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Research Article

A New Epistemological Insight of the Coniacian-Santonian Oceanic Anoxic Event (OAE3)

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Abstract

Eighteen planktic and eleven benthic foraminiferal species were recorded from the dark grey to black shale facies of the Matulla Formation in Abu Zeneima area, West-Central Sinai, Egypt. The faunal assemblage is dominated by cosmopolitan whiteinellids, marginotruncanids, Dicarinellids, Contusotruncanids and Heterohelicids. The planktic species with high taxonomic diversity were used to zone the Coniacian and Santonian stages, as well as define the Coniacian/ Santonian boundary, while benthic foraminifera is of minor contribution in age assignment. The stratigraphic analysis of the relations and ranges of these fauna led to the recognition of five biozones*; Dicarinella primitiva* or *Huberella huberi* or *Marginotruncana sinuosa* for the Coniacian, while *Dicarinella concavata* and *Dicarinella asymetrica* for the Santonian. Also, the Coniacian/Santonian boundary was delineated, considering the appearance of *Dicarinella concavata* and disappearance of *Huberella huberi*, as well as the increase of Marginotruncanids (*M. renzi*, *M. sigali*, *M. marginata*, *M. pseudolinneiana*….etc.). Furthermore, the black shales found in the middle part of the Matulla Formation were attributed to the Coniacian-Santonian Oceanic Anoxic Event (OAE3). The occurrence of black shales with planktic foraminifera during the Coniacian–Santonian interval in several countries belonging to five continents, was the main impetus to render this event a global event.

Keywords

Foraminifera, Coniacian, Santonian, OAE3, Egypt

1. Introduction

The Cretaceous strata of Abu Zeneima-Abu Rudeis area of West Central Sinai comprise a relatively thick fossiliferous succession. They form the back bone for understanding the pre-rift tectonics of the Gulf of Suez and the Syrian Arc folding System that occurred in northern Egypt as a result of Alpine movement collision with southern Mediterranean forming several anticlines in northern Egypt. The Oligo–Miocene rifting of the Gulf of Suez had a crucial effect on the Cretaceous rocks especially in West Central Sinai, where several block faulting in the form of horsts, grabens and step faults dominate in the study area. This movement resulted several faulted and fractured NE anticlinal folds in north Sinai and probably extends southward with a lesser effect. The Cretaceous period witnessed four transgressive cycles in Egypt; the Aptian, Cenomanian, Coniacian brought very shallow seas to the passageway that filled by marginal marine sediments. The forth one is the Campanian–Maastrichtian transgression that brought shallow open marine conditions to large parts of Egypt [1]. Excellent outcrops of Coniacian–Santonian strata belonging to the Matulla Formation are

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exposed in West Central Sinai. The stratigraphic section discussed in this paper is lying one kilometer south the Old Abu Zeneima City facing the Abu Zeneima-Abu Rudeis Asphaltic road in West Central Sinai. The paleontologic analysis in the present research focuses on planktic and benthic foraminifera to delineate the Coniacian–Santonian boundary of the studied succession. There are several works describing the Cretaceous sections [2-6].

Most studies on the Coniacian, Santonian and Coniacian–Santonian boundary were based mainly on inoceramids, ammonites, planktonic foraminifera and calcareous nannofossils [7-9]. The biostratigraphic studies led to the subdivision of the studied interval into several biozones based on the encountered planktic foraminifera. The relation of planktic foraminifera with the deposition of black shales was recorded in several areas and different times indicating to the Oceanic Anoxic Events (OAEs). These are episodes of oxygen-depleted conditions in the global ocean that resulted from profound perturbations in the carbon cycle. These events are associated with the formation of black and bituminous shales and deposition of organic carbon-rich sediments, derived from terrestrial and planktic sources, and the subsequent formation of hydrocarbon source rocks.

Three major intervals; upper Barremian–Albian (OAE1), Cenomanian–Turonian boundary (OAE2) and Coniacian–Santonian boundary (OAE3). The last event (OAE 3) is the less studied among the Cretaceous OAEs [10-12], although it is the longest one and, unlike OAE 1 and OAE 2, its record is regionally limited and characterized by a moderate positive $\delta^{13}C$ excursion [13]. The recognized planktic foraminifera was used to delineate the Coniacian and Santonian boundaries through the Matulla Formation in Abu Zeneima section. Furthermore, the relation of Coniacian–Santonian boundary with the black shales (partially bituminous) referring to a global or regional Oceanic Anoxic Event (OAE3) was discussed.

2. Material and Methods

The studied sequence in Abu Zeneima area lies at latitudes 29°00'-29°24'N and longitudes 33°00'-33°14'E (Figure 1). The section was measured on a bed-by-bed scale, up to a total thickness of 80 m and 36 samples were collected, with a detailed investigation for the samples yielding foraminifera (AZ3, AZ16, AZ20, AZ25).

The foraminiferal species (planktic and benthic) were extracted by soaking small rocks pieces in a solution (water and few of H_2O_2) and sieving on a sieve of 0.063 µm using a stream of water while stirring gently with the fingertips. The 0.063 µm residues were transferred into a glass beaker from the edge of the sieve using a small amount of water from underneath. The dry residue was investigated under a binocular reflected light microscope at approximately 40x magnification, where the planktic and benthic foraminifera were picked and placed on a mounting slide for identification. Several schemes (Table 1) of planktic foraminifera were used to correlate the proposed zones with the suitable standard zonation [14-18, 9]. The identified species are photographed by using Scanning Electron Microscope (type: Jeol JSM-6010 LA). The datasets used during the current study are available from the corresponding author on reasonable request and at “Ismail Collection” in the Department of Geology, Faculty of Science, Ain Shams University. Furthermore, the studied photographed specimens under the “Ismail Collection” were deposited under the label "Matbenth1-19 and Matplank1-36".

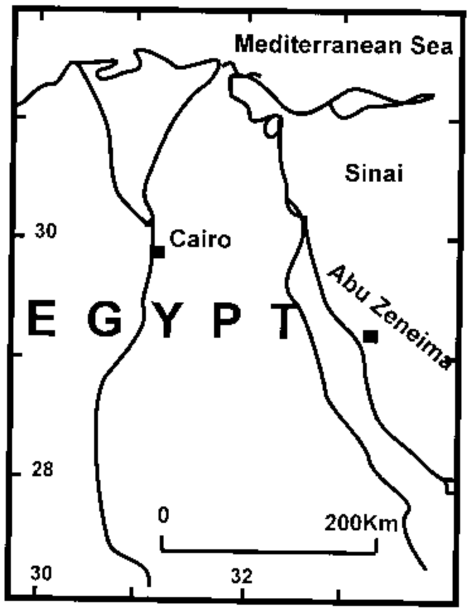

Figure 1. *Location map showing the study area.*

3. Stratigraphy

The Cretaceous rocks are widely distributed in Sinai, where the Lower Cretaceous Sandstones (Malha Formation) dominate in the central and southern Sinai overlying the Pre–Cambrian rocks, while in northern Sinai, a Lower Cretaceous marine to shallow-marine facies (Rizan Aneiza Formation) is well represented, especially in Gabal Manzour near the Maghara mountain series. Also, the Upper Cretaceous carbonate facies (Halal, Abu Qada, Wata, Themed and Sudr formations) are well represented in several outcrops in the northern Sinai (e.g. Gabal El Minsherah).

Table 1. *The different planktic foramininfera biozones in the Tethyan region by different authors.*

stages	substages	Bolli 1966	Postuma 1971	Caron 1985	Robaszynski & Caron 1995
Santonian	L.	*C. fornicata*	*carinata*	*D. asymetrica*	
	M.	*D. concavata*	*D. concavata*	*D. concavata*	*D. asymetrica*
	E.				*D. concavata*
Coniacian	L.				
	E.	*Gr. schneegansi*	*Gr. schneegansi*	*D. primitiva*	

Robaszynski et al. 2000	Obaidalla & Kassab 2002	Petrizzo et al. 2016	Vahidinia et al. 2016	Peryt et al. 2022	This study
Gt. stuartiformis	*S. carpathica*			*Globotruncana linneiana*	D. asymetrica
S. carpathica		*D. asymetrica*			*D. concavata*
D. asymetrica	*D. asymetrica*		*D. asymetrica* *D. concavata*		
D. concavata	No Planktic foraminifera	D. concavata		*Pseudotextularia nuttalli* M. sinuosa	*D. primitiva or* *M. sinuosa or* *H. huberi*

(Note: C=Contusotruncana D=Dicarinella Gr=Globotruncana Gt = Globotruncanita H = Huberella S=Sigalia M=Marginotruncana).

Gabal Halal, Gabal Arif El Naqa, …..etc.). In the central and southern Sinai, the change into carbonate siliciclastic facies characterizes the Upper Cretaceous rocks (Raha, Abu Qada, Wata, Matulla and Sudr formations) in several exposures (Gabal Matulla, Gabal Nezzazat, Gabal Qabeliate, ….etc.). In the study area, the Matulla Formation (Coniacian–Santonian) overlies conformably the Wata Formation (Turonian) and underlies Sudr Chalk (Campanian–Maastrichtian). Thirty-six samples were collected from the Abu Zeneima section with 1.5-2.5 meters distances (Figure 2). It is composed of fluvial cross-bedded sandstone and dark green shales with oysters and very hard limestone in the lower part measures 20.3 m (samples A/Z1-A/Z10). It is followed upward by dark green or dark grey soft shales horizon in the central part measures 15.9 m (samples A/Z11-A/Z16). The upper part is composed of argillaceous limestone and dark grey soft shales horizon measures 22.9 m (samples AZ17-AZ25) with sandstones (sometimes dolomitic) and marls intercalations upwardly measures 20.9 m (A/Z26-A/Z36). There are two black or dark grey shales horizons in the measured section, the first horizon ranges in samples from A/Z11-A/Z16, while the second horizon was represented by samples AZ20-AZ25. Both the lower and upper parts of Matulla Formation yield several species of planktic foraminifera and few species of benthic foraminifera, in addition to some ostracods [3]. The detailed lithologic composition of the measured section runs as follows from base to top:

Bed 1: variegated siltstone, 2 m.

Bed 2: dark green shales, compact, with oysters, 5 m.

Bed 3: very hard limestone with oyster banks and few echinid fragments, 13.3 m.

Bed 4: dark green to black soft shales, partially bituminous and ferruginous siltstone at top, 15.9 m.

Bed 5: hard limestone, marly in some parts with fossil fragments, 7.9 m.

Bed 6: gypsiferous, fissile, soft dark grey shales (bituminous) with rare iron oxides of dark yellow color, 15 m.

Bed 7: very fine sandstone, sometimes silty, violet in color, 5 m.

Bed 8: dark yellow marl with oysters, echinoids and dolomitic in few parts, 8.9 m.

Bed 9: dark yellow siltstone with dolomitic ledges, 7 m.

4. Planktic Foraminifera

Planktic foraminifera are widely recognized as one of the most stratigraphically important groups of organisms for the Upper Cretaceous with a high correlation potential and standard foraminiferal zonations [17, 19-20] mostly utilize tropical/subtropical taxa. Extinctions are limited to one genus (*Whiteinella*), to a few species within the keeled *Marginotruncana* and *Dicarinella* genera, and to species within biserial genera. The Coniacian–Santonian radiation phase is followed by the extinction of *Marginotruncana* and *Dicarinella* in the latest Santonian–earliest Campanian major Santonian turnover [21].

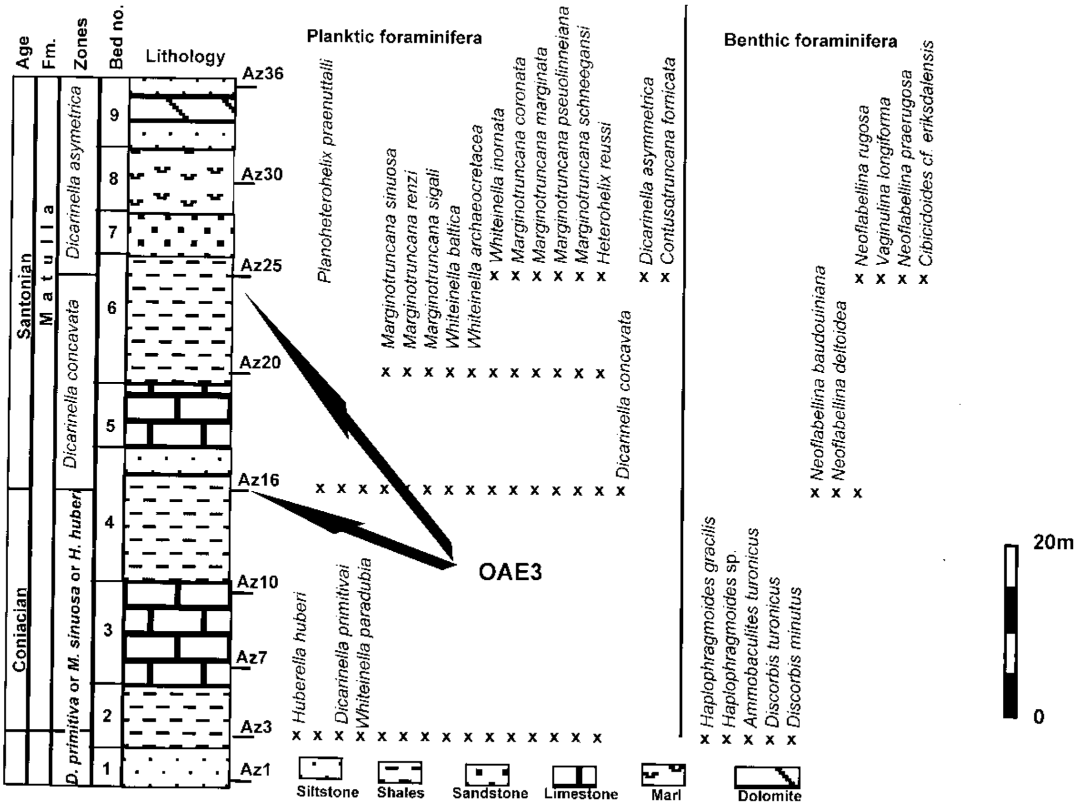

Figure 2. *The distribution chart of planktic and benthic foraminifera in Matulla Formation in west central Sinai.*

4.1. Coniacian

Among the Cretaceous stages, the Coniacian Stage remains the shortest one, lasting about 2.4 million years, where the original concept was based on the largely unfossiliferous, glauconitic, sandy sediments exposed at the Richemont Seminary, near Cognac, Charente, in the Aquitaine Basin, south-west France [22]. There are many marker species used to identify the Coniacian stage by using three groups; Marginotruncanids, Dicarinellids and Heterohelicids. In the study area, The Matulla Formation overlies the Wata Formation (late Turonian) and underlies the Sudr Chalk (Campanian–Maastrichtian). There are two black or dark grey shales horizons in the measured section, the first horizon ranges in samples from A/Z11-A/Z16, while the second horizon was represented by samples AZ20-AZ25. Both horizons yield frequent high diversified planktic foraminifera and few low diversity of benthic foraminifera. Among these diversified planktic foraminifera, three markers were alternatively suggested, where any species of which indicates to the Coniacian: *Dicarinella primitiva or Marginotruncana sinuosa or Huberella huberi.*

4.1.1. First Marker: Dicarinella primitiva

It was first described by Dalbiez F. [23], where last occurrence within *Dicarinella asymetrica* zone, while first occurrence within *M. schneegansi* zone. Several controversial discussions arisen around the occurrence of this species leading to different opinions.

According to Robaszynski F. and Caron M. [24], the first occurrence of *Dicarinella primitiva* has been shown the base of the Coniacian stage. On the other hand, Wonders A. [25] considered the *Dicarinella primitiva* representing the Coniacian stage and the first appearance of *Dicarinella concavata* delineates the Santonian. Caron M. [16] established this zone to represent the early Coniacian and occupy the interval from the first occurrence of *Dicarinella primitiva* to the first occurrence of *Dicarinella concavata.* The majority of planktic foraminifera researchers have believed that Turonian–Coniacian boundary cannot be determined based on planktic foraminifera, but some others believed that the first occurrence of *Marginotruncana sinuosa* has been shown in Turonian–Coniacian boundary [26-28]. Robaszynski F. and Caron M. [17] recorded the first occurrence of both *Dicarinella primitiva* and *Dicarinella concavata* in the late Turonian after correlation with ammonite's species *Subprionocyclus neptuni*. In the study area, the first occurrence of *Dicarinella primitiva* at sample AZ3 and continues till AZ16 but with the occurrence of *Dicarinella concavata* at the same sample. The interval from AZ3 to AZ16 (34.2 m) is represented by this species as a marker for Coniacian. This age assignment is supported by the appearance of *Marginotruncana schneegansi*, *Huberella* *huberi* and *Marginotruncana sinuosa*. Therefore, the lower part of Matulla Formation (AZ3-AZ16) belongs to the Coniacian based on the occurrence of planktic assemblage that includes, *Whiteinella paradaubia, W. baltica, W. inornata, W. archaeocretacea, Huberella huberi, Planoheterohelix praenuttalli, Marginotruncana schneegansi, M. sinuosa, M. renzi, M. sigali* and *M. coronata.*

4.1.2. Second Marker: Huberella Huberi

Huberella huberi was first described by Georgescu M. [29], where last occurrence within *M. schneegansi* zone, while first occurrence within *H. helvetica* zone. The last occurrence of the heterohelicid species *Huberella huberi* Georgescu was proposed as a good indicator of the Turonian–Coniacian boundary [30], although this species is now known to range from the high upper Turonian to the top Santonian [31]. This species has a very short stratigraphic range, although Petrizzo M. [32] reported a highest occurrence of *H. huberi* in the middle Coniacian in southern Tanzania. In the present material, it is found in sample AZ3 only associated with *Dicarinella primitiva, Marginotruncana schneegansi, M. sinuosa, Whiteinella paradaubia, Planoheterohelix praenuttalli* and *Marginotruncana schneegansi.* Therefore, it is considered as second marker for the base of Coniacian stage.

4.1.3. Third Marker: Marginotruncana Sinuosa

This species was first described by Donze P. et al. [33], where last occurrence within *Dicarinella asymetrica* zone in Santonian stage, while first occurrence within *Marginotruncana schneegansi* zone in Turonian stage [34]. Peryt D. [9] used this species to represent the uppermost Turonian-lower Coniacian interval. This species is generally considered ancestral and transitional to *Rosita fornicata* from which it differs in a lower trochospire and the absence of prominent globular chambers in the early whorls [16]. The *Marginotruncana sinuosa* zone may be correlated with the lower part of the *Dicarinella concavata* zone in the Tethyan area [17, 19]. In the present material, flood marginotruncanids were recorded in samples AZ3, AZ16, AZ20; *Marginotruncana schneegansi, M. sinuosa, M. renzi, M. sigali* and *M. coronata*. The first occurrence of *M. sinuosa* at sample AZ3 coincident with the appearance of *D. primitiva-Huberella huberi* assemblage that assures the base of Coniacian and the continuity of *M. sinousa* in higher levels toward the top Coniacian enabled to consider it as a third marker. The appearance of *D. concavata* at sample AZ16 determines the base of Santonian, although the continuity of *M. sinuosa* at sample AZ20 within *D. concavata* Zone.

4.2. Santonian

The Santonian Stage type section is in the Environs of Saintes, Charente [22], where the boundary is drawn at a hardground between glauconitic limestones of the Coniacian below and marls of the Santonian above. The Dicarinellids represent the most important group in the zonation of the Santonian Stage, due to the high diversity and the short ranges for the Dicarinellids species. The base of Santonian stage was recorded using LO of *Dicarinella primitiva*, Whiteinellids group with FO of *Dicarinella asymetrica* [35]. The first occurrence of the planktonic foraminifera *Sigalia* was accepted as a secondary marker for the basal Santonian [36]. In the present study, the Santonian interval was represented by the middle (AZ16-AZ25) and upper (AZ26-AZ36) parts of Matulla Formation. It is characterized by two zones; *Dicarinella concavata* and *Dicarinella asymetrica.*

4.2.1. Dicarinella Concavata Zone (Early Santonian)

This species was first described by Brotzen F. [37], where the last occurrence within *D. asymetrica* zone in Santonian stage, while the first occurrence at base of *Dicarinella concavata* zone in Turonian stage. Caron M. [16] used it as an interval zone from upper Coniacian to lower Santonian or from the first occurrence of *Dicarinella concavata* to the first occurrence of *Dicarinella asymetrica. Dicarinella concavata* was used as an interval from upper Turonian to the base of Santonian [35]. Obaidalla N. and Kassab A. [6] recorded the *Dicarinella asymetrica* and *Sigalia carpathica* zones in the Santonian for the upper part of the Matulla Formation. The appearance of *D. concavata* at samples AZ16, with the disappearance of *Huberella huberi* and rare occurrence of *D. primitiva* determines the base of Santonian. This zone occupies the interval from AZ16 to AZ25 (22.9 m). Also, this zone witnessed the continuity of flood marginotruncanids appearance; *Marginotruncana schneegansi, M. sinuosa, M. renzi, M. sigali, M. marginata, M. pseudolinneiana, M. coronata* and *biserial planktic foraminifer Heterohelix reussi*.

4.2.2. Dicarinella Asymetrica Zone (Late Santonian)

This species was first described by Sigal J. [38], where the last occurrence at top of *D. asymetrica* zone in Santonian stage, while the first occurrence at base of *D. asymetrica* zone in Coniacian stage. This zone has been introduced for the first time by Postuma J. [15] and was shown early Santonian–late Santonian age. Caron M. [16] used this species as a total range zone from the upper part of early Santonian to late Santonian or interval of total range of *Dicarinella asymetrica.* This zone occurs throughout Coniacian–Santonian measured section in the eastern border of the “Cantera de Margas” quarry, Olazagutia, Navarra, N. Spain [39]. Nonetheless, *D. asymetrica* occurs throughout the upper Coniacian at low frequencies [36]. In the present study, the selection of this zone to represent a good marker for the middle–late Santonian was based on the flood occurrence of *D. asymetrica* in sample AZ25 although its occurrence in lower levels with rare occurrence. This zone occupies the interval from AZ26 to

AZ36 (20.9 m). Furthermore, the occurrence of *Contusotruncana fornicata* and disappearance of *D. concavata* assures the zone selection. The assemblage of this zone includes *Marginotruncana renzi, M. sigali, M. marginata, M. pseudolinneiana, M. coronata, Whiteinella baltica, W. archaeocretacea* and *Heterohelix reussi*.

5. Benthic Foraminifera

There are several attempts to use the benthic species as a marker for the Coniacian–Santonian boundary. The stratigraphically important lineages of the genera *Stensioeina* and *Gavelinella* were used for recognizing the base of the Coniacian Stage in Poland [40]. In the Global Boundary Stratotype and Section Point (GSSP) for the base of the Santonian Stage in "Cantera de Margas", Olazagutia, N. Spain, the uppermost Coniacian is characterized by the LO of *Stensioeina granulata*, and the FO of *S. polonica*, *S. granulata incondita*, *Cibicides eriksdalensis*, and *Neoflabellina gibbera* [36]. The lowest occurrence of *Neoflabellina gibbera* was recorded at the base of Santonian of southern Tanzania, in addition to rare specimens assigned to *Neoflabellina* sp. have been found in younger stratigraphic levels [20]. El Dawy M. and Hewaidy A. [41] recorded *Cibicidoides eriksdalensis* [42] in the Maastrichtian of Egypt, but may be the last occurrence for this species. Pervushova E. et al. [43] recorded the first appearance of the *Neoflabelina* genus at the upper Coniacian–lower Santonian in Ulyanovsk-Saratov trough, South of Moscow, Russia. This genus was represented by *Neoflabelina suturalis suturalis* (Cushman), *N. gibbera* (Wedekind), and *N.* cf. *suturalis suturalis* (Cushman). In the study area, the benthic assemblages represent a minor contribution in Coniacian–Santonian stratigraphy. The studied interval with low benthic foraminiferal abundance is associated with low diversity taxa. The calcareous taxa dominate the benthic assemblages, while the agglutinated foraminiferal species are less abundant (Figure 2). The occurrence of benthic foraminifera is represented by six genera; *Haplophragmoides*, *Ammobaculites*, *Neoflabellina*, *Vaginulina*, *Discorbis* and *Cibicidoides*. Eleven species are recorded in the studied Coniacian–Santonian interval (samples AZ3-AZ25); *Haplophragmoides gracilis* Said and Kenawy (1957), *Haplophragmoides* sp., *Ammobaculites turonicus* Said and Kenawy (1957), *Neoflabellina baudouiniana* (d'Orbigny 1840), *Neoflabellina deltoidea* (Wedekind, 1940), *Neoflabellina praerugosa* Hilterman, *Neoflabellina rugosa* (d'Orbigny, 1840), *Vaginulina longiforma* (Plummer, 1927), *Discorbis turonicus* Said and Kenawy (1957), *Discorbis minutus* Said and Kenawy (1957) and *Cibicidoides* cf. *eriksdalensis* (Brotzen, 1936). The Neoflabelinids (*Neoflabellina baudouiniana, N. deltoidea, N. praerugosa, N. rugose*) and *Cibicidoides* cf. *eriksdalensis* characterize the early Santonian (sample AZ16), while the agglutinated species (*Haplophragmoides gracilis, H.* sp., *Ammobaculites turonicus*) and Discorbids (*Discorbis turonicus, D. minutus*) were found at the base of Coniacian (sample AZ3).

6. Coniacian–Santonian (C/S) Boundary

The ideal boundary of a chronostratigraphic unit is characterized by a widely traceable isochronous marker and physical changes, such as global falls in sea-level or oxic-anoxic events, clearly influenced the fossil record. Peryt D. et al. [9] studied the Upper Cretaceous planktic foraminifera of extra–Carpathian Poland and western Ukraine. They (opt.) recorded the *Marginotruncana sinuosa* Interval Zone for the uppermost Turonian through lower Coniacian, *Pseudotextularia nuttalli* Interval Zone for middle-upper Coniacian and *Globotruncana linneiana* Concurrent-Range Zone for Santonian. The Coniacian–Santonian boundary was defined by the first occurrence of the inoceramid bivalve *Platyceramus undulatoplicatus* at Olazagut á, Spain [44, 36]. Dubicka Z. [45] marked the Coniacian–Santonian boundary by the disappearance of foraminifera possessing keels divided by a relatively narrow (*Dicarinella concavata* and *Marginotruncana paraconcavata*) and wavy peripheral band (*Marginotruncana sinuosa*, *M. undulata* and *Contusotruncana morozovae*). The Santonian Working Group (SWG) recommended the lowest occurrence of *Cladoceramus undulatoplicatus* as a marker for the Coniacian–Santonian boundary. The Subcommission on Cretaceous Stratigraphy defines the boundary based on the FO of *Sigalia carpathica*, in some sections in the Romanian Carpathians. Ion J. and Ion J. et al. [46-47] used *Dicarinella asymetrica* and *Sigalia carpathica* to delineate the C–S boundary in southwestern Sinai. Obaidalla N. [48] introduced *Dicarinella asymetrica/ Marginotruncana sinousa* Subzone as a concurrent-range subzone to cover the latest Santonian interval from the lowest occurrence of *Dicarinella asymetrica* to the highest occurrence) of *Marginotruncana sinousa*. In Abu Zeneima section, the Matulla Formation yields several species belonging to Marginotruncanids, Dicarinellids, Whiteinellids and Heterohelicids. Therefore, three alternative marker horizons delineate the Coniacian; *Dicarinella primitiva or Huberella huberi* or *Marginotruncana sinuosa*. On the other hand, the appearance of *Dicarinella concavata* and disappearance of *Huberella huberi* with increase of Marginotruncanids (*M. renzi, M. sigali, M. marginata, M. pseudolinneiana*..etc) determines, to a great extent, the base of early Santonian and delineate the C–S boundary. The occurrence of *Dicarinella asymetrica* and *Contusotruncana fornicata* recognizes the beginning of upper Santonian. Furthermore, the Coniacian is characterized by agglutinated foraminifera; *Haplophragmoides gracilis, Haplophragmoides* sp., *Ammobaculites turonicus, Discorbis turonicus, Discorbis minutus,* while the base of Santonian contains *Neoflabellina baudouiniana* and *Neoflabellina deltoidea*. The following species appear through the Santonian interval*; Neoflabellina praerugosa Neoflabellina rugose, Vaginulina longiforma* and *Cibicidoides* cf. *eriksdalensis.*

7. Oceanic Anoxic Event (OAE3)

OAE 3 was an Atlantic anoxic event given the restricted distribution of black shales as compared to global occurrences of OAE 1 and OAE 2. Schlanger S. and Jenkyns H. [49] and Wagreich M. [50] did not identified OAE 3, mentioning only two major oceanic anoxic events. Several authors recorded this event in different regions [51-52, 2]. Thus, it is a subject of discussion whether OAE3 should be regarded as a global oceanic event, or perhaps as a regional or Atlantic anoxic event [45]. Wagreich M. [53] concluded that OAE 3 is not a global oceanic event but a regional anoxic event that is essentially restricted to the low- to mid-latitudinal part of the Atlantic and some adjacent epicontinental basins such as the Maracaibo Basin and the Western Interior Basin. Furthermore, OAE 3 is not a clearly defined, short-time event, but distributed over a longer time span, at least from the Coniacian to the Santonian. Most of the typical "OAE 3" sections in the equatorial Atlantic display continuous organic matter-rich successions from Cenomanian–Turonian OAE 2 to Coniacian–Santonian black shales. The lack of black shales from the Tethys is notable, as a strong seaway connection of the Tethys with the latitudinal Atlantic had been established during the Upper Cretaceous. Looking for published case studies on typical Coniacian–Santonian OAE 3 strata indicates the fact that such studies are relatively rare, especially if compared to numerous works dedicated to the slightly older Cenomanian–Turonian boundary interval OAE 2. Also, organic-rich strata of Coniacian–Santonian age were reported from subsurface along the Ivory Coast–Ghana transform margin [53] (Wagreich, 2012). High organic carbon sediments of Coniacian–Santonian age, especially marine organic matter bearing black shales, appear in the southern part of North Atlantic, the South Atlantic, the Caribbean Sea, and surrounding basins and shelf areas like the Western Interior, the Maracaibo Basin (Venezuela), Columbia, Brazil, northern Namibia, Angola, Gabon, Ivory Coast, northwest Africa and Morocco [54], Libya and Egypt [55, 50]. Furthermore, sediments linked to OAE 3 have been documented in Venezuela [56-57], Colombia [58-59] Surinam, Ecuador [60] and in areas rather close to Mexico such as Costa Rica and Panama [61], and the Western Interior Seaway, USA [62-63].

Reda El Gammal M. and Orabi H. [64] recorded *Dicarinella concavata* Zone (Coniacian), *Dicarinella asymetrica* Zone (Santonian) and correlated the two zones with the Coniacian–Santonian time interval of Oceanic Anoxic Event 3 (OAE 3) in the first lower marl bed of "Atchan Phosphate A-Beds" Gebel Duwi, Eastern Desert, although Duwi Formation is of hard varieties of silicified phosphatic oyster beds builds up with chert bands and black shales.

In the studied Abu Zeneima section, two black shales horizons were recorded in the middle part of the Matulla Formation; a lower shale horizon (AZ11 – AZ16) and an upper one (AZ20– AZ25). The lower horizon consists of dark green to black soft shales partially bituminous and mostly the Coniacian–Santonian boundary lies at sample AZ16 within the lower third part of this horizon. The upper horizon is composed of gypsiferous, fissile, soft black shales with dark yellowish color in few parts. The lower–middle Santonian boundary lies at sample AZ25 within the upper part of this horizon. The dating of the bituminous horizons was carried out by examination of planktic foraminiferal faunas, where several species belonging to genera, *Marginotruncana*, *Dicarinella*, *Heterohelix* and *Whiteinella* that delineated the precise age assignment. Jenkyns H. [2] noted that Cretaceous OAEs correlate closely with transgressions, and such a correlation exists throughout the stratigraphical column (Figure 3). Therefore, the studied facies mostly lies between the thick black shales and marly pelagic limestones with bituminous levels in the facies distribution Diagram of Jenkyns H. [2] (Figure 4). The author believed that OAE 3 is a short-time event, not a single and distinct event, but several discrete episodes distributed over a longer time spanning the Coniacian–Santonian interval. This explains the occurrence of two black shales horizons through the Coniacian–Santonian interval of the Matulla Formation could be correlated with OAE3 event. Also, most of the typical "OAE 3" sections in the equatorial Atlantic display continuous organic matter-rich successions from Cenomanian–Turonian OAE 2 to Coniacian–Santonian black shales. In general, the most significant feature of OAE's is their relationship to the formation of oil [65]. The palaeogeographical configuration of carbonate platforms fringed by rudistid colonies and fore-reef breccias passing laterally into basinal bituminous pelagic limestones-as in the Cretaceous of the Middle East and Mexico-is a perfect setting for the generation and accumulation of oil [52]. In the Gulf of Suez oil province, a "Brown Limestone" mostly of Santonian–Campanian age is proposed as a source rock. An additional section was analyzed in Gabal Ekma (Sinai, Egypt), which exhibits several layers enriched in organic matter associated with extensive bone beds. They concluded that OAE3 is less well known and appears less expressed than the lower Aptian and uppermost Cenomanian OAEs. The author believes that OAE3 is a global event due to its occurrences in southern part of North Atlantic, the South Atlantic, the Caribbean Sea, Venezuela, Columbia, Brazil, Surinam, Ecuador, Olazagutia (NW Spain), Ten Mile Creek-Arbor Park (Texas USA), northern Namibia, Angola, Gabon, Ivory Coast, northwest Africa, Morocco, Libya, and in areas rather close to Mexico such as Costa Rica and Panama and the Western Interior Seaway, USA (Figure 5). Thus, in Egypt, three areas were recorded; a- Gabal Ekma in Sinai [66], b- Duwi Formation contains some black shales beds below the Campanian phosphatic beds (Coniacian?–Santonian) in Eastern Desert [1, 67-69, 64] and c-the present study in Abo-Zeneima-Matulla range in west central Sinai [3]. Another suggested area, in central Wadi Qena, (Hawashiya

Formation) is composed of 55 m thick sequence of shale, silty shale, marl, sandy marl with some sandstone intercalations. It is dated Coniacian–Santonian based on the occurrence of *Ceratodus* sp., *Metatissotia fourneli, Ostrea boucheroni, O. costei, O. heinzi, Forbesiaster gaensis* and *Lopha dichotoma* [70]. The identified foraminiferal assemblage were illustrated in two figures 6 and 7.

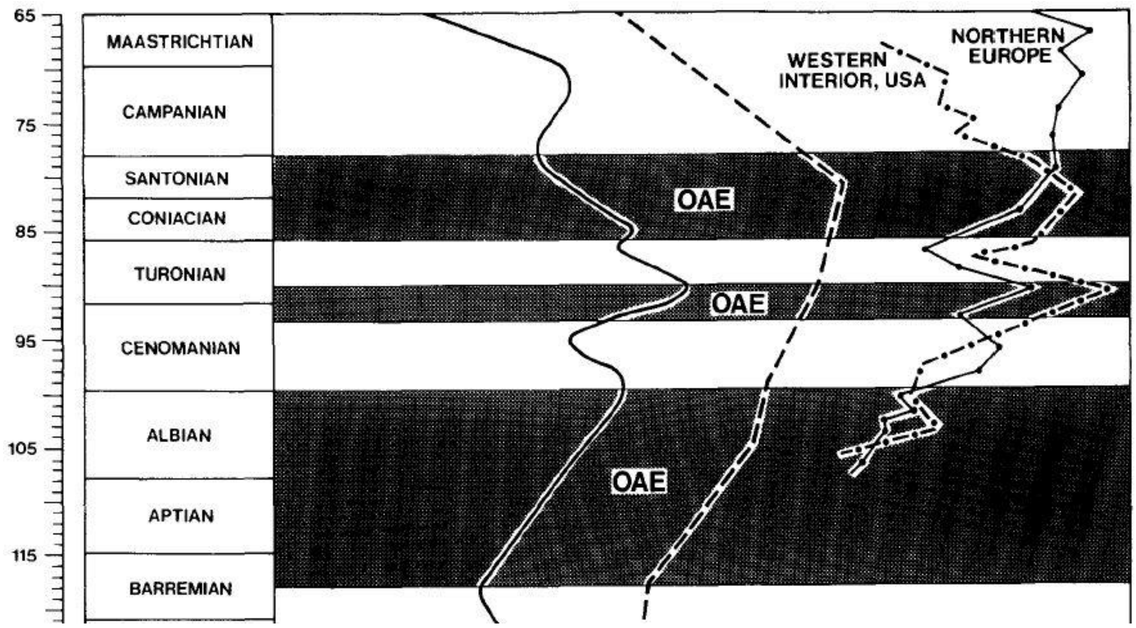

Figure 3. *Relative transgression curves (horizontal scale is arbitrary) plotted against Oceanic Anoxic Events. Transgression to the right, regression to the left (after Jenkyns 1980).*

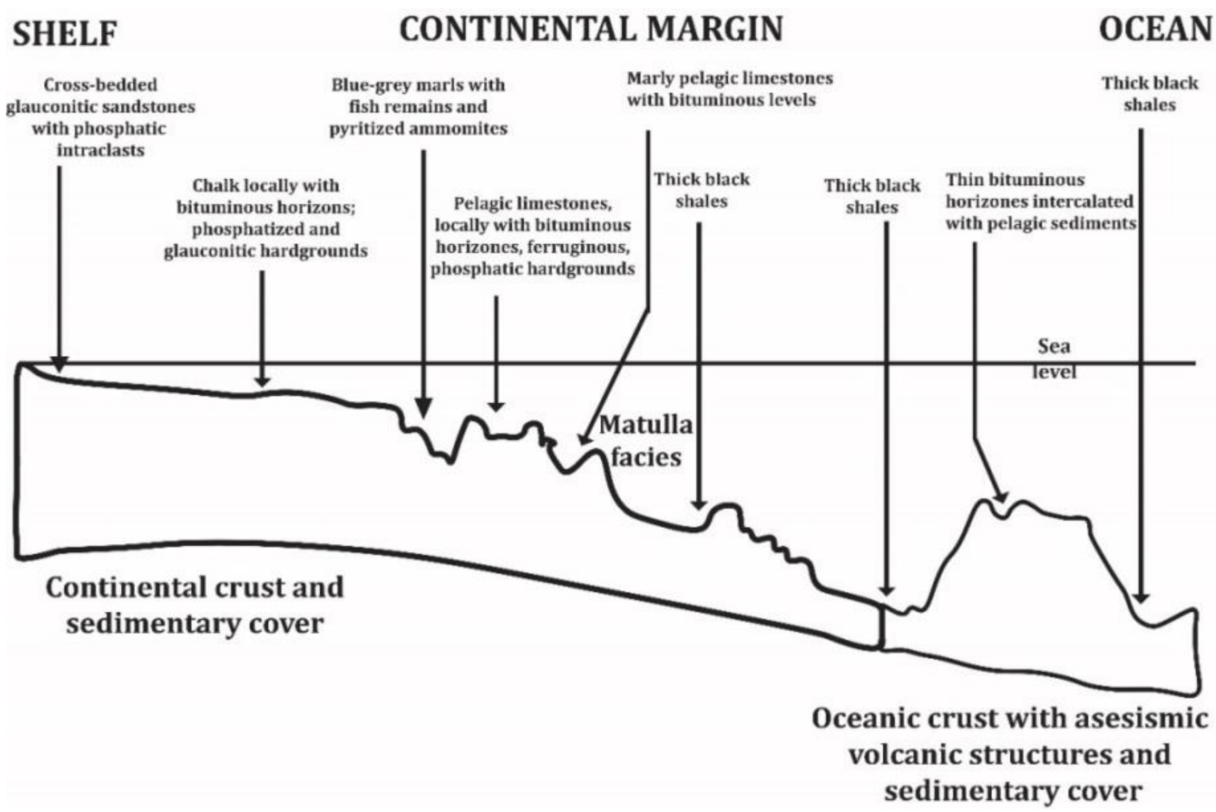

Figure 4. *The facies distribution of Matulla Formation plotted on the suggested diagram by Jenkyns (1980).*

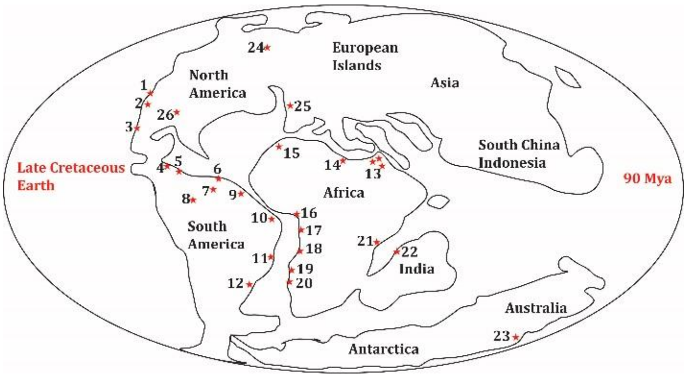

Figure 5. *Occurrences of OAE 3 black shales (red dots) during Coniacian–Santonian times, plotted on a plate tectonic reconstruction for 90 Mya of the Atlantic–Asian–African region. (Schettino and Scotese, 2004): the red dot countries are 1, 2- U.S. Western Interior Seaway (Bottjer and Stein 1994, Dean and Arthur 1998), 3- areas rather close to Mexico, 4- Costa Rica (Erlich et al. 1996 and 2003), 5-Panama (Erlich et al. 1996 and 2003), 6-Venezuela (Davis et al. 1999, Erlich et al. 1999, Crespo de Cabrera et al. 1999), 7-Colombia (Vergara 1997, Rangel et al. 2000), 8- Ecuador (Brookfield et al. 2009), 9- Surinam (Shipboard Scientific Party 2002), 10- Brazil, 11-12 Southern Atlantic areas, 13- Egypt (Wagner et al. 2004, Wagreich 2009), three areas a-Abo-Zeneima-Matulla range in west central Sinai (Ismail 1993), b- Gebel Duwi, in south Eastern Desert (Reda El Gammal and Orabi 2019), c- Gabal Ekma in Sinai (Bomou et al. 2013) 14- Libya, 15-Morocco (Sachse et al. 2012), 16- Ivory Coast (Wagreich 2012), 17- Ghana transform margin (Wagreich 2012), 18- Gabon, 19- Angola, 20- northern Namibia, 21- Tanzania (Petrizzo et al. 2017), 22- Pakistan (Wagner et al., 2004) (black Shales minor distribution), 23- Southern Australia (Wagner et al., 2004), (black Shales minor distribution), 24- Sverdrup Basin in Arctic Canada (Wagner et al., 2004), (black Shales minor distribution), 25- Olazagutia (NW Spain) Bomou et al. (2013), 26- Ten Mile Creek-Arbor Park (Texas, USA). Bomou et al. (2013).*

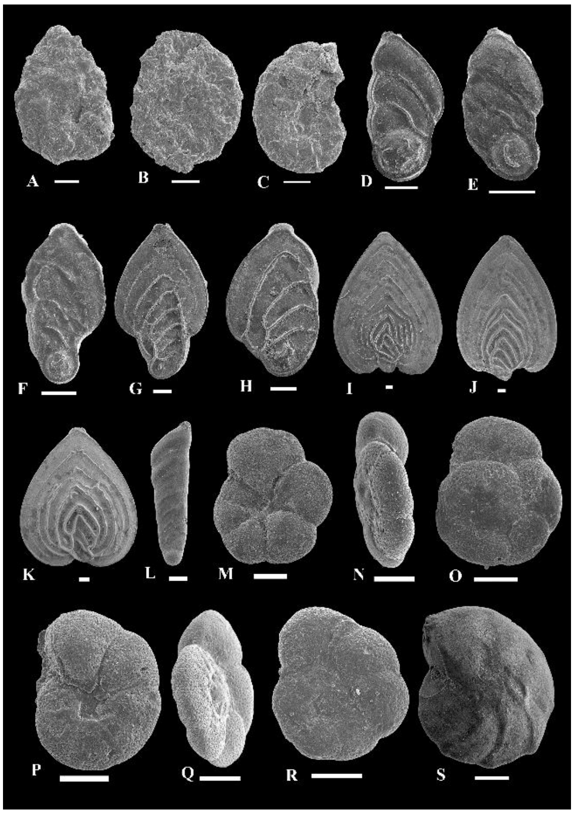

Figure 6. *The identified specimens that deposited in "Ismail Collection"; A- Haplophragmoides gracilis Said & Kenawy, 1957, sample no. AZ3, Coniacian, B- Haplophragmoides sp., sample no. AZ3, Coniacian, C- Ammobaculites turonicus Said & Kenawy, 1957, sample no. AZ3, Coniacian, D, E, F- Neoflabellina baudouiniana (d'Orbigny, 1840), sample no. AZ16, Santonian, G- Neoflabellina deltoidea (Wedekind, 1940) sample no. AZ16, Santonian, H- Neoflabellina praerugosa Hilterman, 1952, sample no. AZ25, Santonian, I, J, K- Neoflabellina rugosa (d'Orbigny, 1840), sample no. AZ25, Santonian, L- Vaginulina longiforma (Plummer, 1927), sample no. AZ25, Santonian, M, N, O- Discorbis turonicus Said & Kenawy, 1957, sample no. AZ3, Coniacian, P, Q, R- Discorbis minutus Said & Kenawy, 1957, sample no. AZ3, Coniacian, S- Cibicidoides cf. eriksdalensis (Brotzen, 1936), sample no. AZ3, Coniacian.*

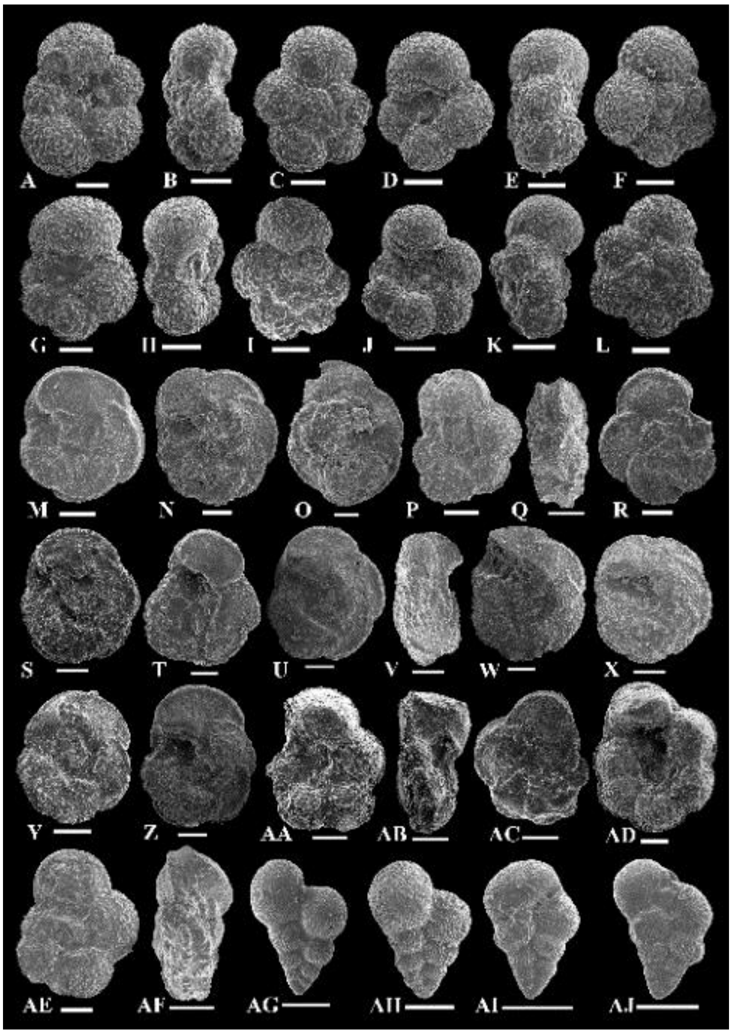

Figure 7. *The identified specimens that deposited in "Ismail Collection"; A, B, C- Whiteinella archaeocretacea, Pessagno, 1967, A ventral view, B side view, C dorsal view, sample no. AZ3, D, E, F - W. baltica, Douglas & Rankin, 1969, D ventral view, E side view, F dorsal view, sample no. AZ20, G, H, I- W. inornata (Bolli, 1957), G ventral view, H side view, I dorsal view, sample no. AZ25, J, K, L- W. paradubia (Sigal, 1952), J ventral view, K side view, L dorsal view, sample no. AZ3, M- Contusotruncana fornicata (Plummer, 1931), ventral view sample no. AZ25, N, O- Marginotruncana coronata (Bolli, 1945), N ventral view, O dorsal view, sample no. AZ20, P, Q, R- M. marginata (Reuss, 1845), P ventral view, Q side view, R dorsal view, sample no. AZ20, S- M. pseudolinneiana, Pessagno, 1967, ventral view, sample no. AZ25, T- M. schneegansi (Sigal, 1952), ventral view, sample no. AZ3, U, V- M. renzi (Gandolfi, 1942), U ventral view, V side view, sample no. AZ20, W, X- M. sigali, (Reichel, 1950), ventral view, sample no. AZ20, Y, Z- M. sinuosa, Porthault, 1970, ventral view, sample no. AZ20, AA, AB, AC- Dicarinella asymmetrica (Sigal, 1952), AA ventral view, AB side view, AC dorsal view, sample no. AZ25, AD- D. concavata, (Brotzen, 1934), ventral view, sample no. AZ16, AE, AF- D. primitiva (Dalbiez, 1955), AE ventral view, AF side view, sample no. AZ3, AG, AH- Planoheterohelix praenuttalli (Haynes, Huber & MacLeod, 2015), sample no. AZ3, AI - Huberella huberi Georgescu 2007 sample no. AZ3,* **AJ-** *Heterohelix reussi (Cshman, 1938), sample no. AZ25.*

8. Conclusions

The paleontologic investigation of the Matulla Formation in Abu Zeneima area, West-Central Sinai, Egypt, revealed eighteen planktic and eleven benthic foraminiferal species, attributing the studied succession to the Coniacian/ Santonian interval. Three markers for the Coniacian were suggested; *Dicarinella primitiva or Marginotruncana sinuosa or Huberella huberi*, while *Dicarinella concavata* and *Dicarinella asymetrica* zones were proposed to the early and late Santonian respectively. The appearance of *Dicarinella concavata* and disappearance of *Huberella huberi*, as well as the increase of Marginotruncanids (*M. renzi, M. sigali, M. marginata, M. pseudolinneiana*….etc.) determines, to a great extent, the base of early Santonian (with *Neoflabellina baudouiniana* and *Neoflabellina deltoidea*) and delineate the Coniacian/Santonian boundary. The occurrence of *Dicarinella asymetrica* and *Contusotruncana fornicata* recognizes the beginning of upper Santonian. The organic rich black shale (two intervals within the Matulla Formation) transgressive sedimentation with planktic foraminifera attributed to the Coniacian–Santonian Oceanic Anoxic Event

(OAE3). This event was regarded as a regional or Atlantic anoxic event, but the occurrence of black shales with planktic foraminifera during the Coniacian–Santonian interval in several countries belonging to five continents, was the main motivation to render this event as global event.

Conflicts of Interest

The author declares that he has no competing interests.

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