



Sequence stratigraphic evolution of the syn-rift Early Cretaceous sediments, West Beni Suef Basin, the Western Desert of Egypt with remarks on its hydrocarbon accumulations

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Abstract

The Beni Suef Basin is a petroliferous rift basin straddling the River Nile containing a thick Mesozoic–Paleogene succession. The Kharita Formation is formed in the syn-rift phase of the basin formation and is subdivided into the Lower and Upper Kharita members. These two members are regarded as two third-order depositional sequences (DSQ-1 and DSQ-2). The lowstand systems tract (LST-1) of the DSQ-1 is represented by thick amalgamated sandstone bodies deposited by active braided channels. Mid-Albian tectonic subsidence led to a short-lived marine invasion which produced coastal marine and inner-shelf facies belts during an ensuing transgressive systems tract (TST-1). At the end of the mid-Albian, a phase of tectonic uplift gradually rose the continent creating a fall in relative sea level, resulting in deposition of shallow marine and estuarine facies belts during a highstand systems tract (HST-1). During the Late Albian, a new phase of land-rejuvenation commenced, with a prolonged phase of fluvial depositional. Fluvial deposits consisted of belts of amalgamated, vertically aggraded sandstones interpreted as braided and moderately sinuous channels, in the lower part of the Upper Kharita Member lowstand stage (LST-2). The continuous basin filling, coupled with significant lowering in the surrounding highlands changed the drainage regime into a wide belt of meandering river depositing the transgressive stage (TST-2). The history of the Kharita Formation finalized with a Cenomanian marine transgressive phase. Economically, the TST-1 and HST-1 play a significant role as source rocks for hydrocarbon accumulations, whereas LST-2 act as good reservoir rocks in the Early Cretaceous in the Basin.

Keywords Sequence stratigraphic evolution · Early Cretaceous syn-rift successions · Hydrocarbon accumulations · West Beni Suef Basin · Egypt

Introduction

The Beni Suef Basin is a rift basin having been explored and exploited for petroleum accumulations during the last 20 years.

It is one of the promising areas, newly considered in the future plan for hydrocarbon potentialities in the Egyptian territories. This basin is located in the vicinity of many well explored basins in the northern part of the Western Desert and the Nile Valley (viz., Gindi basin, Abu Gharadig basin, Asyut basin, etc., Fig. 1). Historically, the oil and gas explorations of the Beni Suef Basin date back to 1997. The Beni Suef Oil Field was discovered by Seagull Energy Corporation and was followed by the discovery of five additional oil fields—Azhar, Yusuf, Gharibon, Lahun, and Sobha by Qarun Petroleum Company.

The Beni Suef Basin lies in North Central Egypt ~ 150 km south of Cairo, extending between the latitudes 29° 25' 50" and, 28° 31' 33.797" N and the longitudes 31° 30' 51.372" and, 29° 50' 7.779" E (Fig. 2a). Topographically, the area is characterized by a plane surface, and the basin itself is bisected by the major course of the River Nile Valley into

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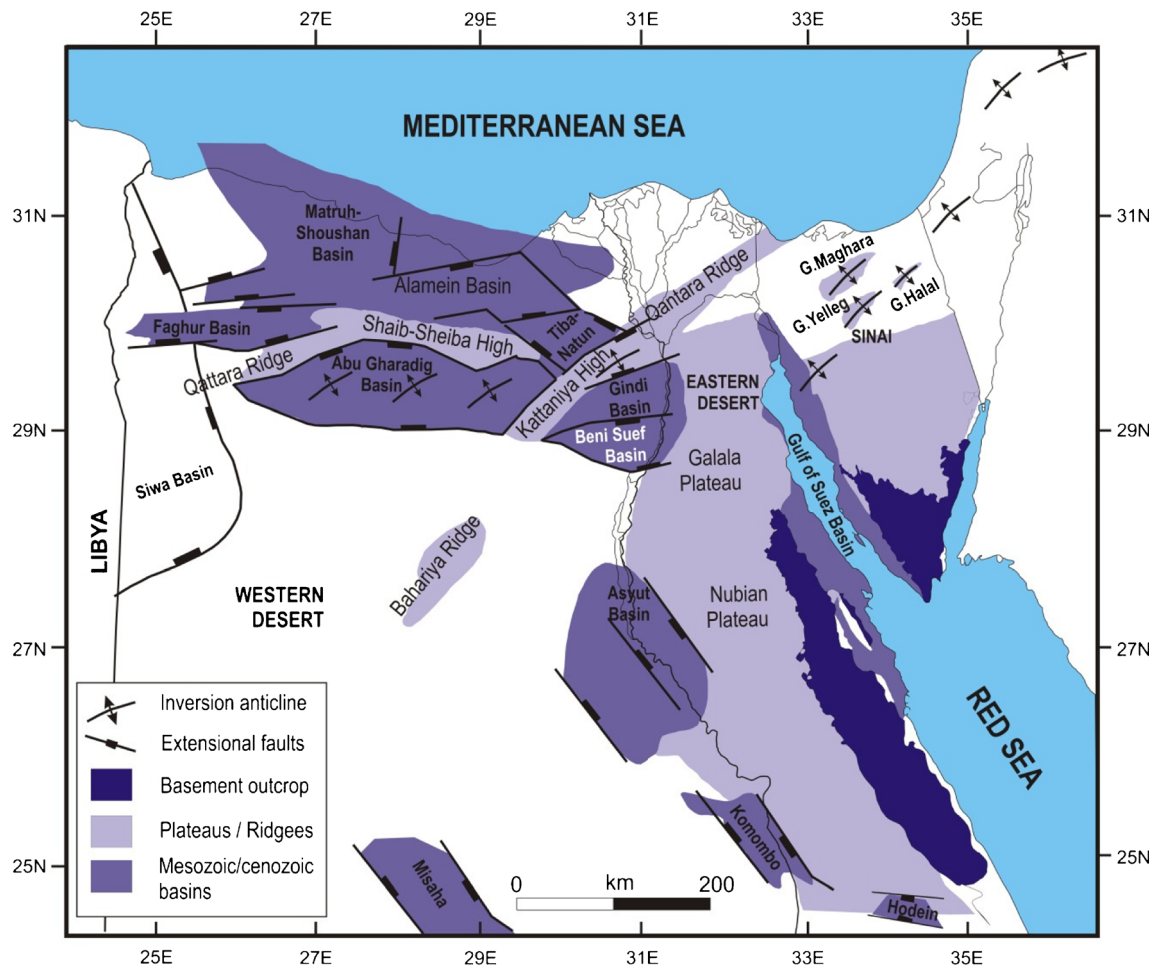


Fig. 1 Mesozoic and Cenozoic basins in Egypt (modified after Dolson et al. 2001; Moustafa 2008; Bevan and Moustafa 2012). Upper Egypt basins are added after Bosworth et al. 2008)

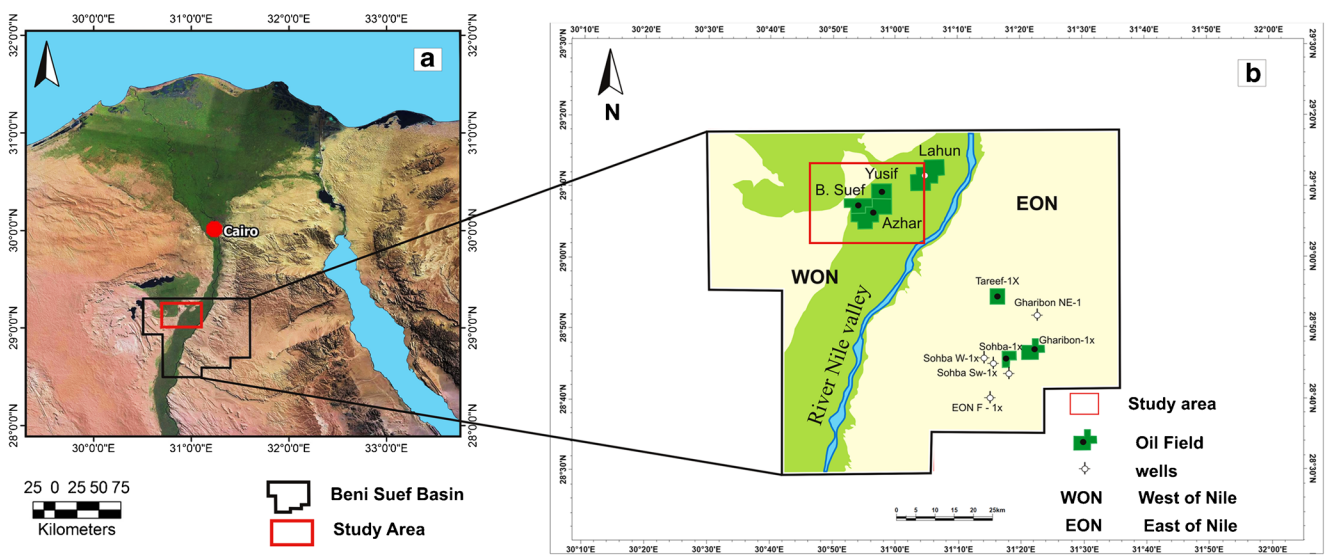


Fig. 2 Location map of the Beni Suef Basin. **a** Google earth image showing the location of the basin. **b** Location map of Beni Suef Concession with the study area

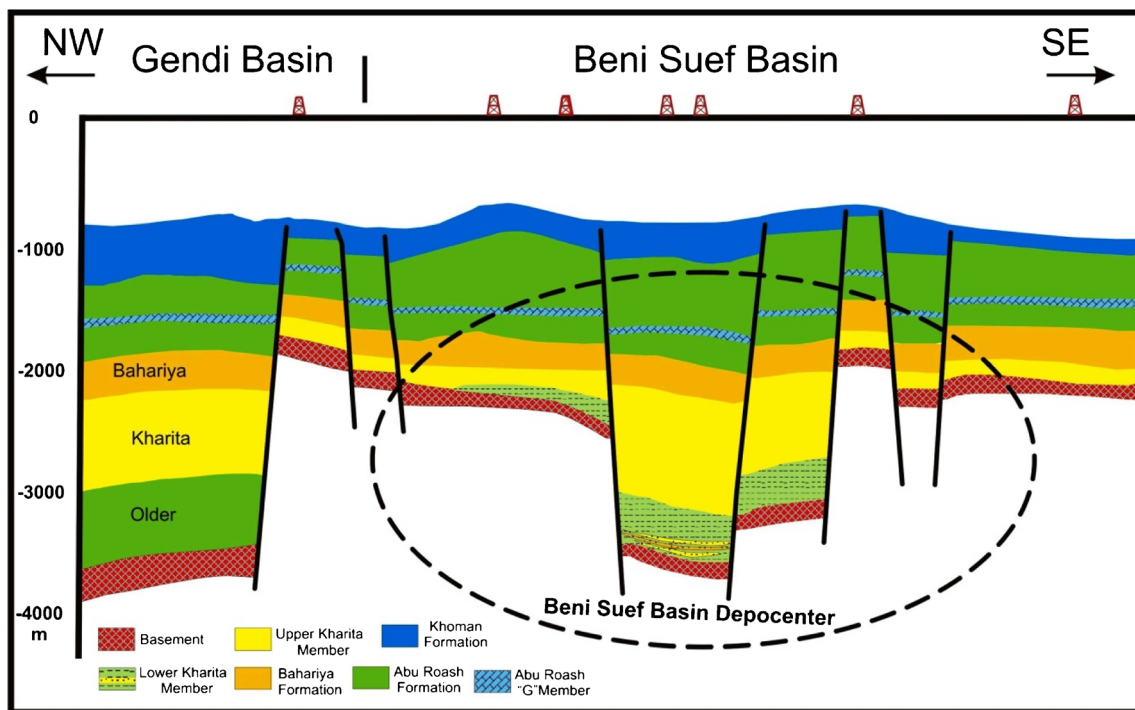


Fig. 3 Regional geological cross section trending NW-SE passing through Beni Suef Basin. (Modified after, El Batal et al. 2016)

two provinces: West of Nile Province (WON) and East of Nile Province (EON), (Fig. 2b). The depocenter of the Beni Suef Basin is located at the Azhar-A2 Well that has the maximum accumulated stratigraphic thickness up to ~4000 m, containing a complete stratigraphic succession of the Early Cretaceous (Albian) Kharita Formation (EGPC 1992) (Fig. 3).

Little has been published about depositional evolution and a sequence stratigraphic framework of the Beni Suef Basin. Thus, the data used in this study presents the first detailed information about the depositional evolution and the sequence stratigraphic framework of the Beni Suef Basin. This study intends to clarify the timing and depositional settings required for the development of source and reservoir rocks in the Early Cretaceous syn-rift Kharita Formation within a framework of sequence stratigraphy.

Datasets

This study is based on the fundamentals of the seismic sequence stratigraphic analysis of the basin fill successions. This analysis was carried herein using 30 seismic profiles that were extracted from (3D) survey in depth domain (Fig. 4). The frequency of the seismic data ranges up to 70 Hz and is in a good quality. These seismic profiles cover the study area (300 km²) of the western part of the Beni Suef Basin (WON). In addition, the geophysical log data of five deep wells (Fig. 4) dug in the studied basin will be examined and interpreted. These geophysical log data belong to the wells:

Azhar-A2, Azhar E-2X, Beni Suef West-1X, Yusif-4X and Fayoum-2X. The logs include mud logs, gamma ray, resistivity, photoelectric, porosity, sonic logs, and litho-composite logs. The seismic profiles and well-logs were kindly provided by the Qarun Petroleum Company with permission of The Egyptian General Petroleum Corporation (EGPC).

Throughout the present study, seismic profiles and well-log data were used to subdivide and differentiate the Early Cretaceous syn-rift sediments into their component third-order depositional sequences using the terminology of Embry and Myers (Emery and Myers 1996) and Catuneanu et al. (2011).

Geologic and tectonic settings

The Beni Suef Basin is situated a little northward of the Egyptian hinge-zone, just with the beginning of the southern fringes of the Egyptian unstable-shelf zone of Said (1962). The basin is considered as one of a series of intra-continental rift basins straddling the River Nile which include the Komombo and Asyut basins whose evolution was proposed to be linked with breakup of the Western Gondwana and the opening of the South and Equatorial Atlantic Ocean during the Early Cretaceous (Bosworth et al. 2008). This tectonic situation resulted in active rifting episodes over large domains as a response to clockwise rotation of north and central Africa (Guiraud and Maurin 1992; Guiraud et al. 2005). The Beni Suef Basin was interpreted as a rift basin in form of a half graben and likely developed in an extensional stress regime originated in the Central and North Africa with

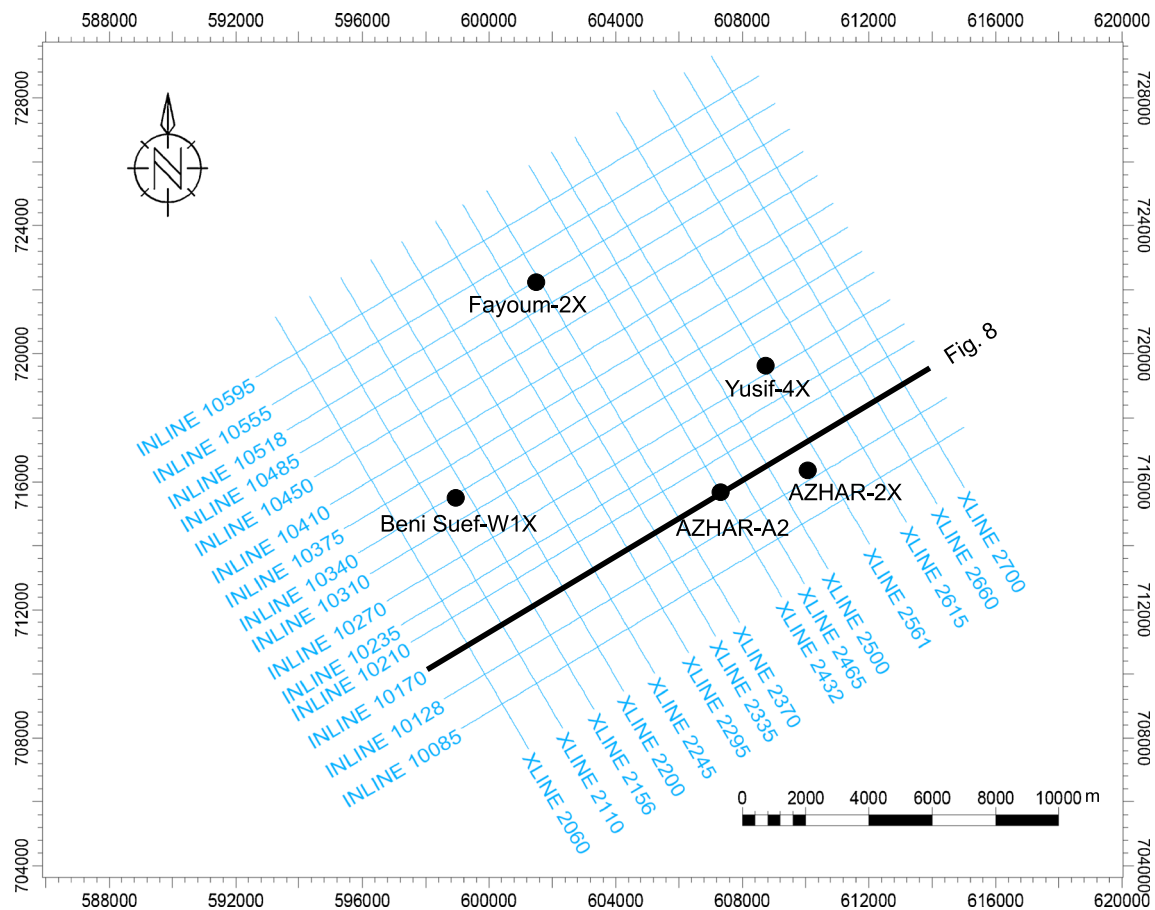


Fig. 4 Index map showing the studied seismic lines and wells. (Data provided by the Qarun Petroleum Company with permission of The Egyptian General Petroleum Corporation (EGPC))

the opening of South Atlantic during the Early Cretaceous (Bosworth et al. 2008) (Figs. 1 and 5). This extensional stress also caused reactivation of the east-west trending Jurassic basins, as in the Sarir Troughs of Libya and Faghur and Abu Gharadig basins of Egypt (Bosworth et al. 2008).

Moustafa (2008) stated that the Jurassic and Early Cretaceous sediments were deposited in North African rift basins, in the form of half-graben basins. The continental rifting was active during the Early Cretaceous in North Africa and Arabia. This event was responsible for the development of E–W oriented rift basins (Guiraud and Bosworth 1999).

Because rift basins are developed in a variety of tectonic settings (Leeder and Gawthorpe 1987; Lambiase and Bosworth 1995; Morley 1999; Withjack et al. 2002), their sedimentary fill shows a great variability (Leeder 1995), including non-marine facies (e.g., Crossley 1984; Frostick and Reid 1987; Leeder and Gawthorpe 1987; Morley 1989; Lambiase 1990) and marine facies (e.g., Surlyk 1978, 1989; Leeder and Gawthorpe 1987; Prosser 1993; Gawthorpe et al. 1994; Gawthorpe and Leeder 2000). The Mesozoic basins in Southern Egypt and Sudan are dominated by non-marine sediments (Nagati 1986; Schull 1988; Taha 1992). In regard to the Beni Suef Basin, it is filled with a Cretaceous mixed

marine and non-marine sedimentary succession attaining more than 4000 m thick in the deepest parts of the basin.

The detailed seismic interpretation of the key tectonic events indicates that there is a remarkable stratal-thickening in the down-thrown side of the Early Cretaceous faults including the strata of the Beni Suef Basin (Fig. 6). This supports the growth nature of the Early Cretaceous faults, which helped in the development of the basin sediments as syn-rift megasequence.

Stratigraphic framework

The Beni Suef Basin has a relatively thick subsurface Mesozoic–Paleogene sedimentary cover of ~4000 m thick, comprising six stratigraphic rock units. These units are named from the base to top: the Kharita Formation (Early Cretaceous, Albian), the Bahariya Formation (Early Cenomanian), the Abu Roash Formation (Late Cenomanian–Santonian), the Khoman Formation (Campanian–Maastrichtian), the Apollonia Formation (Early–Middle Eocene), and the Dabaa Formation (Late Eocene–Oligocene). These stratigraphic units are apart from the stratigraphic column of the North Western Desert (Zahran et al. 2011; EGPC 1992). This stratigraphic succession

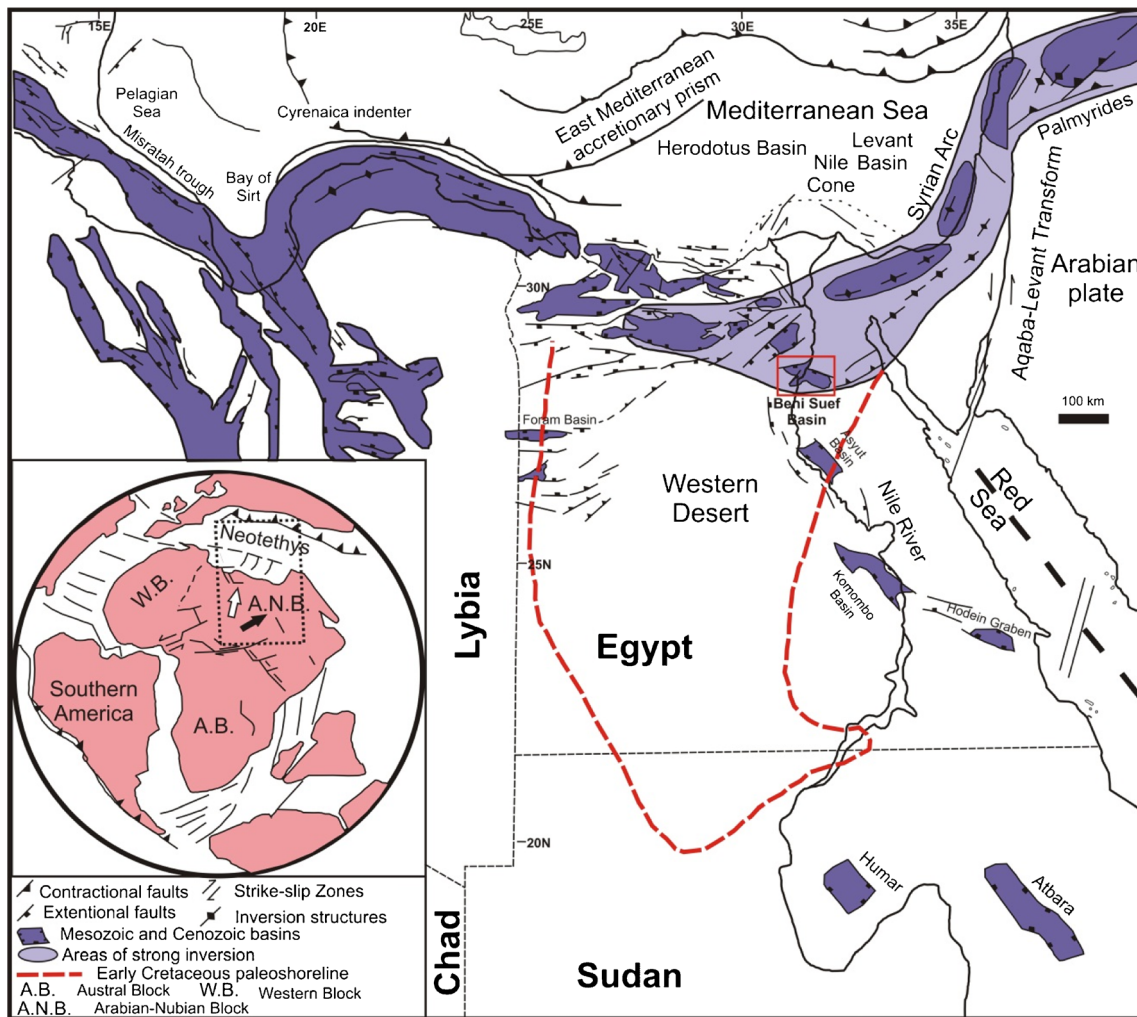


Fig. 5 Tectonic setting of northeast Africa and eastern Mediterranean compiled from Guiraud et al. (2005) and Bosworth et al. (2008). The paleo-shore line of Early Cretaceous is after Wycisk (1994). Inset map shows the reconstruction of West Gondwana breakup during the Early

Cretaceous after Guiraud and Bellion (1995). The white and black arrows in the inset map refer to the motion of the Arabo-Nubian block during Early Barremian and Late Aptian, respectively (Guiraud and Maurin 1992)

rests non-conformably over the crystalline basement rocks, whereas some parts of the Apollonia and Dabaa formations form the exposed rolling land-surface in the study area (Fig. 7). As this study is concerned with the Early Cretaceous time, the Kharita Formation is described in detail as the following:

Kharita Formation (Norton 1967; Ghorab et al. 1971)

In the study area, the Kharita Formation non-conformably overlies the basement rocks and is unconformably overlain by the Cenomanian Bahariya Formation. The basal contact is identified as the marked change between the crystalline basement rocks below and the Kharita Formation sedimentary succession. The upper contact, on the other hand, is detected by a remarkable facies change from gravelly sandstone lensoidal bodies of the fluvial Upper Sandstone Member of the Kharita Formation and to the overlying Bahariya Formation, which is represented by shallow marine and coastal deposits.

Lithology and age

In the study area, the thickness of the Kharita Formation shows significant regional variation ranging from 80 to 1350 m. In general, the Kharita Formation can be subdivided into two members: Lower Kharita Member and Upper Kharita Member (Fig. 7). Lithologically, the Lower Kharita Member is subdivided into two units: a lower sandstone-rich unit and an upper shale-rich unit. The lower sandstone-rich unit starts with a hardground and a ferri-crust horizon over the basement rocks, followed by sandstone with a few thin siltstone interbeds (El Batal et al. 2016). The upper shale-rich unit is composed of thick shale beds intercalated with thin limestone beds in the lower levels and with sandstones interbeds in the upper level. The thick shale beds contain glauconite grains, pyrite nodules, and crystals and are fossiliferous with some distinctive species

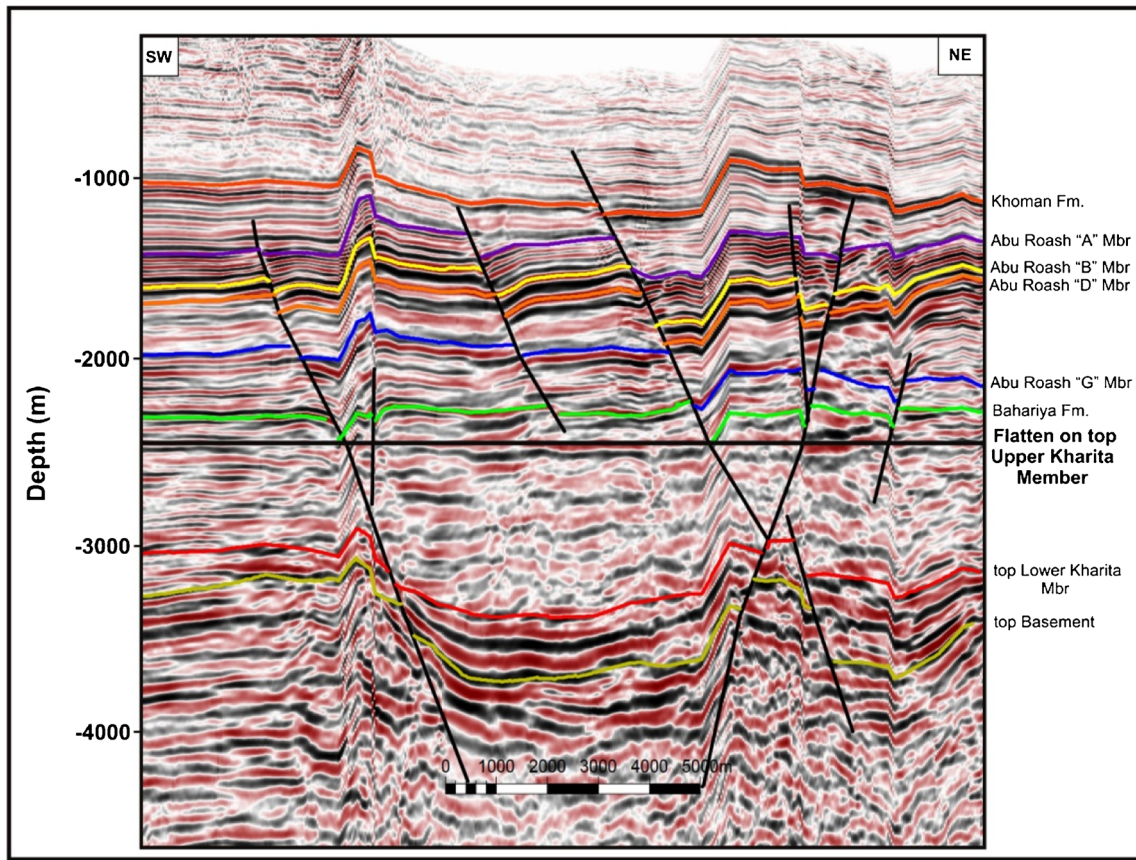


Fig. 6 Seismic flattening on the top of the Kharita Formation showing changes of the thicknesses and growth of strata along the Early Cretaceous faults

of pollen and spores (El Batal et al. 2016). In addition, the beds contain plenty of carbonaceous fragments, wood remains, fossil fragments, some chambers of arenaceous foraminifera, and miscellaneous microfossils (El Batal et al. 2016).

The Upper Kharita Member is composed of sandstones intercalated with a few siltstone and some shale beds that become thicker and more frequent in the upper level of the member. According to EGPC (1992), the age of the Kharita Formation is Albian.

Depth (m)	Age	Formation	Lithology	Description
500	Paleogene	Oligocene	Dabaa	Shale with minor carbonate interbeds
		Eocene	Apollonia	Siliceous limestone with chert nodules
1500	Late Cretaceous	Campanian - Maastrichtian	Khoman	Chalk and Chalky limestone
		Coniacian - Santonian	'A'	Intercalations of Sandstone, siltstone, shale and limestone;
				Started with siltstone and sandstone with carbonate interbeds at "G" Member and ended with limestone with minor sandstone and shale interbeds at "A" Member.
		Turonian	Abu Roash	
2500	Early Cretaceous	Cenomanian	Bahariya	Intercalations of Sandstone and siltstone with shale and minor limestone interbeds.
		Albian	Kharita	Sandstone, siltstone and shale; At lower parts composed mainly of siltstone and shale At upper parts composed of sandstone with siltstone and shale interbeds
Pre-Cambrian Crystalline Basement Rocks				

Depth (m)	Age	Formation & subdivisions	Lithology	Description	
250	Early Cretaceous	Albian	Kharita Formation	Upper sandstone Member	
500					Sand and sandstones intercalated with siltstones and some shale interbeds.
750					Sands are glassy, medium to coarse grained, subrounded to subangular and kaolinitic
1000				Sandstones are tannish off white, soft to moderately hard, fine to medium grained, poorly to moderately sorted and kaolinitic	
1250		Lower Mbr	Shale unit	Siltstones are blocky to sub-blocky, moderately firm and enriched with large quantities at the upper levels	
			Sandstone unit	Shale; varicolored, flicky, firm to moderately firm, highly carbonaceous, fossiliferous, slightly glauconitic, contains some pyrite nodules and crystals and intercalated with some limestones interbeds at lower levels and enriched with sandstones and siltstones at upper levels.	
Pre-Cambrian Crystalline Basement Rocks					

Fig. 7 Generalized lithostratigraphic units in the Beni Suef Basin (modified after Zahran et al. 2011) and major lithologies and lithostratigraphic units of the Kharita Formation in the Western Beni Suef Basin

Depositional environments

The Early Cretaceous Kharita Formation was deposited during a widespread continental fluvial sedimentation phase, which prevailed over the entire northern parts of the Western and Eastern Deserts as well as in Sinai (e.g., Al Ahwani 1982; Barakat et al. 1986; El-Fawal 1988; Taema 2008).

Based upon the available datasets (mud logs, well logs, and seismic sections), the depositional environments of the Kharita Formation can be summarized as follows:

Lower Kharita Member

Description

The Lower Kharita Member is subdivided into two units: a lower sandstone-rich unit and an upper shale-rich unit (see Section 0). Seismically, this member shows uniform parallel configuration with moderate to high continuity in association with relatively high amplitude reflectors and sheet-like to wedge shaped geometry in seismic sections (Fig. 8). This unit shows “blocky” or box-car pattern response of gamma ray (Fig. 8). The lower levels of the upper shale-rich unit shows an increase in the mud content that reflected on gamma ray giving high readings and reach over scale (Fig. 8). The upper levels of the upper shale-rich unit shows an increase in the sandstone content that reflected on gamma ray response showing coarsening-upward shaped (funnel shaped) (Fig. 8).

Interpretation

According to the interpretations of Sangree and Widmier (1979) and Badley (1985) for the seismic facies and their depositional environments, the lower Kharita Member is considered to have deposited in a shelfal environment.

The blocky pattern of gamma ray of the lower sandstone-rich unit can be produced by several different depositional systems such as: aeolian, braided channels, distributary channel-fill, submarine canyon, carbonate shelf margin, and evaporites according the interpretations of Rider (1990), Emery and Myers (1996), Krassay (1998), and Catuneanu (2006). The sedimentological characteristics, vertical stacking patterns of the lower sandstone-rich unit, and cleaning-upward gamma ray log patterns all support the interpretation that the (~ 150 m thick cycles) deposits formed a braided channel belt.

The increase in mud and carbonate contents beside the presence of some glauconites, pyrites, carbonaceous materials, and some distinctive species of pollen and spore in the lower levels of the upper shale-rich unit (El Batal et al. 2016) suggest that the depositional area may have been subjected to a subtle transgression of the Albian sea whose coastal zone started to submerge the northern terminations of the underlying fluvial sediments. These sediments were likely redistributed within the backshore ponds and swamps, foreshore realm, and even inner-shelf depositional environments.

The funnel-shaped gamma ray pattern, in the upper level of the upper shale-rich unit is interpreted to document progradation of coastal depositional systems, such as those

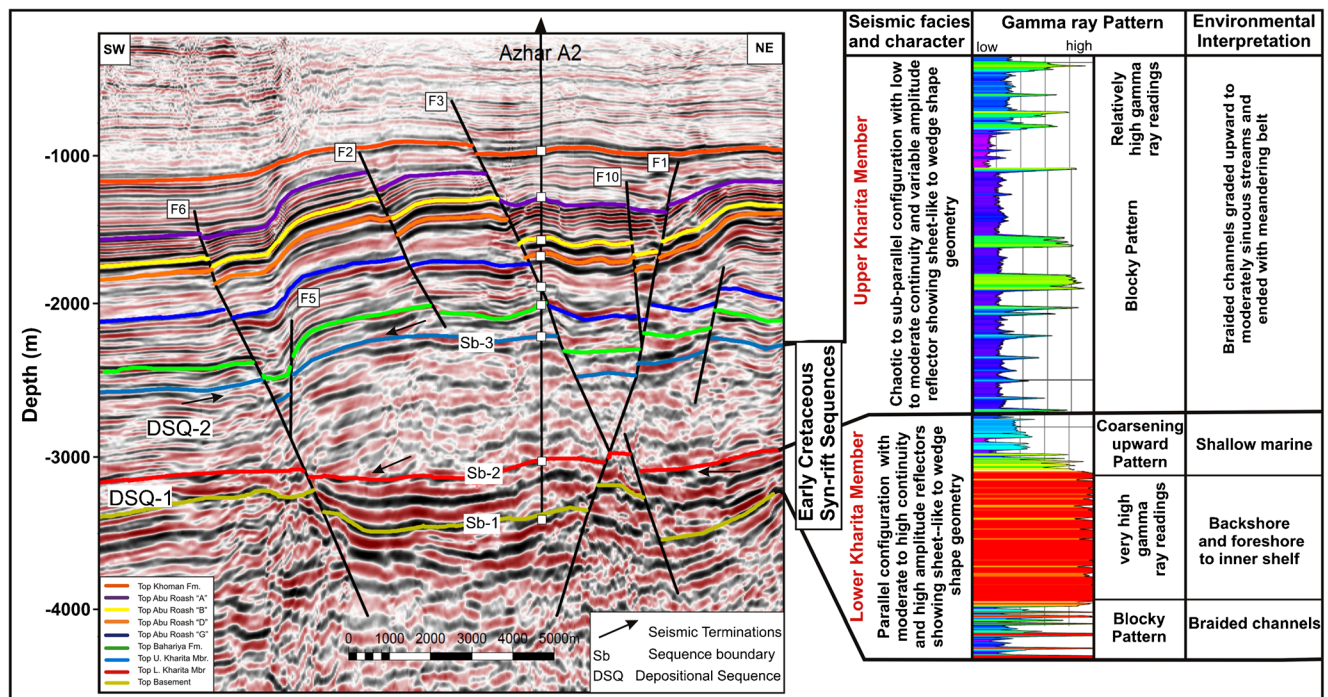


Fig. 8 NE-SW seismic inline 10170 passing through the southern part of the study area showing the seismic facies and gamma ray patterns of the two members of Kharita Formation including the depositional sequences (DSQ-1 and DSQ-2). See Figs. 9 and 11 for more patterns

including river mouth bar, delta front, shoreface, and/or shallow marine environments according to Rider (1990), Emery and Myers (1996), Krassay (1998) and Catuneanu (2006). The sedimentological characteristics, vertical sediment-stacking patterns, and available gamma ray well-log data support that the present coarsening-upward patterns formed as a response to progradation of coastal and shallow marine environments. These environments may have been also associated with mixed fluvial-lacustrine ponds as a response to the proximity to a fluvial system.

Upper Kharita Member

Description

The Upper Kharita Member shows chaotic to rarely sub-parallel configuration with low to moderate continuity, variable-amplitude facies reflectors, and sheet-like to wedge shaped geometry in seismic sections (Fig. 8). The Upper Kharita Member is generally siliciclastic unit, consisting of successive units displaying low gamma ray readings showing blocky, box-car patterns with low neutron porosity readings. On the other hand, the upper level of this member are represented by successions of fining-upward cycles, which are represented by a box-car gamma ray pattern (sandstones) in the lower part and a reverse box-car pattern (mudstone) in the upper part (Fig. 8). This member is ended by frequent fining-upward cycles (Fig. 8).

Interpretation

According to the interpretations of Sangree and Widmier (1979) and Badley (1985) for the seismic facies and their depositional environments, the Upper Kharita Member is interpreted to have deposited in a fluvial environment.

The sedimentological characteristics, vertical sediment-stacking patterns, and blocky and successive cleaning-upward gamma ray log patterns of the Upper Kharita Member support that the deposits are considered to have formed initially within a braided channel belt.

The continuous basin filling resulted in the change of the alluvial profile and came near to the fluvial equilibrium profile at the distal parts of the braided belt. Accordingly, the low accommodation space became rather wide, allowing the stream morphology to display a moderately-sinuuous pattern and build stable overbanks of rather frequent thick mud layers (Reineck and Singh 1973; Selley 1980; Reading 1996; Nichols 2009).

The wireline log patterns of the upper levels cycles of this member can be interpreted to have formed in response to aggradation of meandering fluvial systems, which are characterized by point bar and flood plain deposits (viz., Allen 1974; Reading 1996; Nichols 2009).

The fluvial system, which shows an overall finning upward, may have formed as a response to an overall rise in a water table as a result of transgression in a coastal area. This coastal area may have been a part of the Early Cenomanian Sea (Said 1990).

Sequence stratigraphy

In the study area, the Early Cretaceous succession can be subdivided into two depositional sequences (Figs. 9 and 11). The detailed investigations of available seismic lines and different well-logs help in identifying the stacking patterns of the depositional sequences and depositional surfaces characterizing the examined Early Cretaceous Kharita Formation subsurface sequence. On the basis of the age framework of the formation (EGPC 1992), the two depositional sequences can be defined as third-order cycles. The depositional sequences defined in the present study follow the basic definitions and concepts given by Vail et al. (1977, 1991), Posamentier and Vail (1988), Posamentier et al. (1992a, 1992b), Mitchum et al. (Mitchum et al. 1994), Posamentier and Allen (1999), and Catuneanu et al. (2009). The encountered depositional sequences herein are informally named as DSQ-1 and DSQ-2.

The depositional sequence (DSQ-1)

DSQ-1 is the lowermost depositional sequence in the Early Cretaceous succession in the study area. It is not recorded in all locations, specifically it is not present in the middle parts of the study area (sites of the wells: Beni Suef-W1X and Yusuf-4X, Fig. 10). This discontinuity is considered to be related to both of the non-drilling process in the WON part and to non-deposition of the sequence due to remarkable variations in the basement relief below in the EON part of the Beni Suef Basin. It encompasses the entire sediments of the Lower Member of the Kharita Formation (Fig. 9). The collected cuttings and the well-log data of this sequence indicate that DSQ-1 is a generally siliciclastic unit with a 183–390 m thick. The age of this sequence is generally Albian (EGPC 1992 and El Batal et al. 2016).

The sequence boundaries

According to the concepts of Vail et al. (1977), Vail et al. (1984), Posamentier and Vail (1988), and Van Wagoner et al. (1988), the sequence boundaries are generally unconformable surfaces or correlative conformable surfaces, which are differentiated into type-1 and type-2. Regarding DSQ-1, the seismic profiles prove that the lower sequence boundary (Sb-1) is a non-conformity surface (type-1) with the basement rocks below. This surface is considered to have formed in response to incision of fluvial channels and corresponds to the type-1 sequence boundary.

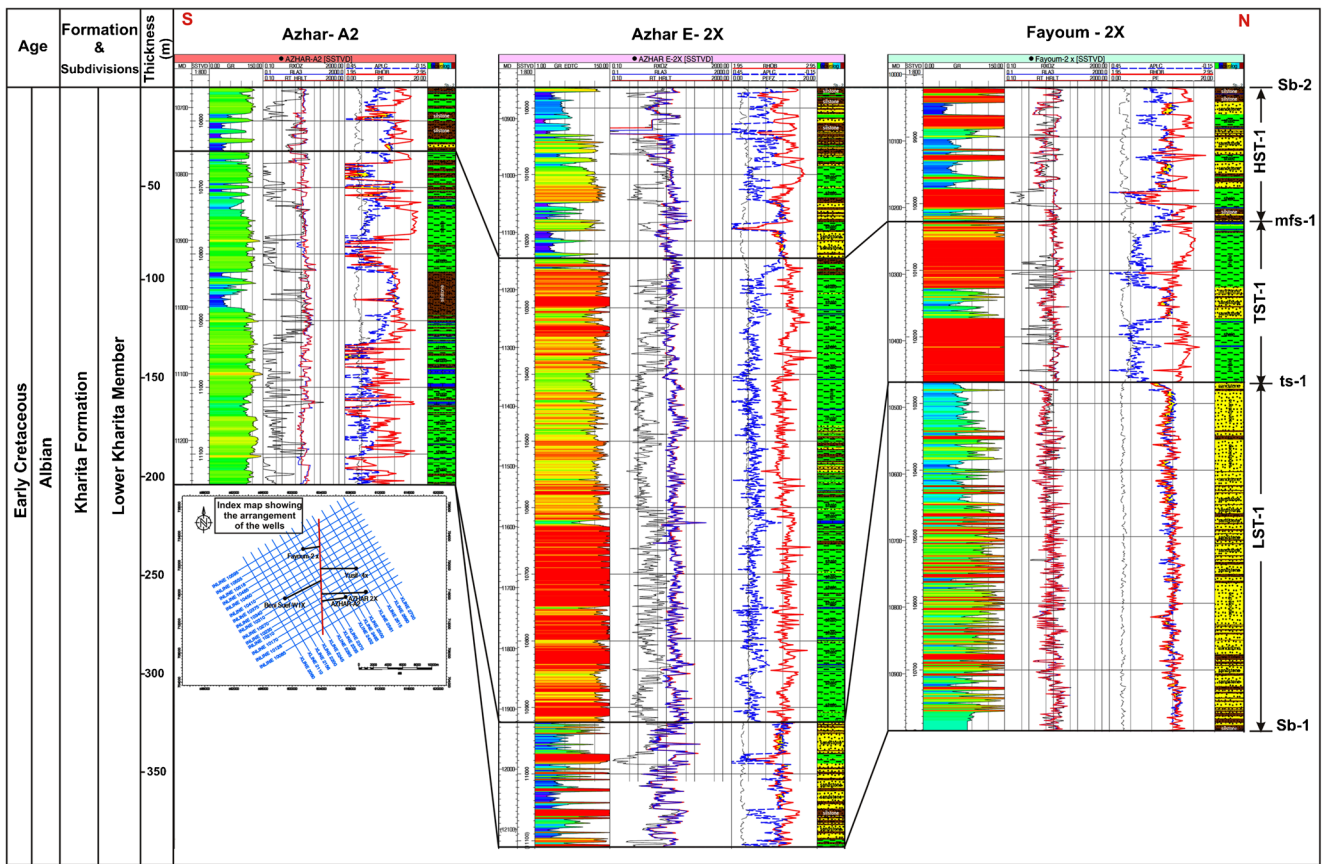


Fig. 9 Depositional sequence (DSQ-1) and its component systems tracts of the Lower Kharita Member. See Fig. 10 for the other explanations

As for the upper sequence boundary (Sb-2), this boundary is seismically defined by onlapping and toplapping termination patterns (Fig. 8) and by the distinctive gamma ray readings and lithological contrast across the boundary (Fig. 9). These criteria prove that surface is an unconformity surface (type-1) formed during a phase of subaerial activity of running-water following a phase of almost mid-Albian tectonic uplift (Moustafa 2008). The boundary marks the passage from shallow to coastal marine shale and siltstone at the end of DSQ-1 to continental gravely sandstone of fluvial braided channels of the basal part of DSQ-2 above.

The transgressive surface

The transgressive surfaces are generally confirming the first actual major marine invasion over the depositional area (Van Wagoner et al. 1988). In the study area, the transgressive surface (ts-1) of DSQ-1 is recorded where the Lower Member of the Kharita Formation is encountered in the study area (Fig. 9). On the wireline logs, the ts-1 is delineated on the basis of the marked log-facies changes from the low gamma ray and neutron porosity (continental sandstones with few siltstone layers) to the high gamma ray and neutron porosity (relatively marine shale, siltstone, and limestone) (Fig. 9). This reflects an incipient rise in relative sea level accompanied by a general

increase in the volume of the accommodation space resulted in much increase in mud contents in the succession.

The maximum flooding surface

The maximum flooding surfaces mark the ultimate marine invasion over the land, after which a coastal regression commences and the highstand systems tracts begin to develop (Van Wagoner et al. 1988). Emery and Myers (1996) documented that at the point of maximum flooding the volume of the accommodation space starts to be reduced so that it only matches with the incising progradation in association with active sediment supply. In the study area, the maximum flooding surface (mfs-1) of DSQ-1 is recorded where the Lower Kharita Member is encountered in the study area (Fig. 9). On the wireline logs, the mfs-1 is delineated by the passage from the high gamma ray reading log-facies (relatively deep marine shale, siltstone, and limestone) to the low gamma ray reading log-facies (sandstones and siltstones having coastal shoreline affinity) (Fig. 9).

Systems tracts

Brown and Fischer (Brown and Fisher 1977) defined the sedimentary systems tract as a linkage of contemporaneous

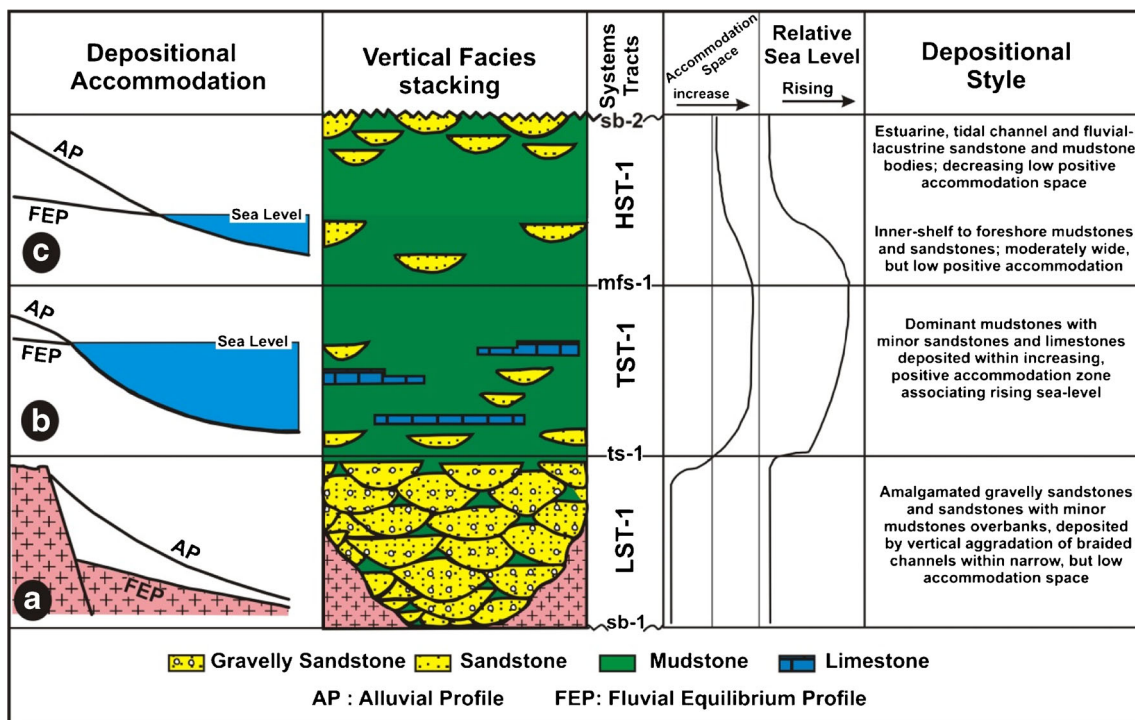


Fig. 10 Schematic illustration of the vertical stacking, depositional environments and accommodation architecture prevailed during the deposition of DSQ-1

depositional systems. Normally, a third-order depositional sequence is differentiated into three systems tracts: lowstand, transgressive, and highstand systems tracts (Van Wagoner et al. 1988; Mitchum and Van Wagoner 1991). In the study area, DSQ-1s evolved through the progressive evolution of the abovementioned system tracts.

The lowstand systems tract (LST-1) This tract is preserved where the Lower Kharita Member is recorded in the study area, with varying thickness between 65 and 162 m and consists mainly of braided fluvial deposits as described above. It is composed of kaolinitic sandstone with a few thin fissile to sub-blocky siltstone interbeds that overlies a hardground and ferri-crust horizons over the basement rocks. Within the lowstand systems tract, multiple stacking of ~20 m thick fining-upward units are recognized from the gamma ray logs (Fig. 9).

As the LST-1 was entirely deposited within a fluvial belt by different riverine processes as described above, the tract evolution does not match with the approaches of shelfal submarine fans and lowstand wedges of Posamentier et al. (1988). In contrary, the LST-1 was developed due to the role of the equilibrium regime within the fluvial drainage net that controls the erosion-deposition rate and style within the fluvial cycle (Posamentier and Allen 1999). The noticeably rugged relief of the unconformity (Sb-1) created a remarkable regional difference between the dominated alluvial profile (AP) and the fluvial equilibrium profile (FEP) of the drainage fluvial net, prevailing at the times of LST-1. Thus, a significantly narrow

area with only low accommodation is considered to have been created. This topographic situation occurred simultaneously with the prevalence of tropical rainy climatic conditions, which dominated northern Egypt during the Early Cretaceous (El-Shazly and Krs 1973). Therefore, an active net of fluvial channels initially started to incise within the rugged slopes to reform the drainage network. Consequently, substantial volumes of the alluvial profile were eroded to neutralize the fluvial equilibrium profile below (Fig. 10a). These fluvial detrital materials were laid down by active braided channels along the high-gradient slopes, filling the entire area of the low accommodation. As a result, the relatively thick sedimentary cover of the LST-1 was developed in a form of amalgamated vertically aggrading successive fining-upward sandstone bodies with minor thin siltstone overbanks.

The transgressive systems tract The transgressive systems tract (TST-1) is relatively thick unit which ranges from 61 to 217 m. It is composed of thick shale beds intercalated with thin limestone beds in the lower levels, with sandstone at upper levels. The shales are silty, brownish gray to reddish brown, fossiliferous, slightly calcareous, and rich in wood remains and carbonaceous materials. Glauconite grains and pyrite nodules are common. The limestones are off-white, argillaceous, and soft to medium hardness. The overall tract is composed of relatively thick (~100 m) cycles, noticeably rich in shale and siltstone with limestone interbeds, and thin sandstone intercalations. This remarkable increase in mud

content is evidenced by the sudden increase in gamma ray values (over scale) coupled with the increase in neutron porosity readings, just above ts-1 (Fig. 9). This increase in mud and carbonate contents assumes that during the TST-1, the area was subjected into an Albian sea transgression (Fig. 10b), whose shore line strikes in an almost E–W trend (Guiraud 2001; Guiraud et al. 2005). The coastal zone of such sea started to submerge the northern terminations of the underlying prograding braided channel belt of LST-1. Accordingly, the received distal fluvial loads (silt and clay with terrestrial carbonaceous fragments) were successively redistributed and reorganized within supratidal ponds and swamps, intertidal realm, and even inner-shelf to build the TST-1. The locally reducing closed marine areas produced the documented pyrite. Due to the continuous sea level rise coupled with simultaneous basin subsidence, the volume of the accommodation zone was gradually increased as indicated by an upward increase in gamma ray response (high mud contents), proving the development of deepening-upward facies toward the mfs-1, just below the HST-1.

The highstand systems tract (HST-1) This is the topmost tract in DSQ-1. It is recorded for the Lower Kharita Member over the study area. It ranges in thickness from 31 to 110 m. Lithologically, the tract consists of well-stacked succession of almost equal proportions of sandstone, siltstone, and shale interbeds, rich in wood remains and carbonaceous materials. The seismic profiles and the wireline logs indicate that HST-1 is generally composed of ~50 m thick coarsening-upward cycles that are represented by cleaning-upward gamma ray responses (increasing sands) (Fig. 9). The number of these cycles increases up section in association with the decrease in thickness. This may document reduction of the accommodation toward the overlying sequence boundary (Sb-2).

With the deposition of HST-1, a marked shallowing phase started, increasing the rate of deposition (S) to more than that of the accommodation (A) volume (i.e., $S > A$). Thus, the high gamma and neutron porosity readings related to the mud and carbonate facies of the underlying TST-1 change upwards to relatively lower gamma ray and neutron porosity readings related to mixed sandstones/siltstones of the HST-1 (Fig. 10c). These shallower prograding facies were deposited within mixed intertidal flats, and possible estuarine and/or mixed fluvial-lacustrine bonds due to the nearness of the fluvial net behind, forming the topmost deposits of the HST-1, and mark the maximum sea level drop during DSQ-1, just prior to (Sb-2).

The depositional sequence (DSQ-2)

The DSQ-2 is recorded all over the study area, overlying DSQ-1. It encompasses the sedimentary succession of the Upper Member of the Kharita Formation (Fig. 11), ranging

in thickness from 90 to 790 m, and it is of Upper Albian age. DSQ-2 entirely consists of thick siliciclastic successions that were deposited within a long-lasting wide fluvial net, grown through various riverine geomorphologic patterns. The uppermost levels of DSQ-2 were strongly influenced by an Early Cenomanian marine invasion, submerging the far-most territories of the sequence.

The sequence boundaries

DSQ-2 rests unconformably over the sequence boundary (Sb-2) mentioned before, associating with the mid-Albian uplift, displaying characters of a type-1 boundary of Van Wagoner et al. (1988). The upper sequence boundary (Sb-3) was developed during Late Albian–Early Cenomanian regional tectonic subsidence, accompanied by widespread Early Cenomanian marine transgression covering vast areas of Egypt, including the study area (Al Ahwani 1982; Barakat et al. 1986; El-Fawal 1988; Taema 2008). Sb-3 is seismically defined by onlapping and toplapping termination patterns (Fig. 8) and by the distinctive gamma ray readings and lithological contrast across the boundary (Fig. 11). Sb-3 is therefore also unconformity surface and has the characters of a type-1 boundary.

The maximum regressive surface (MRS-2)

Catuneanu et al. (2011) stated that “the maximum regressive surface is typically placed at the contact between the amalgamated channel-fills of lowstand top sets (low accommodation conditions) and the overlying flood plain-dominated transgressive fluvial deposits (high accommodation conditions; Kerr et al. 1999)”. As regards to DSQ-2, it is a non-marine fluvial sequence developed through cumulative progradation of a widespread sand-rich, vertically aggrading braided fluvial network (narrow, but low accommodation) that transitions distally into laterally accreting, flood plain-rich high-sinuuous and meandering rivers (low, but wide low accommodation). The time of that geomorphologic change between the mentioned fluvial regimes is thus considered the MRS-2.

Systems tracts

In the Beni Suef Basin, the DSQ-2 was developed within a depositional area surrounded by southern uplifted highs, whereas its remote distal parts are occupied by a coastal area of north-situated sea. This sea, although it is outside of the study area and transgressed over by the Early Cenomanian, however, the role of its ultimate base level of erosion in the study area behind cannot be denied. The sea level controlled the fluvial equilibrium profile (FEP) during the deposition of DSQ-2 throughout the study area and consequently governed the nature and size of the accommodation along the fluvial-dominated depositional environments of DSQ-2.

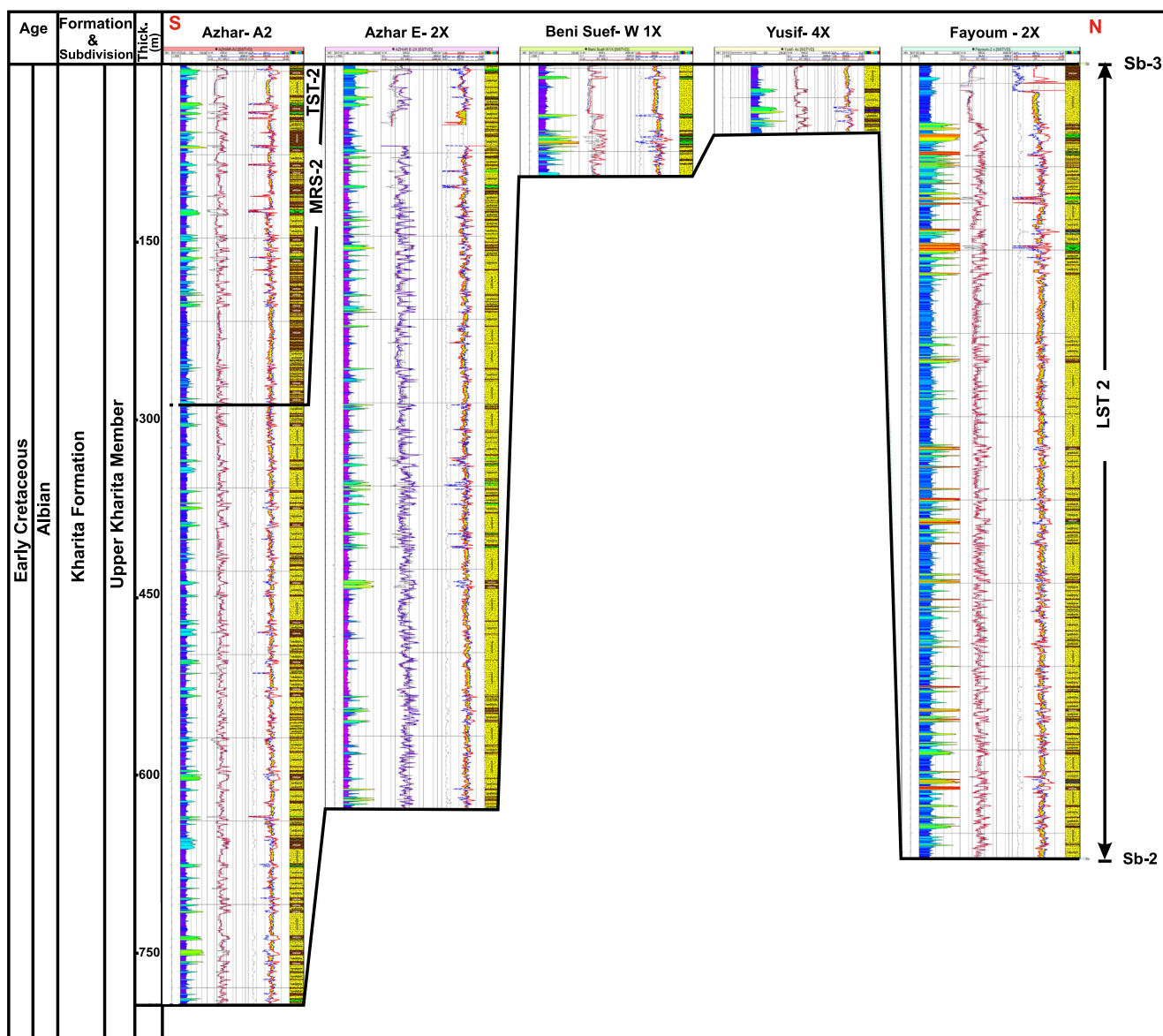
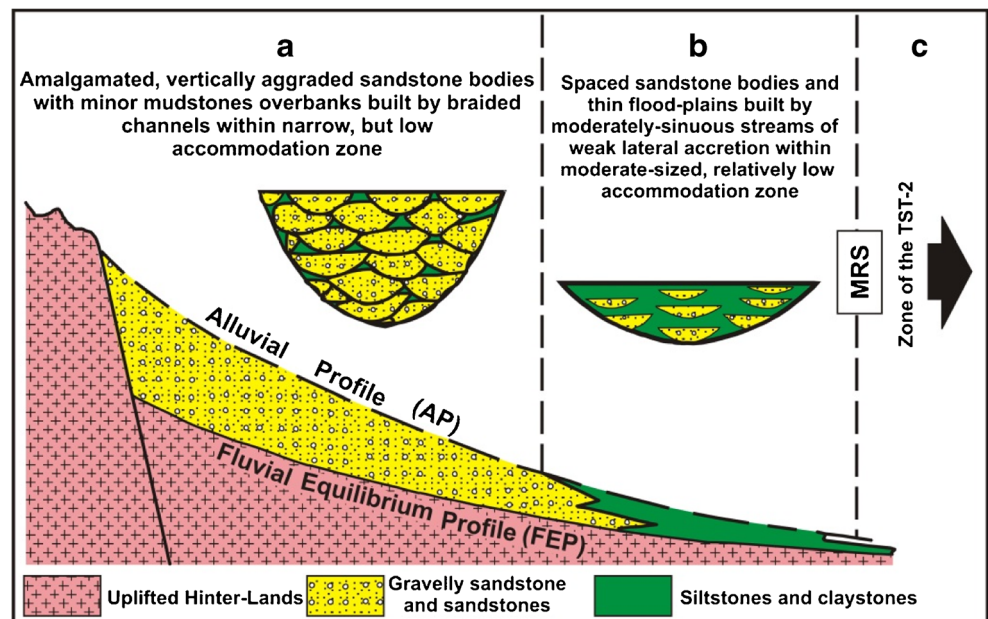


Fig. 11 Depositional sequence (DSQ-2) and its component systems tracts of the Upper Kharita Member. See Figs. 12 and 13 for the other explanations

Accordingly, the fluvial sequence of DSQ-2 is considered as a fluvial sequence controlled by base level changes in the concept of Wright and Marriott (1993), Catuneanu (2006), and Miall (2014). In such a setting, fluvial deposits may have been integrated within the standard lowstand, transgressive, and highstand systems tracts (Posamentier and Vail 1988; Posamentier et al. 1988; Wright and Marriott 1993; Catuneanu 2006). Generally, within these basins, the increase in the accommodation space results in the change of the fluvial style from amalgamated, aggrading braided stream systems in the lowstand systems tract to isolated, laterally accreted meandering streams in the transgressive and highstand systems tract (Shanley et al. 1992; Shanley and McCabe 1994; Van Wagoner 1995). In the study area, DSQ-2 is regarded to have developed through the progressive evolution of the aforementioned systems tracts as follows:

The lowstand systems tract (LST-2) In the study area, this tract is recorded in all examined successions, having a thickness ranging from 90 and 790 m. The seismic profiles and the log profiles of DSQ-2 are interpreted to represent thick sandstones bodies succeeded by thin mudstone layers organized in well-stacked fining-upward fluvial cycles (in the sense of Cant and Walker 1978; Van Wagoner et al. 1988, 1990; Reading 1996). However, the upper levels show enrichment in the mud intervals, both in the thickness and number. The gamma ray characteristics of these cycles indicate a high sand/mud ratio (Fig. 11). This assumes that they were developed as amalgamated sand bodies by vertical aggradation within relatively high, but low accommodation space, occurring when the fluvial equilibrium profile (FEP) was markedly below the alluvial profile (AP), especially close to the foreland-slopes of the tectonically uplifted areas (Fig. 12a). The continuous basin

Fig. 12 Schematic illustration of the accommodation spaces and the vertical stacking of the different fluvial depositional environments prevailed during LST-2 (*a* Braided belt phase and *b* moderately-sinuuous streams belt phase)



filling brought the alluvial profile (AP) close to the fluvial equilibrium profile (FEP), especially at the distal parts of the braided belt. Accordingly, the low accommodation space became relatively low but wide, allowing the stream morphology to display moderately-sinuuous pattern and build stable overbanks of thick mud layers toward the end of LST-2, just below the MRS-2, (Fig. 12b).

The transgressive systems tract (TST-2) The TST-2 is recorded in some parts of the study area, overlying the MRS-2. It encompasses the sedimentary succession of the upper levels of the Upper Member of the Kharita Formation. The age of this tract is Upper Albian. The recorded thickness of this tract is 300 m at Azhar-A2 Well. It is composed of sandstones, siltstone, and shale intercalations, stacked in gamma ray log units displaying successive fining-upward packages (Fig. 11) similar to those of the underlying units of LST-2. However, here, the units having box-car low gamma ray readings (sandstones) are usually succeeded by similar thick/or thicker units of high gamma ray readings in opposite box-car trend (mud-facies). Accordingly, it is assumed that TST-2 was deposited under the similar fluvial system that deposited LST-2, when that system became able to build wide stable flood plains of silts and clays.

Toward the distal reaches of the accommodation area of LST-2, very far from the uplifted scarps, the thick basin fill brought the fluvial equilibrium profile (FEP) very close to the drainage alluvial profile (AP), with simultaneous increase in the accommodation area (Fig. 12). This situation allowed the running streams to unify in a large meandering river system that built wide laterally accreted point bar sand bodies and flood plains (Fig. 13c), usually documented in meandering rivers (viz., Allen 1974; Reading 1996) forming TST-2.

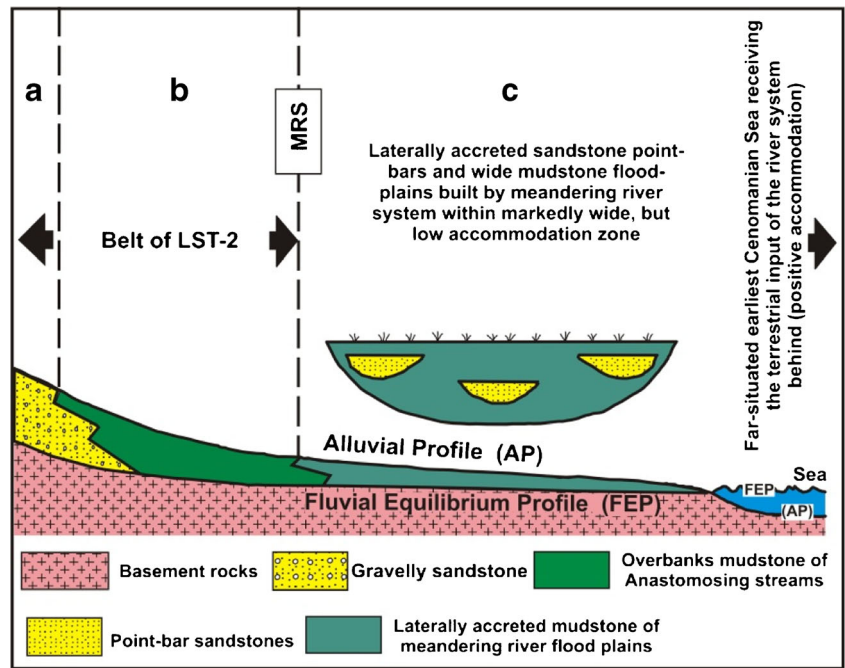
The development of the upper most parts of TST-2 (i.e., the meandering river depositional environment) is considered to have been affected by transgression and regression of a coastal environment that occurred along the margin of the Cenomanian Sea far from the study area (Figs. 13 and 14).

Depositional evolution of the study area

The Early Cretaceous syn-rift Kharita Formation was deposited during a widespread continental fluvial sedimentation phase that prevailed throughout the study area. The depositional style and evolutionary phases of the Early Cretaceous syn-rift sediments in the Beni Suef basin were strongly influenced by temporal variation in tectonic regimes as follows:

- A) During the Early Cretaceous (Albian), the deposition commenced within the Beni Suef Basin. This earliest tectonic phase may have been associated with active faulting, which resulted in significant local deepening in the basin and relative uplifting of the basin margin hinterlands that surrounded the depositional area with significant highs of older rocks. Such topographic situation, coupled with the dominance of rainy tropical climate over the northern Egypt at those times, created a depositional phase commencing with active braided channels depositing relatively thick amalgamated sandstone and gravelly sandstone, resulting in vertical aggradation within significantly narrow, but low accommodation space (Fig. 10a). The continuous progradation of such a fluvial drainage network ceased due to submergence below a marine invasion of mid-Albian marine sea, whose shore line trending in almost E–W (Guiraud 2001; Guiraud et al. 2005). This

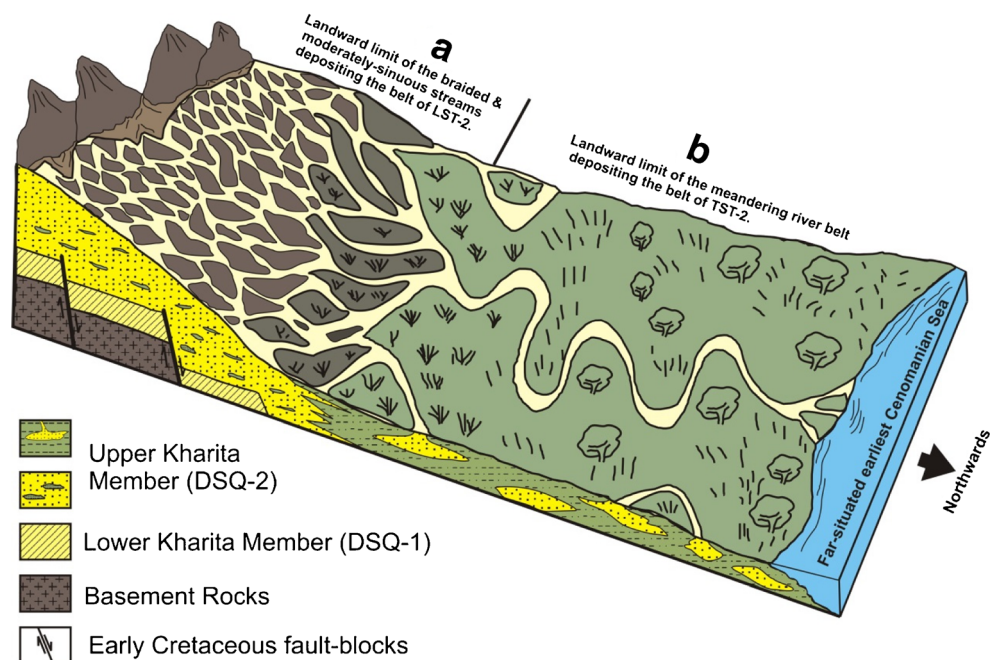
Fig. 13 Schematic illustration of the accommodation spaces and the vertical stacking of the fluvial depositional environments prevailed during TST-2 (*a*, *b* Facies belt of LST-2 and *c* meandering river belt phase of TST-2)



marine invasion initiated as a result of a short-lived tectonic subsidence, producing the coastal marine and inner marine shelf facies of TST-1 (Fig. 10b). Possibly as a result of a mid-Albian tectonic uplift, a marine regressive phase initiated accompanied with gradual sea level drop and shallowing marine conditions where the HST-1 was developed (Fig. 10c). Finally, at maximum sea level fall, where the depositional area became an emerged land, the depositional phase of the Lower Kharita Member ceased with Sb-2.

B) During the Late Albian, a new phase of hinterland rejuvenation (uplifting) commenced, which may have been accompanied by a tectonic uplift of the basin margin. As a result, a long-lasting period of fluvial deposition dominated the area within variable accommodation infilled with different fluvial systems from active braided channels, followed by moderately-sinuuous streams during the deposition of LST-2 (Fig. 12) producing thick succession of amalgamated, vertically aggrading sandstones within mud layers at the lower levels of the Upper Kharita Member.

Fig. 14 Hypothetical model showing the evolution of DSQ-1 and DSQ-2 (LST-2 and TST-2) of the Kharita Formation in the western of the Beni Suef Basin



- C) The continuous basin filling coupled with significant lowering in the surrounding highs resulted in a marked reduction for the topographic gradient of the depositional area; with simultaneous widening of the fluvial accommodation area. Therefore, the preceding vertically aggrading fluvial patterns gave way to more constructive high-sinuuous, meandering rivers with stable prolific flood plains of TST-2 (Fig. 13c). The far distal branches of such a fluvial network were deposited their fine loads into a possible Early Cenomanian sea forming a wide tidally influenced fluvial environment belt, recorded at the upper levels of the Upper Kharita Member (Fig. 13).
- D) The depositional history of the Kharita Formation represents long-lived continental sedimentation from different fluvial depositional systems (Fig. 14) that played the active and prominent role in the evolution of the prolific rock unit. This multistory continental depositional history was succeeded by a major Cenomanian marine transgression, covering vast areas of the Egypt (Fig. 14).

Remarks on the hydrocarbon accumulations

The findings of the foregoing sequence stratigraphic analysis of the Early Cretaceous Kharita Formation in the Beni Suef Basin indicate the following:

- A) The transgressive systems tract (TST-1) and the highstand systems tract (HST-1) are rich in the wood remains, carbonaceous materials, spore, and pollen acquired from the underlying fluvial network. These tracts can act as source of natural gases. Exploration should be directed for further regional search for such tracts, especially the TST-1. The geochemical analyses of the total organic content (TOC) and the Kerogen-type, made for the TST-1 and the lower levels of the HST-1, suggest this as a source rock in the Beni Suef Basin, having high (TOC) and type-III Kerogen (Zahran et al. 2011; Makky et al. 2014; El Batal et al. 2016). Thus, TST-1 and the lower levels of HST-1 are herein considered as gas-prone and therefore should be a focus for further exploration.
- B) LST-2 of the DSQ-2 is dominated by sand-rich sediments and has the potential to act as a good reservoir rock in the Early Cretaceous of the Beni Suef Basin (i.e., according to the relationship between the porosity and permeability) especially the Azhar field and Beni Suef fields. These sandstones are characterized by effective porosity ranging between 14 and 22%, water saturation of 20 to 38%, and net pay 21 to 25 m in the Azhar and Beni Suef fields (Zahran et al. 2011).

Conclusions

The tectonic setting

The detailed seismic interpretation of the key tectonic events has indicated that Early Cretaceous Kharita Formation is formed in the syn-rift phase of the basin.

The phases of environmental deposition

The depositional style and evolution of the Early Cretaceous syn-rift sediments in the Beni Suef Basin was strongly influenced by such tectonic disturbances and can therefore be divided into the following phases:

- Early Cretaceous (Albian): the deposition commenced within the Beni Suef Basin. The tectonic events and their associating fault blocks resulted in significant variations on the basin paleo-topography and the surrounding tectonically rifted hinterlands surrounded the depositional area with significant highs of older rocks. This topographic situation, coupled with the dominance of rainy tropical climate over the northern Egypt at those times, created a depositional phase initiating with active braided channels depositing relatively thick amalgamated sandstone and gravelly sandstone coupled with vertical aggradation within significantly narrow, but low accommodation space.

The progradation of such a fluvial drainage network ceased due to submergence below a marine invasion of mid-Albian marine sea whose shore line trending in almost E–W. This marine invasion was initiated due to a short-lived tectonic subsidence, producing the coastal marine and inner marine shelf facies of the TST-1.

Possibly as a result of a mid-Albian tectonic uplift, a marine regressive phase initiated accompanied with gradual sea level drop and onset of shallowing marine conditions where the HST-1 was developed. Finally, the sea level reached its maximum low, and the depositional area became emerged land, ending the depositional phase of the Lower Kharita Member over the Sb-2.

- Late Albian: a new phase of land-rejuvenation, accompanied by a tectonic uplift exposed the high hinterlands around the depositional area. As a result, a long-lived period of fluvial deposition dominated the depositional area within variable fluvial accommodation infilled by different fluvial systems from active braided channels, followed by moderately-sinuuous streams, during the deposition of the LST-2 producing thick succession of amalgamated, vertically aggrading sandstones within mud layers at the lower levels of the Upper Kharita Member.

The continuous basin filling coupled with significant lowering in the surrounding highs resulted in a marked reduction for the topographic gradient of the depositional area, with simultaneous widening of the fluvial accommodation area. Therefore, the preceding vertically aggrading fluvial patterns gave way to more constructive high-sinuuous, meandering rivers with stable prolific flood plains of the TST-2.

The far distal branches of such fluvial network were depositing their fine loads into a possible Early Cenomanian sea forming a wide estuarine-like belt, recorded at the upper levels of the Upper Kharita Member.

- The depositional history of the Kharita Formation was terminated under the major Cenomanian marine transgression, covering vast areas of the Egypt.

The hydrocarbon prospects

The sequence stratigraphic analysis and the concluded depositional setting of the Kharita Formation have provided the following perspectives:

- TST-1 and HST-1 are rich in the wood remains, carbonaceous materials, spore, and pollen acquired from the underlying fluvial net. These tracts can act as source of natural gases. Exploration should be directed at further regional search for such tracts, especially the TST-1.
- LST-2 of the DSQ-2 is characterized by sand-dominated sediments. It could act as a good reservoir rock in the Early Cretaceous in the Beni Suef Basin, especially the Azhar field and Beni Suef field.

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