

## The Southern Atlas Front in Tunisia: Regional-Scale Geometry and Structural Evolution

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### Abstract

This chapter provides an overview of data-compilation, recently published, as well as newly collected data on the structure and evolution of Southern Atlas front in Tunisia. The Northern Chotts Range, one of most geologic features in southern Atlas, separates a dominantly deformed area of Gafsa to the north, from a relatively undeformed area of Chotts basin and Saharan platform to the south. The Cenozoic contractional period shapes a chain with mixed thick- and thin-skinned tectonic style, controlled by deep-seated basement faults with shallower décollement within the sedimentary cover. The present-day general “en echelon” fold distribution of the overall Northern Chotts Range, the age and the geometry of units, are likely the surface expression of the “en echelon” WNW- to- NW-trending faulting, which controls the fold’s emplacement and style. These systems usually exhibit a fault kinematics, with striation showing a multiphase history. During Mesozoic times, the extensional activity of WNW- to- NW-trending normal faults is associated with significant thickness and/or facies variations comprising abundant syntectonic sequences. The growth of major synsedimentary typical normal fault systems, which produce a general framework delivering tilted blocks basin geometry, displays well-developed half-graben fill and large rollover structures along the southern Atlas. The Northern Chotts Range is, therefore, considered as the results of the Mesozoic inherited faults

reverse–reactivation. The Chotts basin was previously considered as a large anticline related to the Cenozoic compressional events to explain the gentle deep observed “antiform structure”. It was, therefore, marked as the far-foreland of the southern Tunisian Atlas. Like many other inverted margin, extensional inherited structures are still preserved in the southern Tunisian Atlas. The Chotts preserves Mesozoic extensional structures, of which the so-called Chotts anticline is defined in this study as large inherited rollover structure. The subsequent tertiary compressional front will be, therefore, repositioned in the Northern Chotts Range Front.

### Keywords

Tectonic inversion • Sequential restoration • Tethyan rifting • Chotts basin • Southern Atlas • Tunisia

### 5.1 Introduction

The relative motions between Africa and Europe have recorded, in Tunisian Atlas, a kinematic evolution of a long-living Alpine foreland structure. In northwestern Africa, the Maghrebian fold-and-thrust belt extends about 2000 km from Morocco to Tunisia. This chain, which define the Atlas orogen, is acknowledged as one of some type-example of intercontinental chain (Ziegler et al. 1995; Guiraud 1998; Beauchamp et al. 1999; Frizon de Lamotte et al. 2000; Laville et al. 2004; Roure et al. 2012; Gharbi et al. 2015). This belt result from polyphase tectonic history related to the collision between Africa and Eurasia started at about 70 Ma (Roure and Colletta 1996; Bracène and Frizon de Lamotte 2002; Guiraud et al. 2005; Said et al. 2011b; Frizon de Lamotte et al. 2011; Masrouhi and Koyi 2012; Roure et al. 2012; Masrouhi et al. 2014a, b; Van Hinsbergen et al. 2014; Gharbi et al. 2015; El Amari et al. 2016). The complex geodynamic history shaped this belt, records mainly two major periods. The first one of Mesozoic rifting

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occurred after the late Paleozoic collision with Laurasia, is followed by passive margin stage defined the Tethyan Mesozoic evolution. A second Cenozoic period during which active compressional tectonic prevailed from Late Cretaceous to present-day (Ziegler et al. 1995; Piqué et al. 2002; Laville et al. 2004; Guiraud et al. 2005; Said et al. 2011b; Roure et al. 2012; Gharbi et al. 2013, 2015; El Amari et al. 2016). This period is responsible for the major uplift in the evolution of the belt overprinting the inherited Tethyan structures during successive stages. The overprinting of two different large-scale system is expressed in the Southern Atlas of Tunisia by multidirectional structures.

Different tectonics reconstructions and/or models were made to explain the multidirectional structures along the Southern Atlas of Tunisia. Previous studies of the structural styles in southern Atlas of Tunisia distinguish four different models and can be summarized as follows: (i) “en echelon folds related mainly to the NW-trending dominant strike slip faults (Zargouni 1984; Zargouni et al. 1985; Abbès and Zargouni 1986; Burolet 1991; Abbès et al. 1994; Bédir et al. 2001) (ii) recent thrust systems deformed the sedimentary cover with a preferential decollement level localized in the Triassic evaporites themselves separate the sedimentary cover from the rigid ante-Mesozoic basement (Outtani et al. 1995; Ahmadi et al. 2006, 2013) (iii) active Mesozoic salt diapirism nucleated the subsequent fold location (Hlaiem 1999; Zouaghi et al. 2011) (iv) reactivation of preexisting Mesozoic inherited faults coupled to variable distribution of sequences led to identify a shallow decollement levels and recorded deep basement fault inversion at depth (Gharbi et al. 2013, 2015; El Amari et al. 2016).

This paper summarizes the tectono-sedimentary data acquired during the last decade in the South Atlas front of Tunisia. Data are coupled to new seismic interpretation to reconstruct the tectonic style and deformation history of the far-foreland of Tunisia. Sequential restoration has been developed to consider the style of extension during the Mesozoic times. The extension amount is calculated (amount of extension/Time) for keys-periods to precise the rift stage expansion of the southern Tethyan margin in Tunisia.

## 5.2 Geological Setting

### 5.2.1 Structural Pattern

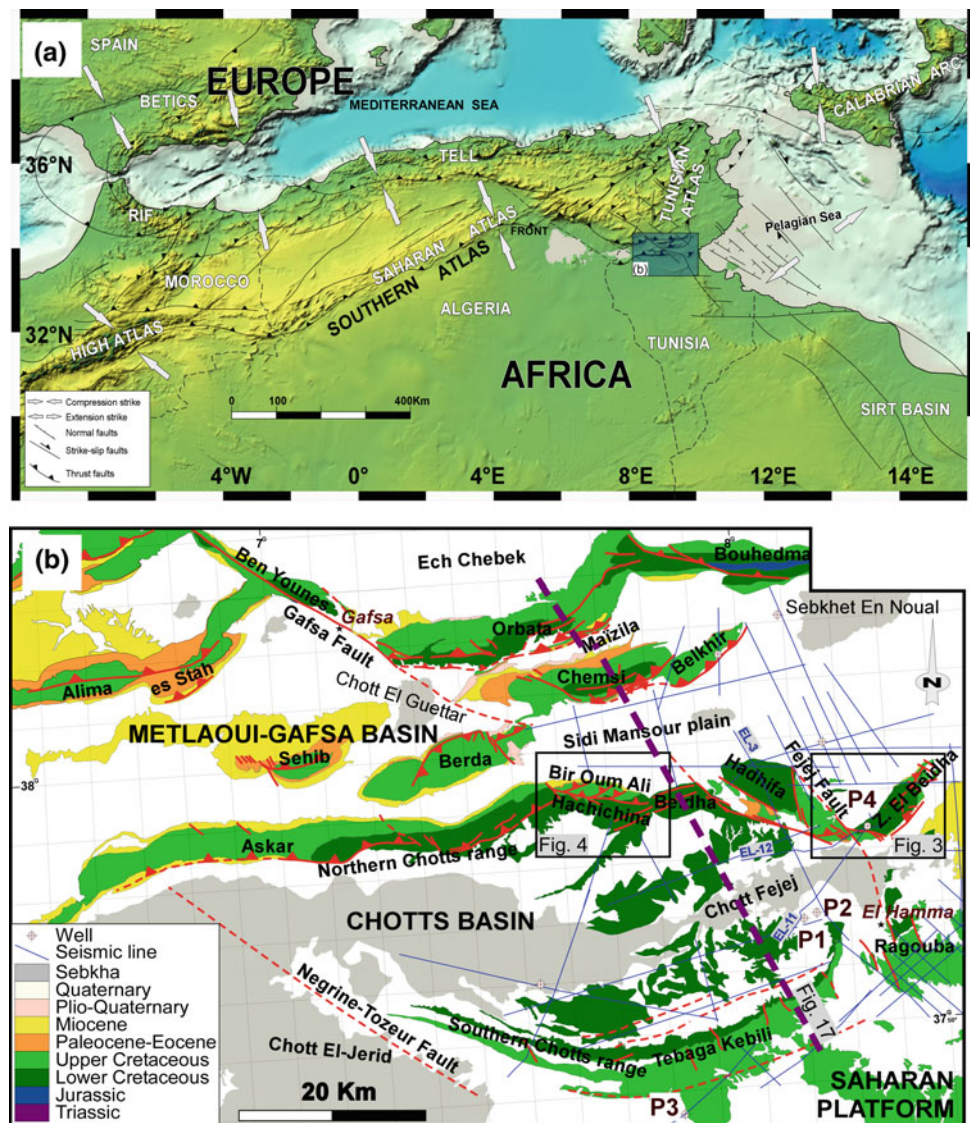
The Atlas Mountains, that extends from Morocco to Tunisia, is a fold-and-thrust belt (named by authors the Maghrebides belt) formed during the alpine orogeny. The eastern part of this belt (Fig. 5.1a) lies the Tunisian domain including: (i) the Tellian domain in the north which corresponds to the Alpine Tellian thrust range. This orogen consists, in its

Tunisian portion, of thrust sheets transported southeastward during Middle Miocene paroxysmal compressional event. (ii) In the south, the Tunisian Atlas is divided into three domains, so-called by authors as the Northern, the Central, and the Southern Tunisian Atlas.

Major NW-trending lateral strike-slip faults (Gafsa and Negrine-Tozeur, Fig. 5.1b) are recognized in the southern Tunisian Atlas fold-and-thrust belt. They were structurally connected to the present-day distribution of folds during the 70s and 80s reconstructions. The 100-km-long Gafsa's dextral strike-slip fault is a NW-trending system, which cuts the Bou Ramli, Ben Younes and Orbata anticlines in the north and the Zemlet el Beidha and Koudiat Hammamet anticlines in the south (Zargouni 1984; Zargouni et al. 1985; Abbès and Zargouni 1986; Burolet 1991; Abbès et al. 1994; Hlaiem 1999). Westward, the Gafsa–Metlaoui basin is recognized by previous work as delineated by a second dextral strike-slip fault system named Negrine–Tozeur fault (Zargouni 1984; Zargouni et al. 1985). In the eastern part, and from north to south, the Sehib, Berda, Chemsî and Belkheir folds separate the Gafsa–Metlaoui basin from the northern Chotts range (Fig. 5.1b). The Northern Chotts range lies the southernmost folded segment in the Southern Atlas Front of Tunisia, which is composed of the Askar, Bir Oum Ali, Hachichina, Beidha, and Zemlet el Beidha anticlines. These aforementioned east-trending anticlines, separate the Metlaoui–Gafsa Basin from the Chotts Basin in the south. The gentle south-dipping series observed at the southern Chotts Range, were used to interpret the Chotts basin as a large anticline bounded by the curved Tebaga de Kebili ridge at the southern edge of the Chotts El-Fejej (Zargouni and Abbes 1987; Fakraoui 1990; Bouaziz et al. 1994; Swezey 1996). Otherwise, the Chotts basin is a foredeep depozone of the Atlassic foreland system (DeCelles and Giles 1996; Said et al. 2011b; Gharbi et al. 2013, 2015). This basin is considered as a Mesozoic graben bordered, to the northern and southern sides, by contemporaneous normal fault systems (Fig. 5.1b). More recently, Gharbi et al. (2015) published a ~120 km-long-balanced cross-section of region. Authors were interpreted for the first time that this large anticline is likely a wide Mesozoic rollover limited to the south by the preserved Tebaga Kebili normal fault system.

The present-day southern Tunisian Atlas fold-and-thrust belt shape is the result of the positive inversion of the southern Tunisian Tethyan margin mini-basins of compressional tectonic that prevailed during Cenozoic times, shows two main contractional stages. The first stage corresponds to the rifting stage, highlighted for Late Permian (?) to the Early Cretaceous (Guiraud 1998; Piqué et al. 2002). An extensional tectonic regime dominates this period which is contemporaneous with the Tethyan and Atlantic opening. Early Triassic salt basins were formed, during the earlier stage of this evolution (Soussi et al. 2017) covered all of

**Fig. 5.1** **a** Structural sketch map of the Atlas belt within its geodynamics context. Gray arrows represent the present-day NW to N oriented horizontal compression related to the convergence between Africa and Europe (after Michard et al. 2002; Faccenna et al. 2004; Serpelloni et al. 2007; Billi et al. 2011). Black square indicates the location of the study area. **b** Simplified geological map of the southern Atlas foreland of Tunisia. Using the geographic Coordinate system (modified Gharbi et al. 2015). Locations of seismic lines (with blue colors) and wells are shown (with red colors). Detailed geological map of the Zelmet el Beidha of Fig. 5.3 and the Bir Oum Ali–Hachichina structure of Fig. 5.9 are shown by the black frame



what is now Tunisia. The extensional setting prevailed during Jurassic and Early Cretaceous (Boughdiri et al. 2007; Souquet et al. 1997; Masrouhi and Koyi 2012; Masrouhi et al. 2014a) is related to the opening of Tethyan and the Central Atlantic. This extensional tectonic regime was also accompanied, in several regions of the Atlas, by volcanic and halokinetic activity testifying to the extensional nature of these periods (Laaridhi-Ouazaa 1994; Guiraud et al. 2005; Mattoussi Kort et al. 2009; Masrouhi et al. 2014a, b). During Aptian–Albian times, the extensional activity is associated with WNW- to NW-trending normal faults that are associated with significant thickness and/or facies variations comprising abundant syntectonic sequences (Gharbi et al. 2013), in addition to active salt tectonic. The Aptian–Albian times are identified as time of maximum extension in the Tunisian southern Tethyan margin basins, which are especially well documented for the Early Cretaceous rifting stage

(Souquet et al. 1997; Bouaziz et al. 1999; Gharbi et al. 2013; Masrouhi et al. 2014b; El Amari et al. 2016). During Cenomanian to Santonian times, the Tethyan extensional basin in Tunisia has received mostly pelagic to hemi-pelagic sediments, typifying a slow deposition product of a post-rift subsidence-related sequences (Morgan et al. 1998; Gharbi et al. 2015).

The second main stage, started since Late Cretaceous, corresponds to compressive events that had caused the inversion along the inherited normal fault and the initiation of folding and trigger a positive tectonic inversion related to the Africa and Eurasia plate convergence (Guiraud and Bosworth 1997). The southern foreland fold-and-thrust belt of Tunisia results from two main superimposed compressional events: Mid-to-late Eocene defining the Atlassic contractional event (Frizon De Lamotte et al. 2000; Masrouhi et al. 2008; Khomsi et al. 2009; Gharbi et al. 2015)



and Middle–Late Miocene to present-day compression corresponding to the Alpine compression event (Zargouni and Ruhland 1981; Zargouni and Termolières 1981; Zouari et al. 1990; Chihi 1992; Dlala 1992; Said et al. 2011a; Gharbi et al. 2014; El Amari et al. 2016).

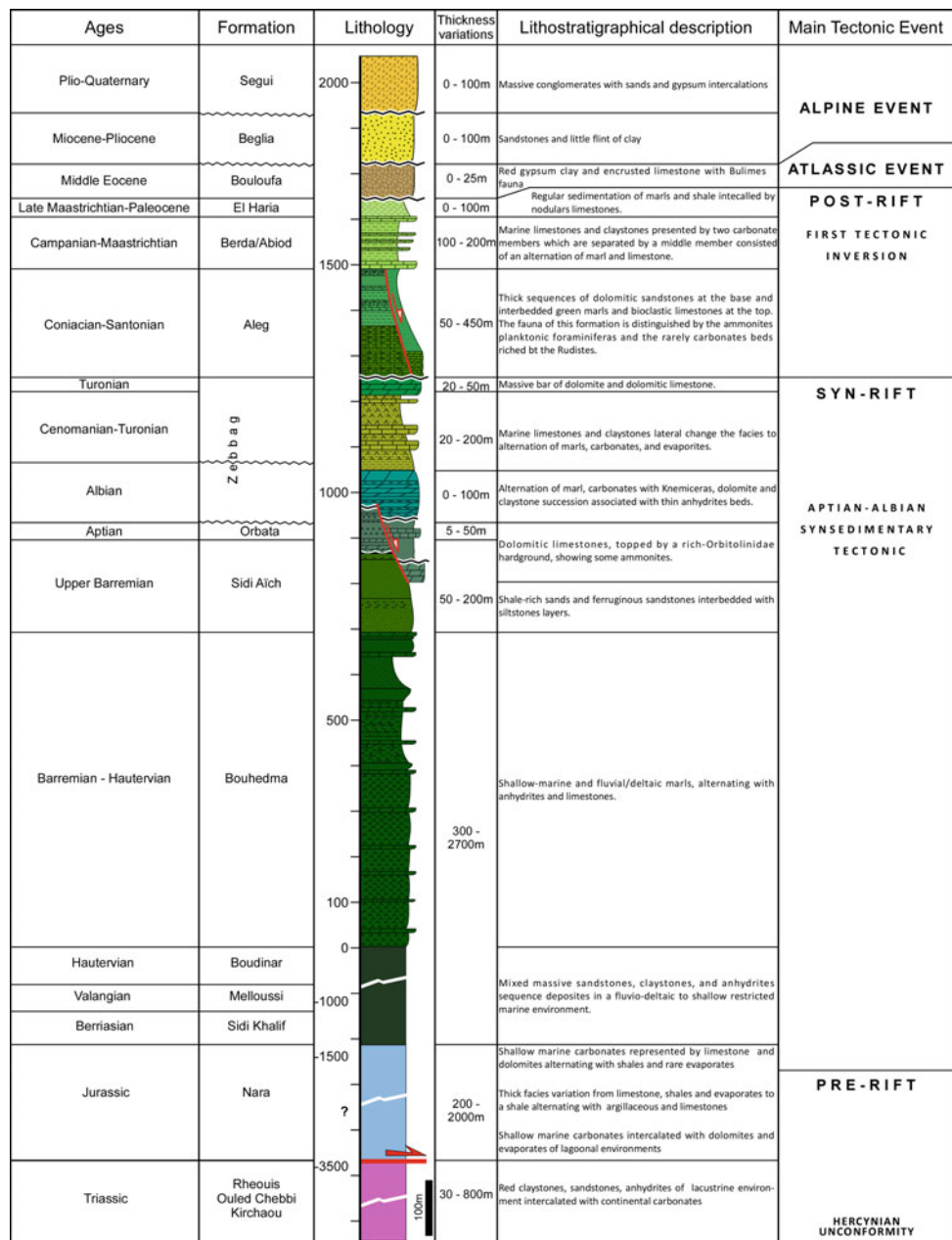
### 5.2.2 Generalized Lithostratigraphy of the Southern Atlas Domain

The lithostratigraphy of the southern Atlas of Tunisia domain is derived from outcrops around the Chotts Basin and exploration well data. The Mesozoic–Cenozoic

lithostratigraphy of units that are exposed in study area is illustrated in the log of Fig. 5.2.

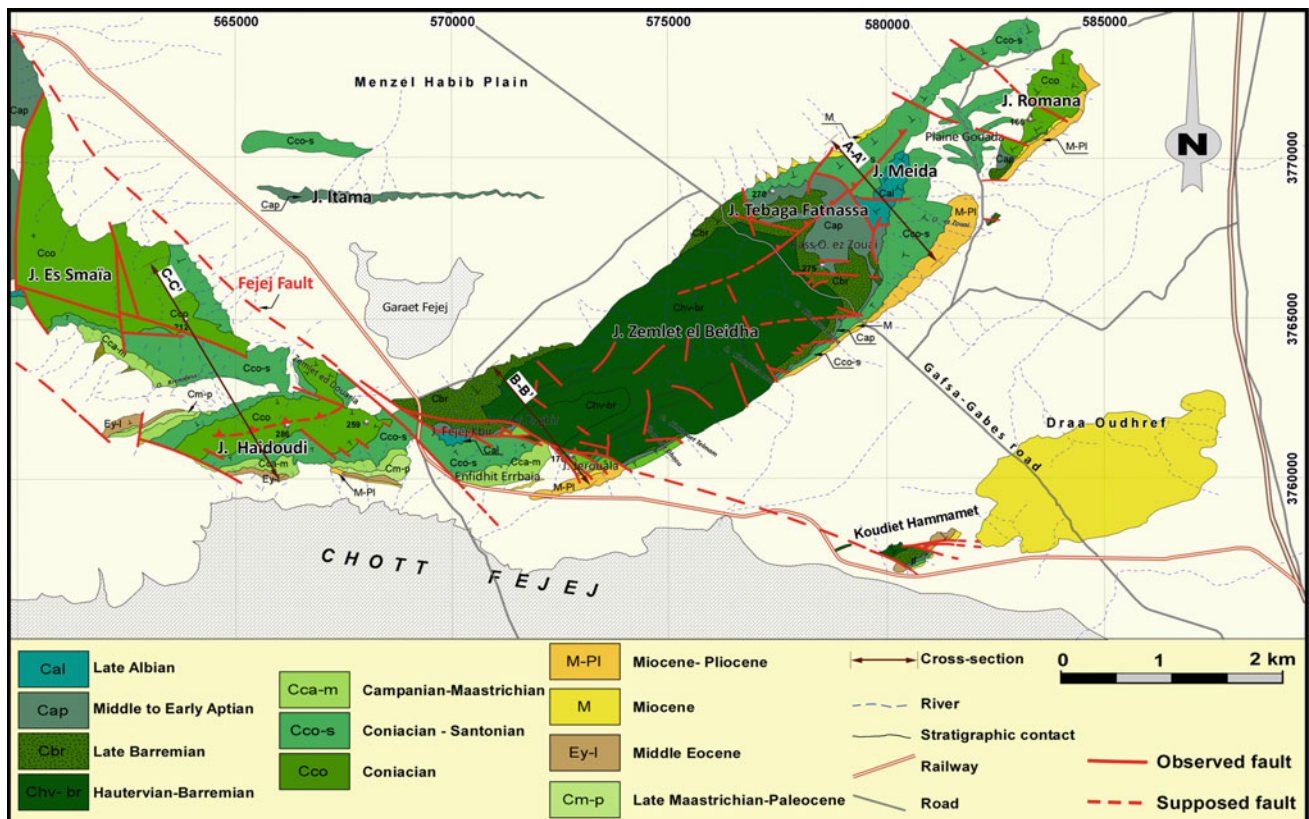
The oldest rocks exposed in the field belong to Trias and are known in the Hadifa diapir. Triassic series consist of evaporites, red claystones, sandstones, anhydrites, halite, carbonates and gypsum deposited with a continental origin during the pre-rifting in relation to the crustal extensional movement of the Tethyan passive margin are started along the African plate (Stampfli et al. 1991; Ben Ismail 1982; Kamoun et al. 2001; Bouaziz et al. 2002). The Triassic Formation show important variations that can reach thicknesses of more than 800 m in petroleum wells. During the Jurassic stage, the rifting continuous by a shallow water

**Fig. 5.2** Synthetic stratigraphic and lithotectonic sedimentary columns Northern Chotts Range. Major unconformities are enhanced by a wavy line



marine deposits at the Lias (Faure and Peybernes 1986; Soussi 2002; Sekatni et al. 2008) followed by the lagoon to marine deposits of the Middle and late Jurassic series which mainly consist of thick limestones intercalated with dolomites, claystones and anhydrites (Tlig 2015). Thicknesses range from ~200 m in the Kebili to 2000 m in the exploration wells along the Chotts Fejej. This extensional tectonic regime accompanied with highly subsidence, continued during the early Cretaceous. The Early Cretaceous transgression is accompanied by shallow marine conditions invaded the Southern Atlas. Sequences have started with the deposition of Berriasian–Hauterivian continental deposits of the Sidi Khalif, Melloussi and Boudinar Formation. At the base, these deposits typify a shallow restricted marine environment to fluvio-deltaic sequences consisting of mixed sandstones, anhydrites and claystones (Marie et al. 1984; M'Rabet 1987; Boukhalfa et al. 2015). The above-described sequences are overlain by shallow-marine and fluvial/deltaic marls, alternating with anhydrites and limestones Hauterivian–Barremian Bouhedma Formation (Damotte 1990). Thickness of Hauterivian–Barremian continental deposits varies from 300 m in the Metlaoui–Gafsa basins (Riley et al. 2011; Gharbi et al. 2015) to 2000 m in the LMG-1 well in

the southern part (El Amari et al. 2016). The Hauterivian–Barremian Bouhedma Formation crops out mainly in the core of the Northern Chotts Range anticlines (e.g., the Koudiat Hammamet, Zemlet el Beidha and Beidha anticlines; Figs. 5.1b and 5.3). The Bouhedma Formation is overlain by shale-rich sands and ferruginous sandstone of Sidi Aïch Formation recently dated by Boukhalfa et al. (2015) as Late Barremian. In the southern Tunisian Atlas, the Sid Aïch Formation's thicknesses range between from ~50 to 200 m. During the Aptian times, the deposition of the Orbata Formation characterized by the syn-rift sediment (Ben Youssef et al. 1985; Ben Youssef and Peybernes 1986; Lazzez and Ben Youssef 2008) was generally related to a transgression that invaded all of is what now the Northern Chotts range. The Orbata Formation conformably overlies the Sidi Aich Formation, in all sections described in this belt (Ben Youssef and Peybernes 1986; Louhaichi and Tlig 1993; Gharbi et al. 2013, 2015). The Orbata Aptian-aged is commonly described as composed at the base by the Bedoulian dolomitic bar that is capped by the marly and sandy carbonates. The top of this Formation consists of Gargasian sandy unit. In the Chotts basin, during the hiatus from the upper Aptian (Clansaysian) to the lower–Middle



**Fig. 5.3** Detailed geological and structural map of Zemlet el Beidha-Jebel Haidoudi structure (ZBHS). See location on Fig. 5.1b (Gharbi et al. 2013). Coordinate system is UTM zone 32, WGS 84 system (metres). Location of the cross section of Fig. 5.4 is shown

Albian which is named Aptian–Albian crisis is probably related to tilted blocks geometry prevailed during the Aptian–Albian rifting (Ben Youssef and Peybernes 1986; Guiraud and Maurin 1992; Souquet et al. 1997). During this period, of significant tectonic extension, thicknesses range from few meters in the East to ~50 m in the Bir Oum Ali structure (central part of the Northern Chotts Range (Fig. 5.1b)). Following this period, an Albian transgression invaded (Ben Youssef 1999; Guiraud et al. 2005) the Southern Tunisian Atlas, leading to the deposition of dolomite and claystone sequences interbedded with thin anhydrites beds. In the southern part (Tebaga Kebili; Figs. 5.1b and 5.2), the Zebbag Formation thick sequences of massive dolomite covers the Albian series. The Albian marine deposits range from a few meters in eastward of the Northern Chotts Range to a maximum observed thickness of ~100 m in the Jebel Berrani (South Bir Oum Ali, Figs. 5.1b and 5.2) to. During Late Cretaceous, a general regional transgression is recorded during the Cenomanian–Turonian times. This later is accompanied by the deposition of marine limestones and claystones ranged by authors as the upper member of the Zebbag Formation. Significant thickness variations exist also in these marine series, which are from ~20 m in Northern Chotts Range to ~200 m in the Tebaga Kebili.

The above-described Zebbag Formation is usually capped by massive bar of dolomite and dolomitic limestone of the Guettar member dated as Uppermost Cenomanian–Early Turonian (Abdallah et al. 1995; Abdallah and Meister 1997). The Coniacian–Santonian-aged Aleg Formation, is composed by thick sequences of the post-rift sediments (Gharbi et al. 2013, 2015; El Amari et al. 2016). These sequences are made of dolomitic sandstones at the base and interbedded green marls and bioclastic limestones at the top. Campanian–late Maastrichtian series consist of marine limestones and claystones of the Abiod Formation (locally named Berda Formation) and characterized by significant thickness and facies variations. Thicknesses range from ~80 m in Northern Chotts Range to ~400 in the Tebaga Kebili (Figs. 5.1b and 5.2). The late Cretaceous sequences are overlain by the marine dark marls of El Haria Formation dated as Maastrichtian–Paleocene. The Paleocene series show a lateral variation of thickness which are ranged from few meters in the East to ~80 m in the Bir Oum Ali structure. This previously mentioned sequences are normally overlain by the Eocene Limestone of Metlaoui Formation in western part of the Northern Chotts Range and by the Eocene continental carbonate of Bouloufa Formation in the Eastern part. The Miocene sandstones of the Beglia Formation unconformably overlie the Eocene series. The continental Mio-Pliocene Segui Formation, considered as syntectonic sequences, is the result of the reliefs erosion that

were uplifted during contemporaneous compressional event. This Formation unconformably overlie all the above-mentioned series along the chain.

### 5.3 The Northern Chotts Range Structure

The structural arrangement of the Northern Chotts Range shows E- to NE-trending folds as shown in Fig. 5.1b, and regional NW- to WNW-trending oblique faults systems (e.g., El Fejej and Negrine–Tozeur faults; Zargouni 1985; Zargouni et al. 1985; Zargouni and Abbes 1987; Gharbi et al. 2013, 2015; El Amari et al. 2016).

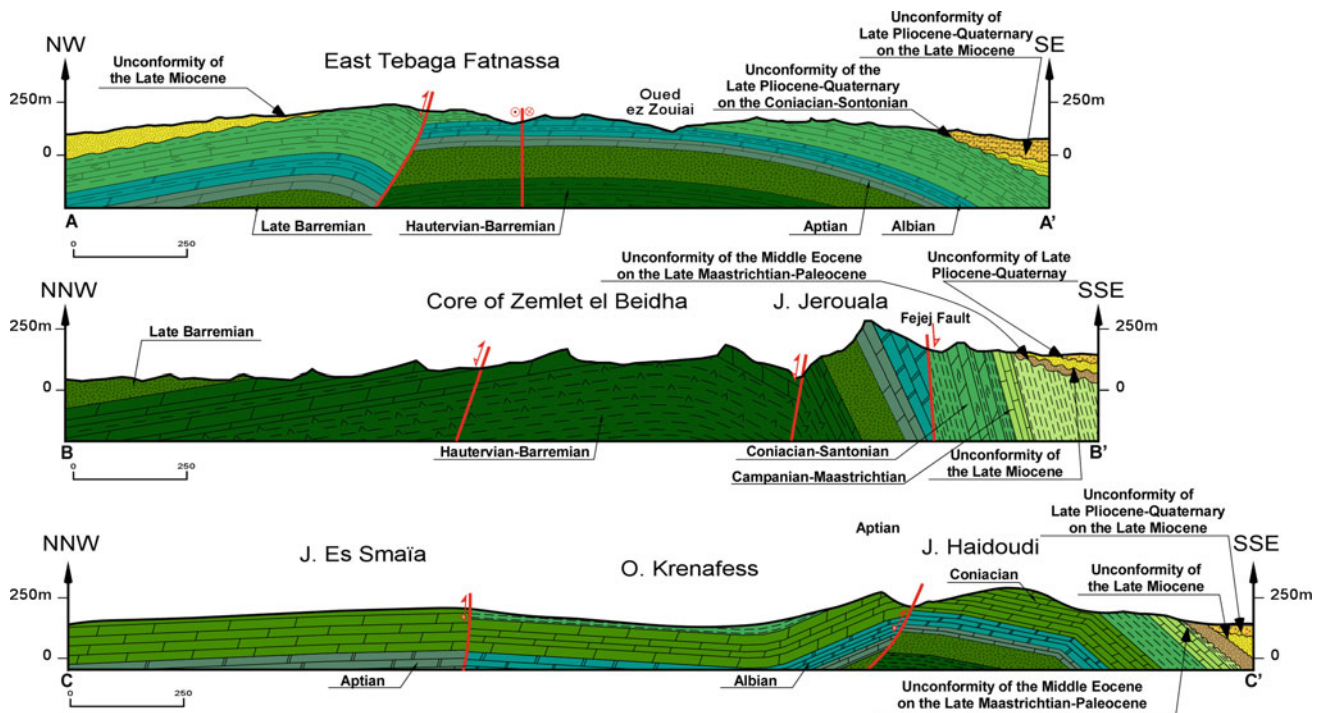
Most of previous studies, propose a scenario in which the Northern Chotts range results from the NW-trending lateral strike-slip faulting (Zargouni 1985; Zargouni et al. 1985; Rabiaa 1985; Fakraoui 1990; Fakraoui et al. 1991; Abbès et al. 1994; Bédier 1995) associated with asymmetric “en echelon” fold with steeper southern limbs than gentle northern limbs. A second interpretation was presented with fault-propagation model generated folding during the Cenozoic thin-skinned tectonics (Creuzot et al. 1993; Outani et al. 1995; Ahmadi et al. 2006, 2013). Based on a geologic mapping, lithotectonic sedimentary sections identification together with seismic reflection data, a recent study of Gharbi et al. (2015) concluded that the Northern Chotts Range, separates two sedimentary basins in which tectonic style is different. The northern one corresponds to the Metloui–Gafsa basin where the deformation is mainly controlled by deep thick-skinned and shallow thin-skinned thrusting. The southern part, including the Chotts basin, illustrates mainly a deformation governed by the deep thick-skinned tectonics.

The following sections address the structural analysis of the Northern Chotts Range, which is based on field observations across the Eastern and the central parts of the Range, and interpretation of seismic reflection profiles across the Chotts Fejej Basin.

#### 5.3.1 Geologic Field Data and Structural Analysis

Data used are derived from the preexisting 1/25000 geologic map published by Gharbi (2013) and El Amari et al. (2016), of the Zemlet el Beidha–Jebel Haidoudi (ZBHS) and Bir-Oum Ali–Hachichina structure (BOAHS), and controlled by six surface geological cross-section. Fault kinematics analysis, provides an idea on the Cretaceous tectonic regime in the Northern Chotts Range. Seismic interpretation coupled to surface data is exploited as a part of this work to





**Fig. 5.4** Geological cross sections showing the tectonic style of Zemlet el Beidha-Jebel Haidoudi structures (ZBHS). For location, see Fig. 5.3

dissect the local style and the development of the Northern Chotts Range in its ZBHS and BOAS portions (Fig. 5.1b, 5.3, 5.4 and 5.5).

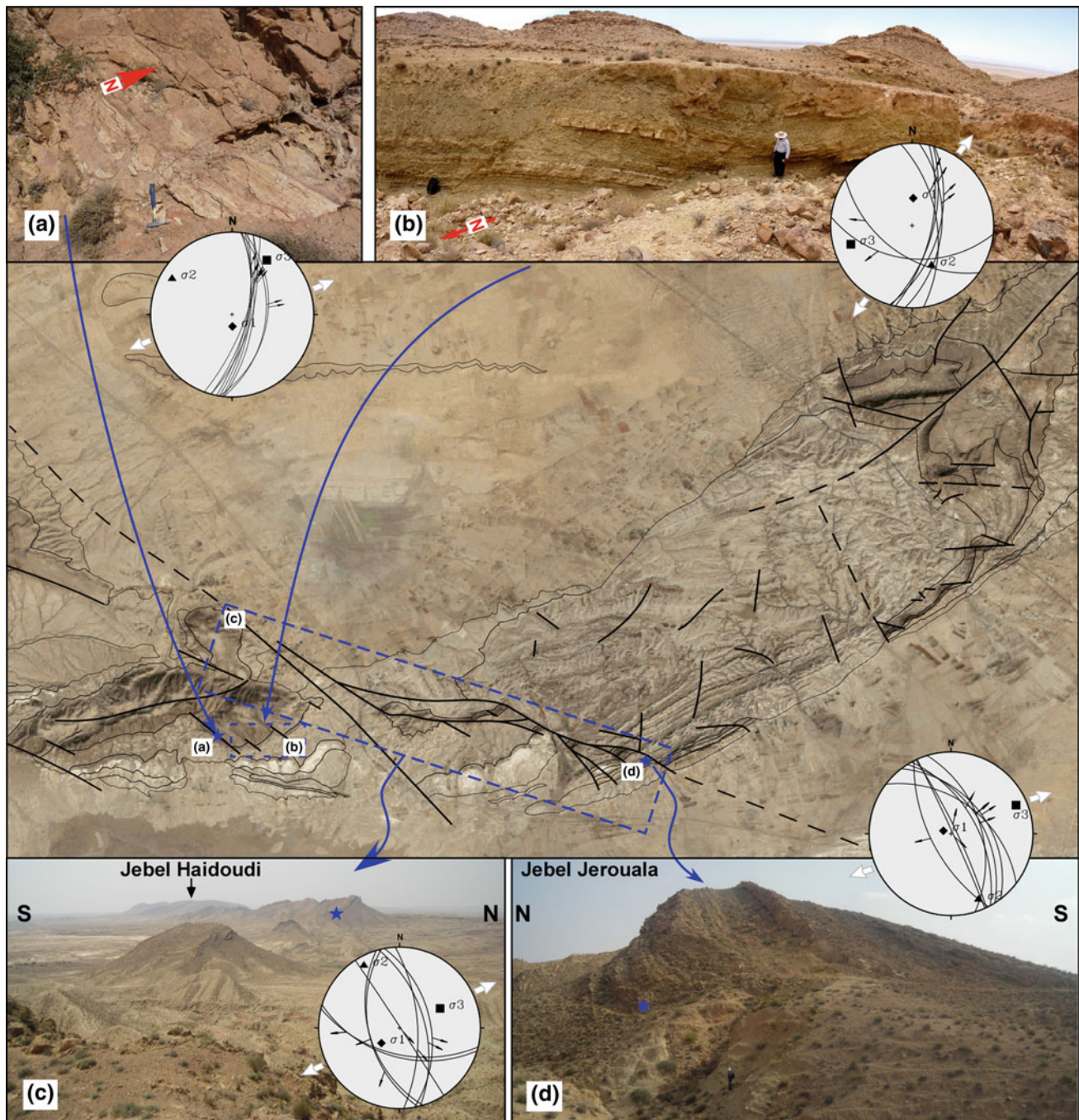
### 5.3.1.1 Zemlet El Beidha-Jebel Haidoudi Structure

The ZBHS is located in the eastern part of the Northern Chotts range. This structure, of about 24 km long, have a curve-shaped geometry (Fig. 5.1b and 5.3) with two main anticlines separated by the NW-trending Fejej fault.

The Zemlet el Beidha is a south-to-south-east verging asymmetric anticline with only an east closure and shows, from west to east, a curved axis that changes from E strike to NE strike (Fig. 5.3). This 16 km long and 3–5 km wide structure, is located between the Menzel Habib plain to the north and the Chotts Fejej and Draa Oudhref respectively southwest and southeast (Fig. 5.3). The Zemlet el Beidha anticline is respectively cored by the Hauterivian–Barremian in the central part, the Albian in the Jebel Meida and the Coniacian–Santonian in the Jebel Romana and Gouada plain (Fig. 5.3). This structural arrangement, simple at surface, is illustrated by two geological cross sections presented in Fig. 5.4. The north-eastern segment of the ZBHS, as shown by the cross-section A–A', is a gentle deformed Cretaceous sequences covered unconformably by Late Miocene–Pliocene to Quaternary series. Along this cross section A–A', the surface geometry of the ZBHS shows a  $\sim 20^\circ$  N-dipping

backlimb made of Coniacian–Santonian green marls alternated with bioclastic limestones unconformably overlain by Miocene continental sandstones. The forelimb is formed by the Aleg  $45^\circ$  S-dipping Formation, itself unconformably overlain by the Segui late Plio-Quaternary Formation. Eastward of the Djebel Tebaga Fatnassa a disturbance of dips is recorded in the limestones of the Aleg Formation possibly associated with N-dipping reverse faulting (Figs. 5.3 and 5.4). Westward at the central part of the ZBHS, numerous N100–110°E apparent trending strike-slip faults, along Khanguet Aïcha and Khanguet Amor, regions affect the  $45^\circ$  S-dipping limb (Fig. 5.3).

Along the second surface elaborated B–B' cross-section (Figs. 5.3 and 5.4; the western part of the ZBHS), at the Jebel Fejej and Jebel Jerouala, shows a northern limb formed by late Barremian sequences that dips  $\sim 5^\circ$ – $10^\circ$  northward while the southern limb dips about  $70^\circ$ – $80^\circ$  southward. The ZBHS shows a highly deformed forelimb geometry usually affected by the NW to WNW-trending Fejej strike-slip systems (Figs. 5.3 and 5.4; Abdeljaouad and Zargouni 1981; Zargouni et al. 1985; Abbès and Zargouni 1986; Abbès et al. 1994). The striae measured on the fault planes of the Jebel Jerouala and Jebel Fejej (see sites c and d in Fig. 5.5) are rotated to reestablish their bedding to its initial horizontal orientation. Using the fault diagram, the back-tilting of these NW-trending apparent strike-slip fault give a result of SW-dipping normal faults. The structural



**Fig. 5.5** Based on Google Earth satellite images, the structural mapping of Zemlet el Beidha-Jebel Haidoudi structure (ZBHS) shows the Cretaceous extensional (normal faulting) tectonic regime resulting from the back-tilting diagram. **a** Striations recorded on fault plane indicates a Coniacian normal faulting characterized by NE-trending extension. **b** Coniacian–Santonian normal faulting (recorded on south flank of the Jebel Haidoudi anticline) associated with NE-trending

extensional tectonic regime. **c** West-looking panoramic view of the tilted bloc structures from the Jebel Khaguet Telmam to Jebel Fejej through Jebel Jerouala related to a regional NE-trending extension regime. **d** Synsedimentary normal fault with lower hemisphere stereograms of fault slip data and shown the NNE-trending direction of extension. Red dashed plane corresponds to the bedding plane

analysis portrays a Cretaceous extensional tectonic regime characterized by NE-trending state of minimum stress axis (Fig. 5.5c, d).

The fault kinematic analysis carried out by Gharbi et al. (2013) shows that restoration of the back-tilted of all ZBHS present-day apparent strike-slip faults, testifies to the



occurrence of normal faults activity developed during a NE-trending Cretaceous extensional tectonic regime. The geologic map and the fault kinematics analysis, of this work, portray an ancient normal faulting reactivated as strike-slip ones well observed in the Khanguet Aïcha as well as the Khanguet Amor (see Fig. 5.3) is. The Cretaceous inherited faults affect the Hauterivian to Albian series and are regularly sealed by the Coniacian–Santonian Formation (Gharbi et al. 2013). Along the ZBHS area, the normal faulting is usually associated with thickness and facies variations, which explicitly concerns the Aptian–Albian sequences. The normal faulting activity is associated in the ZBHS with syntectonic conglomerates that were deposited in the half-grabens structures (a, b, c in Fig. 5.6; Gharbi et al. 2013). The extensional tectonic movement forms the growth strata into some hanging-walls like the preserved listric normal fault in Jebel Tebaga Fatnassa (Fig. 5.7). The Late

Barremian–Aptian dolomite strata is cut by the NE-trending preserved normal. The tilted block geometry records the Aptian growth strata and indicates their normal activity during the Aptian stage. The normal faulting continues during the Albian times and creates the growth-strata geometry into hanging-walls. The E-dipping normal fault cuts the Albian sequences of the Jebel Es Smaïa (Figs. 5.3 and 5.8) and generates growth strata.

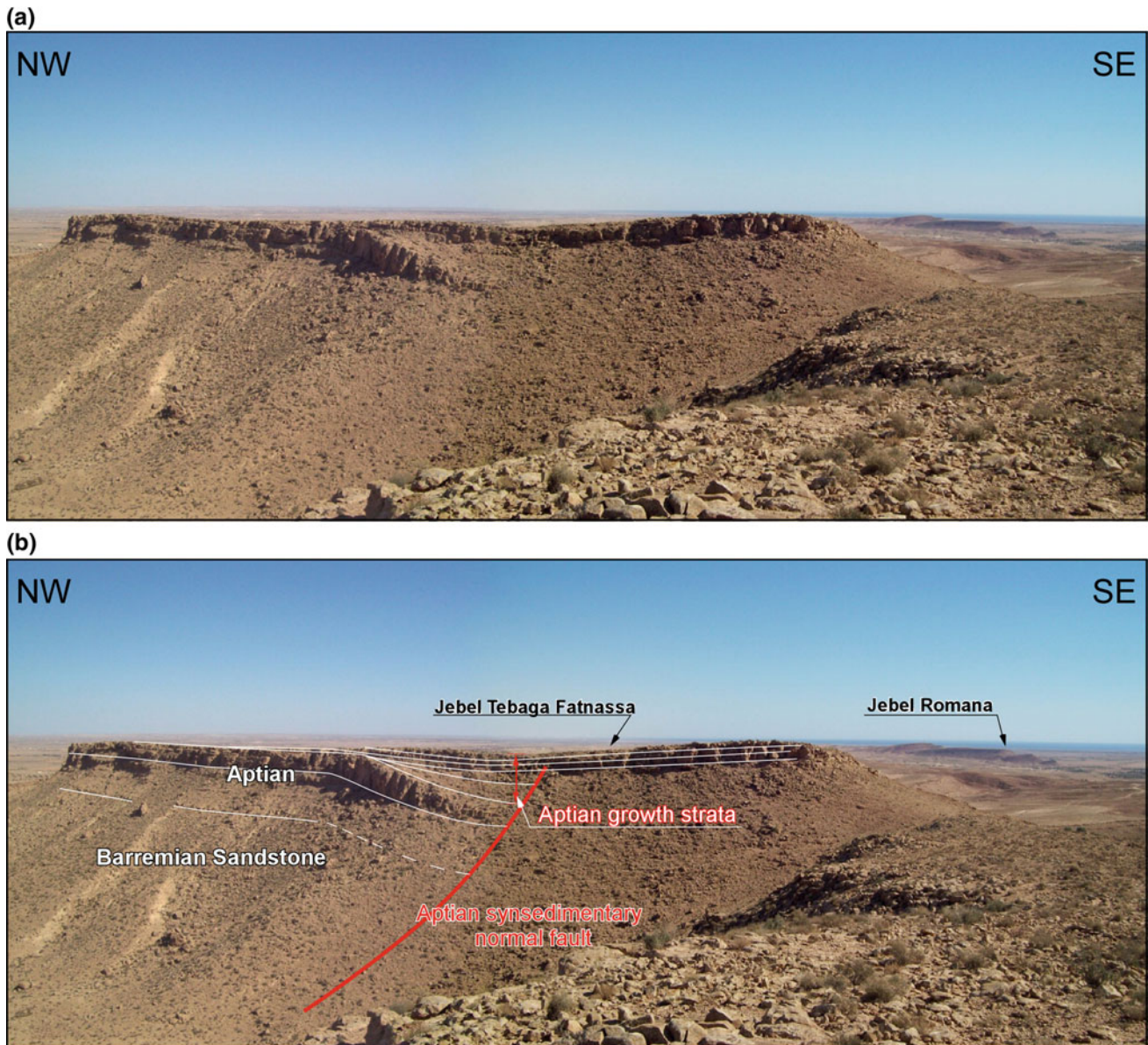
Along the 2.5 km-long NNW–SSE surface C–C' cross section, across Jebel Es Smaïa at the north and the Jebel Haidoudi anticline at the south (Figs. 5.3 and 5.4). Here, the fold Jebel Haidoudi is an asymmetric fold with a core occupied by Coniacian dolomites showing a  $\sim 15^\circ$  N-dipping northern backlimb and  $\sim 40^\circ$  S-dipping southern forelimb. In this south limb, the Late Cretaceous strata unconformably overlain by Plio-Quaternary continental deposits (Fig. 5.4). The north limb is affected by



**Fig. 5.6** Syntectonic index of extensional regime. **a** The Aptian conglomerate. **b** The metric bed of Aptian conglomerates located in the Khanguet Amor. **c** Small Aptian conglomerates resedimented in the

Jebel Jerouala. **d** Rudist fossils (arrows) within the Aleg Formation (Coniacian–Santonian)





**Fig. 5.7** Preserved Aptian normal fault associated with growth strata in the Jebel Tebaga Fatnassa indicating that these Aptian series was deposited during the extensional tectonic regime

ENE-trending reverse fault that separates the Jebel Haidoudi anticline from the Oued Krenafess syncline in the south. This later syncline forms the footwall of the NW-trending strike-slip fault that delimits the Jebel Es Smaïa monocline at the north (Figs. 5.3 and 5.4).

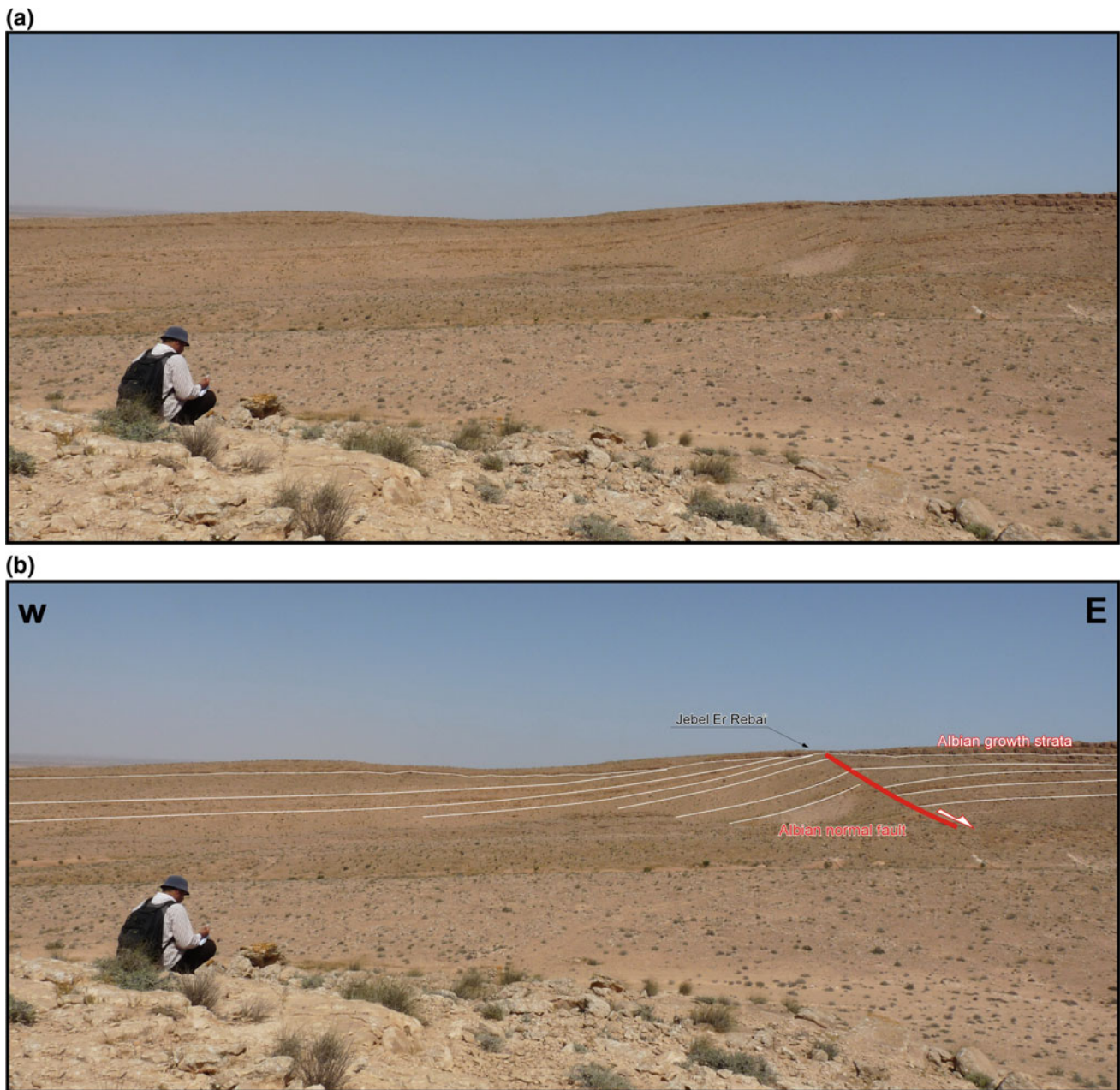
In the southern limb of Jebel Haidoudi anticline, a main  $\sim 45^\circ$  to  $70^\circ$ -NE-dipping normal faults are observed, most of them are a preserved synsedimentary sealed normal faults. This normal faulting is usually sealed by the Santonian marls (Figs. 5.3 and 5.4) attesting an ante-Santonian synsedimentary activity. The Coniacian dolomitic sequence thickness increases toward the NE hanging wall and are characteristic of synsedimentary faults activity. The numerical analysis of

data, consisting of bedding rotation data to restore the horizontal bedding planes, highlights a  $\sim N30$  to  $65^\circ$ -E-trending tectonic extension that prevailed during the Coniacian-Santonian times (see a and b in Fig. 5.5).

### 5.3.1.2 Bir Oum Ali-Hachichina Structure

The general structure of BOAHS comprises two major anticlines separated by the Bir Oum Ali-Hachichina fault systems (BOAHFS). Deformation of this area exposed two different styles with a northern highly deformed anticline and a southern gentle deformed one (Fig. 5.9). Anticline of the BOAHS shows a curved-axis which changes which change from West to East (El Amari et al. 2016). As shown



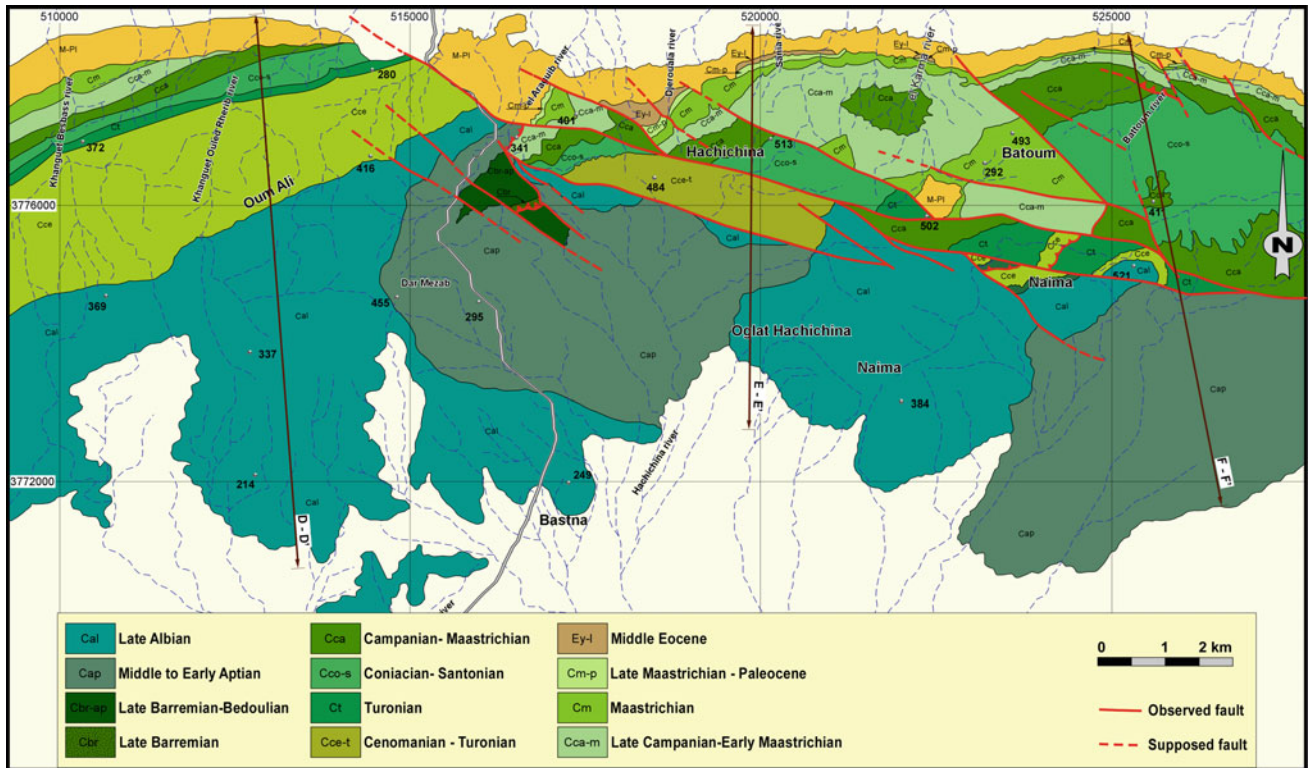


**Fig. 5.8** Preserved Albian synsedimentary “growth faults” in the Jebel Es Smaïa related to the extensional tectonic regime

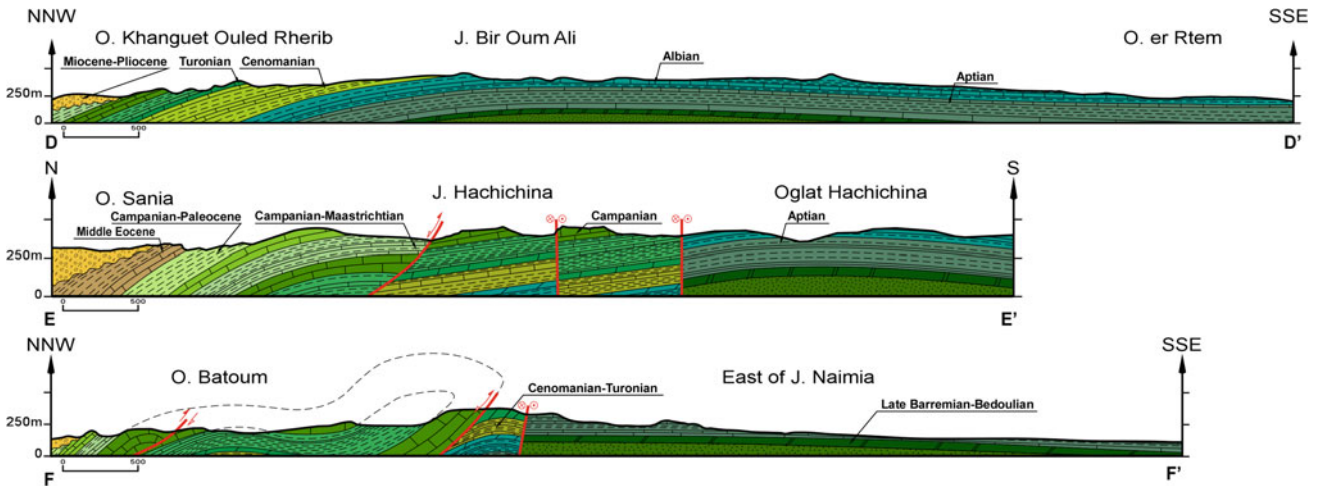
on the geologic map, the BOAHS have a NE-trending axis in the Jebel Bir Oum Ali, a NW-trending one in the Jebel Hachichina and an ESE-trending axis in the Jebel Naimia (Figs. 5.9 and 5.10 D–D’). Three surface constructed cross-sections (Figs. 5.9 and 5.10), along the BOAS anticline, highlight that the southern part is only formed by the Early Cretaceous series showing a long southern limb and a short northern one characterized by  $\sim 10^{\circ}$ – $15^{\circ}$  S-dipping southern forelimb and  $\sim 45^{\circ}$ – $65^{\circ}$  N-dipping northern backlimb (El Amari et al. 2016). While the southern side is simple and shows a little deformed side of the BOAHS, the

northern part shows a complex pattern. This part is characterized by the anticlines succession with curved hinge line and showing a right stepping “en echelon” arrangement. These two different sides are separated by the BOAHFS and does show a syncline in-between (Figs. 5.9 and 5.10). The curved secondary (in respect to general structure) anticline succession is well observed along O. El Araguib, O. Sania, O. Karma, east of O. Karma, the O. Batoum, and the O. Saoudi, at the northeastward. Furthermore, from west to east geometric complexity increase in O. Karma, O. Batoum, and the O. Saoudi anticline with usually south overturned





**Fig. 5.9** Detailed geological and structural map of Bir-Oum-Ali–Hachichina structures (BOAHS) See location on Fig. 5.1b (El Amari et al. 2016). Coordinate system is UTM zone 32, WGS 84 system (metres). Location of the cross section of Fig. 5.10 is shown



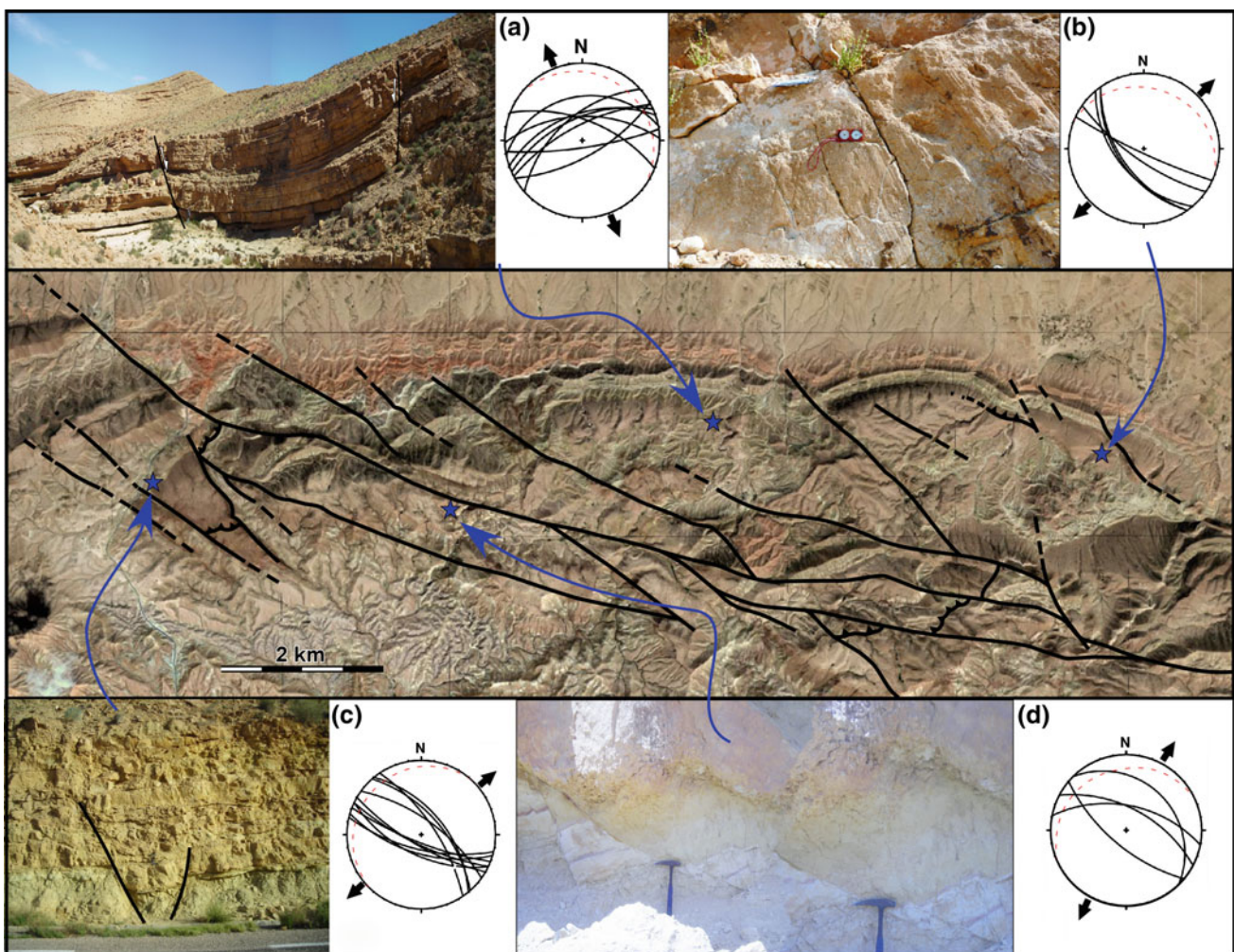
**Fig. 5.10** Geological cross sections showing the tectonic style of Bir-Oum-Ali–Hachichina structures (BOAS). For location, see Fig. 5.9

limbs (Figs. 5.9 and 5.10, El Amari et al. 2016). This area offers a well outcropping  $\sim 15^{\circ}$ – $20^{\circ}$  angular unconformity between the aforementioned Cretaceous series and Miocene–Pliocene sequences. Eastward, this angular unconformity is localized between Paleocene–Eocene and Miocene–Pliocene series in the Oued Sania and Oued el Karma (Figs. 5.9 and 5.10, El Amari et al. 2016).

Several previous works (Abdeljaouad and Zargouni 1981; Rabiaa 1985, Zargouni 1985; Fakraoui 1990; Abbès et al. 1994) have usually interpreted the BOAHFS as strike-slip fault systems, mainly active during Cenozoic times. The examination of all adjacent areas limited by this fault systems, based on new geologic mapping (El Amari et al. 2016), the surface geologic cross-sections (Fig. 5.10) and

the fault kinematics analysis does not reflect this old interpretation. The first of evidences, is that north-dipping BOAHFS separate a north hanging wall filling by the Late Cretaceous–Paleogene series and a south footwall that consists of Early Cretaceous strata. These data confirm an inverted fault system in which the second contractional throw does not compensate the first extensional one. In addition, secondary anticlines are in close relationship with the BOAHFS (Fig. 5.10). Furthermore, the majority of measurements carried out along all this system fault reveals that this N100°–110° E-trending BOAHFS exhibits usually striation with a first normal movement generation cut by second dextral strike-slip one (Fig. 5.11a–d). The fault kinematics analysis of the back tilted fault surfaces carried

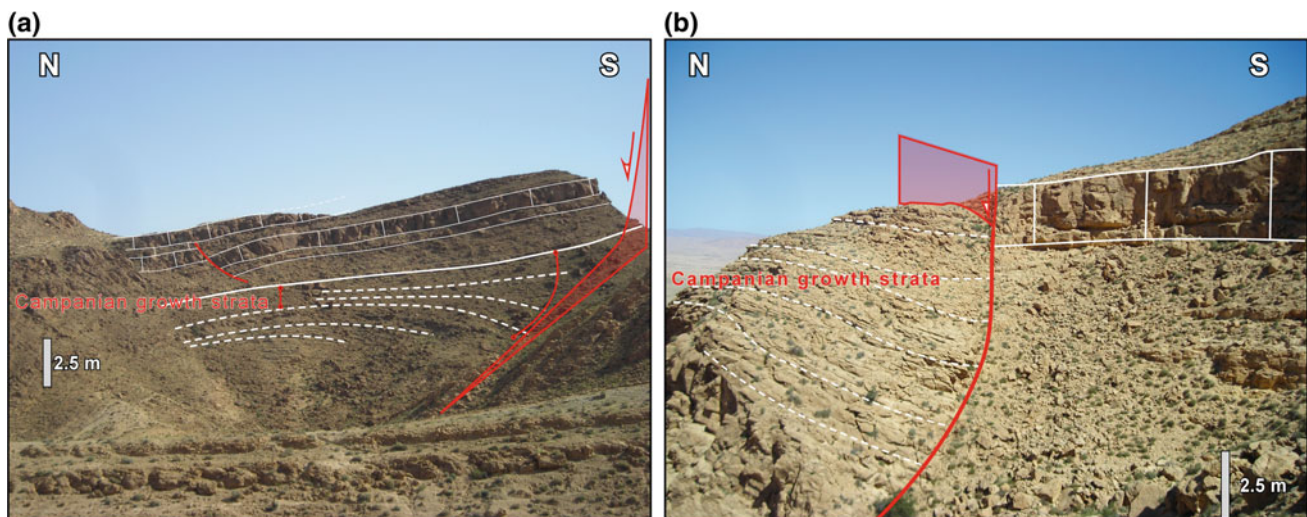
out along the BOAHFS shows that the Aptian is characterized by the N40°E-trending minimum stress axis ( $\sigma_3$ ) (Fig. 5.11c). This extensional regime is associated with graben and half-graben structures (Fig. 5.11a, c, and d). During Coniacian–Santonian, BOAS domain is also controlled by the same faults reactivated by normal faulting with a tectonic regime characterized by a NNE ( $\sim$ N15° to 20°E)-trending tectonic extension (Fig. 5.11d) responsible also for half-graben structure. During Campanian, BOAS is controlled again by normal faulting with tectonic regime characterized by a NNW ( $\sim$ N170°E)-trending tectonic extension (Fig. 5.11a). In addition, the Campanian normal faulting generates syntectonic conglomerates and the growth strata in the hanging-walls these normal faults (Fig. 5.12).



**Fig. 5.11** Based on Google Earth satellite images, the structural mapping of Bir-Oum-Ali–Hachichina structures (BOAS) shows the Cretaceous extensional (normal faulting) tectonic regime resulting from the back-tilting diagram. **a** Campanian normal fault results from an extensional tectonic regime characterized by NNW ( $\sim$ N170°E)-trending; **b** striations recorded on fault plane indicates a Coniacian–

Santonian normal faulting characterized by NE-trending extension; **c** NW-trending graben related to a NE-trending extension; **d** half-graben structure recorded in the Coniacian–Santonian deposits related to a regional NNE-trending extension regime. Red dashed plane corresponds to the bedding plane (El Amari et al. 2016)





**Fig. 5.12** Panoramic view, looking NE, of a preserved Late Cretaceous normal fault showing growth strata located in the hanging wall that indicate a normal faulting active during Campanian time (El Amari et al. 2016)

### 5.3.2 Subsurface Structural Data

Three seismic profiles EL03, EL11 and EL12 (Figs. 5.13 and 5.14) are used in this work to illustrate the southern Atlas of Tunisia deep geometry. Data presented are based on the conversion of the travel times to depth and calibrated by the exploration wells (P1, P2, P4, Figs. 5.1b, 5.13 and 5.14) and present work surface data.

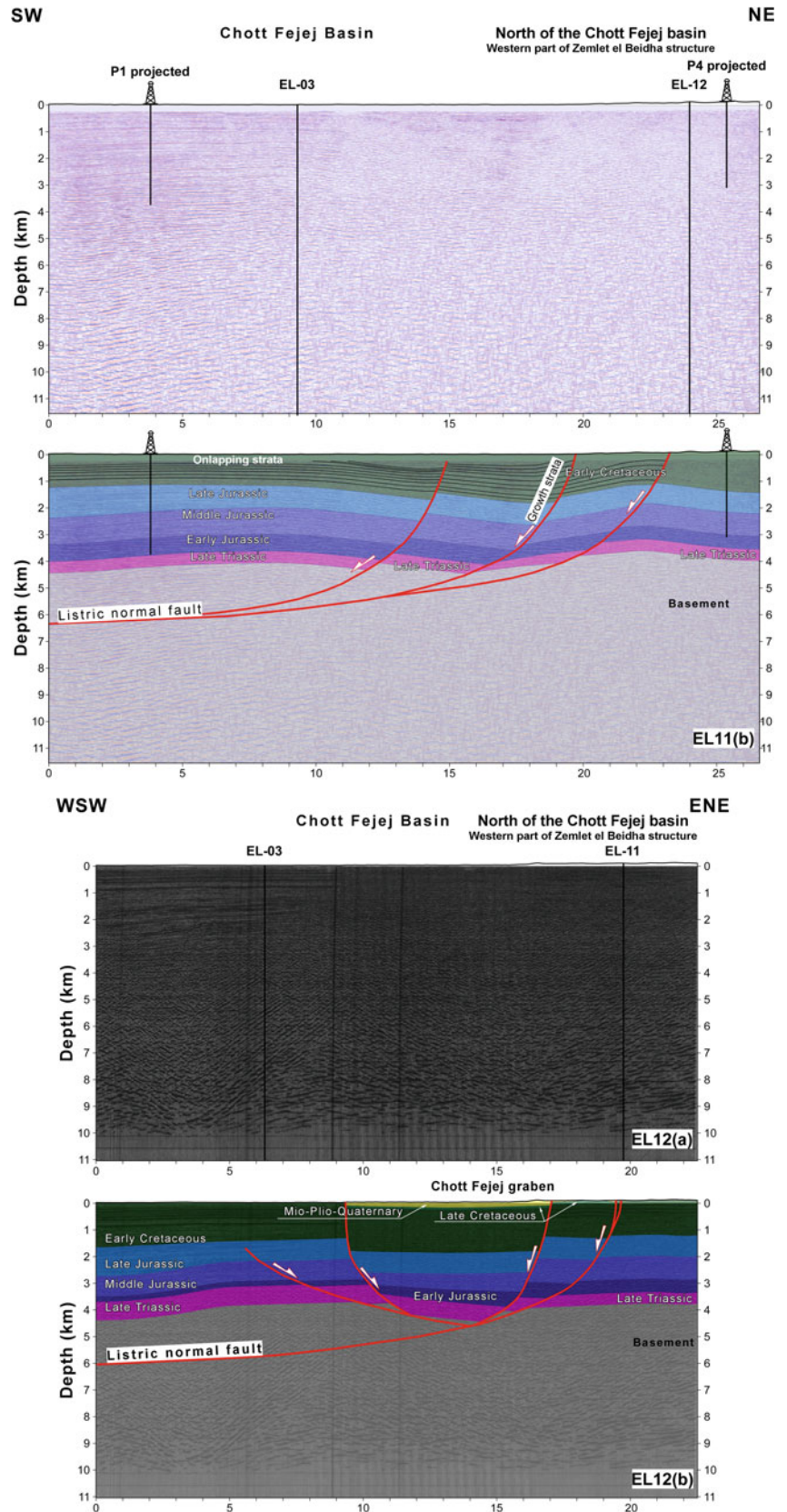
The interpreted seismic profiles EL11 (Fig. 5.13a) highlights that Mesozoic sequences vary considerably in both facies and thicknesses along the southern Atlas of Tunisia. The thickness of Mesozoic sequences increases toward the Chotts Fejej compared to thin series in the Northern Chotts Range. This profile highlights also that the thick sequences are expanded on listric southwest-verging growth normal fault. In the eastern part of the ZBHS, the Early Cretaceous series thickness exceeds ~1800 m. The same thickness is recorded for the Jurassic. These series of the Cretaceous and Jurassic reach the 2000–2300 m beneath Chotts Fejej basin. These significant and rapid variations attest a main episode of subsidence in the Chotts Fejej basin, associated with deep normal faulting during the Mesozoic times. These southwest-facing normal faults recorded especially in the Jurassic and Cretaceous Formations were recently interpreted as synsedimentary “growth faults” by Gharbi et al. (2015) and associated with large rollover anticline. Growth faults are mainly developed in what is now the Chotts Fejej basin. The Maximum throw is recorded at the Triassic–Jurassic sedimentary interface, suggesting a rapid subsidence and active growth faults during this period. Furthermore, high throw gradients were detected near the upper tips of these faults in the Early Cretaceous qualified to be characteristic of syn-sedimentary growth normal faults.

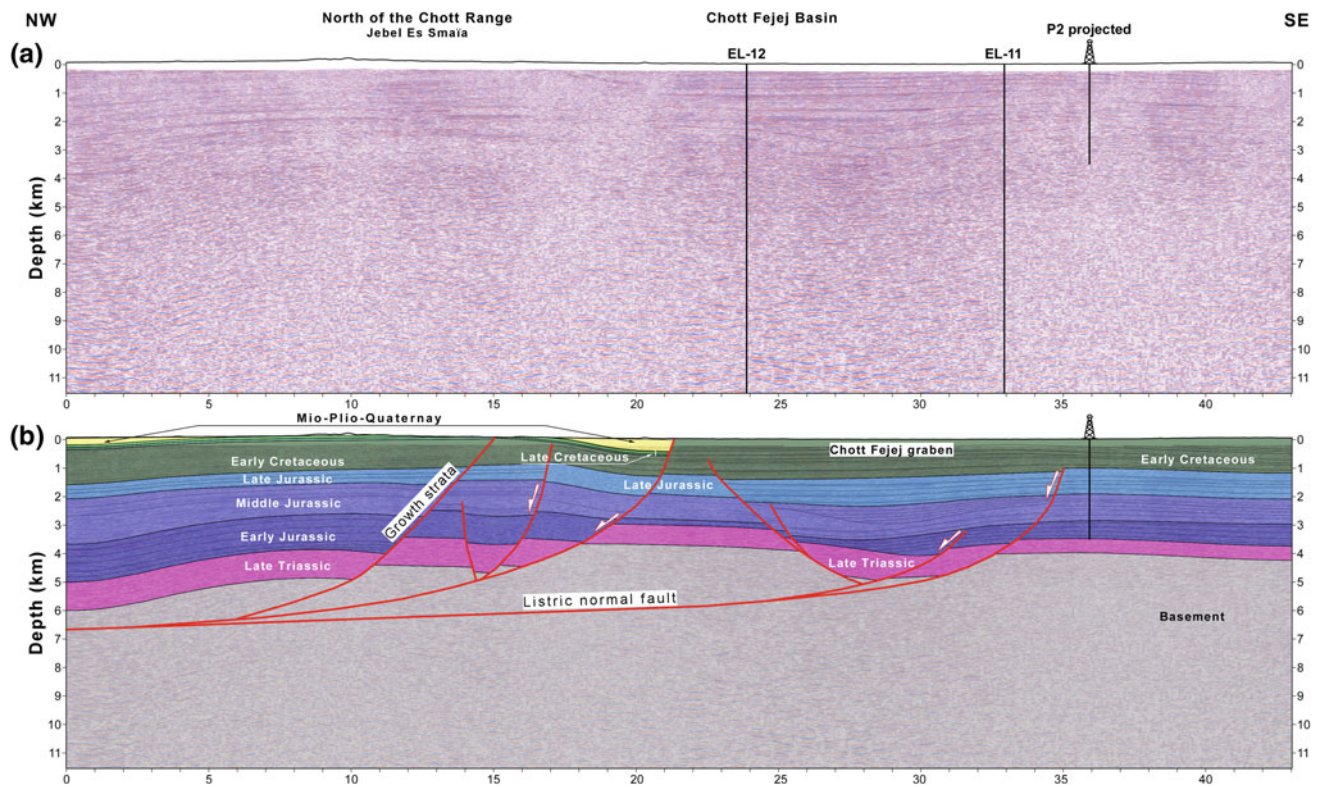
Diachronous Early Cretaceous lithostratigraphic successions led to a reactivation of the preexisting normal faults during the sedimentation during this period. This fact is testified by the sedimentary package associated with normal dragging of the strata in the hanging-wall of the faults (Fig. 5.13a). The geometry of the growth strata in the Early Cretaceous series are well defined on the EL11 seismic profile. High thickness triggers differential overloading along the growth faults. Into these hanging-walls of normal fault, Early Cretaceous filling draws an onlapping structure (Fig. 5.13a). A detailed analysis of these profiles has been carried out to predominant role of inherited extensional structures in evolution of the southern Tethyan margin, and their influence on the geometry of the Atlasic thrust belt.

The ENE–WSW seismic line of EL12 (Fig. 5.13b) offers well-imaged structures of the buried Chotts Fejej basin that occur over a listric fault geometry confirming the above-mentioned configuration in the seismic Line EL11. This line EL12 highlights a main graben structure beneath the Chott Fejej Basin likely resulting from a local intensive extensional tectonic located beneath a major regional listric normal fault. The sedimentary pile, that shows a thickness variation recorded at least since Jurassic and Early Cretaceous, has deeply controlled by these faults systems. The rapid accumulation of the Jurassic and Early Cretaceous sediments in the Chotts Fejej graben announce a high subsidence related to the diachronic activity of the normal fault. Analysis of the seismic profiles EL11 and EL12 crossing the Chotts Fejej Basin (Fig. 5.1b) permits to identify faults with normal components bounding the subsiding domains (Fig. 5.13). These faults are associated with other synthetic faults that have contributed to the formation of a Fejej graben. The study area is characterized by thick Jurassic and



**Fig. 5.13** Subsurface data showing the preserved extensional structures reflected the structural architecture of the ancient southern Tethyan margin. EL11a and EL12a are the uninterpreted, migrated, depth-converted seismic reflection data from the Chotts Fejej basin. For location, see Fig. 5.1b. Horizons were calibrated using projected data from the P1 and P4 wells and surface data. Interpreted seismic section of the EL11b showing the half grabens systems of the Chotts Fejej basin connected to an intrabasement detachment and associated with syn-rift growth strata. Interpreted seismic section of the EL12b showing the deep Jurassic-Early Cretaceous graben beneath the Chotts Fejej basin connected to the same intrabasement detachment mentioned in the EL11b





**Fig. 5.14** **a** Uninterpreted, migrated, depth-converted seismic reflection data from the Chotts Fejej basin. **b** Interpreted seismic line of EL03 showing the preserved extensional structures associated with the

preserved Chotts Fejej graben, and horst and rollover anticline limited by the listric normal fault connected to the intrabasement detachment. For location, see Fig. 5.1b

Early Cretaceous deposits, which are progressively thickening, associated with listric faults (Fig. 5.13). The geometry and the thickness variations are related to the regional extensional tectonics during the synrift period.

The deep structure of the Northern Chotts Range is well illustrated by the NNW–SSE trending seismic reflection line EL03 (Fig. 5.14). Reflectors have been calibrated using projected data of P2 well onto the section and present seismic interpreted of EL11 and EL12. To the south, the Chotts Fejej basin is formed above a normal movement of the fault systems which delimited a deep graben beneath Chotts Fejej and associated with rapid subsidence during Jurassic and Early Cretaceous. To the north, a similar extensional structure created by listric normal faulting delimits a tilted blocks geometry with north-verging beneath the Jebel Es Smaïa (Fig. 5.14).

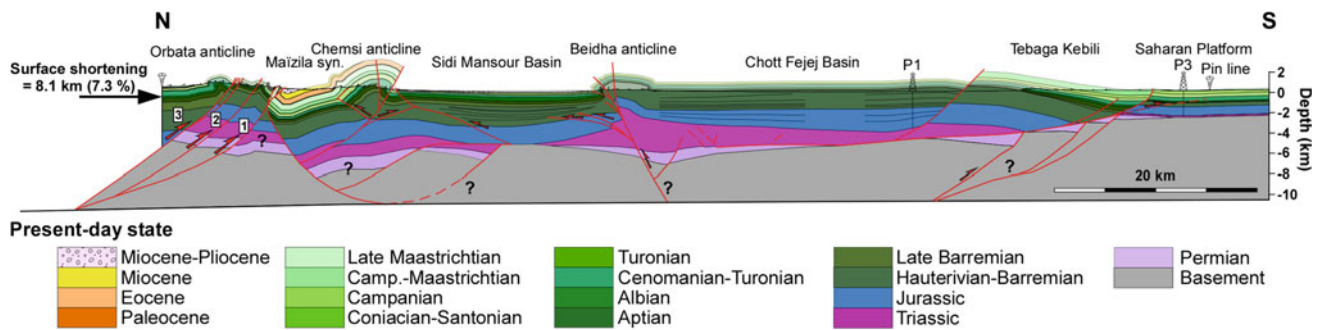
Deep structural inheritance indicated by seismic interpretation is well illustrated by the synsedimentary normal faulting associated with the growth strata and the thickness and facies variation of Jurassic and Early Cretaceous. This structural architecture presented in the study area reflects the geometry of the south Tunisian basin as part of the southern Tethyan margin.

#### 5.4 Sequential Restorations of the Southern Tethyan Rift Margin of Tunisia

The sequential restoration of balanced cross sections is viewed today as a sound way calculate the extension and/or shortening amount and to estimate the slip rate, and the depth of the décollement surface in both contractional and extensional tectonics (Castelluccio et al. 2015). This method is considered today as the only way to decipher the tectonic evolution of deformed structures in the time. Our sequential restoration published in previous works by Gharbi et al. 2015 quantify for the first time the extension amount of Mesozoic period of the Tethyan margin rifting stage of in South Tunisia (Fig. 5.15). We expose hereinafter the role of the rift-related structures in the structuration of the southern Atlas domain of Tunisia.

The calculated amount of extension, along the southern Atlas domain of Tunisia, shows a total horizontal extension of about 9.4 km during the Tethyan rifting. This amount is calculated for four stages of rift i.e. Permian, upper Barremian, Aptian–Albian, and Coniacian–Santonian (Fig. 5.16). The Tethyan margin rifting in southern Tunisian





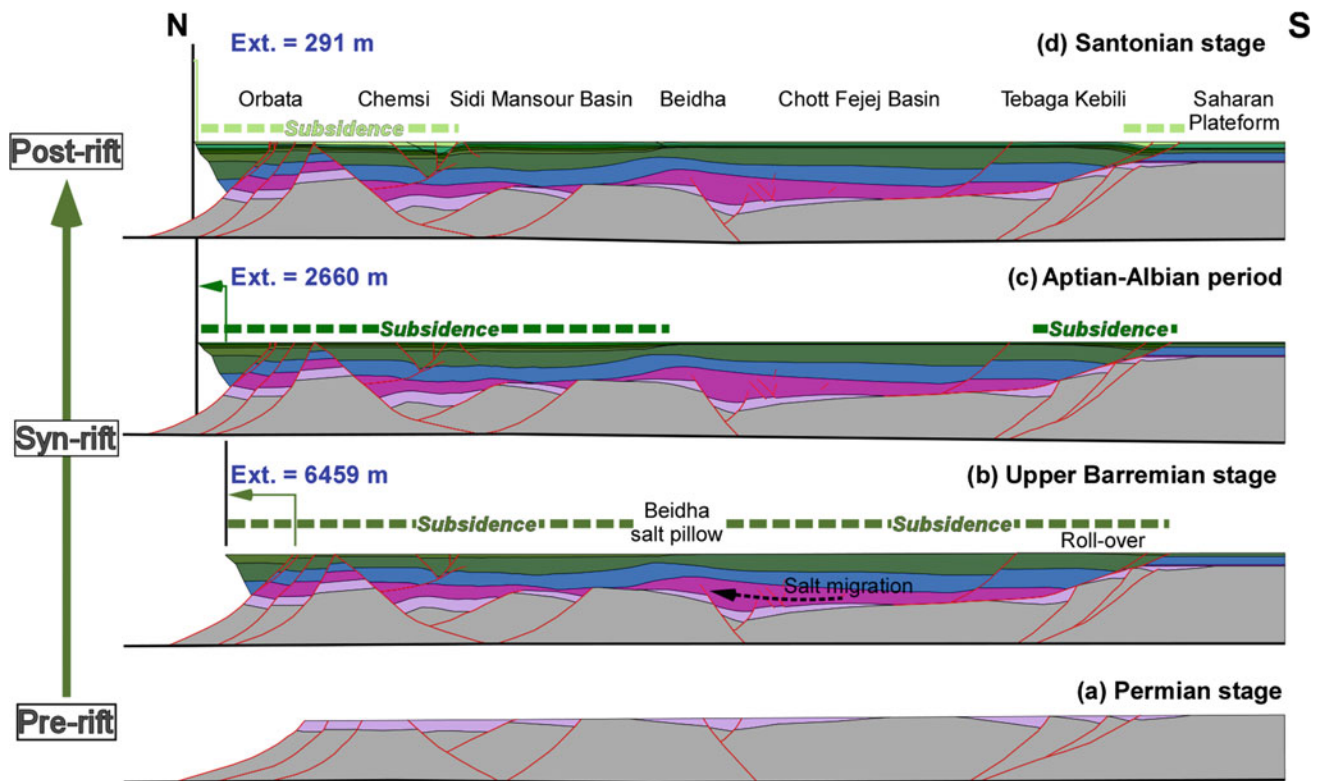
**Fig. 5.15** Balanced cross sections across southern Atlas foreland of Tunisia. For location, see Fig. 5.1b shows that the structural architecture of the Tunisian foreland consists in a by mixed thick- and thin-skinned tectonic style, controlled by deep-seated basement faults

(corresponding to inherited Permian (?) to Cretaceous normal faults) and shallower décollement within the sedimentary cover (Gharbi et al. 2015)

domain is started by the Permian–Triassic pre-rift stage where its sedimentary platforms are governed by extensional tectonic regime. The structural style was designed by normal faults associated with tilted blocs, grabens and horsts (Fig. 5.16a). A Triassic basin formed in the beginning of this rifting stage were filled by evaporitic massive salt layers (mainly halite and gypsum) with clays and dolomites reflecting an epicontinental environment (Kamoun et al. 2001). Following, a rapid subsidence typifies the rifting event during the Jurassic–Early Cretaceous stage. This period is characterized by extensional tectonic episodes linked to the opening of the Central Atlantic Ocean. Structures developed during this period were infilled by Early Cretaceous fluvio-deltaic to shallow marine environment sequences (Louhaïchi and Tlig 1993; Gharbi et al. 2013). The Early Cretaceous period is synchronous with the growth of major syndepositional typical normal fault systems which produce a general framework delivering tilted blocks basin geometry responsible of the dislocation of the continental platform in the southern Atlassic domain of Tunisia. The sequential restoration proposed by this work shows a wide-ranging extension that reach  $\sim 6.5$  km at the Upper Barremian showing high subsidence rate and flexure of the south Tunisia margin in what is now the Chotts basin (Fig. 5.16b). The Chotts Fejej basin is dissected by listric normal faults branched on the Triassic intra-basement. Accumulation of Jurassic–Early Cretaceous thick sediments in the Chotts Fejej basin allows the lateral migration of the evaporitic Triassic salts towards the north associated to the development of the salt pillow beneath the Northern Chotts Range (Fig. 5.16b). Northward, the sequential restoration permits to define an ancient southern Tethyan margin in Tunisia likely controlled by the extensional structures. The extensional deformation was accommodated by basement normal faults bounding horsts and grabens structures patterned on tilted blocks major's ones. Normal faults controlled the sedimentation where the deposits were thicker

and showed growth strata architectures in the hanging wall. Furthermore, this tectonic event induced variation in thickness and facies of the sedimentary pile (Hlaïem, 1999; Bédier et al. 2001; Bouaziz et al. 2002; Patriat et al. 2003; Gharbi et al. 2013, 2015; El Amari et al. 2016). The calculated amount of stretching that occurred between upper Barremian and Aptian–Albian is of about  $\sim 2.5$  km (Fig. 5.16c). The southern Atlassic basin was affected by growth syndepositional strata well integrated in the extensional tectonics leading to the deposition of a syn-rift sequence controlled by alternating horsts and grabens structures. The syndepositional normal faulting delivering a general tilted blocks geometry, for which the Aptian–Albian ages are perceived to have the most extreme extensional related-structures time of the south Tethyan edge in southern Atlas of Tunisia (Gharbi et al. 2013, 2015; El Amari et al. 2016). In addition, Aptian–Albian sequences display abundant conglomeratic horizons and slumping, in addition to significant thickness changes (Gharbi et al. 2013; Masrouhi et al. 2014a; Naji et al. in press). This period shows in south Tunisia sedimentary gap of Upper Aptian–Lower Albian sequences. Detailed investigations portray an unconformity, reordered in the study area, as a consequence of rift derived tilted blocks. This configuration is well known today in this structural setting and qualified to be an “Atlantic type passive margin setting”. This setting is recently well elaborated in central and northern Tunisia (Jaillard et al. 2017; Naji et al. in press) particularly for the Aptian–Albian times. During this time, data are agreeable with the intraplate extensional deformation which is linked to the opening of South Atlantic central segment. The northward motion of the African Plate has been accompanied by N trending extension registered in the central and north African basins (Martinez et al. 1991; Guiraud and Maurin 1991; Guiraud et al. 2005). In addition, the syn-rift structures of the southern Tethyan margin in Tunisia are accompanied by episodes of volcanism that is testified by basalt flows observed in the pelagian blocks of





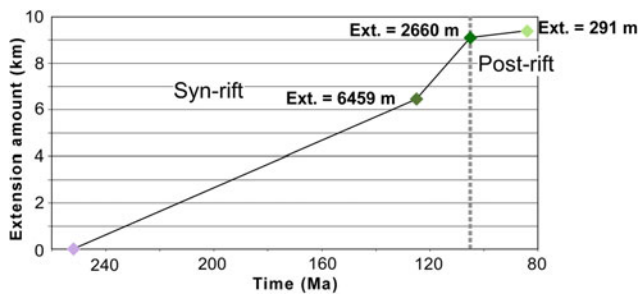
**Fig. 5.16** Sequential restorations of the southern Tethyan rift margin of Tunisia (a–d). e Extensional amount versus time. Ext.: Extension (Gharbi et al. 2015)

eastern Tunisia (Laaridhi-Ouazaa 1994; Ellouz et al. 2003; Patriat et al. 2003). This extensional geometry is well exposed in a deep through at the northern region, i.e., Tunisian through (Boltenhagen 1985; Burolet 1991; Martinez et al. 1991; Soua 2016; Masrouhi et al. 2014a; Naji et al. in press) and in northern Algeria (Vila 1980; Herkat and Guiraud 2006; Marmi and Guiraud 2006).

During the Cenomanian–Santonian post-rift stage, a 300-m extension is perceived in south Tunisian basin (Fig. 5.16d). This small amount of extension is associated with thick sequences deposition rate of pelagic and benthic facies (Soua et al. 2009; Naji et al. in press). These characteristics are indicative of post rift stage sediment accumulation. Furthermore, this period was described as associated to an important transgression in the southern Atlasic domain of Tunisia. The Ancient normal faults, inherited from Jurassic to Early Cretaceous rifting stage, have controlled the distribution of the Cenomanian–Santonian deposits. Regionally, these extensional structures are usually sealed by the Coniacian–Santonian post-rift sequences, which themselves testifies for a post-rift stage with major transgression (Abdallah and Rat 1987; Herkat and Guiraud 2006).

## 5.5 Amount of Mesozoic Extension Rate in the Chotts Basin

In this work, we provide new detailed sequential restorations of the southern Tethyan rift margin in Tunisia. We quantify the long-term extension mainly accommodated by the Cretaceous normal faulting structures. With this procedure described above by the section-time restoration, it is possible to decipher three mainly stages characterized this ancient passive margin. As shown the Fig. 5.16, the amount of Mesozoic extension rate varies during the time. After the Permian–Triassic pre-rift stage, we calculate an extension rates averaged  $\sim 6.5$  km with a velocity of opening about  $\sim 550$  m/Ma during the Upper Barremian (Fig. 5.17). The velocity of extension increases and reached more than 1000 m/Ma. This extensional deformation occurred during the Aptian–Albian stage indicates the maximum of opening of the southern Tethyan margin and reached 2.5 km of extension rate (Gharbi et al. 2015). During the Cenomanian–Santonian post-rift stage, the velocity of extensional decreases for reach 6.5 m/Ma with 300 m of extensional rates.



**Fig. 5.17** Amount of Mesozoic extension rate recorded in the southern Tethyan margin in Tunisia versus time. Ext.: Extension (Gharbi et al. 2015)

## 5.6 Discussion and Conclusions

During the past 65 years, various interpretations of the geologic results pending from the Southern Atlasic front of Tunisia have been proposed. The reviewing of the geological data highlights four different eras in term of structural interpretation i.e. between 1952 and 1994 geologic interpretation was dominated by the view that the present fold distribution is the result of (i) strike-slip faulting, (ii) between 1997 and 2002 geoscientists featured an interpretation is the consequence of salt tectonic activity (1997–2002) or the result of both aforementioned processes, (iii) in parallel, for the same period from 1995 to 2006, geologists highlighted a model of anticline structures that were interpreted as developed and the result of ramp-related folding, deformed the sedimentary cover (thin-skinned model) over the rigid basement during a single tectonic event, (iv) between 2011 and 2017, geoscientists working in the area, lead to the inversion of inherited major fault in the development of tertiary structures. The inherited Triassic–Jurassic–Early Cretaceous normal faults are actively involved in the far-foreland tertiary deformation of the Southern Atlasic Front in Tunisia.

The first era, from 1952 to 1994, featured a general hypothesis of strike-slip faulting generating the fold distribution of the Southern Atlas (Castany 1954; Abdeljaouad and Zargouni 1981; Rabiaa 1985; Zargouni 1985; Abbès and Zargouni 1986; Fakraoui 1990; Abbès et al. 1994, among others). During the 70s and 80s, many detailed mapping by many geologists has begun to elucidate the southern Tunisia structural complexities. Two major NW-trending lateral strike-slip faults (i.e. Gafsa and Negrine-Tozeur) were recognized in the southern Tunisian Atlas fold-and-thrust belt. They were structurally connected to the present-day distribution of folds, which was widely accepted by the 70s and 80s geologic reconstructions. In this way, ZBHS and BOAHS were interpreted previously as curved, right-stepping “en echelon” geometry folds (Abdeljaouad

and Zargouni 1981; Rabiaa 1985; Zargouni 1985; Abbès and Zargouni 1986; Fakraoui 1990; Abbès et al. 1994) a model which was generalized for all the Northern Chotts Range. However, the case of ZBHS and BOAS does not show in any point the classical relationship between folds and strike-slip faults. Indeed, the deformation must be relatively comparable along the two adjacent blocks moving sideways for which these anticlines are much different, and these structure does not correspond to a doubly plunging and relatively short with steeply dipping axial planes that must exist if it was the case of strike-slip fault controlling the folding.

The second period from 1997 to 2002, a salt tectonics developed model (Hlaiem et al. 1997; Hlaiem 1999) featured an evolution in which a significant diapirs began to rise-up during Early Jurassic. This tectonic model highlights a structural configuration in which the subsequent tertiary folding is preferentially nucleated on the preexistent diapir apex. In the same period, composite model of strike-slip faulting and salt diapir generated in response to shearing faulting (Bédir et al. 2001; Zouaghi et al. 2011). However, this is in pure contradiction to the diapiric structure itself, in which structure must be circular and associated with radial faulting. Our interpreted seismic reflection shows the absence of salts structure beneath these anticlines. Excluding the Jebel Beida to the East of the BOAHS, this geometry is not found anywhere in this belt and does not show significance of salt tectonics activity (Masrouhi et al. 2013; Masrouhi et al. 2014a, b).

The third period, from 1995 to 2006, was dominated by south verging thrust system on which folds are located (Outtani et al. 1995; Ahmadi et al. 2006). This model, interprets the anticline structures in this zone as developed and the result of ramp-related folding, deformed the sedimentary cover (thin-skinned model). Ramps were presented as usually connected in the Triassic evaporites over the rigid basement during a single tectonic event. Field data collected in these works highlight usually “en echelon” geometry folds underlain by steeply dipping faults. In this model, the previously syn-rift strata thicken toward the border-fault zone are omitted. Unconformities and Mesozoic growth strata refute this interpretation.

The fourth period (2011–2017), which was characterized by the rise of inherited role of the pre-existent faults systems, featured a structural evolution controlled by deep-seated basement faults (corresponding to inherited Permian (?) to Cretaceous normal faults) and shallower décollement within the sedimentary cover (Riley et al. 2011; Gharbi et al. 2013, 2015; El Amari et al. 2016).

This chapter provides an overview of data-compilation recently published by Gharbi et al. (2013, 2015), El Amari et al. (2016) in addition to newly collected data. Detailed



geological mapping, local structural analyses, interpretation of seismic reflection profiles and the sequential restoration of balanced cross section along the southern Tunisian Atlas front, together with recent published data reveal a structural similarity between the ZBHS and BOAHS, which likely link to a general tectonic style of the all Northern Chotts Range structures. The age, the geometry of the units, and the present distribution of several secondary thrust-related anticlines give evidences of the reactivation of the pre-existing normal faults acting now as thrust ramps generating an associated folding (Fig. 5.15). Most of this shortening is accommodated by mixed thick- and thin-skinned tectonic style, controlled by deep-seated basement faults (corresponding to inherited Permian (?) to Cretaceous normal faults) and shallower décollement within the sedimentary cover. Field relationships between units and the present distribution of faults and folds clearly involve two different times of shortening evolution, i.e., Eocene and Miocene–Quaternary events. The most recent study of stress state in southern Tunisia (Gharbi et al. 2014) highlighted a stress state characterized for the Miocene time by NW-trending regional compressional tectonic regime. This NW-trending compression was possibly responsible for the right-lateral strike-slip reactivation of the E-trending BOAHFS. This major fault system was probably accompanied by minor, to the respect of the main strike-slip ones, reverse movement along the E-trending BOAHFS (El Amari et al. 2016). During the Quaternary to present-day period, a modern N-trending state of stress was also considered by recent studies as a compressional tectonic regime (Gharbi et al. 2014). During this phase, the N-trending compression is responsible for thrust tectonics, which as well typified as reverse–reactivation of the Mesozoic inherited faults (El Amari et al. 2016).

The new interpretation of the preserved extensional structures using the surface and deep–subsurface data sets refined by the sequential restorations of the balanced cross section allow us to highlight the role of pre-existing rift basin architecture on the evolution of the southern Atlas fold-and-thrust belt of Tunisia. Cretaceous sedimentary cover of BOAHS is more deformed than the ZBHS. These structures are cut by N100–110° E-trending fault systems. These systems usually exhibit a fault kinematics, with striation showing a multiphase history with a first generation indicating normal movement and a second as dextral strike-slip (Figs. 5.5 and 5.11). The second-order fault systems associated to the main trend of these anticlines are usually apparent strike-slip faults. Unfolding of the structure easily shows an inherited normal faulting. In addition, the normal faulting generates growth strata (surface see Figs. 5.7, 5.8, 5.12 and subsurface Figs. 5.13a and 5.14) filled by a syntectonic sequences associated to typical syntectonics conglomerates (Fig. 5.6) and abundant

soft-sediment sequences associated to the first normal faulting activity. Like many other extensional areas, the Mesozoic history of this margin was dominated by growth of listric normal faults, which are associated with well-developed half-graben fill and large rollover structures. The subsurface data provides a well image in the Chotts Fejej basin as governed by deep listric normal faults. Seismic profiles well featured this geometry with listric fault system vertical at surface and rapidly decreases becoming planar at depth. These growth normal faults, controlling the genesis of the ZBHS and BOAHS, are symptomatic of this evolution with up-thrown side largely more thicker and characteristic of growth related-normal faults strata (Figs. 5.13 and 5.14). These E-trending listric extensional growth faults draws the structural architecture of the south Tethyan margin in south Tunisia. A preserved Jurassic–Early Cretaceous graben is identified beneath the Chotts Fejej range, which is associated to the listric normal fault connected to an intra-basement detachment. The Chotts Fejej basin was usually considered as a large anticline (Zargouni and Abbes 1987; Fakraoui 1990; Bouaziz et al. 1994; Swezey 1996; Bédier et al. 2001) marked the far-foreland of the southern Tunisian Atlas. Lithostratigraphic data provided by petroleum well, presented above, reveal that the depth of the top Triassic salt horizons is reaches more than ~3 km. In addition, the surface and subsurface interpretation allow to identify a southwest-verging listric normal fault. In the footwall of this later, the top of the Triassic level is reaches more than ~3.2 km in the P4 well while in the hanging wall this horizon is reaches more than ~3.5 km in the P2 well. These results are concordant with the regional calculated tectonic subsidence rates in the Chotts basin (Patriat et al. 2003).

Many authors believe that the E-trending fault systems are inherited from the southern Tethyan rifting growth periods (Souquet et al. 1997; Patriat et al. 2003; Raulin et al. 2011; Dhaoui and Gabtni 2013; Gabtni et al. 2011; Masrouhi et al. 2014a, b; Gharbi et al. 2015; El Amari et al. 2016; Naji et al. in press). The basement normal faults recorded in this domain were likely responsible for development of the evaporites basins during the Late Triassic–Jurassic synrift times (Kamoun et al. 2001). The continued synrift tectonic process generates an extension of about ~6.5 km and associated to high subsidence rates during Jurassic–Early Cretaceous times (Gharbi et al. 2015). This extensional tectonic context is naturally related to the opening of the Central Atlantic Ocean. The rifting period seems to be synchronous with the dislocation of the continental platform and the development of major synsedimentary normal fault systems producing tilted block basin geometry in the southern Atlasic domain of Tunisia (Abbès and Tlig 1991; Louhaïchi and Tlig 1993; Gharbi et al. 2013, 2015; El Amari et al. 2016). This setting is recognized in Tunisia, which is

synchronous with segmentation between platforms in central-southern Tunisia (Gharbi et al. 2013) and the deep Tunisian trough in northern Tunisia. During upper Barremian and Aptian–Albian times, the Chotts basin was probably extended about  $\sim 2.5$  km showing typical geometry of a rollover related structure (Gharbi et al. 2013, 2015). This Barremian and Aptian–Albian original situation was accompanied in some segments by progressive unconformities. The Upper Aptian–Lower Albian regional unconformity is the well-known, which was identified in this area as mainly related to growth normal faulting. This geometry was possibly the reason misleading the previous interpretation of compressional “Austrian event” as responsible for the observed sedimentary gap and progressive unconformities. In addition, the rifting has been accompanied by an episode of volcanism, which is testified by basalt flows observed in the pelagian blocks of eastern Tunisia (Ellouz et al. 2003; Patriat et al. 2003) and southern Tethyan margin in the southern Atlas of Tunisia (Gharbi et al. 2015). During this period, extensional normal faulting has produced space for the salt to rise (Masrouhi et al. 2014b) and caused different salt geometry. In this evolution, the Albian is recognized to have been the time of the maximum regional extension occurring during the Early Cretaceous rifting stage (Masrouhi et al. 2014b). During Cenomanian–Santonian post-rift period, the margin records a low extension associated with an important transgression in the southern Atlassic domain of Tunisia and thick deposits of pelagic and benthic facies (Abdallah and Meister 1997; Soua et al. 2009).

Based on the above-presented results, the following conclusions can be drawn:

1. The present-day “en echelon” fold distribution is conceivably the surface expression of the “en echelon” faulting, which controls the fold’s emplacement and style. The present-day general tectonic style of the all Northern Chotts Range structures, the age and the geometry of units, and, the distribution of thrust-related anticlines, all of them are significant of a pre-existing normal faults reactivation, acting now as thrust ramps generating an associated folding. The Northern Chotts Range is well typified as the results of reverse–reactivation of the Mesozoic inherited faults. Toward the end, this multiphase evolution shapes a chain with mixed thick- and thin-skinned tectonic style, controlled by deep-seated basement faults (inherited Permian (?) to Cretaceous normal faults) and shallower décollement within the sedimentary cover.
2. The Chotts basin was previously considered as a large anticline related to the Cenozoic compressional events to explain the gentle deep observed “antiform structure”. It was, therefore, marked as the far-foreland of the southern

Tunisian Atlas. Like many other inverted margin, extensional inherited structures are still preserved in the southern Tunisian Atlas. The Chotts basin appears to well preserve the Mesozoic history of this margin, which was dominated by growth of listric normal faults, themselves associated with well-developed half-graben fill and large rollover structures. The subsequent tertiary compressional front will be, therefore, repositioned in the Northern Chotts Range Front.

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