# Structure, paleogeographic inheritance, and deformation history of the southern Atlas foreland fold and thrust belt of Tunisia

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[1] Structural analysis of the southern Tunisian Atlas was carried out using field observation, seismic interpretation, and cross section balancing. It shows a mix of thick-skinned and thin-skinned tectonics with lateral variations in regional structural geometry and amounts of shortening controlled by NW-SE oblique ramps and tear faults. It confirms the role of the Late Triassic–Early Jurassic rifting inheritance in the structuring of the active foreland fold and thrust belt of the southern Tunisian Atlas, in particular in the development of NW-SE oblique structures such as the Gafsa fault. The Late Triassic–Early Jurassic structural pattern is characterized by a family of first-order NW-SE trending normal faults dipping to the east and by second-order E-W trending normal faults limiting a complex system of grabens and horsts. These faults have been inverted during two contractional tectonic events. The first event occurred between the middle Turonian and the late Maastrichtian and can be correlated with the onset of the convergence between Africa and Eurasia. The second event corresponding to the principal shortening tectonic event in the southern Atlas started in the Serravalian-Tortonian and is still active. During the Neogene, the southern Atlas foreland fold and thrust belt propagated on the evaporitic décollement level infilling the Late Triassic–Early Jurassic rift. The major Eocene "Atlas event," described in hinterland domains and in eastern Tunisia, did not deform significantly the southern Tunisian Atlas, which corresponded in this period to a backbulge broad depozone.

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## 1. Introduction

[2] In Tunisia, the southern Atlas Mountains correspond to an active foreland fold-thrust belt [*Ben Ayed*, 1986; *Zargouni*, 1986; *Zouari*, 1995; *Ahmadi*, 2006] limited to the west by a system of oblique ramps and tear faults accommodating several tens of kilometers of dextral offset of the southern Atlas front (Figure 1). This type of transfer zone has been described in most of the frontal parts of thrust belts, but its origin has been rarely studied in detail owing to the lack of appropriate surface and subsurface geometrical constraints. Regional studies are generally necessary to tackle such complex structural patterns. The southern Tunisian Atlas and its surroundings have been subject to petroleum exploration [*Ben Ferjani et al.*, 1990; *Mejri et al.*, 2006] and present abundant seismic reflection data and some exploration wells. Excellent outcrop conditions permit to compile structural and stratigraphic data usable to calibrate seismic interpretations.

[3] In this paper, combined surface and subsurface data are used to present an updated structural and kinematic model for the southern Tunisian Atlas and the neighboring Sahara platform and central Tunisian Atlas (Figure 1). Four balanced cross sections are constructed through the southern Atlas and the Sahara platform to constrain the geometry and style of deformation, and the role of the precontractional faults pattern on the evolving structural evolution. The geometry and origin of the oblique ramps such as the Gafsa fault, which is well known for its seismic hazard [*Ben Ayed*, 1986; *Castany*, 1955; *Saïd et al.*, 2011], are analyzed from E-W seismic reflection transects and field data, and a Late Triassic–Early Jurassic paleogeographic reconstruction is proposed. Various pulses of contractional deformation associated to the development of the southern Atlas fold and thrust belt are documented thanks to their sedimentary signatures.

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## 2. Geological Setting

### 2.1. The Atlas of Tunisia

[4] The Atlas orogen is the result of the NS to NNW directed convergence between the African and the European

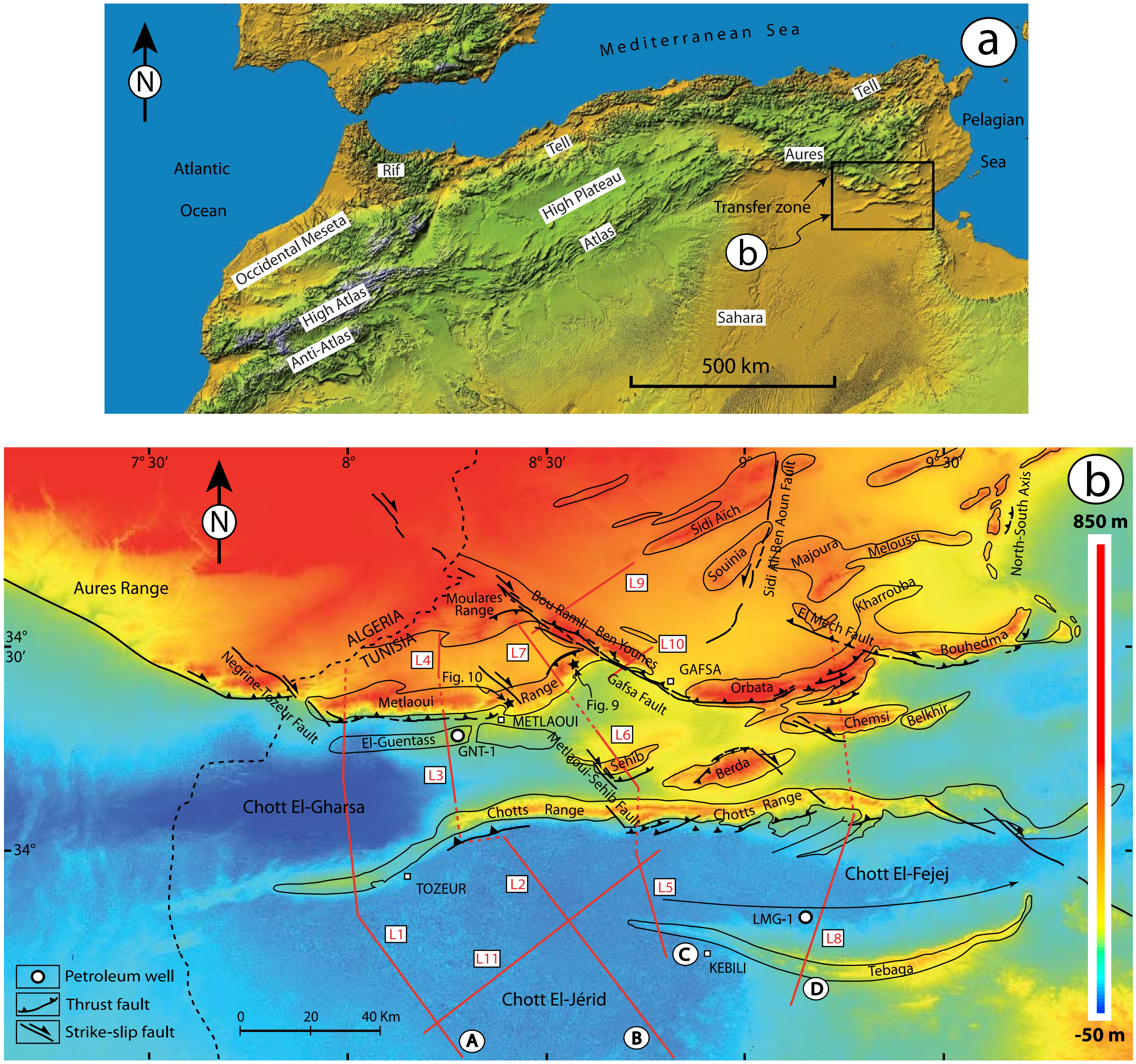


**Figure 1.** (a) Digital elevation model (DEM) of the Atlas with location of the study area. (b) Tectonic setting of central and southern Tunisia with location of the balanced cross sections (A–D) and the data set used in this study (DEM from the NASA Shuttle Radar Topography Mission GTOPO30). Continuous red lines represent reflection seismic sections (L1–L11) used for this study. Petroleum wells are also shown.

plates. The Tunisian segment of the orogen currently collides with the so-called Alboran-Kabylias-Peloritan-Calabria (ALKAPECA) domain [*Bouillin*, 1986] to the north at a tectonic convergence rate of approximately 8 mm yr$^{-1}$ [*DeMets et al.*, 1990, 1994]. It consists of two systems: the Tell and the Atlas. The Tell corresponds to an accretionary complex displaced southeastward and the Atlas is composed of folds and thrust faults trending mainly NE-SW [*Ben Ayed*, 1986; *Burollet*, 1956]. The southern Tunisian Atlas (Figure 1) is a foreland fold and thrust belt limited by several NW-SE oblique ramps or tear faults such as the Gafsa fault and the Negrine-Tozeur fault [*Outtani et al.*, 1995; *Zargouni et al.*, 1985] (Figure 1b). These oblique ramps or tear faults accommodated the decoupling between the central part of the "Maghreb indenter" [*Piqué et al.*, 1998] and its eastern edge which experienced lateral escape toward the SE [*Casero and Roure*, 1994; *Sioni*, 1996]. The Tunisian Atlas foreland basin extends onto the Sahara platform and corresponds to an active subsiding zone evidenced by the El Fejej, El Jerid, and Bou Charad "Chotts" basins (Figure 1). In the Pelagian platform of southeastern Tunisia, normal faulting along NW to NNW structural trends controlled the subsidence at least from Miocene times [*Guiraud*, 1998; *Jongsma et al.*, 1985].

[5] Episodes of widespread compressive deformation have occurred in the Atlas system since Late Cretaceous times [*Ben Ferjani et al.*, 1990; *Frizon de Lamotte*, 2009]. Two distinct episodes of orogenesis (Middle-Late Eocene-Oligocene and Late Miocene-Pliocene-Pleistocene) have been traditionally defined at regional scale [*Frizon de Lamotte*, 2009]. The Eocene "Atlas event" has been mainly evidenced

and reconstituted in Algeria [*Laffitte*, 1939; *Guiraud*, 1975; *Bracène and Frizon de Lamotte*, 2002; *Benaouali-Mebarek et al.*, 2006]. In Tunisia, it has been recently described from seismic reflection data in the Gulf of Hammamet and the adjacent Sahel coastal plain [*Khomsi et al.*, 2009]. The second orogenic episode, which spans from the Middle Miocene to the Present, is better known and traditionally subdivided into two main periods of contraction: the Serravalian-Tortonian and the Post-Villafranchian [*Aissaoui*, 1984; *Delteil*, 1982; *Ouali*, 1985; *Yaïch*, 1984; *Zouari*, 1995]. The first period of contraction resulted in the emplacement of large thrust sheets in northwestern Tunisia and of thrusts and folds in central and eastern Tunisia [*Ben Ayed*, 1986]. The second period is characterized by folding of the northern thrust sheets and enhancement of the previous structures [*Rouvier*, 1977]. *Frizon de Lamotte et al.* [2000] argue that the shortening achieved during the Serravalian-Tortonian period is probably smaller because it is mainly associated with the development of single fault propagation folds. Along with previous authors [e.g., *Burollet*, 1956; *Castany*, 1955], *Frizon de Lamotte et al.* [2000] propose a Plio-Pleistocene age for the main deformation.

### 2.2. Tectonic Setting of the Southern Tunisian Atlas

[6] This study focuses on the southern Atlas fold and thrust belt and its relationships with the Sahara foreland and the central Atlas hinterland. We present here the structural outlines of these three tectonic domains from the weakly deformed foreland basin to the internal zones of the Tunisian Atlas. The map of Figure 1b shows the morphologic expression of the active faults of the southern Tunisian Atlas.

[7] The Chott basin is an endoreic depression, which corresponds to the foreland basin of the southern Tunisian Atlas and more precisely to the foredeep depozone of the foreland basin system (according to the nomenclature of *DeCelles and Giles* [1996]). This foredeep depozone is represented by two interconnected Chotts known as the Chott El-Jérid to the west and the Chott El-Fejej to the east (Figure 1b). The Chott El-Fejej occupies the core of a mega-anticline called "Fejej dome" whose southern limb corresponds to Jebel Tebaga (Figure 1b). Previous studies based on seismic data in the Chott Jerid [*Chaari and Tremolières*, 2009] have documented the western extension of this dome. According to these authors, the anticline corresponds to a large wavelength tectonic inversion of a graben initiated in the Permian and the Triassic, which was characterized by a strong subsidence during the Late Jurassic–Early Cretaceous times. The geometry of this structure is illustrated on the regional cross sections elaborated during this study.

[8] The Southern Atlas Fold and Thrust Belt (SAFTB), known as the Gafsa basin, is bounded to the south by the Chotts Range (southern Atlas front) and to the north by the Gafsa oblique fault and the Orbata-Bouhedma Range (Figure 1b). The SAFTB comprises the Moulares Range, the E-W Metlaoui Range, and the ENE-WSW Sehib, Berda, Chemsi, and Belkhir folds (Figure 1b). The main deformation is Neogene in age and still active, as attested by the moderate regional instrumental seismicity of most of the structures [*Dlala and Hfaiedh*, 1993; *Saïd et al.*, 2009]. According to several authors [*Ahmadi et al.*, 2006; *Mercier et al.*, 1997; *Outtani et al.*, 1995], who used balanced cross sections and forward modeling to characterize the deformation, the folded structures of the SAFTB are the result of thin-skinned tectonics. Most of the anticlines observed in the basin are interpreted as fault propagation folds [*Ahmadi*, 2006]. They are asymmetric with steep or overturned forelimbs and gentle backlimbs. They consist in E-W trending, S verging anticlines, and ENE-WSW trending anticlines, which developed between major NW-SE trending oblique ramps such as the Negrine-Tozeur fault, the Metlaoui-Sehib fault, the Gafsa fault, and the El Mech fault (Figure 1b).

[9] The central Tunisian Atlas extends north of the Gafsa oblique fault and the Orbata-Bouhedma Range and is characterized by a higher mean topography than the Gafsa basin (Figure 1b). Outcrops in this region are mainly Early Cretaceous in age and the Late Cretaceous-Paleogene series are lacking. This stratigraphic hiatus characterizes the so-called "Kasserine Archipelago" [*Boltenhagen*, 1985; *Burollet*, 1956; *Gourmelen*, 1984; *Marie et al.*, 1982; *Sassi*, 1974] interpreted as an area that was uplifted and emerged during Late Cretaceous and Paleogene times. This domain is characterized by the NE-SW trending anticlines of Sidi Aïch, Souinia, Majoura, Méloussi, and Kharrouba (Figure 1b). Most of these folds have an asymmetric geometry with a southward verging. To the east, the central Tunisian Atlas is limited by the North-South axis characterized by positive flower structures and salt extrusions [*Yaïch*, 1984; *Ouali*, 1985; *Rabhi*, 1999; *Hlaiem*, 1999]. Such transpressional structures are wrongly mentioned in the entire Tunisian South Atlas, where they are often described as related to halokinetic processes [*Zargouni et al.*, 1985; *Bédir*, 1995; *Zouaghi et al.*, 2009] (Figure 1b). They correspond in fact to the reactivation of preexisting basement faults resulting in compressional or transpressional structures according to the original faults planes orientation. The diapiric extrusions occurred only along the transpressive N-S or NW-SE reactivated faults, where they resulted from remobilizations of salt by strike-slip movements [*Hlaiem*, 1999].

### 2.3. Stratigraphy and Main Décollement Levels

[10] In the Tunisian South Atlas area, only Cretaceous and Cenozoic strata and some Triassic salt injections along the Gafsa fault are outcropping. In the Gafsa and Chott basins, some wells reached the Jurassic strata, which can be correlated in seismic sections. Some deep seismic horizons suggest the presence of sedimentary formations below the Late Triassic–Early Jurassic evaporites represented by chaotic seismic facies. These deep strata can be interpreted as the continental sandstones of the basal Triassic Ouled

**Figure 2.** Synthetic stratigraphic log of the southern Tunisian Atlas with main tectonic events and unconformities. The stratigraphic log is compiled from works of *Ahmadi* [2006] and *Mannaï-Tayech* [2009]. The different thicknesses are supplied from outcropping and wells data. Tectonic events and unconformities are synthesized from previous works (see text) and the present study.

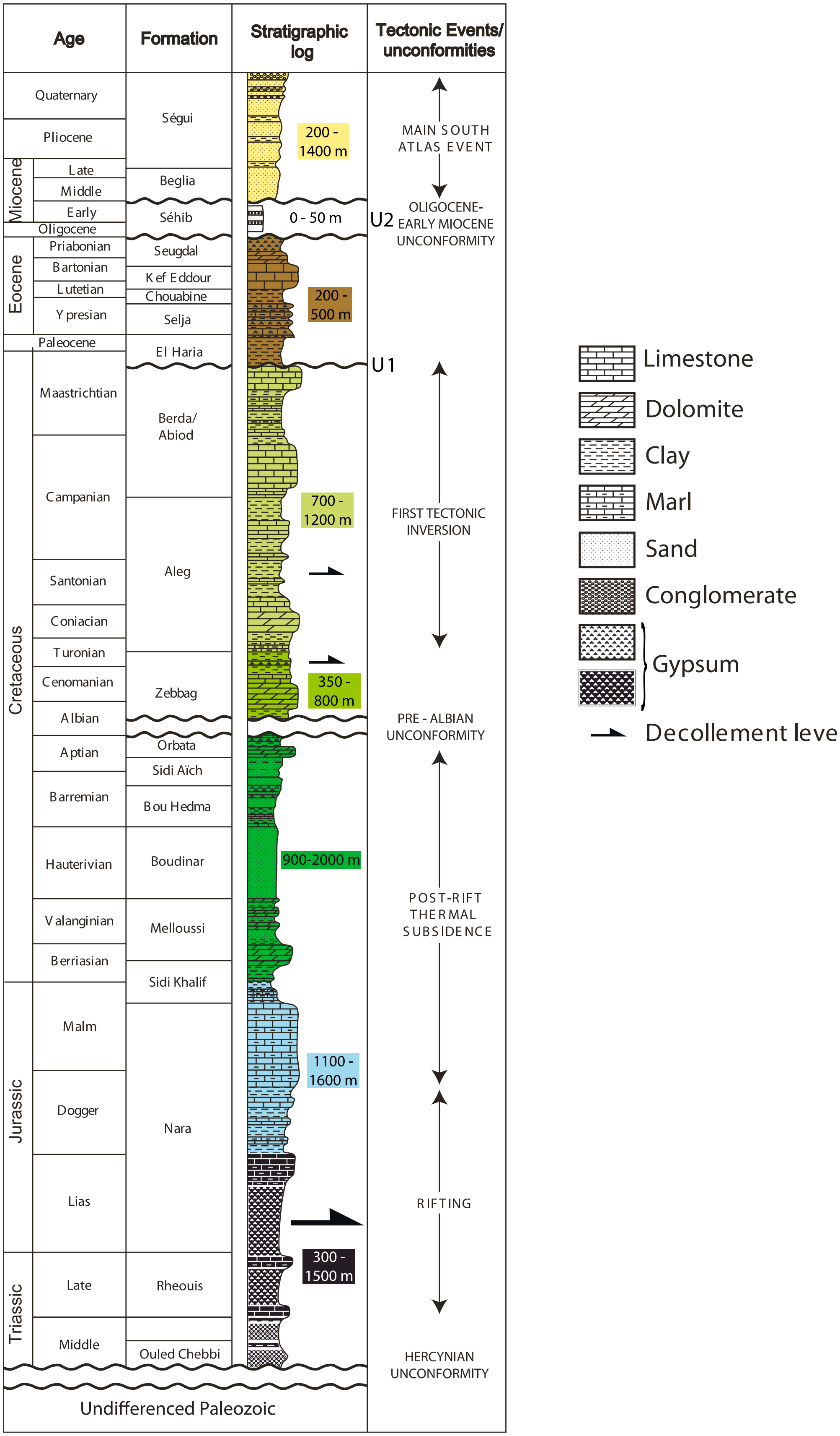
Age
Formation
Stratigraphic log
Tectonic Events/ unconformities
Quaternary
Pliocene
Miocene
Late
Middle
Early
Oligocene
Eocene
Priabonian
Bartonian
Lutetian
Ypresian
Paleocene
Cretaceous
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Jurassic
Malm
Dogger
Lias
Triassic
Late
Middle
Ségui
Beglia
Séhib
Seugdal
Kef Eddour
Chouabine
Selja
El Haria
Berda/ Abiod
Aleg
Zebbag
Orbata
Sidi Aïch
Bou Hedma
Boudinar
Melloussi
Sidi Khalif
Nara
Rheouis
Ouled Chebbi
Undifferenced Paleozoic
200 - 1400 m
0 - 50 m
200 - 500 m
700 - 1200 m
350 - 800 m
900-2000 m
1100 - 1600 m
300 - 1500 m
U2
U1
MAIN SOUTH ATLAS EVENT
OLIGOCENE-EARLY MIOCENE UNCONFORMITY
FIRST TECTONIC INVERSION
PRE - ALBIAN UNCONFORMITY
POST-RIFT THERMAL SUBSIDENCE
RIFTING
HERCYNIAN UNCONFORMITY
Limestone
Dolomite
Clay
Marl
Sand
Conglomerate
Gypsum
Decollement level

**Figure 2**

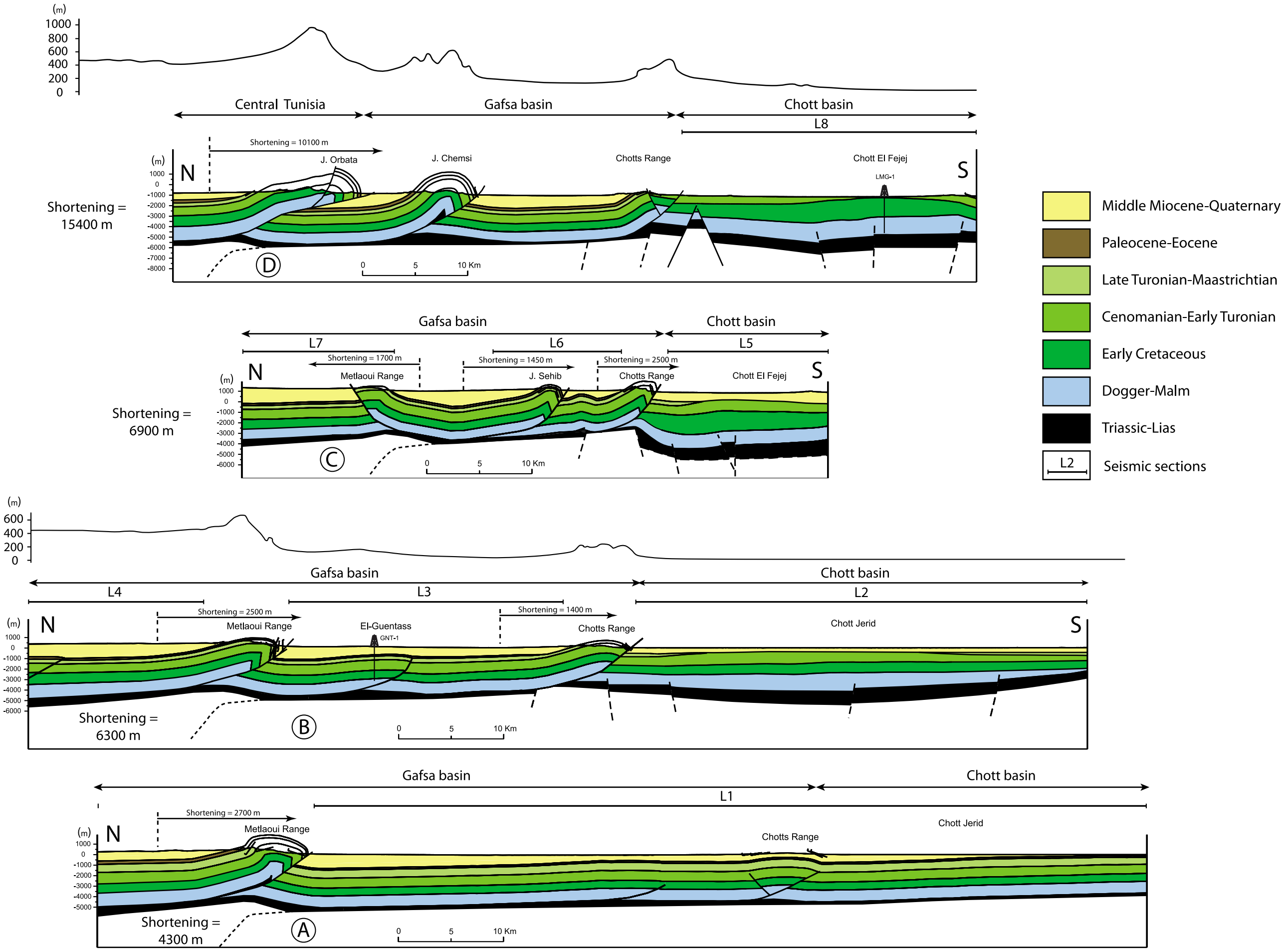


**Figure 3.** Balanced cross sections across the southern Tunisian Atlas. Detailed topographic profiles are shown for cross sections B and D. Balanced cross sections and data set are located in Figure 1b. Seismic sections used for the construction (L1–L8) are represented with continuous lines. Horizontal shortenings are calculated using Midland Valley 2DMove software.

Chebbi and Kirchaou formations [*Ben Ferjani et al.*, 1990] separated from the Paleozoic sequences by the Hercynian unconformity [*Aliev et al.*, 1971; *Boote et al.*, 1998]. In the study area, there are no wells that reached the Paleozoic, but a regional gravity model suggests the presence of a thick sedimentary Paleozoic series below the Tunisian southern Atlas [*Gabtni et al.*, 2005]. The regressive evaporitic units of the Late Triassic and Lias, deposited in grabens controlled by E-W faults and contemporaneous to the Tethyan rifting and the opening of the central Atlantic Ocean [*Bouaziz et al.*, 2002; *Frizon de Lamotte et al.*, 2011; *Raulin et al.*, 2011], constitute the main décollement level of the southern Atlas [*Vially et al.*, 1994]. They present complex salt body geometries (salt pillows and domes) mostly distributed along extensional structures that probably controlled later thrust propagations. In the Gafsa basin, between the Chotts Range and the Metlaoui Range, the presence of this chaotic evaporitic level is confirmed by the study of *Hlaiem* [1999]. It is illustrated by a regional migrated reflection seismic section crossing the Guentass anticline and the Chotts Range [*Hlaiem*, 1999, Figure 7]. The Late Jurassic–Early Cretaceous period is characterized by active subsidence and the development of an extensional sag basin [*Underdown and Redfern*, 2008]. Late Jurassic deposits consist in platform limestones and mudstones. They are overlain by an argillaceous sequence of Early Neocomian age, which can form a secondary décollement level in some places. The Late Neocomian-Aptian deposits comprise mainly sandstones (Melloussi, Boudinar, Bou Hedma and Sidi Aïch formations) and dolomites, marls and clays at the top (Orbata formation). The Albian-Maastrichtian successions are separated from the Early Cretaceous by a regional unconformity known as the Late Aptian Austrian unconformity by petroleum industry [*Klett*, 2000; *Azaïez et al.*, 2007; *Lazzez et al.*, 2008] and that we named "Pre-Albian Unconformity" in this paper (Figure 2). Late Cretaceous strata are dominated, in the lower part, by mudstones and evaporites forming incompetent levels and potential décollements (Zebbag and Aleg Formations), and, in the upper part, by shallow marine carbonates occupying the core of several folds in the Gafsa basin (Abiod formation or locally Berda formation). *Zouaghi et al.* [2009] identified in the Late Cretaceous strata six second-order seismic sequences influenced by important tectonic deformation events. These sequences are apparently unconformably overlain by the marine Late Maastrichtian, Paleocene, and Eocene

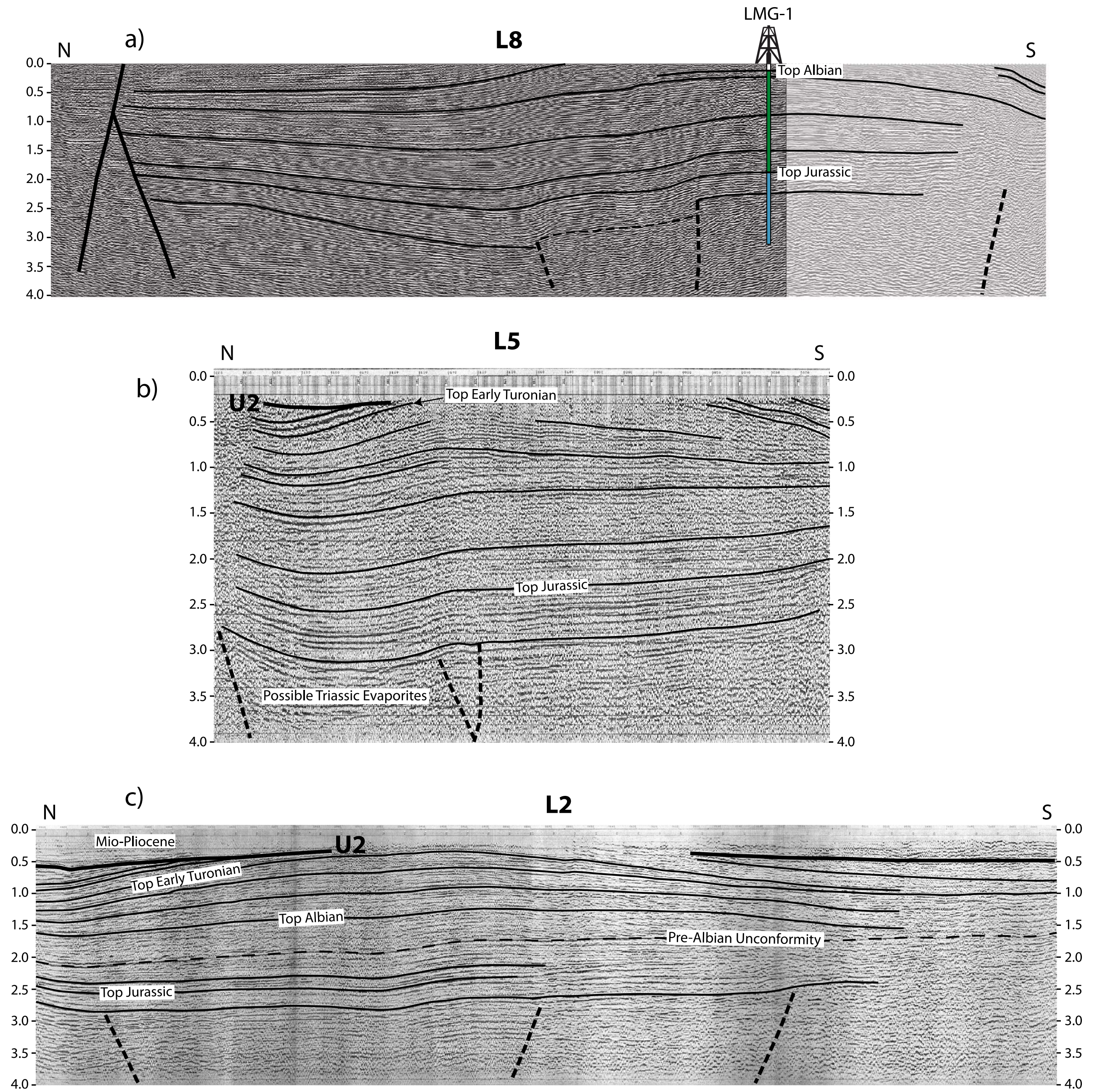


**Figure 4.** (a) Cross section L8. Interpreted seismic section crossing the Chott El-Fejej used for the construction of cross section D (Figure 3). (b) Cross section L5. Interpreted seismic section crossing the Chott El-Fejej used for the construction of cross section C (Figure 3). (c) Cross section L2. Interpreted seismic section crossing the Chott El-Jerid used for the construction of cross section B (Figure 3). U2 corresponds to the Oligocene-Early Miocene unconformity. L8, L5, and L2 are located in Figure 1b.

successions, which consist of clays, calcareous shales with intercalations of marl, interbedded gypsum, dolomite, fossiliferous limestones, and gray phosphatic limestones. In the Sehib anticline, the phosphatic clays and fine limestones of the Chouabine formation are deformed by decametric fold and thrust structures [*Ahmadi*, 2006], attesting that these levels can constitute another potential décollement. The Miocene deposits are foreland deposits separated from the underlying Eocene formations by an unconformity of probable Oligocene age, and whose erosion can reach in some places the Late Cretaceous strata, as shown by the seismic sections presented by *Zouaghi et al.* [2009]. Evidences of the Oligocene and Late Maastrichtian unconformities will be presented and discussed further in this paper. The Miocene series consist of the red continental silty sands rich in Helicidae of the Séhib formation [*Burollet*, 1956; *Mannaï-Tayech*, 2009] and the medium to coarse grained yellow sands of the Beglia formation attributed to the Serravalian-Tortonian [*Biely et al.*, 1972; *Robinson and Black*, 1974; *Mannaï-Tayech*, 2006, 2009]. The foreland Miocene series

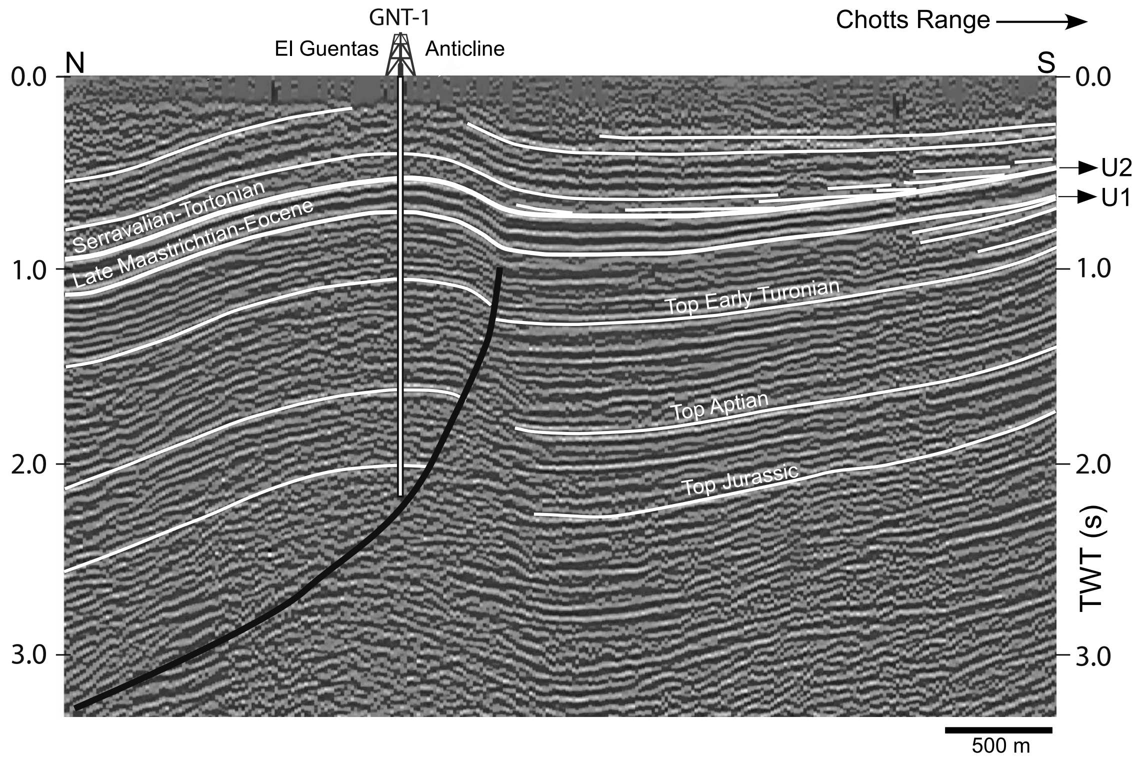


**Figure 5.** Interpreted seismic section (L3) crossing the El Guentass anticline (see location in Figure 1b). Two unconformities are outlined, U1 at the base of the early Maastrichtian and U2 sealed by the Serravalian-Tortonian Beglia formation.

are overlain by Pliocene to Quaternary continental wedgetop deposits known as the Segui formation. This latter consists of a gypseous silty to sandy succession becoming conglomeratic to the top [*Burollet*, 1956; *Castany*, 1951; *Tlig et al.*, 1991; *Zargouni et al.*, 1985] and is characterized by common growth strata patterns at the forelimb of most anticlines.

## 3. Regional Balanced Cross Sections

[11] In order to study the structural architecture of the Tunisian southern Atlas and its lateral variations, four regional balanced cross sections were constructed across the main structures of the central and southern Tunisian Atlas (Figure 3) according to thrust tectonic concepts [*Dahlstrom*, 1969; *Suppe*, 1983; *Woodward et al.*, 1985]. The cross sections were balanced using Midland Valley 2DMove Software on the basis of bed length and thickness conservation, and flexural slip algorithm. They are perpendicular to the fold axis except in the weakly deformed foreland domain where their orientation is constrained by the available seismic sections (Figure 1). The construction of the balanced cross sections is based on 1:100 000 geologic maps from the Tunisian Geological Survey, seismic and well data (see Figure 1 for location) from the Tunisian petroleum company and structural data collected during field works. The stratigraphic thicknesses of the units younger than Early Cretaceous are determined from surface outcrops and well data. The thicknesses of Jurassic and Triassic units were estimated from two-dimensional seismic data whose interpretation was calibrated by wells and outcrop data.

[12] The four balanced cross sections (Figure 1) characterized by a mix of thick-skinned and thin-skinned tectonic styles show lateral variations in regional structural geometry and amount of shortening.

[13] On cross sections B, C, and D, the Sahara foreland (Chott basin) is deformed by the partial tectonic inversion of an E-W graben apparently Triassic and Early Jurassic in age (Figure 3). This inverted structure corresponds to the well-exposed and drilled “El Fejej dome” characterized by a 5°N dipping northern limb and a 20°S dipping southern limb corresponding to the Jebel Tebaga (cross sections C and D, Figure 3). This anticline is sealed near the surface by the Chott El-Fejej salt deposits recording current subsidence of the basin. The anticline extends to the west under the Chott Jerid (cross section B, Figure 3), where it has already been described by *Chaari and Tremolières* [2009] as the results of a tectonic inversion. Toward the western boundary of the Tunisian southern Atlas (cross section A, Figure 4), the inverted Triassic-Jurassic graben disappears and the Chott basin is weakly deformed and simply records foreland subsidence. No regional evaporitic pinch outs are visible in subsurface data, and thickness variations are essentially controlled by Late Triassic–Early Jurassic normal faults.

[14] The Chotts Range corresponds to the active Tunisian southern Atlas front (Figure 1b). It is a complex fault propagation fold, which branches on the main décollement level (Triassic-Jurassic evaporites) and developed on the northern shoulder of the El Fejej inverted graben (Figure 3). The propagation of the southern Atlas front deformation was stopped by the pinch out of the Triassic-Jurassic evaporitic unit on this structural high. In the Chott basin, the main

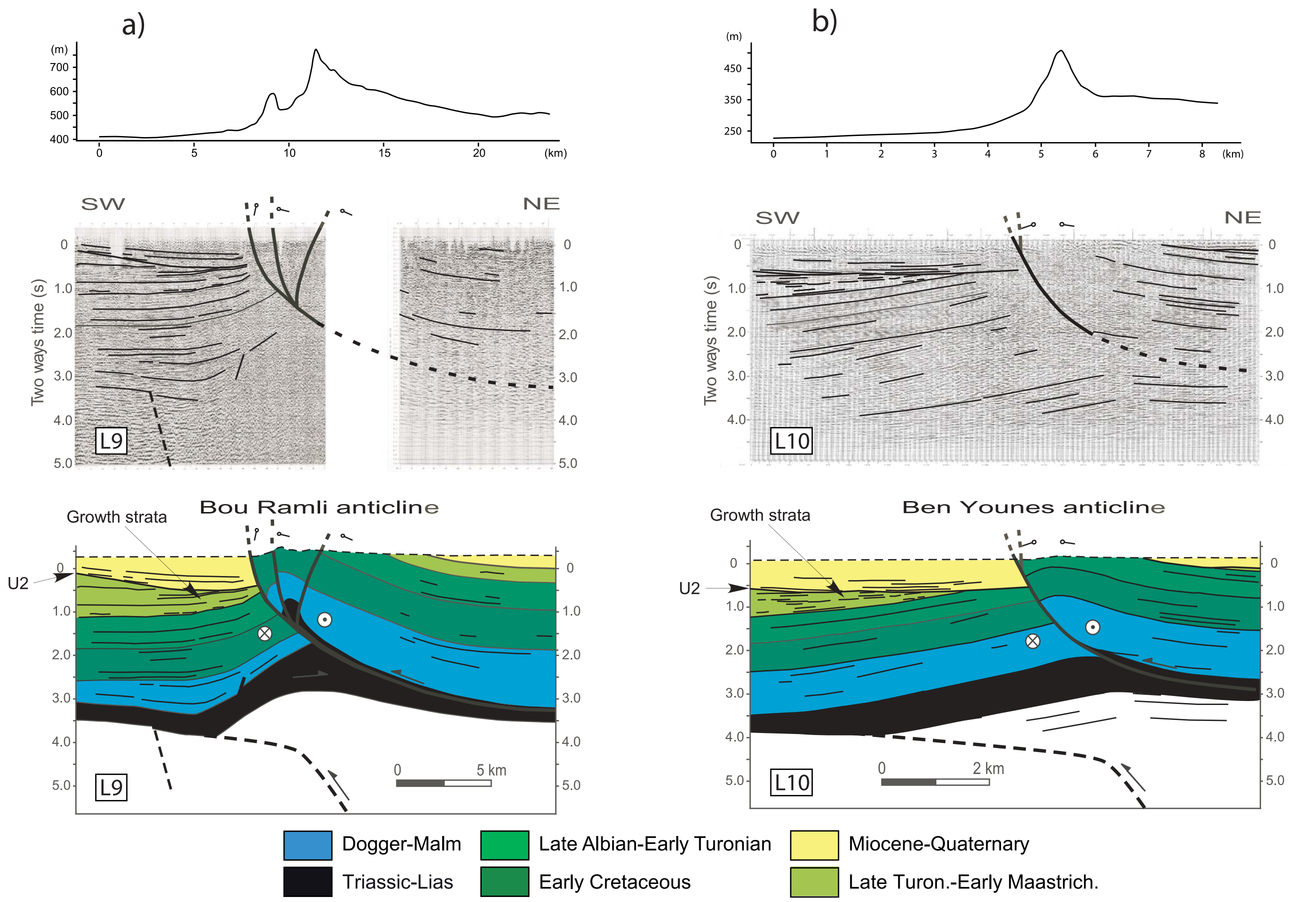


**Figure 6.** Seismic sections and corresponding geological cross sections crossing the Gafsa fault through the (a) Bou Ramli (L9) and (b) Ben Younes (L10) anticlines (see location in Figure 1). Note the topographic step related to the fault offset.

décollement is shifted downward in the El Fejej graben and becomes inactive. On cross section A, where the El Fejej graben does not exist anymore, the frontal fault propagation fold developed further to the south compared to the eastern part of the range, resulting a map curvature of the Chotts Range (Figures 1 and 3).

[15] Independent anticlines corresponding to other fault propagation folds developed north of the Chotts Range. On cross section B (Figure 3), the seismic section L3 crossing the drilled El Guentass anticline (Figure 5) shows that these fault propagation folds are also connected to the Triassic-Jurassic evaporites décollement. Seismic data suggests the presence of salt pillows that could control the thrusts propagation (Figure 3). This interpretation is also supported by the study by *Hlaiem* [1999] of the halokinesis and structural evolution in southern Tunisian Atlas. The series underlying the pillows probably correspond to the basal Triassic continental sandstones of the Ouled Chebbi and Kirchaou formations [*Ben Ferjani et al.*, 1990] as suggested by the presence of some deep seismic horizons.

[16] Further to the North, the Metlaoui and Orbata-Bouhedma ranges separated by the oblique Gafsa fault mark the southern limit of more elevated tectonic domains (digital elevation model of Figure 1b and topographic profiles in Figure 3). The corresponding topographic step requires a regional uplift and thick-skinned tectonics involving the preevaporitic substratum under the fault propagation folds of Metlaoui and Orbata (Figure 3). We interpret this thick-skinned thrusting as the complete tectonic inversion of Triassic-Jurassic normal faults dipping to the north and probably forming the southern limit of rift subbasins comparable to the El Fejej graben. This interpretation is supported by the recent gravity forward modeling of *Riley et al.* [2011], which consider also the Metlaoui frontal thrust as an inverted Mesozoic normal fault. Shortening on the deep reverse faults is transferred into the evaporitic décollement and accommodated by thin-skinned tectonics in the post-Triassic sedimentary cover. The Metlaoui Range comprises three "en echelon" fault propagation folds reflecting lateral variations in the propagation of the deformation, which may be probably linked to structural inheritance due to the Triassic-Jurassic rift geometry. In the easternmost of these folds, the shortening is accommodated by a northward verging back thrust changing drastically the geometry of the Metlaoui Range. Further to the east, the Orbata-Bouhedma anticline (cross section D, Figure 3) is part of a large thrust sheet, with 10 km of southward horizontal displacement, connected to the oblique Gafsa fault (Figures 1 and 3). The role and inheritance of the Gafsa oblique fault, which separates the central Atlas domain

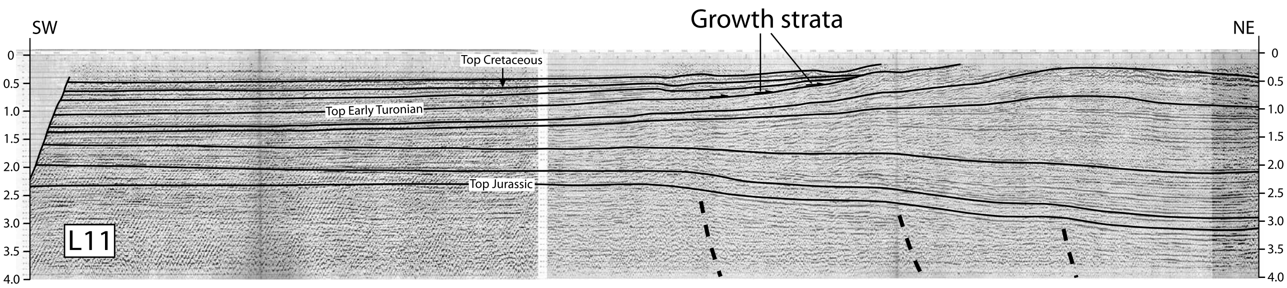


**Figure 7.** Longitudinal seismic section (L11) through the Chotts basin (see location in Figure 1b) showing the western border of the extensional Mesozoic basin and the inversion of the El Fejej graben.

from the Metlaoui domain, will be illustrated and discussed in section 4.

## 4. Oblique Ramps, Tear Faults, and Paleogeography

[17] Transfer zones have been studied by analog modeling [*Baby et al.*, 1996; *Schreurs et al.*, 2002; *Ravaglia et al.*, 2004] that showed the role of lateral variations of the mechanical stratigraphy in the development of oblique ramps and tear faults. The above structural analysis shows the importance of the Gafsa fault in the structuring of the Tunisian southern Atlas. The fault is a dextral oblique ramp striking N120°E, which constitutes an important transfer zone of horizontal displacement from the complex fault propagation fold of Métlaoui and the large thrust sheet of Orbata (Figures 1 and 3). The Gafsa oblique ramp is the longest and most active structure of the region as shown by its seismic activity [*Ben Ayed*, 1986; *Vogt*, 1993; *Saïd et al.*, 2011]. In order to better constrain its geometry and origin, we analyzed two structural cross sections through the Ben Younes and Bou Ramli anticlines, using reflection seismic data (cross sections L9 and L10, Figure 6) calibrated from field observations and previous studies [*Zouaghi et al.*, 2005, 2009]. These cross sections show that the Bou Ramli and Ben Younes anticlines correspond to fault propagation folds associated with the Gafsa fault that appears as a southwest verging thrust. The core of the Bou Ramli anticline is extruded by secondary steep opposite faults (Figure 6a) reflecting the dextral strike-slip component of the thrust. The southwest verging thrust is connected

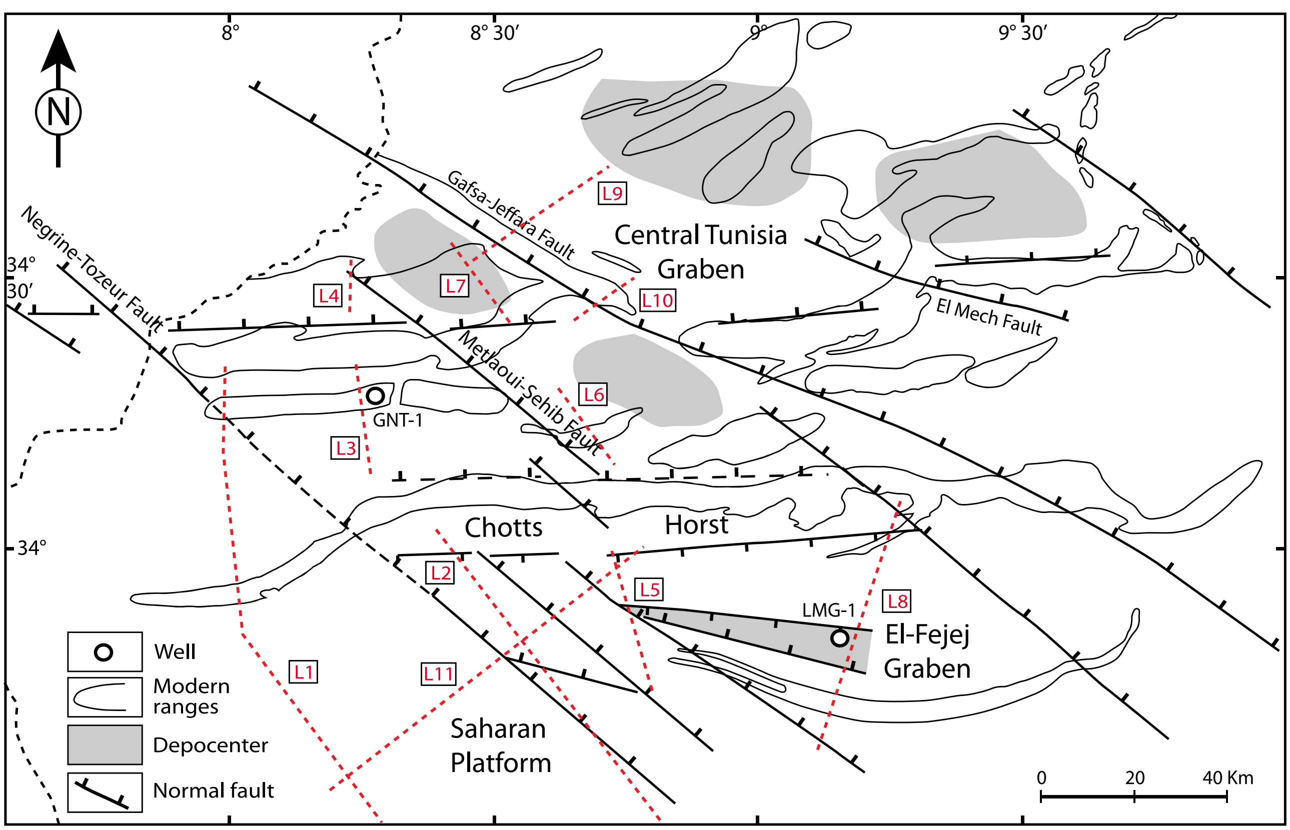


**Figure 8.** Late Triassic–Early Jurassic structural pattern of the central and southern Tunisian Atlas. Faults and depocenters are superimposed on the map of modern ranges derived from Figure 1b.


**Figure 9.** View of growth strata in the Campanian-Maastrichtian Berda/Abiod formation on the southern limb of the Metlaoui Range (see location in Figure 1b).

to the evaporitic Triassic-Jurassic décollement level of the central Atlas domain (Figures 3 and 6). In the footwall of the thrust, seismic data suggests an uplift of the pre–Late Triassic (evaporites) substratum (see deep parallel reflectors in the Figure 6b) associated to a blind deep NE dipping ramp, whose horizontal displacement propagated in the evaporitic décollement level of the Gafsa basin. The preevaporites substratum is represented by deep parallel reflectors in the seismic section L10 (Figure 6a), yet described as "sub salt beds" by *Hlaiem* [1999] and corresponding probably to continental strata of the Middle Triassic [*Ben Ferjani et al.*, 1990]. This thick-skinned thrust drove the uplift of the entire central Atlas domain that resulted in its current elevated topography with respect to the southern Tunisian Atlas (see Figures 1b and 6). The cross sections L9 and L10 (Figure 6) show that the Triassic, Jurassic and Early Cretaceous series are thicker in the hanging wall than in the footwall of the Gafsa fault. Therefore, we interpret the Gafsa footwall reverse basement fault as resulting from the inversion of the western limit of a Triassic-Jurassic graben located below the central Atlas domain. It is probably related to a shortcut near the crest of a former tilted block. This paleogeographic control of the Gafsa fault has been documented earlier by several authors [*Zargouni et al.*, 1985; *Ben Ayed*, 1986; *Zouari et al.*, 1990; *Hlaiem*, 1999]. The Orbata thrust, which branches onto the Gafsa oblique ramp, represents the southern limit of the central Atlas inverted graben. As in the Gafsa fault system, it is associated to a deep inverted basement fault driving the uplift of the central Atlas domain (see cross section D of Figure 3). Further to the east, the Orbata anticline is offset by the oblique dextral El Mech fault, which seems to present the same cartographic pattern as that of the Gafsa oblique ramp.

[18] The southern Atlas presents other NW-SE trending oblique faults. At the surface (Figure 1b), in the Gafsa and Chotts basins, the most spectacular of these oblique structures are the Negrine-Tozeur and the Metlaoui-Sehib tear faults. We interpret the Negrine-Tozeur fault as the result of the reactivation of the western border of the Late Triassic–Early Jurassic rift system. This border is clearly imaged more to the south on a NE trending seismic section (section L11, Figure 7), where it coincides with the western limit of the El Fejej graben. The westernmost of the rift faults seen on the seismic section L11 is indeed aligned with the Negrine-Tozeur tear fault limiting to the west the Métlaoui thrust. It constitutes in fact the major paleogeographic limit controlling the mega transfer zone between the Algerian and Tunisian southern Atlas fronts [*Boudjema*, 1987] (see Figure 1). Accordingly, we interpret the parallel Métlaoui-Sehib tear fault as another reactivated NW-SE trending Triassic-Jurassic normal fault. The set of NW trending parallel normal faults correspond to the first-order faults system of the Late Triassic–Early Jurassic rifting pattern; it played a major role in controlling the current structural architecture of the Tunisian southern Atlas. The map of the Figure 8 shows the paleogeographic outline that we propose for the central and southern Atlas domains.

## 5. Timing of Compressive Deformation

[19] In the study area, field observations and seismic imagery permit to evidence unconformities and syntectonic deposits recording several periods of compressive deformation from Late Cretaceous times to the present. We present here the sedimentary signatures of the different pulses of compressive deformation associated with the development of the southern Atlas fold and thrust belt.

[20] Late Cretaceous syntectonic sedimentation has been already described by several authors [*Hlaiem*, 1999; *Zargouni*, 1986; *Zouaghi et al.*, 2009]. In the central Atlas domain of the study area, the Kasserine Archipelago [e.g., *Burollet*, 1956; *Zouaghi et al.*, 2009] comprises a set of NE-SW trending anticlines whose amplification has been recorded since the middle Turonian [*Zouaghi et al.*, 2009]. This early compressive deformation period is imaged by the seismic information in the footwall of the Gafsa fault (Figure 6), where late Turonian growth strata onlap the southwestern limb of the ramp anticline. These growth strata have been also observed by *Zouaghi et al.* [2009], which have generated isopach maps of the Late Cretaceous major sequences in the Gafsa region. The time isopach map of the Turonian supersequence [*Zouaghi et al.*, 2009, Figure 10] shows clearly the uplift of the NW-SE Gafsa Ridge due to the first inversion event of the central Atlas. This first contractional tectonics continued until the Maastrichtian and drove the emersion of the famous central Tunisia Islets mentioned above (known also as Kasserine Archipelago) and characterized by the absence of Coniacian-Maastrichtian deposits

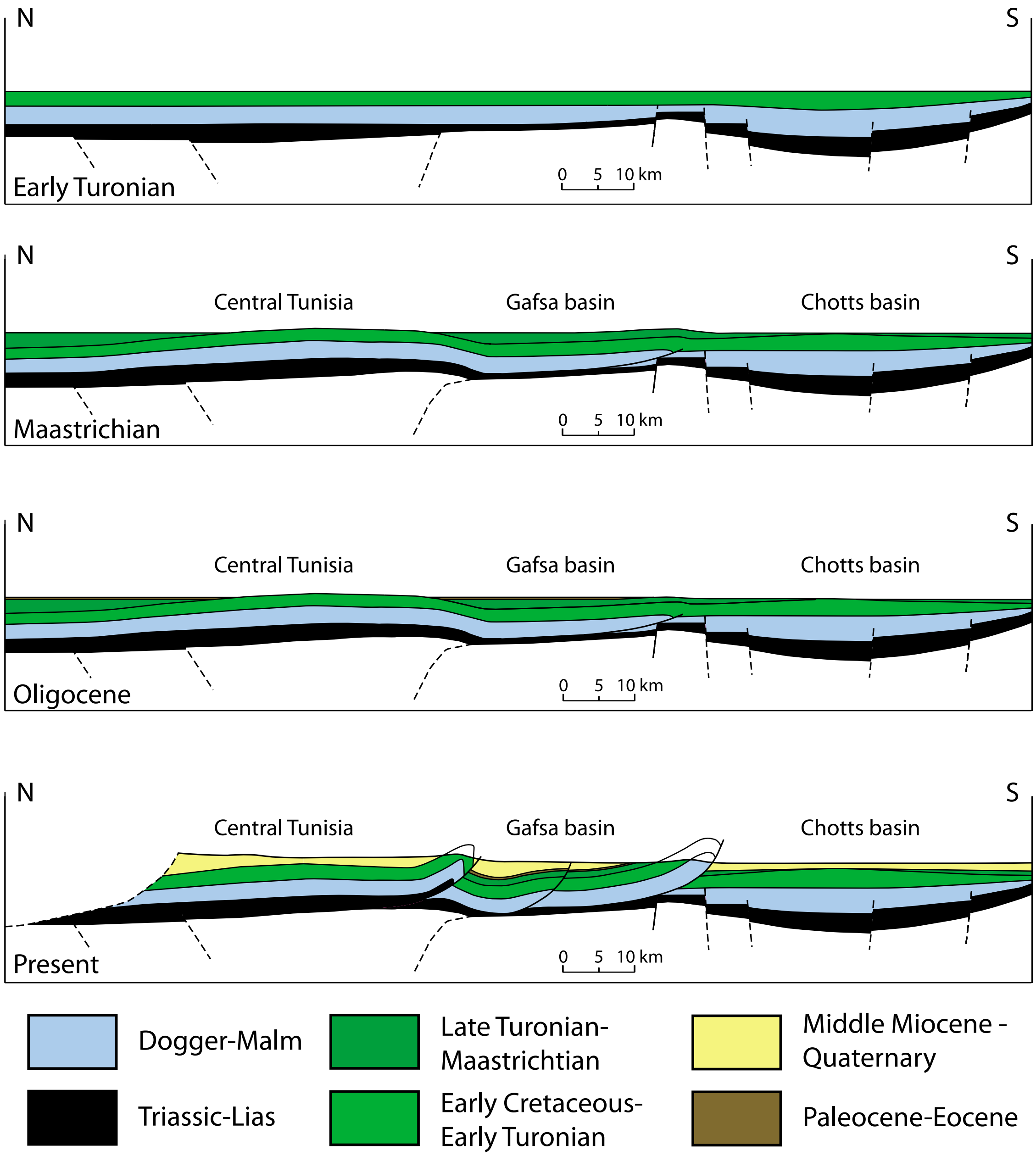


**Figure 10.** Schematic kinematic evolution of the central and southern Tunisian Atlas illustrating the mean stages since the Late Cretaceous to the Present.

[*Zouaghi et al.*, 2009]. Late Turonian growth strata are also observed on the limbs of the dome of the El Fejej inverted graben (Figure 7), and in the exposed southern limb of the Métlaoui Range (Figure 9). To summarize, the Late Cretaceous growth strata patterns observed in different contractional structures of the study area recorded incipient tectonic inversion of the Triassic-Jurassic rifts.

[21] The seismic section L3 crossing the El Guentass anticline (Figure 5) and calibrated by the GNT-1 well [*Zouaghi et al.*, 2009] supplies valuable information on the timing of deformation. Late Cretaceous deformation is expressed in the southernmost part of the section (northern limb of the Chotts Range), where Cretaceous reflectors are truncated by an unconformity (U1, Figure 5) located in the late Maastrichtian, at the base of the clay of the Haria formation (Figure 2). U1 seals the first pulse of contractional deformation, which therefore ended in the late Maastrichtian. The Paleocene-Eocene strata are represented by strong reflectors capped by a younger unconformity (U2, Figure 5). Above this unconformity, the Neogene foreland infill begins with the Serravalian-Tortonian Beglia formation, which onlaps the northern limb of the Chotts Range. This onlap is outcropping in the Chott Range, where the Paleocene-Eocene strata are entirely eroded. Indeed, *Chaari and Tremolières* [2009] described in the Chotts Range an erosional surface truncating the Late Cretaceous Berda formation and sealed by the Beglia formation. According to these authors, the angle between the Cretaceous and the erosional surface is 7° and between the Cretaceous and Miocene 10°. This Serravalian-Tortonian growth strata pattern recorded the onset of

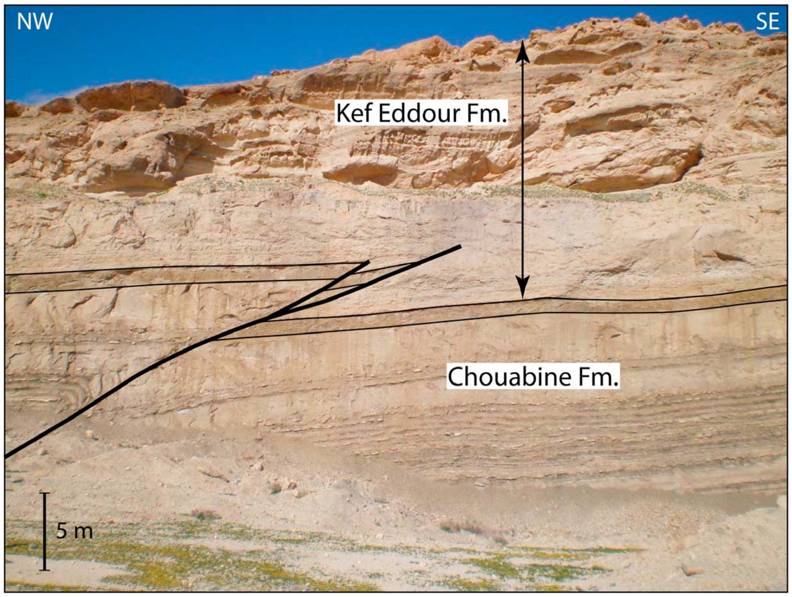


**Figure 11.** View of Eocene compressive deformation observed in the Métlaoui mine (see location in Figure 1b). The slip on the reverse fault is about 10 m.

the Neogene propagation of the Chotts Range thrust (see Figure 3), which apparently suffered a first uplift during the Late Cretaceous contractional event sealed by the erosional surface U1 (Figure 5). Between U1 and U2, the Paleocene-Eocene series do not show growth strata patterns and seem to have recorded a period a relative tectonic quiescence in this region. In the footwall of the Gafsa fault (Figure 6), the Neogene deposits onlap also U2, which corresponds to a strong angular unconformity truncating the Late Cretaceous strata deformed by the first inversion event (Late Cretaceous). This erosional surface is also visible on the Chott El-Fejej inverted graben (Figure 4).

## 6. Discussion

### 6.1. Mesozoic Inheritance

[22] The present structural analysis confirms the role of the Mesozoic rifting inheritance in the development of the active foreland fold and thrust belt of the southern Atlas. Indeed, the current structural pattern of the southern Atlas mimics the paleostructural map of the Mesozoic complex extensional period (Figure 8). In continental Tunisia, various authors have described a Late Triassic–Early Jurassic rifting followed by a period of thermal subsidence from Mid-Jurassic to Early Cretaceous [*Kamoun et al.*, 2001; *Bouaziz et al.*, 2002]. This is consistent with our observations showing that Mesozoic normal faults die generally in the Jurassic infilling (Figures 3, 4, and 7). The Jurassic structural pattern derived from our study (Figure 8) is characterized by a family of first-order NW-SE trending normal faults dipping to the east and by second-order normal faults trending E-W, defining a lozenge-shaped system of grabens and horsts (Figure 8). The geometry of the evaporitic units disturbed by halokinetic structures played an important role in the localization and development mode of some thrust folds. The most striking inheritance is due to the NW-SE trending normal fault set, which now controls the dextral oblique transfer zones from the El Mech fault to the Negrine-Tozeur fault (Figure 1b). The later fault corresponded to the western margin of the Triassic-Jurassic basin and induced during the inversion the apparent dextral offset of the southern Atlas front between Tunisia and Algeria.

### 6.2. Foreland Evolution

[23] The Tunisian South Atlas foreland evolution is resumed in Figure 10. The Late Triassic–Early Jurassic rifting faults have been inverted during two contractional tectonic events. The first contractional event occurred between the middle Turonian and the late Maastrichtian and can be correlated with the onset of the Africa-Eurasia convergence [*Dewey et al.*, 1989; *Stampfli et al.*, 1991; *Dercourt et al.*, 1993; *Frizon de Lamotte*, 2009]. Inversion of the central Tunisia graben and of the El Fejej graben began during this first pulse of contractional deformation. This deformation is sealed by a late Maastrichtian unconformity (U1), which marks the initiation of a period of relative tectonic quiescence in this region as no significant syntectonic sedimentation is detected in the Paleocene and Eocene intervals. The only Eocene deformation observed in the study area is expressed by decametric fault propagation folds sealed by phosphate deposits as documented by *El Ghali et al.* [2003] in the Metlaoui mine (Figure 11). Therefore, the major Eocene "Atlas event" described in the Algerian Atlas [*Laffitte*, 1939; *Bracène and Frizon de Lamotte*, 2002; *Benaouali-Mebarek et al.*, 2006] or in eastern Tunisia (Gulf of Hammamet and adjacent Sahel coastal plain) [*Khomsi et al.*, 2009] did not apparently deform significantly the Gafsa basin and surrounding areas. These areas likely corresponded to the distal part of the Eocene Atlas foreland basin system. In such a context, the Paleocene-Eocene phosphatic limestones and clays of the Gafsa area may have deposited in the shallow and broad backbulge zone of the Paleogene foreland basin system (according to the nomenclature of *DeCelles and Giles* [1996]). The Eocene is

capped by a regional unconformity (U2), which started to develop in Oligocene times. The U2 unconformity is deformed by the Neogene thrust tectonics and sealed by Serravalian-Tortonian growth strata on the flanks of the main thrust anticlines. These deposits recorded the onset of the principal and still active thrust propagation in the southern Atlas. In some places, a condensed sedimentary package called Sehib formation and including probably the Oligocene and the Early Miocene [*Mannaï-Tayech*, 2009] is preserved. This condensed series, equivalent to the U2 disconformity (see Figure 2), recorded the post-Eocene period of tectonic quiescence, largely described in the Algerian Atlas [*Laffitte*, 1939; *Guiraud*, 1975; *Bracène and Frizon de Lamotte*, 2002; *Benaouali-Mebarek et al.*, 2006] where it signed the end of the so-called "Atlas event."

## 7. Conclusions

[24] Deformation in the southern Tunisian Atlas fold and thrust belt is characterized by a mix of thick-skinned and thin-skinned E-W thrust structures partitioned by the development of NW-SE oblique ramps and tear faults. The origin of such structural pattern is related to the inversion of a Late Triassic–Early Jurassic rift system composed by a family of first-order NW-SE trending normal faults dipping to the east and by second-order E-W trending normal faults.

[25] The more significant inverted NW-SE faults are the Gafsa oblique ramp and the Negrine-Tozeur tear fault. The Gafsa oblique ramp is still active and presents the most important lateral shortening. It is absorbed by the Orbata thrust, which constitutes its frontal termination. The Negrine-Tozeur tear fault marks another important paleogeographic limit; it corresponded to the western margin of the Triassic-Jurassic basin and drove the apparent dextral offset of the southern Atlas thrust front between Tunisia and Algeria. Such models of transfer zones related to Mesozoic rifting can be probably exported to other parts of the Tethys realm.

[26] The first event of inversion tectonics in the Tunisian South Atlas occurred during the late Turonian–early Maastrichtian interval. From the late Maastrichtian to the end of the Eocene, the study area corresponded to the backbulge depozone of the Atlas foreland basin system. The Oligocene and Early Miocene was a period of tectonic quiescence with erosion or poor sedimentation. The principal shortening tectonic event in the southern Tunisian Atlas started in the Serravalian-Tortonian and is still active. This timing of compressional events must be compared with other parts of the Atlas Mountains to better understand the propagation of the orogenic wedge and the associated foreland basin system. It is obvious that a contractional event defined in one part of the orogen is differently recorded in other part. A big work is left to do in the Atlas System.

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