Cenomanian - Turonian rudist assemblages and sequence stratigraphy on the North Sinai carbonate shelf, Egypt

Shaban Ghanem Saber, Yasser F. Salama, Robert W. Scott, Gouda Ismail Abdel-Gawad and Mohamed Fouad Aly

ABSTRACT

The Middle to Upper Cenomanian Halal and Turonian Wata formations crop out at Gabal Minsherah, Gabal Yelleg and Gabal Maaza in the northern Sinai Peninsula, Egypt. This paper describes the rudist assemblages of the two formations in a sequence stratigraphic framework. Tabular thickets of conical to cylindrical elevator radiolitid rudists were the most common benthic type on the northern Cenomanian – Turonian Sinai shelf. The thickets were either single beds or multiple beds intercalated with marl or packstone. Most biostromes were laterally restricted and do not extend to nearby outcrops. The Cenomanian rudist biostromes are thin and composed mainly of several species of Radiolitidae and less common Caprinidae together with coralline sponges and benthic foraminifers. The Turonian rudist biostromes are composed of several species of Radiolitidae.

The Cenomanian Halal Formation grades upward from basal quartz arenite into bioclastic-oolitic grainstone overlain by bioclastic packstone and wackestone. Dolomite beds are part of the highstand facies. The Formation is composed of transgressive-regressive Halal Sequences 1 and 2. The base of the overlying Wata Formation is Sequence Boundary 3 at the base of Wata Sequence 3, which is Lower to Middle Turonian. The sequence boundary between the Halal and the Wata is marl-on-marl with Upper Cenomanian ammonites overlain by a condensed interval with ammonites of several Lower Turonian zones that are particularly well exposed at Gabal Minsherah. The boundary is interpreted by graphic correlation as a million-year-long hiatus after which carbonate deposition resumed and low-diversity rudist assemblages recovered. The hiatus is correlated to the global anoxic event OAE 2. Following OAE 2 carbonate deposition resumed and produced microfacies similar to those of the Cenomanian. The Upper Turonian Wata Formation is composed of Wata Sequences 4 and 5.

INTRODUCTION

The Cenomanian – Turonian succession documents major paleoenvironmental changes in the world oceans. Carbonate production on the shelves was greatly reduced or even terminated near the end of the Cenomanian Stage, and reefal and other shallow-marine communities were stressed or went extinct. This crisis dramatically altered rudist bivalve communities, which were major contributors to Cenomanian carbonate deposits (Ross and Skelton, 1993; Steuber and Löser, 2000). During the Turonian recovery period, low-diversity radiolitid banks accrued and the new hippuritid group gradually evolved. This Cenomanian – Turonian Crisis was one of a succession of Cretaceous anoxic oceanic events beginning in the Valanginian that stressed shallow-water marine communities (Scott, 1995). In deeper basins organic-rich black shale was deposited during the Crisis, but upon shelves hiatuses are well documented (Philip, 1993; Scott, 2003; Johnson et al., 2002).

During Cenomanian – Turonian time the Sinai Peninsula was a broad shallow shelf or carbonate ramp sloped northward across which the east-west shoreline of the Neo-Tethys Ocean fluctuated as sea level changed (Darwish, 1994; Bauer et al., 2001, 2004). Over the Peninsula, the Cenomanian – Turonian Crisis corresponds to a hiatus and the absence of organic deposits (Lewy, 1989; Buchbinder et al., 2000; Bauer et al., 2001, 2004). In Egypt Cenomanian and Turonian rudists were most abundant and diverse before and after the Crisis (Steuber and Löser, 2000; Aly et al., 2005a). Therefore the paleocommunity succession provides clues to the processes of extinction and recovery during the global oceanic crisis.
Important Cenomanian – Turonian sections crop out in the northern Sinai Peninsula (Figure 1), and their lithological succession, facies and sequence stratigraphy have been extensively studied (Kora and Genedi, 1995; Lüning et al., 1998; Saber, 2001, 2002; Bauer et al., 2001; 2004; Abdel-Gawad et al., 2004; El Qot, 2006; Wanas 2008). The purpose of this paper is to describe the rudist assemblages at Gabal Minsherah, Gabal Yelleg and Gabal Maaza (Figure 1) in the context of a sequence stratigraphic framework. These sections are located on the Syrian Arc fold belt, north of the mid-Sinai hinge zone that transects the Sinai Peninsula east to west (Darwish, 1994). Lateral correlations of Cenomanian – Turonian rock-units used here are summarized in Figure 2.

Figure 1: Locations of three sections studied in the northern Sinai Peninsula, Egypt: Gabal Minsherah (30°17′58″N and 33°41′22″E), Gabal Yelleg (30°22′25″N and 33°28′21″E) and Gabal Maaza (30°38′42″N and 33°26′37″E).
CENOMANIAN HALAL FORMATION

Lithology: The Halal Formation (Figure 2) is about 420 m thick at Gabal Yelleg and thins northward to Gabal Maaza (270 m) and southeastward to Gabal Minsherah (220 m) (Figure 3). The lower part of the Halal Formation is composed mainly of cross-bedded limestone and sandstone (Figures 4a and b), massive limestone with dolostone, and marl intercalations. The upper part is mainly interbedded chalky white fossiliferous limestone, grey limestone, dolostone and marl; calcareous mudstone interbeds are rare. The topmost bed is marly ammonite limestone.

Boundaries: The Halal Formation unconformably overlies the deltaic Aptian – Albian Risan Aneiza Formation in the Maaza section (Bachmann et al., 2003; Aly et al., 2005b), and in the Yelleg and Minsherah sections the boundary is disconformable. This formation is in disconformable contact with the overlying Turonian Wata Formation. The contact between the Halal and Wata formations is at the contact of marl overlain by marl in the Gabal Minsherah section (Figures 3 and 5).

Paleontology and Age: The Halal Formation is assigned to the Cenomanian Stage based on a distinct molluscan assemblage. The middle part of the studied sections contains Neolobites vibrayeanus (d’Orbigny), which occurs in the Upper Cenomanian Substage just below the Metoicoceras geslinianum Zone in France (Kennedy and Juignet, 1981) and in the Negev Desert (Lewy, 1996). The uppermost beds contain Calycoceras spp., Vascoceras cauvini Chudeau, and Metengonoceras dumbli (Cragin). Common bivalves throughout the Halal Formation are Ceratostreon flabellatum, Gyrostrea delettrei (Coquand), Ilymatogyra africana (Lamarck), and Costagyra olisiponensis (Sharpe) with Chondrodonta joannae (Choffat) that support the Cenomanian age for the Halal Formation and the equivalent Cenomanian Formation in Sinai (Abdel-Gawad et al., 2004, 2007; El Qot, 2006, 2008; Samuel et al., 2009). Associated taxa are the gastropods Nerinea gemmifera Coquand and Strombus incertus (d’Orbigny) together with the coralline sponges Actinostromarianina sp. and Steineria sp., and the octocoral Polytrema chalmasi Thomas & Péron (Abdel-Gawad and Gameil, 1995; Abdel-Gawad, 2001) (Figures 4c and d). Common benthic foraminifers include miliolids, Praevalveolina cretacea (d’Archiac), P. tenuis Reichel, Orbitolina (Orbitolina) concava (Lamarck), and Cuneolina pavonia d’Orbigny that indicate the Middle to Upper Cenomanian substages. Planktic foraminifers are minor. Echinoids and rare pelagic crinoids also occur in some beds of the Halal Formation. The top of the Cenomanian at Gabal Yelleg section is a reddish yellow chalky limestone bed rich in Costagyra olisiponensis (Figure 4e).

Lateral Variations: In the Sinai Peninsula, the Cenomanian Stage consists of mixed carbonate and siliciclastic more than 500 m thick (Darwish, 1994). It is defined as the Halal Formation (Said, 1971) or the Galala Formation (El-Azabi and El-Araby, 1996; Wanas 2008) (Figure 2). Along the eastern side of the Gulf of Suez at the El Giddi Pass, the Cenomanian Stage is divided into the Galala Formation and the lower part of Abu Qada Formation (Saber, 2001). South of the mid-Sinai hinge zone (Figures 1 and 2) the Halal grades into the more siliciclastic Raha Formation (Darwish, 1994; Bauer et al., 2001, 2004; Abdel-Gawad et al., 2004; El Qot, 2006; Samuel et al., 2009).

| Stage                  | Age (Ma) | North Sinai Hinge | South Sinai  |
|------------------------|----------|-------------------|-------------|
| Coniacian-Santonian     | 89.3     | Themed Formation  | Matulla Formation | Ghorab, 1961 |
| | ± 1.0     | Wata Formation | Wata Formation | Ghorab, 1961 |
| Late Cretaceous Turonian| 93.0     | Galala Formation  | Abu Qada Formation | Ghorab, 1961 |
| OAE2                   | 97.1-99.6| Halal Formation   | Raha Formation | Ghorab, 1961 |

Figure 2: Correlation chart of selected Cenomanian, Turonian and Coniacian-Santonian formations in the northern and central Sinai Peninsula.
TURONIAN WATA FORMATION

Lithology: The Wata Formation is 80 and 115 m thick at Gabal Minsherah and Gabal Yelleg, respectively (Figure 5). The lower part is composed of marl, gypsumiferous shale and light gray chalky oolitic limestone. The basal upper part is gray shale, calcareous mudstone and fine-grained glauconitic sandstone, which pass upwards to mainly interbedded dolostone, marl and fossiliferous limestone.

Boundaries: The Turonian Wata Formation (Ghorab, 1961) disconformably overlies the Halal Formation in the northern Sinai. It is overlain disconformably by the Late Coniacian-Santonian Themed Formation (Abdel-Gawad et al., 2004; El Qot, 2006).

Paleontology and Age: The Wata Formation in the northern Sinai spans from the upper part of the Lower Turonian to the Upper Turonian Substage (Figure 2). Beds in its lower part yield ammonites (Figure 4f): Pseudapidoceras flexuosum Powell, Choffaticeras segne (Solger), and Mammites nodosoides (Schlotheim). P. flexuosum is a member of the lower Lower Turonian Zone IV and C. segne occurs with M. nodosoides in the upper Lower Turonian Zone V in north Sinai and the Eastern Desert of Egypt (Luger and Gröschke, 1989; Kassab, 1994, 1996; Abdel-Gawad et al. 2007; El Qot, 2008). In the Negev Desert, M. nodosoides and C. segne define upper Lower Turonian zone T6a and Kamerunoceras turoniense (d’Orbigny) defines the overlying lower Middle Turonian zone T6b (Buchbinder et al., 2000). The same succession is reported in southern Negev Desert (Freund, 1961). The uppermost rudist bed is overlain by a marly bed with the Upper Turonian ammonite Coilopoceras requienianum (d’Orbigny), which ranges through the Upper Turonian Zone VI in Egypt (Luger and Gröschke, 1989; Kassab, 1994; Abdel-Gawad et al. 2004; El Qot, 2006; Abdel-Gawad et al. 2007; El Qot, 2008). C. requienianum occurs with Romaniceras deverianum (d’Orbigny) defines the Upper Turonian Substage in France (Devalque et al., 1982).

The upper part of the Wata Formation has a diverse rudist assemblage of Praeradiolites ponsianus (d’Archiac), Distefanella cf. lombricalis (d’Orbigny), Durania arnaudi (Choiffat), Durania gaensis (Dacqué), Durania humei var. inermis Douville, Radiolites saucigesi (d’Hombres-Firmas), and Radiolites cf. lewyi Parnes (Figure 5). The gastropod Nerinea requieniana d’Orbigny and benthic foraminifers are subordinate. Turonian strata are absent along the steep flanks of Gabal Maaza (Jenkins et al., 1982).

Lateral Variations: South of the Sinai hinge zone the lower part of the Wata Formation consists of interbedded marl and sandstone with few limestone beds that are mapped as the Abu Qada Formation (Ghorab, 1961; Bauer et al., 2001, 2003, 2004; Abdel-Gawad et al., 2004; El Qot, 2006 (Figure 2). The upper limestone and dolomite interval correspond to the Wata Formation.

Figure 3: Lithostratigraphic and biostratigraphic framework of the Cenomanian Halal Formation in the studied sections.

The sequence stratigraphic correlation and distribution of rudist assemblages is only shown for Gabals Minsherah and Yelleg. Lateral distance between the sections not to scale. Datum is the Halal-Wata formation disconformity.
The definition of the Cenomanian – Turonian rudist assemblages in the studied sections was based on the rudist species, rudist morphotypes, rudist fabrics, the associated biota, and the associated sedimentological facies. The rudists and associated fauna were carefully collected bed-by-bed from the three studied sections. Representative complete rudist specimens were selected for description, oriented thin sections and photographing. One hundred and thirty-six complete and incomplete rudist specimens were collected mainly from the Minsherah and Yelleg sections. The calcitic outer layer of radiolitid specimens is well preserved with its internal wall structure and external ornamentation and the aragonitic inner layer was replaced by sparry calcite. Rudist taxonomy is summarized in the Appendix.

Figure 4: (a) Cross-bedded oolitic limestone at the base of Cenomanian Halal Formation, Gabal Yelleg.
(b) Cross-bedded sandstone at the lower part of the Halal Formation, Gabal Yelleg (sample 30).
(c) Gastropod-oyster bank in the lower part of Cenomanian Halal Formation, Gabal Maaza (sample 6).
(d) Coralline sponge bed with Steineria sp. in the Cenomanian Halal Formation, Gabal El Minsherah (samples 75-76).
(e) Chalky limestone with Costagyra olisiponensis (Sharpe) at the top of the Cenomanian Halal Formation, Gabal Yelleg (sample 125).
(f) Ammonites from sample 78 at the Cenomanian-Turonian boundary, Gabal Minsherah.
The integrated study of biological (e.g. shell size, shell thickness, packing density and packing index) and sedimentological characteristics (e.g. characters of the substrate) may, in fact, contribute to the definition of rudist communities with limited or even without taxonomic data (see Masse et al., 2004). The termination of rudist assemblages has been interpreted by Johnson et al. (2002) as related to the destructive action of storms or to episodes of rapid sedimentation followed by re-colonization by another rudist community. Alternatively, Moro et al. (2002) attributed the vertical succession of the rudist assemblages to a different tolerance of environmental factors, such as deepening and shallowing of the depositional setting in response to relative sea-level changes.

Six rudist assemblages at Gabal Minsherah and nine at Gabal Yelleg, as well as other parautochthonous assemblages at Gabal Maaza are recorded. The succession of rudist assemblages differs between the two main formations. Cenomanian assemblages are dominated by radiolitids. Turonian assemblages are characterized by Durania and radiolitids are less common. Compared to rudist assemblages from the Mediterranean region (e.g. Apulia region in southern Italy, Laviano et al., 1998), the Sinai rudist assemblages are much less diverse suggesting that environmental conditions in the Sinai were not optimal for rudists.

In Oman, four rudist banks characterize the Cenomanian carbonate platform (Philip et al., 1995). Praeradiolites is common in floatstone and wackestone and is locally associated with Sphaerulites or Ichthyosarcolitites. These species form recurrent biostromes up to 10 cm thick and several square kilometers in area. Eoradiolites forms thickets up to 50 cm thick and 10 m wide. Sauvagesia, Durania, Chondrodonta and nerineids form biostromes in the upper part of the Cenomanian section. The basal Turonian facies are coarse-grained graded grainstone with inclined bedding and hippuritids. These talus beds indicate that Hippurites buildups once were present.

In Algeria, seven rudist associations occur in the Middle and Upper Cenomanian (Chikhi-Aouimeur, 1998): Caprinula, diverse caprinids with Ichthyosarcolitites, Biradiolites, Eoradiolites, Praeradiolites, Durania blayaci-Sauvagesia tellensis, Durania gr. arnaudi. These associations are widespread throughout northern Algeria and represent a deeper to shallower nearshore cline.

Gabal Minsherah Section

In the Cenomanian – Turonian succession at Gabal Minsherah small rudist biostromes are intercalated with different microfacies that bear non-rudist biota. Six rudist assemblages are recorded from base to top (Figures 3, 5, 6a and b).

**M1 Praeradiolites cf. biskraensis/Eoradiolites liratus Assemblage**

This assemblage is represented by two thickets of Eoradiolites liratus (Conrad) and Praeradiolites cf. biskraensis (Coquand). It is intercalated with foraminiferal wackestone, lime mudstone and calcareous mudstone with rudist fragments, dendroid coralline sponges (Abdel-Gawad, 2001), other bivalve fragments, and rare benthic foraminifers. The constratal elevator rudists are moderately densely packed in a matrix of mudstone (Figure 6a). The facies overlying and intercalated with the rudist thickets have diverse and common benthic foraminifers associated with other taxa such as Chondrodonta and coralline sponges. Stem fragments and reproductive bodies of dasyclad and other calcareous algae are widespread (Bauer et al, 2004). The presence of the rudist rudstone, with in situ preserved shells, intercalated with lime mudstone and foraminiferal bioclastic wackestone indicates a low energy inner shelf environment. Overlying this assemblage is the first occurrence of praealveolinids and Neolobites, which correlates with the interval in the Gabal Yelleg section between assemblages Y1 and Y4. This assemblage resembles the first praealveolinid radiolitid unit in the Cenomanian Natih Member E at Al Jabal al-Akhdar in northern Oman (Philip et al., 1995). In Algeria *P. biskraensis* dominates biostromes that grew close to shore where stromatolites and gypsum formed (Chikhi-Aouimeur, 1998).

**M2 Parautochthonous Eoradiolites liratus/Caprinidae Assemblage**

This assemblage comprises Eoradiolites rudstone and caprinid and foraminiferal bioclastic wackestone where the main components are less than 2 mm in diameter. They overlie high-energy bioclastic intraclastic packstone. At the base of this assemblage large Eoradiolites liratus form a parautochthonous...
Saber et al.

fabric consisting of fragments that were uprooted and transported not far from their life position. The dense packing of *Eoradiolites* shells and the paucity of matrix together suggest that this assemblage was winnowed perhaps during storms (e.g., Skelton et al., 1995). Above the *Eoradiolites* rudstone is a loosely packed caprinid in a matrix of wackestone. This facies is overlain by foraminiferal bioclastic wackestone. The assemblage is locally associated with chondrodontid bivalves, coralline sponges, and benthic foraminifers of shallow-marine environments. In Algeria and Morocco the *Eoradiolites* gr. *liratus-zizensis* association is common in marly lithologies (Chikhi-Aouimeur, 1998).

**M3 Ichthyosarcolites triangularis Assemblage**

This assemblage is dominated by poorly preserved recumbent shells of *Ichthyosarcolites triangularis* Desmarest floating in wackestone matrix in life position with an open fabric (Figure 6b). The underlying bioclastic intraclastic packstone substrate has *Chondrodonta* and rare benthic foraminifers that is part of a shoaling-up depositional cycle. The widespread distribution of *Ichthyosarcolites* sp. suggests a eurytopic, shallow-marine environment (Steuber and Loser, 2000). This assemblage and the underlying assemblage resemble the rudist of the Cenomanian C and D members of the Natih Formation in Al Jabal al-Akhdar, northern Oman (Philip et al., 1995). In Algeria *Ichthyosarcolites* forms biostromes with diverse caprinids and sauvagesiids (Chikhi-Aouimeur, 1998). The low-diversity assemblage in northern Sinai suggests somewhat more restricted conditions there than elsewhere in the Mediterranean region.

**M4 Praeradiolites sp. Assemblage**

This assemblage represents the youngest Cenomanian rudist colonization in the Halal Formation at Gabal Minsherah. It is separated from the underlying *Ichthyosarcolites* Assemblage by a *Thalassinoides* bed that begins a new depositional cycle in the upper part of the Halal Formation (Figure 3). *Praeradiolites* sp. is in an upright in-life position forming small bouquets that are intercalated with nerineid gastropods, chondrodontid bivalves and coralline sponge beds. The rudist bouquets are underlain by wackestone and marl with benthic foraminifers, stem fragments and reproductive bodies of dasyyclad and other calcareous algae are widespread (Bauer et al., 2004), and capped by chondrodontid rudstone. The associated biota and facies with the rudists indicate weak to moderate energy in the inner-shelf environment. This assemblage is similar to the Sauvagesiinae bank in the Upper Cenomanian Natih Member A in northern Oman (Philip et al. 1995).

**M5 and M6 Durania Assemblages**

The M5 Assemblage is composed of erect *Durania* and represents the first recovery of rudist paleocommunities in the Turonian Wata Formation in the northern Sinai following the OAE2 Crisis (Figure 5). The lower *Durania* thicket is rudstone and intercalated with lime-mudstone and dolostone microfacies, and is separated from the younger M6 Assemblage by interbedded dolostone, lime mudstone, shale, and quartz arenite microfacies. The upper *Durania* rudstone is overlain by calcareous mudstone, lime mudstone and wackestone microfacies with oysters, echinoids, ostracodes, and benthic foraminifers. The microfacies and faunal association indicate the low-energy inner shelf environment.

**Gabal Yelleg Section**

At Gabal Yelleg, nine rudist assemblages are recorded from the Cenomanian – Turonian succession (Figure 3).

**Y1 Eoradiolites liratus Assemblage**

The rudists of this assemblage comprise a thicket that overlies the high-energy bioclastic oolitic grainstone and marl facies (Figure 6c). The presence of the complete right valves and unoriented fragments of *Eoradiolites liratus* (Conrad) supports their in situ parautochthonous accumulation (e.g., Ross and Skelton, 1993). In addition, the very densely packed rudist aggregates and the paucity of the matrix indicate the toppling and fragmentation of the rudist shells during high-energy events. Rudist fabrics and the associated microfacies indicate inner shelf settings repeatedly affected by high-energy events.
North Sinai carbonate shelf, Egypt

| Sample Number | Lithology                  | Sequence Stratigraphy | Sample Number | Lithology                  | Rudist and associated fauna |
|---------------|---------------------------|-----------------------|---------------|---------------------------|-----------------------------|
| 128           | Coilococeras requienianum  |                       | 110           | Limestone                 |                             |
| 130           | Durania humei var. inermis |                       | 100           | Oolitic Limestone         |                             |
| 135           | Distefanella cf. lombricalis Praeradiolites ponsianus |   | 90            | Flinty Limestone          |                             |
|               | Durania arnaudi            |                       | 90            | Chalky Limestone          |                             |
|               |                           |                       | 80            | Dolostone                 |                             |
|               |                           |                       | 70            | Marl                      |                             |
|               |                           |                       | 60            | Calcareous mudstone       |                             |
|               |                           |                       | 50            | Shale                     |                             |
|               |                           |                       | 40            | Sandstone                 |                             |
|               |                           |                       | 30            | Radiolitidae              |                             |

**Figure 5:** Lithostratigraphic, biostratigraphic and sequence stratigraphic framework for the Turonian Wata Formation at Gabal Minsherah and Gabal Yelleg. Lateral distance between the sections not to scale. Datum is top of Wata Formation.
**Y2 Radiolites sp. /Præradiolites cf. irregularis Assemblage**

This assemblage in the lower part of the Halal Formation composes two rudist thickets that are overlain by marl, lime-mudstone, oyster rudstone and wackestone microfacies rich in benthic foraminifers (Figure 6d). The succession indicates shallowing up from the deep inner shelf to restricted lagoonal environments. The lower rudist thicket at the base of the depositional cycle is dominated by elevator *Radiolites* sp. packed in life position. *Præradiolites cf. irregularis* Douvillé is another common isolated elevator rudist in the upper thicket of the assemblage. The right valves of the rudists show no preferred orientation in both the thickets, suggesting the absence of any water current energy trend. The present assemblage preferred the shallowest part of the subtidal zone where it is associated with benthic forams, echinoids, stem fragments and reproductive bodies of dasyclad and other calcareous algae.

**Y3 Eoradiolites sinaicus Assemblage**

This rudist assemblage of complete right valves of *Eoradiolites sinaicus* Douvillé is intercalated with lime mudstone and foraminiferal wackestone. The thick-shelled individuals formed loosely structured congregations (e.g. Gili et al., 1995). The associated fauna are miliolids, ostracodes, dasyclad reproductive bodies, bryozoa, and echinoids that may indicate quiet marine conditions of the inner shelf environment.

Figure 6: (a) *Præradiolites/Eoradiolites* assemblage (M1), autochthonous, moderately packed fabrics of elevator morphotypes with *Præradiolites cf. biskraensis* and *Eoradiolites liratus* in life position; Halal Formation, Gabal Minsherah.
(b) *Ichthyosarcolites* assemblage (M3), recumbent *Ichthyosarcolites triangularis* in life position with an open fabric; Halal Formation, Gabal Minsherah.
(c) Bioclastic oolitic grainstone, ooids with concentric and radial structures, nuclei of carbonate fragments and quartz grains in sparite cement; Halal Formation, Gabal Yelleg, P.L.
(d) Foraminiferal wackestone in the Halal Formation at Gabal Yelleg; Miliolids with micritized test wall and chambers filled by sparite P.L.
Y4 Biradiolites zumoffeni/Bournonia fourtau Assemblage
This assemblage is separated from the underlying assemblage by a succession of microfacies: echinoid and foraminifer bioclastic wackestones, lime-mudstone and dolostone microfacies, and oyster banks in marl. This assemblage is represented by bouquets of Bournonia fourtau Douvillé and Biradiolites zumoffeni Douvillé that alternate with chondrodontid rudstone, rudist floatstone, foraminifer bioclastic wackestone rich in miliolids and praevalveolinids. The rudist facies caps a shallowing up cycle. The rudists of this assemblage are elevator morphotypes but they are rarely found in life position; instead most are oblique or parallel to the bedding plane. The presence of Chondrodonta with rudists in this assemblage and the intercalated facies with non-rudist bivalves, echinoids, miliolids, and other benthic foraminifers indicates a shallow inner shelf environment. This assemblage is terminated by foraminifer bioclastic wackestone rich in praevalveolinids (Figure 7a) that indicates a restricted lagoon and shoaling trend.

Y5 Eoradiolites liratus Assemblage
This assemblage is dominated by complete horizontal shells of Eoradiolites liratus (Conrad). The rudist bed is overlain by foraminifer bioclastic wackestone rich in gastropods, chondrodontid bivalves, ostracodes, miliolids, praevalveolinids, and other benthic foraminifers. This facies is overlain by the Caprinula sp. assemblage. E. liratus tended to live as an elevator, but may have been reworked by currents and storms. This assemblage accumulated in the inner shelf or carbonate platform interior under effect of storms.

Y6 Caprinula sp. Assemblage
This assemblage is characterized by the recumbent rudist Caprinula sp. in a matrix of wackestone and is the highest rudist assemblage in the Cenomanian Halal Formation at Gabal Yelleg. The Caprinula bed is overlain by marl, foraminifer bioclastic wackestone and lime-mudstone with echinoids, calcareous algae, ostracodes, miliolids, and other benthic foraminifers. The microfacies and the associated fauna suggest the inner shelf environment.

Y7 Distefanella cf. lombricalis/Praeradiolites ponsianus Assemblage
This assemblage is the oldest Turonian rudist assemblage at Gabal Yelleg and is characterized by the elevator rudists Distefanella cf. lombricalis (d’Orbigny) and Praeradiolites ponsianus (d’Archiac). The rudists are in life position or were derived not far from it as indicated by the low degree of fragmentation. The assemblage composes a bank about 3 m thick, about 50 m above the base of the Turonian Wata Formation.

The basal part of the Wata is dominated by transgressive facies of Wata Sequence 3 as echinoid bioclastic wackestone, rudist floatstone and the high-energy facies of peloidal oolitic packstone and bioclastic grainstone of highstand system tract. These beds are overlain by LST facies of Wata Sequence 4 (lime-mudstone, dolostone and marl) and the TST facies of the same sequence (rudist rudstone and floatstone). The muddy matrix of the rudist bears echinoids, stem fragments and dasyclad reproductive bodies, benthic foraminifers, and ostracodes. This facies suggests a low energy inner shelf environment for the rudists of this assemblage.

Y8 Durania Assemblage
This assemblage is represented by two thickets of Durania arnaudi (Choffat), Durania gaensis (Dacqué), and Durania humei var. inermis Douvillé that are intercalated with lime-mudstone, dolostone and rudist floatstone microfacies about six m thick. The rudist individuals were mutually supporting and were partly supported by lime mud (Figure 7b). The autochthonous accumulation of Durania spp. reflects its tendency for constratal growth (Gili et al. 1995). In addition, the presence of planktic foraminifers, echinoids and bivalves in the intercalated lime-mudstone and floatstone indicates the deep inner to outer shelf environments.

Y9 Radiolites/Durania Assemblage
This assemblage is composed of Radiolites sauvgesi (d’Hombres-Firmas), Radiolites cf. lewyi lewyi Parnes, and Durania arnaudi (Choffat) (Figure 5). This assemblage of rudist elevator individuals in life position is about 8 m thick in the upper part of the Wata Formation. The assemblage is underlain
by lime-mudstone and marl of the outer shelf environment with abundant planktic foraminifers and echinoids. The facies above this assemblage is marl with ammonites. The rudists in this assemblage are associated with echinoids, benthic forams and stem fragments and reproductive bodies of dasyclads. The environment of the rudists here was deep inner shelf.

**Gabal Maaza Section**

At Gabal Maaza the rudist assemblages in the Cenomanian Halal Formation are represented by floatstone microfacies consisting of rudist fragments floating in a matrix of rudist shell fragments, *Chondrodonta* fragments and echinoid plates and spines bound together by neomorphic micrite. These parautochthonous assemblages accumulated seaward of Gabal Yelleg. The rudist floatstones are interbedded with lime mudstone, dolostone, foraminiferal bioclastic wackestone, bioclastic intraclastic packstone, and bioclastic oolitic grainstone. Moreover, rudist fragments and shells, among which are *Eoradiolites liratus* (Conrad) and *Distefanella* sp., show evidence of significant transport and winnowing possibly by storm surges.
SEQUENCE STRATIGRAPHY

Lewy (1990) was the first to interpret Cenomanian – Turonian transgressive-regressive (T-R) sedimentary cycles in the Negev Desert and Sinai Peninsula. He considered the oldest cycle as mainly Lower Cenomanian, the middle one to span the Cenomanian – Turonian boundary, and the youngest to occur in the upper part of the Turonian Stage. The related transgressive events flooded the shelf from northwest to the southeast. Sequence stratigraphic studies in other parts of the Sinai Peninsula include Darwish (1994), Lüning et al. (1998), Saber (2001), Bauer et al. (2003, 2004) and Wanas (2008).

In the study area, we divided the Cenomanian – Turonian successions into five sequences. Table 1 summarizes the lithological, paleontological and microfacies characteristics of the sedimentary facies that are used to describe the lowstand (LST), transgressive (TST) and highstand systems tracts (HST) and maximum flooding surfaces (MFS).

| Microfacies No. | Microfacies type          | Components and Sedimentary structures                                      | Depositional environments                  |
|----------------|---------------------------|----------------------------------------------------------------------------|---------------------------------------------|
| MF1            | Quartz arenite            | Quartz grains, glauconite, rare bioclastics, flat bedding, cross bedded    | Subtidal bars, sand flat                    |
| MF2            | Calcareous mudstone       | Calcareous, gypsiferous, non fossiliferous, flaser and wavy bedding         | High intertidal flat with quiet conditions   |
| MF3            | Bioclastic oolitic grainstone | Oolites, oysters, gastropods, echinoids, rudist fragment, algae and benthic foraminifers rare of glauconite, quartz and peoids, cross-bedded | Subtidal oolitic shoals                     |
| MF4            | Bioclastic intraclastic grainstone | Intraclasts with minor echinoids, algae, oysters and foraminifers | Subtidal shoals/ bars                       |
| MF5            | Peloidal oolitic packstone | Oolites and peoids with rare bivalves and miliolids                           | Subtidal shoals                             |
| MF6            | Bioclastic intraclastic packstone | Intraclasts, peoids, ostracods, miliolids and echinoids                  | Subtidal shoals                             |
| MF7            | Echinoid bioclastic wackestone | Echinoids, planktonic foraminifers, pelagic crinoids, calcispheres and ostracods | Quiet, deep subtidal with open circulation  |
| MF8            | Foraminiferal bioclastic wackestone | Miliolids, orbitolines, praealveolina, oysters, algae and rudists | Quiet, subtidal lagoons with restricted circulation |
| MF9            | Oyster rudist bank        | Oyster with little matrix                                                   | Brackish water, shallow subtidal shoal with high energy |
| MF10           | Rudist rudstone           | Rudist fragment with little matrix                                           | Shallow subtidal                            |
| MF11           | Rudist floatstone         | Rudist fragments float in micrite with rare echinoids, bivalve and foraminifers | Deep subtidal close to the carbonate skeletal shoals from which the coarse skeletal debris was reworked and redeposited in quiet subtidal water |
| MF12           | Chondrodonta rudstone     | Chondrodonta shells that parallel to each others and capped the rudist facies. | They accumulated on the top of the rudist shoals or biostromes by waves or current during the storm events |
| MF13           | Lime mudstone             | Neomorphozed micrite with rare bioclasts                                    | Lower intertidal zone of restricted circulation and quiet water condition |
| MF14           | Dolostone                 | Fine to medium dolomite rhombs, or coarse dolomite rhombs                   | Lower intertidal zone of restricted circulation and quiet water condition |
Halal Sequence 1: Cenomanian

In the outcrops studied the base of Sequence 1 (SB 1) is at the Albian – Cenomanian boundary. This boundary separates the Albian Risan Aneiza Formation from the overlying Halal Formation. At Gabal Yelleg the contact is marked by thin, ferruginous hard crust with plant remains, iron concretions and pitholiths. At Gabal Minsherah, El-Azabi and El-Arabi (1996) placed the Albian – Cenomanian sequence boundary between the intertidal symmetrically rippled sandstones of the Risan Aneiza Formation and the overlying shallow shelf lagoonal facies of the Galala Formation, which is correlative with the Halal Formation (Figure 2). In the exposed Cenomanian succession of the Sinai and Gulf of Suez, the correlative Albian – Cenomanian boundary was identified by Darwish (1994).

The LST of Sequence 1 is characterized by subtidal bars facies that consists mainly of cross-bedded sandstones (quartz arenite microfacies) (Figure 4b) with minor mudstone deposited in mudflat facies. In the studied sections the transgressive surface (ts) is marked by high accumulation of glauconite and bioturbated sediments.

The TST facies is composed mainly of cross-bedded oolitic limestone, chondrodontid rudstone (Figure 7c), rudist rudstone (Figure 7d), rudist floatstone with oyster banks and lower intertidal carbonates, lime-mudstone and dolostone. The facies associated with the TST reflect deep subtidal, quiet energy, open-marine wackestone rich in echinoids and minor, quiet, restricted subtidal lagoonal facies (mainly miliolids). The rudist assemblage in TST at Gabal Minsherah is Praeradiolites cf. biskraensis/Eoradiolites liratus (M1). At Gabal Yelleg the Eoradiolites liratus (Y1), Radiolites sp./Praeradiolites cf. irregularis (Y2), Eoradiolites sinaiticus (Y3) and Biradiolites zumoffeni/Bournonia fourtau (Y4) assemblages are in the TST of Sequence 1. The MFS is placed at the highest traceable deep subtidal facies.

At Gabal Yelleg the HST is composed mainly of lower intertidal dolostone facies (Figure 8a). The dolostone package resulted from aggradation when accommodation space was filled as rapidly as it was created so that water depth remained constant. At Gabal Minsherah the HST consists of lower intertidal carbonates (lime mudstone and dolostone), intercalated with calcareous mudstone sediments deposited in a quiet mudflat environment and intraclastic bioclastic grainstone facies of subtidal shoals.

Halal Sequence 2: Cenomanian

This Sequence is delineated at the base by Middle – Upper Cenomanian sequence boundary (SB 2) where it is overlain by Neolobites vibryeanus of early Late Cenomanian age (Abdallah et al. 2001, Kassab and Obaidalla, 2001). This boundary is a hardground with Thalassinoides networks and iron oxide mottling. The oxidized bored hardground records a minor break in sedimentation or low sedimentation rate associated with a short term sea-level fall.

The LST is composed of shallow subtidal facies of cross-bedded bioclastic intraclastic grainstone at Gabal Minsherah. However, at Gabal Yelleg this system tract is not evident and the sequence boundary is overlain by marl bearing ammonites.

The TST facies begins with shallow subtidal sediments (rudist rudstone) at Gabal Minsherah. These facies are overlain by quiet, open and deep echinoid bioclastic wackestone subtidal facies, which is intercalated with lower intertidal carbonates (lime mudstone and dolostone). Parautochthonous Eoradiolites liratus/Caprinidae (M2), and Ichthyosarcolites triangularis (M3) assemblages are recorded in this system tract at Gabal Minsherah. At Gabal Yelleg, the TST begins with marl, rich in ammonites, overlain by rudist floatstone and bioclastic intraclastic packstone. The Eoradiolites liratus (Y5) and Caprinula (Y6) assemblages are in the TST of Sequence 2 at Gabal Yelleg. The MFS is at the top of a highly fossiliferous limestone bed with echinoids and foraminifers that indicate quiet, open-marine and deep subtidal facies (echinoid bioclastic wackestone) (Figure 8b). This facies is mainly overlain by lower intertidal carbonates (lime mudstone and dolostone) at Gabal Yelleg that form the HST. At Gabal Minsherah, the HST is composed of rudist biostromes and chondrodontid rudstone, and
quiet water subtidal lagoon with restricted circulation (e.g. foraminiferal bioclastic wackestone with intercalation of dolostone and lime mudstone). The *Praeradiolites* sp. assemblage (M4) is in the highstand systems tract of Sequence 2 at the Gabal Minsherah section.

**Wata Sequence 3: Turonian**

Sequence boundary 3, at the base of Sequence 3 between the Cenomanian Halal Formation and the Turonian Wata Formation, represents a million-year-long hiatus as interpreted by graphic correlation. This disconformity is indicated by upper Lower Turonian ammonites above uppermost Cenomanian ammonites. This sequence boundary is correlated with the global anoxic event (OAE2).

Transgressive surface (TS 3) coincides with SB 3 and the LST is not developed. Deposition of the Turonian Wata Formation followed a hiatus of ca. 1 million years during OAE 2. Early Turonian deposition began with outer-shelf marl and chalky limestone rich in ammonites, echinoids, and planktic foraminifers in echinoid bioclastic wackestone. These deposits comprise the TST of Sequence 3 and are characterized by glauconite and pyrite and are highly bioturbated, which indicate condensation. The HST consists of shale overlain by bioclastic oolitic grainstone indicative of shallow subtidal, high energy environments at Gabal Minsherah. At Gabal Yelleg, the HST is also composed of grainstone and packstone as a shallow subtidal high energy facies.
Wata Sequence 4: Turonian

The lower boundary of Sequence 4 (SB 4) is marked by a change from shallow subtidal facies below, to lower intertidal dolostone and lime mudstone that represent the LST of Sequence 4. The TST is represented by subtidal shoals facies, such as rudist rudstone, and low-energy, lower intertidal lime mudstone and dolostone and deep subtidal rudist floatstone (Figure 8c). Rudists re-colonized the carbonate shelf during the TST of Sequence 4 with the Distefanella cf. lombricalis/Præradiolites ponsianus and Durania assemblages (Y7, Y8, M5). The HST is formed of lower intertidal lime mudstone at Gabal Yelleg and lower intertidal carbonates intercalated with the mudflat facies at Gabal Minsherah.

Wata Sequence 5: Turonian

Sequence 5 is bounded below by Middle Turonian SB 5, which is marked by a change from mudflat facies to sandflat facies above it at Gabal Minsherah. At Gabal Yelleg, the boundary is distinguished by a hardground. The LST varies from sandstone deposited in a sandflat environment at Gabal Minsherah to lower intertidal carbonate facies (dolostone) at Gabal Yelleg. The TST consists of quiet, deep-water subtidal facies of echinoid bioclastic wackestone with rare of shallow-water subtidal facies in the form of rudist biostromes. Rudists re-colonized the carbonate shelf during the TST of Sequence 5 with the Distefanella cf. lombricalis/Præradiolites ponsianus and Durania assemblages (Y7, Y8, M5). These biostromes of elevator morphotypes are intercalated with the low-energy microfacies of the inner shelf. During transgression of Sequence 5 Durania and Radiolites species occupied the inner shelf. The MFS is placed at the top of the highest chalky limestone rich in echinoids and foraminifers. The HST facies consists of subtidal shoal facies peloidal oolitic packstone (Figure 8d) and quiet, restricted subtidal lagoonal wackestone. The topmost part of this systems tract is lower intertidal carbonate (lime mudstone) at Gabal Yelleg.

SEQUENCE CHRONOSTRATIGRAPHY

The sequence boundaries and rudist biostromes can be dated by graphic correlation interpolation. Graphic correlation is a quantitative, non-statistical, technique that determines the coeval relationships between two sections by comparing the ranges of event records in both sections (Carney and Pierce, 1995). A graph of any pair of sections is an X/Y plot of the bases of first occurrence (FO) and tops of last occurrences (LO) of taxa found in both sections; it compares the rate of sediment accumulation in one section with that in the other (Miller, 1977). The technique enables the stratigrapher to consider the sedimentologic events together with the biotic events so that conclusions based on one can test the other. Also, the event beds may add to the precision and accuracy of the correlation.

The biostratigraphic control of the Gabal Minsherah section is excellent and therefore it was selected for plotting against the most up-to-date MIDK45 database (Figure 9a; Scott et al., 2000; Scott, 2009). The age of the Halal Formation is constrained by the FO of Neolobites vibrayeannus and the LO of Costagryra olisiponensis; the base of the section is projected to 94.10 Ma and the top of the Halal is 93.34 Ma. The resulting rate of sediment accumulation for the Halal at the Minsherah section is 287 m/My. This rate is within the 15—500 m/My range of comparable Mesozoic carbonates (Enos, 1991). The base may be older if an alternative line of correlation (LOC) were used. However, the right-hand LOC correlates the quartz arenite at the base of the exposure with the Tunisian sequence CeSB 4 (Robaszynski et al., 1993).

In the Minsherah section, the Cenomanian – Turonian marl-over-marl disconformity is defined by the first occurrences of three ammonite species in the basal bed of the Wata Formation. The projected duration of the hiatus is 0.91 My (Figure 9a). The top of the LOC is constrained by the LO of Nerinea requieniana, which may range younger. The calculated RSA is 114 m/My.

Graphic correlation of the Minsherah section also projects numerical ages for the rudist assemblages M1, M2 and M3 in TSTs and M4 in HST (Figure 9b). The ages of the rudist assemblages are projected from the MIDK45 database, in which the age of the Cenomanian – Turonian boundary is 93.0 Ma (Figure 9a).
Figure 9: (a) Graphic correlation interpretation of the Gabal Minsherah section. First occurrences are blue rectangles and last occurrences are red circles. The rate of sediment accumulation is the slope of the regression line. (b) Graphic log to same scale as interpolated ages of a. Rudist assemblages M1–M6. Sequences of Bauer et al. (2003): CeSin 6, 7, TuSin 1, 2.
Four sequences in the southern Sinai Peninsula (Bauer et al., 2001, 2003, 2004) correlate with Sequences 1–5 defined here (Figure 9b). They placed sequence boundary SB CeSin 7 at the base of the Abu Qada Formation at the Cenomanian–Turonian contact (Samuel et al., 2009), which correlates with our SB3. They interpreted SB TuSin 1 about 20–40 m above the base of the Abu Qada at the contact between a rudist bed capped by a hardground and the overlying bioturbated siltstone with plant remains, which corresponds to our SB4.

Correlation of Cenomanian–Turonian sequences defined in Tunisia (Robaszynski et al., 1990, 1993) with northern Sinai sequences is also tested by means of the MIDK45 database. The northern Sinai Sequence 2 correlates with Tunisian sequence CeSB 5 (Figure 9a), which occurs in the upper part of the Fahdene Formation. The Fahdene is overlain by the Bahloul Formation, which records OAE 2 (Robaszynski et al., 1990, 1993; Scott, 2003). The hiatus between the Halal and Wata formations correlates with the time of downlap and maximum flooding of Tunisian sequence CeSB5 that spans the Cenomanian–Turonian boundary. The SB4 sequence contact correlates closely with the Tunisian TuSB 1 at 92.18 Ma, but the sequence boundary at the base of the glauconitic sandstone is projected to be much older than TuSB 2 because the LO of Nerinea requieniana is so old. This correlation should be tested by more data.

CONCLUSIONS

The Cenomanian Halal and Turonian Wata formations in the northern Sinai Peninsula of Egypt are composed of five transgressive-regressive sequences and represent a shallow carbonate shelf. In the Gabal Yelleg and Gabal Minsherah sections, Halal Sequences 1 and 2 grade up from basal quartz arenite into bioclastic-oolitic grainstone overlain by bioclastic packstone and wackestone. Dolomite beds are part of the highstand facies. The Turonian Wata Formation is composed of three sequences. The conformable contact between the Halal and Wata formations is recognized by Upper Cenomanian ammonites overlain by a condensed marl interval with upper Lower Turonian ammonites. This condensed section represents a million-year-long hiatus as interpolated by graphic correlation that correlates with OAE 2 anoxic event. Carbonate deposition resumed in Early Turonian. Sinai Cenomanian Sequences 1 and 2 correlate approximately with Tunisian Sequences CeSB 4 and CeSB 5, and at least the older Sinai Turonian Sequence 3 correlates with Tunisian TuSB 1 supporting the hypothesis that these sequences responded to eustatic sea-level rise on the North African shelf.

The Cenomanian–Turonian shelf in northern Sinai was dominated by rudists (Radiolitidae, Ichthyosarcolitidae, and Caprinidae). They were the most important benthic carbonate producers mainly in transgressive systems tracts of Sequences 1, 2, 4 and 5 and in highstand systems tract of Sequence 2. The rudist-bearing strata are intercalated with carbonate strata bearing other carbonate platform biota. Tabular thickets of conical to cylindrical elevator radiolitid rudists are the most common benthic morphotype. They are in either single beds or multiple beds intercalated with marl or packstone. Most biostromes are laterally restricted and do not extend to nearby outcrops. The high diversity Cenomanian rudist biostromes are thin and composed mainly of several species of Radiolitidae and less common Caprinidae together with coralline sponges and benthic foraminifers. The low diversity Turonian rudist biostromes are composed mainly of one or two species of Radiolitidae.

ACKNOWLEDGMENTS

We thank Gamal El-Qot (Benha University) for his help during the field work. We would like to thank GeoArabia’s two anonymous reviewers for their constructive comments and remarks. Thanks are extended also to GeoArabia’s Editor-in-Chief, Moujahed Al-Husseini, and Production Manager, Nestor Buhay II, for the important improvement of the original manuscript and redrawing the stratigraphic sections.
REFERENCES

Abdallah, A.M., G.I. Abdel Gawad and M.S. Mekawy 2001. Stratigraphy of the Cenomanian and Turonian sequence of El-Giddi Pass, northwest Sinai, Egypt. Egypt. Proceedings of the Sixth Conference on the Geology of Sinai, p. 211-229.

Abdel-Gawad, G.I. and M. Gameil 1995. Cretaceous and Paleocene coral faunas in Egypt and Greece. Coral Research Bulletin, 4, 1-36, Dresden.

Abdel-Gawad, G.I. 2001. On some Upper Cretaceous coralline sponges from Egypt. Egyptian Journal of Paleontology, v. 1, p. 299-325.

Abdel Gawad, G.I., H.A. El Sheikh, M.A. Abdelhamid, M.K. El Beshtawy M.M. Abed, F.T. Fürsich and G.M. El Qot 2004. Stratigraphic studies on some the Upper Cretaceous successions in Sinai, Egypt. Egyptian Journal of Paleontology, v. 4, p. 263-303, Cairo.

Abdel-Gawad, G.I., G.M. El-Qot and M.S. Mekawy 2007. Macrobiostratigraphy of the Upper Cretaceous succession from Southern Galala, Eastern Desert, Egypt. Proceedings of the Second International Conference on the Geology of Tethys, Cairo University, v.2, 329-349, Cairo.

Aly, M.F., S.G. Saber, G.I. Abdel-Gawad and Y.F. Salama 2005a. Cenomanian – Turonian Rudists buildups of northern Sinai, Egypt. Egyptian Journal of Paleontology, v. 5, p. 253-286.

Aly, M.F., G.I. Abdel-Gawad, and A. Gaber 2005b. Uppermost Albian-Basal Cenomanian ammonites from north Sinai, Egypt. Egyptian Journal of Paleontology, v. 5, p. 347-385, Cairo.

Aly, M.F., A. Smadi and H. Abu Azzam 2008. Late Cenomanian-Early Turonian ammonites of Jordan. Revue de Paléobiologie, Genève, v. 27, no. 1, p. 43-71.

Bachmann, M., M.A. A. Bassiouni, J. Kuss 2003. Timing of mid-Cretaceous carbonate platform depositional cycle, northern Sinai, Egypt. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 200, 131-162.

Bauer, J., A.M. Marzouk, T. Steuber and J. Kuss 2001. Lithostratigraphy and biostratigraphy of the Cenomanian-Santonian strata of Sinai, Egypt. Cretaceous Research, v. 22, p. 497-526.

Bauer, J., J. Kuss and T. Steuber 2003. Sequence architecture and platform configuration (Late Cenomanian–Santonian), Sinai, Egypt. Sedimentology, v. 50, p. 387-414.

Bauer, J., T. Steuber, J. Kuss and U. Heimhofer 2004. Distribution of shallow-water benthics (rudists, calcareous algae, benthic foraminifers) in the Cenomanian- Turonian carbonate platform sequences of Sinai, Egypt. Courier Forschungsinstitut Senckenberg, v. 247, p. 207-231.

Buchbinder, B., C. Benjamine and S. Lipson-Benitah 2000. Sequence development of Late Cenomanian-Turonian carbonate ramps, platforms and basins in Negev Desert. Cretaceous Research, v. 21, p. 813-843.

Carney, J.L. and R.W. Pierce 1995. Graphic correlation and composite standard database as tools for the exploration biostratigrapher. In K.O. Mann and R.R. Lane (Eds.), Graphic correlation, Tulsa, SEPM (Society for Sedimentary Geology) Special Publication 53, p. 23-43.

Chikhi-Aouimeur, F. 1998. Distribution paléogéographique des rudistes du Cénomanien Moyen a Supérieur en Algérie. Geobios, v. 22, p. 93-99.

Darwish, M. 1994. Cenomanian-Turonian sequence stratigraphy, basin evolution and hydrocarbon potentialities of northern Egypt. Second International Conference on Geology of the Arab World, Cairo University, p. 315-362.

Devalque, Ch., F. Amédro, J. Philip and F. Robaszynski 1982. State of lithostratigraphic and biostratigraphic correlations in the Late Turonian of the Uchaux and Ceze Massifs: The ammonites and rudists zones. Mémoires du Muséum National d´Histoire Naturelle, N.S., Serie C, 49, p. 58-69.

El-Azabi, M.H. and A. El-Araby 1996. Depositional facies and palaeoenvironments of the Albian-Cenomanian sediments in Gabal El-Minshera, north central Sinai, Egypt. Geological Society of Egypt, Special Publication 2, p. 151-198.

El-Qot, G.M. 2006. Late Cretaceous macrofossils from Sinai, Egypt. Beringeria, v. 36, p. 1-163, 34 pls., Wuerzburg.

El-Qot, G.M. 2008. Upper Cenomanian-Lower Santonian ammonites from Galala plateaux, North Eastern Desert, Egypt: A systematic paleontology. Egyptian Journal of Paleontology, v. 8, p. 247-289, Cairo.

Enos, P. 1991. Sedimentary parameters for computer modeling. In E.K. Franseen, W.L. Watney, C.G.St.C. Kendall and W. Ross (Eds.), Sedimentary modeling, Lawrence, Kansas Geological Survey Bulletin 233, p. 63-99.

Freund, R. 1961. Distribution of Lower Turonian ammonites in Israel and neighbouring countries. Bulletin Research Council of Israel, v. 10, no. 12, p. 79-114.

Gili, E., J.P. Masse and P.W. Skelton 1995. Rudists as gregarious sediment-dwellers, not reef-builders, on Cretaceous carbonate platforms. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 118, p. 245-267.
Ghorab, M.A. 1961. Abnormal stratigraphic features in Ras Gharib oil Field, Egypt. Proceeding 3rd Arab Petroleum Congress, Alexandria, Egypt 2, p. 1-10.

Jenkins, D., J.C. Harms and T.W. Oesleby 1982. Mesozoic sediments of Gebel Maghara, North Sinai, Arab Republic of Egypt. 6th Exploration Seminar, Cairo, Egypt.

Johnson, C.C., D. Sanders E.G. Kauffman and W.W. Hay 2002. Patterns and processes influencing Upper Cretaceous reefs. In W. Kiessling, E. Flügel and J. Golonka (Eds.), Phanerozoic Reef Patterns. SEPM (Society for Sedimentology), Special Publication 72, p. 549-585.

Kassab, A.S. 1994. Upper Cretaceous ammonites from the El Sheikh Fadl-Ras Gharib Road, Northeastern Desert, Egypt. Neues Jahrbuch Geologische Palaontolgische Mh., v. 2, p. 108-128.

Kassab, A.S. 1996. Cenomanian-Turonian boundary in the Gulf of Suez region, Egypt: towards an interregional correlation, based on ammonites. Geological Society Egypt, Special Publication 2, p. 61-98.

Kassab, A.S. and N.A. Obaidalla 2001. Integrated biostratigraphy and interregional correlation of the Cenomanian–Turonian deposits of Wadi Feiran, Sinai, Egypt. Cretaceous Research, v. 22, p. 105-114.

Kennedy, W.J. and P. Juignet 1981. Upper Cenomanian ammonites from the environs of Samur, and provenance of the types of Ammonites vibrayeaus and Ammonites geslinianus. Cretaceous Research, v. 2, p. 19-49.

Kora, M., and A. Genedi 1995. Lithostratigraphy and facies development of Upper Cretaceous carbonates in East Central Sinai, Egypt. Facies, v. 32, p. 223-236.

Laviano, A., G. Sirna and G. Facchini 1998. Rudist facies distribution in the central southern Apennines and Apulia, Italy. Geobios, v. 22, p. 169-180.

Lewy, Z. 1989. Correlation of lithostratigraphic units in the upper Judea Group (Late Campanian-Late Coniacian) in Israel. Israel Journal of Earth Science, v. 38, p. 37-43.

Lewy, Z. 1990. Transgressions, regressions and relative sea level changes on the Cretaceous shelf of Israel and adjacent countries, Acritical evaluation of Cretaceous global sea level correlations. Paleoceanography, v. 5, p. 619-637.

Lewy, Z. 1996. The approximate position of the Middle-Upper Cenomanian substage boundary in Israel. Israel Journal of Earth Science, v. 45, p. 193-199.

Luger, P. and M. Gröschke 1989. Late Cretaceous ammonites from the Wadi Qena area in the Egyptian Eastern Desert. Palaeontology, v. 32, no. 2, p. 355-407, pl. 38-49.

Lüning, S., A.M. Marzouk, A.M. Morsi and J. Kuss 1998. Sequence stratigraphy of the Upper Cretaceous of central-east Sinai, Egypt. Cretaceous Research, v. 19, p. 153-196.

Masse, M.F., J.P. Masse and V. Chazottes 2004. Quantitative analysis of rudist assemblages: a key for palaeocommunity reconstructions: The Late Barremian record from SE France. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 206, p. 133-147.

Miller, F.X. 1977. The graphic correlation method in biostratigraphy. In E.G. Kauffman and J.E. Hazel (Eds.), Concepts and Methods of Biostratigraphy. Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa., p. 165-186.

Moro, A., P.W. Skelton and V. Ćosović 2002. Palaeoenvironmental setting of rudists in the Upper Cretaceous (Turonian-Maastrichtian) Adriatic carbonate platform (Croatia) based on sequence stratigraphy. Cretaceous Research, v. 23, p. 489-508.

Philip, J. 1993. Late Cretaceous carbonate-siliciclastic platforms of Provence, southeastern France. In J.A.T. Simo, R.W. Scott and J.P. Masse (Eds.), Cretaceous carbonate platforms. American Association of Petroleum Geologists, Memoir 56, p. 375-385.

Philip, J. and C. Airaud-Crumiere 1991. The demise of the rudist bearing carbonate platform at the Cenomanian/Turonian boundary: A global control. Coral Reefs, v. 10, p. 115-125.

Philip, J., J. Borgomano and S. Al-Maskiry 1995. Cenomanian-Early Turonian carbonate platform of northern Oman: stratigraphy and palaeo-environments. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 119, p. 77-92.

Robaszynski, F., M. Caron, C. Dupuis, F. Amedro, J.M. Gonzalez Donoso, D. Linares, J. Hardenbol, S. Gartner, F. Calandra and R. Deloffre 1990. A tentative integrated stratigraphy in the Turonian of central Tunisia: Formations, zones and sequential stratigraphy in the Kalaat Senan area. Bulletin Centres Recherches Exploration Production Elf-Aquitaine, v. 14, p. 213-384.

Robaszynski, F., M. Caron, F. Amedro, C. Dupuis, J. Hardenbol, J.M. Gonzalez Donoso, D. Linares and S. Gartner 1993. Le Cénomanien de la région de Kalaat Senan (Tunisie centrale): Litho-biostratigraphie et interprétation séquentielle. Revue de Paléobiologie, v. 12, p. 351–505.

Ross, D.J. and P.W. Skelton 1993. Rudist formations of the Cretaceous: a palaeoecological, sedimentological and stratigraphic review. In V.P. Wright (Ed.), Sedimentology Review 1. Blackwell Scientific Publications, Oxford, p. 73-91.

Saber, S.G. 2001. Lithostratigraphy and facies development of the Cenomanian- Turonian sediments at El Giddi Pass area, west northern Sinai, Egypt. The Second International Conference on the Geology of Africa, v. 2, p. 323-343.
Saber, S.G. 2002. Depositional facies and paleoenvironments of the Cenomanian- Santonian succession in Gabal Ekma, west central Sinai, Egypt. Egyptian Journal of Geology, v. 46, p. 471-494.
Said, R. 1971. Explanatory notes to accompany the geological map of Egypt. Geological Survey Egypt, Report No. 56, 123 p.
Samuel, M.D., A.A. Ismail, A.M. Akarish and A.H. Zaky 2009. Upper Cretaceous stratigraphy of the Gebel Somar area, north-central Sinai, Egypt. Cretaceous Research, v. 30, p. 22-34.
Scott, R.W., 1995. Global environmental controls on Cretaceous reefal ecosystems. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 119, p. 187-199.
Scott, R.W., W. Schlager, B. Fouke and S.A. Nederbragt 2000. Are Mid-Cretaceous eustatic events recorded in Middle East carbonate platforms? In A.S. Alsharhan and R.W. Scott (Eds.), Middle East Models of Jurassic/Cretaceous Carbonate Systems. SEPM Special Publication 69, p. 77-88.
Scott, R.W. 2003. High resolution North African Cretaceous stratigraphy: Status. In E. Gili, M.H. Negra and F.W. Skelton (Eds.), North African Cretaceous Platform Systems: NATO Science Series, IV. Earth and Environmental Sciences 28, Kluwer Academic Publishers, Amsterdam, p. 1-17.
Scott, R.W. 2009. Chronostratigraphic Database for Upper Cretaceous Oceanic Red Beds (CORBs). In X. Hu, C. Wang, L. Jansa, R. Scott and M. Wagreich (Eds.), Cretaceous Oceanic Redbeds: A Clue to Ocean/Climate Change: SEPM (Society for Sedimentary Geology), Special Publication 91, 31-53.
Skelton, P.W., E. Gili, E. Vicens and A. Obrador 1995. The growth fabric of gregarious rudist elevators (hippuritids) in a Santonian carbonate platform in the southern Central Pyrenees. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 119. p. 107-126.
Skelton, P.W. and A.B. Smith 2000. A preliminary phylogeny for rudist bivalves: sifting clades from grades. In E.M. Harper, J.D. Taylor and J.A. Crame (Eds.), The evolutionary biology of the Bivalvia, Geological Society, London, Special Publication 177, p. 97-127.
Steuber, T. 1999. Cretaceous rudists of Boeotia, central Greece. The Palaeontological Association Special Papers in Palaeontology, v. 61, p. 1-229.
Steuber, T. 2000. Rudist species locality data: unpublished CD.
Steuber, T. and H. Löser 2000. Species richness and abundance patterns of Tethyan Cretaceous rudist bivalves (Mollusca: Hippuritacea) in the central-eastern Mediterranean and Middle East, analyzed from a palaeontological database. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 162, p. 75-140.
Wanas, H.A. 2008. Cenomanian rocks in the Sinai Peninsula, Northeast Egypt: Facies analysis and sequence stratigraphy. Journal of African Earth Sciences, v. 52, p. 125-138.
Ziko, A., M. Darwish and S. Eweda 1993. Late Cretaceous – Early Tertiary stratigraphy of the Themed area, east central Sinai, Egypt. Neues Jahrbuch Geologisches palontologisches Mh., H. 3, p. 135-149.

APPENDIX

Taxonomic Notes. Classification from Skelton and Smith (2000); taxonomy and ranges from Steuber (1999, 2000).

Superfamily Hippuritoidea Gray, 1848
Family Caprinidae d’Orbigny, 1847 (1850)
Caprinula sp. d’Orbigny, 1859; ranges from Albian to Late Cenomanian

Family Radiolitidae d’Orbigny, 1847
Biradiolites zumoffeni Douvillé, 1910 = Distefanella zumoffeni (Douvillé, 1910a); Cenomanian
Bournonia fourtai Douvillé, 1910; Turonian – Maastrichtian (Steuber, 1999, p. 55-56. First described at Abu Roash, Egypt)
Distefanella lombricalis (d’Orbigny, 1842); Cenomanian – Maastrichtian
Durania arnaudi (Choffat, 1886); Cenomanian – Campanian
Eoradiolites liratus (Conrad, 1852); Albian – Campanian
Eoradiolites sinaticus Douvillé, 1913; Cenomanian
Praeradiolites biskraensis (Coquand, 1880); Cenomanian – Turonian
Praeradiolites ponsianus (d’Archiac, 1835); Turonian – Coniacian (Steuber, 1999, p. 91-92). This Middle to Upper Turonian species is widespread throughout the Mediterranean Tethys.
Radiolites sauvagesi (d’Hombres-Firmas, 1838); Cenomanian-Maastrichtian (Steuber, 1999, p. 101-106), Upper Turonian-Coniacian in the Mediterranean Tethys.
Radiolites lewyi lewyi Parnes, 1987; Upper Turonian
Family Ichthyosarcolitidae Douvillé, 1847
Ichthyosarcolites triangularis Desmarest, 1817; Cenomanian-Turonian

Downloaded from http://pubs.geoscienceworld.org/geoarabia/article-pdf/14/4/113/5444617/saber.pdf by guest on 14 January 2022
ABOUT THE AUTHORS

Shaban Ghanem Saber is an Assistant Professor of stratigraphy and paleontology, Beni Suef University, Egypt. He obtained his BSc (1986), MSc (1991) and PhD (1996) degrees from Cairo University. His PhD title is “Stratigraphy and facies analysis of the Cretaceous rocks at northern Sinai, with especial emphasis on Gabal Halal area”. He teaches stratigraphy, sedimentary rocks, sedimentation, physical geology and geology of Egypt. His current research is focused on the stratigraphy, facies and sequence stratigraphy of the Cretaceous rocks, particularly the rudist formations in Egypt.

Yasser F. Salama holds an MSc from Beni-Suef University, Egypt, where he has been Assistant Lecturer in Geology since 2006. His MSc thesis focused on the Cretaceous rudist accumulations and their facies in North Sinai. In 2009, he received an Egyptian grant for his PhD project entitled Cretaceous rudist accumulations in North Egypt. Salama will also be a Visiting Scholar at Western Michigan University, USA, from 2009 to April 2011 to complete his PhD study. The main goal of his research is taxonomy of rudists, paleoecology, diageneric in rudist shells, facies associations and sequence stratigraphy.

Robert W. Scott is President of Precision Stratigraphy Associates providing quantitative solutions to stratigraphic problems and training in sequence stratigraphy. He is also a Research Associate of the Department of Geosciences, The University of Tulsa, USA, directing student research on carbonate reservoirs and paleontology. Robert was a Research Geologist at Amoco Production Company for 20 years where he provided stratigraphic and paleontologic data on Mesozoic and Cenozoic rocks. He taught geology for eight years. Robert earned the PhD at the University of Kansas and the MSc and BSc degrees at the University of Wyoming, USA. He has served as Secretary-Treasurer of the Society for Sedimentary Geology (SEPM) and as an officer of the SEPM Foundation.

Gouda Ismail Abdel-Gawad is a Professor and Head of the Geology Department at Beni Suef University, Egypt. He teaches courses of paleontology, historical geology, paleoecology and geology of Egypt in Cairo, Beni Suef and Fayoum universities, as well as in Garjoun University, Libya. He is presently supervising of 21 PhD and MSc students in Cairo, Beni Suef, Banha, Suez Canal and Monofiya universities, Egypt. He is the Treasurer of the Egyptian Paleontological Society. He completed his undergraduate degrees at Cairo University and his PhD from Warsaw University, Poland. His main research interest are the Egyptian Cretaceous fauna and stratigraphy (systematic paleontology of mollusks and their paleoecologic analyses), and his current research is the rudist formations and their associated fauna, especially coralline sponges.

Mohamed Fouad Aly is a Professor at Cairo University, Giza. He has an MSc in Paleontology and Stratigraphy (1988) and a PhD in Macropaleontology (1994), both from from Cairo University. He taught at United Arab Emirates University, El Ain, from 1994 to 1999. Mohamed Aly has published papers on the stratigraphy and paleontology of Egypt, United Arab Emirates and Jordan. His interests include macropaleontology, ammonite biostratigraphy, paleoecology and facies analysis. He is an Editor of the Arabian Journal of Geosciences and reviewer of the Open Journal of Paleontology and Journal of African Earth Sciences.

Manuscript Received November 13, 2008; Revised May 28, 2009
Accepted June 6, 2009; Press version proofread by the authors on July 14, 2009