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Cenomanian rocks in the Sinai Peninsula, Northeast Egypt: Facies analysis and sequence stratigraphy

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a r t i c l e i n f o a b s t r a c t

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| Article history:  Received 18 February 2008  Received in revised form 29 May 2008  Accepted 16 June 2008 Available online 28 June 2008  Keywords:  Cenomanian rocks  Inner-mid ramp facies  Sequence stratigraphy  Sinai  Egypt | Five stratigraphic sections of the Cenomanian rocks exposed in the Sinai Peninsula are described and interpreted on the basis of field observations and facies analysis in order to reconstruct their depositional environments and sequence stratigraphic framework. Based on their lithologic characteristics, the Cenomanian successions consist of mixed siliciclastic–carbonate rocks. The Cenomanian successions are dominated by carbonate production in the northern and eastern parts of the study area. Siliciclastic supply increases southward. Detailed petrographic investigations made it possible to recognize several clastic and carbonate facies types. The facies recognized and their related palaeoenvironments document a lateral transition between inner- and mid ramp settings. The inner-ramp setting occurs in the south and west central Sinai where the peritidal flat, lagoonal, high-energy shoals facies dominate. The mid-ramp setting is assumed to have developed in the north and east central Sinai where intertidal and low-energy subtidal facies interfingers with a few storm-influenced deposits occur. The main factors controlling ramp deposition were eustatic sea-level fluctuations combined with environmental influences such as autochthonous carbonate productivity and siliciclastic supply.  In terms of sequence stratigraphy, the Cenomanian successions in Sinai exhibit two superimposed depositional sequences, each of which shows retrogradational (transgressive systems tract) and aggradational to prograditional (highstand systems tract) packages of facies. The retrograditional facies display a predominance of subtidal carbonate facies, whereas the prograditional and aggradational facies show an increase of peritidal carbonates and siliciclastic deposits. |

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# Introduction

In Egypt, the Cenomanian rocks are widely exposed in Sinai and Eastern Desert, whereas subsurface equivalents occur in the Western Desert (Table 1). The marine facies of the Cenomanian rocks cover most of the northern part of Egypt, whereas the continental facies with shallow marine incursions characterize the Cenomanian rocks in the southern part of Egypt (Issawi et al., 1999). In Sinai, most of the previous studies of the Cenomanian strata were focused on litho-and biostratigraphy (e.g., Fawzi, 1960; Cherif et al., 1989; Khalil, 1993; Ziko et al., 1993; Kora et al., 1994; Kora and Genedi, 1995; Bauer et al., 2001; Kassab and Obaidalla, 2001; Kora et al., 2001; Abdel-Shafy et al., 2002; Abdel-Gawad et al., 2004a,b and references therein).

A few localized studies of depositional facies and sequences of the Cenomanian strata have been carried out in north Sinai (Abdallah et al., 1996; El-Azabi and El-Araby, 1996; Bachmann and Kuss, 1998; El-Araby, 2002), west central Sinai (Khalifa et al., 2003), east central Sinai (Kora and Genedi, 1995) and southwest Sinai (Kora

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| \* Tel.: +20 48 2238323; fax: +20 48 2235689.  E-mail addresses: hamdallawanas@yahoo.com, wanas2000@yahoo.com.  1464-343X/$ - see front matter 2008 Elsevier Ltd. All rights reserved.  doi:10.1016/j.jafrearsci.2008.06.004 |

et al., 2001; Saber, 2002). The present study focuses on the facies analysis, depositional environments and sequence stratigraphic framework of the Cenomanian rocks cropping out in Sinai, from south to north, and particularly at Gabal Ekma (southwest Sinai), Gabal Al-Makarah (southwest Sinai), Khashm El-Tarif (east central Sinai), Gabal El-Fallig (west central Sinai) and Gabal Manzour (north Sinai) (Fig. 1). This approach makes it possible to follow the lateral facies changes and establish a depositional model for the Cenomanian strata in Sinai. To achieve this work, five stratigraphic sections of the Cenomanian rocks were measured, described and sampled. The indurated rocks were thin-sectioned and investigated under the polarized microscope to illustrate and describe the microfacies types. The sandstone and limestone microfacies were described following the classification of Pettijhon et al. (1987) and Dunham (1962) with modification of Embry and Klovan (1972), respectively.

# Geological setting

The Sinai Peninsula is situated between the African and Arabian Plates and lies in the northeastern part of Egypt. Tectonically, the Sinai Peninsula was divided into stable shelf (southern and

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| Table 1 |

See above-mentioned references for further information.

south-central Sinai) and unstable shelf (northern and north-central Sinai) (Said, 1962). In the mid- and Late Cretaceous times, the Sinai

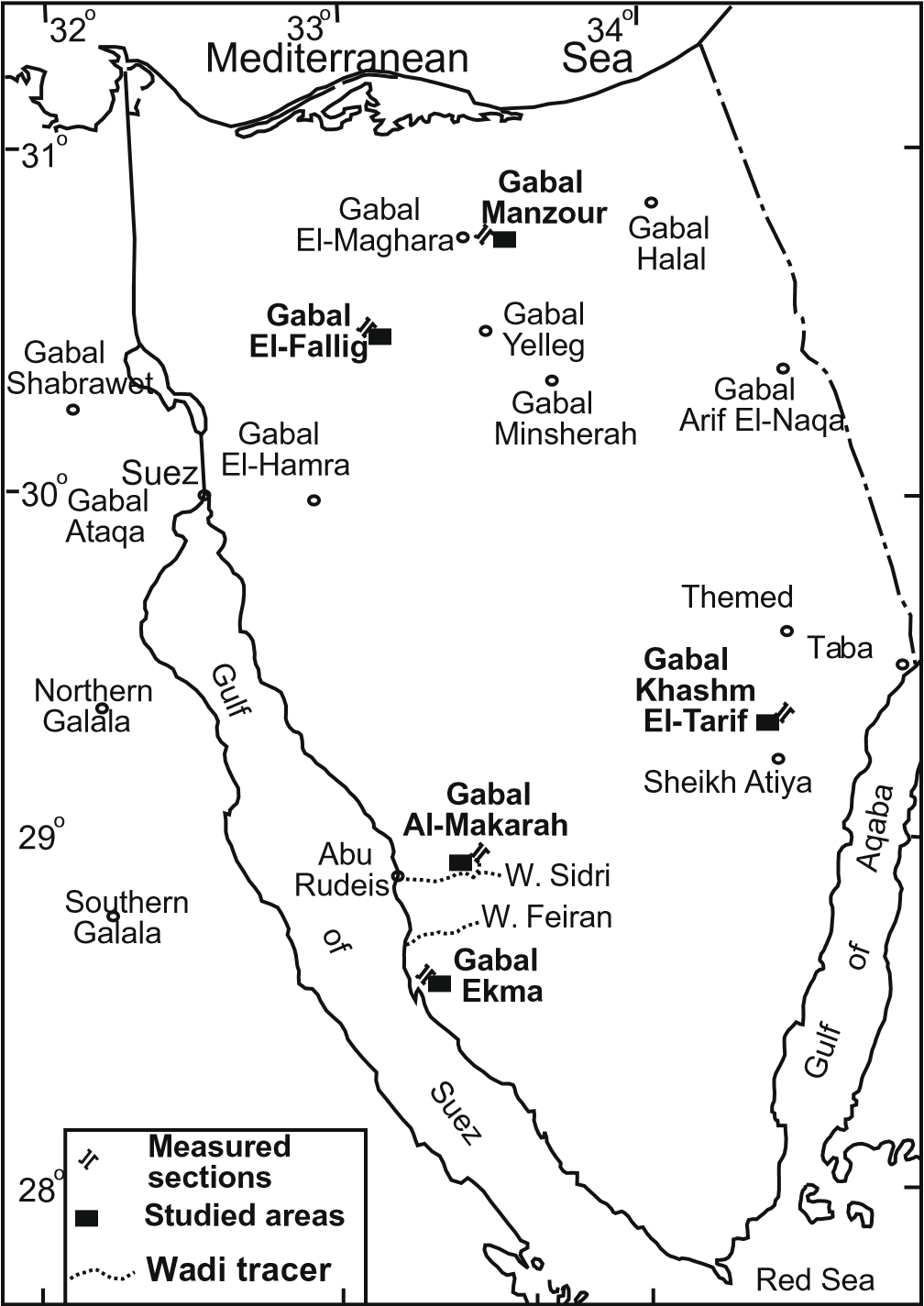


Fig. 1. Location map of the studied areas and measured sections.

Peninsula was part of a broad shallow shelf situated on the southern passive margin of the Neo-Tethys, where a carbonate platform with siliciclastic intercalations was established (Kuss and Bachmann, 1996; Bauer et al., 2001). In the mid-and Late Cretaceous times, the main phase of compressive tectonic activities related to the Syrian Arc System that was initiated at the Late Cenomanian time (Bartov and Steinitz, 1977; Kuss and Bachmann, 1996). Therefore, the study area (Sinai) is believed to have remained tectonically rather quiet throughout Cenomanian time (Kuss and Bachmann, 1996).

# Lithostratigraphy

In Sinai, different formational names have been introduced for the Cenomanian rocks by different authors. The Cenomanian rocks were attributed to the ‘‘Raha Formation” (Ghorab, 1961), ‘‘Galala Formation” (Abdallah and El-Adindani, 1963) and ‘‘Halal Formation” (Said, 1971) in southwest central Sinai, east central Sinai and northern Sinai, respectively (Table 1). Issawi et al. (1999) reported that the Halal Formation is a localized facies; hence they named the Cenomanian beds in Sinai as the Galala Formation. In the present study, because the Cenomanian rocks throughout Sinai display facies and paleoenvironmental changes, the author prefers to use the term Raha/Galala/Halal formations to describe the Cenomanian rocks from south through central to north of Sinai, respectively (Table 1). Boundaries of the Cenomanian Raha/Galala/Halal formations differ in their characters throughout the studied localities. At Gabal Ekma, Gabal Al-Makarah and Gabal Khashm El-Tarif, the Raha/Galala formations unconformably overlie the Barremian-Aptian Malha Formation. At these localities, the lower contact of the Raha/Galala formations are distinguished by the occurrence of ferruginous crust and iron-filled vertical pipes that invade downward in the reddish white sandstones of the underlying Barremian-Aptian Malha Formation (Figs. 2 and 3). At Gabal El-Fallig and Gabal Manzour, the lower boundary of the Halal Formation made conformable relationship with the underlying Abtian–Albian Risan Aneiza Formation. It is located at the first appearance of the typical Ceno-

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| Fig. 2. Correlation chart showing sedimentological, paleoenvironmental and sequence stratigraphic characteristics of the Cenomanian facies at the studied localities in the |

Sinai Peninsula. For symbols (see Fig. 3).

manian fauna (Exogyra sp.) in the marl bed that lies directly above the yellowish olive-coloured, oolitic, orbitolinoid-rich dolomitic limestones of the underlying Risan Aneiza Formation (Figs. 2 and 3). At all the studied localities, the upper boundary of the Cenomanian Raha/Galala/Halal formations are conformably overlain by the ammonite-rich marls/calcareous shales of the Upper Cenomanian-Lower Turonian Abu Qada Formation (Figs. 2 and 3). The measured thickness of the Raha/Galala/Halal formations ranges from 135 m at the southern part of the study area to 175 m in the northern sections (Figs. 2 and 3).

From the lithological point of view, the Cenomanian rocks exhibit significance lateral and vertical changes from south to north of the study area (Figs. 2 and 3). These rocks can be subdivided into three informal rock units: lower, middle and upper (Figs. 2 and 3), which can be correlated with other published subdivisions of the Cenomanian rock units as shown in Table 1. The lower unit is a mixed clastic–carbonate facies, in which the clastic facies is dominated and becomes increasingly abundant in the southern parts of the study area. Glauconitic sandstones/siltstones/claystones/shales intercalated with few thin beds of sandy dolomitic limestones and marls form the lower unit in the southern sections (Figs. 2 and 3). In the northern and central sections, the lower unit mainly consists of oyster-rich silty marls and massive and nodular marly limestones (Figs. 2 and 3) with an occasional occurrence of calcareous siltstone and claystone interbeds. The middle unit is dominated by carbonate facies (limestones, dolomitic limestones and marls), which show differences in character and thickness from one locality to another. In the middle unit of the northern sections, the thinbedded chalky limestones with chert nodules are predominant (Figs. 2 and 3), while the burrowed bioclastic limestones dominate the middle unit of the southern sections (Figs. 2 and 3). Oolitic/ cross-bedded and rudist-bearing limestones (Figs. 2 and 3) predominate the middle unit of the central sections. The upper unit displays mixed carbonate–clastic facies, in which the carbonate facies (dolomitic limestones and dolostones) is increasingly developed at the Gabal Al-Makarah, Gabal El-Fallig and Gabal

Manzour, while the siliciclastic input (sandstones, siltstones and calcareous sandy claystones) is prevailed at Gabal Ekma and Gabal Khashm El-Tarif (Figs. 2 and 3). In general, the Cenomanian rocks of Sinai show a southward decrease in thickness accompanied by an increase in siliciclastic components. The northern- and northeastern parts of Sinai experienced relatively high carbonate production (Figs. 2 and 3).

# Facies associations and interpretations

Twenty-four sedimentary facies of both clastic and carbonate rocks are recognized in the studied Cenomanian rocks. These facies are grouped in seven facies associations that are assignable to five depositional environments (peritidal, lagoon, high-energy shoals of ooids and patch reefs, and intertidal–subtidal to storm-influenced open marine). The distribution of the different facies recognized through the studied sections is illustrated in Fig. 2 and outlines and discusses below.

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| |  | | --- | | **Lithologies Fossils Sedimentary patterns**  Dolomitic limestoneRudists ForaminiferaThalassinoides Iron nodule  Dolostone  Sandstone  Fissile shale  Siltstone  Limestone  Marl  **G**  Sandy limestoneEchinoids MiliolidsBurrows Thin-bedded  Silty marlBivalvesBird eyes Rippled  CalcareousOystersBrecciated Cross-bedded  DolomiticGastropodOoidUnconformity surface  GlauconiticAmmonitesChert nodule & bandNodular  **Abbreviations**  **HST** Highstand systems tract **Lm.** Lime-mudstone **R.Bou.** Rudist boundstone  **TST** Transgressive systems tract **Fn.Lm.** Fenestral lime-mudstone **Oy.Ru** Oyster rudstone  **SB** Sequence boundary **M.Pl.W.** Miliolid textulariid peloidal wackestone **Oy.Fl.** Oyster floatstone  **TS** Transgressive surface **P.B.W.** Pelecypod bioclastic wackestone **Gs.P.** Gastropod packstone  **MFS** Maximum flooding surface **Inr.W.** Intraclastic wackestone **Pl.P.** Peloidal packstone  **F.Dl.m.** Fossiliferous dolomicrite  **Dl.B.W** Dolomitic bioclastic wackestone **E.B.P.** Echinoidal bioclastic packstone  **Dl.m.** Dolomicrite **O.Gr.** Oolitic grainstone **Fr.P.** Foraminiferal packstone  **Cr.D.** Coarse-crystalline dolomite **Inter.** Intertidal **O.B.P.** Oolitic bioclastic packstone  **D.QA.** Dolomitic quartzarenite **Subt.** Subtidal  **S.** Sandy |   Fig. 3. Legend to symbols used in Fig. 2. |

## Facies association-A: Peritidal flat/ beach clastics

The peritidal area refers to supra-intertidal flat (Shinn, 1983). This clastic facies association includes sandstone, siltstone and shale. It occurs mainly in the lower and upper units of the Raha Formation at Gabal Ekma (Figs. 2 and 3). This facies association occurs as an interbedded yellowish brown sandstone (1–2 m thick), green shale (1–1.5 m thick) and siltstone (0.5–1 m thick). Sandy dolomitic fossiliferous limestone ledges (10–15 cm thick) and marlstone gullies (0.5–1 m thick) occur within this facies association (Figs. 2 and 3). Sometimes, the sandstone occurs as lenses. The shales are fissile, bioturbated, cracked, glauconitic and highly dissected by gypsum veins. They contain few oyster shells. The siltstones are yellowish green in colour and are characterized by small ripple marks. Red–green mottling is noticed in both the shales and siltstones. Microscopically, the sandstones display two main microfacies: dolomitic and calcareous quartzarenites (Figs. 2 and 3). The dolomitic quartzarenite (D.QA) is composed of about 70– 75% quartz grains cemented by dolomite rhombs (Fig. 4A). Bivalve shell fragments are rare. The quartz grains are fine- to medium grained, moderately sorted and subrounded to subangular. Most of the quartz grains are monocrystalline with straight to slightly undulose extinction, while few of them are of poly- to semi-composite types with undulose extinction. The dolomite cement occurs as rhombs of idiotopic fabric and equigranular texture (Fig. 4A). These dolomite rhombs have dark brown iron-rich cores with clear outer rims.

Interpretation: The high maturity of the quartzarenite indicates deposition in high-energy shallow water at a passive continental margin (Pettijhon et al., 1987). Also, the sub-angular to subrounded quartz grains seem to exclude prolonged transport (Pettijhon et al., 1987). This in turn indicates a more proximal source and suggests that this quartzarenite facies was developed close to the shore/beach where the quartz grains could be supplied either by rivers or erosion of the coastal area. The paucity of carbonate fossils in this lithofacies implies unfavorable ecological conditions for organisms (such as low oxygenation and high organic acid). Such conditions prevail in the depositional setting close to a supratidal environment where coastal marshes generate organic acids responsible for dissolving calcareous shells (Olsen et al., 1999). This dolomitic quartzarenite is closely similar to that described by Khalifa (1996) at the supra-and upper intertidal zone of mixed clastic–carbonate cycles. The occurrence of gypsum-filled desiccation cracks in the shale facies can be related to arid climate in a supratidal sabkha setting (Shinn, 1983; Bauer et al., 2001). The occurrence of bioturbated shales and rippled siltstones that are intercalated with lenses of sandstones indicates mixed mud-sand tidal flat deposition (Reineck and Singh, 1975). Also, the red–green mottling and bioturbations in shales and siltstones reflect deposition in a supratidal–intertidal flat area, where there was diagenetic redox-morphic potential, related to bioturbations, which led to a complex Fe2/Fe3 distribution (Selley, 1996).

## Facies association-B: Peritidal flat carbonates

This facies association is mainly represented by three facies: fossiliferous dolomicrite (F.Dl.m), sandy dolomicrite (S.Dl.m), fenestral lime–mud (Fn.Lm) and coarse-crystalline dolostone (Cr.D). The fossiliferous dolomicrite and sandy dolomicrite facies are essentially encountered in the lower and upper units of the Raha Formation at Gabal Ekma and the upper unit of the Raha Formation at Gabal Al-Makarah (Figs. 2 and 3). The coarse-crystalline dolostone facies (Cr.D.) forms the major part of the upper unit of the Halal Formation at Gabal Manzour and Gabal Khashm El-Tarif (Figs. 2 and 3). The dolostone beds are yellowish brown in colour, ledge forming and thick-bedded (2–3 m thick). The fenestral lime– mud also recognized with limited distribution in the uppermost part of the lower unit of the Galala at Gabal Khashm (Figs. 2 and 3). These facies always cap the massive limestones or shales and marls (Figs. 2 and 3). Each bed of this carbonate facies association

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| Fig. 4. Photomicrographs showing: (A) dolomitic quartzarenite consisting of quartz grains cemented by zoned dolomite rhombs, the Raha Formation at Gabal Ekma, XPL, (B) fossiliferous dolomicrite which includes few bivalve shell fragments in fine-crystalline dolomite rhombs, PPL, the Raha Formation at Gabal Ekma, (C) sandy dolomicrite consisting of fine-crystalline, unzoned dolomite rhombs of idiotopic fabric and equigranular texture, the Raha Formation at Gabal Ekma, PPL, (D) coarse-crystalline dolomite that consists of tightly interlocking mosaic of idiotopic, zoned dolomite rhombs, The Halal Formation at Gabal Manzour, (E) fenestral lime mudstone, in which the fenestral suites filled with calcite crystals and quartz grains, the Galala Formation at Gabal Khashm El-Tarif, XPL and (F) wackestone rich in benthic forams of miliolids and textuariids, |

the Raha Formation at Gabal Al-Makarah, XPL. The entire scale bars = 250 lm.

varies in thickness from 0.5 to 1 m. Its rocks are brownish yellow in colour and very hard. The fossiliferous dolomicrite (F. Dl.m) consists of scattered oyster shell fragments (10–20%) in fine dolomite rhombs cement (Fig. 4B). The dolomite cement contains a little amount of micrite patches (3–5%) suggesting a former Mg-calcite composition. The sandy dolomicrite (Dl.m) consists mainly of a tightly packed mosaic of fine-crystalline dolomite rhombs with a few detrital silt-sized quartz grains (2–3%) (Fig. 4C). At Gabal Ekma, the dolomicrite has fibrous gypsum-filled pores. The coarse-crystalline dolostone facies (Cr.D.) is composed of tightly interlocking mosaic of idiotopic dolomite rhombs (Fig. 4D). Most of the dolomite rhombs are clear, whereas others have dark cloudy cores and clear outer rims. The dolomite rhombs have equigranular fabric. The fenestral lime–mudstone (Fn.Lm) is composed mainly of micrite with fenestrae filled with sparry calcite, which has relics of fine dolomite rhombs (Fig. 4E).

Interpretation: The fine crystalline dolomites have been interpreted to be a result of penecontempraneous dolomitization of precursor micrite in supratidal flat sediments during regressive phase in upper intertidal to supratidal setting (Warren, 2000). The recognized finely crystalline dolomites with rare evaporates are in a close similarity with the dolostones of upper intertidal– supratidal zone in platform carbonate that were formed during sea-level fall (Khalifa, 1996; Qing et al., 2001; Abu El-Hassan and Wanas, 2005). On the other hand, the gypsum crystals filled-pores associated with fine crystalline dolomite may be formed by intensive evaporation of marine water in a supratidal zone during a short period of sea-level fall (Tucker and Wright, 1990), which in turn indicates a brief drop in sea-level. The presence of coarsecrystalline dolomite facies refers to late diagenetic dolomitization of subtidal carbonate in a mixing zone with meteoric water during a progressive sea-level fall (Warren, 2000). The occurrence of coarse-crystalline dolostone facies directly above the subtidal limestone facies suggests a progressive shallowing of sea-level (Mutti and Simo, 1994). Consequently, in the present work, the occurrence of coarse crystalline dolomites above the shallow subtidal pelecypod bioclastic wackestone (P.B.W.) and/or lower intertidal gastropod and oolitic bioclastic packstones (Figs. 2 and 3) could indicate an upper intertidal environment. The fenestral lime–mudstone is a characteristic upper intertidal facies indicator (Shinn, 1983).

## Facies association-C: Lagoonal clastics

This facies association is made up of green glauconitic mudrock and yellowish green glauconitic silty marl. The mudrocks and marls are massive and contain scarce fossil remains. This facies association forms most of the lowermost part of the lower unit of the Raha Formation at Gabal Al-Makarah (Figs. 2 and 3). It intercalates with few beds of dolomitic quartzarenite and burrowed limestone (Figs. 2 and 3).

Interpretation: The massive nature of mudrocks and silty marls of facies association-C suggests deposition from suspension within shallow protected water of a low-energy regime (Pettijhon et al., 1987). The occurrence of glauconite in mudrocks and/or marls reflects a slow rate of deposition in slightly oxidizing to reducing shallow marine water (McRae, 1972). It also indicates deposition in a low-energetic restricted water environment (El-Albani et al., 2005). Occurrence of silts within marls indicates deposition in low-energy environment near the source of clastic erosion. Consequently, the massive glauconitic mudrocks and marls of facies association-C reflect deposition in a restricted shallow marine, slightly oxidizing to reducing quiet water (lagoonal water) near the clastic source.

## Facies association-D: Lagoonal carbonates

The facies association-D includes lime–mudstone, miliolid foraminiferal peloidal wackestone and gastropod to peloidal packstone facies.

### Lime–mudstone (Lm)

The rocks of this facies have been mainly recorded in the uppermost part of the lower unit of the Raha Formation at Gabal AlMakarah (Figs. 2 and 3). They are bioturbated and grayish white in colour. This facies usually occurs in an intercalation with marls and fossiliferous limestone facies. Microscopic investigation reveals that this lime–mudstone facies is dense micrite (95%) with rare shell debris (2–3%).

Interpretation: The scare fossils-lime mud reflects restricted shallow subtidal, quiet marine water of high salinity (Flügel, 1982; Pittet et al., 1995). This is compatible with the standard microfacies SMF-23 of Wilson (1975). Therefore, the poorly fossiliferous lime–mudstone at Gabal Al-Makarah indicates deposition in shallow subtidal zone of a restricted quiet water (lagoon).

### Miliolid textulariid peloidal wackestone (M.Pl.W.)

This facies is distributed widely in the lower and middle units of the Raha Formation at Gabal Al-Makarah (Figs. 2 and 3). It often underlies the lime–mudstone facies and overlies the packstone and grainstone facies (Figs. 2 and 3). The rocks of this facies are grayish white, hard and massive. Each bed of this lithofacies ranges in thickness from 2 to 3 m. Petrographic investigation reveals that this facies consists of 20–30% benthic foraminifera (miliolids and textulariids) and peloids embedded in micrite matrix (Fig. 4F). The micrite matrix is partially neomorphosed to microspars. Few micritized pelecypod shell fragments are also recorded in this facies.

Interpretation: The presence of diverse miliolids and/or small textulariids typically indicates restricted shallow-deep subtidal quiet water, probably a restricted lagoon or sheltered bays (Hottinger, 1997; Pittet et al., 1995). The occurrence of peloids and heavy micritized skeletal particles in the micrite matrix suggests deposition in a protected quiet water zone where responsible microbial boring mats (endolithic algae, bacteria, or fungi) are in more prevailance (Tucker and Wright, 1990). Therefore, the miliolid foraminiferal peloidal wackestone has been deposited in shallow-deep subtidal water of a restricted lagoon.

### Gastropod packstone (Gs.P.)

This facies has a wide distribution in the middle unit of the Raha Formation at Gabal El-Makarah (Figs. 2 and 3). It often occurs in an intercalation with silty marls (Figs. 2 and 3). Each bed of this facies attains a thickness of about 5 m. The rocks of this facies are usually yellowish white and hard. Bioturbations have been observed in the beds of this facies. Petrographically, the gastropod packstone facies consists exclusively of skeletal components (70–75%) and lime– mud matrix (Fig. 5A). The skeletal components mainly include non-oriented, small-sized gastropod shells (65%) of low diversity (10%).

Interpretation: In general, the packstone facies reflects deposition in a shallow subtidal-lower intertidal environment (Wilson, 1975). The occurrence of disoriented, small-sized gastropod shells of low diversity in association with micrite matrix indicates deposition in a low energy, restricted lagoonal water (Khalil, 1993; Pittet et al., 1995). Therefore, the gastropod packstone facies suggest a shallow subtidal lagoonal environment of deposition.

### Peloidal packstone (Pl.P.)

This facies occurs in the middle unit of the Raha Formation at Gabal El-Makarah (Figs. 2 and 3). It often occurs below the miliolid peloidal wackestone and above silty marls. Each stratum of this facies is 2–3 m in thickness and is yellowish white in colour and burrowed. In thin section, the peloidal packstone facies (Fig. 5B) is composed essentially of peloids (70–80%) embedded in lime– mud matrix (20–30%). The peloids are rounded to oval in shape and exhibit sharp contacts with their matrix. The lime–mud matrix shows recrystallization to microspars, in which there are relics of original micrite.

Interpretation: An abundance of peloids in lime–mud matrix with low diversity of fossils suggests deposition in a restricted shallow subtidal water and slow sedimentation rate (Wilson, 1975; Flügel, 1982). Consequently, the recorded peloidal packstone is a characteristic facies for a shallow subtidal restricted water zone.

## Facies association-E: High-energy shoals of ooids and patch reefs

The high-energy shoal environment represents the platform margin, separating the open marine from restricted lagoon (Burchette and Wright, 1992). In the present study, the high-energy shoal facies association includes three main characteristic carbonate facies: oolitic grainstone, rudist boundstone and oyster rudstone.

### Oolitic grainstone (O.Gr.)

The rocks of this facies mainly occur throughout the Halal Formation at Gabal El-Fallig (Figs. 2 and 3). They are yellow, hard and sometimes are cross-stratified. This grainstone facies often overlies the rudist boundstone and marls (Figs. 2 and 3). The oolitic grainstone consists mainly of ooids embedded in sparry calcite cement (Fig. 5C). In this oolitic grainstone, the ooids are spherical, oval to elliptical and have nuclei of pelecypod shell fragments. Most of the recognized ooids show both concentric and radial cortices (Fig. 5C), but some of them exhibit mixed cortices, in which the interior layers show radial fabric and the exterior layers are arranged in a concentric fabric (Fig. 5C). In this microfacies, superficial ooids are also distinguished by their single lamella around large nucleus (Fig. 5C).

Interpretation: In general, the grainstone is interpreted to represent high-energy carbonate shoals (Wilson, 1975; Harris et al.,

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| Fig. 5. Photomicrographs showing: (A) gastropod packstone exhibits gastropod shells that embedded in microspars, the Halal Formation at Gabal Manzour, XPL, (B) peloidal packstone that exhibits oval-shaped pellets in microspary calcite cement, the Raha Formation at Gabal Al-Makarah, PPL. The entire scale bars = 250 lm, (C) oolitic grainstone that declares ooids with nuclei of pelecypod shell fragments, the Halal Formation at Gabal El-Fallig, XPL, (D) rudist boundstone consisting of parallel-imbricate rudist shell fragments. Notice, the characteristic rectangular-rhombs meshes of the original microstructure of the rudist wall (see arrows), the Halal Formation at Gabal El-Fallig, XPL, (E) oyster rudstone with abundant bivalve shell fragments that exhibit original fibrous internal structure, the Galala Formation at Gabal Khashm El-Tarif, XPL and (F) oolitic bioclastic packstone consisting of ooids and pelecypod bioclastics embedded in micrite matrix. The bioclastics show partial micritization on their peripheries, the Halal |

Formation at Gabal Manzour, XPL. The entire scale bars = 250 lm.

1997). In addition, ooids with concentric structures and ooid aggregates indicate deposition in an intertidal zone of highly agitated shallow water conditions (Strasser, 1986). Therefore, the recognized oolitic grainstone refers to deposition in a high-energy intertidal shoal.

### Rudist boundstone (R.Bou.)

The rocks of this facies are dominated throughout the Halal Formation at Gabal El-Fallig. They intercalate with the dolostone, marl and oolitic grainstone facies (Figs. 2 and 3). They are dark brown, hard, cavernous and highly fossiliferous with large-sized rudist shells. Each bed of this facies is 2–3 m thick. Microscopically, it is composed of tightly packed skeletal particles of rudists with interstitial material of dense lime mud and few fine- to very fine-grained quartz (Fig. 5D). The rudist shells kept their original internal structure.

Interpretation: Boundstones can form in high-energy water with significant autochthonous carbonate production in well-oxygenated environment above wave base (Flügel, 1982). The occurrence of sandy lime–mud matrix within boundstones can be formed by the trapping action of organisms (Scott, 1995). Rudist buildup forms stratified deposits reflecting a prograditional environment (Scott, 1995). Therefore, the dominance of the stratified deposits of rudist boundstone facies in the Cenomanian succession at Gabal El-Fallig can be belonged to a rudist patch reef of high-energy intertidal shoal environment. This facies may represent the organic reef of the platform margin.

### Oyster rudstone (Oy. Ru.)

This lithofacies is recorded frequently throughout the Halal Formation at Gabal El-Fallig (Figs. 2 and 3). It is also found in the middle unit of the Raha Formation at Gabal Ekma (Figs. 2 and 3). Microscopically, this facies is made up of large (2–5 cm in length) pelecypod shells (Exogyra sp. and/or Ostrea sp.) embedded in lime–mud matrix and/or sparite cement (Fig. 5E). The pelecypod shells either exhibit their original fibrous structure or recrystallized to sparry calcite. Few shells show dense localized partial micritization. In other shells, although micrite envelopes outline their outer margins, their centers were recrystallized to calcite spars (Fig. 5E).

Interpretation: The oyster rudstones reflect deposition in lower intertidal to shallow subtidal shoals with moderate to high-energy conditions in a comparison with SMF 12 (FZ6) of Wilson (1975) and Flügel (1982).

## Facies association- F: Intertidal-subtidal open marine

Open marine depositional environment is an area of deposition that lies in the lee side of islands and shoals toward open marine (Tucker, 1990). The facies association-F includes oolitic bioclastic packstone, pelecypod bioclastic wackestone, echinoidal bioclastic packstone, foraminiferal packstone, massive marlstone facies. These facies dominate in the Galala and Halal formations at Gabal Manzour and Gabal Khashm El-Tarif (Figs. 2 and 3).

### Oolitic bioclastic packstone (O.B.P.)

This facies occurs in the middle unit of the Raha Formation at Gabal Ekma and the Halal Formation at Gabal Manzour (Figs. 2 and 3). It is also recorded in the lower unit of the Galala Formation at Gabal Khashm El-Tarif (Figs. 2 and 3). The rocks of this facies are massive grayish yellow to yellowish brown limestone. Each bed of this facies attains a thickness of about 1.5–2.5 m (Figs. 2 and 3). The rocks of this facies essentially occur as interbeds with the intraclastic wackestone facies and the nodular marl facies (Figs. 2 and 3). Oolitic bioclastic packstone (Fig. 5F) consists of 20–30% ooids and 30–40% bioclasts with binding material of micrite matrix (30–40%). Pelecypod shell fragments represent the bioclasts. Although most of the pelecypod shell fragments are recrystallized to sparry calcite, few of them are micritized. The ooids are of simple and composite types with concentric and radial structures and nuclei of micritic to sparitic carbonate and rare quartz grains.

Interpretation: The occurrence of ooids and abraded shells indicates deposition under agitated conditions above the fair-weather wave base (intertidal zone) (Dunham, 1962; Strasser, 1986). On the other hand, the existence of lime–mud refers to a quiet water deposition (Flügel, 1982). Therefore, co-existence of ooids and bioclasts embedded in lime–mud in the recognized oolitic bioclastic packstone may be proposed to deposit in a lower intertidal environment.

### Pelecypod bioclastic wackestone (P.B.W.)

This facies is distinguished throughout the lower and middle units of the Raha, Galala and Halal formations at all the studied localities (Figs. 2 and 3). It often occurs in an intercalation with the lime–mudstone, packstone and grainstone lithofacies (Figs. 2 and 3). The rocks of this facies are grayish white to yellowish gray in colour. Each bed of this facies attains a thickness varies between 2 and 3 m. Petrographic investigation reveals that this facies is made up of dense micrite matrix (80–85%) and 15–20% skeletal components (Fig. 6A). Bivalve shell fragments represent the skeletal components. In this facies, the most of the bivalve shells are recrystallized to sparry calcite, while some of them are subjected to partial micritization.

Interpretation: In general, wackestone facies indicates deposition in a shallow subtidal environment (Wilson, 1975). The abundance of pelecypod bioclastic in micrite matrix suggests deposition in a shallow subtidal environment with open circulation (Wilson, 1975 and Flügel, 1982).

### Echinoidal bioclastic packstone (E.B.P.)

This facies is recorded frequently throughout the middle unit of the Halal Formation at Gabal Manzour and the Galala Formation at Gabal Khashm El-Tarif (Figs. 2 and 3). The rocks of this facies are massive and hard. In the field, this facies often occurs above marls and attains a thickness of 2–3 m. Microscopically, this facies is built up mainly of echinoid plates (20–30%) and pelecypod shell debris (10–20%) embedded in micrite matrix (Fig. 6B).

Interpretation: The presence of echinoids indicates open marine conditions (Wilson, 1975). The association of echinoids with pelecypod debris in the packstones refers to a deep subtidal environment of deposition (Harris et al., 1997). Consequently, the recorded echinoidal pelecypod bioclastic packstone facies was deposited in a deep subtidal open marine environment with moderate-energy conditions.

### Foraminiferal packstone (Fr.P.)

The rocks of this facies are common in several parts of the middle unit of the Halal and Galala formations at Gabal Manzour and Gabal Khashm El-Tarif (Figs. 2 and 3). They are thin-bedded chalky limestones with chert nodules (Fig. 6C). They often alternate with nodular marlstones. Each bed of this facies attains a thickness varies between 10 and 20 cm. Petrographically; this facies (Fig. 6D) is composed mainly of foraminiferal tests (40–50%) embedded in micrite matrix (20–30%). A few echinoid spines are observed. The foraminifera include both benthic (e.g., miliolids, uniserial and biserial forams) and planktic tests. Scattered patches of microspars are noticed within the micrite matrix due to partial aggrading neomorphism.

Interpretation: The dominance of foraminiferal tests and echinoid spines in the lime–mud matrix indicates a deep subtidal environment below normal wave base with low-energy conditions and open circulation (Wilson, 1975; Harris et al., 1997). Also, the lack of bioturbations and any internal sedimentary structures in the thinbedded chalky limestones refer to deposition in quiet-water deep subtidal environment (Tucker and Wright, 1990).

### Massive marlstone (Mr)

Massive marlstone facies is essentially found throughout the middle units of the Raha, Halal and Galala formations at all the studied localities (Figs. 2 and 3). The rocks of this facies are massive, yellow in colour and fossiliferous. Each bed of this facies is 1–2 m thick.

Interpretation: Massive marls refer to deposition in a low-energy deep subtidal realm, just below fair-weather wave base, where quiet-water conditions allow deposition of fine sediments from suspension (Tucker, 1990).

## Facies association- G: Storm-influenced subtidal open marine

Storm-influenced subtidal marine environment refers to a deep-water area that influenced by storm action and lies above the storm wave base (Burchette and Wright, 1992). This facies association is mainly represented by oyster floatstone, intraclastic wackestone and nodular marl facies (Figs. 2 and 3).

### Oyster floatstone (Oy.Fl.)

The rocks of this facies are yellowish white massive limestones that are intercalated with the thin-bedded cherty limestone (Figs. 2 and 3). These rocks are rich in large sized oyster shells. Each bed of this lithofacies has a thickness ranges from 1 to 2 m. Microscopically, the oyster floatstone (Fig. 6E) is made up of larger-sized pelecypod shells (15–25%) embedded in lime–mud matrix (60– 70%). Most of the pelecypod shells exhibit their original fibrous structure.

Interpretation: The lime–mud matrix of the floatstone reflects deep subtidal quiet water (Flügel, 1982). In contrast, the co-existence of large oyster shell fragments with micrite matrix is attributed to reworking from nearby carbonate skeletal shoals by storm

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| Fig. 6. Photomicrographs showing: (A) pelecypod bioclastic wackestone in which the pelecypod shells are partially micritized, the Halal Formation at Gabal Manzour, (B) echinoidal bioclastic packstone that is made up of echinoid plates and bioclastic debris in dense micrite, the Galala Formation at Gabal Khashm El-Tarif, PPL, (C) thin-bedded limestone with chert nodules in the middle unit of the Galala Formation at Gabal Khashm El-Tarif, (D) foraminiferal packstone containing benthic forams and pellets, the Galala Formation at Gabal Khashm El-Tarif, PPL, (E) oyster floatstone consisting of large oyster shell fragments preserved their original fibrous microstructure and embedded in micrite matrix, the Halal Formation at Gabal Manzour, XPL, scale bar = 250 lm and (F) intraclastic wackestone that is made up of intraclasts within micrite matrix, the Halal Formation at Gabal Khashm El-Tarif, PPL. The entire scale bars = 250 lm. scale bar = 250 lm. |

waves and redeposition in the quiet subtidal water (Tucker and Wright, 1990). Therefore, this facies refers to deposition in a deep subtidal area closer to a carbonate skeletal shoal.

### Intraclastic wackestone (Inr. W.)

This facies characterizes the nodular limestones of the lower and middle units of the Halal and Galala formations at Gabal Khashm El-Tarif (Figs. 2 and 3). The rocks of this facies intercalate with massive and thin-bedded cherty limestones (Figs. 2 and 3). Each bed of this facies displays a thickness of 3–4 m. Microscopically this facies comprises intraclasts and bioclasts (20–30%) embedded in lime–mud matrix (Fig. 6F). The intraclasts are moderately sorted and well rounded. They are made up of dense lime mud.

Interpretation: The occurrence of intraclasts within the wackestone facies suggests reworking from the nearby carbonate shoals to the shallow subtidal water where the micrite formining matrix of the wackestone is deposited. This can take place during storm influence on deposition in the shallow subtidal zone (Lee and Kim, 1992). In addition, nodular nature of the characteristic limestones may refer and support an occasional period of storm activity (Bàdenas and Aurell, 2001).

### Nodular marl (Nod.Mr)

The nodular marls are mainly recorded throughout the lower and middle units of the Halal Formation at Gabal Manzour and Gabal Khashm El-Tarif (Figs. 2 and 3). The marl beds exhibit yellow colour and occur in an intercalation with the massive limestone (Fig. 7A). Occasionally, the marl beds occur within the thin-bedded limestones. Each bed of this nodular marl facies has a thickness ranges from 0.5 to 1.5 m.

Interpretation: Nodular marls and limestones are storm deposits formed after early lithification on the sea floor (Bàdenas and Aurell, 2001). Also, according to Burchette and Wright (1992) the occurrence of carbonate nodules within a carbonate mud matrix is a common feature of deposits that were formed above storm wave base in mid-ramp settings. Consequently, the recognized nodular marls reflect a deposition below the fair-weather wave base (FWWB) and above storm wave base (SWB) in a mid-ramp setting.

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| Fig. 7. Field photographs showing: (A) nodular (N) and bedded limestones (L) in the lower unit of the Galala Formation at Gabal Khashm El-Tarif, (B) the contact between the fluvial purple-coloured sandstone of the Malha Formation (M) and its overlying shallow marine glauconitic sediments of the Raha Formation (R) at Gabal Ekma, Notice, the iron nodules and ferruginous rootlets grading downward in the sandstone of the Malha Formation (see arrows), (C) Thalassinoide network (see arrows) in the uppermost part of the lower unit of the Raha Formation at Gabal Ekma, (D) ferrigenous material-filled dissolution cavities (see dotted lines) in the dolostone bed of the uppermost part of the middle unit of the Raha Formation at Gabal Al-Makarah. Notice, the colour contrast between the fillings and their enclosing dolostone, (E) an irregular surface with iron nodules (see arrows) between the lower and middle unit of the Halal Formation at Gabal Manzour, (F) brecciated limestone with sedimentary fillings of red dolomitic silts, |

the uppermost bed of the lower unit of the Halal Formation at Gabal El-Fallig.

# Depositional model

In the present study, vertical and lateral distributions of sedimentary facies and their interpreted depositional environments revealed an occurrence of a gradual southwest-northeastward environmental change from peritidal flat, lagoonal, carbonate sand shoals, rudist patch reefs to intertidal–subtidal and storm-influenced open marine carbonate facies. In contrast, biohermal reefdominated, a slope break, slumping apron and oceanic depth-related facies that characterize the rimmed shelf (Read, 1985; Tucker, 1990; Burchette and Wright, 1992) have not been recorded. In addition, the Late Jurassic-Early Cretaceous tectonic movements led to establishment of a progressively northward subsiding passive margin in Sinai, which represents a substrate for the Cenomanian deposits (Shata, 1956). Moreover, the tectonic movements were negligible and excluded during Cenomanian time in Sinai (Ayyad and Darwish, 1996; Kuss and Bachmann 1996). On the basis of the fore-mentioned and following the classification of carbonate platform of Read (1985) and Burchette and Wright (1992), the author assumes that the studied sediments probably deposited in a homoclinal ramp setting rather than a rimmed shelf. In this ramp setting (Fig. 8), the proximal inner ramp is believed to be situated at Gabal Ekma, Gabal Al-Makarah where peritidal flat and restricted lagoonal facies have been prevailed, respectively (Fig. 8). The distal inner ramp is considered at Gabal El-Fallig where high-energy shoals of ooids and patch reef facies are predominant (Fig. 8). On the other hand, the mid ramp setting characterizes the areas of Gabal Manzour and Gabal Khashm El-Tarif where the intertidal-subtidal and storm-influenced subtidal open marine carbonate facies are dominant, respectively (Fig. 8). In this study, although the mid-ramp Cenomanian facies cannot be followed laterally over longer distances, they seem to have been extended toward the extreme north of the study area where hemipelagic facies of outer-ramp and basin sediments (e.g., planktonic forams-rich limestones, marls and chalks) were encountered in the subsurface sections in the extreme north of Sinai (Ayyad and Darwish, 1996) and Israel (Lepson-Benitah et al., 1997) (Fig. 8). The entire inner-mid ramp of the study area was finally drowned

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| Fig. 8. Sketch of mixed siliciclastic–carbonate ramp facies model showing the distribution of facies associations and their related depositional environments of the Cenomanian Raha/Galala/Halal formations in Sinai Peninsula, northeast Egypt. A, B, C, D, E, F, and G are facies association types as reported in the text. Ek: Gabal Ekma, Mk: Gabal Al- Makarah, Fg: Gabal El-Fallig, Mz: Gabal Manzour, Tr: Gabal Khashm El-Tarif, Ns: offshore of northern Sinai. MSL: mean sea-level, FWWB: fair-weather wave base. |

SWB: storm wave base. For other symbols (see Fig. 3).

towards the close of the Cenomanian time by a rapid sea-level rise controlling the deposition of the Abu Qada Formation in Sinai (Cherif et al., 1989; Khalifa et al., 2003; Kora and Genedi, 1995; Saber, 2002).

The major tectonic movements were negligible and excluded during Cenomanian time in Sinai (Kuss and Bachmann, 1996; Ayyad and Darwish, 1996). Consequently and among the various factors control sedimentation patterns of mixed clastic–carbonate ramps (Tucker, 1990; Schlager, 2005 for review), the author proposes eustatic sea-level changes in a combination with the paleo-relief of substrate (ramp) and environmental factors (e.g., carbonate biological productivity and siliciclastic input) were the major factors controlling the vertical and lateral facies changes between the sedimentary sequences in the studied localities. Sea-level change herein is noticed by simple shifts of the facies belts from subtidal to peritidal and emerged facies (Figs. 2 and 3). The carbonate production is revealed by the occurrence of rudist patch reef facies, whereas the siliciclastic input is distinguished by the quartzarenite, siltstones and mudrocks facies (Figs. 2 and 3).

# Sequence stratigraphy

During the fieldwork, attention was focused on the determination of surfaces indicating subaerial exposures, hardgrounds and facies contrast, which could help in recognition of sequence stratigraphic surfaces and boundaries in both clastic and carbonate successions. These were distinguished on the basis of the criteria published by Shanmugam (1988) and Hillgärtner (1998). The sequence stratigraphic terminologies of Van Wagoner et al. (1988), Sarg (1988) and Handford and Loucks (1993), supplemented by modern concepts of Friedman and Sanders (2000), Catuneanu (2002) and Schlager (2005) have been applied in this study. The facies distribution and stratal geometry permit the identification of two depositional sequences. Each sequence consists of a package of transgressive and regressive sedimentary facies (systems tracts or facies tracts) and is bracketed by two sequence boundaries (Figs. 2 and 3) as outlined below.

## Sequence boundaries (SB)

In the present study, the sequence boundaries are distinguished where there are horizons indicating abrupt facies changes or submarine hardgrounds and/or subaerial exposures. The following sequence boundaries are distinguished.

### The first sequence boundary (SB1)

This boundary represents the base of the Cenomanian succession. At Gabal Ekma, Gabal Al-Makarah and Gabal Khashm El-Tarif, it is traced between the shallow marine mixed clastic–carbonate deposits of the basal part of the Cenomanian Raha/Galala Formation and the fluvial clastics of the underlying Barremian-Aptian Malha Formation (Figs. 2 and 3). This surface is irregular with ferruginous crust and vertical ferruginous pipes penetrating the underlying bed of the uppermost part of the fluvial Malha Formation (Fig. 7B). Such features suggest a paleosol development at time of subaerial exposure (Retallack, 2001). Thus, this surface belongs to a subaerial unconformity (Catuneanu, 2002). Also, the occurrence of shallow marine deposits above the recognized subaerial unconformity surface refers to a transgressive surface of erosion (Van Wagoner et al., 1988) or a ravinement surface (Catuneanu, 2002). At Gabal El-Fallig and Gabal Manzour, although no criteria of hardground or subaerial exposure are noticed between the Halal Formation and its underlying Risan Aneiza Formation, the first sequence boundary (SB1) is noticed between the dolomicrite of the uppermost bed of the Aptian–Albian Risan Aneiza Formation and the highly fossiliferous marls of the lowermost part of the Cenomanian Halal Formation (Figs. 2 and 3). In this manner, the dolomicrite of the uppermost part of the Risan Aneiza could have taken place in a poor interchange of water with the open sea during an extreme sea-level fall at supra-upper intertidal zone (Sass and Bein, 1982; Luning et al., 1998; Abu El-Hassan and Wanas, 2005). On the other hand, the occurrence of highly fossiliferous marl of the lowermost part of the Halal Formation above dolomicrite of the underlying Risan Aneiza Formation could be prevailed during a better interchange with the open sea and relative sea-level rise (Sass and Bein, 1982; Buchbinder et al., 2000).

### The second sequence boundary (SB2)

At Gabal Ekma, extensively burrowed hardground forming Thalassinoides networks marks this boundary at the top of the lower unit of the Raha Formation (Fig. 7C). Iron crusts and nodules are commonly associated with this hardground. This hardground does not indicate emergence of the sea floor, but it was developed during a minor break or a very slow rate of marine sedimentation accompanying a short-term sea-level fall. This is closely similar to the submarine hardground of Hillgärtner (1998). This sequence boundary can be correlated with the contact between Abu Had Member and Mukattab Member of Cherif et al. (1989). At Gabal Al-Makarah, this boundary is documented by the presence of ferruginous-filled cavities showing contrast in colour with their enclosings (Fig. 7D). These ferruginous material-filled cavities occur in the dolomitic quartzarenite bed of the uppermost part of the lower unit of the Raha Formation. They are similar to the hardground that was developed by macroboring invertebrates during a short-term sea-level drop (Hillgärtner, 1998; Ekdale et al., 2002). At Gabal Manzour, this second boundary (SB-2) is marked by a surface with ferruginous crust and nodules (Fig. 7E) above the carbonate near the top part of the lower unit of the Halal Formation. This surface of iron crust and nodules (Fig. 7E) could be formed during a short period of sea-level fall in the carbonate platform (Sarg, 1988). At Gabal El-Fallig, this sequence boundary is delineated in the uppermost part of the lower unit of the Halal Formation by the brecciated carbonate bed (Figs. 7F). This is similar to that described in the sequence boundaries in the Jurassic and Cretaceous shallow-marine carbonate platform of France, Spain and Oman by Hillgärtner (1998), Molina et al. (1999) and Immenhauser et al. (2001), respectively who ascribed the brecciation in the carbonate platforms to their karstification during an episode of sea-level fall and exposure. At Gabal Khashm El-Tarif, the occurrence of fenestral or bird eyes fabric in the lime–mudstone facies (Fig. 4E) in the uppermost part of the lower unit of the Galala Formation marks this boundary. This is compatible with what has been interpreted to imply a brief episode of a minor break in submarine sedimentation that could have occurred during a short-term sea-level fall.

## Depositional sequences

On the basis of their stratigraphic setting, facies changes and sequence boundaries and surfaces, the studied Cenomanian rocks (Raha/Galala/Halal formations) display the occurrence of two depositional sequences formed in response to eustatic sea-level changes (Figs. 2 and 3).

### Sequence-1

This depositional sequence characterizes the lower unit of the studied Raha/Galala/Halal formations (Figs. 2 and 3). It starts with the transgressive surface of erosion (TS1), which is amalgamated with the SB1 at the base of the studied rock units (Figs. 2 and 3). The upper boundary of this sequence is demarcated by SB2. Sequence-1 comprises transgressive (TST) and highstand (HST) systems tracts (Figs. 2 and 3). The TST, which corresponds to a rapid rise in eustatic sea level, is delineated by the prevalence of retrogradational facies above the underlying fluvial deposits of the Malha Formation and/or the dolostones of the uppermost part of the Risan Aneiza Formation (Figs. 2 and 3). The retrogradational package of facies consists of sand/mud tidal flat facies in the southern sections and intertidal-shallow subtidal limestone facies in the northern sections (Figs. 2 and 3). Deep subtidal marls and green shales that terminate this TST (Figs. 2 and 3) mark the maximum flooding surface (MFS). Shallowing upwards facies started by shallow subtidal and ended by upper intertidal facies follows this MFS. These shallowing upwards facies can belong to the HST.

### Sequence-2

This depositional sequence forms the middle and upper units of the studied Raha/Galala/Halal formations. It is started by SB2 and ended by TS2. Facies of this sequence can be grouped into transgressive and highstand systems tracts (Figs. 2 and 3). The TST forms the lower part of the middle unit of the studied formations. The TST package of this sequence consists of sediments of intertidal to shallow subtidal molluscan wackestones, packstones and grainstones that show an upward trend to deeper subtidal marl and foraminiferal wackestones and packstones. The foraminiferal wackestone facies mark the MFS2 relative to their overlyings and underlings (Figs. 2 and 3). The succeeding facies of MFS2 are interpreted as HST. This HST constitutes the uppermost of the middle unit and whole upper unit of the studied formations. The HST can be subdivided into early and late stage. The early stage of HST shows an upward shallowing relative to those of the underlying TST. Such early HST is mainly represented by intertidal-shallow subtidal facies above the deep subtidal facies of the underlying TST (Figs. 2 and 3). The late stage of HST is distinguished above the early HST. This is because the rate of eustatic sea-level fall is higher than it was during the deposition of the underlying early HST, meanwhile there is no subaerial exposure at the top of early HST facies (Schlager, 2005). The late stage HST is distinguished by the supra-intertidal dolomicrites and coarse crystalline dolomites above intertidal-shallow subtidal limestone facies (Figs. 2 and 3). Such occurrence of dolomites above intertidal-shallow subtidal carbonate platform has been interpreted to indicate a relative progressive shallowing of sea-level (Mutti and Simo, 1994). This is similar to that described in the late HST of the carbonate platform of the Risan Aneiza Formation at Gabal El-Halal in Egypt (Luning et al., 1998) and the Yates formation at the Guadalupe Mountains in USA (Mutti and Simo, 1994). Above the recognized late HST and in the sense of Van Wagoner et al. (1988), transgressive surface (TS2) is detected where the quiet water, deep subtidal open marine facies of the Lower Turonian Abu Qada Formation drowned above the late HST of mixed siliciclastic carbonate, inner-mid ramp of the Cenomanian succession at all the studied localities, without remarkable subaerial exposure or lowstand deposits (Figs. 2 and 3). In the sense of Schlager (2005), this TS2 represents a drowning surface.

# Conclusions

Five stratigraphic sections of the Cenomanian rocks (Raha/Galala/Halal formations) have been measured and studied in Sinai. This has been done to deduce the depositional environments and establish the sequence stratigraphic framework of the Cenomanian rocks in Sinai. The studied Cenomanian successions are characterized by siliciclastic/carbonate deposits, in which the siliciclastic components increase toward the southern parts of Sinai with decreasing carbonate deposits. The Cenomanian rocks are subdivided into three informal rock units: lower, middle and upper. Within the Cenomanian rocks, different clastic and carbonates facies have been differentiated according to their texture and composition. Different depositional environments that have been recognized in these rocks include peritidal flat, lagoon, high-energy shoals of ooids and rudist patch reef and intertidal–subtidal to storm-influenced open marine. The facies and their related depositional environments indicate that the Cenomanian rocks in Sinai were deposited on a ramp setting. This ramp shows a gradual southwest-northward transition from inner-to mid-ramp. The inner-ramp facies are dominated in (Gabal Ekma and Gabal Al-Makarah) south and west central Sinai (Gabal El-Fallig) whereas the mid-ramp facies have been found in north (Gabal Manzour) and east Sinai (Gabal Khashm El-Tarif). In general, the Cenomanian facies characteristics show a gradual northward increase in open marine carbonate facies with simultaneous southward increase in shallow marine clastic facies. The present study proposes that eustatic sea-level change coincided with environmental factors (e.g., carbonate production and siliciclastic supply) are the main factors controlling deposition of the Cenomanian deposits in Sinai.

Relying on distribution and stacking pattern of the recognized facies and their related paleo-environments, two superimposed depositional sequences were distinguished. Each of these sequences is bounded by sequence boundaries. These sequence boundaries have been delineated by obvious criteria of facies contrast, hardgrounds and subaerial exposures. Both sequence-1 and sequence-2 have transgressive and highstand systems tracts. In conclusion, the present study declares that the transgression of the Neo-Tethys in Sinai during Cenomanian came from the north toward the south.

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