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Sequence stratigraphy of the Lower Cenomanian Bahariya Formation, Bahariya Oasis, Western Desert, Egypt

O. Catuneanu [a], M.A. Khalifa [b], H.A. Wanas [b,*]

[a] *Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences Building, Edmonton, Alberta, Canada T6G 2E3*
[b] *Geology Department, Faculty of Science, Menoufia University, Shebin El-Kom, Egypt*

Abstract

The Lower Cenomanian Bahariya Formation corresponds to a second-order depositional sequence that formed within a continental shelf setting under relatively low-rate conditions of positive accommodation (<200 m during 3–6 My). This overall trend of base-level rise was interrupted by three episodes of base-level fall that resulted in the formation of third-order sequence boundaries. These boundaries are represented by subaerial unconformities (replaced or not by younger transgressive wave ravinement surfaces), and subdivide the Bahariya Formation into four third-order depositional sequences.

The construction of the sequence stratigraphic framework of the Bahariya Formation is based on the lateral and vertical changes between shelf, subtidal, coastal and fluvial facies, as well as on the nature of contacts that separate them. The internal (third-order) sequence boundaries are associated with incised valleys, which explain (1) significant lateral changes in the thickness of incised valley fill deposits, (2) the absence of third-order highstand and even transgressive systems tracts in particular areas, and (3) the abrupt facies shifts that may occur laterally over relatively short distances. Within each sequence, the concepts of lowstand, transgressive and highstand systems tracts are used to explain the observed lateral and vertical facies variability.

This case study demonstrates the usefulness of sequence stratigraphic analysis in understanding the architecture and stacking patterns of the preserved rock record, and helps to identify 13 stages in the history of base-level changes that marked the evolution of the Bahariya Oasis region during the Early Cenomanian.

1. Introduction

The Bahariya Oasis is located in the heart of the Western Desert between latitudes 27° 48′ and 28° 30′ N and longitudes 28° 32′ and 29° 10′ E, about 370 km southwest of Cairo and 190 km west of Samalut in the Nile Valley (Fig. 1). This Oasis is one of the most geologically important areas in the Western Desert, and attracted considerable attention especially in the last four decades, since the discovery of iron ore deposits in the El Gedida, Ghorabi and El Harra localities (Said, 1962; El Akkad and Issawi, 1963; El Bassyouny, 1970; Issawi, 1972; Khalifa, 1977; Franks, 1982; Dominik, 1985; Khalifa and Abu El-Hassan, 1993; Soliman and Khalifa, 1993; Khalifa et al., 2002, 2003).

The presence of Cenomanian rocks in the Bahariya Oasis was first recorded by Lyons (1894), with the identification of *Exogyra* sp. fossils. Further work on the stratigraphic framework of this region was done by Ball and Beadnell (1903), who established that the oldest exposed rocks in the Oasis are of Cenomanian age. Stromer (1914) was the first to introduce the term

* Corresponding author.
E-mail addresses: octavian@ualberta.ca (O. Catuneanu), wanas2000@yahoo.com (H.A. Wanas).

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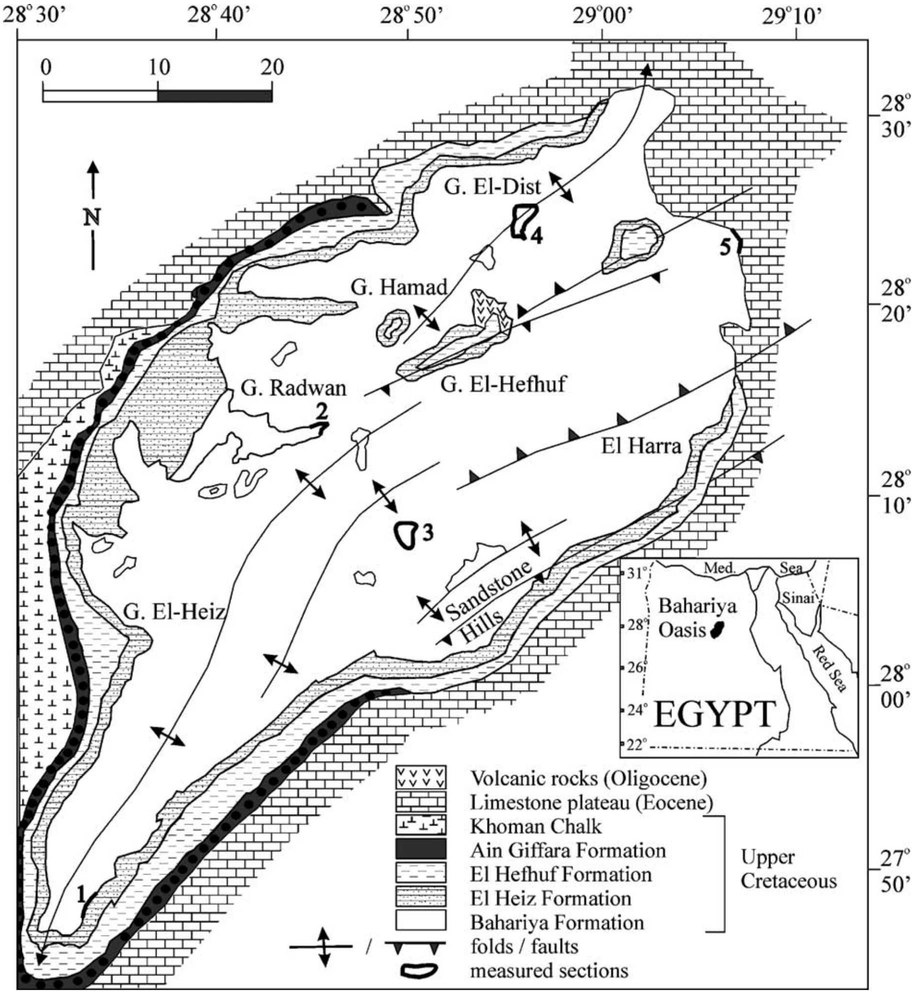


Fig. 1. Location map, and general geology of the study area (modified from El Akkad and Issawi, 1963). The stratigraphic objective is represented by the Lower Cenomanian unconformity-bounded Bahariya Formation, which has an estimated duration of 3–6 My (Palmer, 1983). Measured sections: 1 — Naqb El-Selim; 2 — Gabal Radwan; 3 — West of Sandstone Hills; 4 — Gabal El-Dist (type section for the Bahariya Formation); 5 — Naqb El-Bahariya.

Bahari-Jestufe for the Cenomanian sandstones and claystones that crop out on the floor and along the escarpments of the depression. Later, Said (1962) used the term Bahariya Formation instead of Bahari-Jestufe. He mentioned that the Bahariya Formation consists predominantly of sandstones with numerous intercalations of ferruginous layers, and termed the lowermost sandstone beds as the “Dinosaur bed” at the Gabal El-Dist locality. It is now firmly established that the age of the Bahariya Formation is Early Cenomanian (e.g., Soliman and Khalifa, 1993), and current estimates indicate that its deposition took place during a time interval of c. 3–6 My (Palmer, 1983).

The Bahariya Formation includes the lowest and the oldest exposed beds in the Bahariya Oasis. It forms the floor of the Oasis and the basal part of the surrounding scarps (Fig. 1). The base of the Bahariya Formation is unexposed, but inferred to be unconformable at the contact with the underlying basement (El Bassyouny, 1970), while its top shows an unconformable relationship with the overlying Upper Cenomanian El Heiz Formation (Khalifa and Abu El-Hassan, 1993), or the Lower–Middle Eocene El-Naqb Formation (El Bassyouny, 1970, 2004). The exposed thickness of the Formation ranges from c. 90 m in the central part of the Oasis, to over 100 m in the northern sections.

From a lithological point of view, the Bahariya Formation exhibits significant lateral and vertical changes of facies. In the central parts of the Oasis, the Formation consists of three informal lithologic units defined by interbedded siltstones and sandstones (lower unit), cross-bedded amalgamated sandstone bodies (middle unit) and dark colored ferruginous sandstones (upper unit) (Soliman and Khalifa, 1993). In the northern parts of the Oasis, two distinct units are recognized, i.e. a lower unit consisting of siltstones and mudstones with plant remains, and an upper unit composed of glauconitic claystones with thin ferricrete interbeds. The correlation of these units was so far based primarily on lithological grounds (Soliman and Khalifa, 1993).

Between its limits, the Bahariya Formation forms an unconformity-bounded sequence (El Bassyouny, 1970), which in turn shows internal cyclicity at higher frequency levels. This makes it an ideal candidate for a sequence stratigraphic study, which has never been performed before within the confines of the Bahariya Oasis. The aim of this paper is to construct the sequence stratigraphic framework for the Bahariya Formation, which should improve our understanding of the succession of events that marked the Early Cenomanian evolution of this area and led to the preserved stratigraphic architecture within the Oasis, as seen today.

2. Geological setting

Egypt lies on the northeastern margin of the African Plate, where it forms a part of the East Sahara Craton (El Emam et al., 1990). Geologically, Egypt is subdivided into three structural provinces. From south to north, they are represented by the Arabo-Nubian Craton, a stable shelf, and an unstable shelf (Said, 1962; Meshref, 1982, 1990). Within this setting, the Bahariya Oasis is placed at the transition between the stable and unstable shelf provinces (Khalifa et al., 2002). The partitioning of Egypt's territory into these structural provinces reflects a complex history of extension, collision and wrench fault tectonism within the northern part of the African Plate brought about by the relative movement between Africa and Laurasia (El Emam et al., 1990).

Interpretation of gravity data shows that the Western Desert, which encloses the Bahariya Oasis, is essentially part of a Jurassic–Cenomanian divergent ("passive") continental margin (El Emam et al., 1990) which evolved as such in relation to the opening and development of the Tethys Sea. Sedimentation on the continental shelf during the Lower Cenomanian is thought to have taken place during a stage of overall low-rate base-level rise, which resulted in the deposition of an extensive succession of deposits (Ibrahim, 1990). The amount of accommodation generated on the shelf during this time was generally between 100 and 200 m, as documented by the more or less constant thickness of the Bahariya Formation at a regional scale. Localized increases in the thickness of the Bahariya Formation, up to 400–500 m, are recorded to the north of the Oasis, in relation to restricted, fault-bounded basins formed within the unstable shelf structural province. An example of such restricted and highly subsiding basin is represented by the Abu Gharadig Basin, placed 300 km north of the Bahariya Oasis, which may be related to processes of rifting that commenced in the Jurassic (Ibrahim, 1990; Ibrahim and Aly, 1994). This restricted extensional basin may be superimposed on a failed suture that was reactivated as the Pangea supercontinent began to split into Gondwana and Laurasia. The extensional nature of the Abu Gharadig Basin is evidenced by the thinning of its underlying crust (El Emam et al., 1990). No such extension has been noted within the perimeter of the Bahariya Oasis, whose sedimentation history was generally unaffected by the manifestation of syn-depositional structural elements (Aram, 1990).

3. Sedimentology

3.1. Data

The data for this paper were primarily collected by means of outcrop facies analyses performed in five main sections located within the confines of the Bahariya Oasis (Fig. 1). The results of this work, as well as the interpretation of the data, are illustrated in Figs. 2–7.

The studied sections show a dominantly clastic succession, with lithologies ranging from claystones and shales to sandstones and conglomeratic lag deposits. Numerous iron-rich paleosol horizons, referred to as ferricretes herein, are present almost throughout the Bahariya Formation. The observed clastic lithofacies range in color from white to yellow, green, grey or black, with a variety of sedimentological features represented by different types of physical structures, grading, load, and water-escape structures. Some of these lithofacies may dominate parts of the stratigraphic succession, or may repeat themselves in a predictable fashion forming c. meter-scale cyclothems. The dominance of a particular lithofacies, or group of lithofacies, in different parts of the Formation allows the definition of eight main facies associations, as outlined below.

3.1.1. Facies association 1

This association is characterized by a repetition of meter-scale fining-upward cyclothems, each consisting of light colored fine- to very fine-grained sandstones with horizontal lamination, ripple cross-lamination, convolute bedding (Fig. 2A) and load structures (Fig. 2B) at the base, capped by yellow siltstones and dark grey mudstones with black wood, leaf imprints and dinosaur bones. This facies association is present at the base of the Gabal

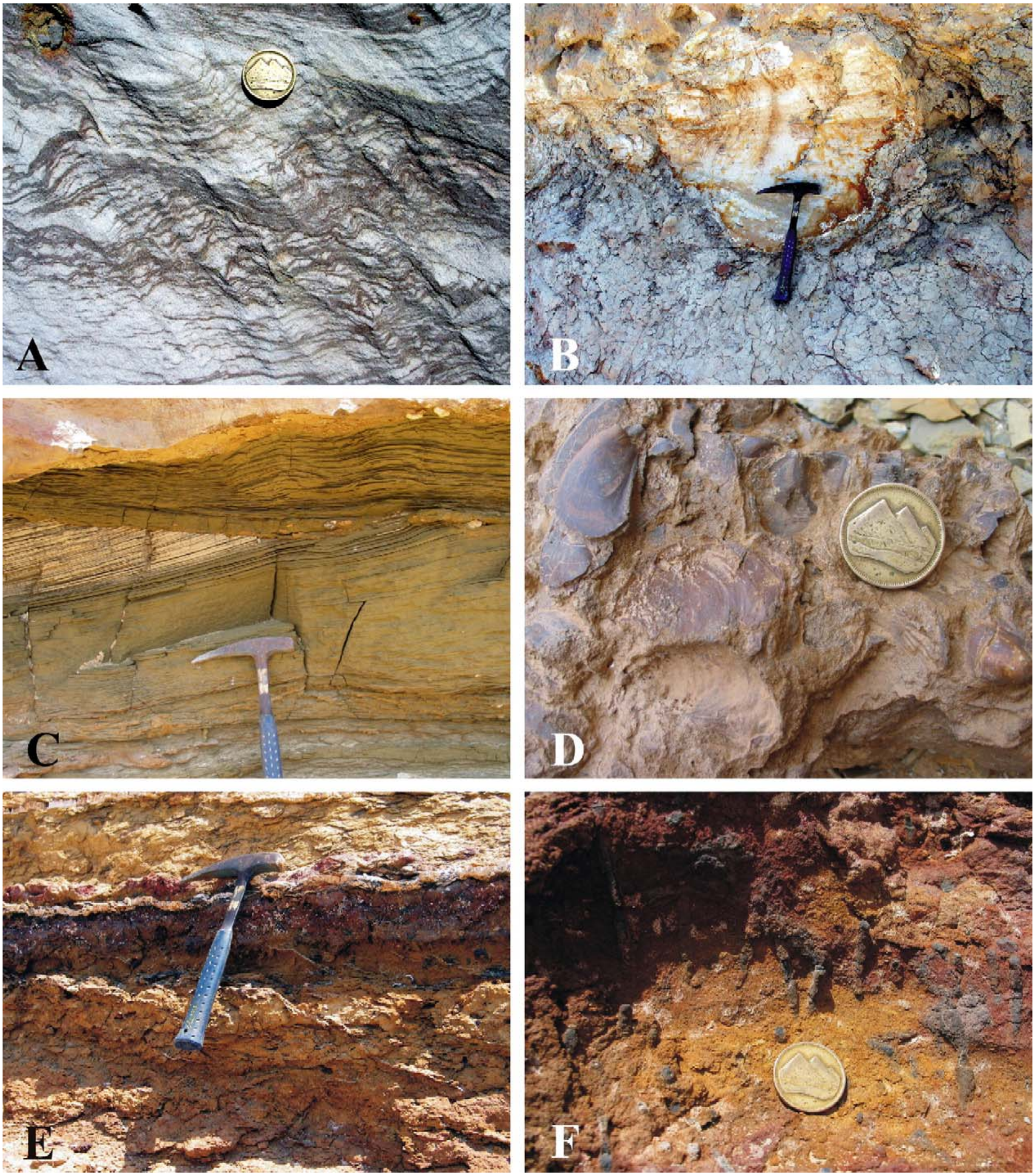


Fig. 2. Field photographs of the various facies observed in the Bahariya Formation at the Bahariya Oasis. A — convolute bedding characterizing the lithologies of the facies association 1 at Naqb El-Bahariya section; B — load structure of white siltstone within grey mudstone of the basal lithologies of the Bahariya Formation at Gabal El-Dist; C — swaly cross-bedding in the sandstones of the facies association 2 in the middle unit of the Bahariya Formation at Gabal El-Dist; D — bivalves (*Exogyra* sp.) that are concentrated as lag deposits at the top of ferricrete horizons in the cyclothems of facies association 2 at Gabal El-Dist; E — meter-scale package of yellow claystone topped by red iron-rich horizon in the facies association 3 at Gabal El-Dist section; F — vertical ferruginous root casts within the iron-rich horizon and its underlying claystone of the facies association 3 of the Bahariya Formation at Naqb es Sillim. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

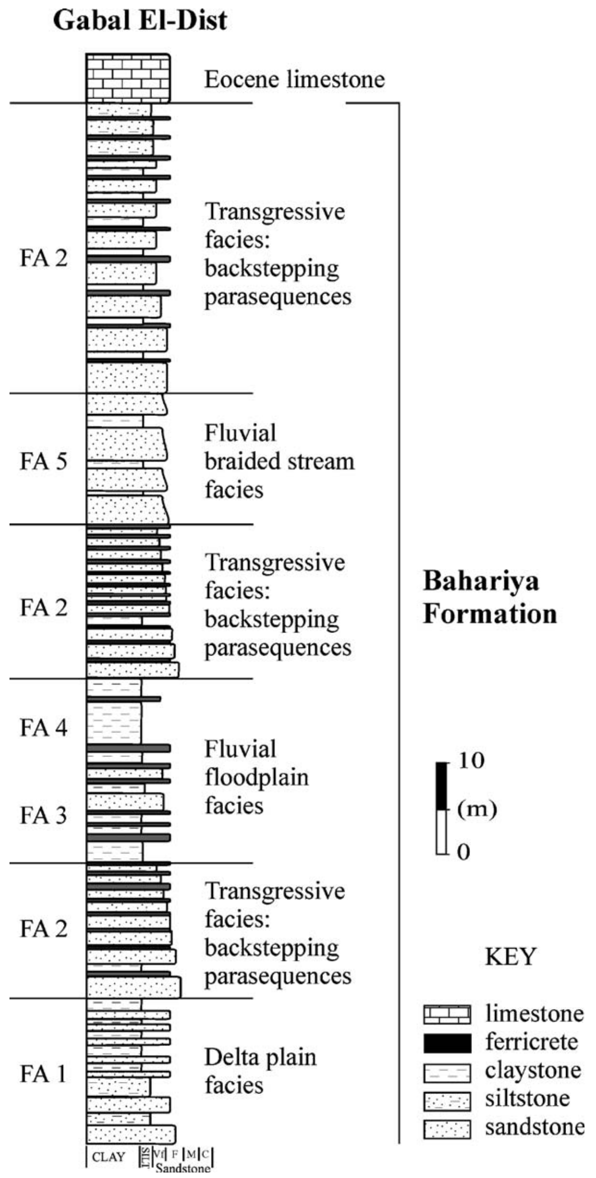


Fig. 3. Vertical profile of the Bahariya Formation in Gabal El-Dist (type section, with the location shown in Fig. 1). The profile indicates the observed facies associations (FA; see text for lithofacies descriptions), as well as the interpretation of paleodepositional environments.

El-Dist and Naqb El-Bahariya sections (Fig. 1), with thicknesses of about 15 m (Figs. 3 and 4). The base of this facies association is unexposed, and the top contact is sharp but apparently conformable in the Gabal El-Dist section and unconformable in the Naqb El-Bahariya section (Figs. 3 and 4). The unconformable contact is indicated by the abrupt change in lithology from fine-grained sandstones and siltstones of the facies association 1 to the overlying coarse- to medium-grained sandstones (Fig. 4).

3.1.2. Facies association 2

This association consists of c. meter-scale coarsening-upward cyclothems, which start with yellow to creamy-colored claystones at the base grading upwards into fossiliferous glauconitic siltstones and sandstones. The sandstones display swaley cross-bedding (Fig. 2C), and each coarsening-upward rhythm is topped by a centimeter to decimeter thick ferricrete layer. In this case, the formation of ferricrete is attributed to the *in situ* alteration of glauconite under subaerial conditions. This is indicated by the occurrence of glauconite and kaolinite (alunite?) remnants within the ferricrete layers (El Sharkawi and Al Awadi, 1981). The fossil assemblage includes marine bivalves (e. g., *Ostrea* sp. and *Exogyra* sp.; El Bassyouny, 2004). Beside them being present within the siltstone to

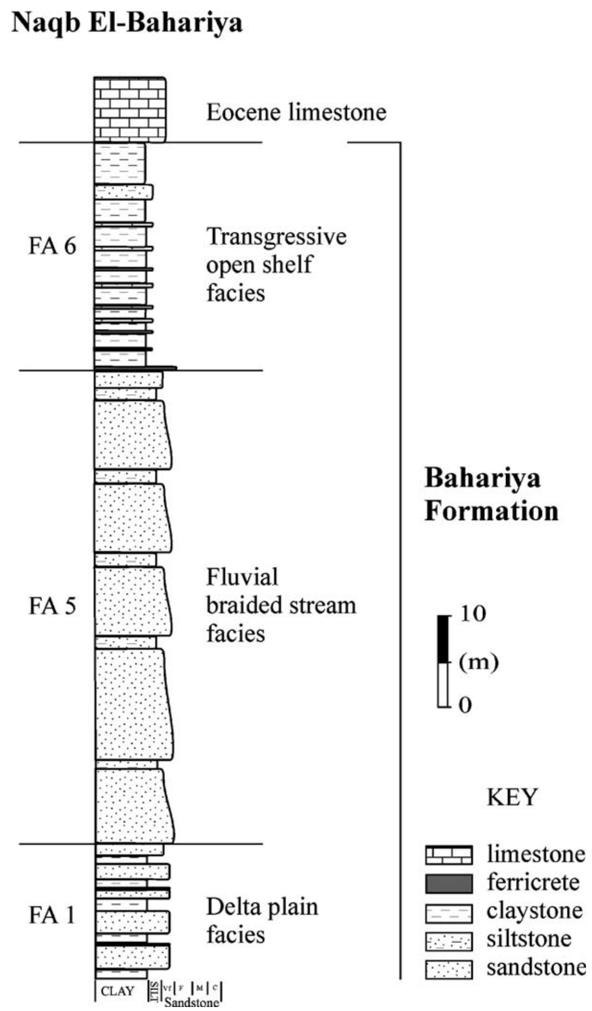


Fig. 4. Vertical profile of the Bahariya Formation in the Naqb El-Bahariya section (location shown in Fig. 1). The profile indicates the observed facies associations (FA; see text for lithofacies descriptions), as well as the interpretation of paleodepositional environments.

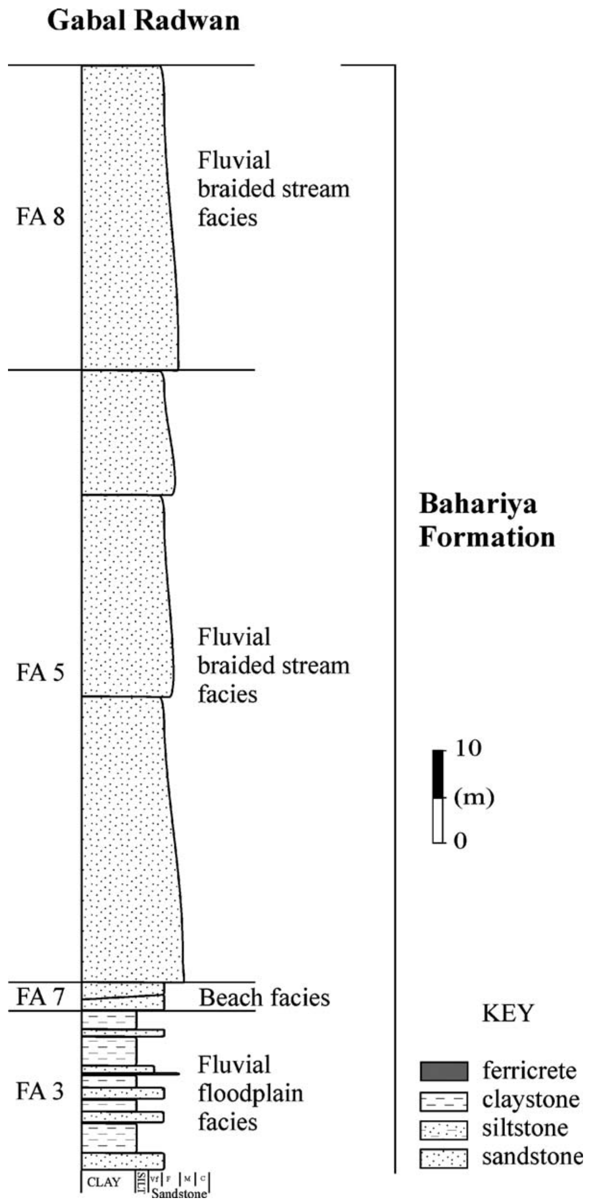


Fig. 5. Vertical profile of the Bahariya Formation in the Gabal Radwan section (location shown in Fig. 1). The profile indicates the observed facies associations (FA; see text for lithofacies descriptions), as well as the interpretation of paleodepositional environments.

sandstone portions of the cyclothems, the marine bivalves are also concentrated as lag deposits at the top of each ferricrete layer (Fig. 2D). A gradual decrease in the thickness of individual coarsening-upward cyclothems is recorded upward. This facies association occurs only in the Gabal El-Dist section (Fig. 1), being present three times with thicknesses of up to 32 m (Fig. 3). The third (and youngest) occurrence of facies association 2 is somewhat different from the underlying two, showing thinner and less mature ferricrete layers (Fig. 3). The first (oldest) occurrence of facies association 2 is bounded by apparently conformable contacts. The middle occurrence of facies association 2 is bounded by lag deposits. The upper (youngest) occurrence of facies association 2 is unconformably overlain by the dolomitic limestone of the lower Middle Eocene El-Naqb Formation (Fig. 3).

3.1.3. Facies association 3

This association consists of c. meter-scale packages of grey, yellowish and reddish claystones topped by iron-rich paleosol (ferricrete) horizons (Fig. 2E). Plant roots are abundant, and present within both the ferricrete layers and the underlying claystone intervals (Fig. 2F). Even though rare dessication cracks and wood fragments filled with iron oxides are also present within the claystone intervals. Concretions are occasionally associated with the paleosol horizons, and rip up clasts are

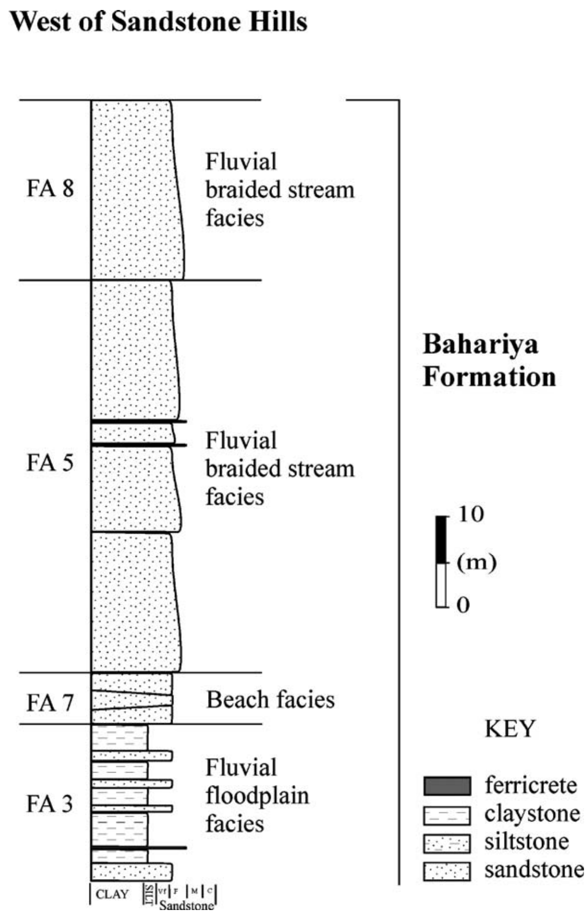


Fig. 6. Vertical profile of the Bahariya Formation West of Sandstone Hills (location shown in Fig. 1). The profile indicates the observed facies associations (FA; see text for lithofacies descriptions), as well as the interpretation of paleodepositional environments.

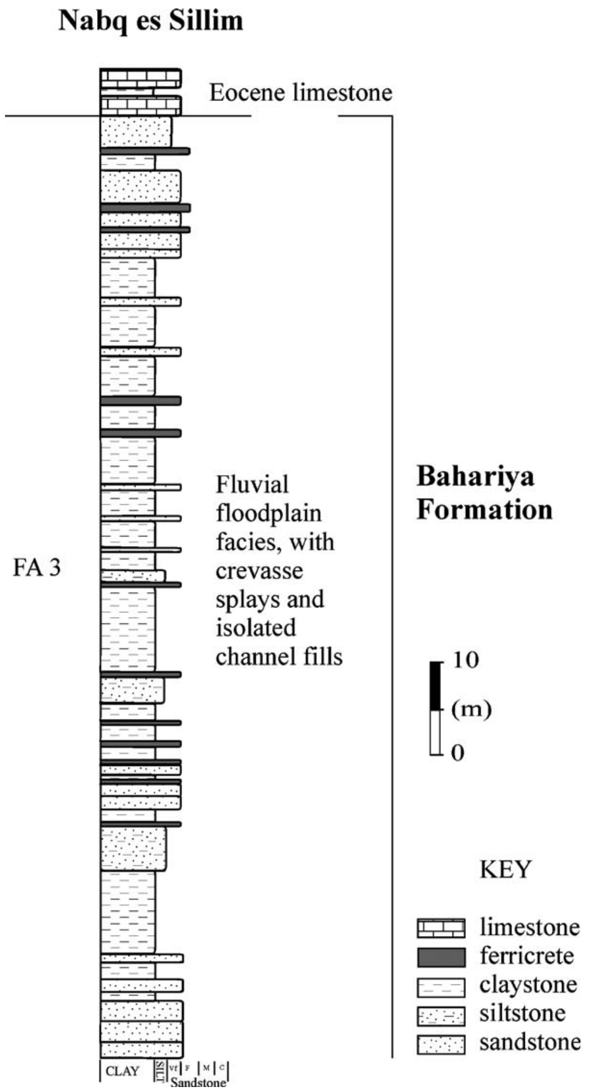


Fig. 7. Vertical profile of the Bahariya Formation West of Naqb El-Selim (location shown in Fig. 1). The profile indicates the observed facies associations (FA; see text for lithofacies descriptions), as well as the interpretation of paleodepositional environments.

found above the ferricretes, at the base of the cyclothems. The thickness of individual claystone–ferricrete cyclothems generally varies between 0.5 and 3 m. Facies association 3 is present in the Gabal El-Dist section (Fig. 3), at the base of the Gabal Radwan and West of Sandstone Hills sections (Figs. 5, 6), and also in the southern part of the Bahariya Oasis, where it forms the bulk of the Naqb El-Selim section (Fig. 7). The basal contact of this unit is sharp but apparently conformable in the Gabal El-Dist section, and is unexposed in the other sections. The top contact is sharp and scoured in the central part of the Bahariya Oasis (Gabal Radwan and the West of Sandstone Hills sections), but is transitional in the Gabal El-Dist section.

3.1.4. Facies association 4

This association is dominated by black shales with abundant plant remains, interbedded with up to 2 m thick fine-grained sandstone intervals and thin (cm–dm scale) ferricrete layers. Facies association 4 is only present in the Gabal El-Dist section (Fig. 3). The contact with the underlying facies association 3 is conformable and gradual, whereas the contact with the overlying facies association 2 is unconformable. This unconformable contact is distinguished by the occurrence of lag deposits.

3.1.5. Facies association 5

This facies association is defined by the dominance of light, creamy color, coarse-to fine-grained sandstones organized in meter-scale fining-upward packages. These packages are amalgamated and bounded by prominent scour surfaces associated with lag deposits. Multiple reactivation surfaces are present within each individual unit. Subordinate clays and silts with plant remains are occasionally interbedded with the sandstones. The sandstone units have a low height to width ratio, which confers them great lateral extent. Sedimentary structures include decimeter to meter scale cross-bedding (both planar and trough), flaser bedding, convolute bedding, and overturned foresets. Facies association 5 is the most laterally persistent unit of the Bahariya Formation, being present in all studied sections, but records significant changes in thickness from one section to another, even over relatively short distances. For example, this association is only 14 m thick in the Gabal El-Dist section, and thickens to about 50 m in the Naqb El-Bahariya section within a distance of 20 km (Figs. 3, 4). The contact of facies association 5 with the adjacent (underlying and overlying) units is always sharp (Figs. 3, 4 and 5), with pronounced erosion at the base.

3.1.6. Facies association 6

Facies association 6 is only found in the Naqb El-Bahariya area (Fig. 1), where it forms the top of the section (Fig. 4). With a preserved thickness of 27 m, this association is defined by a relatively monotonous succession of green glauconitic shales which sharply overlie the deposits of facies association 5. At the top, this facies association is unconformably overlain by the dolomitic limestone of the lower Middle Eocene El-Naqb Formation (Fig. 4).

3.1.7. Facies association 7

Facies association 7 has only been identified in the central part of the Bahariya Oasis (West of Sandstone

Hills and Gabal Radwan sections; Fig. 1), with a thickness ranging from 4 m at Gabal Radwan section to 8 m in the section at the western area of Sandstone Hills (Figs. 5, 6). It is a lithologically homogeneous unit, composed of light cream fine- to medium-grained sandstones with a distinct low-angle cross-stratification. Several reactivation surfaces are observed in any given location, separating packages with consistent foreset orientations. This association is bounded by sharp contacts both at the base and top.

3.1.8. Facies association 8

This facies association is generally similar with facies association 5 excepting that the sandstones are black in color and that the succession is punctuated by the presence of multiple ferricrete horizons. Facies association 8 is only present in the central part of the Bahariya Oasis (at the top of the West of Sandstone Hills and Gabal Radwan sections; Fig. 1), with a preserved thickness of about 20 m (Figs. 5, 6). This unit is bounded by a sharp contact with conglomeratic lag deposits at the base, and by the present-day topographic profile at the top.

3.2. Interpretation

The interpretation of the paleo-depositional environments in which the sediments of the Bahariya Formation accumulated during the Early Cenomanian is based on the observed facies associations presented above. Rock types, grading trends, nature of facies contacts, and sedimentary structures are primary proxies for such interpretations. The results of our paleo-depositional environment interpretations are synthesized in Figs. 3–7.

3.2.1. Facies association 1

This facies association corresponds to a low energy environment in which sediment supply was relatively high and yet dominated by finer-grained sediment fractions. Fluctuating energy levels with time are also inferred, as suggested by the interbedding of sands and muds, possibly representing autocyclic shifts in the location of subenvironments. The presence of fining-upward cyclothems, as well as the nature of the fossil content, point towards a fluvial-dominated environment in which the water table was relatively high and the energy of unidirectional flows was minimal. Such conditions are often found in delta plain settings characterized by a nearly flat topography and the presence of straight (or very low sinuosity) single channel systems (Elliott, 1986). This interpretation is also in agreement with the absence of any discernable downstream or lateral accretion macroforms. The fining-upward cyclothems likely reflect a shift from sand-filled distributary channels (lowest energy, straight single channels) to mud-dominated interdistributary areas characterized by sedimentation from suspension in stagnant water. The load structures (load casts, load balls) often observed at the base of the fining-upward cyclothems, together with the frequent convolute bedding that is present in the sandstones, reflect high sedimentation rates and associated water escape and soft sediment deformation (Allen, 1982). The observed aggradational trend indicates that the base-level was rising at the time of deposition, hence this delta plain was part of a normal regressive delta.

3.2.2. Facies association 2

This facies association is composed of high-frequency progradational packages, each starting with abrupt drowning (flooding surface) and ending with subaerial exposure (paleosol development). The fact that each new cycle brings transgression and a marine environment over the area of occurrence is documented by the presence of marine fossils (*Ostrea* sp. and *Exogyra* sp.) within the clastic rocks, which also concentrate as lag deposits at the base of each cyclothem. The base of these packages is therefore erosional, most likely represented by minor (low order) wave ravinement surfaces. Such transgressive scours are one type among several candidates that may serve as “flooding surfaces”, marking abrupt water deepening in the basin (see Catuneanu, 2002, 2006, for a discussion on flooding surfaces). The presence of wave ravinement surfaces at the base of the observed cycles indicates that the Jabal El-Dist section was generally located within the coastal area, and immediately adjacent environments, during the deposition of this facies association. Wave ravinement surfaces are cut by waves in the upper shoreface, so likely the marine facies of these cyclothems are subtidal, accumulated above the fair-weather wave base. A shoreface environment is also supported by the presence of swaley cross-stratification (Tucker, 1991). Following transgression, a gradual progradation of the coastline was recorded, as documented by the coarsening-upward trend of each cyclothem (Nummedal et al., 1987). These regressive episodes proceeded to the point where the coastline passed through the Gabal El-Dist location, leaving the area subaerially exposed. This is evidenced by the development of paleosol (ferricrete) horizons at the top of the prograding cyclothems. These high-frequency transgressive–regressive cycles took place during stages of base-level rise, as indicated by the vertical aggradation that accompanied the transgressive and regressive shoreline shifts. The balance between sedimentation and the rates of base-level rise dictates the overall transgressive or regressive character of the shoreline trajectory. In this case, the gradual decrease in the thickness of individual coarsening-upward cyclothems that is recorded up section is a diagnostic feature for overall coastal backstepping (Catuneanu, 2003), which means that facies association 2 accumulated during an overall transgression of the shoreline.

3.2.3. Facies association 3

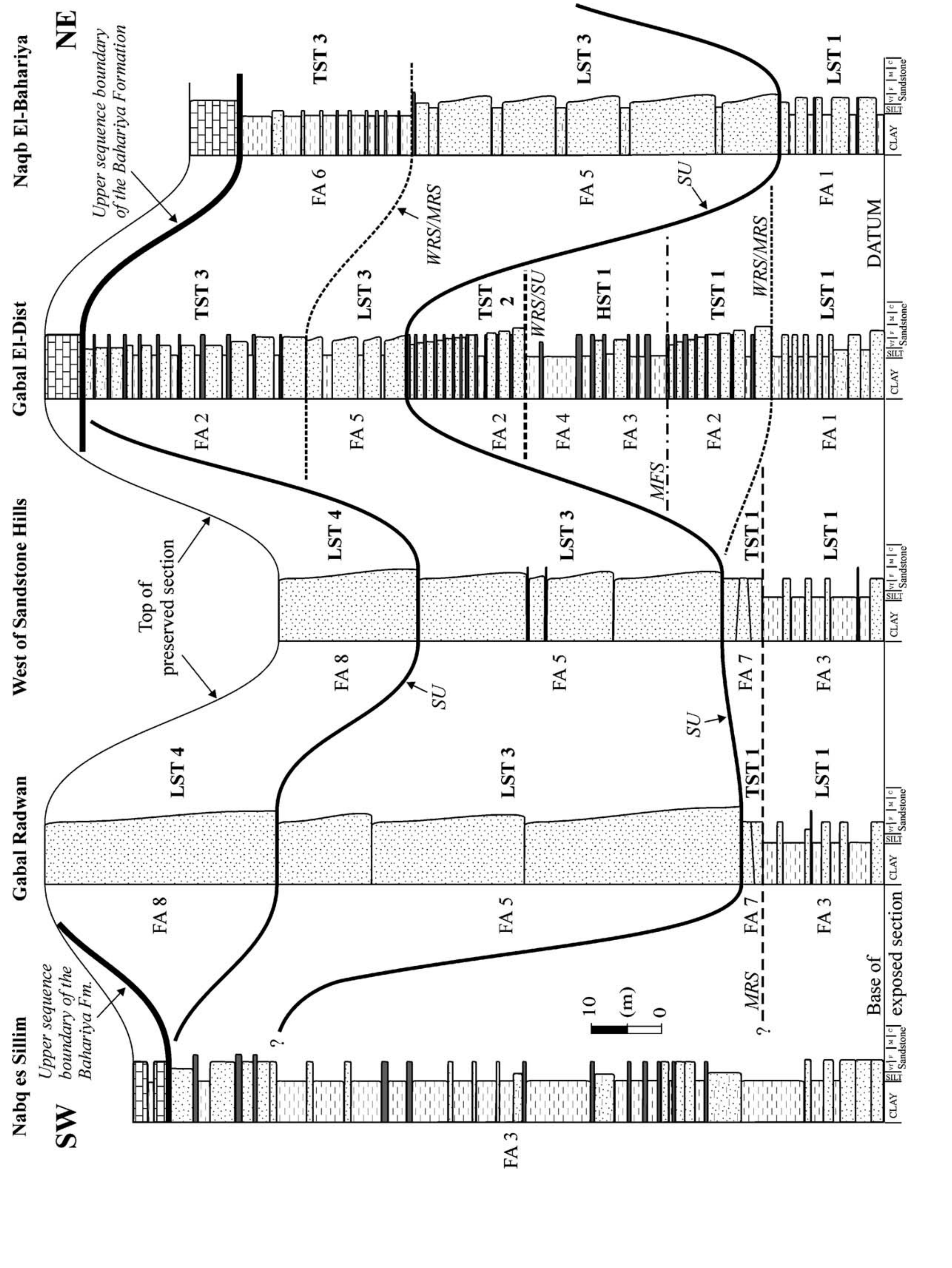
This association of claystones and ferricretes, marked by abundant plant roots and other plant fragments replaced by iron oxides, is characteristic of a low energy nonmarine environment (Selley, 1972), in which periods of time of vertical aggradation (accumulation of claystones) alternated with periods of time of sediment starvation (formation of ferricretes). These high frequency fluctuations in sediment supply, water discharge, and/or fluvial accommodation took place during a stage of overall base-level rise, as evidenced by the gradual build up of the sedimentary succession. The claystone intervals are interpreted to correspond to sedimentation from suspension in fluvial floodplain environments, whereas the formation of ferricretes marks periods of paleosol development. The flooding of the overbank environment, following an interval of subaerial exposure dominated by pedogenic processes, was associated with slight scouring of the substrate as evidenced by the presence of rip up clasts at the base of each claystone–ferricrete cyclothem. Subordinate crevasse splay sands, with sharp but non-erosional boundaries and with gently inverse grading trends, are occasionally interbedded with the claystones of this facies association. The abundance of crevasse splay deposits tends to increase from North (Gabal El-Dist section) to South (West of Naqb El-Selim section) within the Bahariya Oasis. Few isolated channel fills, with a ribbon-like geometry, have been observed in the Naqb El-Selim area. This association of architectural elements suggests a fluvial system with confined, low energy and high sinuosity channels, as commonly seen in meandering rivers (Miall, 1996; Selley, 1996).

3.2.4. Facies association 4

This association reflects similar paleo-depositional conditions to the ones noted for facies association 3, with the bulk of sediment accumulated in floodplain environments, and to a lesser extent in channels and crevasse splays. This combination of fluvial architectural elements is again typical for low energy, high sinuosity meandering rivers. The dominance of carbonaceous material in the floodplain fines, which confers them the characteristic black color that defines this facies association, suggests a possibly wetter climate (Retallack, 1986) relative to the underlying facies association 3. This also indicates a high water table and abundant vegetation in the overbank environment at the time of deposition (Retallack, 1986). This highly vegetated environment also points towards stable river banks, which in turn supports the idea of a confined nature of the interpreted meandering channels (Miall, 1996), and which is in agreement with the observed dominance of floodplain facies over the sandier channel and crevasse splay architectural elements (Kraus, 1987). As the transition between facies associations 3 and 4 is gradual, and they both reflect similar paleo-depositional environments, they may be grouped into one genetic unit during the deposition of which the climate gradually changed from drier to wetter conditions. In conclusion, the vertical aggradation of facies association 4 indicates continued base-level rise during its deposition, even though at smaller temporal scales the process of sediment accumulation was temporarily interrupted by periods of paleosol formation.

3.2.5. Facies association 5

This association is also the product of sedimentation in a fluvial environment, but it marks a major shift from the low energy meandering style of facies associations 3 and 4, by displaying the features of high energy, low sinuosity braided rivers. This association of facies is typical of amalgamated braided stream channel fills, reflecting low accommodation conditions as generally found at the base of fluvial depositional sequences. This interpretation is in agreement with the presence of large-scale cross-bedded sandstones, which are likely the product of downstream accreting, inside-channel bedforms and macroforms (Miall, 1996). The multiple reactivation surfaces observed within individual channel fills correspond to the third-order fluvial surfaces in the hierarchy proposed by Miall (1996), and signify autocyclic reorganization of the fluvial system and associated changes in flow direction. The low height-to-width ratio of the channel fills indicates rivers of unconfined nature, which partly explains the low preservation potential of floodplain fines. In addition to this, the lack of floodplain facies may also be attributed to low rates of base-level rise (low fluvial accommodation), which may only allow for sediment preservation in the channel subenvironment characterized by lower elevations. The significant changes in the thickness of this braided stream succession across the study area (Figs. 3, 4, 5 and 6) suggests an irregular topography at the onset of deposition of this facies association, which is commonly caused by differential fluvial incision during the previous stage of base-level fall (Shanley and McCabe, 1994). We therefore interpret these facies as incised valley fill deposits which contributed to the peneplanation of the


SW
Nabq es Sillim
Gabal Radwan
West of Sandstone Hills
Gabal El-Dist
Naqb El-Bahariya
NE
Upper sequence boundary of the Bahariya Fm.
Upper sequence boundary of the Bahariya Formation
Top of preserved section
Base of exposed section
10
(m)
0
LST 4
LST 3
LST 1
TST 1
TST 2
TST 3
HST 1
FA 1
FA 2
FA 3
FA 4
FA 5
FA 6
FA 7
FA 8
SU
MRS
WRS/MRS
WRS/SU
MFS
DATUM
CLAY
SILT
Sandstone

syn-depositional topography in the early stages of renewed base-level rise.

3.2.6. Facies association 6

This unit is marked by the presence of authigenic glauconite, and is interpreted as a product of marine sedimentation (Odin, 1988). The succession is lithologically homogeneous, being exclusively composed of shales. The lack of sand-size sediment suggests a distal position relative to the sediment entry points into the marine basin, most likely below the storm wave base. Beyond the influence of storm currents, the depositional environment for facies association 6 is probably represented by an outer shelf setting.

3.2.7. Facies association 7

This unit shows the characteristics of a beach deposit, with well-sorted fine-to medium-grained sands and typical low-angle stratification (Hoyt, 1967). The reactivation surfaces observed within this unit correspond to storm events (Mowbray and Visser, 1984), when the beach is eroded. Bounded by reactivation surfaces, each conformable package of low-angle stratified strata represents an episode of beach construction during weather. The slight change in the dip direction of the beach face accretion surfaces across the reactivation scours is caused by the reorganization of the beach morphology during storm events.

3.2.8. Facies association 8

Except for color and the presence of more frequent ferricrete horizons, this association is similar to facies association 5 in terms of types and stacking patterns of architectural elements. Therefore, this succession is also interpreted as the product of sedimentation in a braided stream fluvial environment. The deposits of facies association 8 fill a syn-depositional topographic low in the central part of the Bahariya Oasis, which truncates into the underlying strata of facies association 5. The localized nature of this topographic low, interpreted here as an incised valley, explains the lack of correlation and the limited geographic distribution of this facies association.

4. Sequence stratigraphy

The sequence stratigraphic interpretation of the clastic deposits of the Bahariya Formation is based on the observed facies associations, as well as on the nature of the contacts that separate them. This type of analysis is important because it allows one to understand the evolution and the history of base-level changes during the Early Cenomanian time in the Baharyia Oasis, and also to explain the significant lateral changes of facies, their correlation and temporal relationships within the study area. For a review of sequence stratigraphic concepts and terminology see Catuneanu (2002, 2006).

The lack of high resolution biostratigraphic (or of any other dating method) time control to constrain the correlations is a reality in many Phanerozoic case studies, and almost the norm in all studies of Precambrian successions. The application of sequence stratigraphic principles can however be successfully performed even in the near absence of constrained time lines, where the facies geometry, stacking patterns, and depositional models are well understood (see Catuneanu et al., 2004, for a discussion). In this case study, the lack of tectonic tilt and the preservation of the original horizontality of the stratal units provide additional hints to constrain the correlation of the studied sections. The flat nature of the Bahariya Oasis topography, which parallels the water table, provides a good reference horizon for the correlation of the basal units of the exposed sections in the studied localities. We take this reference quasi-horizontal line as a datum for the stratigraphic cross-section (Fig. 8).

4.1. Systems tracts and bounding surfaces

Systems tracts are packages of strata composed of age-equivalent depositional systems, and correspond to specific stages of shoreline shifts (Brown and Fisher, 1977; Posamentier and Vail, 1988). Four such stages may be distinguished during a full cycle of base-level changes, i.e. a late-rise (highstand) normal regression, a forced regression (base-level fall), an early-rise normal regression, and a transgression. The sediments accumulated in all depositional environments across the basin during these stages result in the formation of highstand (HST), falling stage (FSST), lowstand (LST) and transgressive (TST) systems tracts respectively. Each systems tract is bounded by particular types of sequence stratigraphic surfaces with a specific timing relative to the reference curve of base-level changes, and lateral facies shifts are expected along dip in response to changing depositional environments. For a full account

Fig. 8. Cross-section of correlation of the studied localities, showing the sequence stratigraphic framework of the Bahariya Formation (see Fig. 1 for the location of stratigraphic sections). Abbreviations: LST — lowstand systems tract; TST — transgressive systems tract; HST — highstand systems tract; FA — facies association (see text for lithofacies descriptions and interpretations); SU — subaerial unconformity; MRS — maximum regressive surface; MFS — maximum flooding surface; WRS/MRS — wave ravinement surface that replaces the maximum regressive surface; WRS/SU — wave ravinement surface that replaces the subaerial unconformity.

of these sequence stratigraphic concepts, see Catuneanu (2002, 2006).

The subdivision of the Bahariya Formation into systems tracts is fairly straight-forward, based on the sedimentological characteristics of the facies associations described above, as well as on the nature of contacts that separate them. The type section (Gabal El-Dist) of the Bahariya Formation is also the most complete and diverse from a sequence stratigraphic point of view, preserving the highest number of systems tracts. For this reason, we will start first with an account of the systems tracts encountered in the Gabal El-Dist section, after which we complete the sequence stratigraphic framework of the study area by correlating this type section with the other four studied sections.

4.1.1. Gabal El-Dist section

Each facies association in the Gabal El-Dist section (1 to 5, with the association 2 repeated three times) corresponds to an entire, or part of a systems tract. Facies association 2 displays a retrogradational character, being composed of backstepping parasequences, and therefore is interpreted as a TST. Underlying the oldest TST in this section, the delta plain deposits of facies association 1 correspond to a LST. The contact between these two systems tracts is marked by a wave ravinement surface that replaces the maximum regressive surface, as there is no evidence of fluvial or coastal transgressive deposits below the wave ravinement surface. The wave ravinement surface is associated with a 20–30 cm thick fossiliferous lag deposit (Fig. 2D), and marks an abrupt shift of facies in a landward direction from delta plain below to fully marine above. Even though scoured, this contact is most likely associated with very little or no discernable stratigraphic hiatus in the rock record because the change from lowstand normal regression to subsequent transgression takes place during continuous base-level rise. The base of the LST, which coincides with the base of the Bahariya Formation, is not exposed but is inferred to be represented by an unconformity (El Bassyouny, 1970, 2004).

The oldest TST of the Gabal El-Dist section is conformably overlain by the floodplain-dominated fluvial deposits of facies associations 3 and 4. These fluvial deposits mark a basinward shift of facies relative to the underlying (TST) marine facies, and are therefore interpreted as the HST of the first (oldest) depositional sequence of the Bahariya Formation (Fig. 8). This HST is truncated at the top by a sequence boundary (contact with overlying TST; Fig. 8), and is separated from the underlying HST by a maximum flooding surface.

The middle TST of the Gabal El-Dist section forms a depositional sequence on its own, as it is bounded by sequence boundaries both at the base and at the top. The LST of this second sequence is missing, due to either non-deposition or subsequent wave ravinement erosion. The HST of this sequence is missing as well, most likely due to subaerial erosion (fluvial incision) subsequent to its deposition. The upper boundary of this middle TST/second sequence is represented by a proper subaerial unconformity, whereas the lower contact is a wave ravinement surface replacing the subaerial unconformity.

The third depositional sequence in the Gabal El-Dist section includes two systems tracts, i.e. a LST (facies association 5) overlain by a TST (facies association 2) (Fig. 8). The HST of this upper depositional sequence is not preserved, as the succession is truncated by the present-day topographic profile. The LST of this sequence is a typical fluvial low-accommodation succession, and is overlain by the retrograding marine facies of the TST. The boundary between these two systems tracts is represented by a wave ravinement surface that replaces the maximum regressive surface. As in the case of the first depositional sequence of this section, there is no evidence of fluvial or coastal transgressive deposits being preserved below the wave ravinement surface, which means that the maximum regressive surface is not preserved either. The lower boundary of this third sequence is represented by a subaerial unconformity, at the contact between the backstepping parasequences of the middle TST/second sequence and the overlying amalgamated braided channel fills.

4.1.2. Naqb El-Bahariya section

The Naqb El-Bahariya section shows a simpler succession of systems tracts relative to the Gabal El-Dist locality, even though the two sections attain comparable total thicknesses, due to the process of valley incision that took place prior to the accumulation of the amalgamated braided channel fill deposits (facies association 5; Fig. 8). This incised valley explains the abrupt increase in the thickness of braided fluvial facies which replace laterally, but are younger than, three of the systems tracts noted in the Gabal El-Dist section: the lower TST, the HST, and the middle TST. These three systems tracts are not preserved in the Naqb El-Bahariya locality, being eroded by the fluvial incision associated with the subaerial unconformity at the base of the third depositional sequence (Fig. 8).

From the base, the first/oldest systems tract encountered in the Naqb El-Bahariya section is the LST composed of the delta plain facies of association 1, which correlates to the basal LST of the Gabal El-Dist locality. These systems tracts occur at the same stratigraphic level within the Bahariya Formation, and include virtually identical facies. The rest of the first/oldest depositional sequence (TST and HST systems tracts in the type section), as well as the second depositional sequence (middle TST in the type section), are missing here. The basal LST is directly overlain by the third depositional sequence of the Bahariya Formation, being truncated at the top by the sequence boundary (subaerial unconformity).

The remaining part of the Naqb El-Bahariya section is the correlative of the third depositional sequence in the Gabal El-Dist section (Fig. 8). The lower part of this sequence, which forms the bulk of the exposed stratigraphy in this locality, consists of thick incised valley fill deposits, interpreted here as a LST. These amalgamated channel fill sandstones suggest deposition under low accommodation conditions (Shanley and McCabe, 1994), as expected from a stage of early base-level rise, lowstand normal regression. This LST is overlain by transgressive marine facies (TST — facies association 6) which represent the more distal equivalent of the upper TST in the Gabal El-Dist section. This correlation is in agreement with the regional trend of basin deepening towards N–NE, which explains the lateral change of facies from shoreface (Gabal El-Dist) to shelf (Naqb El-Bahariya) along dip within this TST. The boundary between the LST and the TST of this depositional sequence is represented by a wave ravinement surface that replaces the maximum regressive surface. The lack of a preserved maximum regressive surface is indicated by the absence of any discernable fluvial or coastal transgressive facies (Embry, 1993). In this locality, the wave ravinement surface (systems tract boundary in this case) also reworks a lower-order subaerial unconformity, as the transgressive shales directly overlie the uppermost preserved paleosol (ferricrete) horizon of the LST. The youngest (TST) systems tract in this section is truncated at the top by the present-day topographic profile.

4.1.3. West of Sandstone Hills and Gabal Radwan sections

The stratigraphic succession in the central part of the Bahariya Oasis also starts with a LST, as in the correlative sections to the North. This basal LST seems to be preserved throughout the study area, and groups together strata placed at the same elevation and stratigraphic level within the Bahariya Formation. The LST facies in the West of Sandstone Hills and Gabal Radwan sections are dominated by floodplain fluvial deposits, which represent the proximal equivalent of the delta plain facies to the North. This correlation is also supported by the syn-depositional configuration of the basin, with topographic gradients dipping to the N–NE. In this interpretation, the shoreline at the time was probably oriented ESE–WNW and positioned just North of the present-day Bahariya Oasis.

The fluvial facies of the basal LST are overlain by backstepping beach deposits (facies association 7), which are therefore interpreted as part of a TST. The boundary between LST and TST in these central sections is marked by a maximum regressive surface, and not by a wave ravinement surface as was the case with the base of the other TSTs discussed above for the northern part of the study area (Fig. 8). This is because in open coastal settings, wave ravinement surfaces always form *at the top* of backstepping beaches, as the shoreface (with its wave action) retrogrades over coastal sediments. The maximum regressive surface at the base of the transgressive beach deposits is superimposed on a lower-order subaerial unconformity, as the beach sediments directly overlie the uppermost paleosol (ferricrete) horizon of the underlying LST. As observed in the field, the maximum regressive surface is slightly scoured, probably in relation to the backstepping of the higher energy intertidal swash zone over the overbank deposits of the LST. The transgressive beach is truncated at the top by a subaerial unconformity (sequence boundary) associated with processes of fluvial incision, so the preserved TST (only 2–3 m thick) is most likely only the lower part of an originally better developed transgressive succession. This beach correlates to the lower part of the first/oldest TST in the Gabal El-Dist locality (Fig. 8), and represents the proximal equivalent of the subtidal environment present in the type section. Again, this correlation is in agreement with the regional configuration of the basin, in which the marine facies are positioned to the North of the coastal facies at any given time step.

The lower LST–TST package of the central sections, discussed above, is sharply overlain by the braided stream deposits (facies association 5) which form the LST of the third depositional sequence of the Bahariya Formation (Fig. 8). The thickness of this LST in the central part of the study area is greater then in the Gabal El-Dist section, suggesting the presence of another incised valley in the region of the West of Sandstone Hills and Gabal Radwan sections. The existence of this incised valley is also confirmed by the absence of the HST and the middle TST noted in the Gabal El-Dist locality, which are laterally replaced in the central sections by the braided fluvial deposits of the incised valley fill (Fig. 8). These LST incised valley fill deposits are bounded at the base and at the top by major subaerial unconformities. In contrast to the northern sections, no other systems tracts are preserved within this third depositional sequence, suggesting stronger erosional processes associated with its upper boundary in this central region of the Bahariya Oasis.

The top of the West of Sandstone Hills and Gabal Radwan sections consists of a younger generation of braided stream deposits (facies association 8), which is unique within the study area and has a relatively localized area of occurrence. This unit is bounded at the base by a subaerial unconformity, which truncates a significant portion of the underlying sequence, and at the top by the present-day topographic profile (Fig. 8). Similar to facies association 5, we interpret this package as the LST fill of a younger incised valley, which forms the lower part of a fourth depositional sequence and replaces laterally the older TST facies of the third depositional sequence (Fig. 8).

4.1.4. West of Naqb El-Selim section

The southern part of the Bahariya Oasis is placed in the most proximal position of the paleo-continental shelf relative to all other studied sections, within an area that was subject to nonmarine sedimentation during the entire Bahariya Formation time interval. The West of Naqb El-Selim section consists of a fully fluvial succession, dominated by facies association 3. The relatively monotonous nature of this succession makes the task of tracing the continuation of sequence stratigraphic surfaces within this area difficult, and at this point the correlation proposed in Fig. 8 between the West of Naqb El-Selim section and the other studied localities in the central and northern parts of the Bahariya Oasis should only be regarded as tentative.

4.2. History of base-level changes

Our analysis shows that within the study area, the Bahariya Formation is composed of four depositional sequences whose architecture and spatio-temporal relationships are illustrated in Fig. 8. These sequences are bounded by major subaerial unconformities, replaced or not by transgressive wave ravinement surfaces, and correspond to four distinct stages of base-level rise in the Early Cenomanian evolution of the Bahariya Oasis separated by periods of base-level fall (timing of sequence boundaries). The following main stages, which are presented in chronological order starting with the oldest, contributed to the preserved architecture of the Bahariya Formation stratigraphy:

1. *Lowstand normal regression 1*: this stage of early base-level rise was dominated by high sedimentation rates (as suggested, for example, by the suite of sedimentary structures of facies association 1), higher than the rates of base-level rise, and resulted in the progradation and aggradation of the basal LST of the Baharyia Formation. This systems tract seems to be preserved across the entire study area.
2. *Transgression 1*: increased rates of base-level rise resulted in the overall flooding of the northern and perhaps central parts of the study area. The maximum transgressive shoreline was probably located close to the West of Sandstone Hills and Gabal Radwan sections, as suggested by the preserved beach deposits in these areas. The sediments accumulated in the Bahariya Oasis during this transgression formed a TST that is currently preserved in the Gabal El-Dist type section, as well as in the central part of the Oasis (Fig. 8). This TST has been completely eroded in the Naqb El-Bahariya locality during subsequent stages of base-level fall.
3. *Highstand normal regression 1*: this is the stage of late base-level rise of the first depositional sequence of the Bahariya Formation, when sedimentation rates outpaced again the rates of base-level rise. As a result, nonmarine sedimentation was re-established on top of the marine facies of the underlying TST. Highstand deposits generally have a low preservation potential due to the erosional processes associated with the formation of the subaerial unconformity during subsequent base-level fall. This HST is no exception, as it is only preserved in the Gabal El-Dist type section.
4. *Forced regression 1*: this stage of base-level fall resulted in the formation of a subaerial unconformity (first sequence boundary within the Bahariya Formation) across the study area. This subaerial unconformity was subsequently downcut by younger sequence boundaries (incised valleys), and was replaced in the Gabal El-Dist section by a younger transgressive wave ravinement surface. This stage of base-level fall terminates the deposition of the first sequence of the Bahariya Formation.
5. *Lowstand normal regression 2*: no LST deposits are preserved as part of the second depositional sequence of the Bahariya Formation. This may be due to non-deposition, or subsequent transgressive wave ravinement erosion.
6. *Transgression 2*: the sediments of the second transgressive stage in the Bahariya depositional history are only preserved in the Gabal El-Dist locality. This TST was eroded by processes of subsequent valley incision in all other studied sections, and, in the type section, is the only remnant of the second depositional sequence of the Bahariya Formation.
7. *Highstand normal regression 2*: no HST deposits are preserved as part of the second depositional sequence of the Bahariya Formation. The absence

of highstand strata is attributed to processes of subaerial erosion that took place during the stage of forced regression 2.

8. *Forced regression 2*: this is the stage of base-level fall that resulted in the formation of the sequence boundary that separates depositional sequences 2 and 3. This sequence boundary is particularly prominent, with significant topographic relief associated with the presence of a system of incised valleys. The magnitude of base-level fall that took place during this stage was of minimum 36 m, which equals the difference in thickness between the facies association 5 deposits in the Gabal El-Dist and Naqb El-Bahariya sections.
9. *Lowstand normal regression 3*: this stage of renewed base-level rise resulted in the deposition of LST incised valley fill deposits which leveled the highly irregular topography that existed along their basal sequence boundary by the end of the preceding falling stage. These LST deposits are interpreted to have accumulated during the early stage of base-level rise (lowstand), under low accommodation conditions. The high sediment supply from rejuvenated source areas likely outpaced the amount of newly created accommodation, leading to a normal regression of the shoreline which was positioned to the North of the study area during that particular time.
10. *Transgression 3*: following lowstand, the rates of base-level rise increased to the point where they outpaced the amount of sediment supply, leading to a third marine flooding of the study area. The sediments accumulated during this transgression (TST of depositional sequence 3) are now preserved at the top of the northern sections, and are eroded by processes of fluvial valley incision in the central part of the Bahariya Oasis.
11. *Highstand normal regression 3*: no HST deposits are preserved to date as part of the second depositional sequence of the Bahariya Formation. The absence of highstand strata is attributed to processes of subaerial erosion that took place subsequent to their sedimentation.
12. *Forced regression 3*: this stage of base-level fall terminated the deposition of the third sequence of the Bahariya Formation, and resulted in the formation of at least one incised valley in the central part of the study area. This incised valley truncates into the underlying third sequence, removing its HST and TST (see the West Sandstone Hills and Gabal Radwan sections in Figs. 5, 6). The thickness of this incised valley fill (facies association 8) provides a minimum estimate for the amount of base-level fall that took place during this stage.
13. *Lowstand normal regression 4*: these LST deposits (facies association 8; Fig. 8) are interpreted as the youngest preserved strata of the Bahariya Formation. They form the fill of an incised valley, replacing laterally the older TST strata of the depositional sequence 3. This LST is the only preserved portion of the depositional sequence 4, being truncated at the top by the present-day topographic profile.

4.3. Hierarchy of sequences

The concept of hierarchy is a key in sequence stratigraphy, and deals with the relative importance of cyclothems observed at different scales (Mitchum and Van Wagoner, 1991; Catuneanu et al., 2005). For example, in this case study the systems tracts we delineated provide the basic subdivision of the Bahariya Formation/sequence into genetic packages that show consistent trends. At a closer look, however, most of these systems tracts show internal cyclicity at much smaller scales. The TSTs observed in the Gabal El-Dist section consist of numerous cyclothems bounded by minor (lower order) wave ravinement surfaces, each replacing a same-order subaerial unconformity — these are the contacts between ferricrete horizons (paleosols formed during times of subaerial exposure) and the overlying transgressive marine facies. Each of these meter-scale cyclothems is therefore a depositional sequence on its own, corresponding to a full cycle of high-frequency base-level change. As demonstrated before, sequence stratigraphic studies may be performed at any scale, including the delineation of systems tracts and sequence stratigraphic surfaces even within study areas of only a few square meters (e.g., Posamentier et al., 1992).

The Bahariya Formation itself is an unconformity-bounded depositional sequence which corresponds to a major stratigraphic cycle in the evolution of the passive margin setting of the Western Desert. The entire package of passive margin deposits corresponds to a first-order sequence, as being related to one distinct tectonic setting. Hence, according to the hierarchy system based on the magnitude of base-level changes that resulted in the formation of the sequence (Embry, 1995), the Bahariya Formation can be assigned a second-order level of stratigraphic cyclicity. In this context, the four depositional sequences which form its stratigraphic subdivisions, may be regarded as third-order sequences.

This conclusion regarding the hierarchical level of the four depositional sequences of the Bahariya Formation is also in agreement with the hierarchy system based on cycle duration, as originally devised by Vail et al., 1977. These four sequences accumulated within a period of time of c. 3–6 My, indicating stratigraphic cycles of approximately 1 My duration for each sequence. Such cycles have also been delineated as "third-order" by the proponents of the time-based hierarchy (see Catuneanu, 2006, for a full discussion of the concept of sequence stratigraphic hierarchy).

5. Conclusions

1. The unconformity-bounded Bahariya Formation is a second-order depositional sequence, as representing a major subdivision of the first-order Jurassic–Cenomanian passive margin succession of the Western Desert in Egypt.
2. The construction of the third-order sequence stratigraphic framework for the Bahariya Formation was based on a detailed sedimentological study, and paleo-depositional environment interpretations, performed in five main localities in the Bahariya Oasis.
3. Eight distinct facies associations have been recognized, corresponding to changes in clastic lithology, color, sedimentary structures and stratal stacking patterns. These facies associations reflect shifts in paleo-depositional environments from outer shelf (deepest marine facies recorded in the study area) to shoreface, coastal, and fluvial (high and low energy systems).
4. Lateral and vertical changes of facies, as well as the nature of facies contacts, are explained by using a sequence stratigraphic model in which systems tracts and sequence stratigraphic surfaces are linked to particular stages in the evolution of the basin. These stages reflect consistent trends of aggradation, progradation, retrogradation or erosion at the third-order level of stratigraphic cyclicity.
5. The Bahariya Formation is composed of four stacked depositional sequences, each corresponding to a stage of overall base-level rise in the basin. Sequence boundaries signify stages of base-level fall, whose magnitude may be estimated from the amount of valley incision as inferred from the thickness variation of lowstand deposits across the Bahariya Oasis.
6. The history of base-level changes and associated shifts in depositional trends has been reconstructed for thirteen consecutive time steps during the Early Cenomanian interval, showing repeated cycles of lowstand normal regressions, transgressions and highstand normal regressions, separated by stages of fluvial valley incision.
7. At least two generations of incised valley systems have been identified, which explain the absence of some systems tracts in particular areas, significant thickness variations of incised valley fills, and the abrupt lateral facies changes observed across relatively short distances.

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