*Facies Analysis and Sequence Stratigraphy of the Upper Albian-Cenomanian Succession along the Jeffarah Escarpment, NW Libya

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Abstract

The focus of this study is on the upper Albian-Cenomanian Jennawen and Ain Tobi formations development on the Jeffarah Escarpment (JE) along NW Libyan region, with correlations of the equivalent transgressive and regressive sequences toward the Tunisian portions at Dahar Escarpment (DE). The ultimate aim is a better understanding of facies distribution, which can guide exploratory-play evaluation. Stratigraphic and sequential correlation framework from the JE allowed meaningful interpretation of Cretaceous sedimentation patterns and seaward facies prediction of potential reservoirs, the Jennawen and the Ain Tobi formations.

The Jennawen and Ain Tobi lithostratigraphic units form together three 3rd order transgressive-regressive (T-R) sequences. Depositional cycles are made of fluvial, marsh and shallow marine sediments which pass upward into shallow lagoonal and tidally-influenced carbonates. In the eastern flank of the JE, two 3rd order T-R sequences were identified, while only one sequence was recognized in Wazen, western flank of the JE, indicating palaeotopographic control and significant erosion of the Ain Tobi carbonates. The overall late Albian-Cenomanian sequence is overlying unconformably the Lower Cretaceous Kiklah Formation and is gradually, passed upward into Yefren marl of restricted shelf depositional setting.

The late Albian-Cenomanian sequence distribution, thickness variation and existence of stratigraphic gabs along JE are controlled by the pre-Cretaceous palaeotopography, relative sea level changes and tectonics.

A comparison of the Jeffarah succession with neighboring domains in Sirte Basin, Libya and Tunisian onshore, evidences great similarities in the depositional facies and sedimentation history. Sedimentologic and petrographic study of the late Albian-Cenomanian Jennawen and Ain Tobi sequences reveal high reservoir potential with good porosity percentage and high net/gross ratios.

Porosity within the transgressive Jennawen sandstones ranges from 5-25% and is of intergranular and vugy types. Porosity distribution within the Ain Tobi carbonates does not only obey enhancement close to the sequence boundary (SB), hence, porosity development is ascribed to the migration pathway of the dolomitizing fluid. Accordingly, similar potential reservoirs and proven petroleum plays are expected to be explored at the Libyan and Tunisian onshore and offshore regions.

Extended Abstract

1. Introduction

This study is focused on the relationship between the outcropping upper Albian-Cenomanian succession along the JE, Tunisian DE and their subsurface extension toward the adjacent Gabes-Tripoli Basin (G-T Basin) (Figure 1). In this study, the proposed sequence stratigraphic framework by Mriheel (2019) for the exposed Mesozoic succession of the JE is followed (Figure 2).

Stratigraphic correlations were based on six logged outcrop sections along JE (Mriheel, 2019, Hamruni and Mriheel 2021) within their possible analogue in the Tunisian DE sections (Bodin *et al.,* 2010 and Krimi *et al.,* 2017). Correlation with the G-T Basin subsurface wells (Mriheel, 2019) has also been considered for Libyan and Tunisian offshore regions. The JE offers opportunities to study this period, since it offers good exposures and accessible sites for field trips and studies of tidally-influenced siliciclastic and carbonates successions. The objective of this work was to support exploration efforts for targeting upper Albian-Cenomanian petroleum plays in the Libyan and Tunisian onshore and offshore regions, using sequence stratigraphy in mapping of exploration trends. Proven Cretaceous HC accumulations have been confirmed toward the Libyan and Tunisian onshore and offshores.

Figure 1. Showing the location of the study area Jeffarah escarpment (a) relative to North African political boundaries (b). The position of the constructed East-West transect (Figure 7) along the Jeffarah-Dahar Escarpment is also shown.

Methods

This facies analysis and sequence stratigraphic study is based on logging of six sections from eastern to western part of the JE, using standard logging technique. Image stratigraphy (IS) has been applied as a tool to trace stratal terminations, facies geometry and observe the tidal flat and lagoonal parasequences stacking pattern of the different systems tract. Hand samples have been collected for every bed and whenever there were changes in facies. Representative sixty eight samples were collected for petrographic analysis. Both macro-structure and micro-texture

examinations of the Jennawen and Ain Tobi samples were conducted during outcrop and laboratory microscopic studies. High-resolution stratigraphic correlations have been defined using field physical correlation and sequence stratigraphic concepts.

2. Geological Background

The Libyan JE, Tunisian DP and G-T basins are located on the northern passive continental margin of the African Platform (Figure 1). The tectonic evolution of the regions are dominated by Mesozoic rifting of the northern African Margin, resulting in the break-up of Pangaea and the development of several Mediterranean basins (Finetti, 1982). Deposition of the Mesozoic mega-sequences took place during several rifting phases effecting the Mediterranean basins, starting from Triassic and passing through the Jurassic and terminated during Lower Cretaceous. The region witnessed compressional phases during late Cretaceous and Eocene followed by Oligocene-Quaternary rifting (Mriheel, 2019).

3. Facies and Sequence Stratigraphy Analysis

The Cretaceous mega-sequence is represented by the Cretaceous second-order transgressive sequence (Figure 2). Within the Cretaceous sequence, four 4^{th} order T/R depositional sequences are identified. The sequence extends from the Hauterivian to Turonian, comprising sequences SII-1, SII-2, SII-3 and SII-4 (Figure 2). The late Albian-Cenomanian Jennawen and Ain Tobi sequences represent SII-3 and the lower part of sequence SII-4 respectively (Mriheel, 2019).

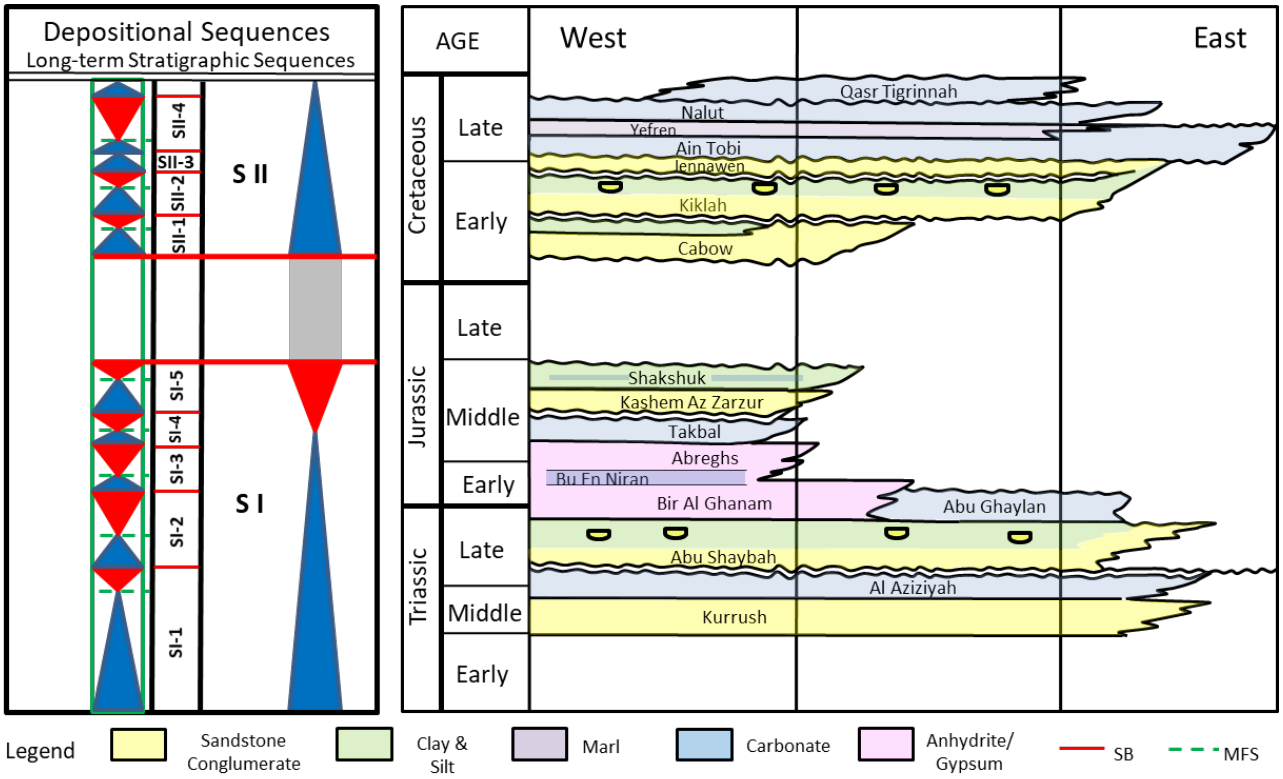

Figure 2. Stratigraphic scheme for the Jeffarah Escarpment from Mriheel, 2019

SII-4 is comprising of thick sequence of carbonate and marl which includes the Ain Tobi, Yefren and Nalut lithostratigraphic units. The Ain Tobi Fm represents only the lower part of SII-4 and has been further subdivided into four 4th order T-R sequences (Hamruni and Mriheel 2021).

Six main facies association have been recognized within the Ain Tobi Formation. The transgressive Jennawen Fm is represented by tidally-influenced marginal marine siliciclastics and change facies occasionally to channels and marsh sediments. The description of the Jennawen and Ain Tobi sedimentary facies and the interpretation of the depositinal enivironments are shown in Figures 3-6.

The regional facies distribution of the Ain Tobi succession and it's equivalent in Tunisian DE Rhadouane Fm is shown in sequence stratigraphic transect (Figure 7). The spatial facies distribution are constructed in a sequential order that illustrates the evolution of the depositional systems in response to relative sea-level changes.

Four sedimentary boundaries/discontinuities have been identified (Figure 7). The first boundary (B1) is the palaeosol and the onlaped surfaces at the base of the upper Albian Jennawen Fm, which corresponds to Late Albian emergence period. B2 is marked by estuary/bay-fill mud with vertebrate bones or sharp contact at the base of tidal flat carbonate of the Ain Tobi succession. B3 is karstified surface of the Cenomanian dolomite, which corresponds to the short-lasting Cenomanian emergence period. B4 is marked by mineralized surface (hard-grounds), locally with thin ferruginous oolitic bed at the top of progradational HST. The hard-grounds are interpreted as hiatuses. These boundaries/ discontinuities define transgressive-regressive, depositional sequences (Figure 7). Main facies characteristic and component sequences of the late Albian-Cenomanian Jennawen and Ain Tobi are summarized as follows:

Jennawen Formation

The first sequence of the Jennawen Fm is represented by a 3rd order transgressive marginal marine and tidally influenced siliciclastics, interrupted by channles and locally change facies into marsh depositional settings with well developed rootlets. Main facies characteristics are summarized in Figures 3-5. The sandstones are bioclastic, bioturbated, laminated/rippled, cross-bedded and occasionally demonstrating mud drapes and reactivation surfaces. The overall Jennawen succession is a transgressive sequence, finning upward and capped by estuary/bay-fill mud and in some locality the sequence is terminated with deep lagoon low bioturbated mud which represents major flooding event. The absence of the regressive term of the sequence explained by either erosion or non deposition of the progradational parasequence sets.

The basal sequence boundary of the Jennawen sequence corresponds to the middle Albian unconformity associated with paleosoil development or marked with a slight onlaping surface over the Kiklah siliciclastics. The upper boundary is marked by estuary/bay-fill mud with vertebrate bones or sharp contact at the base of tidal flat carbonate of the Ain Tobi succession. Toward Tunisia, the transgressive Charenn Fm is equivalent to Jennawen sequence SII-3 of Mriheel 2019.

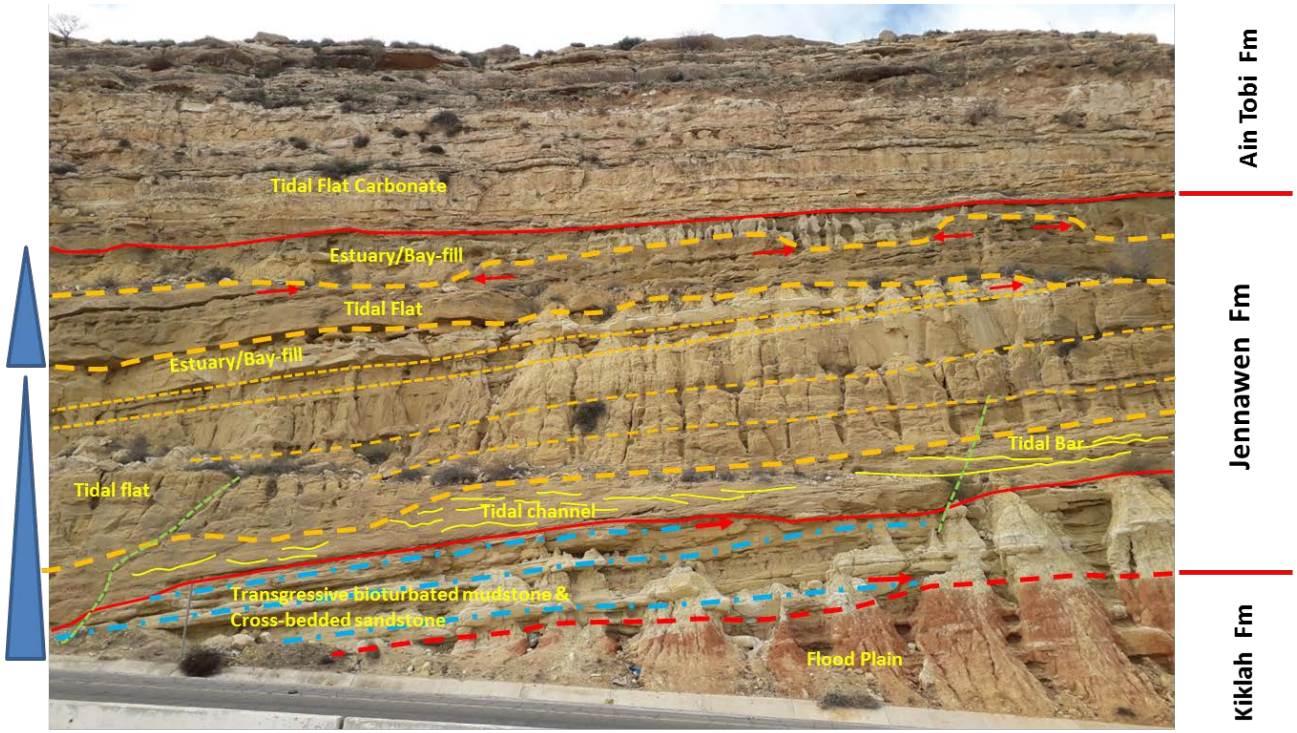

Figure 3. Showing how image stratigraphy (IS) ease interpretation of stratigraphic architecture of the tidally-influence sediments of Jennawen Fm, Abu Ghylan section, Libya.

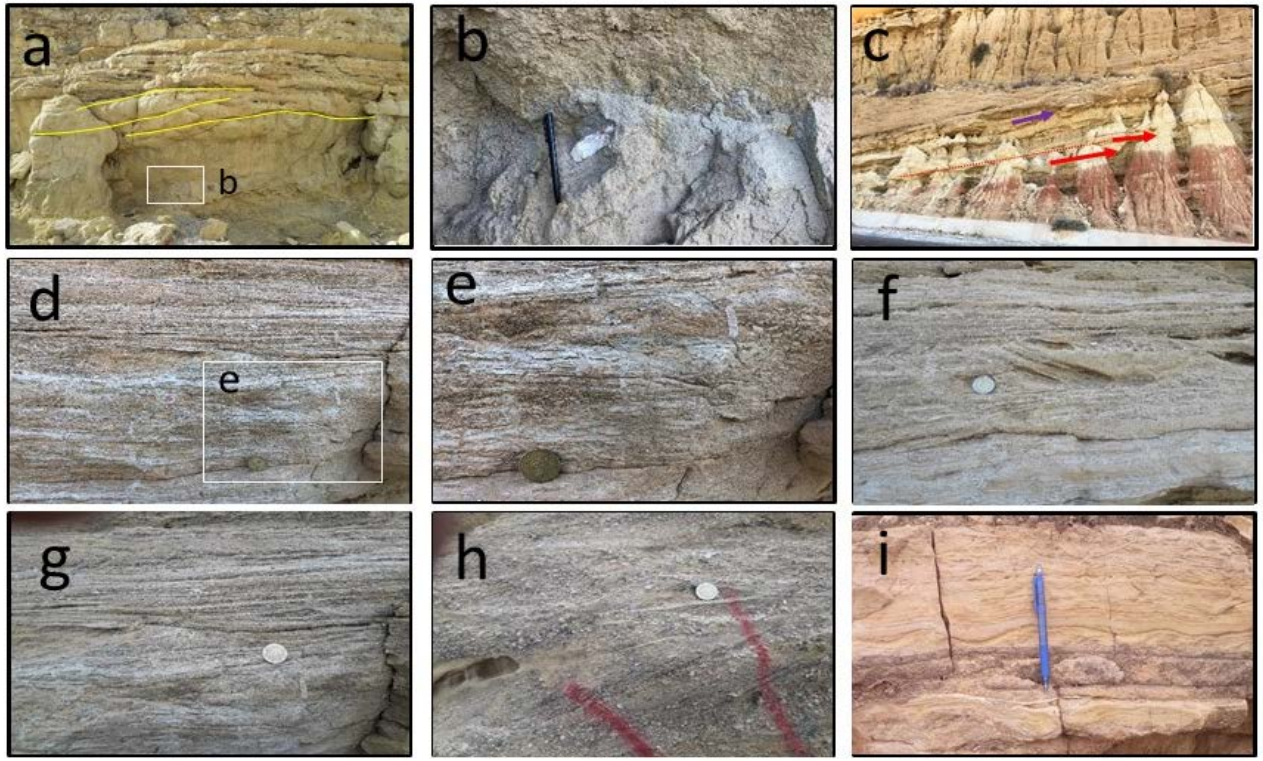

Figure 4. Field photographs showing the Jennawen Fm at the Abughaylan section; a estuary/bay-fill mud near to the discontinuity surface (B2) between Jennawen and Ain Tobi Fms; b. close view of (a) showing green-grey mud with vertebrate bones within the Jennawen Fm; c. channel conglumeratic sandstone overlies transgressive calcareous and bioturbated mud alternating with clay of the Jennawen Fm. The base of the channel is scoured surface marked by truncation stratal terminations, while the transgressive package on laps the Kiklah Fm; d. laminated, trough crossbedded & bioturbated sandstone; e. close view of (d) showing vertical burrow; f Laminated & crossbedded sandstone, probably induced during neep and spring tide with possible mud drapes; g. laminated, trough cross bedded and bioturbated sandstone; h very coarse & conglumertic sandstone with sigmoidal cross bedding; i. current ripples generally expose eroded crests at the upper part of the photo and ripple at the lower part of the photo is outlined by thin film of mud drape, the Fam Mulghah section. The mud is draped during high tide.

Ain Tobi Formation

The Cenomanian sedimentary succession of the Ain Tobi carbonate ramp is composed of six main facies association (Hamruni, 2022). They are peritidal, rudist biostorm, shallow lagoon, deep lagoon, shoal, rudist bank and forebank (Figure 7).

The sequence stratigraphic transect is oriented almost in E–W direction, parallel to the Libyan-Tunisan coastal line from the JE to DE (Figure 7), showing the details of the sequence stratigraphic framework of the Ain Tobi Cenomanian succession.

The Ain Tobi shallow carbonate ramp succession represents the lower part of the 3rd order sequence SII-4 (Mriheel, 2019). According to Hamruni and Mriheel 2021, the Ain Tobi sequence can be further subdivided into four 4th order T-R sequences at western areas (Gharian), three 4th order T-R sequences at central area (Jadu) and only one 4th order sequence at western area (Wazen) (Figure 7). The main Ain Tobi 4^{th} order sequences charcteristics are sumarized below and the sequences laterally continuity and distribution are illustrated in Figure 7.

The first T-R sequence S-1 of the Ain Tobi Fm is a tidal flat dolomitized limestone. The second sequence S-2 is also dominated by tidal influenced facies. Generally, all the Ain Tobi sequences show increasing ratios of subtidal facies relative to intertidal and the subtidal thickness is increasing toward maximum flooding surface, expressing a keep up phase due to sea level rise. The third sequence S-3 usually begins with sharp base with occasionally reworked sediment, and ends up with

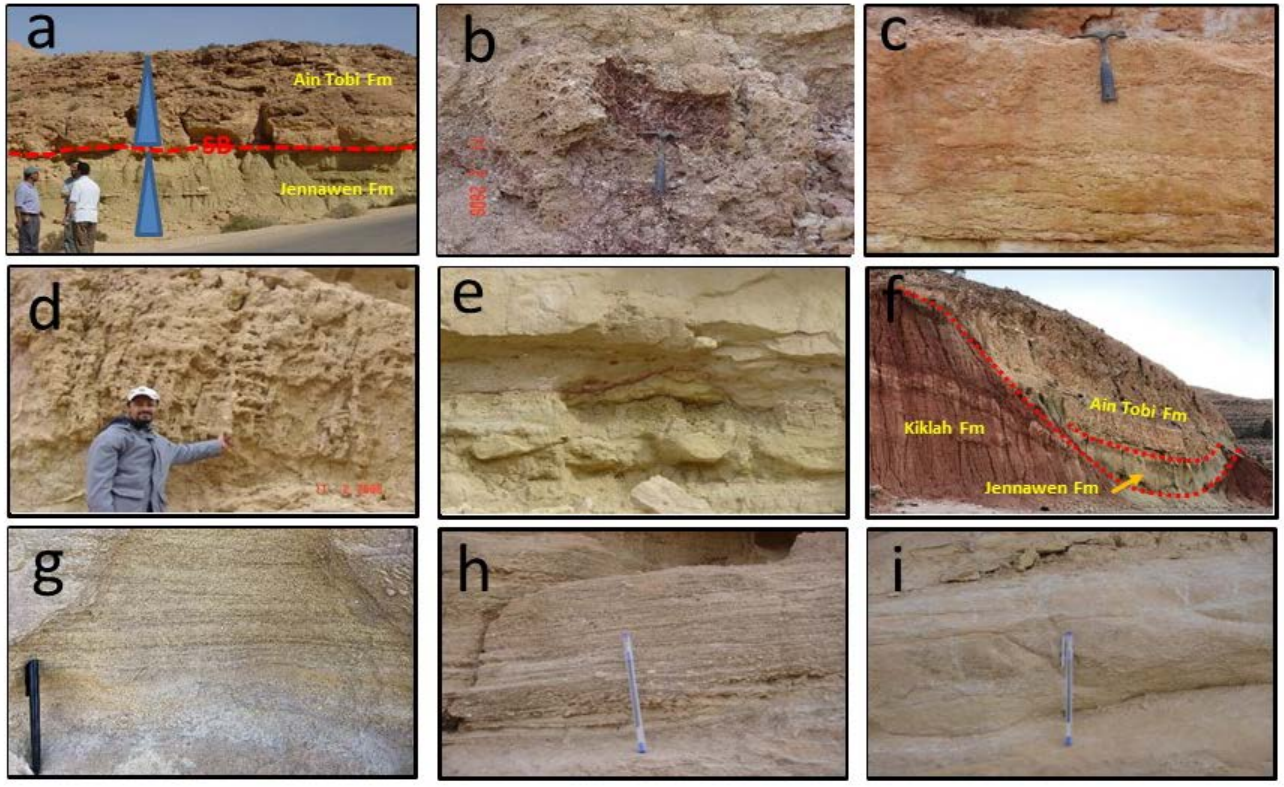

Figure 5. Field photographs showing: a. the Ain Tobi Fm highly weathered and brecciated carbonates unconformably overlies the marginal marine transgressive clay and calcareuos sandstone of the Jennawen sequence at the Jadu section; b. reddish brown calcareous claystone,

paleosol bed (unconformity surface) between the Kiklah Fm and the lower parts of the Jennawen Fm, the Jadu section section; c. light yellow rippled and bioturbated siltstone and sandstone; d. rootlets in green-red clay and silt, representing the marsh sediments of the Jennaween Fm, Jadu section; e. light yellow sandstone with lag deposits (field of view is about 2.0 m); f. unconformable contacts between the Kiklah Fm and the upper part of the Jennawen Fm (about 3.0 m thick) induced probably by mass sliding, during Alpine tectonic movements, the Abu Ghaylan section; g. laminated tidal-falt sandstone, the Abu Ghaylan section; h. conglumeratic sandstone with horizontal lamination and scattered pebbles at the lower part of the tidally-influenced channel, the Abu Ghaylan section; i. bioturbated calcareous mudstone within the lower transgressive succession of the Jennawen Fm, the Abu Ghaylan section.

irregular surface and shallow karstification at the top. The S-3 contains allochthonous sediment of rudist fore-bank facies, which changes laterally into oolitic shoal. The fourth sequence S-4 is characterized by retrograditional to progradational stacking patterns, from peritidal and shallow lagoon into the shoal and deep lagoon facies, and back into peritidal and shallow lagoon.

Toward Tunisia, the Rhadouane Fm is equivalent to the Ain Tobi succession and is comprised of two 3rd order sequences. (see Fugure 7). This study confirms that the facies architecture of Ain Tobi carbonate succession is primarily controlled by both relative sea-level change and paleotopography.

Considering the HC plays, the Lower Cretaceous source and reservoir rocks are proven plays in the eastern Sirte Basin and Gulf of Gabes. Important petroleum Upper Cretaceous source rock in the G-T Basin is the Makbaz Formation (equivalent to the Tunisian Bahloul Formation). Turonian marine deposits are source rocks in the eastern Sirt Basin. The Upper Cretaceous marine deposits are source rocks in the Sirt Basin and in the Gulf of Gabes. The Upper Cretaceous sediments are reservoirs in the Gulf of Gabes (Carr, 2003). Mriheel, 2019 suggested that more HC could be found in the upper Albian-Cenomanian transgressive Jennawen sandstones, Ain Tobi equivalents, and Zebbag carbonate reservoirs.

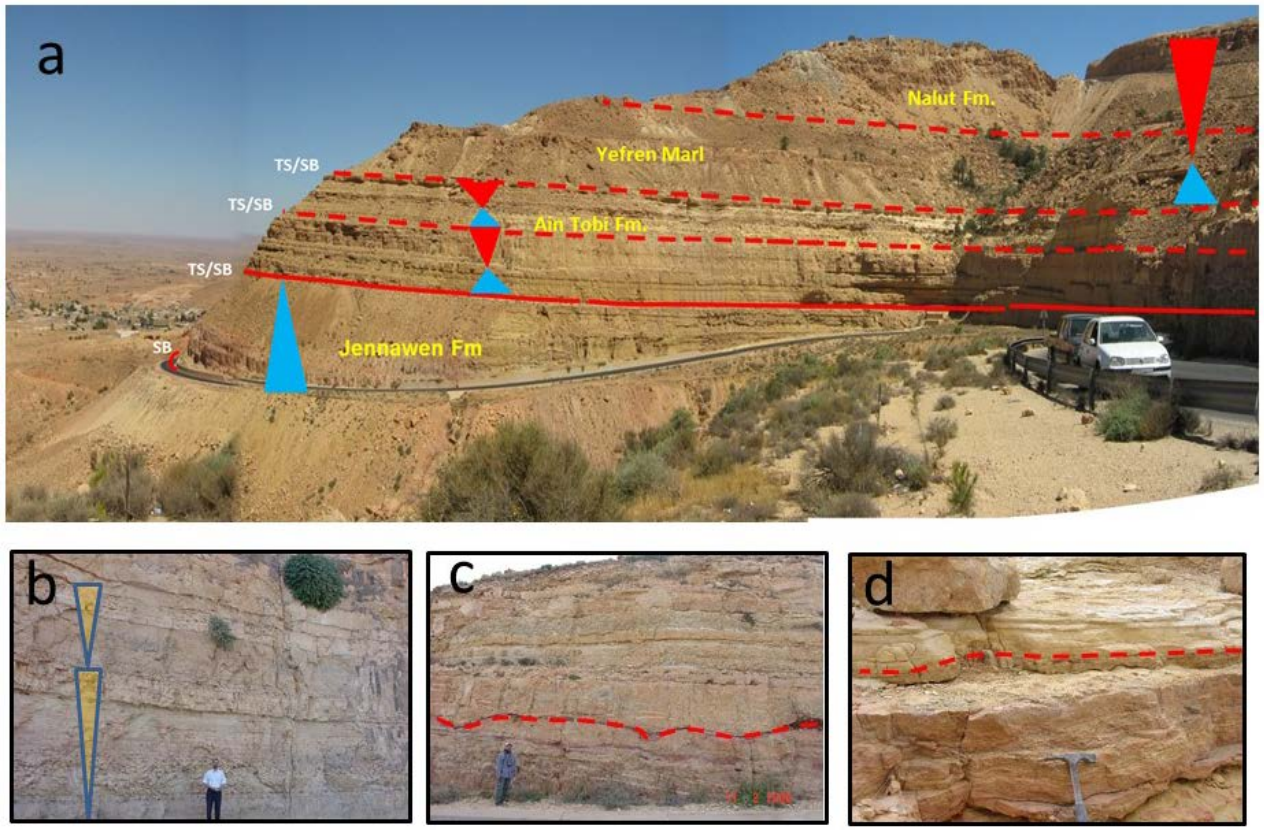

Figure 6. Image stratigraphy (IS) has been applied to trace stratal terminations and key surfaces as well as in recognizing the parasequence stacking patterns of the different systems tract of the Ain Tobi and the Jennawen fms in the studied sections. a. general view of the Jennawen and the Ain Tobi fms in the Jadu section, showing high resolution sequence stratigraphy analysis which can be achieved using (IS); b. typical shallowing-upward parasequences in the lagoonal-tidal flat carbonates of the Ain Tobi Fm, the old road of Abu Ghaylan section; c. a karstified surface, representing the SB of the first Ain Tobi 3rd order sequence, the Jadu section; d. a mineralized surface (hard-grounds) with a thin ferruginous oolitic bed at the top of the second Ain Tobi 3rd order sequence, the Jadu section. The hard-grounds are interpreted as hiatuses. These boundaries/discontinuities define transgressive-regressive, depositional sequences.

4. Discussion

The upper Albian-Cenomanian is characterized by a mild tectonic period during which a transgreesion event prevailed along the passive northern African Margin. The transgressive marginal marine sliciclastics deposited over many parts of the Western desert of Egypet (Bahariya Fm), Cyrenica, Sirt Basin (Bahi and Maragh Fm), Jefarah, Ghadames Basin (Jennawen Fm) and DE Tunisia (Charenn Fm). In the Libyan JE and Tunisian DE the Cenomanian records a broad development of shallow marine carbonate ramp and is represented by the Ain Tobi and the

Rhadouane fms. However, in Tunisia, the tectonic activity during the late Albian and early Turonian witnessed some degree of fault reactivations (Bouaziz 1995; Ben Ayed 1993) which affected the instability of depositional environment as expressed by seismic and slumped breccias.

The upper Albian-Cenomanian deposits in the Jeffarah and the Dahar domain are characterized by a facies deposits extending from pertidal-subtidal environment to middle ramp organized in a T-R elementary sequences (Figure 7). Formation of these sequences are in principle related to the changes in relative sea level and sedimentation rates as well as paleogeographic control.

The correlation of cross-sections along the Libyan JE and the Tunisian DE shows a thickness reduction of upper Albian-Cenomanian deposits from the eastern JE to the western parts toward the Wazen high and from the western Tunisian DE to the eastern parts toward the Wazen high. In the eastern part of the studied area (Abu Ghaylan section), the cross-sections are much more complete with four 4th order sequences but they thin westward and onlaping of the Ain Tobi S1, S2 and S3 on the paleoghigh is progressively proceeded until the time of the transgressive period of S4 commenced. It is then when the transgression covers the Wazen paleohigh and lead to the submergence of the area and deposition of the transgressive abbrecciated carbonate facies. Subsequently, the regressive phase of S4 covers both the Libyan and Tunisian JE and DE respectively (Figure 7).

Thus, the section shows the same thickness during S4 deposition along the JE and DE and the little thickness variation can be interpreted as a result of eastward progradation and erosional process.

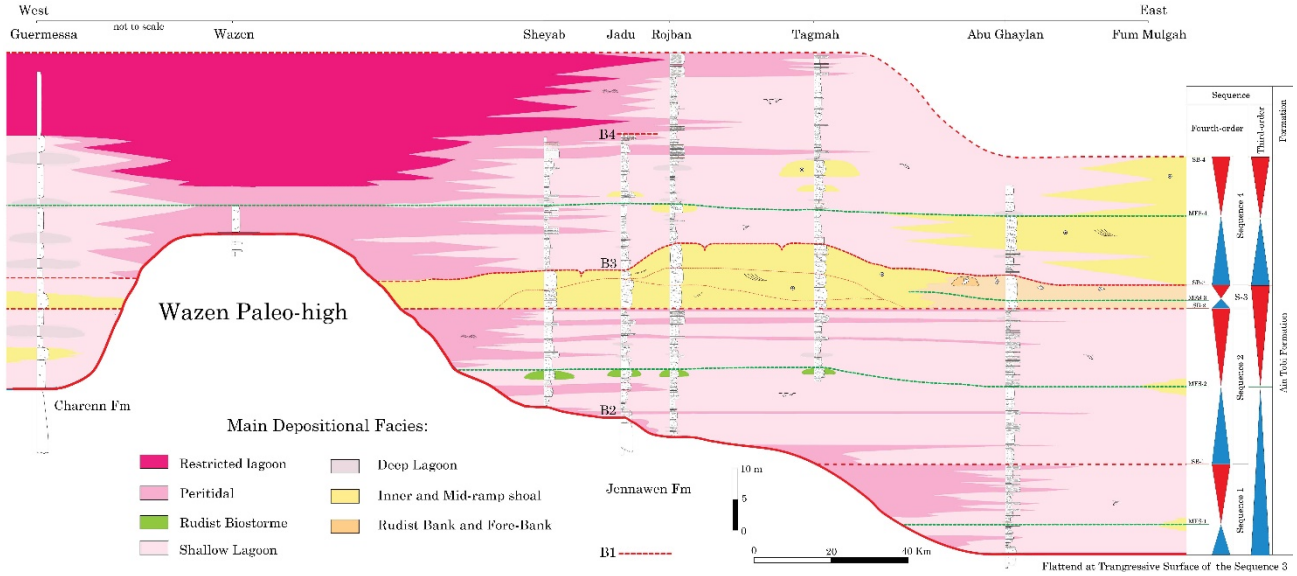

Figure 7. East-West transect along the Jeffarah-Dahar Escarpment showing the sequence stratigraphic framework for the Late Albian-Cenomanian Ain Tobi Fm and its equivalent Rhadouane Fm in Tunisisan Dahar domain. The thick red lines represent the sequence

boundaries. The green lines mark the maximum flooding surfaces. Note the on lapping surfaces of the 4th order sequences 2 and 3 toward Wazen Paleo-high from the Libyan and Tunisian sides and the submergence of the Wazen Paleo-high during the time of the 4th order sequence 4.

In comparison with the previous studies, this work presents more details compared with the study of Mriheel (2014 and 2019). The two 3rd order sequences of the Ain Tobi Fm of Mriheel (2014) study which extends from the base to the evaporate level of the Ain Tobi Fm have been subdivided into four 4th order sequences (S1-S4) by Hamruni (2022). The Ain Tobi succession overlies the late Albian-Cenomanian Jennawen transgressive sequence with the absent of the regressive term of the Jennawen sequence which explained by erosion or non deposition (see Figure 6).

5. Conclusions

The upper Albian-Cenomanin outcrops formed on a broad slowly subsiding epeiric tropical platform. The depositional environment ranges from marginal marine tidaly influenced siliciclastics facies of the Jennawen Fm to peritidal, lagoonal, shoal and middle carbonate ramp facies of the Ain Tobi Fm.

The upper Albian-Cenomanian Jennawen and the Ain Tobi successions representing three 3rd order sequences developed on the northern African passive margin during major transgression period followed a long lasting regression phase that persisted in the Early Cretaceous times and records deposition of thick continental facies.

The upper Albian-Cenomanian Jennawen succession is comprised of one 3rd order transgressive sequence with the absent of the regressive term of the sequence which explained by erosion or no deposition. The Ain Tobi successions consist of two 3rd-order sequences superimposed by four 4th-order sequences.

Facies analysis and sequence stratigraphic studies of the late Albian-Cenomanian Jennawen and the Ain Tobi sequences along the Libyan JE, allow to propose that 1) the spatial and temporal distribution and thickness variations are controlled by relative sea level changes and paleotopography, 2) the Tunisian upper Albian-Cenomanian Charenn and the Rhadouane fms are equivalent lithostratigraphic units to the Libyan Jennawen and the Ain Tobi fms respectively, 3) Sea level rise allowed deposition first of the upper Albian-Cenomanian Jennawen marginal marine siliciclastics and S1 of the Ain Tobi Fm in eastern parts of the JE, and then the S2 and S3 deposited in the eastern and western sides of the Wazen emergent zone. Sea level rise during S4 allowed submergence of the Wazen paleohigh and deposition of the sequence.

6. Acknowledgements

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7. References

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