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Cretaceous paleomargin tilted blocks geometry in northern Tunisia: stratigraphic consideration and fault kinematic analysis

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Abstract
New stratigraphic data, lithostratigraphic correlations, and fault kinematic analysis are used to discuss the basin geometry and sedimentation patterns of the northeastern Tunisia during Cretaceous times. Significant facies and thickness variations are deduced along the northeastern Atlas of Tunisia. The NW-SE 80-km-long regional correlation suggests a high sedimentation rate associated with irregular sea floor. The fault kinematic analysis highlights N-S to NE-SW tectonic extension during Early Cretaceous. During Aptian–Albian times, an extensional regime is recognized with NE-SW tectonic extension. The Cenomanian–Turonian fault populations highlight a WNW-ESE to NW-SE extension, and Campanian–Maastrichtian faults illustrate an NW-SE extension. The normal faulting is associated to repetitive local depocenters with a high rate of sedimentation as well as abundant syntectonic conglomeratic horizons, slump folds, and halokinetic structures. The sequence correlation shows repetitive local depocenters characterizing the basin during Early Cretaceous times. All the above arguments are in favor of basin configuration with tilted blocks geometry. This geometry is shaped by major synsedimentary intra-basin listric normal faults, themselves related to the extensional setting of the southern Tethyan paleomargin, which persisted into the Campanian–Maastrichtian times. The results support a predominant relationship between tilted blocks geometry and sedimentation rather than E-W "Tunisian trough" as it was previously accepted.

Keywords Cretaceous · Tilted blocks · Stratigraphic consideration · Fault kinematic · Tunisia

Introduction

The present-day structure of the Northern African margin in Tunisia results from a complex tectonic evolution that operated since Late Permian with the beginning of the breakup of Pangea and ended with the Cenozoic Alpine orogeny of the Maghrebide chain. The geodynamic evolution of the northern margin of Africa has been characterized by extension, crustal stretching and thinning, as well as subsidence during the Mesozoic Tethyan rifting (Boughdiri et al. 2007; Gharbi et al. 2013; El Amari et al. 2016; Soussi et al. 2017; Naji et al. 2018). The Mesozoic passive margin, where rifting occurred, was followed by subsequent inversion during Late Cretaceous–Cenozoic subduction and ended by the Alpine collisional process (De Lamotte et al. 2009; Khomsi et al. 2016). During the Jurassic time, a regional extensional tectonic regime produced the dislocation of the existing continental platform, which is related to the opening of the Central Atlantic and led to the development of normal faults, tilted blocks, and halokinetic and volcanic activity (Mattoussi Kort et al. 2009; Masrouhi et al. 2014a; Dhahri and Boukadi 2017). The Tunisian Atlas has particularly recorded the effect of Tethyan rifting as revealed by considerable facies and thickness variations within the Mesozoic sequences (Ben Ferjani et al. 1990; Masrouhi and Koyi 2012; Gharbi et al. 2015; El Amari et al. 2016).The complex structural pattern of Tunisia is mainly a consequence of the polyphased Cenozoic

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reactivation of inherited extensional fault systems which controlled fault-related folds (Masrouhi et al. 2008; Dhahri and Boukadi 2010; Gharbi et al. 2015; Khomsi et al. 2016).

The present study focuses on the basin geometry and sedimentation patterns of northeastern Tunisia during Cretaceous times. In this study, new sedimentologic, stratigraphic, paleontologic, and structural data are reported to understand the basin configuration of the southern Tethyan paleomargin in northern Tunisia. This work aims to contribute to the debate about the basin paleogeography during Mesozoic times on the basis of structural field data, stratigraphic precisions, lithostratigraphic correlations, and fault kinematic analysis.

Geologic setting

The northern Tunisian belt forms the northeastern edge of the African plate and set the eastern limits of the Atlas System. Except its northerly range which corresponds to the Numidian thrusted range, the northern Tunisian Atlas is classically subdivided into two distinguished structural units (Fig. 1a): the first unit corresponds to the southeastward major thrusted unit called the Teboursouk thrust unit which represents the front of the Alpine Range. This area shows thick Aptian–Albian sequences and exhibits frequent outcropping salt structures belonging to the northeastern Maghreb salt province (Masrouhi et al. 2013; Jaillard et al. 2017). The second one called the Zaghouan–Ressas unit corresponds to the front of the northern Tunisian Alpine Range. During Mesozoic times, the present Zaghouan thrust fault corresponds to a paleogeographic line between a relatively shallow platform to the south, with a condensed Aptian section from a deep basin to the north with a thick Aptian–Albian section (Morgan et al. 1998; Chihaoui et al. 2010; Soua 2016).

The Meso–Cenozoic geological evolution of the Northern African margin can be summarized in two main periods. The first period, from the Late Permien? to the Early Cretaceous, of the Mesozoic rifting is related to the Tethyan and Atlantic oceans' opening (Guiraud 1998). Recent works demonstrate that the opening of Central Atlantic operates during Jurassic and Early Cretaceous (Souquet et al. 1997; Boughdiri et al. 2007; Masrouhi and Koyi 2012; Naji et al. 2018). Furthermore, related Cretaceous salt movement confirms a hyperactive extension and thick and/or thin-skinned tectonic extension (Masrouhi et al. 2014b). In addition, frequent synsedimentary normal faults are recognized to produce a general tilted blocks geometry. During this period, the Aptian–Albian ages are described to have developed syndepositional facies and thickness heterogeneities of the south Tethyan margin in north Tunisia (Souquet et al. 1997; Gharbi et al. 2013; Masrouhi et al. 2014b; Naji et al. 2018). Commonly, the Cretaceous sequences, outcropping in northern Tunisia, display significant thickness and/or facies variations with abundant soft-sediment deformations and syntectonic growth strata (Gharbi et al. 2013; Naji et al. 2018).

The second main period, started since Late Cretaceous (at Campanian–Maastrichtian transition), causes a basin-positive inversion related to the African and Eurasian plate convergence (Guiraud and Bosworth 1997; Khomsi et al. 2009; Gharbi et al. 2015; El Amari et al. 2016).

Lithostratigraphy of Early Cretaceous successions

Jebel Sidi Salem section

The Sidi Salem–Messella is a NE-trending structure located along the Zaghouan–Ressas thrust system (Fig. 1b). The Early Cretaceous outcropping in this structure includes sequences ranged from Neocomian to Albian (Fig. 2). The outcropping Cretaceous sequences are subdivided as follows:

a. The first unit consists of marl-to-marly limestone succession, which is attributed to the Neocomian without additional precision (Fig. 2). These units, including pelagic and benthic fauna, indicate deposit of a marine environment.
b. The Neocomian deposits are covered by gray marls interbedded with quartzitic and clayey limestone beds with ammonites at the base and topped by dark marls. This ~ 150-m-thick unit of clayey facies delivered a faunal assemblage dominated by benthic foraminifera *Lenticulina*, *Nodosaria*, and *Dentalina* (Elkhazri et al. 2009; confirmed by M. Ben Youssef) which indicated the Barremian age.
c. Green to gray laminated marls intercalated with sandstones and gray nodular limestone beds showing in outcrop abundant belemnite and ammonite macrofauna. The common presence of bi-pyramidal quartz indicates halokinetic activity during this period. This ~ 300-m-thick unit is dated as Aptian. Nagazi (2016), with an extensive biostratigraphic analysis, shows that the Jebel Sidi Salem's Aptian sequences are subdivided as follows:
    - Early Aptian (Bedoulian) is dominated by a planktonic association which contains *Gorbachikella grandiapertura*, *Hedbergella sigali*, *Schackoïna cabri*, *Lenticulina bizonae*, and *Leupoldina protuberans* associated with benthic foraminifera *Lenticulina ouachensis*, *Gavelinella barremiana*, *Nodosaria paupercula*, and *Gavelinella* sp.
    - Middle Aptian (Gargasian) is identified by micropaleontological association with *Globigerinoides barri*, *Globigerinoides ferreolensis*, *Leupoldina protuberans*, *Globigerinelloides algerianus*, *Globigerinelloides ferreolensis*, and *Hedbergella trocoïda*.

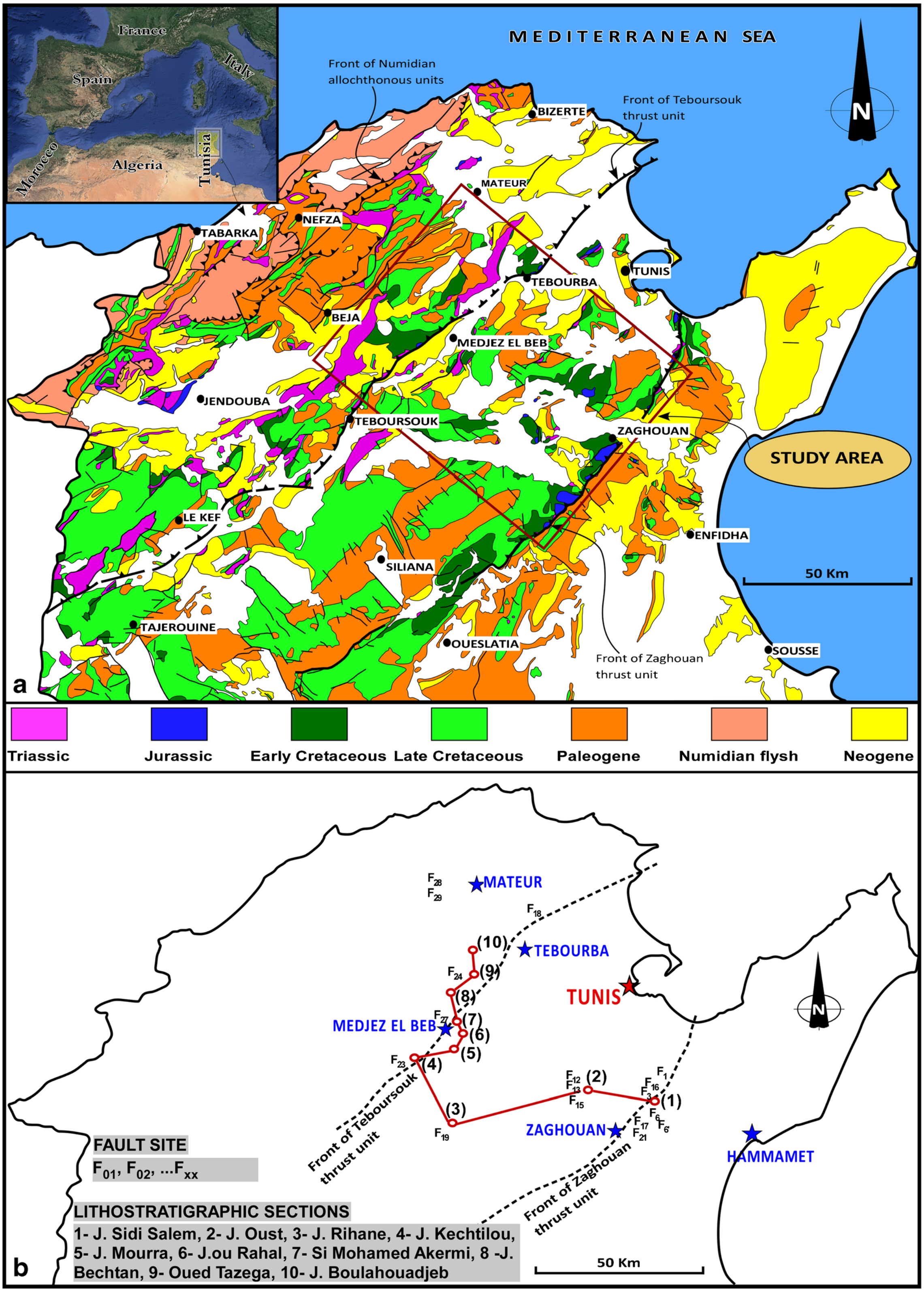

Fig. 1 **a**, **b** Simplified geologic map of northern Tunisia (modified from Bel Haj Ali et al. 1985) with location of the studied sections in northeastern Tunisia. The inset on the top left shows the location of Tunisia in North Africa

- Uppermost Aptian (Clansayesian) is marked by the appearance of *Hedbergella trocoïda* (Gandolfi), *Pseudoplanomalina cheniourensis* (Sigal), and *Hedbergella palanispira* associated to benthic foraminifera such as *Gavelinella* sp., *Ammodiscus tenuissimus*, and *Trochammina* sp.

- Aptian sequences are covered by gray-to-black marl succession with thin beds of nodular and quartzitic limestone. According to the biostratigraphic analysis of Nagazi (2016), this unit contains the following planktonic foraminifers' assemblage: *Ticinella primula*, *Ticinella bejaouansis*, *Rotalipora ticinensis*, *Hedbergella trocoïda*, *Ticinella roberti*, and *Rotalipora subticinensis*, which indicate a middle Albian age. The top of the unit is made of marl sequences with platy limestone succession beds which are attributed to the uppermost Albian (Vraconian in the literature) on the basis of the following micropaleontological association: *Planomalina buxtorfi*, *Biticinella breggiensis*, *Rotalipora appenninica*, *Dentalina guttifera*, and *Praedorothia hechti*, *R. subticinensis*, and *B. ticinensis*. The 180-m-thick Albian sequences contain abundant black shale levels, testifying for deep-sea environment deposition. The Albian strata are characterized by abundant slumps and carbonate nodules symptomatic of contemporaneous submarine slope.

d. A 120-m-thick series made of nodular limestone was interbedded by marls dated as Early Cenomanian. The top of these monotone sequences is marked by thinly laminated, dark gray limestone and marl of the uppermost Cenomanian–Early Turonian-aged Bahloul member.
e. Coniacian–Santonian-aged sequences of the Aleg Formation conformably overlie the previous Cenomanian–Turonian series. They are defined by thick sequences of limestone interbedded with marl layers at the base and thick marly sequences at the top. The Coniacian–Santonian series can reach a maximum of ~450 m in thickness in the northern flank of Sidi Salem anticline. These sequences are topped by the Campanian–Maastrichtian Abiod Formation with three well-known terms.

Jebel Oust type section

The Jebel Oust is a large 15-km N 40° E-trending anticline structure which exposes a series ranging from Jurassic sequences in the core to Campanian–Maastrichtian outcrops in the limbs. In this locality, which is considered in northern Tunisia as the type section of Lower Cretaceous (Ben Ferjani et al. 1990; Souquet et al. 1997), 2600-m-thick siliciclastic and marly sequences (Fig. 3) have been deposited (Fig. 3). According to Souquet et al. (1997), this *reference section* is made of the following:

a. Ninety meters of debris flow deposits and marl calpionellid-bearing mudstone parasequences which correspond to the Tithonian–Berriasian transition followed by mud flow and debris flow deposits of 40 m thick which marked the early Berriasian. The Berriasian *p.p.* is made of ~160 m of greenish muds with thin bedded sandstones and siltstones. The following micropaleontological association was described by Maamouri and Salaj (1978): *Tintinopsella carpathica*, *Spirillina neocomiana*, *Trocholina infragranulata* North, *Trocholina vasserodi* Guillaume, *Trocholina molesta* Gorbatchik, *Trocholina burlini* Gorbatchik, *Spirillina neocomiana* Moullade, and *Spirillina minimina* Schacko. These units are covered by 160-m carbonate-dominated sequences which are attributed by Souquet et al. (1997) to the uppermost Berriasian–Early Valanginian.
b. A large 900-m-thick unit consists of siliciclastic turbidites with pelites, thin-bedded sandstones, slumped quartzite bed, and sometimes, sliding blocks which correspond to Valanginian deposits. This unit is covered by 120-m-thick rich ammonite mudstones marked by the *Castellensis* zone which indicates the lower Hauterivian (Souquet et al. 1997) followed by aggrading marl–mudstone parasequences. To the top, a ~280-m-thick siliciclastic and carbonate storm with marl succession is attributed to the Late Hauterivian.
c. The Barremian is made up of siliciclastic tempestites and slumped sandstone beds (Fig. 3) followed by a thick nodular limestone bar and siliciclastic storm topped by black shales. This ~600-m-thick unit delivered to Maamouri and Salaj (1978) *Anomila* (*Gavelinella*) *sigmoicosta barremiana* and *Epistomina* (*Brotzenia*) *hechti* which indicate the Early Barremian. The top of sequences delivered the following: *Conorotalites bartensteini bartensteini*, *Glavihedbergella subcretacea*, and *Schackoina pustulans* which indicate the Late Barremian.
d. The Aptian is marked by offshore muds with siliciclastic turbidites (Fig. 3).
e. The Jebel Oust Late Cretaceous series were studied by Turki (1975) in the eastern section of the structure. This section shows that the Albian series begins by 60-m-thick marly sequences, topped by 180-m platy limestone of the uppermost Albian.
f. The thinly laminated organic-rich 100-m-thick limestones of Bahloul Formation. These series are covered by 450-m-thick Coniacian–Santonian limestone–marl successions topped by 150-m-thick Campanian–Maastrichtian Abiod sequences.

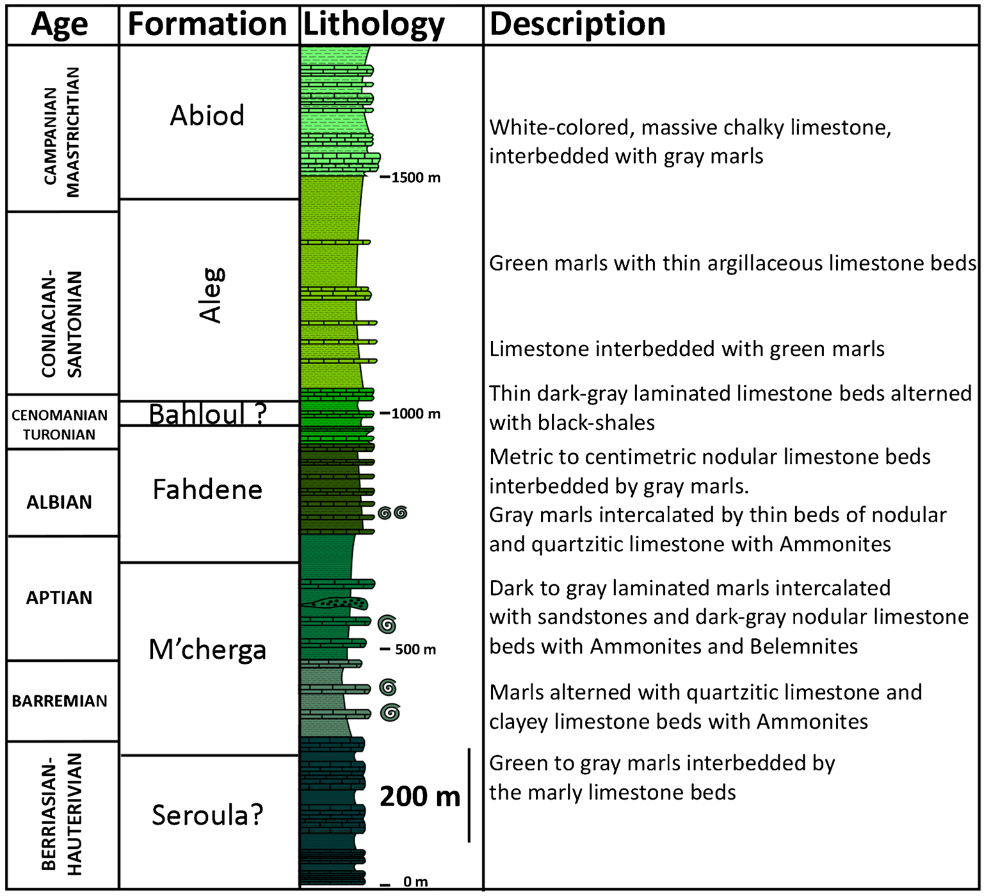

Fig. 2 Detailed lithostratigraphic subdivision of Cretaceous sequences in Jebel Sidi Salem

Jebel Kechtilou section

The Jebel Kechtilou is a NE-trending faulted anticline. It corresponds to one of numerous structures disturbed during Cretaceous rifting by halokinetic intrusion. Active extensional tectonics have been recorded along the Jebel Kechtilou particularly within Aptian–Albian deposits (Haggui 2012). The Aptian–Cenomanian series display numerous metric *olistostromes* associated to frequent reworked blocks, slumps, and nodules; all are interpreted as deriving from submarine gravity sliding (Naji et al. 2018). The Upper Cretaceous sequences of Jebel Kechtilou have been well described by El Ouardi (1996) and revised in this work (Fig. 4). From the bottom to the top, outcropping Cretaceous series are made of the following:

a. A thick series of ~ 160-m yellow and yellow–green marls with decametric-to-metric limestone bed successions. Polygenic conglomerates mark the top of these series, themselves covered by ~ 120 m of silty green marls topped by 40 cm of breccia layer. These series delivered to Haggui (2012) *Leupoldina pustulans*, *Hastigerinella bizonae* Chevalier, *Ticinella* Roberti (Gandolfi), *Ticinella bejaouensis*, and *Ticinella roberti* indicating the Aptian age.
b. Approximately 120-m bar is composed of gray platy limestone beds with ammonites, which were dated as Early Albian. This unit is covered by 80-m-thick middle-to-late Albian deposits consisting of dark gray marls interbedded by gray clayey limestones. They contain an assemblage with *Rotalipora ticinensis* and *Hedbergella breggiensis*. At the top, ~ 120-m-thick platy limestone bar was attributed to the uppermost Albian on the basis of *Planomalina buxtorfi* microfauna's occurrence in thin section (Haggui 2012).
c. Cenomanian sequences show, at the bottom, ~ 120-m-thick gray limestone bar. The base of sequences contains *Rotalipora cushmani*, *Rotalipora greenhornensis*, *Hedbergella simplex*, *Hedbergella* sp., and *Lenticulina* sp. (Det. Maamouri in El Ouardi 1996) which indicate the Late Cenomanian. The top, of this middle sequences, contains *Whiteinella archaeocretacea*, *Helvetoglobotruncana helvetica*, *Ammodiscus cretaceus*, and *Heterohelix* sp. indicating early to middle Turonian age. These series are covered by ~ 90-m gray marls with gray decametric-to-metric limestone succession beds

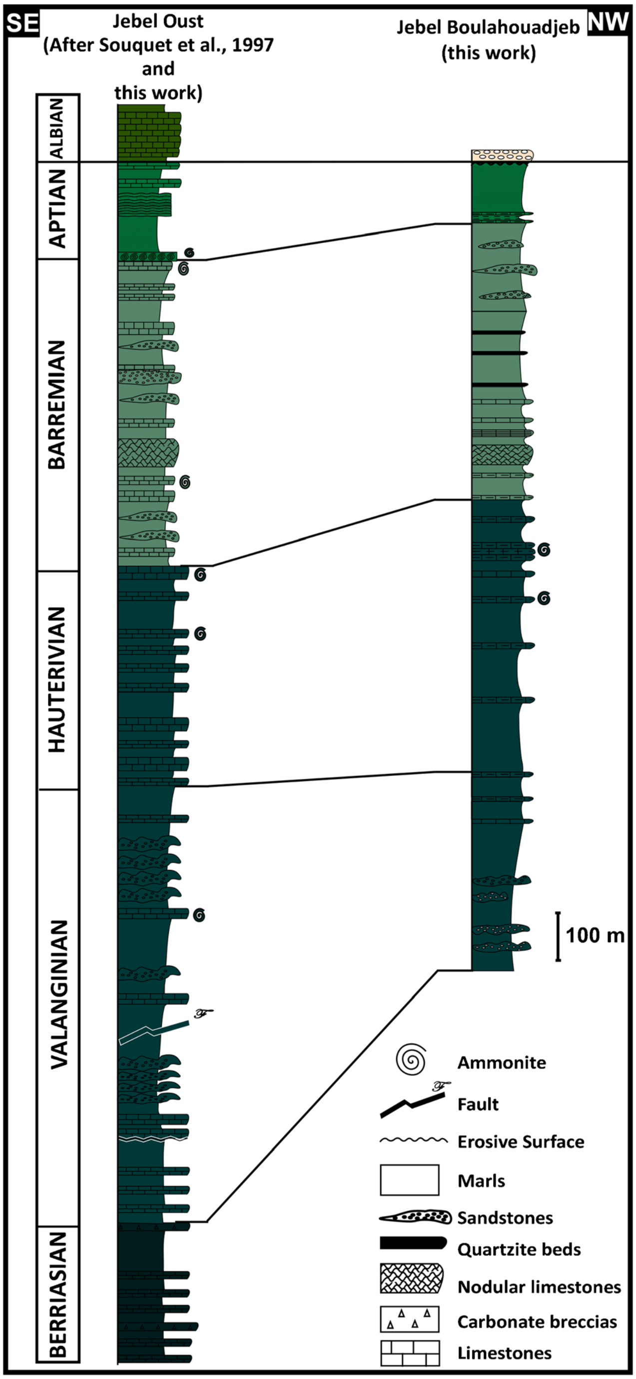

Fig. 3 NE-SW lithostratigraphic correlation of the Early Cretaceous series of Jebel Oust and Jebel Boulahouadjeb sections

which was dated as Late Turonian based on microfaunal association with *Marginotruncana schneegansi*, *Marginotruncana pseudolinneiana*, and *Hedbergella flandrini*.

d. Approximately 180-m-thick series is made of monotone marl–limestone successions topped by metric rich inocerame limestone beds. The samples collected from the upper part of this series delivered a Coniacian association consisting of *Dicarinella primitiva*, *Dicarinella concavata*, *Marginotruncana schneegansi*, *Marginotruncana praeconcavata*, *Hedbergella flandrini*, and *Lenticulina rotulata*.

e. Approximately 900-m-thick gray flaky marls with a micropaleontological association include *Sigalia carpatica* (Det. Zaghbib-Turki and Rami in El Ouardi 1996), attesting a Santonian age. The Santonian marls are covered by ~220-m gray marls with white to gray clayey limestone beds, dated as Early Campanian with *Globotruncana elevata* fauna. The Campanian sequences are followed by ~140-m white limestone beds alternated with marly joints, dated as middle to upper Campanian containing *Globotruncana ventricosa* and *Globotruncanita stuartiformis*.

Jebel Rihane section

The Jebel Rihane section corresponds to a WNW-to NW-trending syncline (Ben Yagoub 1978). It is located eastern of Jebel Oust structure and is mainly made up of Upper Cretaceous deposits. This structure exposes a Cretaceous series ranging from Aptian to Maastrichtian. Ages are deduced from the works of Floridia (1963) and Ben Yagoub (1978), in which they indicate that the Jebel Kechtilou section shows reduced thickness with a comparable microfaunal assemblage. The Jebel Rihane section clearly exposes a considerable thickness variation of Aptian–Albian sequences suggesting a local basin configuration. This configuration reflects a tilted blocks geometry produced by the reactivation of inherited faults (Naji et al. 2018).

Medjez-El-Bab sections

The Medjez-El-Bab area exposes Early Cretaceous sequences in the Jebel El Mourra, Jebel Bou Rahal, and Sidi Mohamed Akermi localities with significant thickness changes ranging from tens to hundreds of meters (Fig. 5).

Jebel El Mourra section

The Jebel El Mourra is a NE-trending anticline structure consists by Triassic and reduced Early Cretaceous series. It was subject to various interpretations as a salt dome structure by El Ouardi (1996) or as a single salt sheet extruded during the Cretaceous, forming a submarine salt glacier by Masrouhi and Koyi (2012). The Cretaceous series plunging above Triassic rocks are as follows:

a. Twenty meters of decametric platy limestone beds is separated by marly joints. This first unit delivered

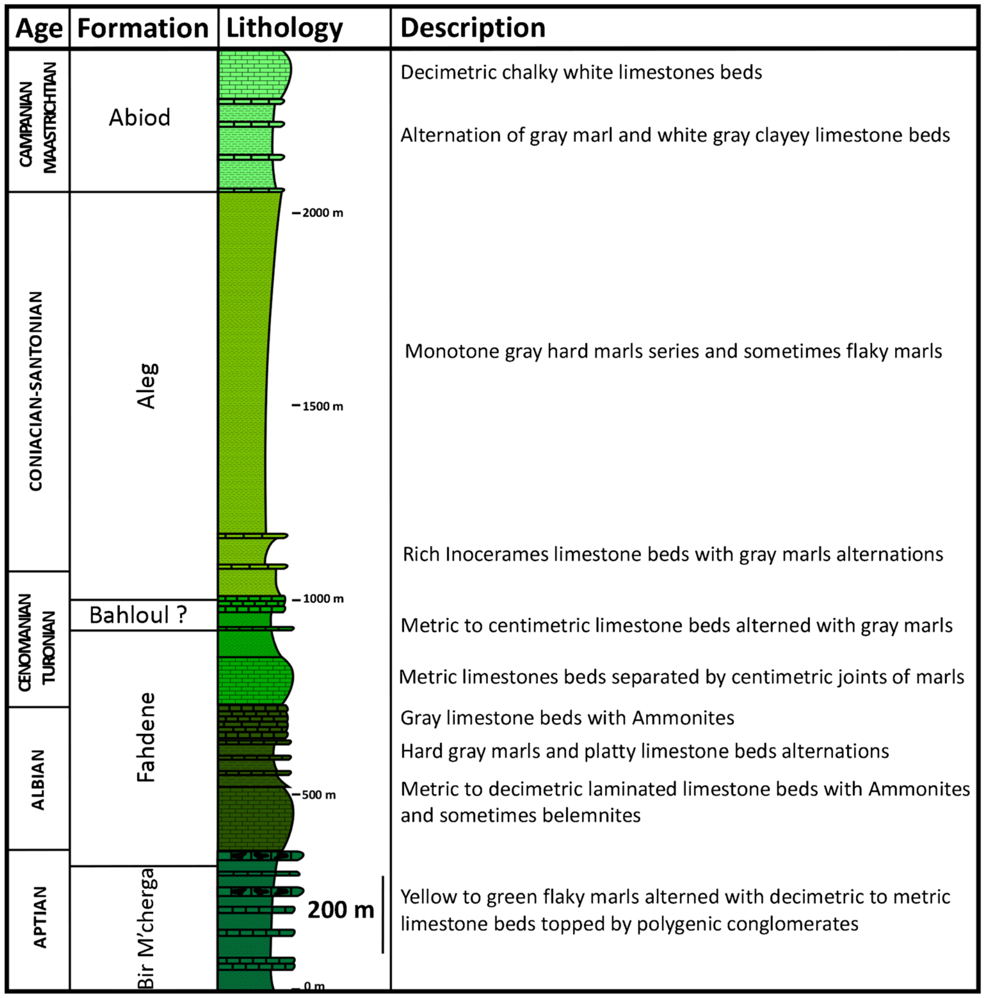

Fig. 4 Detailed lithostratigraphic subdivision of Cretaceous sequences in Jebel Kechtilou

Planomalina buxtorfi Gandolfi, *Rotlipora appenninica* Morrow, *Hedbergella planispira* Tappan, and *Hedbergella delrioensis* Carsey (Det. Zaghbib-Turki and Rami in El Ouardi 1996) which allow to attribute it to the uppermost Albian. The latter is covered by an observation gap of 15 m thick.

b. Marls alternated with metric-to-decametric limestone beds are topped by gray marls. This 55-m-thick unit is covered by Plio-Quaternary conglomeratic deposits. Marls delivered to El Ouardi (1996) the following microfauna association: *Dicarinella concavata* Brotzen, *D. primitiva* Dalbiez, *Marginotruncana undulate* Lehmann, *Marginotruncana sinuosa* Porthault, *Marginotruncana tarfayaensis* Lehmann, *M. pseudolinneiana* Pessagno, *Hedbergella flandrini* Porthault, *Lenticulina rotulata* Lamarck, and *Dorothia oxycona* Reuss, indicating the Late Coniacian age. The upper marls delivered *Marginotruncana pseudolinneiana* Pessagno, *M. undulate* Lehmann, and *M. tarfayaensis* Lehmann indicative of Santonian age.

Masrouhi and Koyi (2012) described a coral algal reef on the Upper Albian marls dated by *Planomalina buxtorfi*. The Cenomanian sequences were characterized by the occurrence of *Globotruncana appenenica*, and the Turonian limestones by the presence of *Helvetoglobotruncana helvetica*. The Coniacian–Santonian delivered *Globotruncana coronata* and *Dicarinella concavata* in the bottom and *Dicarinella concavata asymetrica* in the top.

Jebel Bou Rahal section

Jebel Bou Rahal is a NE-trending southeast dip limb of the Medjez-El-Bab anticline structure and shows an interbedded Triassic salt sheet with Early Cretaceous sequences. According to El Ouardi (1996), the Cretaceous series (Fig. 5) shows the following from the bottom to the top:

a. The first unit is formed by ~ 160-m green clays with limestone and sandstone bed successions in which limestone beds predominate to the top. This unit is attributed to the Upper Barremian–Aptian age by a correlation of lithological units of nearby sections.
b. The second unit shows at the base ~ 80-m green marls and scarce gray decametric clayey limestone beds, followed by

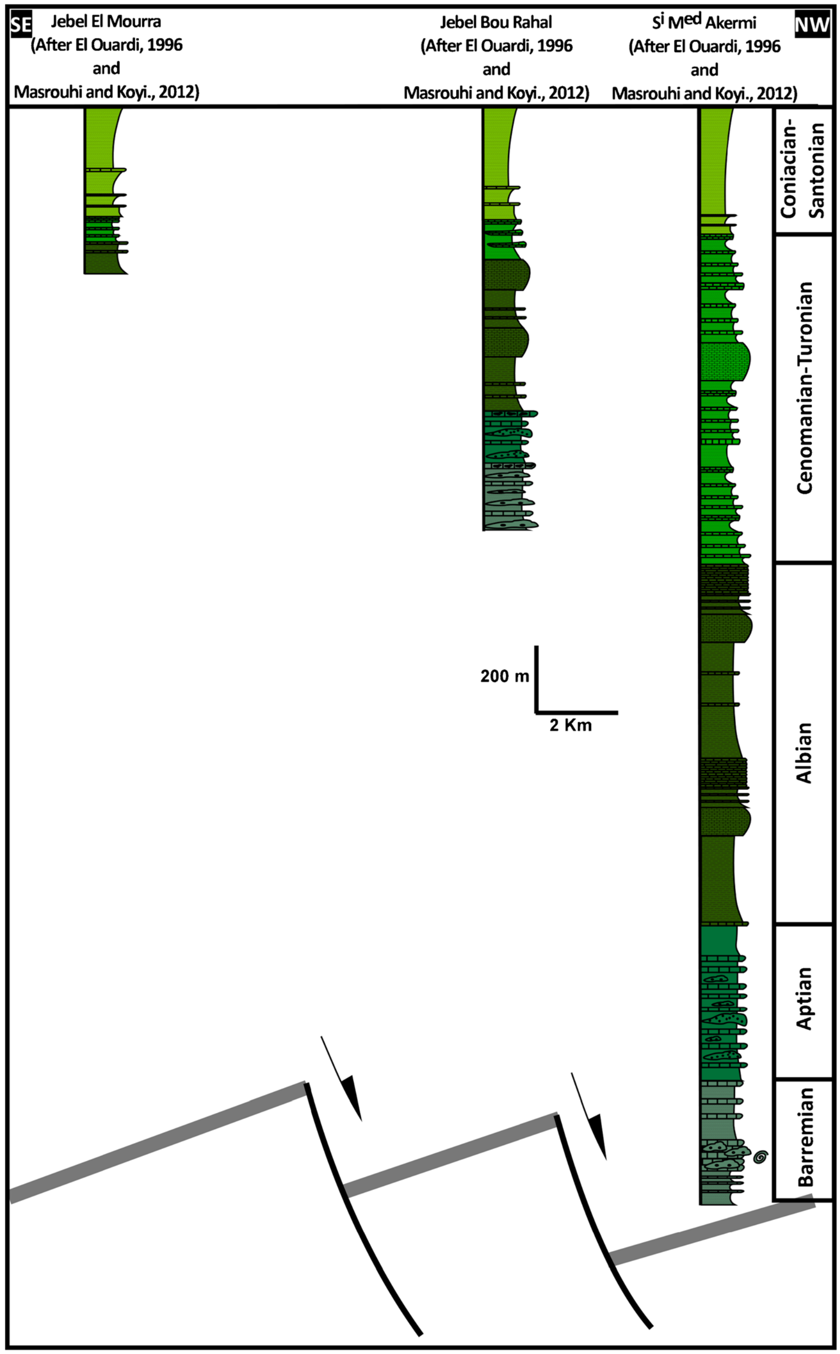

Fig. 5 NW-SE lithostratigraphic correlation of Cretaceous sequences in the Medjez-El-Bab area (Jebel El Mourra, Jebel Bou Rahal, and Sidi Mohamed Akermi)

~40-m-thick gray limestone bar, itself covered by 35-m-thick marls with ammonite-rich flaky limestone sequences. This unit is topped by ~25-m-thick gray platy limestone bar covered by ~25-cm-thick yellow siltstone sequences. The platy limestone unit contains *Planomalina buxtorfi*, *Hedbergella simplex*, *Hedebergella planispira*, *Hedebergella delrioensis*, and *Rotalipora appenninica* (Det. Zaghbib-Turki and Rami in El Ouardi 1996), characterizing the uppermost Albian. The lower part of this series delivered *Tincinella roberti*, *Tincinella bejaouaensis*, *Hedebergella infracretecea*, *Nodosaria prismatica*, *Nodosaria nuda*, *Ramulina* sp., *Dentalina linearis*, and *Lenticulina muensteri* (Det. Salaj in El Ouardi 1996) which attest the Early Albian. The middle bar of flaky limestone delivered to El Ouardi (1996) the following association: *Tincinella bejaouaensis*, *Tincinella roberti*, *Dentalina* sp., and *Lenticulina* sp. which indicate early to middle Albian age.

c. The platy limestone unit is covered by ~4-m-thick bar consisting of limestone breccia that resides monogenic conglomerates. This unit is attributed to the Cenomanian–Turonian age.

d. Marls with metric-to-decametric limestone bed successions delivered *Dicarinella concavata*, *Dicarinella primitiva*, *Marginotruncana sinuosa*, *Marginotruncana pseudolinneina*, and *Globotruncana angusticarinata* (Det. Salaj and Rami in El Ouardi 1996) which attest the Late Coniacian age.
e. The last unit is covered by an observation gap of 250 m thick then an outcrop of ~ 120-m-thick gray marls topped by Nummulitic limestone beds of the early Eocene. These marls delivered *Dicarinella asymetrica*, *Dicarinella concavata*, *Marginotruncana tarfayaensis*, *Marginotruncana sinuosa*, *Sigalia carpatica*, and *Dorothia oxycona* (Det. Zaghbib-Turki and Rami in El Ouardi 1996) which indicate the Santonian age.

Jebel Bou Rahal to Sidi Mohamed Akermi section

The Jebel Bou Rahal locality exhibits thick Cretaceous sequences ranging in age from Barremian to Coniacian (Fig. 5). According to El Ouardi (1996), from the base to the top, this section exposes the following:

a. Approximately 80 m of gray to dark marls has thin-bedded sandstone layers and gray bioclastic limestone bed intercalations. These successions are covered by ~ 60-m-thick carbonate unit made of three limestone bars topped by platy gray to black limestone beds with ammonites. The first bar exposes reworking blocks with the same facies. The top of this first unit is formed by ~ 40 m of silt and sandy marls with gray sandy limestone layers. This fist unit was dated as Late Barremian age, on the basis of rich microfauna association (El Ouardi 1996).
b. Approximately 120-m-thick green marl sequences contain iron and celesto-barite nodules with metric and decimetric gray limestone beds characterized by belemnites and breccia. This series is covered by a 50-cm-thick polygenic conglomerate unit. These were dated as Bedoulian–Gargasian on the basis of the following association: *Lingulogavenillela sigmoicosta barremiana*, *Epistomina carpeuleri*, *Hedbergella infracretecea*, *Hedbergella tuschepsensis*, *Hedbergella bolli*, *Hedbergella* sp., *Leupoldina pustulans*, *Leupoldina protuberans*, *Dentalina nana*, *Dentalina* sp., *Lenticulina roemeri*, *Lenticulina* sp., *Ortokarstenia senestralis*, *Ammodiscus tenuissimus*, *Vaginulina arguta*, and *Nodosaria* sp. (El Ouardi 1996). These sequences are covered by 75-m-thick gray flaky marls, themselves topped by 40-cm-thick breccia beds. These marls delivered *Planomalina chiniourensis* which mark the Late Aptian.
c. Approximately 200-m-thick green marls with numerous gray decimetric limestone bed successions are characterized by slump folds and septaria (Masrouhi and Koyi 2012) followed by an observation gap of 60 m, and then 120-m-thick gray platy limestone bar. These rich ammonite limestone beds are surmounted by 170-m-thick marls with limestone intercalations. The lower part of successions and the lower part of platy limestone bar delivered to El Ouardi (1996) a rich microfauna association including *Tincinella roberti*, *Tincinella bejaouaensis*, *Haplophragmoides concavus*, *Haplophragmoides nonioninoides*, and *Textularia* sp., which indicate the Early Albian. The upper marl–limestone alternations indicated a middle Albian age attested by *Ticinella primula* (El Ouardi 1996). These sequences are covered by 100-m-thick gray rich ammonite and rudist hard limestone with marls and slumped platy limestones. This level is dated as the uppermost Albian with *Planomalina buxtorfi* fauna.
d. Approximately 120-m-thick bar consisting of dark gray laminated limestone beds with abundant ammonites. These beds show repetitive clayey joints. It was dated as by El Ouardi (1996) on the basis of the following assemblage: *Rotalipora cushmani*, *Rotalipora greenhornensis*, *Hedbergella simplex*, *Whiteinella archaeocretacea*, *Helvetoglobotruncana helvetica*, and *Ammodiscus cretaceus* which attests the Late Cenomanian–Early Turonian age. These series are topped by 90-m marl–limestone alternations. Micropaleontological analysis indicates a Late Turonian age attested by the disappearance of *Helvetoglobotruncana helvetica* and the appearance of *Marginotruncana schneegansi* (Det. Zaghbib-Turki and Rami in El Ouardi 1996).
e. Large monotone limestone–marl successions dating Coniacian–Santonian age on the base of the following microfauna association delivered *Globotruncana coronata* and *Dicarinella concavata* at its bottom and *Pseudolinneiana* sp., *Dicarinella asymetrica* and *D. concavata* at its top (Masrouhi and Koyi 2012).

Jebel Bechtab section

The Jebel Bechtab, located in the southwestern part of the Lansarine belt, is a NNE-trending faulted anticline, crossed by Triassic evaporitic bodies. This structure is made of Hauterivian–Barremian to Oligo–Miocene sequences (Masrouhi et al. 2013). The Glib Abiod locality situated in the southeast of Bechtab structure exposes a reduced Late Cretaceous series described by Masrouhi et al. (2013) as follows:

a. Approximately 40-m unit is formed by dark gray marls with successions of gray platy limestone including ammonites. This unit delivered *Rotalipora subticinensis*, *R. ticinensis*, *Ticinella breggiensis*, and *Ticinella primula* which indicates the Late Albian–uppermost Albian.

b. Approximately 120-m-thick deposits are made up of schistose marls with successions of platy limestone on the base and metric limestone beds to the top. Middle limestone beds delivered to Masrouhi et al. (2013) the following: *Rotalipora greenhornensis*, *Rotalipora cushmani*, *Rotalipora reicheli*, and rare *Hedbergella* which attest the middle to Late Cenomanian. The following sequences delivered rich filaments and globigerina microfacies with *Rotalipora reicheli*, *Rotalipora cushmani*, *Dicarinella imbricate*, and *Whiteinella* sp. which indicate the Late Cenomanian–Lower Turonian.
c. Approximately 120-m-thick sequences consist black schistose and marl–limestone successions. The middle part of this series delivered *Dicarinella concavata*, *Dicarinella asymetrica*, and *Sigalia carpatica* which attest the Santonian age.
d. Approximately 60-m-thick chalky limestone sequences consist the Campanian–Maastrichtian Abiod Formation.

Oued Tazega section

Two kilometers to the south, the Cretaceous outcrop of Oued Tazega shows the following lithostratigraphic succession (Fig. 6):

a. Approximately 70-m-thick gray marl has siliciclastic intercalations with the following assemblage (Solignac 1927): *Puzosia ligaata d'orb.*, *Holcostephanus astieianus d'orb.*, *Holcosdiscus aff. Incertys d'orb.*, *Phylloceras infundibulum d'orb.*, *Duvalia dilatata BLV*, and *Belemnopsis pistilliformis* of Valanginian p.p.–Hauterivian age. This age attribution was confirmed by Peybernes et al. (1996) as lateral equivalent of the Valanginian p.p.–Hauterivian Seroula Formation.
b. Approximately 150-m-thick sequences are made of shale, gray marl, and limestone alternations. To the top, the marly series shows sandstone successions. This unit is dated as Barremian age by its position.
c. Approximately 200-m-thick sequences of gray marls, alternating with gray limestone beds with clear patina, delivered rare microfauna, i.e., *Lenticulina*, and could be attributed to the Aptian age.

Jebel Boulahouadjeb section

Jebel Boulahouadjeb is a NNE-trending anticline located in the northwestern of Tebourba region. It is part of the large salt structure of Lansarine–Baouala. It exposes thick Early Cretaceous sequences as previously described (Solignac 1927; Zargouni 1975; Masrouhi et al. 2013) and revised by the present work. This section shows the following lithological succession (Fig. 6):

a. Approximately 400-m-thick pelitic sequences are characterized by the stacking of lenticular sandstone deposit of variable size (from cubic centimeters to blocks of a few cubic meters). The top of this first unit is marked by schistose gray–blue marls, alternating with thin marly limestone beds. These series are attributed to the Valanginian-aged Seroula Formation (Khessibi 1967; Peybernes et al. 1996). The Valanginian–Hauterivian boundary is located in the upper marl–limestone sequences.
b. Approximately 600-m-thick sequences are made of schistose gray marl showing intercalations of marly limestones with pyritic ammonites and aptychus (Solignac 1927). The following microfauna association was described: *Lissocers grasianum d'orb.*, *Phylloceras infundibulum d'orb.*, *Phylloceras semisulcatum d'orb.*, and *Holodiscus incertus d'orb*. Limestone beds provided *Calpionella tintacica* and *Calpionella carpatica* with rare Hedbergellas and Lagenidae allowing to attribute the base of this set to the Early Hauterivian (dét. Raoult; in Zargouni 1975). The upper part of these sequences delivered *Epistomina eichenbergi*, *Spirillina neocomiana*, *Lenticulina ouachensis*, *Dorothia hauterivica*, and *Lenticulina gaultina*. Above-studied samples delivered *Epistomina eichenbergi*, *Trochamina* sp., *Hedbergella planispira*, *Gavelinella* sp., *Lenticulina ouachensis*, *Dorothia hauterivica*, *Lenticulina eichenbergi*, and *Vaginulina* sp. attributed to the Hauterivian–Barremian age.
c. Approximately 100-m-thick hard nodular gray limestones, usually as great benches or platy alternating with schistose gray marl layers, contain *Silisites seranonis d'orb.*, *Paranophites angulicostatus d'orb.*, *Crioceras angulicostatus* Wolam., and *Crioceras barremense* Kil., which allow to attribute to the Barremian age (Solignac 1927). In thin section, this level shows a micrite with Radiolaire and Hedbergellas. The gray schistose marls enclose some intercalations of centimetric beds of brown quartzites. These sequences are covered by green pelites with sandstone blocks of varied size and rare carbonate intercalations.
d. Approximately 400-m-thick sequences delivered spicules of echinoderms associated to *Lenticulina eichenbergi*, *Ammobaculites cretaceus*, *Gavelinella barremiana*, *Conorotalites bartensteini-intercedens-aptiensis*, *Epistomina ornata*, *Epistomina eichenbergi*, and *Trochamina* sp., of the Upper Barremian.
e. Approximately 250-m-thick sequence is mainly formed by gray schistose marl alternations with marly limestones

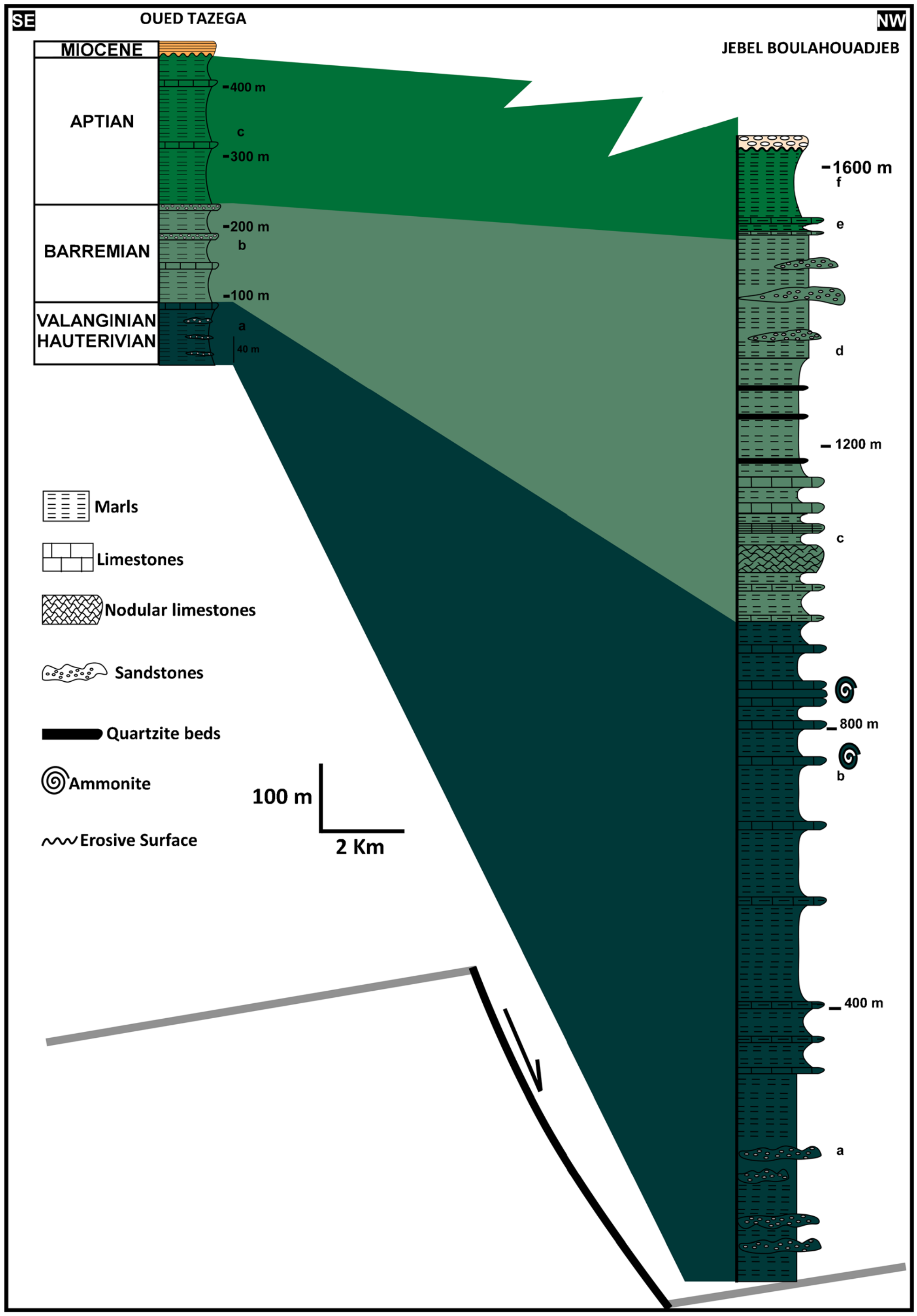

Fig. 6 Detailed lithostratigraphic section of the Early Cretaceous series in Oued Tazega and Jebel Boulahouadjeb. (a–c) Lithological units. For detailed description, see the text

rich in organic matter beds. This interval constitutes an important reference level for correlating the subsidence of deposit areas on the Barremian–Aptian boundary.

f. Approximately 120-m-thick sequences of gray marls are covered by the Quaternary plain of Oued Et Tine containing *Lenticulina gaultina*, *Conorotalites aptensis*, *Valvulina* sp., *Ammobaculites*, *Dorothia oxycona*, and *Dorothia trochus* which indicate the Aptian age.

Lithostratigraphic correlation

In the northern Tunisia, the Early Cretaceous sequences have been described as "flyschoid deposits" (Memmi 1981, 1989; Souquet et al. 1997). The Jebel Oust is considered in northern Tunisia as the type section of Lower Cretaceous. On the basis of Souquet et al. (1997), two second-order phases of sequence stacking are distinguished: (1) synrift prograding phase controlled essentially by tectonic subsidence and sedimentary infilling extending from Late Tithonian to Hauterivian and (2) post-rift retrograding/prograding phase driven by transgressive–regressive processes extending from Barremian to Albian.

The correlation of Early Cretaceous-measured sections, from northeastern Tunisia, shows a significant facies and thickness changes ranging from tens of meters to hundreds of meters (Fig. 7). The Sidi Salem locality situated in the southeast of the study area exposes a reduced Early Cretaceous series (Berriasian–Barremian) compared to the Jebel Oust reference section where Early Cretaceous series reaches 2000 m of thickness. This variation attests an inconstant sedimentation rate along north Tunisia during Early Cretaceous. This local distribution sedimentation was qualified by previous work as the result of the so-called "Zaghouan flexure" (or Zaghouan fault) separating the subsiding Jebel Oust area from other edges with reduced thickness (Jebel Sidi Salem). Apparently, no significant flexure has worked at the base of the current Zaghouan fault during the Barremian, but it is possible to envisage a synsedimentary fault or set of faults further west separating subsiding areas of the Tunisian trough (Jebel Oust) from other sections with reduced thickness (Turki 1988; Elkhazri et al. 2013). Further north, in the Medjez-El-Bab area, the Barremian is the old Cretaceous deposits in outcrop. In this area, Barremian sequences of Jebel Bou Rahal do not exceed 100 m; however, 4 km to the north, the section of Sidi Mohamed Akermi exposes 180-m-thick Barremian deposits (Fig. 5). To the northwest, in the west of the Lansarine structure, the Oued Tazega locality exposes 220-m-thick Valanginian–Barremian deposits, while the Jebel Boulahouadjeb—which is located 2 km to the north—exposes 1500-m-thick sequences for the same period. Consequently, Jebel Boulahouadjeb is qualified as a significant depocenter with a very high rate of sedimentation. Taking into account the inherited fault systems that controlled this structure, the Boulahouadjeb depocenter is created in response to an active listric deep normal fault growth and associated to halokinetic movement. The Cretaceous series of Jebel Boulahouadjeb, reviewed in the present study, reveals strong facies and thickness similarities with the Jebel Oust *reference* section (Fig. 3). Similarly, Early Cretaceous series exposes frequent siliciclastic turbidite and reworking metric sandstone blocks of varied size comparable to those described by Souquet et al. (1997) in Jebel Oust.

The compilation of the Early Cretaceous sequence data was conducted to a number of paleogeographic concerns. The Lower Cretaceous sequences, of northeastern Tunisia, show a considerable thickness and facies variation reflecting an irregular sea floor (Fig. 7). The Jebel Boulahouadjeb thick section, 50 km to the northwest of Oust locality, shows strong facies and thickness similarities of Jebel Oust *type section*. These two sections reflect an active subsidence, which suggest basement fault activity (probably Zaghouan and Teboursouk faults) under an extensional to transtensional tectonic regime. Between these two localities, further sections show reduced Early Cretaceous sequences. In details, the 80-km-long correlation clearly reflects basin infilling very similar to other Tethyan provinces that are controlled by tilted blocks geometry. In addition, this correlation revealed for the Early Cretaceous a repetitive depocenter limited and shaped by major synsedimentary listric normal fault systems.

The Aptian–Albian ages are perceived to have deposited the thick and rapid sedimentation rates. The Aptian–Albian epoch was also characterized by previous studies as the most extreme extensional period of the south Tethyan margin in north Tunisia (Souquet et al. 1997; Masrouhi et al. 2014b; Naji et al. 2018).

After the Aptian period, the sandstone deposition is more limited in space, and sedimentation becomes uniform with homogeneous facies mainly composed of marls and fine-grained limestones. During the Albian period, a mudstone limestone platform is installed overall the basin. Furthermore, Aptian–Albian sediment shows a considerable thickness variation but no significant facies variation (sequences are of pelagic to hemi-pelagic facies). During this period, Jebel Oust remains a subsidence area with a high rate of sedimentation. To the west, Jebel Rihane and Jebel Kechtilou structures show also a significantly thick Aptian–Albian series with thickness that differs from one section to another (Ben Yagoub 1978; El Ouardi 1996; Haggui 2012). In these two localities, numerous Aptian–Albian slump folds are associated to further instability of features. Sequences are qualified to contain numerous features of soft-sediment deformation correlated to the tectonic extension (Naji et al. 2018). From Jebel El Mourra to Jebel Bou Rahal (Medjez-El-Bab area), Aptian–Albian series range from 20 to 225 m. Four kilometers to the north, the Sidi Mohamed Akermi area exposes 785-m-thick Aptian–Albian deposits. This area exposes a specifically significant thickness variation of Aptian–Albian sequences (Fig. 5) associated to numerous slump folds, calcareous nodules, breccia, and conglomerates which indicate a sedimentation operated above an irregular sea floor. Consequently, the distribution of sediments was clearly to have been operated under tilted block geometry tectonic control. The correlation highlights also a repetitive high-sedimentation rate depocenter separated by an area with less rates (Fig. 5). Few kilometers southwest of Oued Tazega, reduced Aptian–Albian sequences are found in the Jebel Bechtab structure. In Oued Tazega and Boulahouadjeb structures, only Aptian series are correlated, for which thickness strongly varies from ~ 200 m in Oued Tazega to ~ 1400 m in Jebel Boulahouadjeb, and with abundant synsedimentary features such as slump folds (Figs. 8 and 9), sealed normal faults, *olistolith* blocks, and breccia (Masrouhi et al. 2013; Naji et al. 2018).

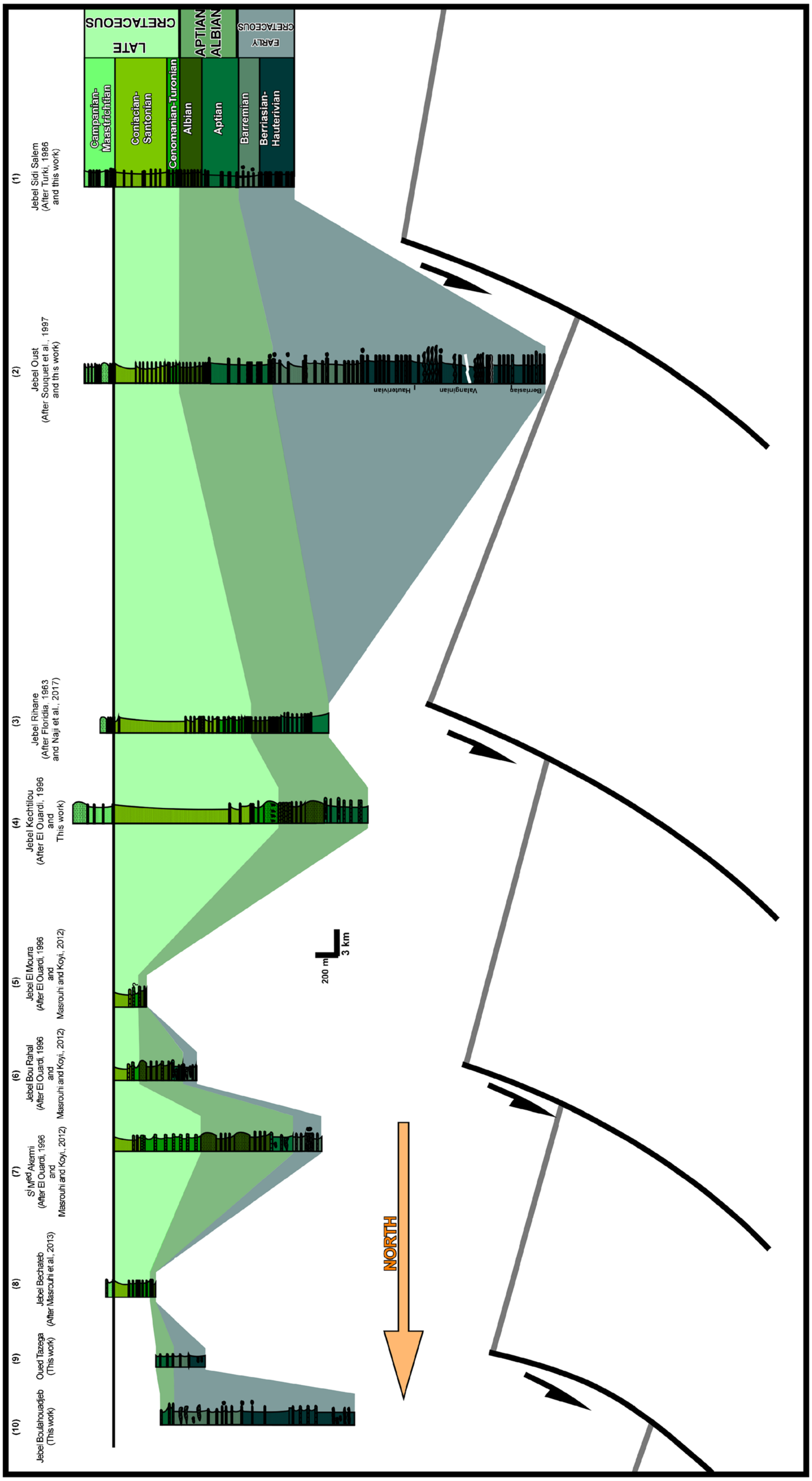

Fig. 7 Lithostratigraphic correlation of Cretaceous sequences in northeastern Tunisia from Jebel Sidi Salem (south) to Jebel Boulahouadjeb (north) including the Jebel Oust-type section

The correlation of Late Cretaceous series shows the same configuration with considerable thickness variations, but without facies change (Fig. 8). Since the Cenomanian, the facies heterogeneity decreases and all sequences are of pelagic to hemi-pelagic facies. A significant thickening is attested in Jebel Oust, Jebel Rihane, Jebel Kechtilou, and Sidi Mohamed Akermi which reflects a persisted tilted blocks geometry, revealed for the Late Cretaceous and possibly shaped by major synsedimentary normal fault systems (Fig. 9). Coniacian–Santonian deposits seem to seal all the abovementioned differentiations and is described as post-rift marl-rich sequences (Naji et al. 2018).

Fault kinematic analysis

The paleostress regimes are reconstructed based on the analysis of fault slip data populations measured in the field at several sites. Brittle deformation is frequently quantified using fault kinematic analysis methods. These methods are based on

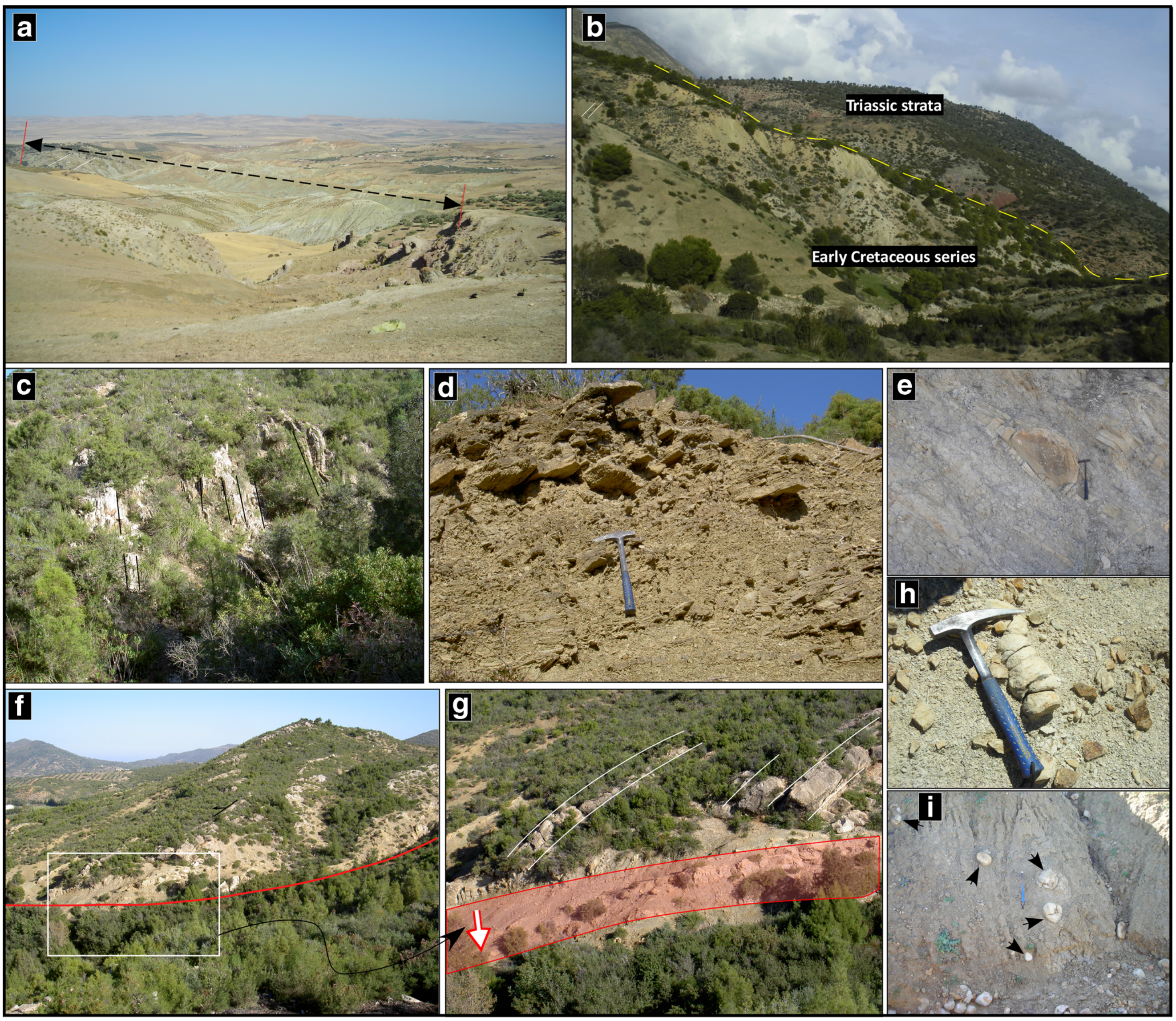

Fig. 8 Photographic plate illustrating some important tectono-sedimentary features in the study area. **a** Panoramic view looking to the northwest of the Boulahouadjeb showing thick Lower Cretaceous series. **b** Panoramic view showing the contact between the Triassic strata of Lansarine structure and the Early Cretaceous sequences in Oued Tazega. **c** Panoramic view illustrating tempestite deposits in the Early Cretaceous series of Jebel Sidi Salem structure. **d** Detailed photographic plate of **c**. **e** Field photo looking to the northeast showing nodular limestone of the Uppermost Albian outcropping in the northern limb of Jebel Sidi Salem, testifying to a synsedimentary paleoslope. **f** Field photo of the sealed synsedimentary Early Cretaceous normal fault in the Jebel Sidi Salem area. **g** Detailed view of photo (**f**) showing the fault plane. **h**, **i** Field photos showing nodular Aptian–Albian limestone sedimentation (septaria) (black arrows), testifying to a synsedimentary submarine slope

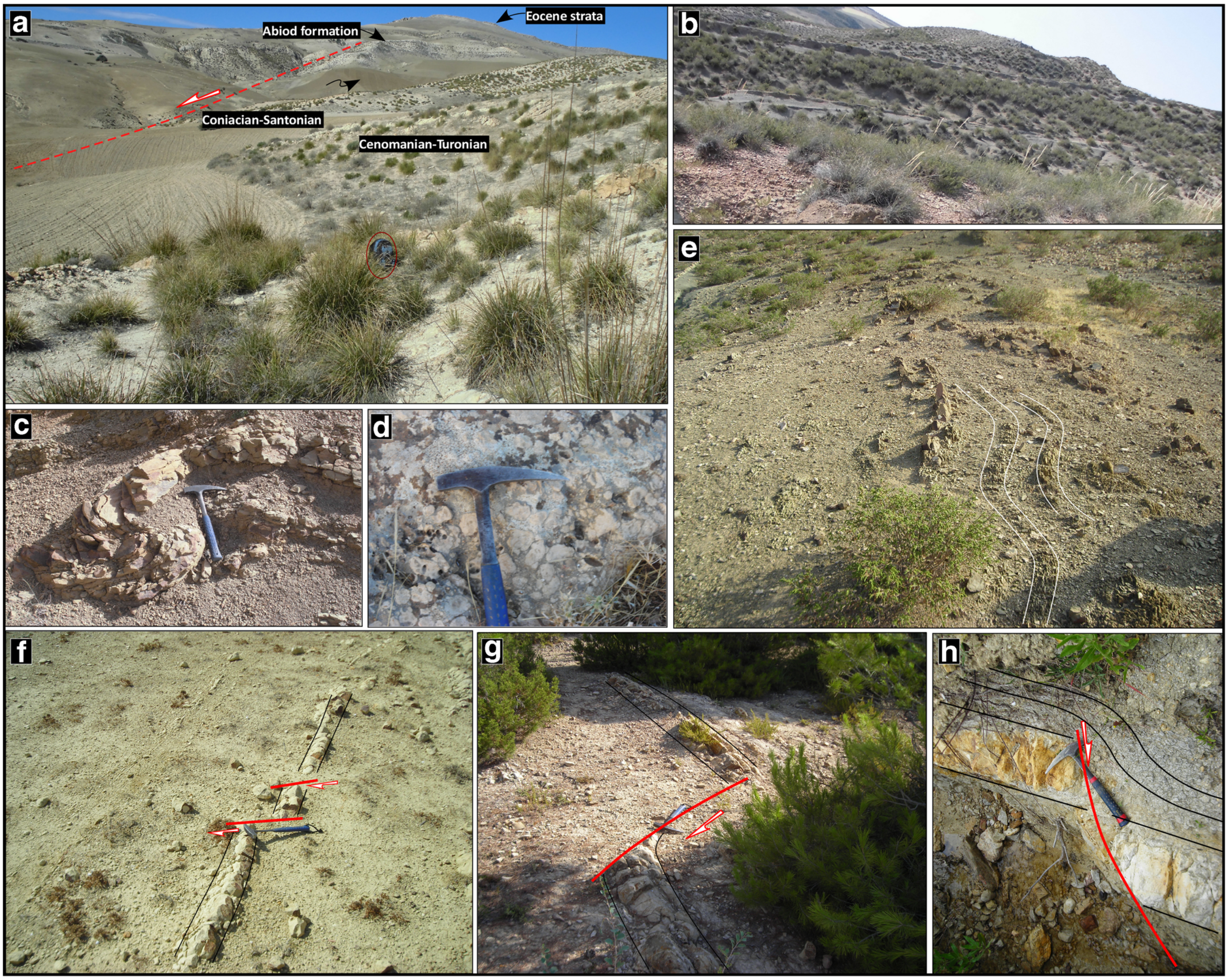

Fig. 9 Photographic plate illustrating some important tectono-sedimentary features in the study area. **a** Panoramic view looking to the northeast showing the Cenomanian–Eocene series of Jebel Bechtab structure. **b** Panoramic view looking to the north showing the thick Early Cretaceous series of Jebel Oust. **c** Field photo showing Barremian sandstone slump folds of the northern limb of Jebel Oust, testifying to a sedimentation above an irregular sea floor. **d** Syntectonic conglomeratic redeposits in the Albian sequences of Medjez-El-Bab area. **e** Field photo showing slump structures between two parallel layers (Medjez-El-Bab structure), testifying to a sedimentation above an irregular sea floor. **f** Small-scale extensive deformation preserved showing a sealed normal fault in the Aptian sequences of Jebel Oust. **g** Synsedimentary sealed normal fault in the Cenomanian sequences of the southern limb of Glib El Abiod structure. **h** Small-scale sealed normal fault in the Aptian deposits (M'Cherga formation) of Jebel Oust

measurements of mesoscale faults and associated striation. Sometimes, the observed fault planes have more than one set of striation. Distinct families of striae have been separated on the basis of geological field data using a relative chronology of the striations (cross-cutting relationships) and their relations with known regional tectonic events. The fault kinematic analysis commonly determines the reduced stress tensor, i.e., the directions of principal stresses ($\sigma_1 > \sigma_2 > \sigma_3$), and the stress ratio: $R = (\sigma_2 - \sigma_3 / \sigma_1 - \sigma_3)$. Therefore, to support our structural interpretation, more numerous striated fault planes ranging from Early to Late Cretaceous series are measured and computed. The fault kinematic analysis of mesoscale faults documents a quantitative reconstruction of paleostresses. These paleostresses provide useful information on the compressional, extensional, or strike-slip origin of larger structures.

Early Cretaceous faults

Early Cretaceous sequences display abundant conglomeratic horizons and slumping, in addition to significant thickness changes (Masrouhi et al. 2013; Gharbi et al. 2015; Naji et al. 2018). The Early Cretaceous sequences studied in this work show abundant ~NW, ~NE, and ~E-trending centimetric and metric-to-decametric-scale sealed normal faults. Fault data collected from Early Cretaceous of Jebel Oust and Jebel Sidi

Salem structures are rotated, using a fault diagram, to their original orientation to restore their initial tectonic extension. The back-tilted fault diagrams typify a NNW-SSE to NE-SE extensional tectonic regime. Locally, E-trending extension is highlighted.

The first three sites show a homogenous NNW-trending extensional regime. In details, the first stereoplot (Fig. 10, F13) shows an extensional stress regime with a NNW-SSE minimum stress axis (σ_3). These measurements have been done in the Valanginian series of the Jebel Oust's northern limb. The second site is located in the Oued Tazega locality. These measurements have been done in the Barremian strata. The stereoplot shows (Fig. 10, F24) a typical extensional paleostress regime with a NNW-SSE minimum stress axis. The other fault kinematic data (stereoplot F6 in Fig. 10) collected from the Sidi Salem-Messella structure highlight normal fault populations. This stereoplot provides a similar state of paleostress with a NNW-SSE local minimum stress axis (σ_3).

One stereoplot (Fig. 10, F17) typifies a ~N-trending extensional tectonic regime. The latter is calculated from the Barremian fault population collected in the same region. Similarly, another stereoplot (Fig. 10, F12) collected from Valanginian sequences of Jebel Oust provides a local NE-trending extensional paleostress tensor.

Four back-tilted fault diagrams (F6', F15, F18, and F21, Fig. 10) show a general E-trending extensional tectonic regime with a local perturbed direction of σ_3 axis. In details, two measurements (Fig. 10, F6' and F21) have been done in Barremian age strata of Jebel Messella structure and provide an E-trending minimum stress axis (σ_3). This different local state of stress could be explained probably by its particular structural setting at the junction of Sidi Salem-Messella major fault systems. The third computed paleostress field (Fig. 10, F15) shows a pattern of WNW-ESE minimum stress axis (σ_3). These measurements have been done in Hauterivian sequences of Jebel Oust. The back-tilted fault diagrams deduced from fault data collected in Barremian sequences of Jebel Baouala (Fig. 10, F18) highlight an E-W extensional tectonic regime.

Aptian–Albian faults

An Aptian–Albian unconformity is reported in the whole of Tunisia. The origin of the associated deformations is still debated. Several authors assign this unconformity as the result of

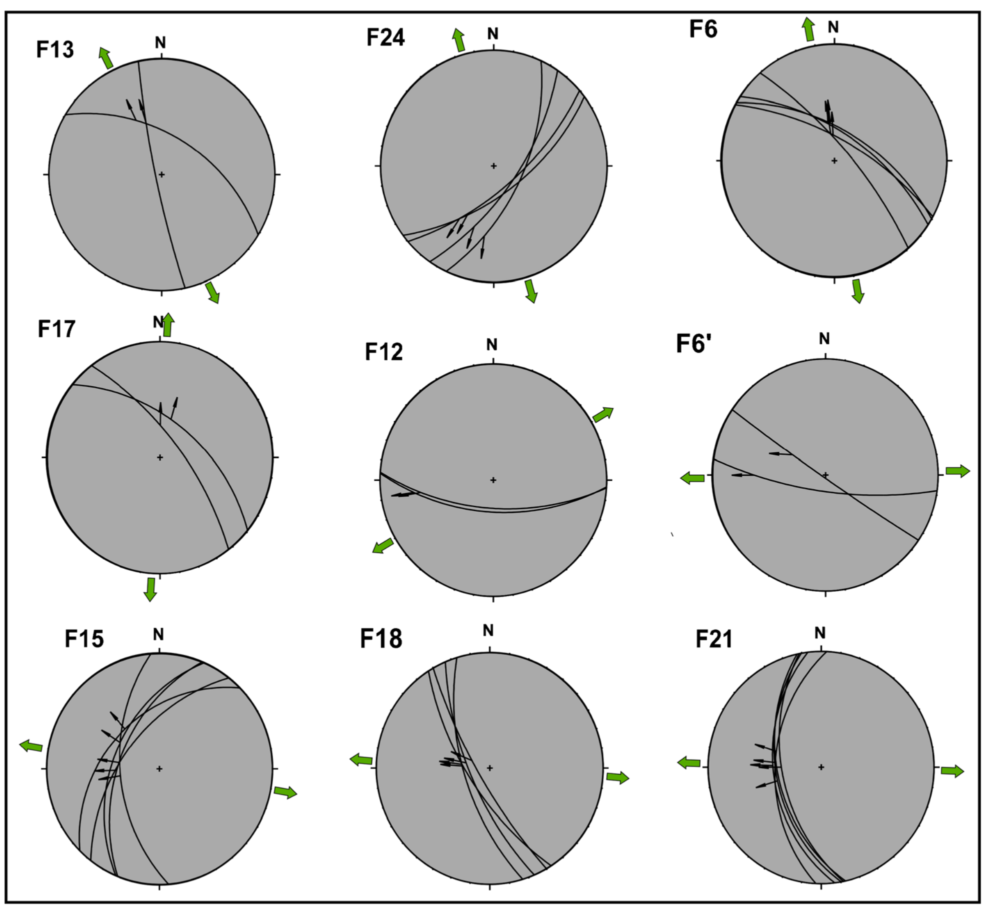

Fig. 10 Fault kinematic analysis of the synsedimentary Early Cretaceous normal faults with lower hemisphere stereogram projection of back-tilted data

an extensional origin which created progressive unconformities of the sedimentary basin fills (Turki 1985; Masrouhi and Koyi 2012; Masrouhi et al. 2013). Numerous Aptian–Albian faults are collected from the northeastern Tunisian domain. The Aptian–Albian deposits seem to be controlled by NW to NE-trending major fault systems. The back-tilted Albian fault diagram shows an extensional tectonic regime with general NE-SW tectonic extension. This state is significantly homogenous in the entire region (Fig. 11).

The first paleostress tensors collected from fault populations measured in the Albian sequences of Jebel Kechtilou (Fig. 11, F23) typify permanently a N-S extensional tectonic regime, which appears prevailed during the entire Albian time. The computed stress tensors belonging to the paleostress state of Jebel Sidi Salem during Aptian–Albian times reveal again a relatively homogenous stress field. Two sites (Fig. 11, F1 and F16) collected from the Albian series provide a tectonic regime with a NE-SW tectonic extension. The last site (Fig. 11, F7) situated in Lella Sellalia located in the northeast of Lansarine structure shows also a local pattern highlighting a NE-SW minimum stress axis during the Aptian–Albian period.

Cenomanian–Turonian faults

The most Cenomanian–Turonian striated fault planes indicate that the dominant stress regime in the northeastern Tunisia is a WNW-ESE to NW-SE extensional tectonic regime (Fig. 12a). The directions of extension computed from fault slip data sets give a remarkably Cenomanian–Turonian homogeneous state of stress in all sites from northeastern Tunisia.

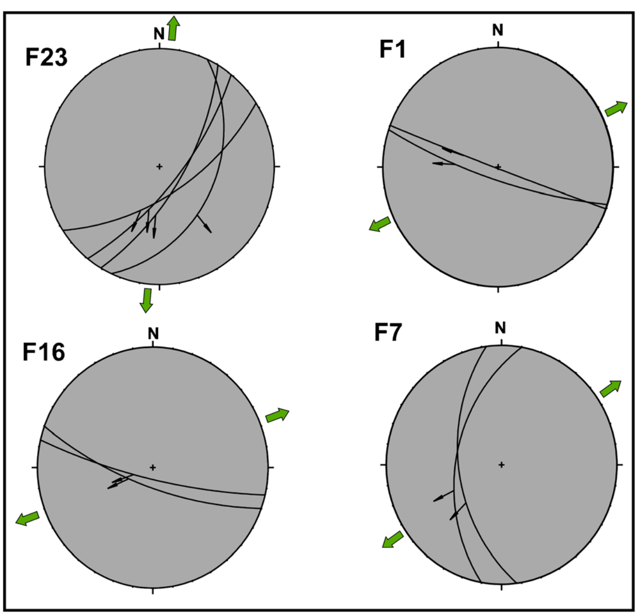

Fig. 11 Fault kinematic analysis of the synsedimentary Aptian–Albian normal faults with lower hemisphere stereogram projection of back-tilted data

The first paleostress tensor is calculated from Cenomanian–Turonian faults of Jebel Kechtilou structure. The stereoplot of this first site (Fig. 12a, F19) highlights a WNW-ESE extensional tectonic regime. The second fault kinematics data (Fig. 12a, F3) collected from the Sidi Salem-Messella structure highlight normal fault populations. The stereoplot F3 provides a local NW-SE minimum stress axis (σ_3), which confirms the regional paleostress state and permits to relate the regional-scale deformation to this dated stress regime.

The Jebel Bechteb structure (Glib El Abiod area) offers also Cenomanian–Turonian fault populations. Most of them are sealed faults, and the calculated paleostress tensor is characterized by a NW-SE minimum stress axis (Fig. 12a, F9').

Campanian–Maastrichtian faults

During Campanian–Early Maastrichtian times, a regional NNW-SSE to NW-SE extension is documented by the synsedimentary fault populations associated to these sequences (Fig. 12b). This extension is calculated from NNW- and NNE-trending conjugate normal fault systems that cut the Campanian–Maastrichtian carbonates of the Abiod Formation in two localities from northeastern Tunisia, and all of them are sealed normal faults. The first site is collected from the Abiod Formation of Dar Zoufira locality. The corresponding fault kinematic diagram (Fig. 12b, F27) provides a NE-SW extensional tectonic regime. Two additional sites (Fig. 12b, F28 and F29) collected from the lower member of the Abiod Formation of Oued Zitoun locality (northwestern part of Mateur region) show an opposite extensional regime. The stereoplot F28 (Fig. 12b) provides a NW-SE minimum axis, and the stereoplot F29 (Fig. 12b) gives a NE-SE minimum axis. This local stress axis perturbation confirms the regional paleostress state and permits to relate the regional-scale deformation to this dated stress regime. This later began to change from pure extensional to transtensional regime related to the African plate trajectory.

Present-day regional geometry of north Tunisia

Since the 1980s, the main crustal structures of North Africa are interpreted as the result of distinguished crustal blocks, which were converged and collided during the Alpine Cenozoic period. In that model, different domains are identified on the basis of their lithologic, chronologic, and structural affinities (Guiraud 1998; Roure et al. 2012). In the Atlas region of Tunisia, the belt is classically divided into six major domains, i.e., the northern allochthonous Numidian domain, the northern Atlassic domain, the central Atlassic domain, the southern Atlassic domain, the Saharan platform, and the

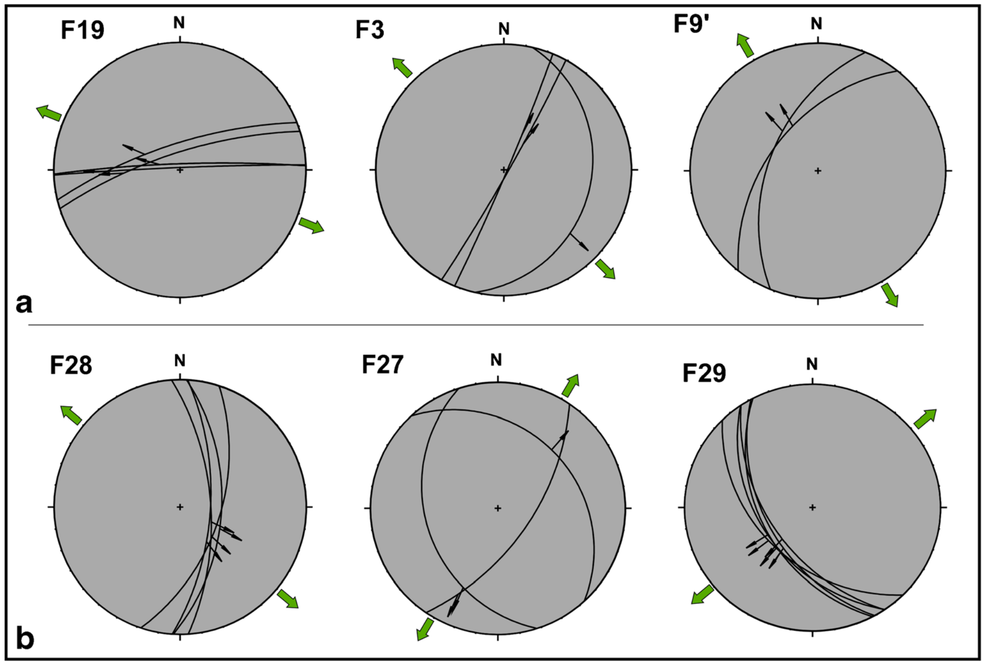

Fig. 12 Fault kinematic analysis of the synsedimentary Late Cretaceous normal faults with lower hemisphere stereogram projection of back-tilted data. **a** During the Cenomanian–Turonian times. **b** During the Campanian–Maastrichtian times

eastern Sahel and Pelagian domain. Despite the geodynamic interpretation of northern Atlassic domain, authors widely accepted two major fault systems, i.e., the Teboursouk thrust fault and the Zaghouan–Ressas thrust fault (Jauzein 1967; Morgan et al. 1998; De Lamotte et al. 2009; Khomsi et al. 2016). The structural style and the kinematic interpretation suffer from little or non-quantitative documentation on a large scale. Only few works attempt to solve the geometrical reassembly by retracing long structural transects (Rouvier 1977; Ben Ferjani et al. 1990; Morgan et al. 1998; Khomsi et al. 2009, 2016).

In the study area, the Zaghouan–Ressas belt thrust contact is the major northeast-trending fault system, which constitutes the southern edge of a major domain called the Zaghouan unit. This later was defined as T2 by Jauzein (1967) in its major fault system enumeration in Tunisia, which was defined by six major lines numbered from T1 to T6. In the Zaghouan area, this system shows the Jurassic platform limestones thrusted over the Cenozoic sequences (Turki 1988; Khomsi et al. 2016). Jurassic sequences are now at 1300 m of elevation, and thus, it is believed that they have elevated up at least 2.5 km above their original position. This structural setting is well defined on the basis of lithostratigraphic and structural affinities. Previous studies outline the implication of the Triassic evaporites in the main thrust fault (Turki 1980; Turki 1988; Khomsi et al. 2016). This fact is in favor to admit that Triassic evaporites are previously concerned by earlier tectonics. It is also clear that thickness and facies variations characterize the Jurassic and Cretaceous sequences controlled early by an active extensional setting (Souquet et al. 1997; Morgan et al. 1998). In a thin-skinned model of deformation, previous studies highlight that such variation guides the style and the position of the major subsequent thrusting (Turki 1988; Souquet et al. 1997; Morgan et al. 1998). However, Khomsi et al. (2016) have distinguished two main detachment levels: Triassic evaporites and Late Eocene shales. In addition, this work implies the role of reverse basement fault at a depth of 2 km. This major tectonic unit shows numerous normal faults that are preserved on the major thrust system. All the abovementioned features are in favor of a system of fault inversion model for the development of the major Zaghouan thrust system. The Zaghouan unit is limited to the north by a thrusted unit called the Teboursouk thrust unit. This front is defined early as a major fault system in north Tunisia (defined as T4 by Jauzein 1967). This area is characterized by thick Aptian–Albian sequences and exhibits frequent outcropping salt structures belonging to the northeastern Maghreb salt province (Masrouhi et al. 2013; Jaillard et al. 2017). In addition, the front of this unit is scattered by dispersal Jurassic outcropping assigned to upper Tithonian–Berriasian sequences (Peybernes et al. 1996). Curiously, these sequences are usually inverted when outcrop. Previous studies have demonstrated that these series are the deepest deposits of the Lower Cretaceous rift (Peybernes et al. 1996). These preconfigurations are inverted by subsequent shortening events and incorporated in a cleaved zone of folding and thrusting. The present-day configuration highlights at least two major events of folding. Triassic evaporites are associated to the shortening and the growth of the structures.

Cenozoic contractional events which resulted in the reactivation of earlier inherited structures, the development of new faults, and the development of major thrust zones are also well

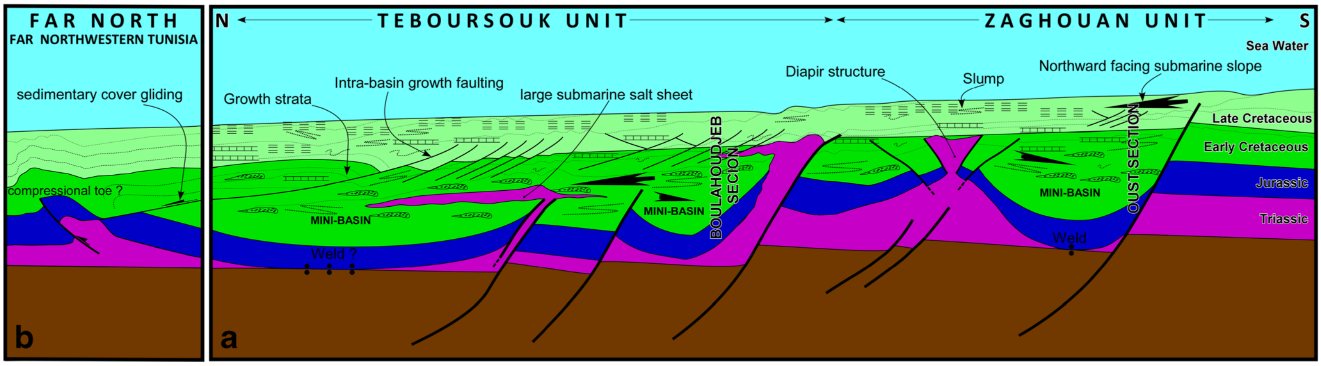

Fig. 13 Simplified reconstructed schematic cross section (not to scale; in detail, this section does not attempt to model the entire basin's elements) of northern Tunisia during Cretaceous showing the general structural configuration of the basin (based on Masrouhi et al. 2013, 2014a; Naji et al. 2018)

identified in the far west Algerian basins illustrating equivalent geological field and events, i.e., the Hodna basin and the Chelif basin (Roure et al. 2012) and Sellaoua basin (for more details, see Herkat and Guiraud 2006). Geologic data document the pre-Neogene inversion of former depocenters in the Saharan Atlas in Algeria (Roure et al. 2012). Previous studies documented some of the Mesozoic normal faults directly extend into the crystalline basement, whereas others become listric at depth and root along Triassic evaporites. Many of them have been reactivated as reverse faults or passively rotated in fold and thrust structures during subsequent compression. In Algerian basins, lateral thickness variations within the Jurassic and Cretaceous series are shown, which reflect the south Tethyan passive margin basins developed during Mesozoic times.

Field relationships between units and the present distribution of faults and folds clearly involve the role of the inherited structures in the growth and the style of north Tunisia fold-and-thrust belt. Halokinetic structures developed during Mesozoic rifting led to the implication of the Triassic evaporites in major thrust systems.

Discussion

During Mesozoic times, the North African domain pertains to the southern Tethyan rifted continental margin. The rift stage, started during Permian (?)–Triassic, is followed during Jurassic and Cretaceous times by passive margin basin's style (Tlig 2015; Martín-Martín et al. 2017; Moragas et al. 2017). The correlation of ten sections studied from the northeastern Tunisia, on the base of new stratigraphic precisions together with existent data from previous works, shows considerable thickness and facies variations of Cretaceous series reflecting clear tilted blocks geometry. The Early Cretaceous series in northern Tunisia, showing a significant thickness variation, reflect that they were deposited above an irregular sea floor. The abundant synsedimentary features (slumps, sealed normal faults, syntectonic conglomerates, lenticular sandstone blocks, etc.) testify for a Mesozoic extensional tectonic regime and display a character of related growth strata (Masrouhi et al. 2013, 2014a; Naji et al. 2018). Based on this study and previous paleogeographic reconstruction's data (e.g., Souquet et al. 1997; Soua 2016), the Early Cretaceous sequences of the Tunisian Atlas can be subdivided into four second-order cycles. The first 2 cycles extending from Late Tithonian to Hauterivian are included within the rifting phase where basement block faulting predominates (creating regional tilted blocks geometry). Third and fourth cycles that extend from the Barremian to Albian can be integrated within a geological setting related to the intra-basin growth faulting. The Jebel Oust section is considered as the type section of Lower Cretaceous in northern Tunisia (Ben Ferjani et al. 1990; Souquet et al. 1997), where 2600-m-thick siliciclastic and marly sequences have been deposited. The present study demonstrates that an equivalent to this reference section is even found 50 km to the north. Therefore, taking in account the current stratigraphic precisions, the 1700-m-thick Jebel Boulahouadjeb section may be also undertaken as a representative section equivalent to reference section in northern Tunisia where the Early Cretaceous is thick and fossiliferous (Fig. 3). Moreover, during Early Cretaceous times, these two localities (Jebel Boulahouadjeb and Jebel Oust) seem to be two significant subsidence depocenters with a high rate of sedimentation, created in response to active normal faulting. Similarly, the reworked blocks and soft-sediment deformations observed until Late Barremian determine the existence of listric active faults controlling the Cretaceous sedimentation of northeastern Tunisia domain. The fault kinematic analysis highlights a NNW to NE extensional regime during Early Cretaceous, showing local E-W extensional regime.

The Aptian–Albian ages are perceived to have the most extreme extension-related structure time of the south Tethyan edge in north Tunisia (Souquet et al. 1997; Masrouhi et al. 2014b). These data are well correlated on regional scale in terms of subsidence, for which recent studies established subsidence curves from the central high Atlas of Morocco to eastern Tunisia (Moragas et al. 2018). The Lower Cretaceous period is recognized as the period of rapid subsidence in northern Tunisia and accompanied by active salt movement. The studied sections show a significant thickness variation of Aptian–Albian deposits accompanied with numerous slump folds (Masrouhi et al. 2013; Naji et al. 2018) which indicates clearly a contemporaneous submarine slope in the regional context of the southern Tethyan rifted continental margin that operates in an extensional regime with tilted blocks geometry. This instability indicates a synsedimentary listric normal fault system activity in a context of an extensional paleomargin.

Since the Cenomanian, the facies heterogeneity decreases. The homogeneity of the Late Cretaceous facies reflects a basin post-rifting subsidence history. The back-tilted fault diagrams show a WNW to NW-trending extension during the Cenomanian time. Coniacian–Santonian deposits seem to seal all the aforementioned differentiations and can be qualified as post-rift marl-rich sequences followed by limestone and marl sequences approximately homogeneous in the entire basin (Fig. 13). During Campanian–Maastrichtian times, a regional NW-trending extension is documented, in which an Upper Cretaceous tectonic regime was related to a general North Africa extensional paleomargin, at least until the earliest Maastrichtian time (Masrouhi et al. 2008; Gharbi et al. 2013).

In addition to the abovementioned criteria, the normal faulting at depth actively controls Triassic salt movements. The Aptian–Albian times were reported as the maximum period of salt structure growth in northern Tunisia (Masrouhi et al. 2013; Jaillard et al. 2017). The evolution of salt structures is related to fault-controlled depocenters that occur and were observed along all the Atlassic margins from Morocco (Moragas et al. 2018) to Tunisia (Jaillard et al. 2017). The tilted block systems are associated to salt evacuation and then the creation of mini-basins in local fault blocks (Fig. 13).

Conclusion

Detailed lithostratigraphic surveys, long sequence correlations, and fault kinematic analysis together with existent data of tectonic-sedimentation relationship allow us to constrain the structural architecture and the deformational style of the Cretaceous basin in northern Tunisia as basin with sedimentation patterns preferentially guided by tilted blocks geometry. The main conclusions are as follows:

- Significant facies and thickness variations are deduced along the northeastern Atlas of Tunisia
- The N-S to NE-SW extensional tectonic regime prevailed during Early Cretaceous, and the WNW-ESE to NW-SE extension during Late Cretaceous
- The normal faulting is associated to repetitive local depocenters with a high rate of sedimentation as well as abundant syntectonic conglomeratic horizons and slump folds
- The tilted block system is associated to salt evacuation and then the creation of mini-basins in local fault blocks.

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