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CARBONATE PLATFORM FACIES DEVELOPMENT OF THE TURONIAN WATA FORMATION IN CENTRAL AND EASTERN SINAI, EGYPT

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ABSTRACT

The Wata carbonate platform in central and eastern Sinai show a clear pattern of evolutionary development during sedimentation. Three facies are recognized in the carbonate platform. Inner-platform in the south, inter-platform basin in the middle, and outer-platform in the northwest. Such classification was probably performed by the effect of Syrian Arc System that culminated during Turonian in Sinai. Inner-platform includes fining-upward cycles, each begins with packstone, followed by wackestone and capped by lime-mudstone or claystone or molluscan bioclastic wackestone at the base capped by sandy oolitic packstone or dolostone. The dominant faunal associations are molluscs, and echinoids. Inter-platform basin occurs north of inner-platform and extends northwest-southeast direction and comprises fining-upward cycles, each of which begins with bioclastic ostracodal packstone, calcisphere packstone, bioclastic packstone, capped by wackestone and lime-mudstone The faunal association includes, sponge spines, ostracodes, molluscan debris and calcispheres. They were deposited in

shoal marine and barrier. The outer-platform occurs at Gebel Giddi and extended northwestwards. The lithofacies are entirely represented by calcisphere wackestone/packstone, with a reduced thickness of 20 m.

Keyword: Carbonate platform, Wata Formation, Turonian, Sinai, Egypt

1. Introduction

Passive margin basins are generally considered to be the major site of carbonate platform formation (e.g. Wright and Burchette, 1999; Einsele, 1992; Bachmann and Kuss, 1998). The largest and most extensively studied Cenozoic platforms come from the Florida–Bahamas region (e.g., Schlager, 1981 &1999; Schlager and Ginsburg, 1981 and Ginsburg, 2001), the Great Barrier Reef (e.g., Davies *et al.*, 1989) and the NW shelf of Australia (Butcher, 1990). Sedimentology and stratigraphy of these platforms are dominantly controlled by the low rate of sedimentation and the localization of siliciclastic supply from the adjacent mature continental landscape or isolation from clastic supply in offshore banks, subsidence at relatively slow rates in the Cenozoic (~0.03–0.04 m/ky, from Schlager and Ginsburg, 1981) as well as regional or eustatic sea-level changes. During the Cenomanian-Turonian a carbonate platform which extended over large parts of northern parts of Sinai was established (Bauer *et al.*, 2002). As a result of eustasy and local subsidence, the sea level fluctuated over the predominantly shallow water platform during the Cenomanian and Turonian leading to cyclic sedimentation of a variety of sedimentary rocks.

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Ghorab (1961) assigned the name Wata Formation for the carbonate succession at Wadi Wata in western Sinai. In central and eastern Sinai, little sedimentological work has been done on the Turonian Wata Formation (e.g., Said, 1971; Barakat *et al.,* 1986; El Azabi and Al Araby, 1996; Bachmann and Kuss, 1998; Luning *et al.*, 1998a and 1998b; Kuss *et al.*, 2000 ; Khalifa *et al.,* 2003; El-Hariri et al., 2012). However, geological discussion on the Wata Formation was done by (Issawi *et al.*, 1981; Cherif *et al.*, 1989; Kora and Hamama, 1987; and Ziko *et al.*, 1993). All the above studies were focused on local Turonian sections without focusing on the lateral and vertical facies changes during the Turonian time. The studied localities in the present work are situated at Gebel Giddi, El Mineidra El Kebira, Gebel Shiti, Gebel Gunna, Gebel El Hazim and Wadi Watir in central eastern Sinai (Fig. 1). Aims of this paper are 1) to describe the facies associations of the Wata Formation, 2) to interpret the possible depositional environments of the studied facies, 3) to document the broad stratigraphical and depositional history of the Wata carbonate platform, and 4) to interpret the reasons for the development of pure carbonate platform in this particular area. This approach will help in understanding the dominant control on development of carbonate platform.

2. Geological setting

The Sinai Peninsula lies at the junction between Africa and Asia continents and represents the Asian part of Egypt. Egypt lies in the northeast of the African Plate, where it forms a part of the Sahara Craton (El Emam et al., 1990) that is considered as a part of a passive continental margin of

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Gondwana. During its passive margin phase, the North African margin was also influenced by pulses of compression, strike-slip and extension in specific areas (Guiraud *et al.*, 2001). Most notably in the Arabian-Egyptian region, the margin was affected by tectonic inversion along the Syrian Arc (Garfunkel, 1999). Geologically, Egypt includes three structural units; the Arabian-Nubian Massif in the south, southern facies belt in the central region; and the northern facies belt in the extreme north. The Arabian-Nubian Shield (New-Proterozoic) in the southern Western Desert, the eastern parts of the Eastern Desert (Red-Sea hills) and the southern Sinai consist of gneisses, granitoids, and meta-sedimentary rocks. It was formed by early evolution from the accretion of island arcs (during New-Proterozoic) and of oceanic terrains (Stern, 1985; Guiraud *et al.*, 2001). The Upper Cretaceous southern facies belt (equivalent to stable shelf of Said, 1962) onlapped on the Arabo-Nubian Massif extending in a northeast-southwest direction. It represents a platform consisting mostly of the Maghrabi/Bahariya formations (Early Cenomanian); El Heiz (Late Cenomanian), El Hefhuf Formation (Turonian-Santonian) and Ain Giffara Formation (Campanian). The above sequence is capped by the Khoman Chalk (Maastrichtian). The northern facies belt of Late Cretaceous age (equivalent to the unstable shelf of Said, 1962) is coeval to the southern facies belt, and was affected by the Syrian Arc System (Late Cretaceous), which formed northeast-southwest trending anticlinal and synclinal structures. The northern facies belt in this study comprises the Galala/Raha formations (Cenomanian), Abu Qada Formation (Cenomanian-Turonian), Wata

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Formation (Turonian), Matulla Formation (Campanian) and the Sudr Chalk (Maastrichtian). The Hercynian Orogeny affected the southern facies belts, where it retarded the deposition of Silurian, Devonian, Carboniferous, Permian, Triassic, and Jurassic rocks. This made a prolonged hiatus between the top of the Naqus Formation and the Lower Cretaceous Malha Formation (422.9- 99.5 Ma). The Laramide Revolution occurred between the Lower Cretaceous Malha Formation and the Cenomanian Galala Formation, making a wide gap or hiatus starting from 112 to 99.6 Ma. Also, the Hercynian Orogeny affected the northern facies belts. This made a prolonged hiatus between the top of the Naqus Formation and the Lower Cretaceous Malha Formation (422.9-112 Ma). The Syrian Arc System can be traced from Syria to the central Western Desert of Egypt, via Sinai and the northern part of the Eastern Desert (Kuss et al., 2000). Folding of the Syrian Arc System began in post-Cenomanian times and reached its acme during the Late Cretaceous (Aal and Lelek, 1994; Farouk and Faris, 2012; Farouk et al, 2014). Hence, the Turonian rocks were deposited on the paleotopgraphy of the structural highs and lows in central and eastern Sinai. This affected on the facies type of the Turonian Wata Formation both laterally and vertically. At Gebel Shiti, Gebel Gunna, and Wadi Watir, the contact between the Abu Qada and the Wata formations is unconformable and is placed between the claystone of the topmost Abu Qada Formation and the limestone containing bivalves and planktonic foraminifera of basal Wata Formation. At Gebel El Hazim, the contact is unconformable and is placed between the brown sandstone of the topmost part of the Abu Qada Formation and the yellowish white limestone with chert bands of the basal Wata Formation (Fig. 2). At Gebel Giddi and El Mineidra El Kebira the Wata Formation conformably overlies the Early Turonian Abu Qada Formation. At the first locality, this contact is placed between the yellowish grey limestone of the uppermost Abu Qada Formation and the white chalky limestone with chert nodules in the basal part of the Wata Formation. The upper contact of the Wata Formation at Gebel Shiti, Gebel El Hazim and Wadi Watir is unconformable and lies between the pale yellow limestone with chert bands of the topmost Wata Formation and the green claystone of the basal Matulla Formation. At Gebel Gunna, the same upper contact is placed between the cherty limestone of uppermost part of the Wata Formation and the dolomite of the basal Matulla Formation (Fig. 2).

Lithologically, the Wata Formation at Gebel Giddi consists of chalky limestone enriched with ammonites and molluscan shell fragments and measures about 28 m in thickness. At El Mineidra El Kebira, this formation is made up of marly limestone intercalated with marls and claystone and assumes about 93.5 m in thickness (Fig. 3A). The limestone is enriched with gastropods, brachiopods, algae, corals, sponges and echinoids (Fig. 3B). Southeastwards, the Wata Formation outcrops and forms the cap of El Tih escarpment such as at Gebel Shiti and Gebel Gunna assuming about 35 m in thickness. This formation increases in thickness further northeast at Gebel El Hazim and Wadi Watir reaching up to 100 m (Fig. 2). At the latter localities the Wata Formation comprises of hard thick to thin bedded limestone and

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dolostone with occasionally marl layers (Fig. 3C). Few clay and sandstone are intercalated with the limestones. The marl beds are fossiliferous with ammonites and molluscan shell fragments.

The Wata Formation contains several benthic foraminifera marker for the Late Turonian age, among which are *Discorbis turonicus* Said & Kenawy, *D. minutus* Said & Kenawy and *Eponides lotus* (Schwager). It also yielded rare and sporadic planktonic foraminifera such as, *Hedbergella delrioensis* Carsey, *H. simplex* Morrow, *H. planispira* (Tappan) *Whiteinella archaeocretacea* Pessagno, *Whiteinella baltica* Douglas & Rankin, *W. inornata* (Bolli) and *Heterohelix moremani* (Cushman). The first appearance of the *Discorbis turonicus* during the Late Turonian has been accepted by several previous workers in Egypt (e.g., El Shinnawi and Sultan, 1972; Andrawis, 1990; Shahin and Kora, 1991; Ismail, 2000; Samuel *et al.*, 2009). In addition to, the Upper Turonian zonal index ammonite *Coilopoceras requienianum* (D'Orbigny) has been found in the Wata Formation. In east central Sinai, the Wata Formation is assigned to the Middle-Late Turonian due to the occurrence of the calcareous nannofossils CC 12 Zone (Bauer *et al.*, 2001, 2003; Farouk, 2015; Farouk et al., 2016).

3. Methods

To delineate the nature of the lower and upper contacts of the Wata Formation with the overjacent and subjacent rock units, six stratigraphic sections have been measured at Gebel Giddi, El Mineidra El Kebira, Gebel Shiti, Gebel Gunna, Gebel El Hazim and Wadi Watir (Figs. 1,2). The rock samples have been studied in thin sections under petrographic microscope. Micro- and macro faunal associations were identified from this rock unit to delineate its biozone and exact age. The measured sections have been correlated on the basis of the ammonite fossils and lithological characteristics.

4. Facies analysis

The petrographic investigation on the Wata Formation revealed the presence of several lithofacies represented by lime-mudstone, molluscan bioclastic wackestone, ostracodal wackestone, foraminiferal wackestone, pelletal foraminiferal packstone, sandy oolitic molluscan packstone, calcispheres packstone, dolosparite, dolomicrite, quartzarenite and claystone (Fig. 2).

4.1 - Lime-mudstone (LM)

The lime-mudstone lithofacies is common in the Wata Formation. At Wadi Watir, it forms a thick horizon near the topmost part of the Wata Formation with a thickness of 12.0 m. At Wadi Hegni (Gebel El Hazim) and Gebel Shiti the lime-mudstone is common and represented by three beds, each of which does not exceed 6.5 m in thickness (Fig. 2). At Gebel Gunna, this lithofacies is reduced in thickness, and is represented by 2.0 m thick near the middle part of the formation. It is also present at El Mineidra El Kebira, where it is intercalated with the calcispheres and ostracodal packstones (Fig. 2). This lithofacies consists of fine dense and dark grey microcrystalline calcite and contains rare foraminiferal skeletal particles floating in the dense lime mud. Such facies are completely obliterated by aggrading neomorphism into

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microsparry calcite (Fig.4A). Also, the lime mud shows slight degree of recrystallization into xenotopic microspar (10 um) and dolomitized in parts.

Interpretation: the lime-mudstone was deposited in calm water due to the absence of variable amount of skeletal particles. Most of lime mud may be derived from the abrasion and micrtization of the skeletal particle especially in the restricted areas. The microspar was originally deposited as micrite with associated clay minerals, as well as the rare skeletal particles, suggesting that this lithofacies was deposited in a subtidal or low ramp environment below wave base (Calvet and Tucker, 1988). Within argillite layers the skeletal material lies parallel to the bedding suggesting slow sedimentation rates (Elrick and Read, 1991). This facies is devoid of indigenous benthonic fauna or burrows suggesting anoxic conditions during deposition (Marquis and Laury, 1989). The absence of wave and current-induced structures suggests a subtidal environment below storm wave base (Keller, 1997).

4.2- Molluscan bioclastic wackestone (MBW)

The molluscan bioclastic wackestone forms the topmost part of the Wata Formation at El-Tih escarpment and Gebel Gunna with a thickness of about 4.0 m, and 20.0 m respectively. At Wadi Watir, it is about 11.0 m thick near the lowermost part of the sequence, each bed ranges in thickness from 3 to 8 m thick (Fig. 2).It is enriched with bivalves and different skeletal debris. Petrographically, it is made of sorted molluscan particles forming about 80% of the rock and shows preferred orientation parallel to the bedding plane.

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Most of the molluscan particles exhibit aggrading neomorphism from their centers and are coated with micrite envelopes (Fig. 4B). The micritic matrix became granular as well as mosaic sparry calcite in parts. Rock particles are mainly molluscan shell fragments and bioclastic grains.

Interpretation: Bivalves rich skeletal assemblages are widely recorded in modern non-tropical carbonate sediments on the Wanganui shelf off central western New Zealand (Gillespie et al., 1992). The assemblage is often best represented in areas with relatively higher sedimentation rate of fine terrigenous material, less favored by many of the other skeletal contributors, and often associated with shallower-shelf waters (Nelson *et al.*, 1988).

4.3- Ostracodal wackestone (OW)

This lithofacies is recorded in the Wata Formation at Gebel Gunna and Wadi Watir assuming a thickness of 10.5 m and 12.0 m respectively. It also occurs at El Mineidra El Kebira intercalated with calcispheres packstone/wackestone. Rocks of this lithofacies are yellowish brown to creamy in colour, hard and are characterized by a papery or thinly laminated appearance. Petrographic investigation revealed that the rock is made up of dark grey dense micrite matrix rich with thin bivalve shells that are composed of calcite with a radial fibrous structure. Ostracodes are scattered randomly in the lime matrix (Fig. 4C). Rare foraminiferal tests are also recorded disseminated in the matrix and show microspar filling the whole tests as a result of aggrading recrystallization (Fig. 4C). Few clear dolomite rhombs are also observed within the lime mud matrix. They are idiotopic with unequigranular fabric and range in size from 0.02 to 0.05 mm. Also, few pores and vugs are more or less filled with coarse mosaic spar as cement.

Interpretation: Bioturbated mudstones and wackestones with moderate fossil diversity (ostracodes, pelecypods, gastropods, miliolids, other benthic foraminifera, dasycladaceans, and sponge spicules) are attributed to semi-restricted lagoons (Colombie and Strasser, 2005). Faunal diversity is low and normal marine fauna are lacking, except for ostracode shells, calcipheres and dasycladacean algae, which indicate quiet, sheltered conditions such as a lagoonal environment (Khalifa and Zaghloul, 1990). Zoophycos burrows indicate deep subtidal conditions. Similar facies elsewhere in the geological record have been interpreted as low energy sub-wave base deposits (Markello and Read, 1981).

4.4- Foraminiferal wackestone (FW)

Foraminiferal wackestone occurs at El Minediara El-Kebiara. It occurs also at the middle part of the Wata Formation in both Wadi Watir and Wadi Hegni (Gebel Hazim) where it attains a thickness of about 20 m, and 12 m respectively. It is composed of yellowish brown limestone, very hard, massive with some chert nodules. This lithofacies is made essentially of skeletal particles closely packed in a dark dense micrite matrix. Skeletal particles are represented by foraminiferal tests (e.g. miliolide, nodosaria, textularia) and some bioclastic grains (Fig.4D). Foraminiferal tests are represented by benthonic type and forming about 30% of the rock. Some of these tests are susceptible to change to microspar by aggrading neomorphism while their

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internal structure is still well preserved. Bioclastic grains account about 5% of the rock. They are represented mainly by ostracodal valves with curved shape and size up to 0.20 mm (Fig.4D). Other elongated bioclastic grains, which refers to molluscan particles, are also encountered. They are replaced by mosaic sparry calcite with straight intercrystalline boundaries with a size of about 0.04 mm (Fig. 4D).

Interpretation: The common presence of benthonic foraminifera, e.g. miliolide indicates restricted water condition. It usually occurs in shallow water and back reef lagoon (Henson, 1950). Moreover, Wilson (1975) has found that miliolide are the most common foraminiferal particles representing the shallow restricted lagoon environments. This lithofacies was deposited in deeper subtidal conditions. The presence of mud-supported texture, and the apparent absence of wave and current structures, suggests that this facies was deposited in a low energy environment below normal wave base (Calvet and Tucker, 1988; Tucker and Wright, 1990). The faunal diversity indicates a stable open marine environment at moderate depth, characterized by the accumulation of foraminifera and molluscan debris.

4.5- Pelletal foraminiferal packstone (PFP)

The pelletal foraminiferal packstone lithofacies has a wide distribution throughout the Wata Formation. It is represented by two horizons at Gebel Shiti with a total thickness of 9.m. At Gebel Gunna, this lithofacies occurs at the lower part of the Wata Formation with a thickness which ranges from 2.0

to 9.0 m. Rocks belonging to this lithofacies are whitish gray to creamy in colour, well-bedded, hard and characterized by comb structure in parts. In thin section, this lithofacies is essentially made up of well rounded micritic pellets that originate from the extensive micritization of the foraminiferal tests. They are well rounded, sorted, vary in size from 0.20 to 0.30 mm and are cemented by microspar which forms the other foraminiferal tests (Fig. 5A). Foraminifera are represented by benthonic forms such as miliolide and ostracodes. Most of the miliolide and ostracodes were extensively micritized to the extent that the whole particles change to dull dark grey, looks like, pellets. Moreover, some relics of the miliolide still occur (Fig. 5A). They are rounded in shape and have a size of about 0.30 mm. Rare bioclastic grains as well as crinoid plates also occurs.

Interpretation: The pelleted forminiferal wackestone that contains a more restricted miliolides and ostracodes indicates brackish water environment (Mack and James, 1986). The predominance of micrite in between particles reflects quiet water condition.

4.6- Sandy oolitic molluscan packstone (SOMP)

The sandy oolitic molluscan packstone is encountered at the lower part of the Wata Formation both at Wadi Watir and Wadi Hegni (Gebel Hazim) with a total thickness of about 21 m (Fig. 2) Rocks belonging to this lithofacies are light grey to yellowish grey in colour, medium-grained, hard, rich with molluscan shell debris, and characterized by large scale cross-bedding at

Wadi Watir. The rock is made essentially of coarse oolitic skeletal particles and detrital quartz grains packed in a coarse mosaic matrix (Fig.5B). Oolites account for about 15% of the rock with a size reaching 0.50 mm in diameter. Some of these oolites suffer aggrading neomorphism to pseudospare starting from the core. Skeletal particles account for about 30% of the rock and are represented by molluscs, echiniods, foraminiferal tests and algae with rare bryozoan fragments (Fig.5B). Molluscan shell walls were replaced by pseudospare as a result of aggrading neomorphism. In addition, some of them show micrite envelopes around their shells as a result of algal borings. Few shell debris of the molluscan grains are subjected to silicification, i.e., cryptocrystalline silica replaced the original shell of the oyster fragments. Fine to coarse-grained detrital quartz grains make 15 % of the rock. These grains show clear diagenetic feature where the grain peripheries are replaced with calcite. Granular spare crystals as well as drusy calcite are acting as cement while the massive spar that represents secondary cement, may be resulted from the recrystallization of the original lime mud (Fig. 5B).

Interpretation: The sandy oolitic molluscan packstone grainstone was probably deposited in current or wave-agitated shallow subtidal environments (Osleger and Read, 1991). The highly diversity of allochems (echinoids, bryozoa, mollusca, peloids, ooids and intraclasts) embedded in a sparry calcite cement, point to an influence of shallower and more agitated water, probably shoal area (Wilson, 1975 and Flugel, 1982). The association of peloids, intraclasts and oolites reflects restricted shoal deposits with moderate

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to high circulation (Luning *et al.*, 1998a). The oolitic-intraclastic grainstone is deposited in agitated, shallow subtidal water as low-relief shoal (Tucker *et al.*, 1993).

4.7 - Calcisphere packstone (CP)

This lithofacies occurs in the Wata Formation at El Giddi area. The rock is yellowish white in colour with thickness of 24 m. The rock consists of calcispheres (35%), bioclasts (15%), algae (3%) echinoid spines (2%) and lime mud matrix (Fig.5C). Calcispheres are common, and show a concentric wall structure. Bioclasts are most probably derived from algal skeletons. Few algal fragments are observed and are represented by coated grains (oncolites). Their internal cells are filled with micrite. The embedding material is a lime mud matrix (45%) and shows thin laminations and containing few empty pores (Fig. 5C).

Interpretation: The calcispheres assemblage is most typical of off-shelf waters where turbulence is minimal, allowing the pelagic settling and accumulation of planktonic foraminifera-rich ooze (Hayton *et al.*, 1995; El-Azabi and Farouk, 2011). This assemblage may occur at shallow depths in partly enclosed basins where low-energy zones develop at the end of current paths as found in Bass Basin, southeastern Australlia (Blom and Alsop, 1988). The presence of oncolite indicates restricted marine water or lagoon (Peryt, 1977). However, a literature overview suggests that two environments were the main habitat of calcispheres, i.e. shallow water sheltered environments and an open marine realm. Calcispheres indicate well - sheltered, very shallow water such as lagoonal, back reef (Marszalek, 1975; Kaźmierczak, 1975 and1976).

4.8- Dolosparite (DSS)

In the Wata Formation, this lithofacies is represented by three horizons that occur between the pelletal foraminiferal packstone lithofacies at Gebel Shiti . Each horizon has a thickness of about 1.50 m. It also occurs at Gebel Hazim (Wadi Hegni) with an average thickness of 5 m. Rocks belonging to this lithofacies are greyish yellow to dark brown, hard, burrowed. The rock mainly consists of well-defined dolomite rhombs (90-95%) and some unfilled pore spaces. The matrix is mosaic sparry calcite with a size ranging from 0.16 to 0.24 mm. Most of the dolomite rhombs are of medium-grained (0.08 mm) and show hypidiotopic to xenotopic fabric and equigranular texture (Fig. 5D). They are of rich inclusion type where they contain thin threads of ferric hydroxide along the rhombohedral cleavage. Vugs and pores are mostly unfilled while rare of them are filled with rounded to subrounded chert nodules with size of about 0.8-0.16 mm. These filled pores that originally may be formed due to burrowing organisms were filled with cryptocrystalline silica.

Interpretation: This type of coarse-grained dolostone suggests later phase of dolomitization, since the coarse dolomite rhombs are usually need long period of time to be formed. This dolomite facies is interpreted to represent an intermediate to late-diagenetic replacement dolomite. The coarse crystal size

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suggests a major, probably long lasting, dolomitization event. Cloudy cores represent replacive dolomite, whereas the clear rims are zoned dolomite cements that occlude intercrystalline porosity (Lohmann and Meyers, 1977 and Amthor and Friedman, 1991). This type includes dolomite cement and dolomite replacing precursor cement. This dolomite type occurs together with fine crystalline dolomite types. Paragenetic relationships indicate that coarse crystalline dolomite is later than fine crystalline dolomite (Khalifa and Abu El-Hassan, 1993) and contemporaneous (replacive dolomite). Coarse-crystalline dolomites may occur as a replacement of limestone during late diagenesis in the deep subsurface (Machel and Anderson, 1989) and this process may be controlled by the coarse-grained texture of the original deposits that are being replaced during late diagenesis (Folk and Land, 1975; Sibley et al., 1993).

4.9- Dolomicrite (DM)

In the Wata Formation, the dolomicrite occurs only at Wadi Hegni (Gebel El Hazim) it is faint yellowish in color, thinly bedded with rare shell debris and measures about 10 m in thickness. Mircroscopically, the rock of this lithofacies consists mainly of very fine dolomite rhombs (70-80%), as well as some detrital quartz grains. Dolomite rhombs are usually hypidiotopic to xenotopic with equigranular texture (Fig.6A). They range in size from 8 to 15 um and are mostly of inclusion rich type along the rhombohedral cleavage, as well as they are lacking zoning. Some unfilled vugs and pore spaces with a size of 0.20 mm in diameter are also recorded.

Interpretation: In many cases dolomicrite can form shortly after deposition or as an early-stage replacement mineral in modern supratidal and shallow intertidal environments as found in the Recent sediments in Arabian Gulf (Friedman, 1968; Shinn et al., 1965; Shinn, 1983). The presence of this facies within the carbonate facies reflect the lowering in sea level during sedimentation that permit the slight evaporation and consequent dolomitization (Folk and Land, 1975).

4.10- Quartzarenite (QA)

In the Wata Formation, the quartzarenite lithofacies lies in the middle part between the sandy oolitic packstone lithofacies at Wadi Watir (Fig. 6B). In thin sections, the rock consists of well sorted quartz grains accounting 95% of the rock with rare feldspar grains and carbonate rock fragments. The quartz grains are medium- to coarse-grained, well rounded, Clay matrix is rarely recorded as very fine dull grains. Quartz grains are rounded and highly compacted with tangential and suture contacts. They range in size from 0.2 to 0.4 mm in diameter. Most of the grains are highly mature and coated with dark ferruginous material as thin films (Fig.6B). The cementing materials are represented essentially by silica overgrowths that form an equal envelopment around the original quartz grains. The silica overgrowths are separated by ferric oxide.

Interpretation: The quartzarenite that is well sorted may be deposited on the shore as dune and beach sands and may include near shore littoral sand. Also, quartzarenite can be found in the intertidal zone. The presence of silica overgrowths as cement indicates subaerial exposure of the sandstone and or deposition in continental environment ,since most of the silica overgrowths in sandstones is considered second phase of cementation as evidenced by the presence of iron oxides coating around quartz grains. This phenomenon was described in the quartzareintes that bound the depositional sequences in fluvial and fluviomarine facies (Salem *et al.*, 1998 and Abdel Wahab *et al.*, 1998). The northward thinning of the qaurtzarenite reflects the proximity of this facies to terrigenous provenance south and eastwards peripheries of basin.

4.11- Claystone lithofacies (CL)

Claystone lithofacies is recorded only in the middle and upper parts of Gebel Shiti in east central Sinai (Fig.2). In the later locality it forms the base of the second cycle and the middle part of the last cycle. It has a thickness varying from 3.0 to 9.0 m. The rock is yellowish gray in colour, highly with thin laminae of gypsum as well as thin bands of ferruginated sandstone (quartzwacke).

Interpretation: The deposition of claystone may be occurred during rapid settling from suspension probably as consequence of clay flocculating from concentrated suspension (Potter *et al.*, 1980) .The claystone can be transported from cratonic area nearby the basin during subsidence or increase in sea level (Osleger and Read, 1991).

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5. Discussion

The Wata carbonate platform in central and eastern Sinai show transitional facies changes from southeast to northwest and can be classified into three coeval environments. These are: inner-platform in the southeast, inter-platform basin in the middle and outer platform in the northwest (Fig. 7A). This opinion is contradicted with Wilmsen and Nagm (2012) who considered that the depositional setting of the Cenomanian and Turonian in the southern Galala plateau as a homoclinal carbonate ramp. This classification is similar to the opinion of Bauer et al. (2002) during their study of Turonian Wata Formation in Sinai. The subdivision of the carbonate platform was affected probably by the Syrian Arc System that was active during the Late Cretaceous (Shahar, 1994: Walley, 1998). In Sinai, "Early Alpine" transgression since the Turonian resulted in the structural inversion of older half grabens (Moustafa and Khalil, 1990).

The inner-platform includes Gebel Shiti, Gebel Gunna, Gebel El Hazim (Wadi Hegni) and Wadi Watir. The most pronounced facies associations are represented by lime-mudstone, dolosparite, dolomicrite, ostracodal wackestone, molluscan bioclastic packstone, sandy oolitic molluscan packstone and quartzarenite. Such facies were probably deposited in shallow subtidal to intertidal environments. These lithofacies show vertical arrangement in the form of fining-upward cycles. Each cycle commences with sandy oolitic molluscan packstone, followed upward either by molluscan bioclastic wackestone and capped by lime-mudstone, or molluscan bioclastic wackestone, capped by lime-mudstone. The vertical arrangement of such cycles that show fining-upward cycles indicates subsidence during sedimentation. This may represent the foundation stage of platform formation (Szulezewzki *et al.*, 1996). The presence of coarse-grained and fine-grained dolomite in the inner platform indicate vibration in sea-level between intertidal to supratidal during sedimentation. The formation of dolomite needs shallowing water and sea-level fall to enable dolomitization process to be performed while the carbonate lithofacies indicate high-stand sea-level (Bauer *et al.*, 2002). At Wadi Watir, the oolitic packstone was accumulated vertically forming the lower half of the sequence. Subsequent to the oolitic facies, the quartzarenite facies was accumulated above the oolitic facies. Their deposition was occurred in shallow subtidal to intertidal zone (Klein, 1970). The quartz grains were derived from the exposed basement rocks in southeastern side of the basin. The oolitic and quartzarenite lithofacies were deposited in high agitation water in shoal marine representing a barrier. Such a barrier may represent the transition from the inner platform to inter-platform setting (Figs. 7A&7B). However, sediment transport, coarse-grained carbonates, and oolitic shoals are generally common on platforms during highstand (James and Kendall, 1992).

The inter-platform basin occurs north of the inner-platform (Fig. 7A) and occurs at El Mineidra El Kebira. In such restricted basins, the lithofacies have an average thickness of 93 m. In the inter-platform basin, the carbonate succession comprises fining-upward cycles, each of which begins with

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bioclastic ostracodal packstone, bioclastic packstone, capped by wackestone and lime-mudstone. Such facies associations reflect increased carbonate production rates. Such fining-upward cycles may indicate local structural control such as continuous subsidence during sedimentation. The packstones were deposited in shallow warm condition near the wave base, when subsidence started the water condition was changed (depth, salinity, wave action….etc.) which permit the sedimentation of wackestone and lime-mudstone. The presence of miliolids, ostracode suggests sheltered and quiet water condition (Wilson, 1975).

The outer-platform occurs at Gebel Giddi and is extended farther northwards (Figs. 7A&7B). The lithofacies are entirely represented by calcisphere wackestone/packstone, with a reduced thickness of 20 m (Fig. 2). The outer platform facies is made up of different lithofacies (e.g.calcisphere wackestone/packstone) that widely differ from the inner and inter-platform facies. The hemipelagic calcisphere wackestone/packstone facies contains decimeter-scale bedding and are arranged in 05- to 40 cm thick beds that are massive, bioturbated and lack evidence of cyclicity. Contacts between beds are sharp and conformable. These lithofacies were deposited from suspension (hemipelagic facies) and transported down slope by gravity. This is similar to the platform margin south-central Pyrenees, Spain (Drzewiecki and Simo, 2000). The thickness of the outer-platform reaches up to 93 m, more or less, three times than the inner- and inter-platform. This indicates that the rate of subsidence in the outer-platform is greater than inner- and inter-platforms.

These subsidence events in each section seem to have been approximately simultaneous through the entire area, although they can have very different responses in each section. For example, a major subsidence event can be recognized in all sections in the Late Cenomanian, but the local consequences of that event were very different: even causing the drowning of the previous shallow platform, whereas in others was the opposite, causing their uplift and emersion.

Calcispheres are usually denoted as hollow, spherical calcareous microfossils of various origins. Some calcispheres were interpreted *e.g.* as being representatives of volvocacean algae (Kaźmierczak, 1976), reproductive cysts of dasycladacean green algae (Marszalek, 1975), radiolarians (Antoshkina, 2006), or post-mortem calcified acritarchs (Kaźmierczak and Kremer, 2005). Many of the Mesozoic and Cenozoic calcispheres are now considered to be calcareous dinoflagellate cysts (Keupp, 1981). As already pointed out by Flugel (2004) and indicated by the above listed authors, calcispheres occurring in an open marine realm mostly represent calcareous dinoflagellates, or organisms related to them, and are most frequently reported from Mesozoic rocks, whereas pre-Mesozoic calcispheres seem to be restricted to shallow-water environments.

6. Deepening platform

Basically, the deepening platform of the Wata Formation is based on cycle thickness, type of cycle, variable sedimentation rates, incomplete shallowing to sea-level, and unconformities. The cycle thickness will explains to some

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extent the accommodation space; the thick cycle may indicate increase in accommodation space and high rate of subsidence, while thin cycle indicates decrease in accommodation space. These phenomena can be explained by Fischer plots that they are conventionally drawn by cumulative departure from mean cycle thickness against cycle number (no less than 50) (e.g., Sadler et al., 1993). In this way, thick cycle packages positively deviate from the mean cycle thickness, and form the rising limbs of the plots, reflecting a long-term increase in accommodation space; whereas thin cycle packages negatively deviate from the average cycle thickness, and form the falling limbs, reflecting a long-term decrease in accommodation space.

The type of the cycles in the studied carbonate sequence in platform in the measured sections can explain the deepening platform. The cycles in the measured sections show fining-upward, some cycles begin with packstone and capped by wackestone or lime-mudstone. Such type of cycles were described by Khalifa (1996) as submergence cycles, i. e., the cycle begins with deposition of packstones in shallow water, then followed upward by subsidence that may resulted in the deposition of fine-grained facies and /or deep water carbonate (wackestone). Incomplete shallowing of see-level may suggest the continuous subsidence during sedimentation process, even lowering in sea-level, but it did not track the rate of subsidence.

Another important point is the time represented by unconformities. In the platform under study, there are no erosional surfaces through the succession. However, the stratigraphic gaps of the unconformities at the base (intra late

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Albian) and the top (intra middle Cenomanian) of the sequence set are substantial, and can be considered in the analysis. As the hiatus represented in these two surfaces are below the resolution of the biostratigraphy, we estimated a corresponding minimum time interval of 0.4 my. However, this value is tentative. Nevertheless, since the unconformities lie below and above the stratigraphic successions considered, possible modification of the hiatus estimates does not notably modify the results of the analysis. This point needs to be considered when comparing these results with those published for other basins.

The contact between the Cenomanian and Turonian rocks is unconformable that may be resulted from the non-deposition along a certain period of time between them. This is evidenced by the absence of the Late Cenomanian–Early Turonian *Mammites nodosoides* Zone (Bartov *et al.*, 1980) or creating a stratigraphic gap in Sinai and Eastern Desert of Egypt (Bauer et al., 2003; Farouk, 2015). A stratigraphic gap occurs across the C/T boundary in large parts of Sinai, apart from slope and basin deposits in the subsurface of northernmost Sinai (Jenkins, 1990). In north Sinai, this gap is probably related to submarine non-deposition or exposure on isolated highs, which reflect the initial pulses of the Syrian Arc movements (Bartov et al., 1980; Kuss et al., 2000).

Moreover, platform drowning is reflected by the rapid deepening of the depositional system during the post-CeSin 7 TST and possibly also influenced the genesis of the stratigraphic gap, as drowned carbonate platforms are often

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characterized by extreme condensation or long hiatuses (Schlager, 1999). For example, platform drowning across the C/T boundary in sequence boundary Sb5 was associated with a long stratigraphic gap in the Lower Turonian *Watinoceras coloradoense* Zone (Philip and Airaud-Crumiere, 1991 and Philip et al., 1998). As in Sinai, this gap was followed by condensed deposits in the Mammites nodosoides zone during the TST, and the establishment of a new platform in the middle Turonian HST (Philip and Airaud-Crumiere, 1991). In the Pyrenees, a shorter interval of strong condensation and a stratigraphic gap in the Early Turonian were also caused by platform drowning (Drzewiecki and Simo, 1997). In this context, it cannot be excluded that drowning in Sinai started before the onset of the post-CeSin 7 TST deposits, and the stratigraphic gap may possibly be related to the drowning phase.

7. Conclusions

Detailed studies of facies and facies associations of the Turonian Wata Formation in central Sinai revealed the presence of three coeval carbonate platform environments: the inner-platform in the southeast, inter-platform in the middle and outer-platform towards the northwest. The inner-platform lithofacies occurs at Gebel Shiti, Gebel Gunna, Gebel El Hazim and Wadi Watir. The most pronounced facies associations are represented by lime-mudstone, dolosparite, dolomicrite, ostracodal wackestone, molluscan bioclastic packstone, sandy oolitic molluscan packstone and quartzarenite. Such facies were probably deposited in shallow subtidal to intertidal

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environments. These lithofacies show vertical arrangement in the form of fining-upward cycles. Each cycle commences with sandy oolitic molluscan packstone at base, followed upward by molluscan bioclastic wackestone and capped by lime-mudstone, or molluscan bioclastic wackestone and capped by lime-mudstone.

The inter-platform basin occurs north of the inner-platform and occurs at El Mineidra El Kebira. The carbonate succession in such basin comprises fining-upward cycles, each of which begins with bioclastic ostracodal packstone, bioclastic packstone, capped by wackestone and lime-mudstone. Such fining-upward cycles may indicate local structural control such as continuous subsidence during sedimentation. The outer-platform basin occurs north of the inner-platform and occurs at Gebel Giddi. The outer-platform comprises of entirely of calcisphere wackestone/packstone without remarked cyclicity.

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Figures Captions.

Fig. 1: Location and geological map of the Sinai showing the location of the studied sections of the Wata Formation.

Fig. (2): Lithostratigraphic correlation chart of the Wata Formation at the east central Sinai, showing its, lateral, vertical facies associations, and thickness variations (horizontal distance not to scale).

Fig. (3A): Filed photograph showing the thin-bedded limestone of the Wata Formation, forming the inter-platform along Sudr El-Haitan Plateau. The outcrop is 200 m long. Photograph is looking north-east.

Fig (3B): Field photograph showing the massive limestone rich in sponges, characterizing the upper part of the Wata Formation, Sudr El-Haitan.

Fig. (3C): Field photograph showing the massive carbonate deposits of the Wata Formation (60 m thick) that unconformably overlies and underlies the Abu Qada and the Matulla formations, respectively, cropping out at Ekma Plateau.

Fig. 4A): A- Photomicrograph showing fine dense and dark grey microcrystalline calcite that contains rare foraminiferal skeletal particles floating in the dense lime-mud, Lime-mudstone lithofacies, Wadi Hegni.

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Fig. 4B): Photomicrograph of the molluscan bioclastic packstone that made up of sorted molluscan particles and showing preferred orientation parallel to the bedding plane. Most of the molluscan particle exhibit aggrading neomorphism from their centers and coated with micrite envelopes, Molluscan bioclastic packstone lithofacies, Wadi Hegni.

Fig. 4C): Photomicrograph of the ostracodal wackestone that comprises ostracodes and peloids embedded in lime-mud matrix. Notice the partial dolomitization of the lime-mud and the peloids, producing fine-grained idiotopic to hypidiotopic dolomite crystals, Ostracodal wackestone lithofacies, El Tih scarp (Gebel Shiti, Gebel Gunna, Gebel Hazim and Wadi Watir).

Fig. 4D): Photomicrograph showing foraminiferal wackestone in which some tests (*Heterohelix* spp.) are scattered in a lime-mud matrix with association of bioclasts and pellets, Foraminiferal wackestone lithofacies, Wadi Watir.

Fig. 5A): Photomicrograph showing the pelletal foraminiferal packstone lithofacies that consists of benthonic foraminifera and rounded to ovoided pellets, embedded in lime-mud matrix. Notice the relics of miliolid partly still preserved within the pellets, El Tih scarp (Gebel Shiti, Gebel Gunna, Gebel Hazim and Wadi Watir).

Fig. 5B): Photomicrograph showing the sandy oolitic molluscan packstone lithofacies that consists of oolites, echinoides stems and shell debris. Notice the aggrading neomorphism of the lime-mud matrix and the syntaxial calcite overgrowth around echinoids, Wadi Hegni.

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Fig.5C): Photomicrograph of the calcisphere packstone, in which the calcispheres are round to spherical with association of spongy spines and debris of bioclasts, Calcispheres packstone, Gebel Giddy and El Mineidra El Kebira.

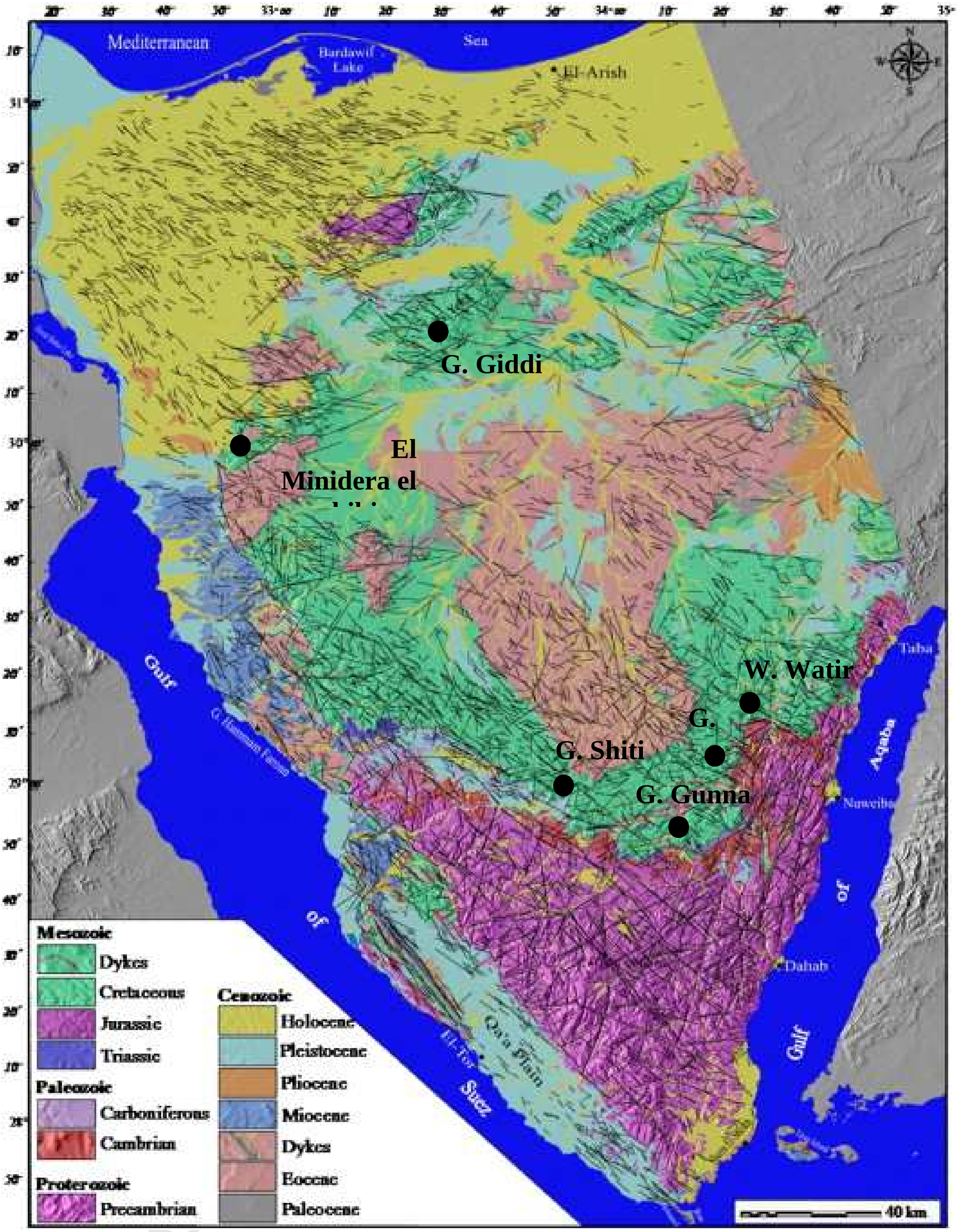
Fig. 5D): Photomicrograph of the dolosparite lithofacies that consists of well-defined dolomite rhombs and some unfilled pore spaces. Most of the dolomite rhombs are of medium-grained (0.08 mm) and show hypidiotopic to xenotopic fabric and equigranular texture. Notice some ferrugination cutting along cracks, El Tih scarp (Gebel Shiti, Gebel Gunna, Gebel Hazim and Wadi Watir).

Fig. 6A): Photomicrograph of the dolomicrite that consists mainly of very fine dolomite rhombs as well as some detrital quartz grains. Dolomite rhombs are interlocked together usually lacking zoning and exhibit hypidiotopic to xenotopic with equigranular texture, Wadi Hegni (Gebel El Hazim).

Fig. 6B): Photomicrograph of the quartzarenite that comprises compact, rounded to subrounded, medium- to coarse-grained quartz grains, Wadi Watir.

Fig. 7A): A schematic diagram showing the possible lateral facies changes and the subdivisions of the platform of the Wata Formation.

Fig. 7B): Schematic diagram showing the depositional environments of the inner- , inter- and outer-platforms of the Wata Formation in Sinai Peninsula in northwest-southeast direction.



Mediterranean
Sea
Bardawil Lake
El-Arish
G. Giddi
El Minidera el
G. Shiti
W. Watir
G.
G. Gunna
Gulf of Suez
Gulf of Aqaba
Taba
Nuweiba
Dahab
El-Tor
Qa'a Plain
Mesozoic
Dykes
Cretaceous
Jurassic
Triassic
Paleozoic
Carboniferous
Cambrian
Proterozoic
Precambrian
Cenozoic
Holocene
Pleistocene
Pliocene
Miocene
Dykes
Eocene
Paleocene
40 km

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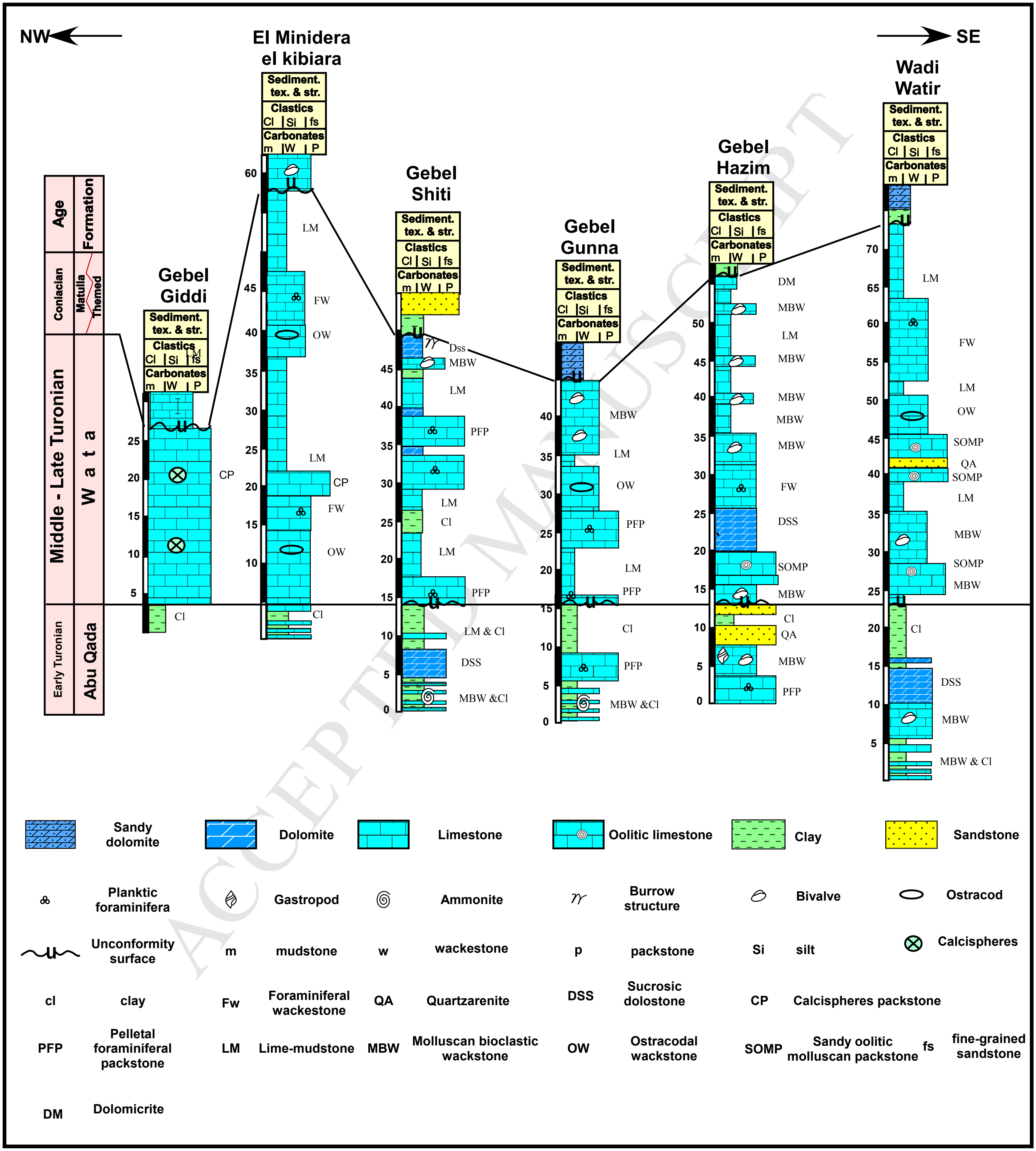

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3A

3B

3C

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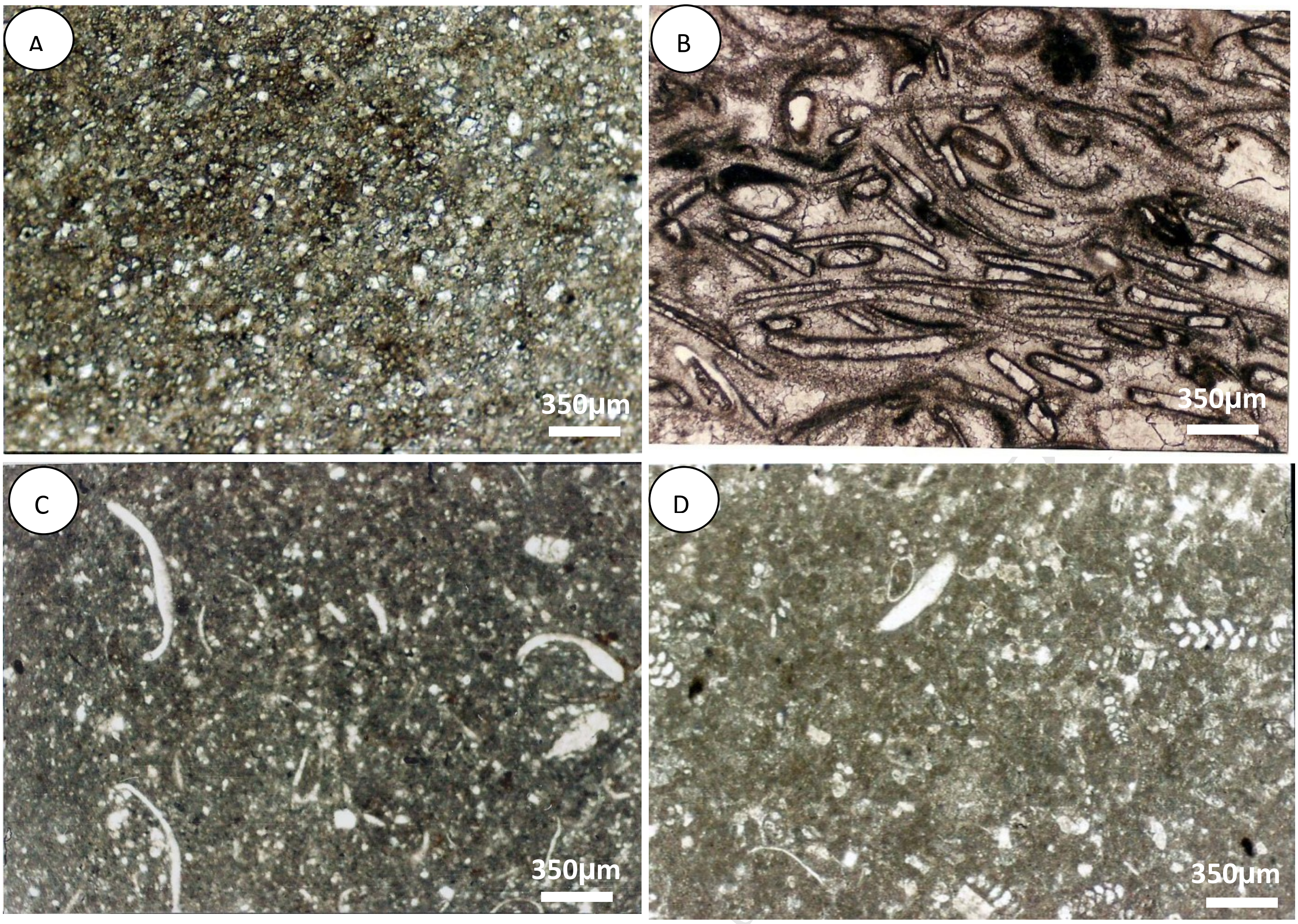

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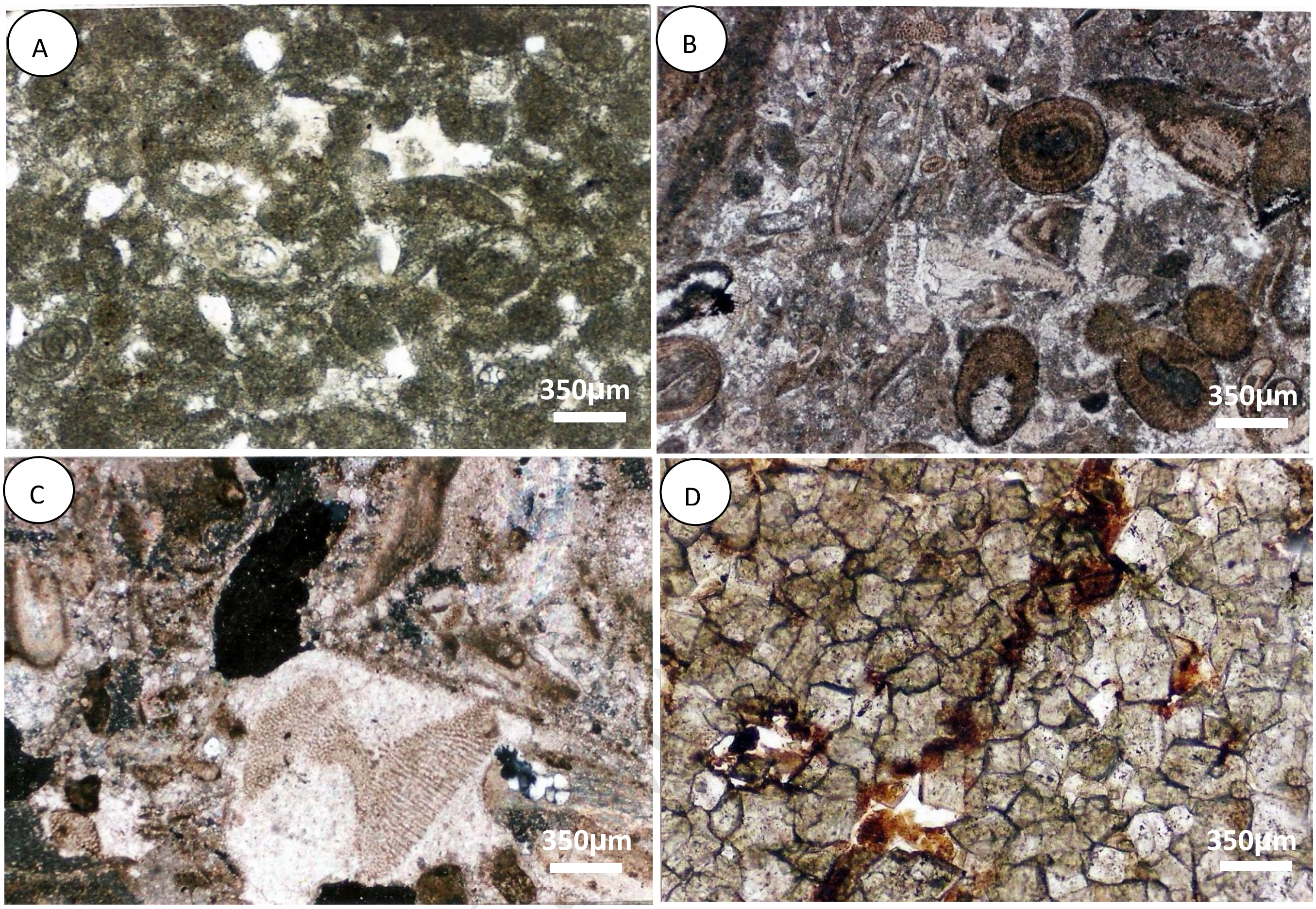
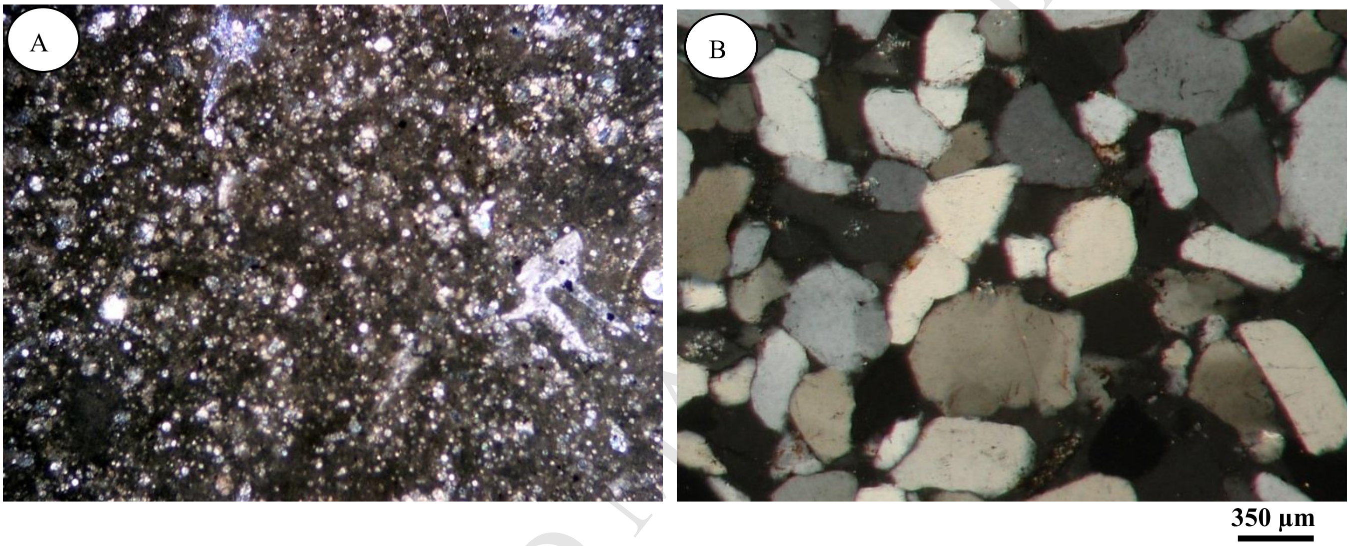

A
350µm
B
350µm
C
350µm
D
350µm



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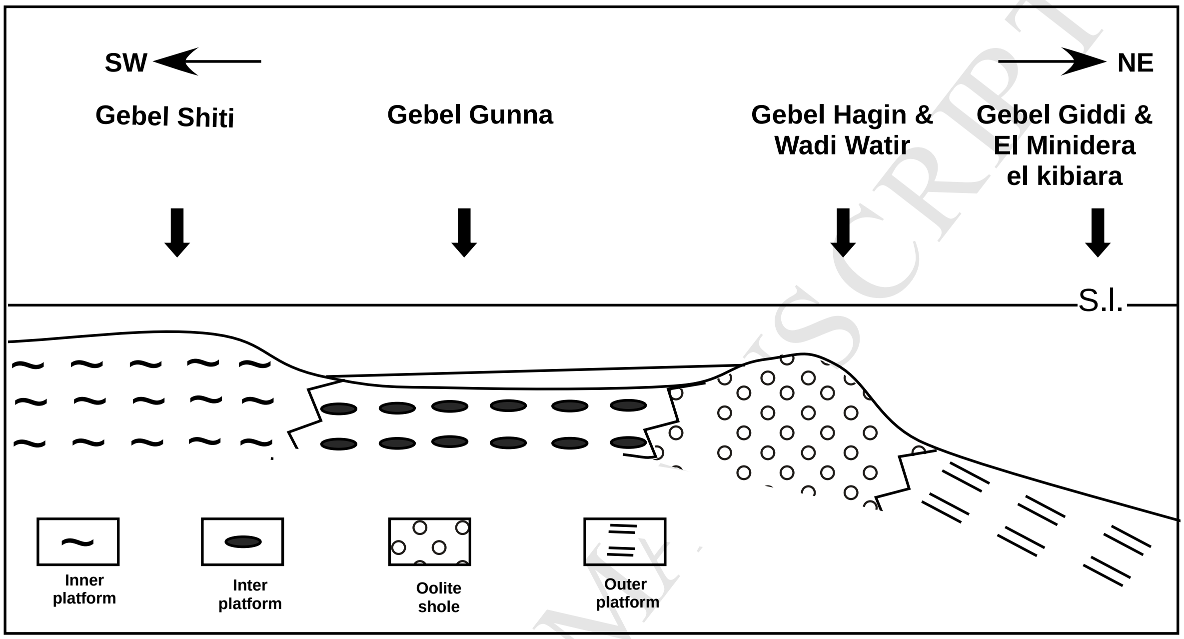
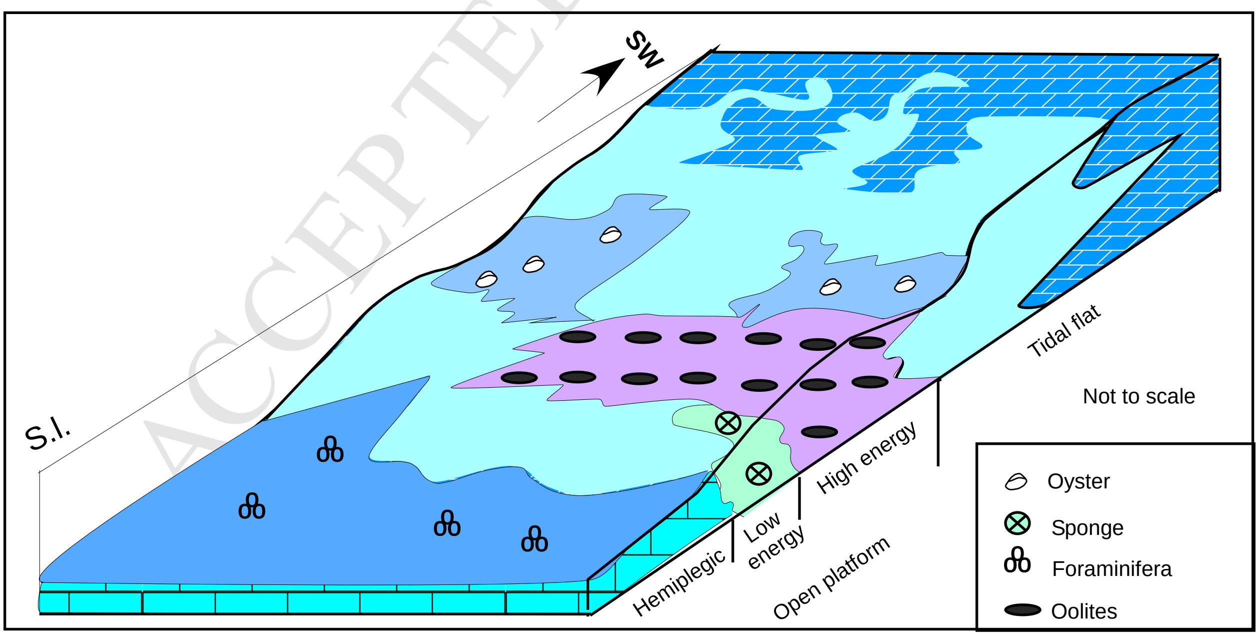

SW
NE
Gebel Shiti
Gebel Gunna
Gebel Hagin &
Wadi Watir
Gebel Giddi &
El Minidera
el kibiara
S.l.
Inner
platform
Inter
platform
Oolite
shole
Outer
platform

A


SW
S.l.
Tidal flat
Not to scale
High energy
Low
energy
Hemiplegic
Open platform
Oyster
Sponge
Foraminifera
Oolites

B

Facies analysis of the Turonian Wata platform in Sinai.

Wata platform is classified into Inner-platform, inter-platform, outer-platform.

Different lithofacies associations have been deduced in each platform type.

Platform classification was probably performed by the effect of Syrian Arc System.

Deepening platform of the Wata Formation is based on the fining-upward cycles.

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