitudinally the Ousselet–Bou Dabbous–Bou Hajar structures. These faults have a significant role in the structural evolution of this area (Abbes et al. 1981; Boukadi et al. 1992; Dhahri and Boukadi 2007, 2010; Dhahri 2009). Based on the present-day morpho-structural disruption of structures, the impact of the NE–SW-oriented faults seems to be more important in this area despite their slight expression in the field (Dhahri 2009; Dhahri and Boukadi 2007, 2010).

Field and geophysical data

Tectonosedimentary records

In the study area, Triassic rocks outcrop along main faults such as the N–S axis (Mezzouna, Rhouis, Faïd), the faults of Mrhila–Cherichira, Bou Dabbous and the Zaghouan thrust (Ouali 1984; Boukadi 1985, 1994; Boukadi and Bédir 1996; Abbes 2004; Dhahri 2009; Dhahri and Boukadi 2007, 2010).

The geological cross section of jebel Faïd (Fig. 4) highlights at least three Cretaceous unconformities with different amplitude gaps, respectively, between the formations of Meloussi–Zebbag, Zebbag–Aleg and Aleg–Abiod. These unconformities testify the instability of the basin floor in this area during the Cretaceous times. The layers thickness variations argue for a general slope to the west. Given that the tectonic regime acknowledged for this period is extensional (Boukadi et al. 1992; Boukadi 1994; Boukadi and Bédir 1996; Piqué et al. 1998; Brunet and Cloetingh 2003; Dhahri and Boukadi 2010), and the slope can be explained by a differential load of Triassic evaporites in this area along the N–S fault. Within the tectonic inversion, Triassic evaporites act as a décollement level for thrusts and facilitated the east-directed thrusts along the N–S axis (Fig. 3).

The geological cross section of jebel Kohl, northwestern Mezzouna (Fig. 5), shows that the western and the eastern contact between Triassic and Upper Cretaceous rocks are

subvertical. These contact exhibit striations, schistosity planes, polygenetic breccias and mineralization (Fig. 5) especially galena in the eastern contact which show relics of former mining activities. The emplacement of Triassic rocks in Mezzouna area (Fig. 2) occurred during local extension. The segment of fault between Meknassy and Mezzouna is NW–SE oriented, and it evolved into pull-apart basin subsequently to NW–SE Eocene contraction leading to the relative sinistral slip of the N–S-oriented segments of the N–S axis (Boukadi 1985) (Fig. 12). Once Triassic evaporites reach the surface, they can continue to rise by passive salt extrusion all along this NW–SE pull-apart basin.

Jurassic series outcrop especially along the Zaghouan thrust and the N–S axis (Sidi Khalif Nara) (Fig. 2). Cretaceous and Neogene rocks show lateral variations of thickness and facies, illustrating significant subsidence to the northwest of the Zaghouan and Mrhila–Cherichira along mainly NE–SW-trending faults and to the west of the N–S axis. Cretaceous to Neogene rocks also dip to the northeast, toward the basin floor, with Cretaceous deposition much thicker to the north of the Mrhila–Cherichira fault than at its southern uplifted block (Buroillet 1956; M'rabet 1981; Marie et al. 1984). It is notable that some basins are inverted subsequent to the Cenozoic tectonic inversion of the Tunisian domain, including the Pelagian basin east of the N–S axis (Dhahri 2009; Masrouhi et al. 2008; Dhahri and Boukadi 2007, 2010; Roure et al. 2012). Thick Neogene deposition covers earliest deformations especially in the Pelagian Shelf (Fig. 3) (Haller 1983; Touati 1985; Gabtni 2005) and to the east of the Ousselet–Bou Dabbous–Bou Hajar structures (Dhahri 2009; Dhahri and Boukadi 2007, 2010).

In the study area, paleogeographic faults of the N–S axis, Zaghouan and Mrhila–Cherichira are well developed. In addition, the expression of NE–SW-trending faults is notable between the Zaghouan and Mrhila–Cherichira faults (Fig. 2). These faults accommodate the thrusting and right-lateral strike-slip subsequent to the Miocene NW–SE contraction. In particular, the ENE–WSW dextral strike-slip affects the limestone of the Bou Dabbous formation in the Bou Morra–Saouef syncline and the northern Bou Hajar anticline (Dhahri 2009; Dhahri and Boukadi 2007, 2010).

Around the Ousselet–Bou Dabbous–Bou Hajar area, folded structures trend alternatively between the NE–SW and N–S directions. However, the faulting seems to be dominated by NE–SW strikes. In this area, it is apparent that the N–S-trending faults are influenced by the right-lateral motion on NE–SW faults. In addition to the Bou Hajar–Nebhana strike-slip, two other major NE–SW-striking faults are well expressed. (1) The Triassic evaporites outcrop along the NE–SW-striking fault of Bou Dabbous pointing out that NE–SW faults constitute an early

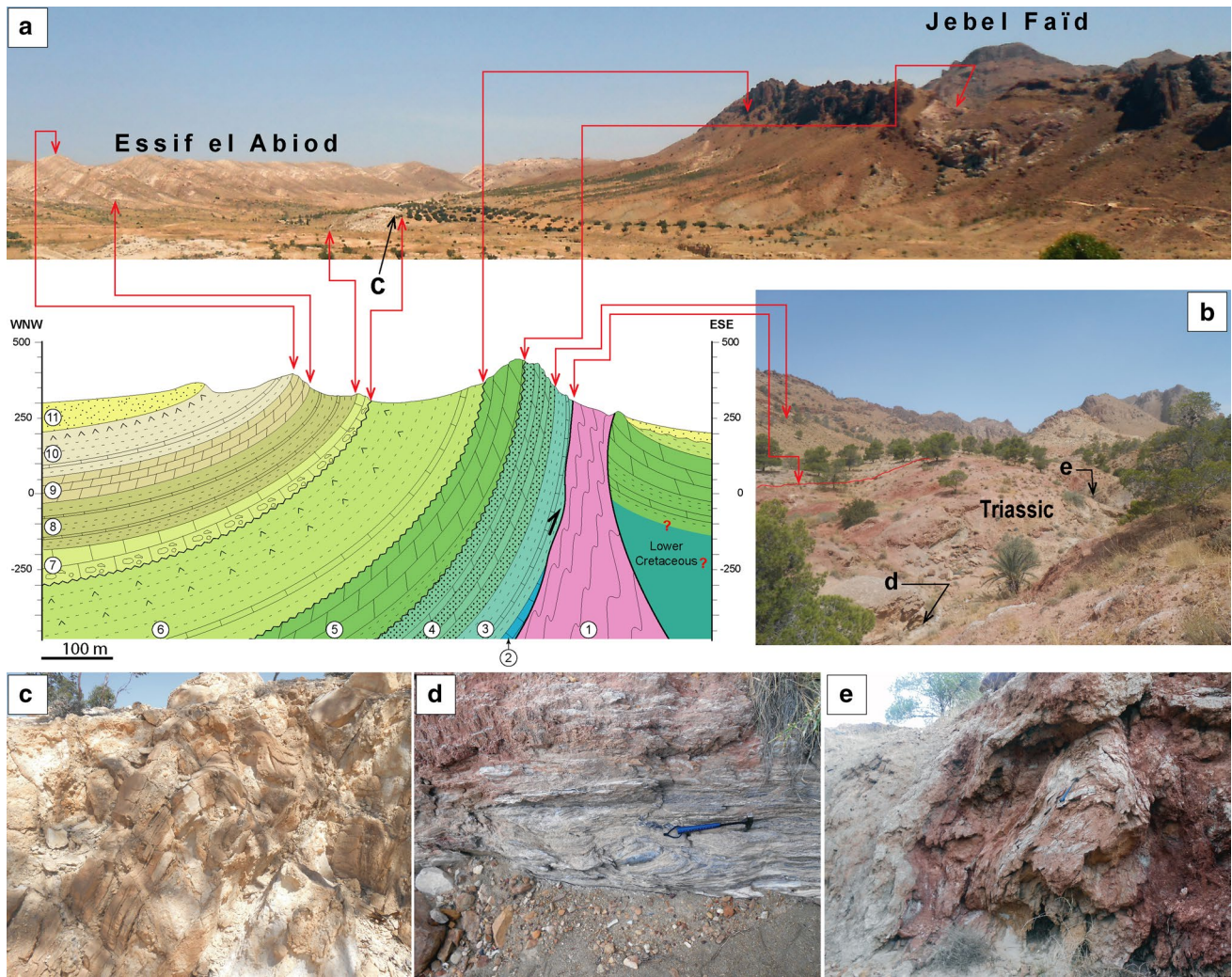


Fig. 4 WNW–ESE-striking geological cross section and field photographs of the jebel Faïd (see Fig. 2 for location). (1) Triassic evaporites, (2) Nara formation, (3) Sidi Khalif formation, (4) Meloussi formation, (5) Zebbag, (6) Aleg Formation, (7) Abiod formation, (8) Haria formation, (9) Lower Eocene, (10) Upper Eocene, (11) Mio-Plio-Quaternary, **a** panoramic view (looking to the north) of the

southern part of jebel Faïd, **b** Triassic red siltstones and gypsum rocks eastern jebel Faïd, **c** synsedimentary deformation within the carbonates of the Abiod formation, **d** 010/70 W dipping Triassic gypsum strata within the eastern trace of the Triassic outcrop, **e** well-preserved metric slump within the Triassic rocks

large-scale fault system in this area. (2) The Ousselet fault affects a series of structures about 30 km long, from the Jebil anticline, in the west, to the Dekhila structure in the east.

Gravity data

The regional gravity data used for this study were obtained from the ETAP after geophysical surveys performed by petroleum companies. All the data were merged and reduced using the 1967 International Gravity Formula. The free air and the Bouguer gravity corrections were made using sea level as a datum and 2.67 g/cm³ as a reduction density. The Bouguer gravity anomaly data were gridded at

2-km spacing and contoured to generate a Bouguer gravity anomaly map (Fig. 6).

The Bouguer gravity map established for central Tunisia (Fig. 6) shows that the isolines of the anomalies are in accordance with the general geologic lineaments of central Tunisia. The Bouguer anomalies correlate with subsurface structures; i.e., they follow the main N–S trend along the N–S axis and an ENE–WSW trend near Cherichira fault. A gravity low with a magnitude reaching –90 mGal is observed in the Central Atlas. This is due to the thinning of the Cretaceous–Neogene series caused by the emersion of central Tunisia during the Late Cretaceous (Buroillet 1956; M’rabet 1981; Marie et al. 1984; Marco et al. 2014). Anomaly values calculated for the domain located northwest of

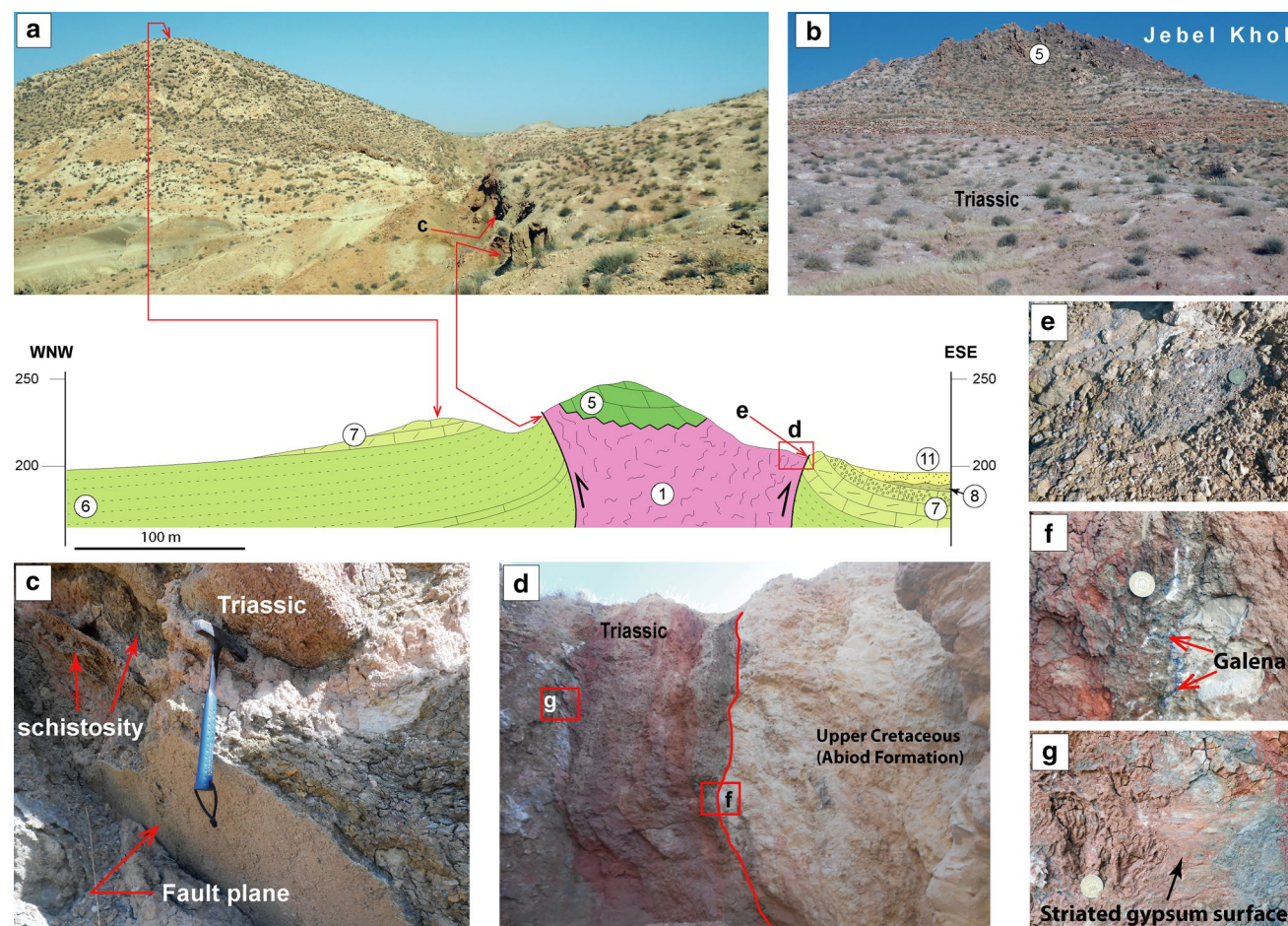


Fig. 5 WNW–ESE-striking geological cross section and field photographs of the Jebel Khol [see Fig. 2 for location]. 1, 5–8 and 11] same as in Fig. 4, **a** subvertical contact of Triassic and Upper Cretaceous rocks to the west of Jebel Khol, **b** relics of the perched syncline of Jebel Khol, **c** detail of the contact of Triassic and Upper Cretaceous rocks to the west of Jebel Khol showing the subvertical fault plane

and associated schistosity features, **d** subvertical contact of Triassic and Upper Cretaceous rocks to the east of Jebel Khol, **e** polygenetic breccias within the eastern contact of Triassic and Upper Cretaceous rocks, **f** galena mineralization associated within the Triassic and Upper Cretaceous contact, **g** striated gypsum plane indicative of tectonic contact

Kairouan are comparable to these of the west of the N–S axis sensu stricto. They show a NW–SE trend between Cherichira and Ousselet structures, whereas the N–S trend is located to the northwest of Kairouan (near Batene structure), which can be interpreted as an extension of the N–S axis. At the Tunisian country scale, the Bouguer gravity anomaly map published by Jallouli and Mickus (2000) shows a -25 to -30 mGal anomaly along the N–S axis, with strong gradients and N–S oriented. The southwestern part of this map (thereabouts limited by the -60 mGal isograms) match with the “Central Tunisia Island”.

In addition, we established the horizontal gradient magnitude (HGM) map for the study area (Fig. 7), which is a technique that has been used by Cordell (1979) to locate near vertical geological boundaries. The HGM tends to have its maxima located over edges of gravity sources corresponding to an abrupt change of density. The HGM is

calculated using north–south and east–west directional derivations using the following formula: $HGM(x, y) = [(\delta G(x, y)/\delta x)^2 + (\delta G(x, y)/\delta y)^2]^{1/2}$, where $G(x, y)$ is the gravity field anomaly value. The HGM map computed for the study area (Fig. 7) shows essentially N–S lineaments, which can be explained by a major discontinuities between two different domains; the Pelagian Shelf to the east and the Central Atlas to the west (Figs. 2, 3). Moreover, we note that the high value of HGM (3 mGal/km) observed to the north of Cherichira is disconnected from these observed along the N–S axis (Fig. 7). This confirms that the N–S axis sensu stricto do not extend to the north of Cherichira.

Two E–W-oriented HGM profiles (Fig. 8) were established to show the lateral variation of the horizontal gradient magnitude of Bouguer anomalies, respectively, to the north and to the south of Cherichira. The profiles illustrate a clear difference between the HGM variations on both side

Fig. 6 Bouguer gravity anomaly map of central Tunisia showing the N–S axis to the south of Cherichira making a limit between the Central Atlas to the west and Pelagian Shelf to the east (see Fig. 2 for location)

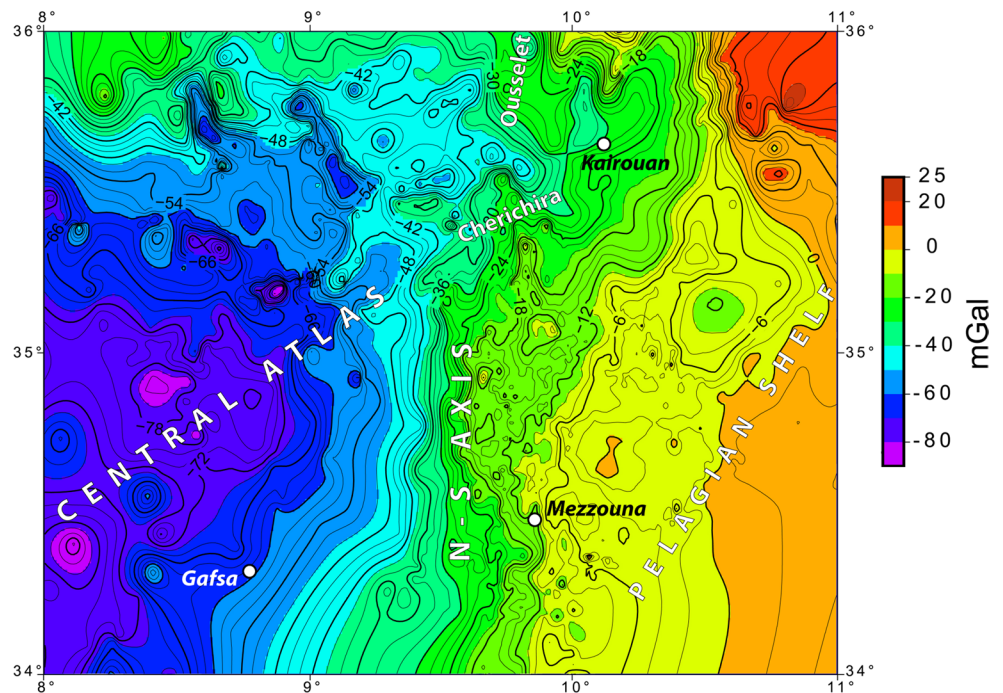
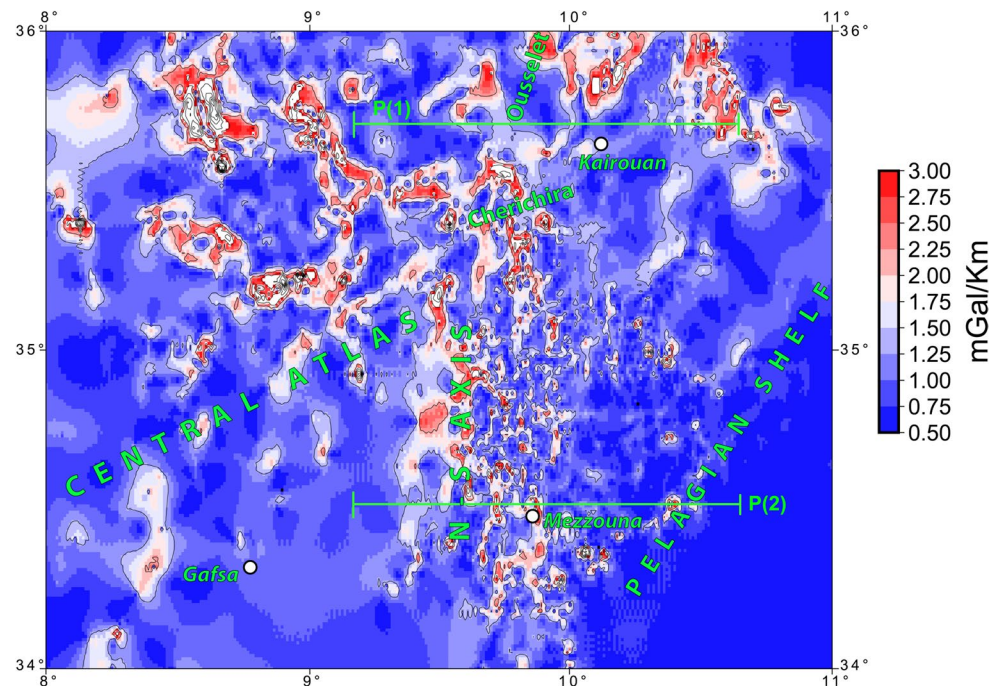


Fig. 7 Horizontal gradient magnitude of Bouguer anomalies (see Fig. 2 for location). **P(1), P(2)** Horizontal gradient magnitude profiles of Fig. 8



of Cherichira fault; P(1) shows moderate HGM variations which correspond to the NE–SW fault system of the Ousselet–Bou Dabbous, but P(2) highlights one dominant peak which is more important than these of P(1) and interpreted as the N–S axis discontinuity.

For more detailed investigation, we focus on the Ousselet–Bou Dabbous area where new gravity data (1492 gravity terrestrial stations) are analyzed (Fig. 9). These

data were obtained from the ONM. All data were merged and reduced using the 1967 International Gravity formula (Morelli 1976). The free air and the Bouguer gravity corrections were made using sea level as a datum and 2.40 g/cm³ as a reduction density. The choice of this reduction density is supported by 20 density measurements related to rocks samples of the surrounding outcrops.

Fig. 8 E–W-oriented profiles showing the lateral variation of the horizontal gradient magnitude of Bouguer anomalies (see Fig. 7 for location)

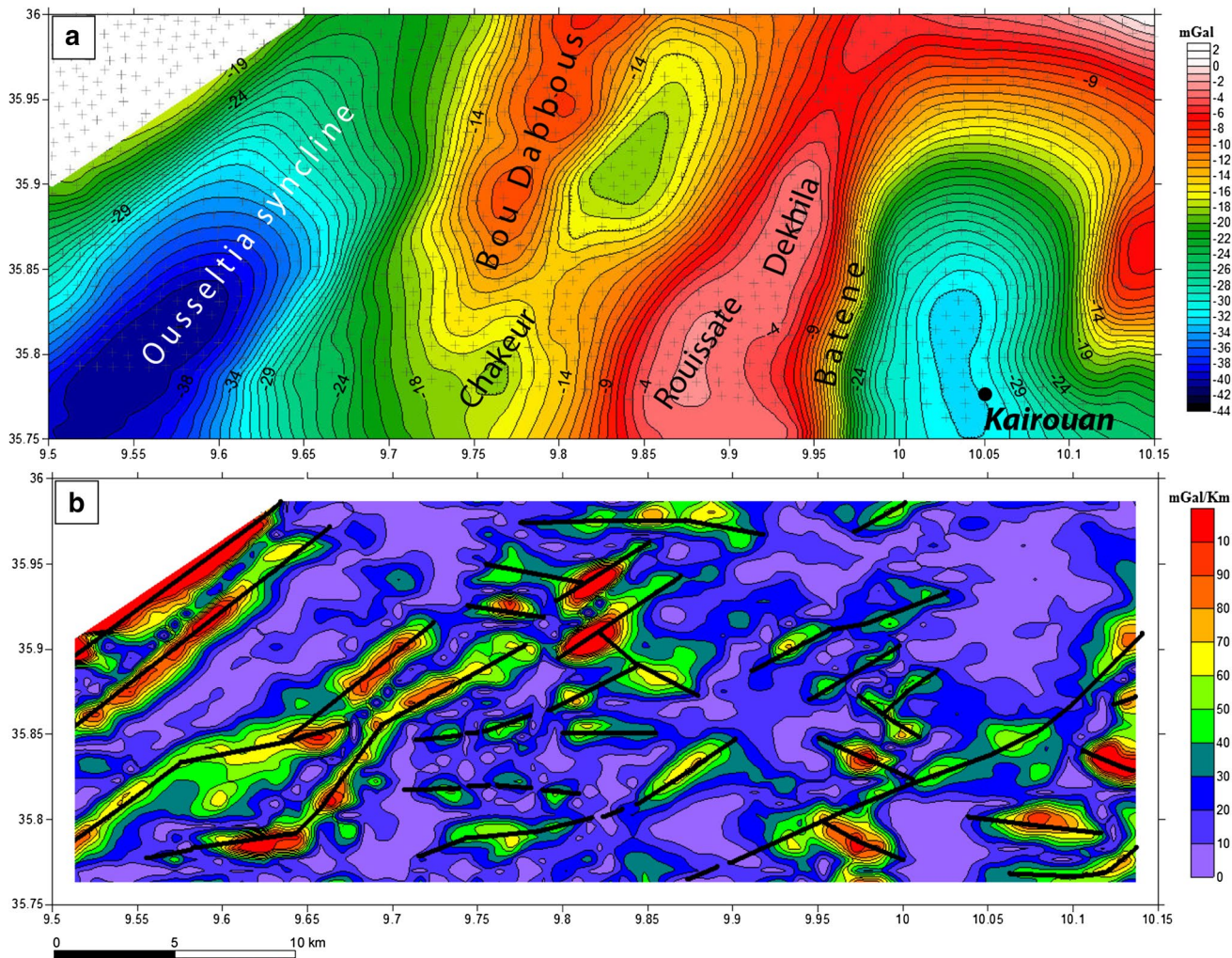
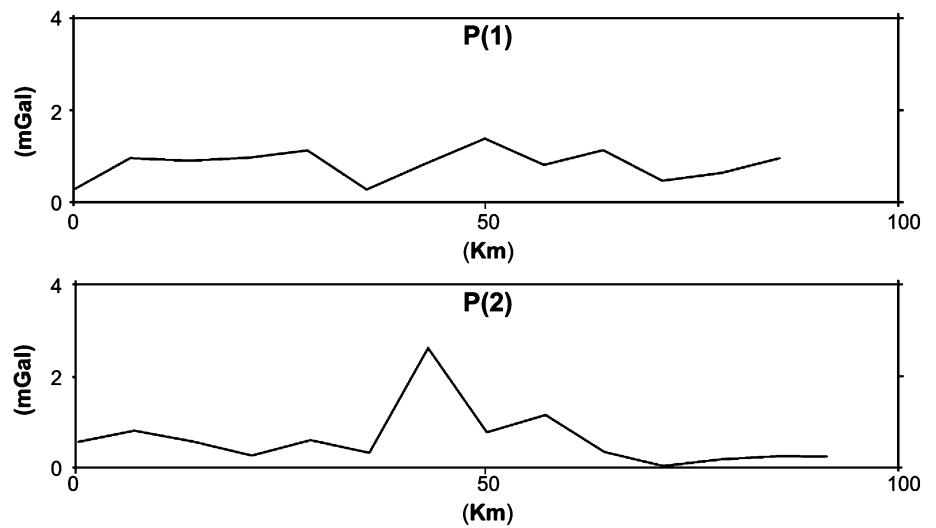


Fig. 9 **a** Bouguer gravity anomaly and **b** interpretation of the second-order derivative of Bouguer anomaly of Ousselet–Bou Dabbous area (see Fig. 2 for location)

Gravity data were gridded at 1-km spacing and contoured to produce a Bouguer gravity anomaly map (Fig. 9a). This map shows an amplitude variation between -44 and $+2$ mGal. We note the presence of negative gravity anomaly, generally associated with synclines and flexural basins, which indicates a mass deficit associated with a subsidence. Anomalies become positive to the west and along the Ousselet–Bou Dabbous structures, suggesting an excess of mass at those localities.

Since the early 1970s, a variety of automatic and semiautomatic methods, based on the use of the horizontal and/or vertical gradients (derivatives) of potential-field anomalies, have been developed to image geological discontinuities such as contacts and faults (Blakely 1995). Accordingly, the second-order vertical derivative map (Fig. 9b) shows the dominance of NE–SW lineaments, which can be correlated with the NE–SW fault system highlighted in this area (Dhahri 2009; Dhahri and Boukadi 2007, 2010). NW–SE to WNW–ESE lineaments are also highlighted nearby the Bou Dabbous and Batene structures. These lineaments are interpreted as normal faults that delimit subsurface graben and half-graben structures well known in the Tunisian Central Atlasic domain.

A 2.5D forward gravity model was performed to image the structural inheritance of the N–S axis. To make a consistent gravity model, seismic profiles and wells data are used. Rock densities were determined from rock density measurements from outcrops and petroleum wells. For deep geological layers (Paleozoic, Precambrian, etc.), densities were estimated from P-wave seismic velocities determined by a deep seismic refraction survey in Tunisia (Buness et al. 1992). A final gravity model was constructed (Fig. 10). Values of density, depth and thickness were varied by up to 10 % during the modeling procedure in order to match the observed gravity anomalies. The final proposed model is reliable with the idea that the N–S axis is a deep paleogeographic fault associated with an E–W crustal thinning with the uplift of Precambrian to Mesozoic cover (Figs. 3, 10). The gravity model also shows an abrupt thinning of the lower crust from ~ 11 to 15 km depth.

Seismic data

Seismic reflection data were used from the ETAP. The seismic survey was performed by Union Texas Western Geophysical Company of America. The seismic data were recorded by a specific seismograph in SEG-D format. Dynamite seismic source was used at 3 m depth (2 kg/hole). The source interval was set to 100 m. The seismic profiles used in this study are time-migrated sections using a finite difference approach.

Three seismic lines (L1–L3) are used to elucidate the structural configuration of the study area. These lines cross the Ousselet–Bou Dabbous structure (L1) and the middle

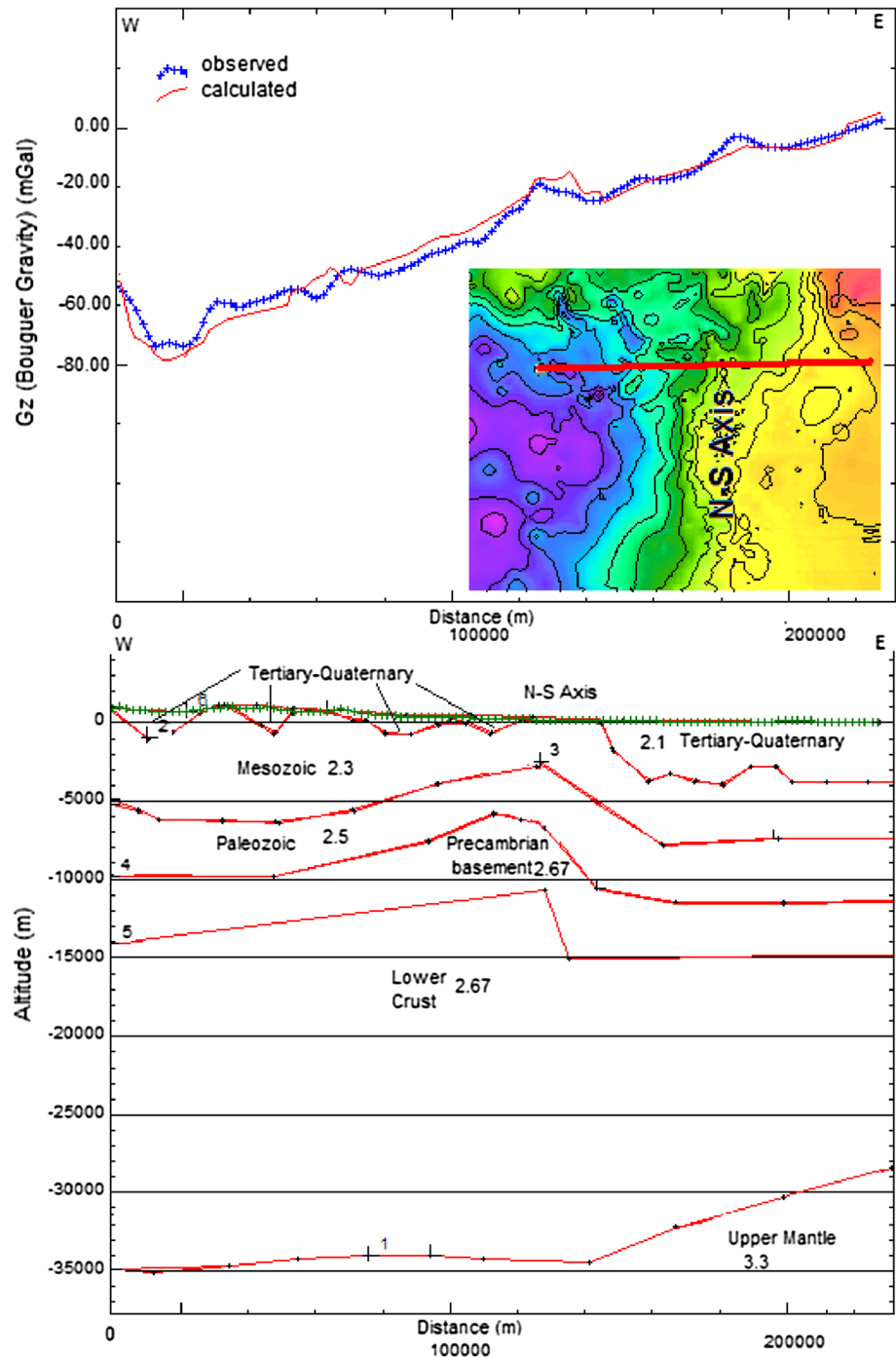
and the southern parts of the N–S axis sensu stricto around Rheouis (L2) and Mezzouna areas, respectively (L3).

These seismic lines are presented to discuss the structural style of the structures north and south of the Cherichira fault. Unfortunately, better quality seismic lines are not available to the north of Cherichira. The lithostratigraphic layers of the seismic line L1 (Fig. 11) are drawn based on the RS101 well which show that the outcropping Abiod formation, Campanian–Maastrichtian in age overlies unconformably the Aptian series to the east, and with respect of the geometry and thickness of outcropping series to the west. This line demonstrates that faulting and associate halokinesis in Ousselet–Bou Dabbous are not comparable to the paleogeographic fault system of the N–S axis southward. We note an Upper Cretaceous subsidence revealed by the thickening of series to the west and thinning of the Cretaceous sedimentation around the Rouissate paleohigh. This seismic line shows also an inverted flower structure in the Ousselet area. To the south of Cherichira fault, the L2 and L3 seismic lines (Fig. 11) cross the Rheouis and Mezzouna structures, respectively. These two seismic lines show especially massive Triassic evaporates piercing along the major paleogeographic faults associated with thickness variations of Mesozoic and Cenozoic series and a reverse slip of the western structural elements as stated by Boukadi (1985) for the Mezzouna structures. It seems that the N–S axis correspond to a steeply dipping major zone of weakness in the Atlasic chain of Tunisia (Fig. 10) that shows evidence of several stages of activity leading to the Triassic evaporates rise up which outcrops in several localities such as Rheouis and Mezzouna (Figs. 2, 4, 5, 8). The loading and piercement of the Triassic evaporites along this weak zone are a key factor in the thinning of the Mesozoic–Cenozoic sedimentary cover along this paleogeographic discontinuity (Fig. 10).

Discussion

To better understand the structure and the geodynamics of the study area, it is fundamental to know the precise kinematic and paleogeographic behavior of associated faults. The present-day configuration of structures reveals complex tectonostratigraphic history (Fig. 12). First, the activity on the paleogeographic faults of Zaghouan, N–S axis and Mrhila–Cherichira began in the Mesozoic and affected the subsequent formation of basins and deposition distribution. Second, paleohighs such as Kairouan Island (Marie et al. 1984), Serj and Rouissate highs, resulting from faulting and halokinesis onset during the Aptian (Dhahri 2009), influenced the formation of grabens/basins and contributed to lateral variations in facies and depositional rates. In fact, the area of northwest Kairouan is located between the

Fig. 10 E–W-oriented gravity model across central Tunisia showing the deep paleogeographic fault of the N–S axis associated with an E–W crustal thinning with the uplift of Precambrian to Mesozoic cover and an abrupt thinning of the lower crust from ~11 to 15 km depth



Central Atlas and Pelagian Shelf, and to the north of the N–S axis. It is also constrained by two main fault systems: the Zaghouan thrust and Mrhila–Cherichira fault (Fig. 12) that affect entire central Tunisia in the NE–SW direction. In addition, this area is affected by NE–SW to N–S strike-slip faults and NE–SW normal faults (Dahri 2009; Dahri and Boukadi 2007, 2010). The NE–SW strike-slips are right-lateral and can be correlated within the dextral N60–90-trending strike-slip faults highlighted in central

Tunisia and that intersect the N–S axis. The main E–W striking faults are commonly associated with diapiric structures and the halokinetic movement of Triassic evaporates such as the Sbiba, Mrhila and Cherichira (Boukadi 1994; Doglioni et al. 1990; Boukadi et al. 1992; Boukadi and Bédir 1996).

The structures of the Ousselet–Bou Dabbous and Nara–Sidi khalif ranges display different structural configurations and geometries. Faulting within the

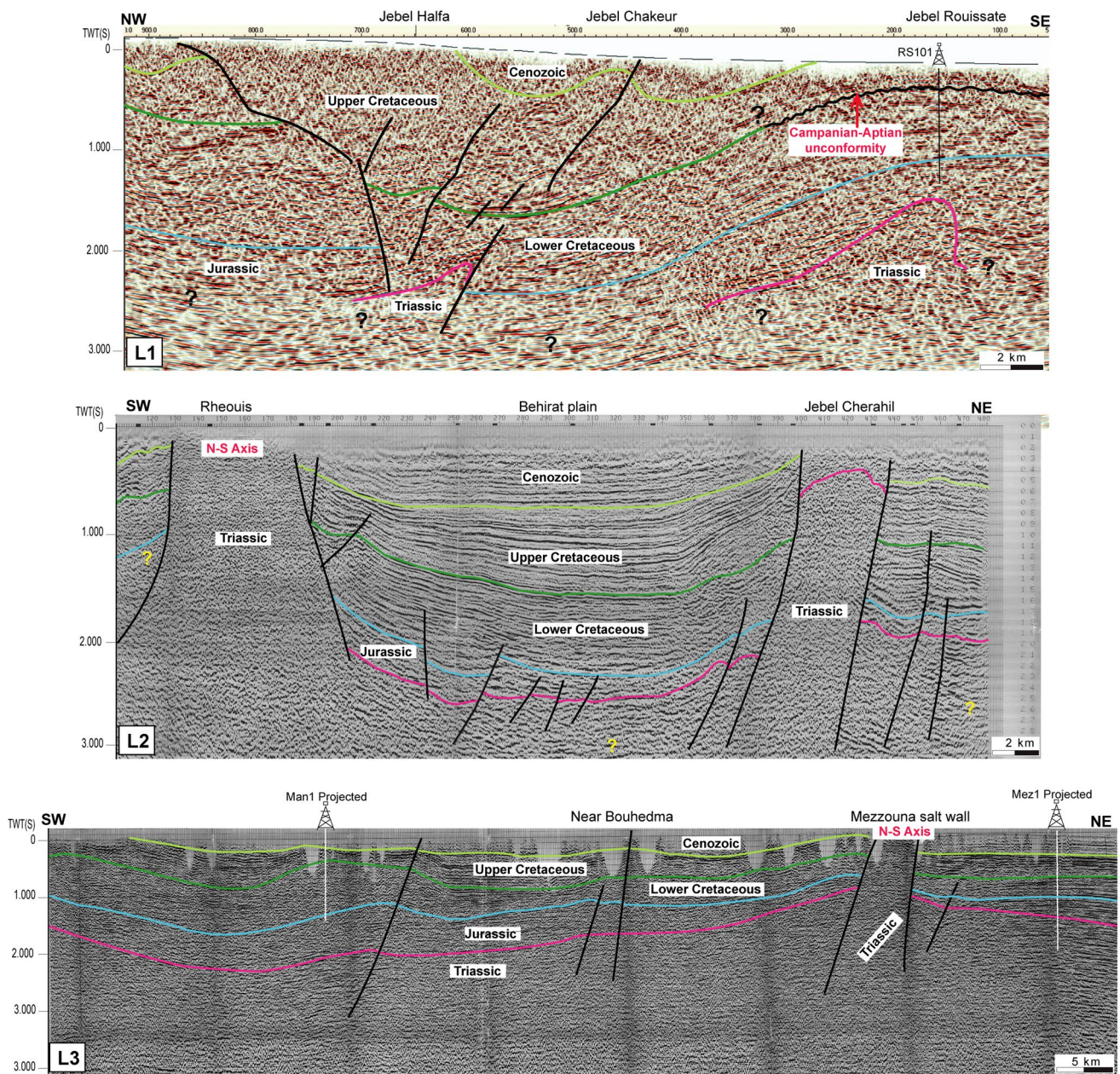
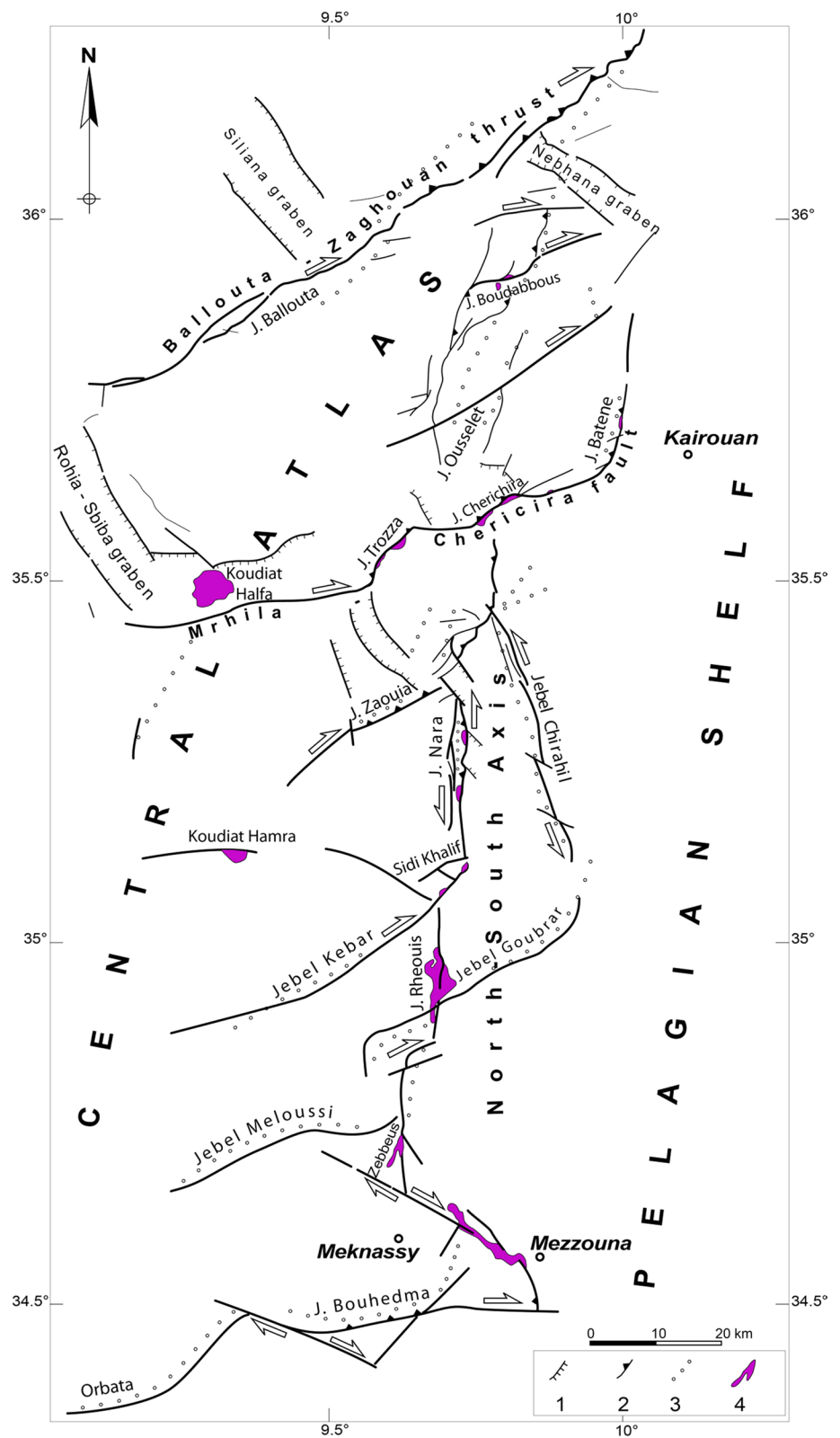


Fig. 11 Interpreted seismic sections along the study area showing the impact of the N–S axis in Mezzouna and Rheouis structures (see Fig. 2 for location)

Ousselet–Bou Dabbous mainly consist of right-lateral NE–SW strike-slip with about 500–1000 m SE-trending cartographic offset (Dahri and Boukadi 2007, 2010). Despite the rotation associated with network of strike-slip faulting, Ousselet–Bou Dabbous folds and fracture orientations still conform to the Atlassic direction known at Central Tunisia scale. Within the Nara-Sidi khalif range, faults are closely associated with the fault zone of the N–S axis where vertical slip is dominant. In the classic structural sketch of Tunisia, the N–S axis exemplifies a tectonic corridor within which complex structures

such as drag folds, monoclines and halokinetic structures extending from the eastern part of the Gafsa chain, to the south, to the Zaghouan thrust to the north. This main structure seems to be ancient and can be related to the Hercynian phase (Buroillet 1981). Due to the Cenozoic tectonic inversion, several segments of this axis evolved as sinistral strike-slip faults and flower structures (Boccaletti et al. 1988; Rabhi 1999; Abbes 2004). In fact, geophysical data do not show evidence of this structural configuration north of the Cherichira fault as previously described.

Fig. 12 Tectonic map of the N–S axis of Tunisia and main adjoining structures; (1) normal fault, (2) thrust fault, (3) fold axis, (4) Triassic extension



According to Dhahri (2009), folded structures north of the Ousselet–Dekhila fault are identified by an Atlassic structural style different to these of the N–S axis. Anticlinal folds

of Halfa, Bou Hajar, Jebil and Chakeur are inclined folds with a slightly northwest-inclined axial surface. The southwestern flanks of these folds are mostly affected by reverse

faulting. This structural configuration mimics the Atlassic style observed in the central Atlas of Tunisia, and not the N–S axis. South of the Ousselet–Dekhila fault, the *jebel Ousselet* consist of N10–20-oriented box-folds bordered by longitudinal faults. It is probable that it constitutes a transitional structure between the Atlassic and the N–S structures styles.

The N–S axis raises the Jurassic series to an altitude about 500 m from Neogene tectonic inversion. Considering the thickness of the Jurassic–Neogene series, the N–S axis should have a kilometer of throw and should have collapsed in the eastern domain corresponding to the Pelagian Shelf during the Neogene. Khomsi et al. (2004) described a comparable series of structures at about 50 km east of the Ousselet–Bou Dabbous, consisting of a ~100 km long thrust front-oriented N–S and with 3–4 km of throw. This structure can be correlated with the N–S axis, because it seems to take 40–50 km of dextral offset across the Cherichira–Batene area and northward along the plain northern Kairouan.

We consider that the structures located to the west of the N–S fault of Batene make part of the Central Atlas of Tunisia and the N–S axis definitively a part of the Zaghuan thrust. The fact that this axis is shifted eastward by a dextral strike-slip at the level of Cherichira structure is in agreement with this interpretation. The N–S fault of Batene and the thrust front described by Khomsi et al. (2004) can be interpreted as a dextral relay of the N–S axis. At least five dextral strike-slip faults cut the N–S axis to the south of Cherichira to show a dextral relay fault system between Mezzouna and Cherichira (Fig. 12). From north to south they are, respectively, Zaouia, *jebel Kebar*–*Sid Khalif*, *jebel Goubrar*, *Meknassy*–*Mezzouna* and *Bouhedma*. The geologic map (Fig. 2) shows that the *Ballouta*–*Zaghouan* and *Mrhila*–*Cherichira* faults are mainly parallel. However, the *Ballouta*–*Zaghouan* fault is the most prominent feature because: (1) The thickness of the sedimentary cover decreases to the north, toward the *Mrhila*–*Cherichira* and *Ballouta*–*Zaghouan* faults, and it is why the deformations of the sedimentary cover within the *Mrhila*–*Cherichira* fault is not accentuated as much as within the *Ballouta*–*Zaghouan* one and (2) the *Zaghouan* thrust is located in front of the transform boundaries of Europe–Africa and sustained the maximum of contraction.

At regional scale, the N–S axis can be considered as a northern extension/branch of the large N–S-striking fault zones of the *Hoggar* fault system in north-central Africa. The *Hoggar* fault system is present throughout Algeria–Libya–Niger and consists of sinistral strike-slip faults that generate local drag folds or pull-apart basins (Guiraud et al. 2005) (Fig. 1). The northern domain of Tunisia is influenced by the NE-striking Tellian thrust front, but the N–S axis is relatively older and appears to be integrated with the N–S fault system of north-central Africa. It especially appears to be related to the *Hoggar* fault system, evidenced

by the expression in *Hassi Messaoud*, within the southern Tunisian–Algerian domain (Fig. 1) and related to the early-Permian intra-plate deformation of the Saharan platform (Guiraud et al. 2005).

Conclusions

This study does not support the existence of major N–S-oriented faults in the *Ousselet*–*Bou Dabbous* area that can be considered as extensions of the Tunisian N–S axis. Accordingly, the classic structural sketch of Tunisia that highlights the major N–S-oriented fault extending from Tunis to the Gabes should be revised. The N–S fault can be limited to the eastern border for the paleogeographic domain of the “Central Tunisia Island”, between the *Cherichira* fault to the north and the *Gafsa* fault to the south. In fact, the area northwest of Kairouan is delineated by the two main paleogeographic faults of *Mrhila*–*Cherichira* and the *Ballouta*–*Zaghouan*, which are NE–SW oriented and seem to be parallel to the Tellian domain and the overthrusting nappes front. Their associated structures record the tectonic history of a transpressional tectonic regime that is related to Africa–Europe convergence and responsible for Tellian domain thrusting. The area between these two faults consists of folded structures that are mainly Atlassic in direction with NW–SE graben structures and is considered as an eastern extension of the Tunisian Central Atlas. The N–S axis (i.e., N–S fault) seems to be correlated in its direction and tectonic style to the strike-slip fault system of the Algerian Saharan domain, southward, in the African craton. However, the N–S-striking faults near Kairouan can be interpreted as dextral relays of the N–S axis.

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