Timing of early to mid-cretaceous tectonic phases along North Africa: New insights from the Jeffara escarpment (Libya–Tunisia)

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ABSTRACT

The Jeffara escarpment spans 400 km from southeastern Tunisia to southwestern Libya, and marks the northern edge of the Berkine–Ghadames Basin. Its horseshoe shape provides a good 3D control of regional-scale depositional architecture. Historically, the political border between Tunisia and Libya hindered the integration of studies over its entirety, which led to the establishment of separate litho-biostratigraphic frameworks. Field-work undertaken on both sides of the border has allowed the unification of lithostratigraphic schemes developed in both countries. Published stratigraphic ages of the different formations and members are compared and integrated in order to propose a unified bio-lithostratigraphic framework. The correlation of serial sections along the Jeffara escarpment shows that two major tectonic unconformities divide the Early Cretaceous sedimentary pattern. The first one is dated as Late Aptian and is commonly associated with the European “Austrian” tectonic phase. The second, which has previously not been recognized as a regional significant surface in Libya, occurs during the Middle Albian and marks moreover the transition from a siliciclastic to a carbonate-dominated sedimentation regime. These two important regional unconformities form the lower and upper boundaries of the Kiklah–Ain el Guettar Formations, and can be associated with intra-plate deformation linked with the opening of the central segment of the South Atlantic and the Equatorial Atlantic oceans.

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1. Introduction

The Jeffara escarpment is an important topographic feature of central North Africa, running from Southeast Tunisia, near Médenine, to North-west Libya, east of Tripoli, for ca. 400 km (Fig. 1). It marks the northern limit of the Berkine–Ghadames Basin. In Tunisia, the escarpment is also known as the Dahar plateau, and is orientated in a north–south trend. The Jeffara escarpment changes its orientation in Libya, where it is called Jebel Nefusa, and strikes in a WSW–ENE orientation. It is made of Mesozoic sedimentary succession, from which the Early to Mid-Cretaceous represents the upper and best-exposed part.

Despite its lateral continuity, and the fact that it belongs to the same geological system, the political border between Libya and Tunisia has hindered the development of modern regional studies on the Jeffara escarpment, and only a few of them in the early 1960s have been undertaken in both countries. This has led to a separate evolution of the stratigraphic and sedimentological

understanding on both sides of the Jeffara escarpment. However, in order to better understand the geodynamic history of Africa, an accurate timing for the different events is necessary in order to compare them on a regional scale. This is not only important for academic purposes, but also for industry, such as petroleum exploration and production for instance, where the basin geodynamic history is of critical importance for the assessment of oil maturation (e.g. Underdown et al., 2007). The separate evolution of the Jeffara escarpment geological understanding has thus likely hampered a better understanding of the regional North Africa geology.

In this study, we present the results of field-work undertaken on both sides of the Tunisian–Libyan border along the Jeffara escarpment. Sedimentological characteristics of Early to Mid-Cretaceous rocks are described and used to unify the conflicting lithostratigraphic units between the two countries. A review of published paleontological findings within these units is presented and used to better constrain their dating. Two regional transects, N–S and E–W, compiling the logged sections and correlating the lithostratigraphic units, are presented. Reconstruction of the temporal and spatial evolution illustrates a number of key tectonic unconformities and allows a better constraint on the geodynamic history of the northern Ghadames Basin. Finally, these results are

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Fig. 1. Location of the Jeffara escarpment. (A) North African political boundaries. The dashed-line box shows the position of figure B close-up (online map creation: www.aquarius.geomar.de). (B) Digital Elevation Model (SRTM data: www2.jpl.nasa.gov/srtm/dataproduct.htm) of the Jeffara escarpment showing the location of the studied sections in Tunisia and Libya.

placed within the broader context of the African plate tectonic evolution and related to the history of the opening Atlantic Ocean.

2. Geological setting

The Jeffara escarpment represents the western and southern limit of the Jeffara coastal plain (Fig. 1) and the northern limit of the Ghadames Basin. This gently southwestward dipping ($1\text{--}2^\circ$) monocline marks the northern end of the Saharan Platform in Tunisia and Libya (Bouaziz et al., 2002). Late Permian to Mesozoic sedimentary rocks are exposed along a ca. 400 km continuous escarpment. The Late Permian that crops out in the Jebel Tebaga of Medenine (Tunisia; Fig. 2a) is the only known outcropping marine Permian in North Africa (e.g. Newell et al., 1976). In this locality, Late Albian sediments unconformably overlay the Permian (Bouaziz et al., 2002). This feature results from the progressive northward truncation of Mesozoic sediments in Tunisia along the Jeffara escarpment (e.g. Bouaziz et al., 1989). In Libya, a similar progressive truncation of Mesozoic sediment toward the east is as well observed (Fig. 2). However, this truncation does not reach

Permian sediments, but extends down to Middle Triassic (Ladinian) sediments, belonging to the Kurrush Fm (El Hinnawy and Cheshitev, 1975). The stratigraphically most complete Mesozoic sedimentary sequence is thus recorded in the vicinity of the Tunisian–Libyan border. The Jeffara plain is bounded to the north by the Jeffara and Sabratah-Cyrenaica normal faults (Hallett, 2002; Fig. 2b), that separate the subsiding offshore Tripolitana Basin. During the Early Cretaceous, the Ghadames Basin was situated along the northeastern margin of Africa, at an approximate palaeolatitude of 10° North (Fig. 3).

The geodynamic history of the Ghadames Basin was mostly influenced by the Hercynian and Alpine unconformities (e.g. Boote et al., 1998; Dardour et al., 2004; Underdown et al., 2007; Galeazzi et al., 2010). The Hercynian phase, which culminated in the Late Carboniferous, inverted the northern Ghadames Basin and formed a prominent east–west anticline (called Jeffara–Nefusa Arch; e.g. Boote et al., 1998) that was eroded during the Permian (Hallett, 2002) (Fig. 2b). Sedimentation resumed during the Mesozoic until Palaeocene times. The Alpine phase reactivated and uplifted the Jeffara escarpment during time of dextral strike-slip movement on the basement-rooted Sabratah-Cyrenaica fault system (Anketell

Fig. 2. (A) Geological map of the Jeffara escarpment. Modified from the geological map of Tunisia (scale 1/500 000) and the geological map of Libya (scale 1/1 000 000). The dashed red lines show the projection lines for the transects presented in Figs. 9 and 10. (B) North-south structural cross-section across the Tripolitania and Ghadames Basins in Libya (modified from Boote et al. (1998)).

and Ghellali, 1991). An Early Cretaceous tectonic phase is moreover reported by various authors and correlated to the “Austrian phase” in Europe (e.g. Echikh, 1998; Bouaziz et al., 2002; Dardour et al., 2004; Underdown et al., 2007), explaining the northward and eastward truncation of the Mesozoic (Triassic to Early Cretaceous) sequence.

Guiraud and Maurin (1992) separated North Africa into two blocks: The West African and the Arabian-Nubian blocks. These are separated by the Benue Trough, the Tenere Basin, the Amguid-Gassi Touil-Algeria and the 10°E lineaments (Moulin et al.,

2010). The 10°E lineament marks the western boundary of the Saharan Metacraton in the Hoggar-Air massif (Abdelsalam et al., 2002; Liégeois et al., 2005) and is known in Libya as the Tiheimboka Arch (e.g. Hallett, 2002). The boundary between the two blocks corresponds to weakness zone (series of major fracture and rift zones), such as the Raghane Shear Zone, that separates the Touareg shield from the Sahara Metacraton (Abdelsalam et al., 2002). In Central Tunisia, it is known as the “Axe Nord-Sud” (e.g. Soussi, 2003). The studied area is situated to the east of this lineament.

Fig. 3. Early Aptian palaeogeography of the Tethyan area (modified after Masse et al. (1993)) showing the position of the studied area along the northeastern margin of Gondwana. The dashed-line rectangle shows the position of the Fig. 1B.

3. Methods

This study is the result of three field-seasons undertaken in South Tunisia and North-West Libya. Sections were measured using a Jacob staff and logged bed-by-bed using traditional field-sedimentology logging techniques. The GPS coordinates of the measured section are given in Table 1.

The first two field-seasons (one and half months in total) were undertaken in Tunisia. The field-excursion guide of Ouaja et al. (2002) was used to familiarize the authors to the geology of the Dahar plateau. Key sections, where Early Cretaceous Formations and Members have been defined in South Tunisia, were visited first. A majority of sections presented by Ouaja et al. (2002) have been re-logged in detail and complemented by addition of the uppermost part (Zebbag Fm), which was not logged in detail by previous studies. New sections were also logged in order to complement the Tunisian transect.

The third field-season was undertaken in Libya, in collaboration with the Libyan Petroleum Institute (LPI), starting close to the Tunisian–Libyan border. Libyan sections were first logged and interpreted using the same classification (lithostratigraphic formations and members) applied in Tunisia. This was then compared to the existing Libyan lithostratigraphic scheme to allow unification with the Tunisian nomenclature (see Chapter 4). Key horizons that cross the political border (some of which can be followed over the whole Jeffara escarpment) were used to subdivide the sedimentary succession. The key horizons are: the “Kimmeridgian Bar” and its Libyan equivalent (this horizon is however not present in the vicinity of the Libyan–Tunisian border); the bones-bed between the

Table 1

GPS coordinates (base and top) of the measured sections.

Section name	Base		Top	
	Latitude	Longitude	Latitude	Longitude
Bir Miteur	N33.14905	E10.28725	N33.14465	E10.28237
BirThelathine	N32.73852	E10.30251	N32.73555	E10.29394
Chenini	N32.91682	E10.27263	N32.90957	E10.27194
Dehibat I	N32.07724	E10.56537	N32.07013	E10.55396
Dehibat II	N32.07814	E10.52184	N32.07474	E10.52054
Douiret Ancien	N32.86795	E10.29146	N32.87209	E10.29146
Gharyan	N32.26850	E13.02995	N32.26524	E13.03389
Ghomrassen I	N33.08921	E10.28937	N33.10380	E10.27310
Ghomrassen II	N33.11741	E10.25600	N33.12342	E10.24980
Jadu	N31.96136	E12.00783	N31.94865	E12.00792
Jebel Charenn	N32.84098	E10.30526	N32.84034	E10.29973
Jebel Oum ed Diab	N32.49934	E10.21321	N32.49536	E10.21069
Ksar Jraa	N33.16180	E10.24565	N33.15521	E10.23907
Kiklah I	N32.13739	E12.64838	N32.13185	E12.65097
Kiklah II	N32.05594	E12.71318	N32.05598	E12.70987
Jebel Ltime	N32.79256	E10.35363	N32.78506	E10.33743
Merbah el Asfer	N32.91596	E10.35714	N32.90939	E10.34618
El Mjabrah	N31.87661	E11.1	N31.86796	E11.17876
Oued el Khil I	N33.20052	E10.26709	N33.20242	E10.26804
Oued el Khil II	N33.16443	E10.25939	N33.16301	E10.25919
Remada I	N32.23333	E10.40750	N32.22603	E10.39621
Remada II	N32.25640	E10.45037	N32.25	E10.44095
Shakshuk	N31.98896	E11.98422	N31.98289	E11.97786
Wazin	N31.97762	E10.73112	N31.97014	E10.72566

Boulouha and Douiret Fm; the highly cemented siliciclastic beds that mark the base of the Aïn el Guettar – Kiklah Fms (easily recognized by the fact that it overlies a soft marly sequence); an

evaporite horizon within the Kerker – Yifran Mbs; and the uppermost Gattar Mb – Nalut Fm that caps the Jeffara escarpment over its entire length. All age attributions presented in this manuscript derive from literature review integrated with the unified litho-stratigraphic nomenclature.

4. A unified litho- and biostratigraphic framework

4.1. Sedimentological description

The Early to Middle Cretaceous sedimentary succession that is exposed in the Jeffara escarpment can be subdivided into two parts according to the main lithology (Figs. 4 and 5). Siliciclastic deposits dominate the lower part of the sedimentary sequence whereas carbonates dominate the upper part. This subdivision reflects the regional sedimentary trend in North Africa and the transition from the “Continental Intercalaire” to the Upper Cretaceous marine series (e.g. Klitzsch and Squyres, 1990; Lefranc and Guiraud, 1990). Along the Jeffara escarpment, the Early Cretaceous siliciclastic deposits were originally interpreted as being mostly deposited in continental subaerial settings (e.g. El-Zouki, 1980a; Bouaziz et al., 1989; Lefranc and Guiraud, 1990). More recent publications (Hammuda et al., 2000; Ouaja et al., 2002; Cuny et al., 2004; Anderson et al., 2007) have however questioned this interpretation and postulated the dominance of shallow marine tidally-influenced deposits.

4.1.1. Tunisia

4.1.1.1. Bir Miteur, Boulouha and Douiret Fms. The Early Cretaceous deposits in Tunisia begin with the Boulouha Fm. This formation overlies the Bir Miteur Fm, dated as Oxfordian–Kimmeridgian (e.g. Ouaja et al., 2002). In the uppermost part of the Bir Miteur Fm, a thick brown dolomitic bed, rich in corals and stromatolites, is present and known by local geologists as the “Kimmeridgian bar” (Fig. 6a; Peybernès et al., 1985). It is dated as Early Kimmeridgian by the presence of the benthic foraminifera *Alveosepta jaccardi* and the algae *Salpingoporella annulata* and *Trinocladus perplexus* (Peybernès et al., 1985; Ben Ismaïl et al., 1989; Kamoun et al., 2003). This feature helps to identify the base of the Boulouha Fm, which is marked by a regional subaerial erosive surface and associated reddish clays or conglomeratic deposits (Barale and Ouaja, 2002; Ouaja et al., 2002).

The Boulouha Fm comprises an alternation of fine sandstone, green marls and yellow¹ dolomite beds (Fig. 7a). A maximum thickness of 72 m has been measured in the Merbah el Asfer section. Numerous silicified tree logs, some up to 20 m long, can be found in this formation (Fig. 6c). The Douiret Fm has a maximum thickness of 110 m near Tataouine. Its base is marked by channelised and cross-stratified fine sandstone, peculiarly enriched in reptilians teeth and bones, fish teeth (shark, *Lepidotes*), silicified wood and intraclast. The lower part has a sedimentary pattern similar to the Boulouha Fm, whereas green marls with few occurrences of yellow dolomitic mudstone or wackestone dominate the upper part (maximum of 70 m in the Jebel Charenn section). The occurrence of these dolomitic beds increases toward the south.

4.1.1.2. Aïn el Guettar Fm. This Formation is principally made of reddish cross-stratified fine to coarse sandstone and siltstone (Fig. 6d), with occasional green marl intervals. The maximum measured thickness was 80 m. Two fining-upward cycles can be identified within this formation, which allow it to be divided into two members; the Chenini and Oum ed Diab Mbs. The upper member is

moreover characterized by the occurrence of distinctive white mica (Ouaja et al., 2002). The Aïn el Guettar Fm is rich in silicified wood and vertebrate fossils (e.g. Benton et al., 2000). In the northern area (e.g. Chenini section), marine trace fossils *Skolithos* sp. and *Diplocraterion* sp. occur at the base of Oum ed Diab Mb (Fig. 6e).

4.1.1.3. Zebbag Fm. The Zebbag Fm has been divided into three members by previous workers; Rhadouane, Kerker and Gattar Mbs (e.g. M'Rabet et al., 1995; Barale and Ouaja, 2002; Ouaja et al., 2002). The Rhadouane Mb consists of an alternation of bioclastic floatstone to rudstone (rich in bivalves and gastropods; Fig. 7c) and biolaminated mudstone (microbialite), that forms a prominent cliff in the landscape (Fig. 6a). Toward the top, marl intercalations occur. The Rhadouane Mb is only present in the northern part of the Jeffara escarpment in Tunisia. Its maximum measured thickness is 35 m. The contact with the Kerker Mb is not well defined and corresponds to the transition from a limestone-dominated to a marl-dominated sequence. The Kerker Mb is characterized by an alternation of yellow marls, biolaminated mudstone (microbialite), rich in birdseye structures and fenestrae fabrics, as well as few wackestone. Intense bioturbation is sometimes observed in the mudstone (Fig. 7e). A distinctive evaporite marker-horizon (made of gypsum and halite; Fig. 7f) is observed in the northern part of the Jeffara escarpment. The top of the Kerker Mb is marked by the occurrence of bivalves, gastropods, echinoids and an ubiquitous, thick (between 3 and 8 m), yellow marl horizon. Measured thicknesses vary between 50 and 140 m.

The Gattar Mb forms the prominent uppermost cliff of the Jeffara escarpment. It consists of brown dolomitic limestone, with the occurrence of gastropods, pelecypods and rudists (e.g. Razgallah et al., 1994; M'Rabet et al., 1995; Abdallah and Meister, 1997). Rare chert nodules can also be observed. The dolomitization is the product of early diagenetic processes (Chaabani et al., 2003) and can be very intense in some areas (Fig. 7g), leading to the complete destruction of the primary sedimentary fabric. Reef-like structures have also been observed in the Gattar Mb (Ouaja et al., 2002). The maximum measured thickness is 33 m.

At the base of the Zebbag Fm, in some localities of the northern part of the studied area, channelized coarse clastic deposits have been observed. They reach a maximum thickness of 18 m in the Oued el Khil section. These clastic deposits consist of quartz grains in the southern part, but pass rapidly into carbonate-clastic deposits in the northern part of the studied area. These sandstones show evidence of tidal influence such as herring-bones cross-stratification (Fig. 7b) and contain marine bioturbations and fauna (bivalves and bryozoans fragments). There is a rapid vertical transition between these sands and the Rhadouane Mb (2–3 m thick), showing a progressive disappearance of clastic grains. We propose to name this new lithostratigraphic unit the “Charenn Mb” and place it at the base of the Zebbag Fm. Its name is a reference to the Jebel Charenn, situated between the towns of Douiret and Tataouine, where these deposits were first observed.

4.1.2. Libya

The studied interval in Libya is divided into four formations (Fig. 4): Kabaw, Kiklah, Sidi as Sid and Nalut Fms (Banerjee, 1980).

4.1.2.1. Kabaw Fm. The Kabaw Fm consists of an alternation of fine grained sandstone, green marls and yellow dolomite beds, and is characterized by the occurrence of silicified wood remains (El-Zouki, 1980b). Some logs can reach up to 16 m long. A bone-bed, rich in reptilian and fish teeth and bones, is observed in the lower part of the sedimentary succession. A green marl-dominated sequence, with the occurrence of yellow dolomitic beds, characterizes the uppermost part of the Kabaw Fm (Fig. 6b). Toward the central part of Jebel Nefusa (Shakshuk section), the

¹ For interpretation of color in Figs. 2, 6, 7, 9, and 10 the reader is referred to the web version of this article.

Fig. 4. Synthetic lithostratigraphic column of the Early to Middle Cretaceous succession along the Jeffara escarpment in Libya and Tunisia. No precise thickness is indicated due to important thickness variability along the Jeffara escarpment.

Fig. 5. Example of key sedimentological field-log and their correlation. For each section, the left column shows the texture (Dunham classification) for carbonate rocks or grain size for siliciclastic rocks. The right column shows the weathering profile. The rose diagram displays all the palaeocurrent measurements for each section, whereas specific palaeocurrent directions (arrows) are given next to the bed where they have been measured. Abbreviation for texture and grain size; m: marl/clay; M: mudstone; W: wackestone; P: packstone; G: grainstone; F: floatstone; B: bindstone; slt: silt; fs: fine sand; ms: medium sand; cs: coarse sand; vcs: very coarse sand; g: gravel.

Kabaw Fm becomes sand-dominated and the occurrence of marls or dolomitic bed is rare. In this section, the contact with the underlying Shakshuk Fm is well exposed and characterized by channelized fluvial deposits. Within the upper part of the Shakshuk Fm, a 2 m thick yellow dolomitic bed, rich in bivalves, gastropods and coral remains, is also observed. The Kabaw Fm is absent in the eastern part of the studied area. The maximum observed thickness is 110 m in the El Mjabrah section. The lowermost part was however not exposed in this section.

4.1.2.2. Kiklah Fm. Along the Jebel Nefusa, significant lateral facies variations characterize the Kiklah Fm (El-Zouki, 1980b). Three

main facies regions can be distinguished. In the western part, the Kiklah Fm comprises reddish cross-stratified fine to coarse sandstone and siltstone, with few occurrences of green marls (Fig. 6f). Numerous silicified tree logs, as well as vertebrate bones and teeth, are present. Two fining-upward cycles can be distinguished within the Kiklah Fm in the western region. In the central region (Jadu, Shakshuk and Kiklah sections), as with the Kabaw Fm, the Kiklah Fm is dominated by sandstone with rare occurrences of red silty clay intervals. In the easternmost logged section (Gharyan), the Kiklah Fm is characterized by the predominance of conglomeratic facies interbedded with clay-rich mudstone. The base consists of carbonate pebbles, reworked from the underlying Abu Ghyran

Fig. 6. Field photograph showing the principal features of the Early Cretaceous deposits along the Jeffara escarpment. (A) Panorama of Bir Miteur (Tunisia, photograph taken from the road C207, GPS coord. N33.14307 E10.29008, looking toward the NW) showing the prominent “Kimmeridgian bar”, marking the uppermost part of the Bir Miteur Fm, and the Rhadouane Mb at the top. (B) Picture of the Kabaw–Kiklah Fms boundary near Wazin (Libya, GPS coord. N31.97377 E10.72446, person circled for scale). The upper part of the Kabaw Fm consists of green marls – beige dolostone alternation. The lower Kiklah Fm consists of medium to coarse loose sandstone. (C) Silicified tree log within the Boulouha Fm, oriented parallel to the main palaeocurrent direction (toward the north), Jebel Ltime section, Tunisia. (D) Cross-stratified red sandstones of the Oum ed Diab Mb (Remada section, Tunisia). (E) *Diplocraterion* sp. ichnofossil within the Oum ed Diab Mb (Chenini section, Tunisia). (F) Transition between red sandstones of the Kiklah Fm and beige carbonate-marl alternations of the Yifran Mb, Sidi as Sid Fm (Wazin, Libya, GPS coord. N31.93434 E10.66568, person circled for scale). Note the lateral accretion packages near the top of the Kiklah Fm.

Fig. 7. Field photograph showing the principal features of the Late Albian – Early Turonian deposits along the Jeffara escarpment. (A) Panorama of the Jebel Boulouha (Tunisia, photograph taken from the road Tataouine–Chenini, looking toward the SW). The topmost Gattar Mb caps the Jeffara escarpment all along Tunisia and Libya, where it is known as the Nalut Fm. (B) Herring-bone cross-stratification within coarse sandstone of the Charenn Mb (Jebel Charenn section, Tunisia). (C) Bioclastic dolostone mostly made of bivalve fragments from the Rhadouane Mb (Bir Miteur section, Tunisia). (D) *Ichthyosarcolithes* sp.? Rudist within the Ayn Tobi Mb (Kiklah section, Libya). (E) Highly bioturbated dolomicrite within the Kerker Mb (Ghomrassen section, Tunisia). (F) Thick evaporite marker bed within the Kerker Mb (Tunisia, Chenini section, GPS coord. N32.91157 E10.27155). (G) Large vugs interpreted as being rudists molds within the highly dolomitized Gattar Mb (Douiret Ancien section, Tunisia).

Fm. Two fining-upward sequences are present in this section. The measured thicknesses vary between 37 and 88 m.

4.1.2.3. Sidi as Sid Fm. The following Sidi as Sid Fm is divided into two members: Ayn Tobi and Yifran Mbs (e.g. [El-Bakai, 1997](#); [Hallett, 2002](#)). The Ayn Tobi Mb comprises dolomitic bioclastic floatstone to rudstone (rich in pelecypods, rudists and gastropods; [Fig. 7d](#)) and biolaminated mudstone (microbialite). There is a gradational transition between the Ayn Tobi and the Yifran Mbs. The latter is characterized by the alternation of yellow marls and biolaminated mudstones (microbialites) with birdseye and fenestrae fabrics. The uppermost part is marked by a thick (<10 m) yellow marl interval. The presence of a bedded evaporitic horizon near the base of the Yifran Mb is also observed in some sections. The Ayn Tobi Mb has a measured maximum thickness of 64 m, and the Yifran Mb thickness varies between 45 and 96 m.

In the Jadu section, the first 37 m of the Ayn Tobi Mb are characterized by the occurrence of siliciclastic deposits (silt to very coarse sandstone, with a carbonate matrix) interbedded with the dolomitic sediments. The Ayn Tobi Mb – Kiklah Fm limit is marked by an erosive surface and reworked palaeosol (calcrete) clasts.

4.1.2.4. Nalut Fm. The Nalut Fm (also known as the Gharyan Fm) caps the Jebel Nefusa over its entire length. This brown limestone unit is made of crystalline dolomite and rare chert horizons and nodules. Rare, poorly preserved pelecypods have been reported ([Hallett, 2002](#)).

4.2. Unified lithostratigraphic scheme between Libya and Tunisia

The lithostratigraphic correlation between Libyan and Tunisian Formations and Members is straightforward utilising the serial logging technique used here ([Fig. 8](#)). The Dehibat and Wazin sections, situated in Tunisia and Libya, respectively, are perfect for this purpose because of their close proximity (there is only ca. 20 km between them) and their relative completeness regarding the Early to Mid-Cretaceous lithostratigraphic succession.

Thus, the Kabaw Fm of Libya is the equivalent of the combined sedimentary package of the Boulouha and Douiret Fms in Tunisia. They share the same lithological and sedimentological features, i.e. an alternation of green marls, fine to medium sandstones and bioclastic dolomitic beds. The upper part of the Kabaw section consists of the alternation of thick green marls layers with dolomitic mudstone, which can be directly correlated to the thick green marl interval at the top of the Douiret Fm. The basal Douiret Fm sandstone bed, rich in fossilized fish, reptile and wood debris ([Ouaja et al., 2002](#)), can also be recognized in western Libya. We propose to subdivide the Kabaw Fm into two members, the Lower and Upper Kabaw Mbs, which are the equivalent of the Boulouha and Douiret Fms, respectively. The correspondence between the Kabaw Fm and the Boulouha–Douiret Fms is further confirmed by the close correspondence of lithostratigraphic unit thicknesses on both sides of the border and their relative position regarding the Late Aptian tectonic unconformity. We moreover propose the correlation between the Tunisian “Kimmeridgian bar” of the Bir Miteur Fm and the coral-rich dolomitic bar of the upper part of the Shakshuk Fm.

The Libyan Kiklah Fm is equivalent to the Aïn el Guettar Fm in Tunisia. The correspondence of these two formations was already mentioned by Tunisian workers (e.g. [Bouaziz et al., 1989](#)) and is further confirmed by the similar thickness of the two formations on both sides of the border, their similar age dating and their relative position regarding the Late Aptian and Middle Albian tectonic unconformities (see below). The Tunisian subdivision of this formation into two members, the Chenini and Oum ed Diab Mbs, can also be recognized in Libya, and thus allows the subdivision

of the Kiklah Fm into a Lower and Upper Kiklah Mbs. In the Dehibat–Wazin region, the Libyan Yifran and Tunisian Kerker Mbs directly overlie the Kiklah and Aïn el Guettar Fms, respectively. These two members have the same lithological characteristic, i.e. dominated by the alternation of dolomitic mudstone–wackestone and yellow marls, and are thus Tunisian and Libyan equivalent. The top of the Jeffara escarpment is capped by a thick succession of brown massive dolomitic beds, attributed to the Gattar Mb in Tunisia and Nalut Fm in Libya (e.g. [Ben Youssef, 1999](#)).

The Tunisian Rhadouane Mb can be correlated to the Ayn Tobi Mb in Libya based on their common lithological characteristic and position relative to the Kerker–Yifran Mbs. In the Jadu area, the lower part of the Ayn Tobi Mb is made of siliciclastic rocks being rapidly replaced by a carbonate-dominated sedimentation. This is also seen in the Charenn – Rhadouane Mbs succession in Tunisia and further supports the lithostratigraphic correspondence between the Ayn Tobi and the Rhadouane Mbs.

4.3. Dating of formations and members

There is a significant variance in the published age dates for the sediment exposed along the Jeffara escarpment between Libya and Tunisia. This can be assessed when comparing published review literature, such as [Tawadros \(2001\)](#) or [Hallett \(2002\)](#) for Libya, and [Barale and Ouaja \(2002\)](#) for Tunisia. This discrepancy arises from the fact that since the late 1960s and the study of [Busson \(1967\)](#), no published field-work has been undertaken by the same research group on both sides of the Tunisian–Libyan border. However, accurate dating of these rocks is important in order to assess the timing and control of the deformations phases in North Africa. [Table 2](#) gives a summary of published stratigraphically significant palaeontologic finds and the subsequent age attribution of lithostratigraphic units in the Jeffara escarpment.

In Tunisia, the Boulouha Fm has yielded the brachiopod *Loriolithyris russillensis* ([Peybernès et al., 1996](#)), which led [Barale and Ouaja \(2002\)](#) to propose a latest Hauterivian? – Early Aptian age for this formation (see also [Ben Youssef, 1999](#)). The Douiret Fm has been dated as Early Aptian with the help of palynomorph assemblages ([Ben Ismaïl, 1991](#)). [Cuny et al. \(2004\)](#) also identified hybodont sharks (*Hybodus* sp., *Priohybodus arambourgi*) and marine ray (“*Rhinobatus*” sp.) remains from this Formation. The age of the Kabaw Fm in Libya is more controversial due to the absence of stratigraphically precise finds. The assemblage of dinosaur vertebra (*Spinosaurus*?), shark teeth (*Priohybodus arambourgi*), fish scales and teeth (*Lepidotes* sp.), crocodile teeth and turtle shells indicate a Wealden age (i.e. Valanginian–Barremian) according to [El-Zouki \(1980b\)](#). The lithostratigraphic equivalence of the Kabaw Fm with the Boulouha–Douiret Fms, as well as their similar position relative to the “Austrian” unconformity, allows us to propose an equivalent age for these formations, i.e. a latest Hauterivian? – Early Aptian age, implying an Early Cretaceous hiatus at the base of the Kabaw–Boulouha Fms ([Fig. 8](#)). This is moreover in agreement with [Belhaj \(1996\)](#) who stated: “Despite extensive palynological analyses of many wells, the Neocomian has not been identified in the study area”, i.e. the western Sirt Basin, “nor in the subsurface of the Ghadāmis Basin”.

The Tunisian Aïn el Guettar Fm has been dated as Early Albian by [Bouaziz et al. \(1988\)](#) and [Benton et al. \(2000\)](#) with the help of an important fish and reptilian fauna (fishes *Protolamna* sp., *Cretodus*?, *Lepidotes*, cf. *Anoemodus*, cf. *Caturus*, *Neoceratodus africanus*, dinosaurian *Carcharodontosaurus saharicus* and *Spinosaurus* sp. (see also [Buffetaut and Ouaja, 2002](#)). [Ben Ismaïl \(1991\)](#) attributed the Chenini Mb to the Late Aptian – Early Albian based on palynological assemblages. [Cuny et al. \(2004\)](#) report the presence of neoselachian sharks (*Cretodus semiplicatus*, cf. *Protolamna*, cf. *Scapanorhynchus*, *Onchoprists dunklei*) and hybodont *Tribodus*

				South Tunisia		Northwest Libya	
				Formations	Members	Formations	Members
Cretaceous	Late	Senonian	Maastrichtian	Berda		Al Gharbiyah	
			Campanian				
			Santonian	Aleg		Mizdah	
			Coniacian			Qasr Taghrinnah	
		Gallic	Turonian	Zebbag	Gattar	Nalut	
			Cenomanian		Kerker	Sidi as Sid	Yifran
					Rhadouane Charenn		Ayn Tobi
			Albian	Middle Albian unconformity			
	Early		Aïn el Guettar	Oum ed Diab Chenini	Kiklah	Upper Kiklah Lower Kiklah	
			Aptian	Late Aptian "Austrian" unconformity			
			Merbah el Asfer Group	Douiret		Kabaw	Upper Kabaw
				Boulouha			Lower Kabaw
		Neocomian	Hauterivian	Hiatus			
			Valanginian				
			Berriasian				
		Malm	Tithonian	Bir Miteur		Shakshuk	
Kimmeridgian							
Oxfordian	Foum Tataouine		Ksar Haddada Ghomrassen				

Fig. 8. Correlation and dating of Tunisian and Libyan formations and members along the Jeffara escarpment for the Late Jurassic – Cretaceous time interval (see text for further details).

tunisiensis. In Libya, the dating of the Kiklah Fm remains controversial and is generally thought to be Aptian–Albian in age without further precision (e.g. Tawadros, 2001; Hallett, 2002). Palynological studies however point towards an Early Albian age (Ward et al., 1987; Tekbali, 2000) based on the presence of *Classopollis*, *ephedroids*, *Callialasporites*, *Araucariacites*, *Eucommiidites*, *Aequitriradites*, *Triporoletes*, *Locopodiadites*, *Klukisporites*, *Cicatricosisporites*, *Perotriletes pannuceus* and *Afropollis*. The lithostratigraphic equivalence of the Kiklah Fm with the Aïn el Guettar Fm would support a latest Aptian? – Early Albian age for these formations.

In the Chott and Medenine areas (southern Central Tunisia), the Rhadouane Mb is dated as Late Albian (*Inflata* and *Substuder* ammonite zone) with ammonite findings (*Knemiceras syriacum*, *K. gracile*, *K. compressum*, *K. aegyptiacum*, *Eopachydiscus aff. marcianus*,

Engonoceras aff. saadense, *E. toussainti*; Ben Youssef et al., 1985; Abdallah and Memmi, 1994). Along the Jeffara escarpment, the Rhadouane Mb is also thought to be Late Albian, despite the absence of any precise dating in published literature. In Libya, its lithostratigraphic equivalent, the Ayn Tobi Mb, is rich in bivalves. The presence of *Exogyra flabellata*, *E. delectrei*, *E. columba*, *Trigonia beyrichi*, *Avicula cenomaniensis*, *Corbula striatula*, *Ichthyosarcoclitus triangularis* and *I. bicarinatus* (Christie, 1955; Desio et al., 1963) allowed El Hinnawy and Cheshitev (1975) to propose a Cenomanian age for this formation (see also Megerisi and Mamgain, 1980). This lithostratigraphic unit appears thus to be time-transgressive from Late Albian in Tunisia to Cenomanian in Libya. This can also be demonstrated by the location of the evaporite marker-horizon in the Kerker–Yifran Mbs which acts as an effective timeline. Indeed,

Table 2
Review of relevant published fauna and flora recovered from Early to Mid-Cretaceous lithostratigraphic units in southern Tunisia – northwestern Libya, and their age attribution.

Formation	Member	Organisms	Age attribution
Tunisia			
Boulouha		Brachiopod <i>Lorolithyris russillensis</i>	Latest Hauterivian? – Early Aptian (Peybernès et al., 1996; Barale and Ouaja, 2002)
Douiret		Palynomorphs	Early Aptian (Ben Ismaïl, 1991)
Aïn el Guettar		Palynomorphs, fishes <i>Protolamna</i> sp., <i>Cretodus</i> ?, <i>Lepidotes</i> , cf. <i>Anoemodus</i> , cf. <i>Caturus</i> , <i>Neoceratodus africanus</i> , dinosaurian <i>Carcharodontosaurus saharicus</i> and <i>Spinosaurus</i> sp.	Late Aptian – Early Albian (Ben Ismaïl, 1991) Early Albian (Bouaziz et al., 1988; Benton et al., 2000)
Zebbag	Rhadouane	Ammonites <i>Knemiceras syriacum</i> , <i>K. gracile</i> , <i>K. compressum</i> , <i>K. aegyptiacum</i> , <i>Eopachydiscus</i> aff. <i>marcianus</i> , <i>Egonoceras</i> aff. <i>saadense</i> , <i>E. toussainti</i>	Late Albian (Ben Youssef et al., 1985; Abdallah and Memmi, 1994)
	Kerker	Ammonite <i>Neolobites medeninensis</i>	Cenomanian (Busson, 1967)
	Gattar	Ammonites (below the Gattar Mb) <i>Calycoceras</i> sp., <i>Vascoceratidae</i> sp., <i>Choffaticeras</i> aff. <i>massipianum</i> , <i>C. aff. securiforme</i> , <i>C. gr. pavill-ieri</i> , <i>C. luciae</i> , <i>N. (Betiokyites) gr. ptioti</i> , <i>Vascoceras</i> sp., <i>V. aff. obessum</i> , <i>Fagesia</i> sp., <i>Thomasites rollandi</i> , <i>Hoplitoides gr. wohlmanni</i> , <i>Neoptychites gr. cephalus</i>	Early Turonian (Razgallah et al., 1994; Abdallah and Meister, 1997)
Libya			
Kabaw		Dinosaurs <i>Spinosaurus</i> ?, sharks <i>Priohyodus arambourgi</i> , fish <i>Lepidotes</i> sp.	Wealden (El-Zouki, 1980b)
Kiklah		Palynomorphs <i>Classopollis</i> , <i>ephedroids</i> , <i>Callialasporites</i> , <i>Araucariacites</i> , <i>Eucommiidites</i> , <i>Aequitriradites</i> , <i>Triporoletes</i> , <i>Locopodiacidites</i> , <i>Klukisporites</i> , <i>Cicatricosisporites</i> , <i>Perotriletes pannuceus</i> , <i>Afropollis</i>	Early Albian (Ward et al., 1987; Tekbali, 2000)
Sidi as Sid	Ayn Tobi	Bivalves <i>Exogyra flabellata</i> , <i>E. delectrei</i> , <i>E. columba</i> , <i>Trigonia beyrichi</i> , <i>Avicula cenomaniensis</i> , <i>Corbula striatula</i> , <i>Ichthyosarcolithes triangula-ris</i> , <i>I. bicarinatus</i>	Cenomanian (Christie, 1955; Desio et al., 1963)
	Yifran	Foraminifera <i>Orbitolina concava</i> , <i>Praealveolina cretacea tenuis</i> , <i>Thomasinella punica</i> , <i>Buccicrenata libyca</i> , <i>Ammomarginulina cf. blanckenhornii</i> , <i>Hemicyclammina cf. sigali</i> , <i>Gavelinopsis pseudobaccatus</i>	Cenomanian (Megerisi and Mamgain, 1980)
Nalut		Foraminifera <i>Praeglobotruncana cf. stephani</i> , <i>Rotalipora</i> sp., <i>Globotruncana</i> sp., <i>Orbitolina</i> sp., <i>Stensioina</i> sp., <i>Kilianina</i> sp., <i>Thomasinella punica</i> , <i>Cuneolina conica</i> , <i>Nezzazata gyra</i>	Cenomanian (Busson, 1967)

this unique event is situated in the middle of the Kerker Mb in the northern part of the Jeffara escarpment (Fig. 9), but at the base of the Yifran Mb (Fig. 10), underlining the diachrony of the top of the Rhadouane–Ayn Tobi Mbs. This diachronous lithostratigraphic unit nicely exemplifies the Late Albian – Cenomanian sea-level transgression onto the African craton (e.g. Ben Youssef and Peybernès, 1986; Burollet, 1989). However, questions remain about the exact age of the Rhadouane Mb and the biostratigraphic correlation between the Charenn Mb and the siliciclastic base of the Ayn Tobi Mb.

The Yifran Mb in Libya is dated as Cenomanian with the help of molluscs and foraminifera assemblages (Christie, 1955; Desio et al., 1963). The presence of *Orbitolina concava*, *Praealveolina cretacea tenuis*, *Thomasinella punica*, *Buccicrenata libyca*, *Ammomarginulina cf. blanckenhornii*, *Hemicyclammina cf. sigali*, *Gavelinopsis pseudobaccatus* confirms this age attribution (Megerisi and Mamgain, 1980). In Tunisia, the equivalent Kerker Mb is as well dated from the Cenomanian (Busson, 1967) by the presence in its upper part of the ammonite *Neolobites medeninensis*.

The Gattar Mb is dated by ammonite biostratigraphy as Early Turonian (Razgallah et al., 1994; Abdallah and Meister, 1997). In Libya, its lateral equivalent (Nalut Fm) was originally dated as Cenomanian (e.g. Christie, 1955; Desio et al., 1963; El Hinnawy and Cheshitey, 1975) using Molluscan fossils. The robustness of this Cenomanian age attribution was however criticised by Busson (1967). Megerisi and Mamgain (1980) attribute to the Nalut Fm a Late Cenomanian–Turonian age based on foraminiferal assemblage (*Praeglobotruncana cf. stephani*, *Rotalipora* sp., *Globotruncana* sp., *Orbitolina* sp., *Stensioina* sp., *Kilianina* sp., *Thomasinella punica*, *Cuneolina conica*, *Nezzazata gyra*). Further north, in Central Tunisia, the Gattar Fm overlays the Bahloul Fm, which marks the Cenomanian–Turonian boundary. This boundary is associated with a second-order maximum flooding surface (e.g. Lüning et al., 2004) and as such, the change from a transgressive sequence (i.e. the Albian–Cenomanian transgression; e.g. Burollet, 1989; see previous

paragraph) to a regressive sequence. This renders the proposed Cenomanian age for the base of the Nalut Fm highly improbable. In agreement with Busson (1967), we thus propose a strict Early Turonian age for this formation in Libya.

4.4. Depositional environments

The sedimentary facies identified from the Boulouha, Douiret and Kabaw Fms suggest deposition in a large shallow embayment, subject to salinity variations and tidal influence. Overall, the Kabaw Fm and the Boulouha–Douiret Fms succession record a second-order marine transgression, starting with fluvial sandstones at the base of the Kabaw Fm and the Boulouha Fm (Ouaja et al., 2002), and culminating with the deposition of the distal-marine green marls in the upper Douiret Fm, where marine ostracods, hybodont sharks and marine ray have been found (Bouaziz et al., 1989; Cuny et al., 2004; see also Anderson et al., 2007).

The Kiklah–Aïn el Guettar Fms were deposited in a similar type of shallow-marine embayment environment, subject to salinity variations and tidal influence. The facies are however more sand-dominated. The two fining-upward cycles that characterize these formations record deepening upward cycles, and a vertical transition from fluvial to tidal and to more open-marine environment can be observed. The presence of neoselachian shark remains in the Chenini Mb (Cuny et al., 2004; see also Anderson et al., 2007) and marine bioturbation in the Oum ed Diab Mb supports the marine interpretation.

The Rhadouane and Kerker Mbs, and the Sidi as sid Fm, were deposited in an environment that was analogous to the present-day Shark Bay in Australia (Logan and Cebulski, 1970), i.e. a carbonate-dominated shallow-marine embayment, with development of widespread microbial mats, where hyper-salinity events lead to the deposition of evaporites. In proximal settings, accumulation of bivalves and gastropods result in the formation of thick bioclastic-rich beds.

Fig. 9. North–south transect along the Dahar Plateau (Jeffara escarpment) using the Cenomanian–Turonian boundary as datum. Note the vertical exaggeration of 175/1. The thick black vertical lines represent the position of the logged sections. The purple band mark the position of the evaporite horizon within the Kerker–Yifran Mbs. The red lines mark the regional tectonic unconformities. The dashed red line within the Boulouha Fm marks the position of the Intra-Boulouha unconformity (IBU). The thickness of the Bir Miteur Fm is reconstructed based on observations from this study and the work of Ouaja et al. (2002, 2004). Abbreviation of section names: Waz: Wazin; Deh: Dehibat; Rem: Remada; Joed: Jebel Oum ed Diab; Bth: Bir Thelathine; Ltim: Jebel Ltime; Jch: Jebel Charenn; Doa: Douiret Ancien; Mea: Merbah el Asfer; Chen: Chenini; Gom: Ghomrassen; Bim: Bir Miteur; Jraa: Ksar Jraa; Oek: Oued el Khil.

Fig. 10. East–west transect along the Jebel Nefusa (Jeffara escarpment) using the Cenomanian–Turonian boundary as datum. Note the vertical exaggeration of 175/1. The thick black vertical lines represent the position of the logged sections. The purple band mark the position of the evaporite horizon within the Kerker–Yifran Mbs. The red lines mark the regional tectonic unconformities. Abbreviation of section names: Ghar: Gharyan; Kik: Kiklah; Shak: Shakshuk; Mja: El Mjabrah; Waz: Wazin; Deh: Dehibat.

The Gattar Mb – Nalut Fm display facies that are typical of a carbonate platform. The presence of reef-like structures, rudist build-ups, as well as a typical micro-fauna (Megerisi and Mamgain, 1980), would suggest that the Gattar Mb was deposited in a shallow marine, neritic environment, with connection to the open sea.

Apart for the Gattar–Nalut lithostratigraphic unit, which does not display any noticeable facies change throughout the studied area, an overall proximal-to-distal trend can be observed for Early to Mid-Cretaceous sedimentary units along the Jeffara escarpment

from south to north. This trend is recorded by a progressive reduction in grain size to the north and enrichment of the sedimentary sequence in clay and marls. This pattern is consistent with models for the palaeogeography of North Africa at the time (Fig. 3) and the dominant palaeocurrent directions measured in sandstone packages, indicating a mean direction of transport toward the north (see also Ouaja et al., 2002). Lateral facies changes can also be observed, such as seen in the Kabaw Fm, which is dominated by siliciclastic sediments in the Shakshuk–Nalut area to the south in Libya,

which contrasts with the more mud-dominated lithology elsewhere toward the north in Tunisia. A number of authors have suggested that this area was situated close to the palaeoriver mouth that was feeding this large shallow embayment with siliciclastic materials (e.g. Palaeo-Oued Tassili-Hamada in [Lefranc and Guiraud \(1990\)](#)).

5. North Africa geodynamic implications

5.1. Timing of tectonic unconformities

In [Figs. 9 and 10](#), two geological transects across the Jeffara escarpment are displayed, using the Cenomanian–Turonian boundary as datum. They highlight the regional architecture of the Early to Mid-Cretaceous deposits along the Jeffara escarpment.

Stratigraphically, the Late Jurassic Bir Miteur–Shakshuk Fms are separated from the Early Cretaceous Boulouha–Kabaw Fms by a hiatus spanning the latest Kimmeridgian to the latest Hauterivian interval ([Fig. 8](#)). [Ouaja et al. \(2002, 2004\)](#) have moreover observed in Tunisia that this hiatus is associated with an angular unconformity in the southern part of the Dahar Plateau (see also [Fig. 9](#)), leading to the disappearance of the “Kimmeridgian bar” south of Remada. Poor outcrop conditions have prevented the tracking of the Shakshuk Fm (equivalent of the Bir Miteur Fm) in the western part of Jebel Nefusa. It is however present in the Shakshuk-Jadu area, ca. 100 km eastward of the border. As pointed out by [Guiraud et al. \(2005\)](#), tectonic deformations are recorded along most of North and Central African basins during the Jurassic–Cretaceous transition. This event is referred to as the Cimmerian unconformity and may reflect distant effects of tectonic activity in southeastern Europe.

Within the lower part of the Boulouha Fm, [Ouaja et al. \(2002\)](#) were the first to report the presence of a tectonic unconformity in the Tataouine area ([Figs. 9 and 11a](#)). This unconformity is only recognizable in this local region and is not expressed anywhere else along the Jeffara escarpment.

Along the north–south transect, two regional angular tectonic unconformities can be observed within Early to Mid-Cretaceous deposits. They bound the Aïn el Guettar Fm in Tunisia and are as such dated as Late Aptian and Middle Albian, respectively. Along the east–west transect, these two unconformities are also recognized and form the lower and upper boundaries of the Kiklah Fm in Libya ([Fig. 10](#)). This further strengthens the correlation between the Aïn el Guettar and Kiklah Fms. The Late Aptian unconformity is marked by the progressive truncation of pre-Middle Cretaceous sequences toward the north and the east. In Libya, this unconformity is well known and called the “Austrian tectonic unconformity” (e.g. [Boote et al., 1998](#)) and associated with the folding and regional tilting of Triassic and Jurassic sequence to the SSW ([Magnier, 1963; Anketell and Ghellali, 1991](#)). The Middle Albian unconformity is more difficult to observe at a regional scale in northwestern Libya but was already noticed by previous researchers working in the eastern part of Jebel Nefusa ([Fig. 11b; Fatmi and Sbeta, 1991](#)). The division of the Kiklah Fm into two members allows this unconformity to be better observed over the entire length of the Jebel Nefusa ([Fig. 10](#)).

The Middle Albian unconformity is best observed along the north–south transect in Tunisia, where it is marked by the folding and truncation of pre-Late Albian sequences. Further north of the studied area (Jebel Tebaga de Medenine), this unconformity is well expressed by the successive truncation of pre-Middle Cretaceous to Triassic sediment and the final superposition of the Rhadouane Mb over Late Permian marine sediments tilted toward the south ([Fig. 11c; e.g. Bouaziz et al., 2002](#)). In the Tataouine area, the presence of an anticlinal structure between the Merbah el Asfer and Je-

bel Oum ed Diab region has already been documented by previous workers ([Busson, 1967; Bouaziz et al., 1989](#)) and was called the “Môle de Touil el Hira” (Touil el Hira High) by [Bouaziz et al. \(1989\)](#). In Libya, the Middle Albian unconformity is documented by an angular unconformity in the central Jebel Nefusa ([Fig. 11b](#)). It can also be recognized to the east of the studied area. Thus, along the eastern Jebel Nefusa, the Sidi as Sid Fm truncates the Kiklah Fm and can rest directly on the Late Triassic – earliest Jurassic Abu Shaybah Fm ([Fatmi and Sbeta, 1991](#); see also [Fig. 4.7 in Hallett \(2002\)](#)). In the Sirt Basin, [Ambrose \(2000\)](#) observes an equivalent major unconformity at the top of the Albian Upper Sarir Fm, sealed by Cenomanian sediments, indicating that this is a regional and not just local feature.

5.2. Discussion on the unconformities spatio-temporal extent

In North Africa, a Mid-Cretaceous tectonic phase is well established by numerous workers and associated with the Austrian tectonic phase in the European Alps (e.g. [Canerot et al., 1986; Guiraud et al., 1987, 2005; Badalini et al., 2002](#); see also [Bulot and Ferry, 2007](#)). However, numerous discrepancies exist with regards to its timing, depending on the under- and overlying sediment, and their dating accuracy.

In Libya, in the Ghadames Basin, the Austrian tectonic unconformity is associated with the unconformity at the base of Kiklah Fm (e.g. [Dardour et al., 2004; Echikh, 1998](#)). The Middle Albian unconformity is considered by previous worker to be a minor event compared to the Late Aptian one (e.g. [Hallett, 2002](#)). In the Hameimat Trough of the eastern Sirt Basin, [Ambrose \(2000\)](#) identified a major angular unconformity at the top of the Sarir Fm, near the Albian–Cenomanian boundary. A second less-well expressed unconformity is also present at the base of the Upper Sarir Sandstone ([Rossi et al., 1991](#)), dated as Late Aptian – Early Albian. Also, the presence of two Early Cretaceous tectonic unconformities has also been observed on recent 3D seismic lines offshore Libya (Al Fraser, BP, pers. com.).

In Central Tunisia, [Zouaghi et al. \(2005\)](#) noted the presence of major unconformities interpreted from 2D seismic, dated as the Late Aptian – Early Albian and the Late Albian. [Azaïez et al. \(2007\)](#) attributed to the Austrian phase the Late Aptian tectonic unconformity that they observed in both field and seismic studies. [Rigane et al. \(2010\)](#) observed two tectonic unconformities in the tectonic evolution of the Jebel El Hamra tilted blocs, which they dated as Aptian–Albian in age. In the Chott area of Tunisia, a tectonic unconformity produces a sedimentary hiatus spanning the Late Aptian to Middle Albian (e.g. [Ben Youssef and Peybernès, 1986; Lazzez et al., 2008](#)). [Bouaziz et al. \(2002\)](#) noted the presence of transpositional events in Tunisia during the Late Aptian – Early Albian and the Middle (intra) Albian. [Ben Slama et al. \(2009\)](#) dated the extrusion of Triassic salt in Northern Tunisia from the Middle Albian. In their review of the Phanerozoic geological evolution of Northern and Central Africa, [Guiraud et al. \(2005\)](#) terminated their first Cretaceous rift phase during Early Aptian and associated it with the “Austrian” unconformity. Their second Cretaceous rift stage was terminated by the Late Albian regional unconformity. [Pletsch et al. \(2001\)](#) highlighted the presence of a Middle to Late Albian transition regional unconformity along the western African margin.

Following the result of our work and the comprehensive literature review, it is evident that the Aptian–Albian of North and Central Africa is characterized by the occurrence of two regional tectonic unconformities, dated as Late Aptian and Middle Albian, respectively ([Fig. 12](#)). Various authors apply the term “Austrian” unconformity only to the Late Aptian unconformity, whereas some authors apply this term to the Middle Albian unconformity as well. Care must therefore be taken in the future when referring to the

Fig. 11. Angular tectonic unconformities observable in the field. (A) Local angular unconformity within the Boulouha Fm (Ghomrassen section, Tunisia, GPS coord. N33.09 E10.28583). (B) Angular unconformity between the Kiklah Fm and the Sidi as Sid Fm (Gharyan–Tripoli road, near Bughilan, GPS coord. N33.26861 E13.02111) marking the regional Middle Albian tectonic phase. (C) Angular unconformity between the Late Albian Rhadouane Mb and Late Permian reef deposits (Jebel Tebaga de Medenine, Tunisia, looking toward the West). The unconformity angle reaches 25° (Bouaziz et al., 2002).

“Austrian” unconformity across North Africa. The term “Middle Cretaceous tectonic phase” should be preferentially used in order to avoid confusion when no precise dating can be achieved.

The local tectonic unconformity observed in the northern part of the Jeffara escarpment in Tunisia (Intra-Boulouha unconformity) is more difficult to relate to global geodynamics due to the absence of precise dating. Its position within the middle of the Boulouha Fm would point toward a Barremian age and would therefore correlate with the first Cretaceous syn-rift phase of Guiraud et al. (2005). In Fig. 12, we can observe that it is associated with a thickening of the Boulouha Fm and we can hypothesize that a local trough was created in this area at that time. However, in the absence of any other observation related to this unconformity, it is not possible to provide further precision.

5.3. Link with the Atlantic Ocean opening

Moulin et al. (2010) presented a new model for the timing of the opening of the Equatorial and South Atlantic Ocean. In this model, two critical stages occur during the Aptian–Albian transition and the Middle Albian: the opening of the Central South Atlantic and the Equatorial Atlantic Ocean, respectively. There is a striking correlation between this timing and the regional tectonic unconformities observed in Northern and Central Africa, which points toward a causal link (Fig. 12).

Anketell and Ghellali (1991) proposed that the unconformity at the base of the Kiklah Fm (i.e. the Late Aptian unconformity) was linked to the initiation of the Sabratah–Cyrenaica fault system in a compressional stress field resulting from sinistral shear on deep-

Fig. 12. Temporal transect sequence showing the geodynamic evolution of the Jeffara escarpment during the Early to Mid-Cretaceous (same colour legend as Figs. 7 and 8; IBU: Intra-Boulouha unconformity) compared to the evolution of the Equatorial and South Atlantic Oceans (modified after Moulin et al. (2010)).

seated basement faults. The Aptian–Albian transition is also marked by the change from northwards to northeastwards movement of the Arabian–Nubian block relative to the West African block (Guiraud and Maurin, 1992). This time interval corresponds moreover to the change of the relative motion and the initiation of the convergence of Africa relative to Europe (Dewey et al., 1989; Rosenbaum et al., 2002). This supports the interpretation that the Late Aptian unconformity is related to sinistral transpressive movement along the Sabratalh–Cyrenaica fault system linked to the opening of the central segment of the South Atlantic Ocean and the northeastward movement of the Arabian–Nubian block.

The Middle Albian compressive event noted by previous authors in Tunisia (e.g. Bouaziz et al., 2002) has been explained by transpressive movement along the 10°E lineament. This tectonic phase is contemporaneous with the opening of the Equatorial Atlantic Ocean and the definitive separation of South America from Africa at about 105 Ma (e.g. Fairhead and Binks, 1991; Moulin et al., 2010). The coeval timing of these two events suggests they are linked and that the Middle Albian unconformity represents intra-plate deformation associated with changes in relative movement of the African blocks. Thus, it is proposed that the opening of the east–west orientated Equatorial segment may have induced a change in the stress regime of the West African block toward a north–south oriented compressional regime. A possible effect

could be a northward movement of the West African block relative to the Arabian–Nubian block and the subsequent transpressional movement along the 10°E lineament.

6. Conclusions

Stratigraphic and sedimentological observations along the Jeffara escarpment in Tunisia and Libya allows us to confidently correlate the Libyan Kabaw Fm with the Tunisian Boulouha and Douiret Fms, the Kiklah Fm with the Aïn el Guettar Fm, the Sidi as Sid Fm with the Charenn, Rhadouane and Kerker Mbs, and the Nalut Fm with the Gattar Mb. A review of published paleontological data in these sediments on both sides of the border allows us to better constrain their dating. Thus, there is a major hiatus at the base of the Kabaw–Boulouha Fms, the latter being dated as latest Hauterivan–Barremian. Furthermore, the Libyan Kiklah Fm is dated as latest Aptian? – Early Albian.

A series of measured sections and detailed transects highlight four tectonic unconformities along the Jeffara escarpment. Above the basal Cimmerian unconformity, a local unconformity is recorded in Tunisia within the Boulouha Fm, in the northern part of the studied area. The two last tectonic unconformities are bounding the Kiklah – Aïn el Guettar Fms. These unconformities represent two regional tectonic events that can be recognized

across Northern and Central Africa. They are dated as Late Aptian and Middle Albian, respectively. The Late Aptian unconformity is usually referred to as the Austrian unconformity. The Middle Albian unconformity correlates to the major tectonic unconformity also recognized at the top of the Sarir Fm (Nubian sandstone) throughout the Sirt Basin in Libya.

Placed into a plate tectonic context, there is a striking coeval timing between these unconformities and the evolution of the opening of the Equatorial and South Atlantic Ocean. Thus, the Late Aptian unconformity can be related to intra-plate deformation linked with the opening of the central segment of the South Atlantic and the accompanying sinistral movement of the Arabian–Nubian block during the Aptian–Albian transition. The Middle Albian unconformity relates to the opening of the Equatorial Atlantic and transpressive stress along the 10°E lineament, linked to north–south orientated movement of the West African block relative to the Arabian–Nubian block.

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