The role of E–W basement faults in the Mesozoic geodynamic evolution of the Gafsa and Chotts basins, south-central Tunisia

DORRA TANFOUS AMRI^{1,2,*}, FERID DHAHRI^{1,3}, MOHAMED SOUSSI¹,
HAKIM GABTNI⁴ and MOURAD BÉDIR⁴

¹UR11ES15, Environnements Sédimentaires, Systèmes Pétroliers et Caractérisation des Réservoirs, Université de Tunis El Manar, Tunis, Tunisia.

²Institut Supérieur des Technologies Médicales de Tunis, Université de Tunis El Manar, Tunis, Tunisia.

³Université de Gafsa, Gafsa, Tunisia.

⁴Laboratoires de GeoRessources, Technopôle de Borj Cédria, Centre de Recherches et des Technologies des Eaux, BP 203, 8020 Soliman, Tunisia.

*Corresponding author. e-mail: dorra_tanfous@yahoo.fr

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The Gafsa and Chotts intracratonic basins in south-central Tunisia are transitional zones between the Atlasic domain to the north and the Saharan platform to the south. The principal aim of this paper is to unravel the geodynamic evolution of these basins following an integrated approach including seismic, well log and gravity data. These data are used to highlight the tectonic control on the deposition of Jurassic and Lower Cretaceous series and to discuss the role of the main faults that controlled the basin architecture and Cretaceous–Tertiary inversion. The horizontal gravity gradient map of the study area highlights the pattern of discontinuities within the two basins and reveals the presence of deep E–W basement faults. Primary attention is given to the role played by the E–W faults system and that of the NW–SE Gafsa fault which was previously considered active since the Jurassic. Facies and thickness analyses based on new seismic interpretation and well data suggest that the E–W-oriented faults controlled the subsidence distribution especially during the Jurassic. The NW–SE faults seem to be key structures that controlled the basins paleogeography during Late Cretaceous–Cenozoic time. The upper Triassic evaporite bodies, which locally outline the main NW–SE Gafsa fault, are regarded as intrusive salt bodies rather than early diapiric extrusions as previously interpreted since they are rare and occurred only along main strike-slip faults. In addition, seismic lines show that Triassic rocks are deep and do not exhibit true diapiric features.

Keywords. Seismic; gravity; E–W and NW–SE faults; Gafsa–Chotts basins; south-central Tunisia.

1. Introduction

At the Paleotethys southern margin scale, syn-sedimentary Jurassic normal faults have been associated to horst and graben features that

delineated the configuration of the seafloor along the Atlasic domain from Morocco to Tunisia. Roure *et al.* (2012), Gharbi *et al.* (2015) and Frizon de Lamotte *et al.* (2009) described active subsidence along the large Saharan Atlas, Tunisian Atlas,

and south Tellian–Rifian troughs by transtension resulting from rapid opening of the Central Atlantic Ocean during the Late Jurassic and the Cimmerian event. In Tunisia, the activity of main N–S and E–W faults began for the most before the Triassic. In the Tunisian central and southern Atlas, these latter have controlled basin configuration and distribution of deposition during the Jurassic and Cretaceous (Ben Ayed 1986; Ben Ismaïl 1991; Chihi *et al.* 1992; Bédir 1995; Zouari 1995; Zitouni 1997; Ben Timzal 2000; Soussi *et al.* 2000; Bédir *et al.* 2000, 2001; Bouaziz *et al.* 2002; Abbes 2004; Gabtni *et al.* 2005, 2006, 2011; Azaïez 2011; Said *et al.* 2011; Ahmadi *et al.* 2013; Dhahri *et al.* 2015; Gharbi *et al.* 2015). A transtensional regime prevailed until Early Cretaceous and was presumably disturbed by a regional NW–SE

transpressional-event followed by a transpressional regime during Late Aptian–Early Albian times (Guiraud *et al.* 1987; Rabhi and Ben Ayed 1990; Bédir 1995; Bédir *et al.* 2001; Bouaziz *et al.* 2002). This regime prevailed during the Late Cretaceous until the onset of the tectonic inversion of the Atlasic domain initiated at the Cretaceous–Cenozoic transition as a result of the Africa–Europe convergence leading to two main shortening episodes during the Eocene and Mio-Pliocene (Boukadi *et al.* 1992; Morgan *et al.* 1992; Piqué *et al.* 1998; Brunet and Cloetingh 2003; Khomsi *et al.* 2006; Malusa *et al.* 2007; Masrouhi *et al.* 2008; Dhahri and Boukadi 2010, 2017; Roure *et al.* 2012; Dhahri *et al.* 2015).

The Gafsa and Chotts domains, subject of this study (figure 1), constitute the eastern extend of

Figure 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 and the location of the study area. Tunisian features are especially delineated. The inset at the left-bottom shows the location of the figure in the Mediterranean area (modified after Guiraud *et al.* 1987 and Dhahri *et al.* 2015).

the Algerian Atlasic chain limited to the south by the South Atlasic Front (Busson 1967; Outtani *et al.* 1995; Bracène and Frizon de Lamotte 2002; Gabtni *et al.* 2005; Malusa *et al.* 2007; Frizon de Lamotte *et al.* 2009). It consists of E–W trending anticlines affected by the NW–SE dextral strike slip system of the Gafsa fault (Zargouni 1985; Ben Ayed 1986; Chihi *et al.* 1992; Boukadi 1994; Bédir *et al.* 2001). Several previous surface and subsurface studies in this area discussed the structural and geodynamic evolution of the Gafsa and Chotts intracratonic basins during Mesozoic and Cenozoic times and the role played by the E–W and NW–SE faults in the genesis of their main associated structural features.

In this paper, we use seismic data calibrated to well logs and satellite gravity data to estimate the role of E–W and NW–SE inherited faults in basin configuration (see Misra and Mukherjee 2015 for review on tectonic inheritance) and the distribution of the depocenters during Triassic–Jurassic times. Seismic data coupled with geological cross sections demonstrate that the NW–SE oriented faults intensively acted during Cretaceous. However, their ante-Cretaceous activity seems to be insignificant. The geodynamic significance of the Upper Triassic evaporites presently outcropping discontinuously along the major Gafsa fault, is also discussed.

2. Geological setting

2.1 Stratigraphic overview

The outcropping lithostratigraphic series comprises Cretaceous and Cenozoic rocks with few Triassic and Jurassic outcrops (figure 2). Triassic is the oldest stratigraphic level reached by mean of wells in Gafsa–Chotts area. Gravity data modeling showed that Paleozoic series are ~2500 m thick and rest at ~7000 m depth (Hlaïem 1998). In central Tunisia, Triassic series mainly outcrops along the Mezzouna corridor and N–S axis chain (Burollet 1956; Boukadi *et al.* 1992; Boukadi and Bédir 1996; Azaïez *et al.* 2007; Dhahri *et al.* 2015; Dhahri and Boukadi 2017). They consist of mixed gypsum, clay, silt and dolomite, well documented northward in the Rheouis Formation (Burollet 1956; Soussi *et al.* 1997, 2001; Courel *et al.* 2000).

The Jurassic series are well exposed along the N–S axis for few tens of kilometers. They are composed of two thick carbonate members (Burollet 1956; Soussi 2002) separated by a middle unit encompassing deep marine marls and limestones

with Toarcian black shales considered as main source rock for the Jurassic petroleum system in the area. These series constitute an attractive deep target for petroleum exploration since they provided gas, condensate and good oil in central Tunisia. They exhibit also good source rocks near the N–S axis where they are sealed by the Early Cretaceous shales of Sidi Khalif Formation (Soussi *et al.* 2000).

The Lower Jurassic lower member is dominantly shallow marine peritidal dolomites. The Upper Jurassic upper member starts with ammonite-bearing limestones of Callovian–Oxfordian age followed by Kimmeridgian–Tithonian dolomites formed during burial phases (Soussi *et al.* 1990; Soussi and M'Rabet 1994).

The Jurassic series of the Saharan domain is represented mainly by siliciclastic sediments and evaporitic facies with shallow marine carbonates are developed during the main Jurassic transgressive phases (Ben Ismaïl and M'Rabet 1990; Enay *et al.* 2005).

In the study area, the uppermost part of Jurassic series (Tithonian) outcrops at Jebel Ben Younes along the NW–SE Gafsa fault and east of Jebel Orbata (figure 2), but several exploration wells (figure 3) crossed a complete Jurassic section displaying important thickness variation (table 1). More recently, the Jurassic succession composed of two carbonate members separated by a dominantly shaly unit have been discovered and well characterized by ammonites in Jebel Bouhedma situated eastward of Jebel Orbata (Bahrouni *et al.* 2016).

Jurassic rocks of Chotts basin are broadly composed of shallow marine to sebkha facies (Lower Jurassic) followed by open marine and fossiliferous shales and limestone (Middle Jurassic). The Upper Jurassic rocks are composed of mixed evaporitic shallow marine oolitic carbonates with some siliciclastic intervals described in several wells. The top of Jurassic series is crossed in W1, W2, W3 and W5 wells at 4360, 2520, 1000 and 2350 m depth, respectively.

The Lower Cretaceous series outcrops especially along the anticlines within the Gafsa and Chotts basins (figure 2). They are characterized by the important variation of facies and thickness and the occurrence of fluvio–deltaic systems passing laterally to deep marine environment (Fanti *et al.* 2012). Towards north, this succession is composed of neritic, lagoonal and continental facies (M'Rabet 1987; Zitouni 1997; Ben Timzal 2000; Bédir *et al.* 2001; Azaïez 2011; Tlig 2015) grading to deltaic complex

Figure 2. Geologic map of the Gafsa-Chotts basin with the location of the seismic lines (L), geological cross sections and petroleum wells (W).

Figure 3. N-S geological profiles showing the main structural features of Gafsa and northern Chotts Range with the Austrian and Cimmerian unconformities. Jebel Morra exhibit a pop-up geometry along with 'normal dragged' units (See Mukherjee 2014 for similar structures).

sedimentation in central Tunisia and open marine facies northward (M'Rabet 1987). The Upper Cretaceous facies comprise shales, marls, carbonates and evaporates.

In the study area, the Cenozoic series are mainly composed of shallow marine to continental deposits. The Paleocene Haria Formation is made of ~60 m thick shales with marine planktonic foraminifera (Burolet 1956; Riley *et al.* 2011) followed by ~70–90 m thick Lower Eocene deposits of the Metlaoui Group consisting of phosphates, shales, carbonates and evaporites. The Upper Eocene series consists of the evaporitic Jebbs Formation. Upper Miocene–Pliocene fluvio-marine facies were locally deposited surrounding the areas uplifted during the Miocene (Burolet 1956). The Quaternary is represented by alluvial and fluvial deposits.

2.2 Tectonic setting

The study area covers most part of the southern Tunisian Atlas (figure 2). It comprises the Chotts basin to the south and the Gafsa Metlaoui range to the north (figure 3). In this area, the folds are related to the Cenozoic compression, crustal shortening and inversion of earlier extensional structures (Haller 1983; Zargouni 1985; Ben Ayed 1986; Bédir 1995; Bouaziz 1995; Hlaïem 1998; Zouari *et al.* 1999; Masrouhi *et al.* 2008; Dhahri and Boukadi 2010; Said *et al.* 2011; Ahmadi *et al.* 2013; Dhahri *et al.* 2015; Gharbi *et al.* 2015). However, the E–W trending chains are interpreted as en echelon folds occurred along dextral wrench faults system (Zargouni 1985; Chihi *et al.* 1992; Zouari 1995). The Chotts Ranges and the Metlaoui Chain are affected by the Gafsa and Negrine–Tozeur NW–SE dextral strike slip faults (Zargouni 1985; Chihi *et al.* 1992). Chihi *et al.* (1992) proposed that the development of the Chotts basin and associated anticlines are due to an E–W strike-slip fault, whereas Zargouni (1985), Boukadi (1994), Zouari (1995), Bédir (1995) and Hlaïem (1998) suggested that they are linked to the NW–SE strike-slip faults of Gafsa and Negrine–Tozeur. In this study, this aspect will be re-examined based on basin infilling and distribution in three zones: the Gafsa–Metlaoui zone (Zone 1), Benkhir zone (Zone 2) and the Chotts basin (Zone 3) (figures 2 and 3). The study of these areas completes the investigations undertaken northward in the Kharrouba–Sidi Ali Ben Aoun area using a similar integrated methodology (Azaïez *et al.* 2007; Tanfous *et al.* 2008; Riley *et al.* 2011) and provides an overview of the geodynamic

Table 1. Thickness variation of the Jurassic and Lower Cretaceous series.

Location	W1	W2	W3	W4	W5	North–south Axis outcrops
Lower Cretaceous Series	1100 m	1825 m	1050 m	Upper 400 m	1800 m	
Jurassic series	550 m	700 m	2500 m	Not reached	700 m	~500 m

evolution of the central and southern parts of the Tunisian Atlas.

3. Materials and methods

Geophysical input in tectonic studies provides a fruitful outcome (e.g., Misra *et al.* 2015). To unravel the tectonic evolution of the Gafsa–Chotts intra-cratonic basins, an integrated approach including 2D seismic, well log data and gravity data was undertaken. Well log and the land gravity data are obtained from the Entreprise Tunisienne des Activités Pétrolières (ETAP). The 2D seismic reflection data processing involved classic calibration using well logs and seismic facies analysis for structural and stratigraphic interpretation (Hlaïem 1998, 1999; Riley *et al.* 2011). These interpretations require an understanding of the subsurface formations which is provided in well reports and in literature. Well logs with common lithostratigraphic subdivisions are established by petroleum companies (AGIP, ETAP, SHELL) and are used (together with outcrops) for the calibration of seismic section. Gravity data were merged and reduced using the 1967 international gravity formula (Morelli 1976). Free air and Bouguer gravity corrections were made using sea level as a datum and 2.67 g/cm^3 as a reduction density. The Bouguer gravity data are computed at BGI from the EGM2008 spherical harmonic coefficients (Pavlis *et al.* 2008). The Bouguer corrections computed at regional scale are obtained using the FA2BOUG code developed by Fullea *et al.* (2008). The Bouguer gravity anomaly data were gridded at 1 km spacing and contoured to produce Bouguer gravity anomaly and horizontal gravity gradient maps to highlight the deep pattern discontinuities of the study area.

4. Lithostratigraphic correlation

Two lithostratigraphic correlations alongside the study area were prepared according E–W and N–S directions (figures 4 and 5) to examine the

facies and thickness variation that affect both the Jurassic and Lower Cretaceous series. These lithostratigraphic correlations between well logs are based on rock type. Since the lithostratigraphic units exhibit some lateral facies variations, it was necessary to follow the Tunisian lithostratigraphic chart established by the ETAP. This chart summarizes the spatial pattern of sedimentary units and allows following the sea level change and the environmental history.

The first correlation panel (figure 4) is oriented E–W and comprises W1 well to the west (Zone 1) and W2 well to the east (Zone 2) (figure 2). It shows that the Jurassic series of the Metlaoui–Gafsa area (Zone 1) and Benkhir area (Zone 2) are relatively thin and remain constant along several tens of kilometers. The Jurassic series of W1 and W2 are made of two carbonate units separated by an intermediate one composed of shales and limestones. The thickness of the Jurassic is about 650 m and is similar in both wells. This regularity of the thickness in Zone 1 and in Zone 2 is also well illustrated in seismic sections (figures 6 and 7).

By contrast, the Lower Cretaceous series (Berriasian to Aptian) displays important thickness variation well illustrated by their thickness increase in Zone 2 situated eastward of Gafsa fault (figure 7).

The N–S lithostratigraphic correlation (figure 5) comprising W5, W2 and W3 shows important thickness variations towards north. The latter is materialized by a strong change of the thickness of the Jurassic which is 500 m in W5, 600 m in W2 and more than 2500 m in W3. This thickness change is particularly well documented within the middle Jurassic series, which reaches 1000 m in W3 and 200 m in W1. The Lower Jurassic deposits are relatively homogeneous as they are composed of shallow marine peritidal carbonates in the three wells (Soussi 2002).

This N–S cross section clearly shows that the Jurassic series of Chotts basin are very thick when compared to those of Gafsa and Benkhir zones.

The Lower Cretaceous series are represented by interbedded dolomitic sandstones, shales and thin limestone layers with scarce anhydrite. They

Figure 4. E–W correlation of lithostratigraphic series of W1 and W2 wells in the Gafsa–Chotts area (see figure 1 for location, Fm: Formation) showing thickness variations of Mesozoic and Cenozoic series. We note the subsidence of the Jurassic–Lowermost Cretaceous series in W2, but this subsidence is not maintained at least for the Albian–Cenomanian series which became thicker in W1 compared to W2.

Figure 5. N-S correlation of lithostratigraphic series of W5, W2 and W3 wells in the Gafsa-Chotts area (see figure 1 for location, Fm: Formation) showing thickness variations of Mesozoic series. We note especially the Jurassic-Lower Cretaceous subsidence inversion.

Figure 6. E-W seismic line (L1) crossing Gafsa Metlaoui Zone calibrated using W1 well (see figure 1 for location). The interpretation shows that the thickness of Jurassic–Lower Cretaceous series are slightly affected near the NW–SE faults. However, the Upper Cretaceous series shows a thickness increase towards the east.

Figure 7. Interpreted seismic section of L3 (see figure 2 for location, L5 and L6: location of the intersection with the seismic lines L5 and L6) through Gafsa Benkhir zone showing a chaotic zone near the Gafsa fault zone. Jurassic series show constant thickness on both sides of this fault; however, Lower Cretaceous series are thicker near Benkhir zone. (1) Berriasian–Valanginian, (2) Hauterivian, (3) Barremian, and (4) Aptian.

are ranged within Asfer Formation, also known as ‘Continental intercalaire’. This siliclastic formation contains numerous lignitic horizons which have been well documented in the W3 well. It is capped by the Sidi Aich Formation made of fine grained transitional to coastal marine deposits (M’Rabet 1987; Azaiez 2011; Boukhalfa *et al.* 2015; Tlig 2015).

The Lower Cretaceous series shows considerable thickness variation towards south (i.e., 1825 m in W2, ~1000 m in W3) contrasting with the Jurassic series relatively thick to the south (2500 m in the Chotts basin) and does not exceed 1200 m near Gafsa basin (figure 5). The Jurassic–Lower Cretaceous deposits are 3800 m thick in Chotts basin, about 3000 m in the block northward Gafsa and significantly reduced to about 1800 m in Gafsa–Metlaoui basin. This correlation indicates a clear subsidence inversion from Jurassic to Lower Cretaceous time. The Jurassic series are thicker in W3 (about 2500 m) than in W2 and W1 (about 600 m); whereas, the Lower Cretaceous series are thicker in W2 (about 1800 m) than in W3 (about 1000 m).

The E–W correlation panel (figure 4) shows that the Lower Cretaceous series are solely affected by important thickness variation east of Gafsa fault (figure 2). The sedimentary series in the Gafsa–Metlaoui basin are notably thicker than W2, at least for the beginning of Late Cretaceous. W1 crossed the uppermost 500 m of the Jurassic series (final depth) comprising platform facies (limestones and dolomites) and about 1100 m of Lower Cretaceous followed by ~2200 m of Upper Cretaceous series (figure 4). These important thickness changes testify subsidence inversion (previous subsiding area becomes relatively uplifted and *vice versa*) during the transition between Lower and Upper Cretaceous in Gafsa and Benkhir zones.

The lithostratigraphic correlation and thickness changes evidence a main fault separating Zone 1 and Zone 2, although so these latter belong to the same paleogeographic domain compared to the Chotts basin. The Zone 2–Zone 3 limit coincides with the northern border of the Chotts subsiding basin and corresponds to a major E–W fault featured in seismic sections (Hlailiem 1999).

The Chotts basin (Z 3) shows pronounced subsidence during Jurassic when compared to the Lower Cretaceous period. The burial rates in this zone is estimated by Hlailiem (1998) at ~48 m/My for the Early Jurassic (Tethyan rifting), ~20 m/My for the Middle Jurassic (post-rifting) and evolving from ~85 to 15 m/My from Late Jurassic to

Early Cretaceous. For the same zone, Patriat *et al.* (2003) estimated a subsidence around 50 m/My during the whole Jurassic and in an ongoing study, we estimate the subsidence at ~60 m/My for the Jurassic–Early Cretaceous period. At the Atlas Tunisian scale, two main Jurassic subsiding areas are distinguished: the Tunisian trough characterized by deep facies (Ammonitico Rosso) and the Chotts basin characterized by shallow marine carbonates with important evaporitic and siliclastic contribution (Soussi and Ben Ismail 2000; Soussi *et al.* 2000). The subsidence of the Chotts trough started probably in the Upper Carboniferous time with ‘en escaliers faults’ (step faults) (Gabtni *et al.* 2006) and has controlled the paleogeography and the deposition distribution from Paleozoic to Cenozoic times.

5. 2D seismic analysis

With the fact that the main faults are E–W and NW–SE oriented, we considered two seismic groups of lines (figure 2). The first includes the ENE–WSW oriented L1 and L3 (figures 6 and 7) in order to check synsedimentary deformations caused by NW–SE faults during Jurassic times. While the second includes the NW–SE oriented L2 (figure 8) and the N–S oriented L4 (figure 9) and L5 (figure 10), in order to define the deformations caused by the E–W faults.

Seismic line L1 crossing the Gafsa–Metlaoui area (Zone 1) is oriented ENE–WSW and is calibrated by means of W1 well (figure 6). This line allows us to identify and correlate the key marker horizons from top to bottom: Top Cenozoic, Top Upper Cretaceous, Top Lower Cretaceous (Aptian horizons of Orbata Carbonate Formation) and Top Upper Jurassic (Malm horizon of Upper Nara Carbonate Formation). The Top of Upper Triassic horizon (Rheouis Evaporite Formation) is estimated.

This profile (figure 5) shows the buried Gantass anticline to the west (figure 2) limited by two major steep faults. This line shows clearly that the thickness of Jurassic and Lower Cretaceous series are relatively constant towards east and therefore keep the same architecture in both Zones 1 and 2. However, the Upper Cretaceous units are thicker westward. The thickness of Cenozoic series decreases from west to east. This configuration highlights an Upper Cretaceous tectonic activity of the segments of NW–SE fault that affects the series near the western periclinal termination of the Sehib

Figure 8. Interpretation of L2 seismic section (see figure 2 for location) showing the structure of the southern Gafsa basin with extensive platform domain affected by E–W synsedimentary normal faults passing to the northwest, to subsiding and half graben tilted blocks.

anticline and around Gantass area in the Gafsa–Metlaoui Zone (figure 2).

The Triassic–Jurassic limit is not well defined because W1 well does not cross the entire Jurassic sequence; it seems that its thickness decreases slightly close to the zone affected by faults. The L3 seismic line (figure 7) is oriented E–W along ~90 km and crosses the Gafsa fault zone. The main feature outlined by this section is recorded within the Lower Cretaceous series. However, the Jurassic series maintains a fairly constant thickness. But the thickness and the seismic facies of the Lower Cretaceous series vary across the Gafsa fault zone:

deposition is from deltaic facies at the east near Benkhir area (Zone 2), and fluviodeltaic at the west, near Gafsa–Metlaoui (Zone 1). Thickening of the Lower Cretaceous series to the east suggests an eastern subsiding depocenter eastern Chemsí and Benkhir structures (figures 2 and 7). When we focus on the Albian and Aptian horizons, we can differentiate a compression related to Albian–Aptian unconformity well known at Tethyan scale (Graziano 2000). The L3 seismic line shows chaotic facies near the Gafsa fault zone, associated to the sliding movement and upwards Triassic evaporites. According to these observations, the Triassic salt

Figure 9. Interpretation of L4 seismic section calibrated with W2 and W4 wells (see figure 2 for location, L3: location of the intersection with the seismic line L3) showing the Mesozoic paleohigh of the Benkhir and the Cretaceous normal slip of the Benkhir fault. (1) Berriasian–Valanginian, (2) Hauterivian, (3) Barremian, and (4) Aptian.

layer seems to be implicated in the controls of the geodynamic evolution of the Gafsa–Metlaoui basin not only during the Triassic and Jurassic but also during the Cenozoic inversion.

- The L2 seismic line (figure 8) shows significant thickening of Jurassic and Cretaceous series to the north. This seismic section highlights therefore the Late Triassic–Jurassic rifting and associated E–W listric faults bounding tilted blocks in half graben structure that subside northward. These E–W synsedimentary faults formed during the Triassic–Jurassic times are responsible for half graben within an extensional platform domain in the southern Gafsa basin. These faults are sealed by the Lower Cretaceous series, but the post-Aptian series also shows considerable thickness variations. It is notable that normal faults controlled the subsidence and the thickening of Jurassic series.

E–W to ENE–WSE sinistral normal faults suggest that a NNW–SSE regional post-rifting extension lasted from Late Jurassic until the Lower Cretaceous and lead to the thickening of Cretaceous deposits in the southern Gafsa basin.

- The L4 seismic line is oriented N–S and was calibrated with W2 and W4 wells (figure 9). It is used to analyze the lateral structural configuration of the eastern border of the Benkhir zone that constituted a paleohigh at least since the Jurassic. Two seismic facies are easily distinguished in Jurassic–Lower Cretaceous horizons:

parallel to sub-parallel and progradational, representing synrift deposits. Chaotic seismic facies correspond to Upper Triassic salt. A steeply, south-dipping fault bordering the Benkhir paleohighs to the north can be interpreted as the southern segment of the Benkhir fault system. The unconformity between the Jurassic horizons and the onlapping Cretaceous sequences can be clearly seen. To the north of Benkhir paleohighs, a restricted basin between Bouhedma E–W fault and Benkhir structures contains relatively thin Upper Jurassic series crossed by W2 well. The uplift of this area during the Late Jurassic–Early Cretaceous eroded Upper Jurassic (Tithonian) strata crossed by W2 (figure 5), forming the Cretaceous unconformity correlated to the Cimmerian Orogeny. Nonetheless, in this area, which is situated on the continuity of the N–S axis lineament, the rising up of the Triassic salt cannot be ruled out.

- The L5 seismic line, N–S oriented, is calibrated by the three petroleum wells, W4, W2 and W3 (figure 10). It comprises of the area extending from Chott El Fejej to the south (Zone 3) and Jebel Bouhedma to the north (Zone 2) (figure 2). This seismic line shows that the Chotts basin is separated from Zone 2 by a steeply dipping, E–W fault (northern Chotts fault). The paleogeographic control of this fault is well illustrated in seismic line L5 (figure 10) by the thickening of Jurassic units towards the Chotts domain. The Jurassic series thickens from 600 m in W2 well

Figure 10. Interpretation of L5 seismic section (see figure 1 for location, L4: location of the intersection with the seismic line L4) calibrated with W2, W3 and W4 wells showing the Jurassic–Lower Cretaceous thickness variations on both sides of the E–W paleogeographic fault of the northern Chotts Ranges. This section also highlights an unconformity that capped the Jurassic series near and to the south of Benkhir (A2 Zone), which is related to the Cimmerian Orogeny. A Lower Cretaceous paleohigh is also prefigured near Benkhir area. (1) Berriasian–Valanginian, (2) Hauterivian, (3) Barremian, and (4) Aptian.

to 2400 m in W3 well, whereas the Lower Cretaceous series show a thickness reduction in the opposite sense (1000 m in W3 to 1600 m thick in W2). The Jurassic–Cretaceous transition is probably marked by a stratigraphic gap testified by the absence of the Tithonian correlated to the Cimmerian Orogeny (Bahrouni *et al.* 2016). In addition, Albian–Turonian series unconformably overlies the Aptian dolomites. The Albian hiatus is also well known in south-central Tunisia. It emphasizes the transition between Zebbag and Orbata formations and it is correlated to the Austrian orogenic phase associated with marine regression, which allows the Aptian platform emersion (Rabhi and Ben Ayed 1990; Chaabani and Razgallah 2006; Marco *et al.* 2014).

The thick Mesozoic series of Chott El Fejej graben is deformed by a compressional, E–W scale anticline. W2 and W3 wells have been drilled, respectively, on a paleohigh (Benkhir) and in a foreland basin margin (the Chott El Fejej graben). This model indicates that subsidence in the Chotts basin is accommodated by the E–W normal faults of the northern Chotts ranges.

6. Gravity data analysis

The Bouguer gravity anomaly values (figure 11a) in the study region vary from -95 to -7 mGal with the anomaly values generally decreasing towards the Chott El Gharsa (gravity low). This decrease is directly correlated with large subsidence and Tertiary sequence thickness. The highest anomaly values are in the eastern part of the Gafsa–Metlaoui basin (Gantass, Jebel Sehib, Chemsî and Benkhir). Based on seismic refraction studies (Buness *et al.* 1989), the probable source of the regional gravity anomaly is deep. The thickness of crust was estimated assuming a single density contrast between the crust and the upper mantle under the region. We can note two broad regions: (1) the thick sedimentary cover of the Chott El Gharsa and Jerid basins in the western part of the map (figure 11a), (2) the thin sedimentary cover of the eastern folded borders of the Gafsa–Metlaoui basin (Gantass, Jebel Sehib, Chemsî and Benkhir).

The N–S horizontal gravity gradient map (HGG) (figure 11b) provides a view of the overall pattern of faulting, which aids in understanding the structural and tectonic framework of the region.

Figure 11. (a) Satellite gravity map of the Gafsa–Chotts area; (b) N–S horizontal gravity gradient map of the Gafsa–Chotts area showing that the E–W faults are the most expressed.

The lineaments distribution interpreted as faults shows clearly the dominance of the E–W direction, especially in Zones 1 and 2. These major contacts, interpreted as faults, correspond to the regional-scale faults. They currently delimit at least three large zones (1, 2 and 3) (figure 2). The first zone corresponds to Gafsa–Metlaoui basin (Zone 1). The second zone corresponds to the Benkhir zone (Zone 2) and it includes several outcropping anticline structures (Sehib, Berda and Benkhir), and

the third zone corresponds to the Chotts basin (Zone 3).

Based on the results of previous gravity studies performed by Gabtni *et al.* (2013), Dhaoui and Gabtni (2013) and from this study, it appears that the E–W represent the dominant trending faults which influence the Tunisian southern tethyan margin during the Triassic–Jurassic rifting. This is similar to what was observed farther west in the Atlasic chain (Malusa *et al.* 2007).

7. Discussions

The Mesozoic geodynamic evolution of the study area is reconstructed based on the compilation of new data as well as previous findings. This evolution is mainly completed in response to successive episodes of extensional tectonic regime that started in the Late Permian. The first recorded extension is Late Permian–Middle Triassic. It is contemporaneous to the rifting related to the Pangea breakup. This extension characterized by N–S to NW–SE extensional paleostress is well recorded within the Permian deposits which are affected by synsedimentary normal faults (Dercourt *et al.* 1985; Martinez *et al.* 1990; Bédir 1995; Bouaziz *et al.* 1999; Frizon de Lamotte *et al.* 2009; Gharbi *et al.* 2015). As a testimony of the impact of the Late Triassic–Early Cretaceous Cimmerian phase, the Triassic sequence shows ENE–WSW normal faults, indicating a major NNW–SSE to NW–SE oriented extension subsequent to the alkaline magmatism highlighted in the Chotts basin by subsurface data (Laridhi-Ouazaa 1994; Gabtni *et al.* 2006). These events can be correlated with the Triassic Paleotethys Ocean opening, which continued until Early Jurassic subsequently to the sinistral movement of Africa (Dercourt *et al.* 1985; Piqué *et al.* 1998; Brunet and Cloetingh 2003; Laville *et al.* 2004; Frizon de Lamotte *et al.* 2009; Dhahri and Boukadi 2010; Gharbi *et al.* 2015). At the northern African margin scale, the Triassic rifting is indicated by Triassic basins, which developed on the early epicontinental platform. During Liassic times, regional extensional tectonics caused the structural disruption of the initial platform (Bouaziz *et al.* 2002; Soussi 2002). In northern Tunisia, the Liassic NE–SW rifting led to the North African passive continental margin until Dogger times, whereas in southern Tunisia, contemporaneous N–S extension resulted in the E–W trending subsiding basins, which lasted from the Jurassic until the Early Cretaceous.

At the study area scale, the Chotts basin exemplifies an extensional detachment fault system as illustrated in figure 12. The listric fault of the South Atlasic front created a subsiding basin northwards in the Chotts Trough (figure 12). This basin is limited to the north by the E–W oriented fault of the northern Chotts Range, which together with the E–W oriented fault of the Orbata–Bouhedma, delimit a horst (Gafsa High, figure 12). About 2500 m of shallow marine facies were deposited in the Chotts Trough during the

Jurassic. This subsidence is due to the activity of the listric fault of the South Atlasic Front and sedimentary load. During the Early Cretaceous, the tectonic regime was similar and considerable thickness variations were recorded within the Lower Cretaceous series made of fluvio-deltaic, coastal and shallow marine facies, with about 1600 m near Gafsa High against 1000 m in the Chotts Trough. This situation reveals new basin configuration; the paleohorst of Gafsa became relatively subsiding compared to the Chotts basin. The question is how the subsidence shifted between the Jurassic and the Early Cretaceous from the south to the north of the E–W fault of the northern Chotts Range.

We suppose that the Chotts basin corresponds to the hanging wall of the main listric fault of an extensional detachment fault system initiated along the south Atlasic front at least since Late Jurassic (figure 12a). During Early Cretaceous, the main sliding is transferred along the segment of the northern Chotts Range leading to the collapse of the Gafsa paleohigh (figure 12b).

This major tectonic activity, which occurred during Jurassic–Cretaceous transition is most likely related to the well-known Cimmerian phase, suggested or well documented by several authors, in Tunisia and or in Algeria (Ben Ayed 1986; Bobier *et al.* 1991; Favre *et al.* 1991; Outtani *et al.* 1995; Kamoun *et al.* 1999; Pogácsás *et al.* 1999; Tanfous *et al.* 2005). Such phase is well recorded within the Upper Jurassic series of the N–S axis, in Jebel Bouzer by synsedimentary faults and progressive onlapping (Gourmelin 1984) and in Jebel El Haouareb, where numerous slumping features have been observed at the top of the Upper Jurassic dolomitic member (Soussi 2002).

The synthetic general reconstruction presented in figure 12 shows that successive tectonic events, involving tilting and uplift bounded by major E–W faults, controlled the facies and thickness variation of the Jurassic–Early Cretaceous series of the southern Atlas and the Chotts domain. The uplifted areas are well marked in the southern shoulder part of the margin resulting in the exposure of the Chotts area and the Saharan platform which underwent active erosion registered by amalgamated major disconformities and important stratigraphic gaps during Late Jurassic–Early Cretaceous (Oujja *et al.* 2002; Fanti *et al.* 2012). To the north, in Jebel Bouhedma, these tectonic events are marked by the development of normal faults, slumping features and the genesis of

Figure 12. Evolutionary kinematic model of the study area showing the configuration of the study area from Jurassic extension to present-day with emphasizes of the E-W faults role and facies and thickness distributions.

conglomeratic horizons where mixed fauna (Kimmeridgian and Tithonian) are well documented (Bahrouni *et al.* 2016). At regional scale, the Late Jurassic–Early Cretaceous tectonic events are accompanied by a major change of sedimentation materialized by the development of a thick fluviodeltaic siliciclastic sequence (Sidi Khalif, Meloussi and Bou Dinar formations) over the Lower Jurassic shallow marine carbonate platform of the Nara Formation (M'Rabet 1987; Soussi 2002).

Thus, within this configuration the Jurassic series of the Gantass–Gafsa–Benkhir are thought to be developed on an E–W paleohigh delimited northward and southward by subsiding areas. According to this hypothesis, the Gafsa–Benkhir domain corresponded during Jurassic time to a platform domain rather than to a subsiding basin as it was and continues to be considered by numerous geologists (Traut *et al.* 1991). The presently oriented E–W anticlines that dominate the geology of the study area constitute strong arguments of the importance of the inherited E–W fault as main physical discontinuities controlling the genesis of the Metlaoui range, Orbata–Bouhedma structure, Sehib, Berda and Chamsi–Benkir structures (figure 2).

According to our understanding of the geodynamic evolution of the study area, these E–W anticlines formed concomitantly or just before the evolution of the NW–SE-oriented Gafsa fault to a strike slip corridor outlined punctually by Triassic evaporites near Gafsa or Hdhifa localities (Chihi *et al.* 1992; Zouari 1995; Hlaïem 1999; Bédir *et al.* 2000, 2001; Zouaghi *et al.* 2005; Gharbi *et al.* 2015) and by the establishment of a positive flower structure. The Triassic outcrops, identified in Jebel Ben Younes and Jebel Hdifa along the Gafsa fault trace, are thought to demonstrate shear movements accompanied by Triassic intrusions. The onset of the halokinesis along open major fractures can be related to the Jurassic–Late Cretaceous extensional regime leading to the development of large-scale strike-slip fault such as those of Gafsa fault, Meknassy–Mezzouna corridor or at large scale, the Sirt rift (Dhahri and Boukadi 2017). This presumably saccadic halokinesis seems to have been aborted when these fractures were closed subsequently to transpressional regimes. The tectonic inversion of the Gafsa fault led to the rise up of Lower Cretaceous series with Triassic evaporites previously injected along the fault zone. The absence of true diapiric features in this seismic line confirms the findings already stated for the

geodynamic significance of the Triassic bodies in Alima structures. Indeed, according to Riley *et al.* (2011), it is well documented that the Triassic rocks are at present very deep and did not therefore play as diapirs during Mesozoic time.

During the Late Aptian–Early Albian, a transpressional event correlated to the Austrian Orogeny (which is an important mid-Cretaceous tectonic event known at the Tethys scale) occurred (Guiraud *et al.* 1987; Rabhi and Ben Ayed 1990; Bédir 1995; Bédir *et al.* 2001; Bouaziz *et al.* 2002). This event is shown in the seismic line of figure 10 by the deformed Jurassic and Lower Cretaceous series topped by the Austrian unconformity. NE–SW to ENE–WSW trending extension directions dominated during Late Cretaceous (Bédir 1995; Bédir *et al.* 2001; Zouaghi 2008; Dhahri and Boukadi 2017), subsequently to the Aptian dextral slip of the Gibraltar–Messine transform fault engendering strike-slip and normal faults along NE–SW and N–S accidents, which led to the extension of the Tunisian margin (Martinez *et al.* 1991). From the south to the north, sedimentation occurred along a gentle slope and evolved respectively from littoral to shallow marine facies near central Tunisia (figure 12c).

Two main shortening episodes in Eocene and Mio-Pliocene times resulting from the Africa–Europe convergence (Boukadi *et al.* 1992; Morgan *et al.* 1992; Piqué *et al.* 1998; Brunet and Cloetingh 2003; Masrouhi *et al.* 2008; Khomsi *et al.* 2009; Dhahri and Boukadi 2010; Roure *et al.* 2012; Gharbi *et al.* 2015) led to the tectonic inversion of the study area (figure 12d).

In the Gafsa basin, Miocene continental deposition (Segui Formation) overlies unconformably the Late Cretaceous–Lutetian series. This regional angular unconformity never exceeds a few degrees suggesting in southern Tunisia a gentle Late Eocene folding probably restricted to uplifted areas engendered by drag folding above main inherited faults. Two main NW–SE trending compressional events occurred in the Late Eocene and in the Middle–Late Miocene alternating with four extensional periods respectively in the Eocene, Oligocene, Early–Middle Miocene and Pliocene (Bouaziz *et al.* 2002).

The main NW–SE faults were reactivated in right-lateral oblique-slip features such as the Gafsa fault (Boukadi and Bédir 1996; Hlaïem 1999; Said *et al.* 2011; Ahmadi *et al.* 2013; Gharbi *et al.* 2015). However, E–W faults are associated to E–W-oriented anticlines (figure 13). The frequent

Figure 13. Jurassic paleogeographic map of central and northern Tunisia (modified after Soussi 2002).

NW–SE second order strike-slip faults parallel to the main Gafsa fault and affecting Sehib, Berda and Orbata–Bouhedma (El Mech fault) support additionally that these features are probably Atlasic features related to the Cretaceous–Tertiary tectonic inversion accompanying the closure of the Tethyan ocean rather than its opening during the Triassic–Jurassic period.

8. Conclusions

According to the geological data presented above and the results of numerous other studies integrating surface and subsurface data (seismic, facies successions, thickness and facies variation, etc.), it is thought that the tectono-sedimentary evolution

of the Chotts basin is closely associated with the Mesozoic and Cenozoic geodynamics of the North African margin. This margin appeared during the Triassic–Jurassic rifting and experienced successive compressional phases subsequent to the Africa–Europe collision that occurred since Late Cretaceous. The rifting phase which began in Tunisia in Permian times and sustained until Jurassic times is characterized by N–S to NW–SE extensional paleostress. This tectonic regime opened several pull apart basins (Misra and Mukherjee 2018; Dasgupta and Mukherjee 2017 as similar outcomes). Some negative flower structures occurred along main faults during this stage and were subsequently re-activated as positive flower faults (Hlaïem 1998, 1999; Bédier *et al.* 2000). The analysis

of seismic transects and gravity data led to conclude that the study area is divided into three distinct structural basin domains separated by main tectonic corridors. The seismic horizons correlation and structural interpretation of the seismic lines crossing the study area show that faults are organized according to E–W and NW–SE direction. These deep structures are documented in the field by the frequent occurrence of synthetic and antithetic Riedel fractures (Mukherjee 2015) and by the superimposed thrust structures along the main strike slip traces. These transpressional structures record successive Mesozoic and Cenozoic tectonic events reflecting the movements of the African and Eurasian plates.

E–W faults bounded tilted and uplifted blocks where the facies and thickness of the Jurassic–Early Cretaceous series exhibit remarkable variations. Uplifted areas in the southern shoulder part (Saharan platform) recorded active erosion registered by amalgamated major disconformities and important stratigraphic gaps during Late Jurassic–Early Cretaceous. To the north, these E–W normal faults are associated to slumping features and to the genesis of conglomeratic horizons. The NW–SE oriented faults do not exhibit any significant role in the tectonic evolution of the study area during Triassic–Jurassic; however, it seems that they acted intensively during the Cretaceous and the Cenozoic tectonic inversion of the area.

The importance of the depth of Triassic layers and the absence of true diapiric features in seismic lines, confirm the absence of Mesozoic diapirism. The Triassic outcrops identified along fault traces are previously injected along the fault zones during extensional periods.

Further surface geological investigations and detailed mapping (ongoing works) along with paleostress studies (such as Misra *et al.* 2014) will certainly improve our understanding of the geometrical and geodynamic relationships between the E–W and NW–SE faults that characterize the area. In particular, such investigations can clarify the role of the E–W and NW–SE faults in controlling both the paleogeography and basin development of the area as well as its evolution within the Mediterranean tectonic frame.

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