Paleogeographic Reconstruction of the Upper Miocene Sequences of the Wadi Yunis Member of the Al Khums Formation, Sirt Basin, Central Libya

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ABSTRACT

The main objective of this work is to reconstruct the paleogeographic distribution of the depositional facies of the Upper Miocene carbonate sequences of Wadi Yunis Member, Al Khums Formation, Sirt Basin. The sequence stratigraphic correlation of 38 field measured high-resolution sedimentological sections indicates that the Upper Miocene Wadi Yunis Member consists of two successive shallowing-up sequences. Each sequence consists of six vertically stacked depositional facies (oolitic grainstone facies, oo-skeletal grainstone-packstone facies, algal pelle-skeletal facies, bioclastic wackestone facies, algal stromatolite facies, and coarsely crystalline selenite gypsum facies). These carbonate depositional facies formed in restricted shelf lagoonal-tidal inlet and beach-bar shoal-subtidal channel complex environments along a NW–SE trending, 150 km long, wave-dominated carbonate ramp.

Mapping analysis of these two depositional sequences resulted in the reconstruction of the paleogeographic distribution of the Wadi Yunis Member depositional facies. During the transgressive systems tract (TST) of the lower shallowing upward sequence, the oolitic grainstone facies belt was deposited above the marly bioclastic wackestone facies. Then a younger channeled oolitic grainstone belt was created above a structural high seaward of the older oolitic grainstone belt, and between these two oolitic belts lagoonal bioclastic wackestone facies were deposited. During the highstand systems tract (HST), channel inlets partially closed and the bioclastic wackestone facies with dwarfed fossils, stromatolites, algal pelletal facie and some gypsum restricted lagoonal facies were deposited. During the lowstand systems tract (LST), the lagoons were completely restricted and selenitic gypsum facies deposited in an eye-ball shaped geometry and the lower shallowing-up sequence completed.

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The upper shallowing-upward sequence preserves the TST. It is made up of channeled lagoonal bioclastic wackestone facies that were later overlain from the seaward side by a new oolitic grainstone belt.

The paleogeographic distribution of the depositional facies of the Upper Miocene carbonate sequences of the Wadi Yunis Member, Sirt Basin, indicates a structurally controlled compartmentalized ramp setting. The elongated carbonated ramp complex body is striking along the NW–SE direction and relatively narrow along the depositional dip section. The low energy/restricted lagoonal deposits are encompassed between two high energy parallel oolitic grainstone belts along 150 km.

Paleogeographic Reconstruction of the Late Miocene Sequences Wadi Yunis Member of Al Khums Formation, Sirt Basin, Central Libya

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ABSTRACT
The main objective of this work is to reconstruct the paleogeographic distribution of the depositional facies of the Late Miocene carbonate sequences of Wadi Yunis Member, Al Khums Formation, Sirt Basin. The sequence stratigraphic correlation of the field measured thirty eight high-resolution sedimentological sections indicates that the late Miocene Wadi Yunis Member consists of two successive shallowing-up sequences that made up of six vertically stacked depositional facies (oolitic grainstone facies, oo-skeletal grainstone-packstone facies, algal pelle-skeletal facies, bioclastic wackestone facies, algal stromatolite facies, and coarsely crystalline selenite gypsum facies). These carbonate depositional facies formed as the product of restricted shelf lagoonal-tidal inlets complex and beach-bar shoals-subtidal channels complex environments along the NW-SE trending, 150 km long wave dominate carbonate ramp. Mapping analysis of these two depositional sequences resulted in the reconstruction of the paleogeographic distribution of the Wadi Yunis Member depositional facies.
During the TST of the lower shallowing upward sequence, the oolitic grainstone facie belt was deposited above the marly bioclastic wackestone facies. Then a younger channelled oolitic grainstone belt was created above a structure-high seaward of the older oolitic grainstone belt and between these two oolitic belts lagoonal bioclastic wackestone facies were deposited. During the HST channels inlets partially closed and the bioclastic wackestone facies with dwarfed fossils, stromatolites, algal pelletal facie and some gypsum restricted lagoonal facies were deposited. During the LST the lagoons were completely restricted and selenitic gypsum facies deposited in an eye-ball shaped geometry and the lower shallowing-up sequence completed. The upper shallowing-upward sequence preserves the TST. It is made up of channelled lagoonal bioclastic wackestone facies that were later overlain from the seaward side by a new oolitic grainstone belt.
The paleogeographic distribution of the depositional facies of the Late Miocene carbonate sequences of Wadi Yunis Member, Sirt Basin indicates a structurally controlled compartmentalized ramp setting. The elongated carbonated ramp complex body is striking along the NW-SE direction and relatively narrow along the depositional dip section. The low energy/restricted lagoonal deposits are encompassed between two high energy parallel oolitic grainstone belts along 150 km.

INTRODUCTION
The study area is located in the centre of the northern part of Sirt basin in the centre of north Libya. It is between 30°00 N to 31°00N latitudes and 18°00E to 19°30E longitudes (Fig.1) in the IRC map sheet NH 34-5 (Innocent and Pertusati, 1984). The outcrops of the Upper Miocene Wadi Yunis Member facies extend in a narrow belt about 2 to 3 km wide and about 150 km long roughly parallel to the present day shoreline.
The aim of this study is to reconstruct the paleogeographic distribution of the Upper Miocene Wadi Yunis Member depositional facies throughout mapping analysis of the two depositional shallowing upward sequences. The mapping analysis process was preceded by a detailed documentation for the sedimentological nature of the Late Miocene sequence, Wadi Yunis Member of Al-Khums Formation, stratigraphic correlation, and then construction of the sequence stratigraphic framework of this mixed carbonate-siliciclastic succession (Fig.2). The Wadi Yunis Member is a ramp system (Ahr, 1973; Tucker, 1996; and Schllager, 2005, Amrouni and El-Hawat, 2015) made up of oolitic shoal complex and lagoonal complex. The oolitic shoal facies associations includes: 1) oolitic grainstone facies, 2) oo-skeletal grain-packstone facies, 3) algal-pelle-skeletal grain-packstone facies. The lagoonal facies associations include: 1) bioclastic wackestone facies, 2) algal stromatolite facies, and 3) coarse crystalline gypsum facies (Amrouni, 2006, Amrouni and El-Hawat, 2015).

GEOLOGICAL SETTING
During the Early Cretaceous the Sirt graben Basin developed as a result of the Hercynian Tibesti-Sirt uplift collapse during the Triassic-Jurassic. The general tectonic setting and history of Sirt basin where the study area is located is documented by Ankatell (1996). The Sirt basin is the southern extension of the Tethys basin that developed as a result of block faulting and subsidence of a part of the Sahara Shield, which had infilled largely by sallow carbonate and deep shales during the Miocene (Selley, 1978). The study area has been mapped by Innocent and Pertusati (1984), for the Industrial Research Centre. The stratigraphic section exposed in the area of study consists of Shallow Tertiary marine carbonate of Oligocene to Quaternary. The Late Miocene Al Khums Formation deposited disconformably on the Early-Middle Miocene Maradah Formation (El-Hawat et. al., 2004). Al Khums Formation comprises two members the lower one is Wadi Yunis Member that consists of cross-bedded and gypsiferous oolitic limestone, while the upper member is Quwayrat Al Jibs Member, which is formed of evaporite associated with chalky limestone and oolitic and detrital limestone (Innocent and Pertusati, 1984).

METHODS
Mapping analysis of the depositional sequences of the Late Miocene Wadi Yunis Member required base maps, GPS measurements, detailed documentation of the measured sedimentological sections, depositional facies analysis, and then sequence stratigraphic correlation. After a detailed facies analysis, the depositional environments determined and the sequence stratigraphic correlation established for the Late Miocene carbonate sequences Wadi Yunis Member through correlating bed-by-bed logged (38) vertical sedimentological sections.At this stage, the detailed regional facies relationships determined for the whole Late Miocene carbonate package and within each shallowing upward sequence. Afterwards, the palaeogeographic maps were created by plotting the depositional facies of each sequence stratigraphic system tract on the base maps at specific location determined by the GPS.
The Late Miocene strata Wadi Yunis Member in the study area were covered by two main stratigraphic cross-sections, the Southern section includes 9 detailed vertical logs along 63.5 km, and the Northern section includes 29 detailed vertical logs along 104.5 km. The vertical log sections' localities were determined by Magellan GPS 310. The cumulative thickness of the vertical measured sections in this study totals 692.5 meters.
A multi-datum technique used for the stratigraphic correlation purpose, the basal part of the oolitic grainstone shoal facies were used as a datum for the Southern part of the study area, whilst in the Northern part includes the coarse crystalline chevron yellow selenitic gypsum facies as a datum for the SE, and the basal part of the lower chalky bioclastic wackestone lagoonal facies as a datum for the NW part.

RESULTS
Seven detailed paleogeographic maps (Figs. 3-9) were generated to demonstrate the seven stages of evolution of the depositional facies sequences of the Late Miocene sequence Wadi Yunis Member (Fig. 2). The mapping documented six depositional facies deposited in two broad depositional environments to form two shallowing upward sequences; upon siliciclastic influenced wave dominated elongated bodies of open shelf ramp platform.
The Late Miocene sequence Wadi Yunis Member consists of six distinctive siliciclastic influenced carbonate depositional facies (Fig. 2 and Table 1). These facies are attributed to lagoonal facies associations and shoal facies associations (Amrouni, 2006; Amrouni and El-Hawat, 2015). The Late Miocene sequence, Al-Khums Formation, Wadi Yunis Member facies associations and environments produced two siliciclastic influenced large scale shallowing upward sequences (Fig. 2 and Table 1). The lower one is a complete large scale shallowing upward sequence with a transgressive system tract (T.S.T), high stand system tract (H.S.T), and low stand system tract (L.S.T) while the upper sequence is an incomplete and only preserve the record of a transgressive system tract (T.S.T).
Seven maps depicted the different stages of the paleogeographic evolution of the Late Miocene depositional sequences of Wadi Yunis Member (Figs. 3-9 and Table 2). Five paleogeographic maps (Figs. 3-7) were generated to document evolution of the lower shallowing upward sequence; three maps for the T.S.T, one map for the H.S.T, and one map for the L.S.T. Moreover, two paleogeographic maps (Figs. 8 and 9) were produces to document the T.S.T of the Upper incomplete shallowing upward sequence.
The first stage of the paleogeographic evolution, transgressive systems tract, of the lower large scale shallowing carbonate sequence (Fig. 3) started by the deposition of semi-restricted marine marly bioclastic wackestone lagoonal subfacies at the base to be overlain by oolitic grainstone high energy shoal facies associations. The second stage (Fig. 4) was the deposition of the second oolitic grainstone facie belt north of the older one to create a small basin in the middle to be filled by bioturbated bioclastic wackestone semi-restricted lagoonal subfacies. The third stage (Fig. 5) was the closing the channels along the northern oolitic belt and the deposition of the Algal pelle-grapestone Muddy tidal low energy shoal facies associations that changes laterally into Algal stromatolite restricted lagoonal facies.
The fourth stage of the paleogeographic evolution, High systems tract, of the lower large scale shallowing carbonate sequence (Fig. 6) was the deposition of silica-bearing gypsified lower bioclastic wackestone lagoonal topsets subfacies above the shoal facies associations. This lagoonal subfacies is characterized by dwarfed bivalves at the base.
The fifth stage of the paleogeographic evolution, Lowstand systems tract, of the lower large scale shallowing carbonate sequence (Fig. 7) was the deposition of a yellow chevron selenitic gypsum layer of on top. This event terminated the final depositional phase of this large scale shallowing upward sequence.
The sixth stage (Fig. 8) of the paleogeographic evolution, transgressive systems tract, of the upper large scale shallowing carbonate sequence began with the deposition of silica-bearing restricted middle and upper chalky bioclastic lagoonal subfacies. These lagoonal facies are sharply overlain by silica-bearing dolomitic oolitic grainstone high energy shoal facies associations of the seventh stage (Fig. 9).

DISCUSSION
The paleogeographic maps analysis of the Late Miocene carbonate sequence facies, (Al Khums Formation, Wadi Yunis Member) required outcrops documentation, depositional facies analysis, sequence stratigraphic correlation, and mapping techniques (e.g. Mial, 1990). The Late Miocene carbonate sequence Wadi Yunis Member is a ramp system (i.e. Ahr, 1973; Tucker, 1996; and Schllager, 2005, Amrouni and El-Hawat, 2015) as can be inferred from the sedimentological analysis. The six depositional facies grouped into two shallow environments the oolitic shoal complex and lagoonal complex. The oolitic shoal facies associations are oolitic grainstone facies, oo-skeletal grain-packstone facies, and algal-pelle-skeletal grain-packstone facies (Fig. 2). The lagoonal facies associations are bioclastic wackestone facies, algal stromatolite facies, and coarse crystalline gypsum facies (Amrouni, 2006, Amrouni and El-Hawat, 2015). The stratigraphic correlation techniques applied to group these depositional packages into genetically related strata that formed the studied sequences (Catuneanu et.al., 2009; Schlager, 2005; Coe et.al., 2003; Kendall et.al, 1991). Finally, these depositional sequences were analyzed and mapped in time and space to understand the palaeogeographic configuration of the basin and the paleogeographic distribution of the depositional facies.
The paleogeographic maps of the Late Miocene carbonate sequence facies, (Al Khums Formation, Wadi Yunis Member) revealed that the depositional basin was elongated in shape and extends for 150 km in the NW-SE parallel to the present day shoreline. Also, the paleogeographic maps indicate that the palaeoshoreline was landward in the south during the 1st stage (Fig. 3) as shown by lagoonal marly bioclastic wackestone overlain by high energy oolitic shoal facies. At the 2nd stage (Fig. 4) a new carbonate shoreline of oolitic shoals developed along a structure high sea-ward north of the previous shoreline to form a lagoon between the two shorelines that filled later with bioturbated bioclastic wackestone of semi-restricted lagoonal subfacies. The 3rd stage (Fig. 5) was a time of restriction in the basin; channels blocked and facies changed into algal pelle-grapestone muddy tidal low energy shoal facies associations that changes laterally into algal stromatolite restricted lagoonal facies. These three stages together represent the T.S.T of the lower shallowing upward sequence.
The basin restriction continued during the 4th stage (H.S.T) to produce the semi-restricted lagoonal topsets subfacies silica-bearing gypsified lower bioclastic wackestone that dominated by dwarfed bivalves at the base (Fig. 6). The 5th stage (L.S.T) was a complete isolation and the deeper parts of the basin filled with yellow chevron selenitic gypsum isolated lagoonal subfacies (Fig. 7). The chevron selenitic gypsum layer indicates a very arid climate in the proximal part of the ramp deposits (Emery and Myers, 1998).
The 6th stage (T.S.T of the upper shallowing upward sequences) was characterized by the silica-bearing middle and upper chalky bioclastic restricted lagoonal subfacies, channels are scarce (Fig. 8). The silica-bearing dolomitic oolitic grainstone high energy shoal facies associations at the 7th stage (Fig. 9) were filling the basin lagoonal zone southward and overlain the restricted lagoonal subfacies of the 6th stage. Moreover, the sever compartmentalization and the depositional facies limited lateral extent indicates that Depositional Mechanism of the Late Miocene carbonate sequence facies Wadi Yunis Member was autocyclic mechanism controlled by tectonics rather than being eustatic (Emery and Myers, 1998).

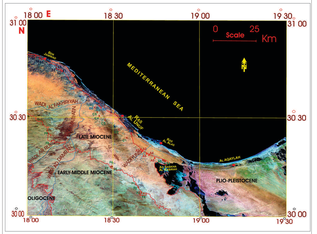

Figure 1 Land Sat Image of the study area in Sirt basin. The letters represent the field visited localities (Amrouni, 2006, Amrouni and El-Hawat, 2015).

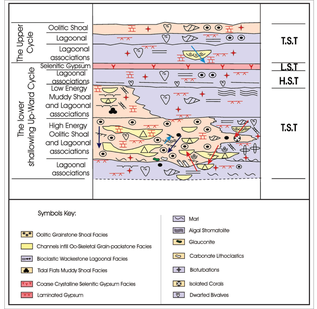

Figure 2 The Study area schematic stratigraphic cross section in the sequence stratigraphic context along 105 km, parallel to the strike section with the color coded symbols of the stratigraphic section (Amrouni, 2006, Amrouni and El-Hawat, 2015).

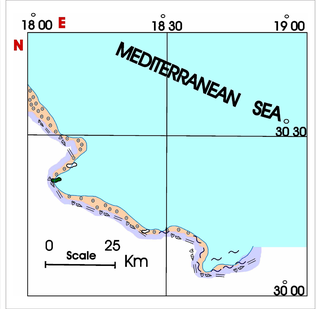

Figure 3 The first stage of the paleogeographic evolution of the transgressive systems tract of the lower shallowing upward sequence of the Late Miocene sequences Wadi Yunis Member (Amrouni, 2006).

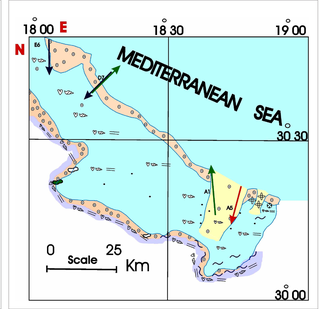

Figure 4 The second stage of the paleogeographic evolution of the transgressive systems tract of the lower shallowing upward sequence of the Late Miocene sequences Wadi Yunis Member (Amrouni, 2006).

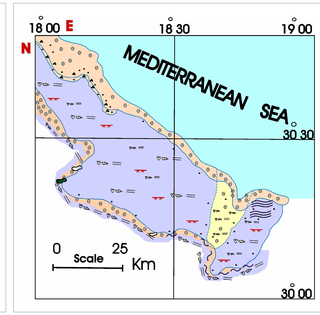

Figure 5 The third stage of the paleogeographic evolution of the transgressive systems tract of the lower shallowing upward sequence of the Late Miocene sequences Wadi Yunis Member (Amrouni, 2006).

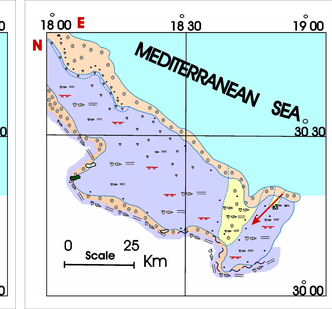

Figure 6 The fourth stage of the paleogeographic evolution of the highstand systems tract of the lower shallowing upward sequence of the Late Miocene sequences Wadi Yunis Member (Amrouni, 2006).

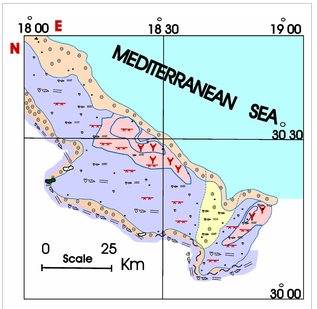

Figure 7 The fifth stage of the paleogeographic evolution of the lowstand systems tract of the lower shallowing upward sequence of the Late Miocene sequences Wadi Yunis Member (Amrouni, 2006).

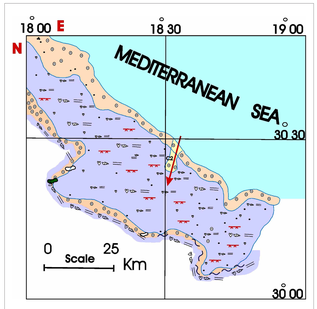

Figure 8 The sixth stage of the paleogeographic evolution of the transgressive systems tract of the upper shallowing upward sequence of the Late Miocene sequences Wadi Yunis Member (Amrouni, 2006).

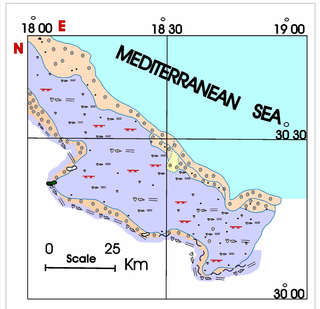

Figure 9 The seventh stage of the paleogeographic evolution of the highstand systems tract of the upper shallowing upward sequence of the Late Miocene sequences Wadi Yunis Member (Amrouni, 2006).

Facies associations	Facies energy level	Facies lithology and texture
Shoal depositional facies associations	High energy Shoal Facies	Oolitic grainstone facies
	Tidal channel Shoal Facies	Oo-skeletal grain-packstone facies
	Low energy Shoal Facies	Algal-pelle-skeletal grain-packstone facies
Lagoonal depositional facies associations	Semi-restricted lagoonal facies	Bioclastic wackestone facies includes three subfacies which are marly, bioturbated, and chalky
	Restricted lagoonal facies	Algal stromatolite facies that changes laterally into the algal-pelle-skeletal grain-packstone facies, tidal flats or low energy shoals
	Isolated lagoonal facies	Coarse crystalline gypsum facies (selenitic gypsum marker bed) associated and embedded within lagoonal chalky bioclastic wackestone subfacies

Table1 The Late Miocene sequence Wadi Yunis Member six siliciclastic influenced carbonate depositional facies.

Paleogeography Maps (stages)	Depositional Sequence	Depositional Sequence	Thickness Facies/Cycles	Depositional Facies	Depositional Environments	Later Facies Changes
7th stage	Upper Shallowing Upward Sequence	T.S.T	1.5-2 m / 1.5-2 m	silica-bearing dolomitic oolitic grainstone	High energy shoal facies associations	None
6th stage			2-2.5 m / 0.5-1.75 m	silica-bearing upper chalky bioclastic	restricted lagoonal subfacies	None
			6-12 m / 0.5-2 m	silica-bearing middle chalky bioclastic	restricted lagoonal subfacies	None
5th stage	Lower Shallowing Upward Sequence	L.S.T	0.5-1.5m/ 0.5-1.5m	Yellow chevron selenitic gypsum	Isolated lagoonal subfacies	None
4th stage		H.S.T	9-12 m/ 1-2 m	silica-bearing gypsified lower bioclastic wackestone	Semi-restricted lagoonal topsets subfacies	None
3rd stage		T.S.T	5-11 m / 0.5-3 m	Algal pelle-grapestone	Muddy tidal low energy shoal facies associations	Algal stromatolite, restricted lagoonal facies
2nd stage			2-30 m / 0.75-1.25 m	Oolitic grainstone	High energy shoal facies associations	bioturbated bioclastic wackestone, semi-restricted lagoonal subfacies
1st stage			6-12 m / 1-3 m	Marly bioclastic wackestone	Lagoonal subfacies	None

Table 2 The paleogeographic evolution stages and the depositional sequences in the Late Miocene Wadi Yunis Member

CONCLUSIONS
The late Miocene Wadi Yunis Member made up of two shallowing-up sequences that contain six carbonate depositional facies. The depositional facies arranged vertical as oolitic grainstone facies, oo-skeletal grainstone-packstone facies, algal pelle-skeletal facies, bioclastic wackestone facies, algal stromatolite facies, and coarsely crystalline selenite gypsum facies. These facies formed in a wave dominate carbonate ramp that includes restricted shelf lagoonal-tidal inlets complex and beach-bar shoals-subtidal channels complex environments The paleogeographic distribution of the Wadi Yunis Member depositional facies was reconstructed by mapping the two depositional sequences facies in time and space. The TST of the lower shallowing upward sequence was made of two parallel northern and southern oolitic grainstone belts and lagoonal facies filled up the space between them by depositing bioclastic wackestone facies. The southern oolitic grainstone facie belt was deposited above marly bioclastic wackestone facies. The ramp became partially restricted during the HST when the channels partial closed as indicated by the lagoonal bioclastic wackestone facies with dwarfed fossils, stromatolites, algal pelletal facie and some gypsum restricted lagoonal facies. The lagoonal restriction continued and complete isolation occurred during the LST as indicated by the of the selenitic gypsum facies. The older depositional sequence completed and the new sequence started. The new sequence was incomplete and only the TST was preserved. It was made of channelled lagoonal bioclastic wackestone facies followed by a new oolitic grainstone belt. The paleogeographic distribution of the depositional facies revealed that the Late Miocene carbonate sequences facies laterally limited. This indicates that the Wadi Yunis Member of Sirt Basin deposited in a structurally controlled compartmentalized ramp setting. The ramp is narrow in the dip direction and extends along the NW-SE strike for more than 150 km.
The low energy lagoonal facies are encompassed between two high energy oolitic grainstone belts.

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