Journal of African Earth Sciences 89 (2014) 133–148

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Sequence stratigraphy of the Cenomanian Galala Formation, north Eastern Desert, Egypt

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ARTICLE INFO

Article history:
Received 22 December 2012
Received in revised form 26 August 2013
Accepted 6 September 2013
Available online 9 October 2013

Keywords:
Sequence stratigraphy
Galala Formation
Eastern desert
Edypt

ABSTRACT

The sequence stratigraphic framework of the Cenomanian Galala Formation (north Eastern Desert, Egypt) is estimated on the basis of the Sedimentological and obtainable biostratigraphic data, in addition to the regional correlation of the studied sections. Five sequence boundaries are identified. The first sequence boundary separates between the Galala and Malha formations. The second, third and fourth sequence boundary exhibit a differentiated nature. It is noticed that such sequence boundaries in Gebel El-Zeit are mainly represented by paleosols and caliche, while those of the Northern Galala, Gebel Ataqa and Gebel Shabraweet are mostly typified by emergence horizons of dolomites and dedolomites. The fifth (last) sequence boundary separates the Galala Formation from the overlying El-Khashm Formation at Gebel El-Zeit, the Northern Galala and Gebel Ataqa and from Maghra El-Hadida Formation at Gebel Shabraweet.

The Galala Formation in the study area is subdivided into four depositional sequences, which are built up of three systems tracts; the lowstand (LST), transgressive (TST) and highstand (HST) systems tracts. The LSTs are realized only from Gebel El-Zeit, where they are made up of clastic facies organized in coarsening- and fining-upward parasequences. The TSTs form a series of aggradational-retrogradational, shallowing-upward parasequences, which transgress across the ramp till the point of maximum flooding is reached. The HSTs are built up of aggradational–progradational, shallowing-upward parasequences of shallow subtidal to peritidal facies.

1. Introduction

Sequence stratigraphy is the study of repetitive genetically-related depositional facies bounded in part by significant surfaces of non-deposition or erosion (Galloway, 1989 and Catuneanu, 2002). A key concept of sequence stratigraphy is the interplay between eustatic sea-level changes and subsidence rate that creates the accommodation that required for sediment accumulation (Jervey, 1988 and Posamentier et al., 1988). The application of sequence stratigraphy concepts to clastic and carbonate depositional systems has been widely developed by Mitchum (1977), Vail et al. (1977), Vail (1987), Haq et al. (1987 and 1988), Posamentier and Vail, 1988; Sarg (1988), Van Wagoner et al. (1988 and 1990) and Posamentier et al. (1992).

The terminologies of Van Wagoner et al. (1988), Sarg (1988) and Handford and Loucks (1993) supported by modern concepts of Catuneanu (2006) are adopted herein. Except the term parasequence that is used in describing an upward-shallowing succession of facies bounded by marine flooding surfaces (Van Wagoner et al., 1988, 1990). Hence, we used the term cycle instead of parasequence in describing the shallowing-upward or coarsening-upward and fining-upward, or deepening-upward cycles in the present study (Khalifa, 1996). The application of sequence stratigraphic principles can however be successfully performed even in the near absence of constrained time lines, whereas the facies geometry, stacking pattern and depositional models are well understood (Catuneanu et al., 2006, 2009, 2010, 2011). The sequence stratigraphy and cyclicity of the Cenomanian rocks of the Eastern Desert was studied by few workers (e.g. El-Azabi, 1999; Khalil and Mostafa, 2001a,b; Essa, 2005; Abu El-Hassan and Tada, 2005 and Khalifa and El-Ayyat, 2007). The aim of present study is to estimate the sequence stratigraphic classification of the Galala Formation, exposed north of the Eastern Desert. This leads to clarify the relation between sequence boundaries, systems tracts and depositional sequences.

2. Geological background

During the Upper Cretaceous interval, a great transgression progressed covering Egypt from the north until latitude 23° N in south reaching its highest amplitude during the Late Cenomanian time

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1464-343X/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.jafrearsci.2013.09.005

(Issawi and Osman, 2000). The tectonism that affected the North African Plate and sea-level changes had a great influence on the depositional history of the Upper Cretaceous successions in Egypt, forming different topographical and structural basins. As a result, the Upper Cretaceous sequence shows a rapid facies change (Issawi et al., 1999). The Cenomanian succession is outcropped in Egypt in three main districts; the Northern and Southern Sinai, Eastern Desert (between Gebel Shabraweet and Wadi Qena) and Western Desert (Bahariya Oasis and doubtfully at Abu Roash area). These areas proved to be active areas of subsidence (Fawzi, 1963). They represent one of the major transgressive cycles during the Cretaceous Period in Egypt, that resulting in forming of very shallow seas to the lows between the elevated massifs (Said, 1990). The transgression of the Cenomanian Sea has progressed generally from the north to the south of Egypt. Generally, the thickness of the exposed marine Cenomanian diminishes gradually towards the south with more clastic facies (maximum thickness is 550 m in the north of Egypt and minimum thickness is 20 m in the south). The Cenomanian rocks form a formal rock unit (Galala Formation) in the northern part of the Eastern Desert (Awad and Abdallah, 1966). The depositional basin of the Galala Formation in the northern part of the north Eastern Desert was deeper than its southern part and free from any argillaceous influx (Metwally and Abd El-Azeam, 1997).

3. Methods

Four stratigraphic sections were measured in the northern Eastern Desert; at Gebel El Zeit, Northern Galala, Gebel Ataqa and Gebel Shabraweet (Fig. 1). In each section, we logged the lithology at decimeter scale and whenever lithologic changes are observed. Identification of fossil association and petrographic investigation

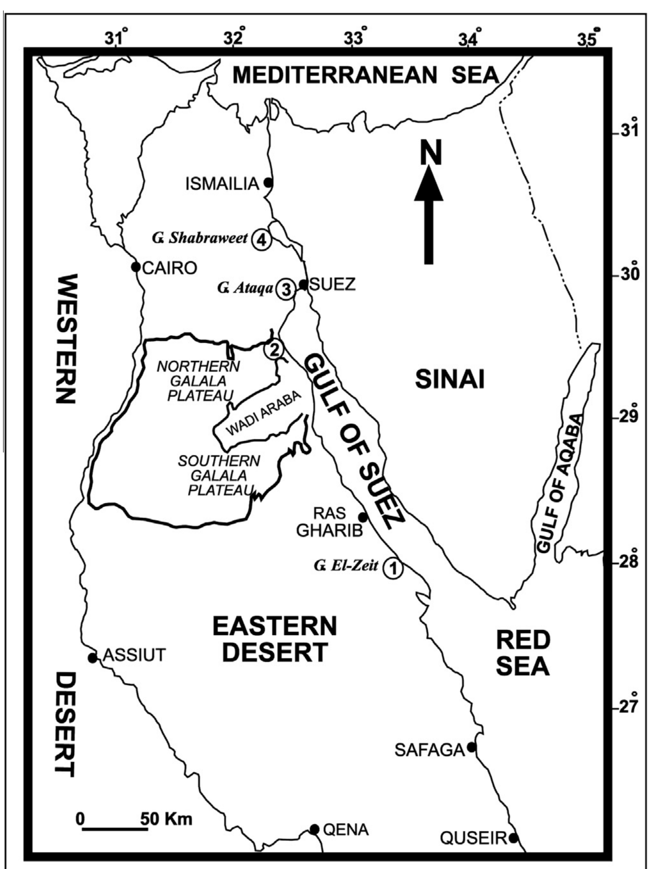

Fig. 1. Location of the studied sections.

of the hard specimens provide a background for interpreting lithology. The sequence stratigraphic study of the Galala Formation is mainly based on the Sedimentological data (Lithostratigraphy and petrography), regional correlation of the studied sections and the available biostratigraphic framework. Sequence stratigraphy was interpreted on the basis of several features including; (1) tracing of erosional surfaces and apparent flooding surfaces in the field, (2) patterns of upward change (fining- and coarsening-upward), (3) types of depositional cycles and 4) types of dolostones occurring in the studied sequence.

4. Lithostratigraphy

The Galala Formation unconformably overlies the fluvio-marine clastic facies of the Early Cretaceous Malha Formation at Gebel El-Zeit and Gebel Shabraweet. The unconformity surface at Gebel El-Zeit separates between the grey, violet, brown sandy claystone of the uppermost Malha Formation and the green to yellowish green claystone of the Galala Formation (Fig. 2A). At the Northern Galala, the Galala Formation conformably overlies the Malha Formation with a sharp contact. The contact is between the red to violet, sandy siltstone of the Malha Formation and the green to yellowish green claystone of the Galala Formation (Fig. 2C). The base of the Galala Formation is unexposed at Gebel Ataqa, while at Gebel Shabraweet; the unconformity surface is represented by an intraformational conglomeratic bed (30 cm) (Fig. 2B). It is placed between the yellow, hard and ferruginous sandstone of the Malha Formation and the yellowish grey and massive limestone enriched in oysters of the lowermost of the Galala Formation.

The Galala Formation is unconformably overlain by El-Khashm Formation at Gebel El-Zeit (Fig. 2D), the Northern Galala (Fig. 3A) and Gebel Ataqa. The unconformable contact is represented by undulated, irregular zone that contains white caliche nodules. At Gebel Shabraweet, the Galala Formation unconformably underlies Maghra El-Hadida Formation. The contact is taken at the top of dark brown to black, ferruginated and cherty dolostone of the uppermost part of the Galala Formation (Fig. 3B). The lithostratigraphic classification of the studied sequence is given in Table 1.

The Galala Formation is composed of well-bedded mixed clastic-carbonate sequence, whereas the percentage of the carbonate rocks increases northward at the expense of siliciclastics. At Gebel El-Zeit, the Galala Formation is made up of claystone (43%), sandstone (31.6%), dolostone (21%), caliche (2%), siltstone (1%), marl (1%) and limestone (0.4%). At the Northern Galala, the Galala Formation is built up of claystone (53%), dolostone (18%), limestone (12%), dolomitic limestone (7.4%), marl (6.7%) and siltstone (3%). These lithofacies are arranged as shallowing-upward cycles. The cycles almost start with claystone at the base and capped by dolostone, dolomitic limestone or limestone. At Gebel Ataqa, the Galala Formation consists of dolostone (39.5%), dolomitic limestone (31%), limestone (26%), claystone (2.2%) and marl (1.3%). At Gebel Shabraweet, the Galala Formation includes dolostone (51%), limestone (19%), claystone (18%), dolomitic limestone (11.9%) and glauco-arenite (0.1%). The thickness of the Cenomanian Galala Formation diminishes southward from Gebel Shabraweet (201.25 m) to Gebel El-Zeit (71.5 m). It reaches to 93 m and 74.5 m and at Gebel Ataqa and the Northern Galala respectively.

Paleontologically, the Galala Formation is rich in the Cenomanian macrofossils. The bivalves (particularly oysters) are the most common fossils. They are represented by *Costagyra olisiponensis* Sharpe, *Ilmatogyra africana* Lamarck, *Amphidonte flabellatum* (Goldfuss), *Rhynchostreon suborbiculatum* (Lamarck), *Inocermas* (*Birostrina*) *tennuiradialis* Zakhera, *Parasea faba* Sowerby, *Dosinia delettrei* (Coquand), *Plicatula auressensis* Coquand, *Glossus solimani* (Abbass), *Venericardia forgemoli* (Coquand), *Meretrix faba* (Sowerby), *Eoradio-*

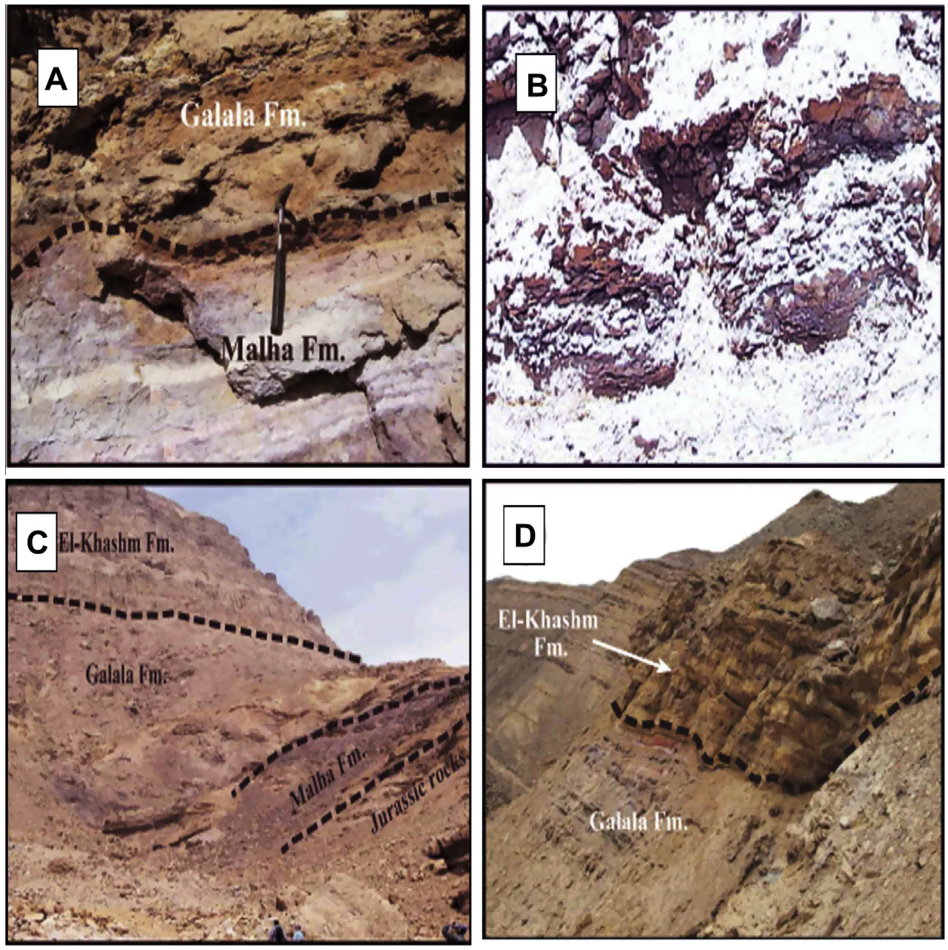

Fig. 2. (A) The lower contact of the Galala Formation with the underlying Malha Formation at Gebel El-Zeit. (B) The lower contact of the Galala Formation at Gebel Shabraweet (conglomeratic bed of mottled dolostone). (C) The sedimentary succession outcropped at the Northern Galala. The succession includes the Jurassic rocks, Malha, Galala and El-Khashm Formations. (D) The upper contact of the Galala Formation with the overlying El-Khashm Formation at Gebel El-Zeit. The contact is between the well-bedded clastic facies of the Galala Formation and the standing dolostones of El-Khashm Formation.

lites liratus (Conrad), *Gyrostrea delettrei* (Coquand), *Granocardium* sp., *Trigonia* sp. and *Anisocardium* sp. The gastropoda are represented by *Tylostoma pallayi* (Fortau), *Tylostoma cosoni* Thomas & Peron, *Cerithium tenoklene*se (Coquand), *Strombus inceratus* d'Orbigny, *Aporrhais dutrugei* Coquand, *Turritella dakhlensis* Abbass and *Columbellina fusiformis* Douvillé. The echinoderms are *Hemiaster* (*Hemiaster) cubicus* Desor, *Hemiaster* (*Mecaster) pseudofourneli* Peron & Gauthier, *Mecaster batnensis* Coquand, *Micropedina olisiponensis* Forbes, *Coenholectypus larteti* Cotteau, *Tiaradia weldoni* Fourtau and *Trochodiadema libanoticum* De Lorial. The cephalopods are belonging to *Angulithes mermeti* (Coquand), *Neolobites vibrayeanus* (d'Orbigny), *Metoicoceras geslinianum* (d'Orbigny) and *Rubroceras alatum* Cobban.

5. Sequence stratigraphy

5.1. Sequence boundaries

A sequence boundary is an unconformity or its correlative conformity (Mitchum, 1977). The sequence boundaries are surfaces of erosion or exposure that represent a significant time gap. They are formed in response of relative sea-level falls. This drop in sea level may be originated by changes in the rate of subsidence or eustatic rise, as long as those changes give birth to a net loss of accommodation space. The sequence boundaries of the Galala Formation are represented by zones of small-scale discontinuities rather than by widespread and well-marked unconformities. They are marked by well-defined subaerial exposure horizons (paleosol and caliche), digenetic features accompanying aerial exposure (pervasive dolomitization, dedolomitization and leaching of fossils) and where abrupt vertical facies changes are notice (Sarg, 1988; Tucker, 1993; Clari et al., 1995 and Molina et al., 1999).

The major sequence Galala Formation at Gebel El-Zeit is segmented by five sequence boundaries (discontinuity horizons). The first sequence boundary (SB.1) in Gebel El-Zeit is represented by a red paleosol horizon with channels (incised valley fill), representing a conspicuous depositional hiatus with a thickness of 10–20 cm (Fig. 3C). In the Northern Galala, the first sequence boundary (SB.1) occurs between the fluvio-marine sandy siltstone of the Malha Formation and the shallow subtidal oyster claystone of the Galala Formation. In Gebel Ataqa, the first sequence boundary (SB.1) is unexposed, while in Gebel Shabraweet, the first sequence boundary (SB.1) is represented by an unconformity zone (30 cm) between the Galala and Malha formations in form of a conglomeratic bed. This bed consists of mottled dolostone and dolomitic limestone pebbles with reworked bivalvia and lithoclasts, probably derived from the overlying Galala Formation.

The SB.2 at Gebel El-Zeit separates between the burrowed ferroan dolomicrite on the top of the first depositional sequence and the pure clastic facies (claystone and siliceous sandstone) of the LST.2.

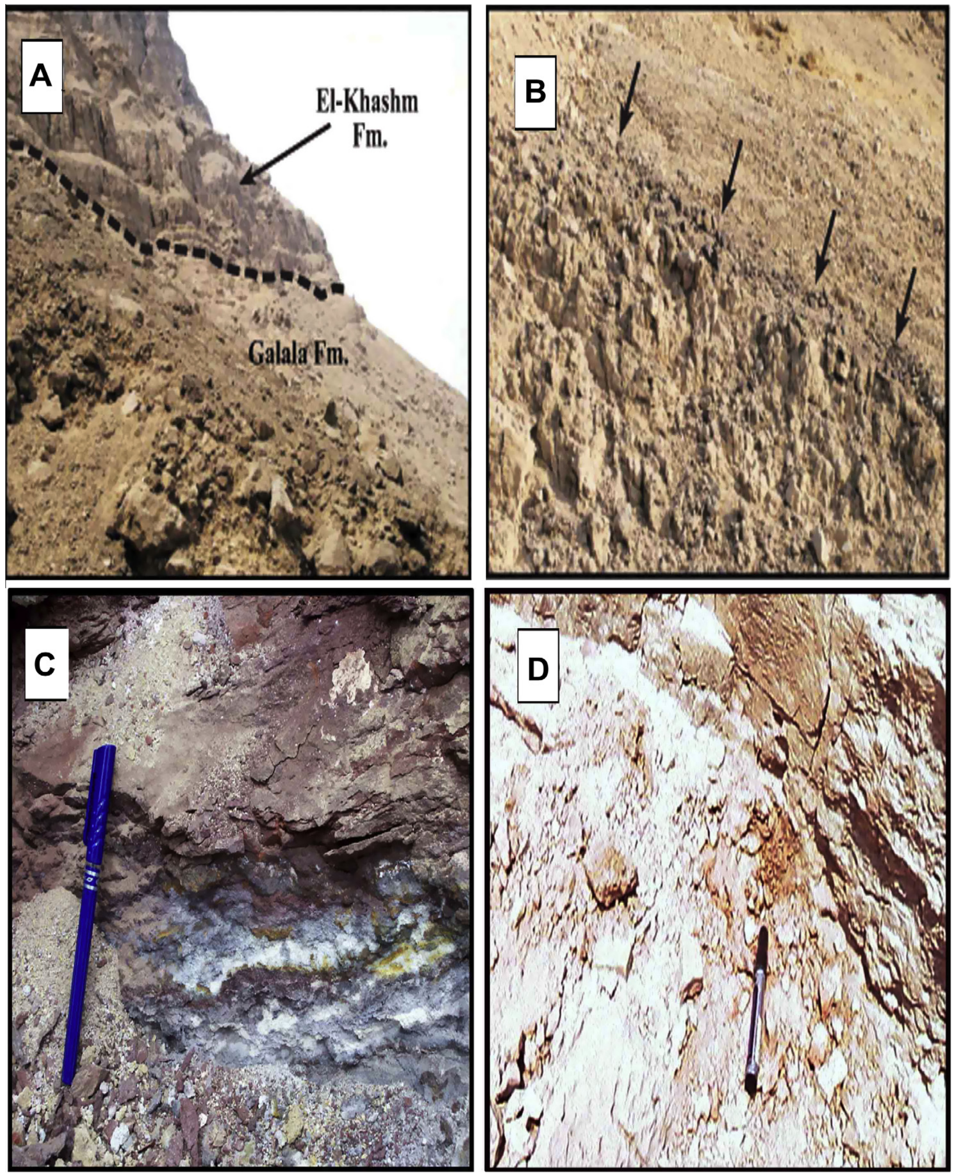

Fig. 3. (A) The upper contact of the Galala Formation with the overlying El-Khashm Formation at the Northern Galala. (B) The dark brown to black, siliceous cherty and ferruginated dolostone (arrows) of the uppermost Galala Formation at Gebel Shabraweet. C. The reddish paleosol horizon with incised valley fills (SB.1 of Gebel El-Zeit). (D) The reddish paleosol horizon (terra rosa), representing the SB.2 of Gebel Ataqa.

In the Northern Galala, SB.2 lies above the yellow burrowed dolomicrite, which shows uneven and sharp contact with the overlying green, oyster claystone at the basal part of the second depositional sequence. In some areas of this dolomicrite, few calcite pockets and vein lets along desiccation cracks indicate the dedolomitization phenomena at the subaerial zone. In Gebel Ataqa, SB.2 occurs above the fresh water, reddish paleosol horizon (0.5 m) analogous to terra rosa. This paleosol bed consists of marly lime mudstone, some caliche nodules, iron oxide patches and some lime-mud lithoclasts (Fig. 3D). The recorded terra rosa zone contains ferruginous-filled, irregular seams and cavities (Fig. 4A) that implies subaerial exposure (Hillgärtner, 1998 and Wanas, 2008). SB.2 of Gebel Shabraweet is indicated by the irregular sharp contact on the top of the dolomicrite of the uppermost TST.1 and below the oyster claystone of the second depositional sequence. This is confirmed by the presence of dedolomites (dolomite replaced by calcite in subaerial zone (Khalifa, 1981) in some areas of this dolomicrite.

In Gebel El-Zeit, SB.3 occurs on the top of the fossiliferous marl and below the green claystone of the basal LST.3. In Gebel Ataqa, SB.3 is placed on the top of the dolomicrite that shows a brecciation (top of the HST.2). It coincides with the top of the second depositional sequence. Such brecciated carbonate horizon (Fig. 4B) was described as a bounding zone by numerous workers (e.g. Molina et al., 1999; Immenhauser et al., 2001 and Khalifa, 2005). They attributed the brecciation in the carbonate platforms to the karstification during periods of sea-level drop and exposure. SB.3 of Gebel Shabraweet is documented by the presence of wavy, irregular fissures and cavities with local paleo-relief and truncated lower bed. They are filled with ferruginous material and mud lithoclasts (Fig. 4C). Around these fissures and cavities, there are several calcite vugs that may indicate subaerial exposure (Fig. 4D). Such features suggest a sea-level drop or uplift (Hardie et al., 1991). They are similar to the hardground that was developed by macro-boring invertebrates during a short-term sea-level drop (Hillgärtner, 1998 and Wanas, 2008).

Table 1
Lithostratigraphic classification of the studied succession in the area under consideration (not to scale).

Age		Gebel El-Zeit (section no.1)	Southern Galala (section no.2)	Northern Galala (section no.3)	Gebel Ataqa (section no.4)	Gebel Shabraweet (section no.5)
Late Cretaceous	Turonian-Santonian	Wata Formation	Wata Formation	Maghra El-Hadida Formation	Maghra El-Hadida Formation	Maghra El-Hadida Formation
	Cenomanian	El-Khashm Formation	Galala Formation	El-Khashm Formation	El-Khashm Formation	Galala Formation
		Galala Formation		Galala Formation	Galala Formation	
Early Cretaceous		Malha Formation	Malha Formation	Malha Formation		Malha Formation

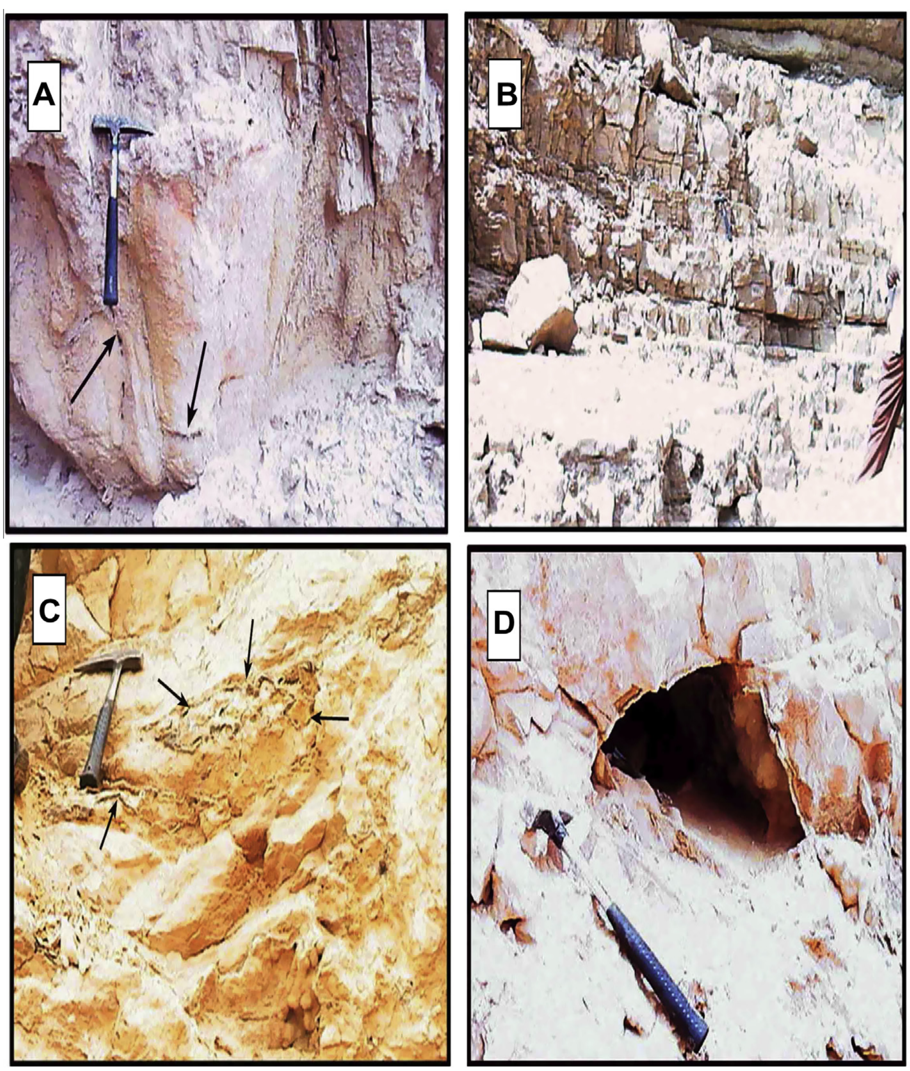

Fig. 4. (A) The ferruginated-filled, irregular seams (arrows) within the terra rosa horizon of Gebel Ataqa (SB.2). (B) The brecciated dolostone (dolomicrite), representing the SB.3 of Gebel Ataqa. (C) The irregular fissures and cavities filled with ferruginous material (arrows) within the dolostone (dolosparite), representing the SB.3 at Gebel Shabraweet. (D) A calcite vug around the ferruginated fissures of the SB.3 at Gebel Shabraweet.

In Gebel El-Zeit, SB.4 is recorded on the top of the HST.3 that ends with white nodular caliche horizon (1.5 m). SB.4 of the Northern Galala occurs at the sharp and uneven contact on the top of the peritidal dolomicrite of the second depositional sequence and the oyster claystone of the basal part of the last depositional sequence. The syngenetic, unzoned, thick-bedded dolomicrite is most probably formed at or near the mean sea level in the intertidal-supratidal settings (Al-Aasm and Packard, 2000). The dolomicrite with high percentage of dolomite was used as a clue for discrimination of discontinuities, when there is a lack of subaerial criteria (Hillgärtner, 1998; Khalifa et al., 2003 and Wanas, 2008). SBA.4 of Gebel Ataqa, occurs above the bridseye dolomicrite on top of the HST.3. It is delineated by an undulated, erosional ravinement surface that separates between the dolomitized hardground (birdseye dolomicrite) below and the lime mudstone above with sharp contact (Fig. 5A). The presence of thick dolostone below this boundary points to low sedimentation rate and denotes a hiatus interval (El-Araby, 2002 and Essa, 2005). In Gebel Shabraweet, SB.4 occurs above the glauco-arenite bed that coincides with the top of the third depositional sequence and below the lime mudstone of the basal part of the fourth depositional sequence. This glauconite bed contains white caliche nodules indicating subaerial exposure (Fig. 5B).

The last sequence boundary of Gebel El-Zeit (SB.5) separates between the Galala Formation and the overlying El-Khashm Formation. It is represented by irregular paleosol horizon (rooted ferruginous sub litharenite) with white caliche nodules (0.5 m). This boundary is termed herein as "caliche zone" (Fig. 5C and D). In the Northern Galala, the last sequence boundary (SB.5) is delineated by an unconformity surface at the top of a truncated cycle that is based by gypsiferous claystone of the uppermost of the Galala Formation with no cap. This claystone comes directly below the standing reddish dolostone of the overlying El-Khashm Formation. The boundary is marked by irregular zone with white caliche nodules indicating subaerial exposure (Fig. 6A). SB.5 of Gebel Ataqa occurs above the white caliche zone on the top of the dolomitic lithoclastic lime mudstone of the fourth depositional sequence and below the hard, massive dolostone of the Late Cenomanian-Early Turonian El-Khashm Formation. The last sequence boundary of Gebel Shabraweet (SB.5) is represented by dark brown to black, very hard, cherty and ferruginated dolostone bed (siliceous ferroan dolomicrite) up to 60 cm in thickness. This bed grades upward into Maghra El-Hadida Formation with a gradational contact. It seems to be formed within a period of intensive weathering reflecting sea-level fall and subaerial diagenesis.

5.2. Depositional sequences

The Galala Formation is considered as one depositional sequence of the third-order that is bounded by two major unconformities. The lower unconformity surface overlies the Aptian–Alpian Malha Formation, while the upper boundary unconformably underlies the Late Cenomanian-Early Turonian El-Khashm Formation at Gebel El Zeit, the Northern Galala and Gebel Ataqa and the Turonian Maghra El-Hadida Formation at Gebel Shabraweet. The intervening succession is subdivided into four depositional sequences from older to younger; A to D, each of which are built up of three systems tracts; the lowstand (LST), transgressive (TST) and highstand (HST) systems tracts. These systems tracts are further subdivided into depositional cycles.

Sequence A:

The first depositional sequence of Gebel El-Zeit (sequence A) occurs on the top of the fluvio-marine facies of the Early Cretaceous Malha Formation to the ferroan dolomicrite that occurs below the SB.2 with a total thickness of 21.4 m (Fig. 2A). The fossil content is of low diversity and mainly represented by plant remains and some bivalve shells. Sequence A is composed of two systems tracts; lowstand (LST.1) and transgressive (TST.1) systems tracts. The LST.1 comprises progradational to aggradational four cycles. The basal cycle is a shallowing-upward cycle; based by claystone, overlain by ferruginous quartz arenite with plant remains and capped

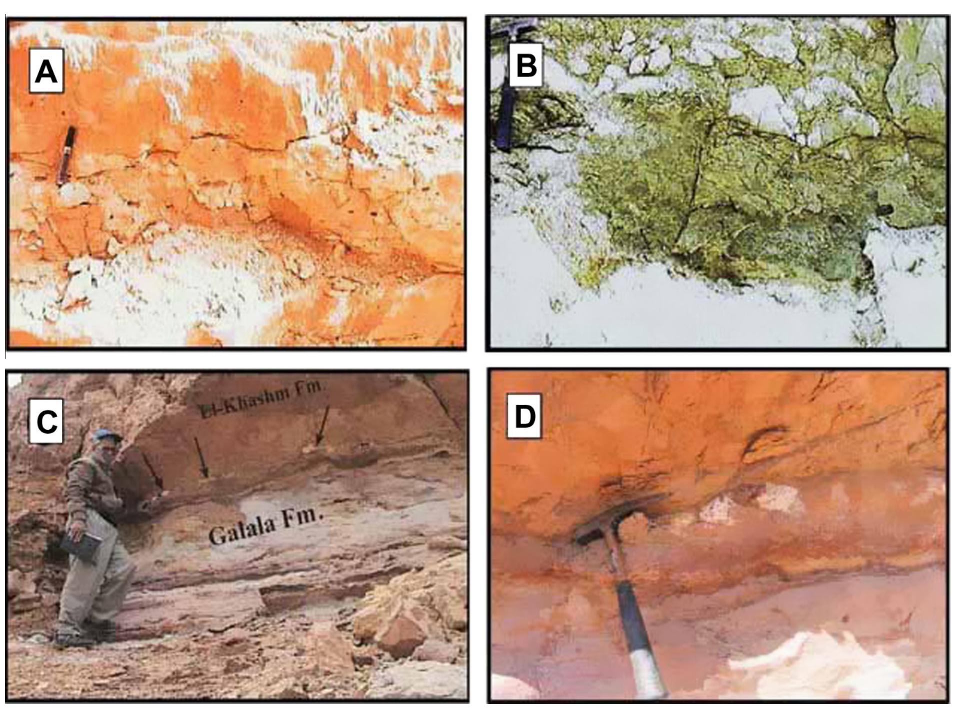

Fig. 5. (A) An undulated erosional ravinement surface, representing the SB.4 of Gebel Ataqa. Such surface separates between the dolomitized hardground (birdseye dolomicrite) below and the marly limestone (lime mudstone) above. (B) A glauconite bed with white caliche nodules, representing the SB.4 of Gebel Shabraweet. (C) The caliche zone (arrows), representing the SB.5 of Gebel El-Zeit. This zone separates between the Galala Formation below and El-Khashm Formation above. (D) A close-up of the caliche zone (SB.5) of the uppermost part of Gebel El-Zeit. Notice: the white caliche nodules.

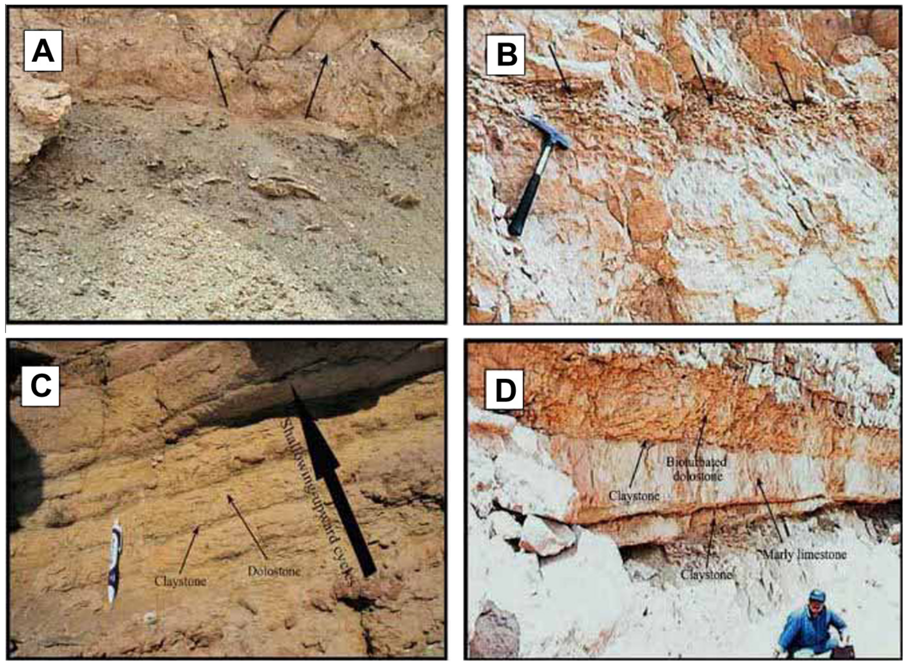

Fig. 6. (A) The caliche zone (arrows); SB.5 of the Northern Galala. (B) Intense bioturabation (arrows); the maximum flooding surface, sequence B, G. Shabraweet. (C) Shallowing-upward cycles; based by thin claystone and capped by bioturbated dolostone, TST.3, Sequence C, G. El-Zeit. (D) Two shallowing-upward cycles; based by thin claystone and capped by marly limestone and bioturbated dolostone, TST.3, sequence C, G. Ataqa.

by massive lime mudstone with dissolved bivalves. The other three cycles are fining-upward peritidal cycles; each consists of burrowed ferruginous and dolomitic quartz arenite with plant remains at the base, capped by sandy glauconitic siltstone. The TST.1 starts at the base with a thick oyster claystone indicating the first flooding event and the true invasion of marine water land ward. It is composed of eleven shallowing-upward cycles showing retrogradational stacking pattern; each of which begins with oyster claystone and is capped by peritidal, burrowed ferroan dolomicrite or by fossiliferous marl. The highstand systems tract (HST.1) is not recorded; it may be removed by erosion (Fig. 7, Section 1).

In the Northern Galala, the sequence A (12.6 m) is bounded by the SB.1 and SB.2. It includes one systems tract (TST.1). The TST.1 comprises eleven shallowing up cycles. The lowest cycle begins with shallow subtidal oyster claystone, intertidal sandy glauconitic siltstone in the middle and is capped by peritidal sandy dolomicrite, while the following ten cycles comprise subtidal claystone with oysters at the base and sandy dolomicrite or dolomicrite at the top (Fig. 7, Section 2).

In Gebel Ataqa, the first depositional sequence (A) is bracketed between the base of the section and the second sequence boundary (SB.2) that coincide with the red paleosol (terra rosa). It attains a thickness of 28 m and comprises two systems tracts (TST.1 and HST.1). The TST.1 is made up of shallowing-upward cycles. Each of which begins with lime mudstone and oyster claystone, capped with dolomitic lime mudstone, birdseye dolomicrite and dolomitic molluscan wackestone. The TST.1 is topped by a maximum flooding surface that is represented by subtidal thick fossiliferous marl at the base of the HST.1. This marl bed is condensed with oyster shell debris. The HST.1 is composed of four shallowing-upward cycles, each starts with oyster marl and capped by ledge-forming dolosparite (Fig. 7, Section 3).

In Gebel Shabraweet, the sequence A includes only one systems tract (TST.1). The TST.1 is restricted between the conglomerate bed (SB.1) and the SB.2 and comprises fourteen shallowing-upward cycles, each of which commences with green subtidal claystone and is capped by dolomicrite, molluscan peloidal packstone, dolomitic echinoidal wackestone and molluscan-echinoidal wackestone. The vertical arrangement of such cycles indicates a retrogradational to aggradational stacking patterns (Fig. 7, Section 4).

Sequence B:

The second depositional sequence in Gebel El-Zeit (sequence B) (14.8 m) is placed between SB.2 and SB.3. It comprises LST.2 & TST.2. The LST.2 consists of six coarsening-upward clastic cycles, each of which contains gypsiferous claystone at the base; capped by coarse-grained siliceous quartzarenite. The TST.2 is defined by the vertical change in facies from pure clastic of the underlying LST.2 to mixed clastic-carbonate cycles showing retrogradational to aggradational facies pattern. The TST.2 includes eight shallowing-upward cycles; each one consists of claystone with badly-preserved oysters at the base, capped by burrowed sandy dolomicrite, dolomitic marl or by burrowed glauconitic dolomitic litharenite. The uppermost two cycles of TST.2 begin with oyster claystone and capped by fossiliferous marl (Fig. 8, Section 1).

Sequence B of the Northern Galala (31.5 m) is limited between SB.2 and SB.4. It comprises TST.2 and HST.2. The TST.2 is made up of shallowing- and deepening-upward successive parasequences. The shallowing-upward parasequences are based by oyster claystone embankment and capped by fossiliferous marl or bioclastic foraminiferal wackestone. The deepening-upward cycles start with sandy glauconitic siltstone and end with fossiliferous marl of subtidal setting. The maximum flooding surface is delineated approximately above the massive, fossiliferous marl bed, which is placed at the end of the TST.2. The HST.2 comprises eleven cycles. The basal one is a truncated cycle with no base that is capped by dolomitic molluscan wackestone. The other ten cycles show a shallowing-upward in facies. Each cycle begins with green claystone or lime mudstone and capped by dolomicrite or dolomitic molluscan wackestone (Fig. 8, Section 2).

At Gebel Ataqa, sequence B (21.8 m) is restricted between SB.2 and SB.3. It starts with a transgressive surface coincides with the SB.2 (terra rosa) due to the absence of the lowstand systems tract. It consists of two systems tracts (TST.2 and HST.2). The TST.2 comprises seven cycles. The basal cycle is a truncated cycle, which

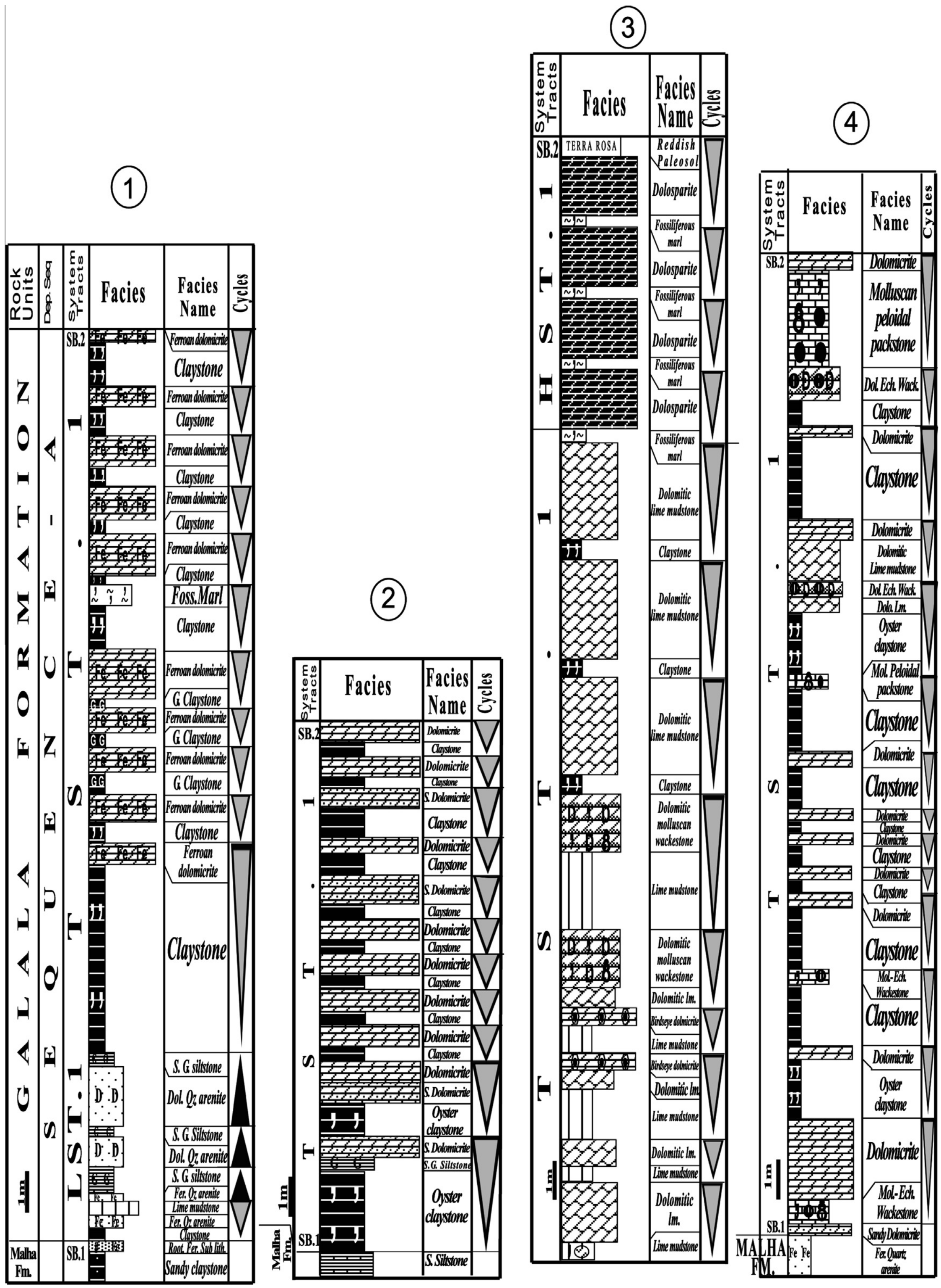

Fig. 7. Facies and systems tracts of the depositional sequence A; 1. at Gebel El-Zeit, 2. at the Northern Galala, 3. at Gebel Ataqa & 4. at Gebel shabraweet.

consists of dolomicrite with no base. The other six shallowing-upward cycles commence with lime mudstone, followed by dolomitic lime mudstone or dolomitic algal bioclastic packstone and are capped by dolomicrite or dolosparite. The HST.2 composed of two shallowing-upward parasequences, each of which starts with thin dolomitic lime mudstone and capped by thick dolosparite or dolomicrite (Fig. 8, Section 3).

Sequence B of Gebel Shabraweet is bracketed between SB.2 and SB.3. It comprises two systems tracts; TST.2 and HST.2. The TST.2 comprises shallowing-upward cycles, each of which begins with green, oyster claystone and capped by oolitic peloidal grainstone, peloidal echinoidal grainstone, dolomicrite and dolosparite. The maximum flooding surface is characterized by intense bioturbation (Fig. 6B) with strongly reduced sedimentation rates at the top of

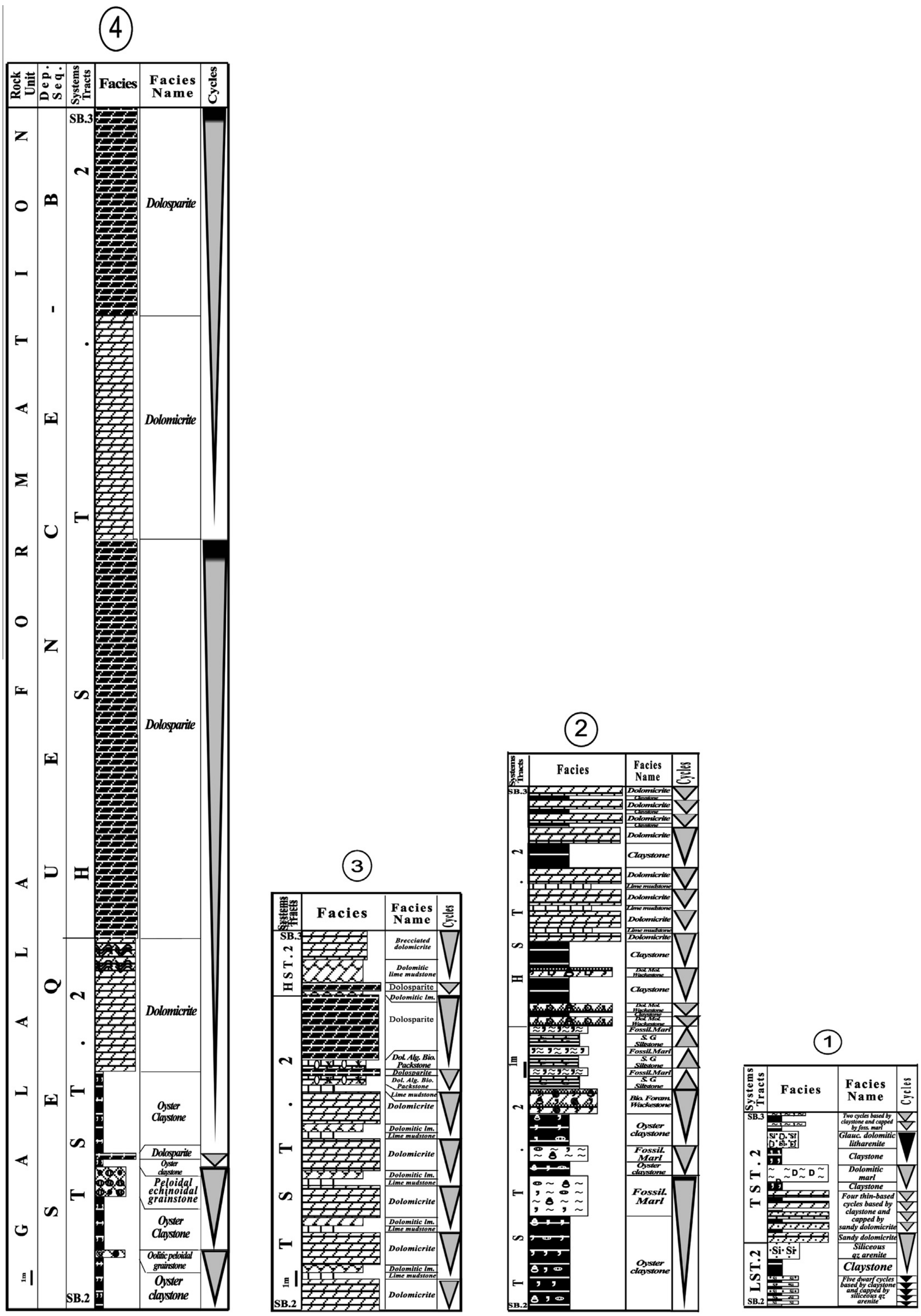

Fig. 8. Facies and systems tracts of the depositional sequence B; 1. at Gebel El-Zeit, 2. at the Northern Galala, 3. at Gebel Ataqa & 4. at Gebel shabraweet.

dolomicrite bed. This surface marks the change from the retrogradational-aggradational facies of TST.2 to the aggradational facies of the HST.2. The HST.2 consists of thick-bedded dolosparite with thick dolomicrite in-between (Fig. 8, Section 4).

Sequence C:

The third depositional sequence in Gebel El-Zeit (sequence C) (13 m) is bracketed between the SB.3 and SB.4. It is composed of three systems tracts; LST.3, TST.3 and HST.3 (Fig. 9, Section 1). The LST.3 comprises a progradational cyclic set; six thin clastic cycles, each cycle comprises claystone at the base and capped by ferruginous quartz arenite. One cycle on the topmost of the LST.3 consists of evaporitic quartz arenite at the base and ends with ferroan dolomicrite. The first flooding event is inferred by the realization of claystone with oyster fragments. The TST.3 is formed during the rapid or abrupt sea-level rise, where there was no deposition of transgressive surface that usually represented in most sequences

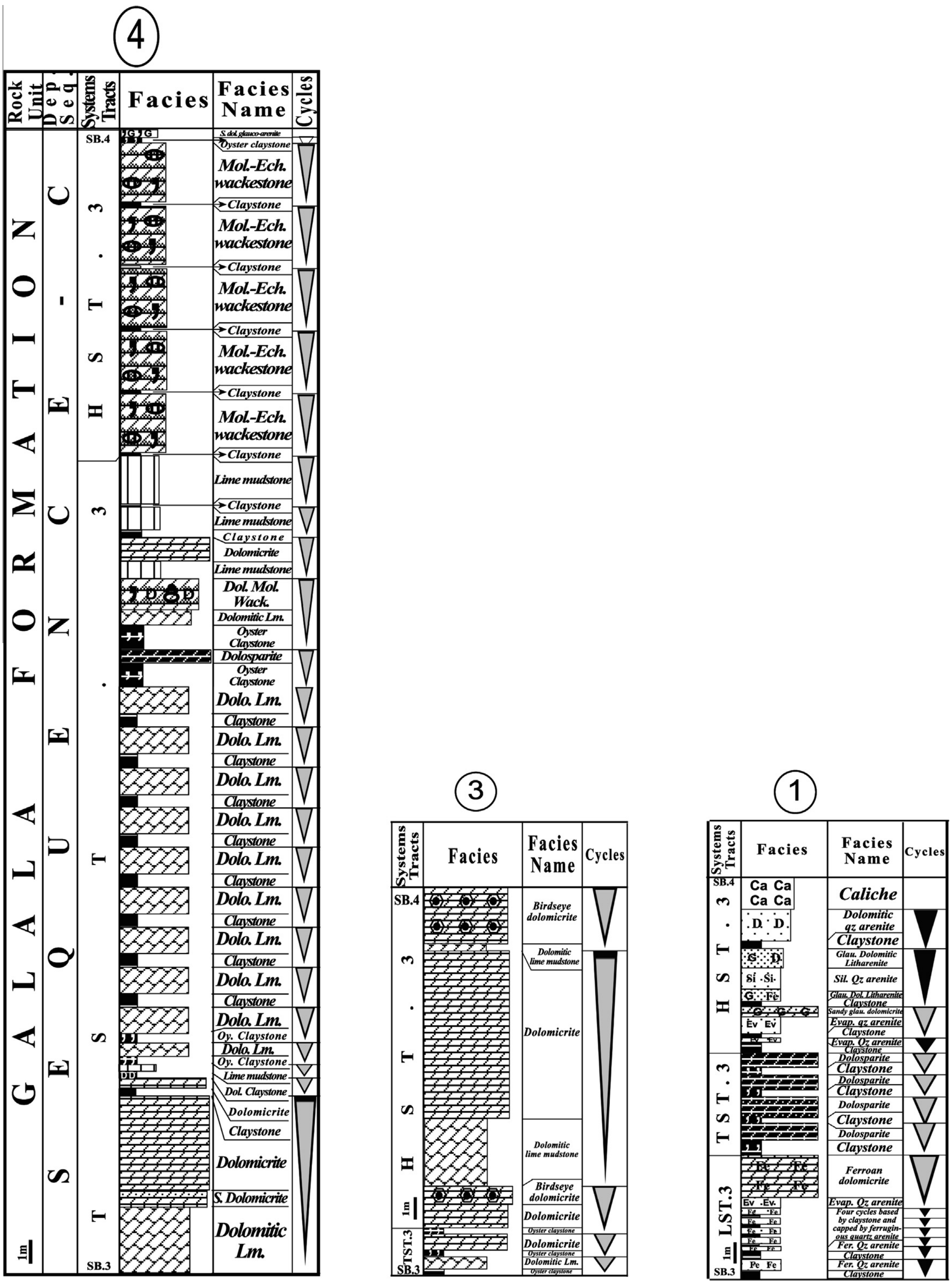

Fig. 9. Facies and systems tracts of the depositional sequence C; 1. at Gebel El-Zeit, 3. at Gebel Ataqa & 4. at Gebel shabraweet.

by green clays. Thus, it was starting on the top of ferroan dolomicrite and then overlain by four shallowing-upward cycles, each of which consists of thin shallow subtidal claystone with oysters at the base and capped by peritidal dolosparite (Fig. 6C). The maximum flooding surface or condensed section can be indicated by the presence of claystone with oysters that contains an appreciable percentage of glauconite (up to 20%), in addition to presence of Manganese spots. The HST.3 displays shallowing-upward facies and exhibits aggradational to progradational cyclic sets. The first cycle comprises thin claystone at the base; capped by evaporitic quartz arenite. This cycle is followed by a shallowing-upward cycle consists of claystone at the base, evaporitic quartz arenite at the middle and sandy glauconitic dolomicrite at the top. Upwards, there are two cycles, which are composed of claystone at the base and topped by glauconitic dolomitic litharenite or dolomitic quartz arenite. The top of the HST.3 is capped by 1.5 m thick caliche bed.

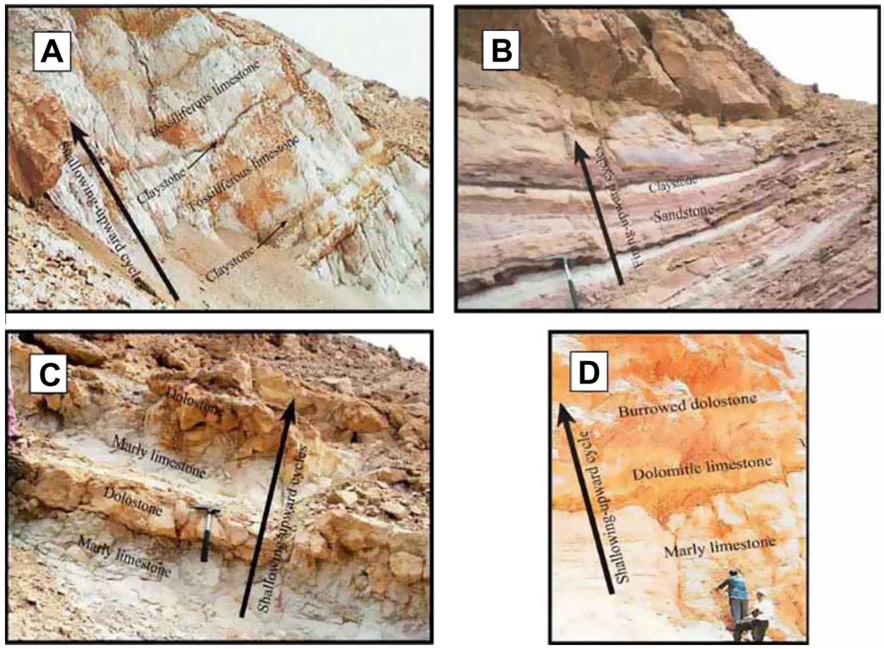

Fig. 10. (A) Shallowing-upward cycles; based by thin claystone and capped by limestone (molluscan echinoidal wackestone), HST.3, sequence C. G. Shabraweet. (B) Fining-upward cycles, LST.4, sequence D, G. El-Zeit. (C) Two shallowing-upward cycles; based by thick white marly limestone and capped by ledge forming dolomicrite, TST.4, sequence D, G. Shabraweet. (D) A shallowing-upward cycle; based by white marly limestone (lime mudstone), followed by greyish white dolomitic lime mudstone and capped by yellow, burrowed dolomicrite, HST.4, sequence D, G. Shabraweet.

This indicates a high rate of sea-level fall results in subaerial exposure.

Sequence C of the Northern Galala is truncated and wedged out probably due to the effect of erosion. At Gebel Ataqa, sequence C (16.9 m) is constrained between the SB.3 and SB.4. It consists of TST.3 and HST.3 (Fig. 9, Section 3). The transgressive surface is merged with the SBA.3. It is distinguished by the vertical facies change and the transition to retrogradational marine facies (oyster claystone). The TST.3 comprises three thin cycles, each of which begins with thin shallow subtidal oyster claystone; capped by intertidal dolomitic lime mudstone and peritidal dolomicrite (Fig. 6D). The change in facies indicates the beginning of progradational and highstand systems tract defining the maximum flooding surface. The HST.3 includes thick carbonate cycles, each begins with dolomitic lime mudstone and capped by dolomicrite and or birdseye dolomicrite. It is noticed that the thickness of the TST.3 (1.8 m) is much thinner than that of the HST.3 (15 m), this suggests that the time of sea-level fall and/or stillstand is exceeding that of subsidence.

In Gebel Shabraweet, sequence C includes TST.3 and HST.3 (Fig. 9, Section 4). The TST.3 begins with a shallowing-upward cycle; based by dolomitic lime mudstone and ends with dolomicrite. This cycle is followed upward by more than eleven shallowing-upward cycles; each consists of subtidal claystone at the base and is mostly capped by dolomitic lime mudstone and few beds of lime mudstone, dolomitic molluscan wackestone, dolomicrite and dolosparite. The HST.3 is built up of five shallowing-upward clastic-carbonate cycles, each one consists of thin subtidal claystone; followed upward by molluscan-echinoidal wackestone (Fig. 10A). The top of the uppermost cycle (oyster claystone) was truncated directly below the SB.4.

Sequence D:

The fourth depositional sequence at Gebel El-Zeit (sequence D) is restricted between the SB.4 and SB.5 with a thickness of about 20.7 m. It is composed only of lowstand systems tract (LST.4) with absence of both the transgressive and highstand systems tracts. LST.4 is made up of coarsening- and fining-upward cycles. The coarsening-upward cycle set is composed of five cycles. The basal one is based by intertidal lagoonal sandy claystone and topped by massive, dolomitic quartz arenite of coastal plain settings. The middle part of this cycle set is built up of three coarsening-upward cycles, based by intertidal lagoonal claystone and capped by cross-bedded ferruginous quartz arenite (intertidal sand bars). The upper- most cycle of this sequence is based by calcareous claystone with plant remains and limonite concretions, followed by dolomitic quartz arenite and capped by a paleosol horizon. The fining-upward cycle set is composed of three cycles; based by upper intertidal to intertidal bar sandstones (cross-bedded ferruginous quartz arenite) and capped by grey, soft claystone (intertidal lagoon). These cycles are followed by a truncated cycle of claystone with plant remains, then the rate of sea-level fall increases and hence a paleosol horizon is established. The uppermost part of the Galala Formation at Gebel El-Zeit includes four fining-upward cycles; each is based by ferruginous quartz arenite and capped with claystones enriched in plant remains of supratidal swamps and marshes.

Sequence D of the Northern Galala starts with the SB.4 and ends with the SB.5 attaining a thickness of about 30.4 m. The facies of this sequence includes only transgressive systems tract (TST.4). The TST.4 consists of successive shallowing-upward cycles, each commences with open marine, shallow subtidal oyster claystone enriched in planktonic forams and is capped by bioclastic foraminiferal wackestone, foraminiferal molluscan packstone, ostracoda molluscan packstone and dolomicrite (Fig. 11, Section 2). This systems tract is formed during periods of base-level rise when the rate of sea-level rise outpaces the rate of sedimentation (Catuneanu, 2002). The TST.4 ends with a truncated cycle; based by claystone without cap. At the topmost part of this claystone bed, there is a caliche zone represents the end of sequence D and marks the boundary between the Galala and El-Khashm Formations.

In Gebel Ataqa, the sequence D (24 m) is limited between the SB.4 and the SB.5 (Fig. 11, Section 3). It consists of only transgressive systems tract (TST.4), which is composed mostly of

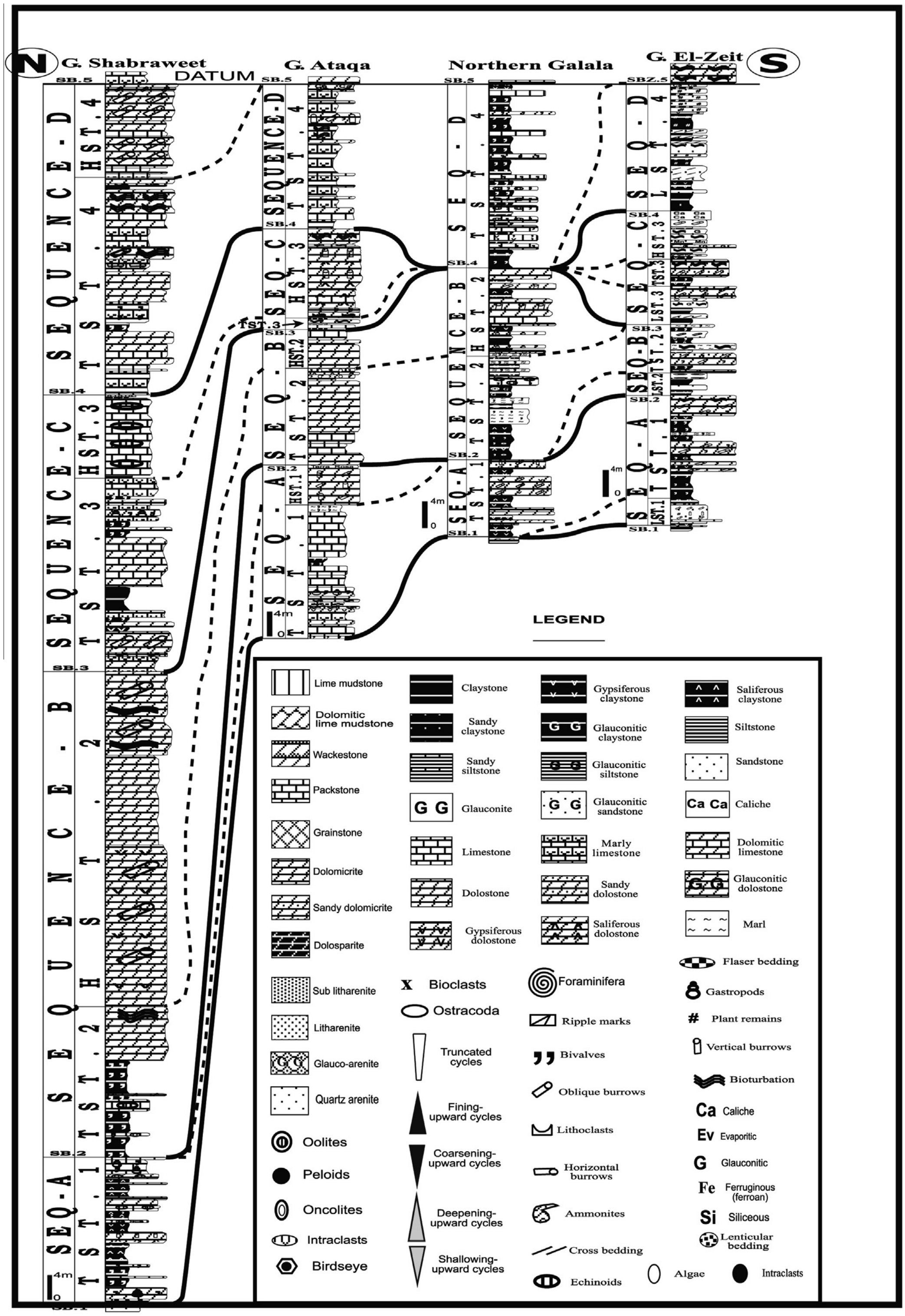

Fig. 11. Facies and systems tracts of the depositional sequence D; 1. at Gebel El-Zeit, 2. at the Northern Galala, 3. at Gebel Ataqa & 4. at Gebel shabraweet.

parasequence sets of lime mudstone (shallow subtidal lagoon) and dolomitic lime mudstone (intertidal). The uppermost bed of this sequence is represented by dolomitic lithoclastic lime mudstone, which contains white caliche nodules (caliche zone) at its topmost part.

Sequence D of Gebel Shabraweet (51.45 m) includes two systems tracts; the TST.4 and HST.4. The TST.4 is characterized by the presence of oyster claystone and molluscan-echinoidal wackestone beds indicating flooding events. It is built up of seven stacked shallowing-upward parasequences. These cycles are based by shallow subtidal to intertidal facies (oyster claystone, lime mudstone and dolomitic lime mudstone) and capped by peritidal dolostone (dolomicrite and dolosparite) (Fig. 10C). HST.4 is developed as the rate of sea-level rise slowed. It is made up of three

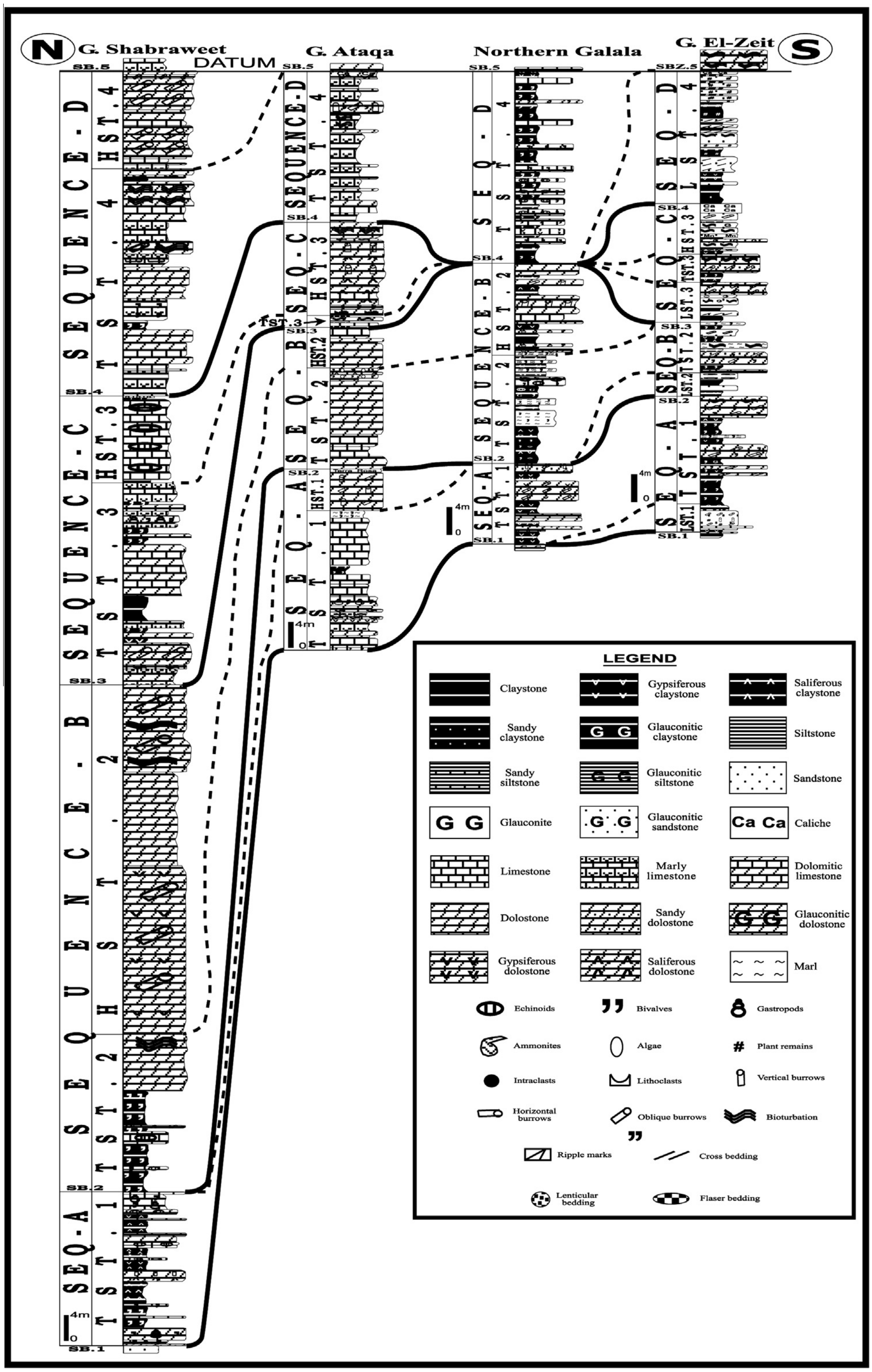

Fig. 12. Correlation of the studied sections in the view of sequence stratigraphy.

shallowing-upward cycles, which are based by limestones (lime mudstone or dolomitic lime mudstone) and capped by dolomitic lime mudstone or dolostones (dolomicrite or siliceous ferroan dolomicrite) (Fig. 10D). Sequence D terminates with cherty ferroan dolomicrite bed that indicates a paleo-erosion event and intensive weathering marking the end of the Galala Formation at Gebel Shabraweet (Fig. 11, Section 4) (see Fig. 12).

6. Discussion

The Galala Formation represents an unconformity-bounded depositional sequence which corresponds to a major stratigraphic cycle in the evolution of the passive margin setting of the Eastern Desert. The Galala Formation can be considered as a third-order depositional sequence (about 6.1 MY). This is in agreement with the hierarchy system based on cycle duration, as originally suggested by Vail et al., 1977. This is closely similar to the Upper Cenomanian Bahariya Formation in the Western Desert (Catuneanu et al., 2006). In this sequence, four depositional sequences which form its stratigraphic subdivisions, and may be regarded as fourth-order sequences.

Each fourth-order depositional sequence includes a variable number of cycles (0.1–0.5 m.y). The hierarchical organization of the sequence stratigraphic elements of the Galala Formation implies that the deposition of the Galala Formation is mainly took place under several cycles of relative sea-level changes, overprinted by intermittent tectonic pulses, which form the dolomite, emergence and subaerial exposure horizons. The sequence boundaries of the studied succession are interpreted to form when the rate of eustatic fall exceeds the rate of basin subsidence at the depositional shore line break, producing a relative fall in sea level at this position.

In the present work, the lowstand facies tract (LST) exhibits limited distribution as it is recorded only from Gebel El-Zeit (southern part of the study area), while it is completely missed or reworked by the effect of the transgressive sediments of the northern other measured sections. The LSTs of Gebel El-Zeit that composed mainly of clastic are arranged in fining- and coarsening-upward cycles. The sediments of these LSTs tend to be deposited in coastal plain to intertidal settings with aggradational/progradational geometries. Posamentier and Vail (1988) claimed that, due to the more gradual initiation of transgression, there is a greater possibility of an extensive deposition of transgressive sediments. Accordingly, the lowstand facies tracts disappear and the transgressive surfaces are amalgamated with the underlying sequence boundaries.

The transgressive facies tract (TST) is interpreted to be formed when the sea level starts its rise (increasing of accommodation, or positive accommodation) (Catuneanu et al., 2010, 2011) and persists till the maximum rate of relative sea-level rise is attained. The transgressive facies tract is recorded in all the studied sections. It begins with the first flooding surface (transgressive surface) and coincides with the sequence boundaries in the sections that are exhibiting no lowstand facies tract and forms a series of back-stepping parasequences which transgress across the platform till the point of maximum flooding is reached at the top of the transgressive facies tract. The TSTs of the Galala sequences show a gradational/retrogradational stacking pattern and are composed dominantly of mixed siliciclastic–carbonate facies. The siliciclastic sediments are mostly claystone, while the carbonates are dominantly limestone with dolomitic limestone and dolostone. The TSTs are built up mostly of shallowing-upward cycles, ranging from deep subtidal to peritidal flats. The upper part of the TSTs is marked by maximum flooding events. The individual maximum flooding surfaces are too difficult to be identified in the outcrop, however they can be inferred by the occurrence of comparatively deepest marine facies (e.g. claystone or marl), presence of globigerinid foraminifera and/or by condensation features of slow deposition rate within the beds (e.g. intense burrowing and glauconitization).

The highstand facies tract (HST) is identified from all the studied sections. The base of the HSTs is usually associated with the maximum flooding facies of the underlying TSTs. The HSTs in interpreted to be formed during the relative rise and highstand-still stand sea level. However, their upper parts indicate the initiation of sea-level fall as evidenced by the presence of very shallow sediments. The highstand facies tracts (HSTs) are totally built-up of shallowing-upward a gradational/progradational cycles of shallow subtidal to peritidal facies. The HSTs of the Galala Formation are composed chiefly of carbonate rocks (limestone, dolomitic limestone and dolostone).

The claystone-dolomitic limestone cycles of the Southern Galala are represented by three cycles with a thickness of 7 m. Such cycles commence with shallow subtidal oyster claystone and terminate with open marine shallow subtidal dolomitic algal bioclastic packstone and dolomitic peloidal packstone.

Ataqa is recorded just below the brecciated carbonate zone (second outcropped sequence boundary). It is built of intertidal dolomitic lime mudstone bed (1.5 m) without cap. One truncated cycle is identified from Gebel Shabraweet. Such cycle is recorded below the glaucoarenite bed that represents the second maximum flooding facies at Gebel Shabraweet. This cycle is made up of shallow subtidal oyster claystone (0.2 m) at the base without any cap.

The unzoned, thick-bedded dolomicrite of syngenetic origin on the top of both depositional sequence 1 and 2 can give a help in realization of sequence boundaries. This is deduced from the fact that the syngenetic dolomicrite is most probably formed at or near the mean sea level in the intertidal-supratidal settings (Al-Aasm and Packard, 2000). This indicates that the last phase of highstand facies tract and seal-level fall periods (negative accommodation) (Catuneanu et al., 2010, 2011). The presence of this lithofacies above at the topmost part of the depositional cycles suggests that it came into being at the last stages of the sea-level fall during which the concentration of Mg ions was sufficient for dolomitization. The fine-grained, syngenetic dolostone (dolomicrite) with high percentage of dolomite was used as a clue for discrimination of discontinuities, when there is a lack of subaerial criteria (Hillgärtner, 1998; Khalifa et al. 2003 and Wanas, 2008).

7. Conclusions

1. The Galala Formation represents a major third-order depositional sequence that is bounded by unconformities boundaries in the studied localities on the passive margin in the Eastern Desert of Egypt. The hierarchical organization of the sequence stratigraphic elements implies that the deposition of the Galala Formation is mainly took place under several cycles of relative sea-level changes; overprinted by intermittent tectonic pulses, which form the dolomite, emergence and subaerial exposure horizons.

2. The Galala sequence is composed of four fourth-order depositional sequences; A to D, each of which includes a variable number of cycles (0.1–0.5 m.y). The recognition of sequence boundaries of the studied succession are interpreted on the basis of Sedimentological studies. This is based on the presence of siliceous quartzarenite, thick dolomicrite and calich nodules.

The lowstand systems tract (LST) is recorded only from Gebel El-Zeit, while it is completely missed or eroded in the transgressive sediments of the other sections. The LSTs of Gebel El-Zeit is composed mainly of clastic facies, arranged in fining- and coarsening-upward cycles. The sediments of LSTs tend to be deposited in coastal plain to intertidal settings with aggradational–progradational geometries. Posamentier and Vail (1988) claimed that, due to the more gradual initiation of transgression, there is a greater possibility of an extensive deposition of transgressive sediments. Accordingly, the LSTs disappear and the transgressive surfaces are amalgamated with the underlying sequence boundaries.

The transgressive systems tract (TST) is interpreted to be formed when the sea level starts its rise (increasing of accommodation or negative accommodation) and persists till the maximum rate of relative sea-level rise is attained. The TST is recorded from all the studied sections. It begins with the first flooding surface (transgressive surface), which coincides with the sequence boundaries in the sections that are exhibiting no lowstand systems tract. The TST forms a series of back-stepping cycles, which transgress across the ramp till the point of maximum flooding is reached at the top of the transgressive systems tract. The TSTs of the Galala

Formation show an aggradational–retrogradational stacking pattern and are composed dominantly of mixed siliciclastic–carbonate facies. The TSTs are built up mostly of shallowing-upward parasequences, ranging from open marine shallow subtidal to peritidal flats. The upper part of the TSTs is marked by maximum flooding events. The individual maximum flooding surfaces are too difficult to be identified in the outcrop, however they can be inferred by the occurrence of comparatively deepest marine facies (oyster claystone or fossiliferous marl), presence of globigerinid foraminifera and/or by condensation features of slow deposition rate within the beds (e.g. intense burrowing).

The highstand systems tract (HST) is identified from all the studied sections. The base of the HSTs is usually associated with the maximum flooding facies of the underlying TSTs. The HSTs are interpreted to be formed during the relative rise and high-stand-still stand sea level. However, their upper parts indicate the initiation of sea-level fall as evidenced by the presence of very shallow sediments. The HSTs are totally built up of shallowing-upward aggradational–progradational parasequences of shallow subtidal to peritidal facies. They are composed chiefly of carbonate rocks.

1. The construction of the third-order sequence stratigraphic framework for the Bahariya Formation was based on the detailed Sedimentological study, and paleo-depositional environment interpretations, performed in five main localities in the Bahariya Oasis.
2. Eight distinct facies associations have been recognized, corresponding to changes in clastic lithology, color, sedimentary structures and stratal staking patters. 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).
3. 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.

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