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ORIGINAL PAPER

Biostratigraphic and paleoecological significance of benthic foraminiferal morphogroups in the uppermost Turonian–upper Campanian of Gebel Duwi Range, Red Sea, Egypt

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Abstract
Identifications of the benthic foraminiferal assemblages (*Gavelinella*, *Stensioeina*, and *Brotzenella*) from one stratigraphic section measured from the platform of the uppermost Turonian-upper Campanian successions of Gebel Duwi Range, Quseir Region, allowed the recognition of seven biozones and two subzones. The Duwi Basin through the uppermost Turonian to upper Campanian increased in depth, the benthic components indicating a time of the Egyptian stable continental shelf. The gradual increase in depth had occurred with no dramatic structure or tectonic changes. The benthic foraminiferal content reveals significant correlates of biostratigraphical and paleoecological changes of the same interval through Eastern, Western, and Central European provinces, and Tethyan epicontinental facies. The benthic foraminiferal contents are of diversified epibenthic and endobenthic taxa suggesting epicontinental inner to outer shelf depositional paleoenvironments and mesotrophic habitat.

Keywords Duwi Formation · Turonian · Campanian · Benthic foraminifera · Biozone

Introduction

Calcareous benthic foraminifera are important tools to date the Cretaceous platform carbonates, where the ammonites and/or planktonic foraminifera are absent or very rare. However, benthic foraminifera are sensitive to environmental changes and, therefore, are facies dependent (Gusic et al. 1988; Velic and Vlahovic 1994; Cause et al. 2003).

The stratigraphic ranges of Late Cretaceous benthic foraminifera may not correspond to their true evolution (appearance-extinction), and they should be used for biostratigraphic correlations with great care, even in environments of long-lasting carbonate platforms (Gusic et al. 1988; Cause et al. 2003). Although several benthic foraminiferal stratigraphic distributions and biozonations have been suggested especially for local areas, a refined, standard biozonation, which can be applied for the Mediterranean region, has not been able to be created for the Upper Cretaceous up till now due to the limitations mentioned above.

Walker and Miller (1992) illustrated that the epifaunal morphotypes are only able to live within a well-oxygenated marine environment. However, infaunal morphotypes can live in an oxygen-deficient environment. Aerobic taxa include morphogroups with a low surface-area-to-volume ratio, while anaerobic taxa have a high surface-area-to-volume ratio (Kaiho 1991). The morphogroup analysis of calcareous benthic assemblages is widely applied for paleoenvironmental studies (e.g., Koutsoukos and Hart 1990; Frenzel 2000; Setoyama et al. 2011, 2017).

This paper aims to establish detailed benthic foraminiferal zonation of the Upper Cretaceous (uppermost Turonian-upper Campanian) epicontinental to neritic sediments of Gebel Duwi Range, Quseir Region (Fig. 1), and correlate it with the adjacent epicontinental platforms.

The basic idea of morphogroup analysis of the foraminiferal fauna in the present study in the Duwi basin allowed us to

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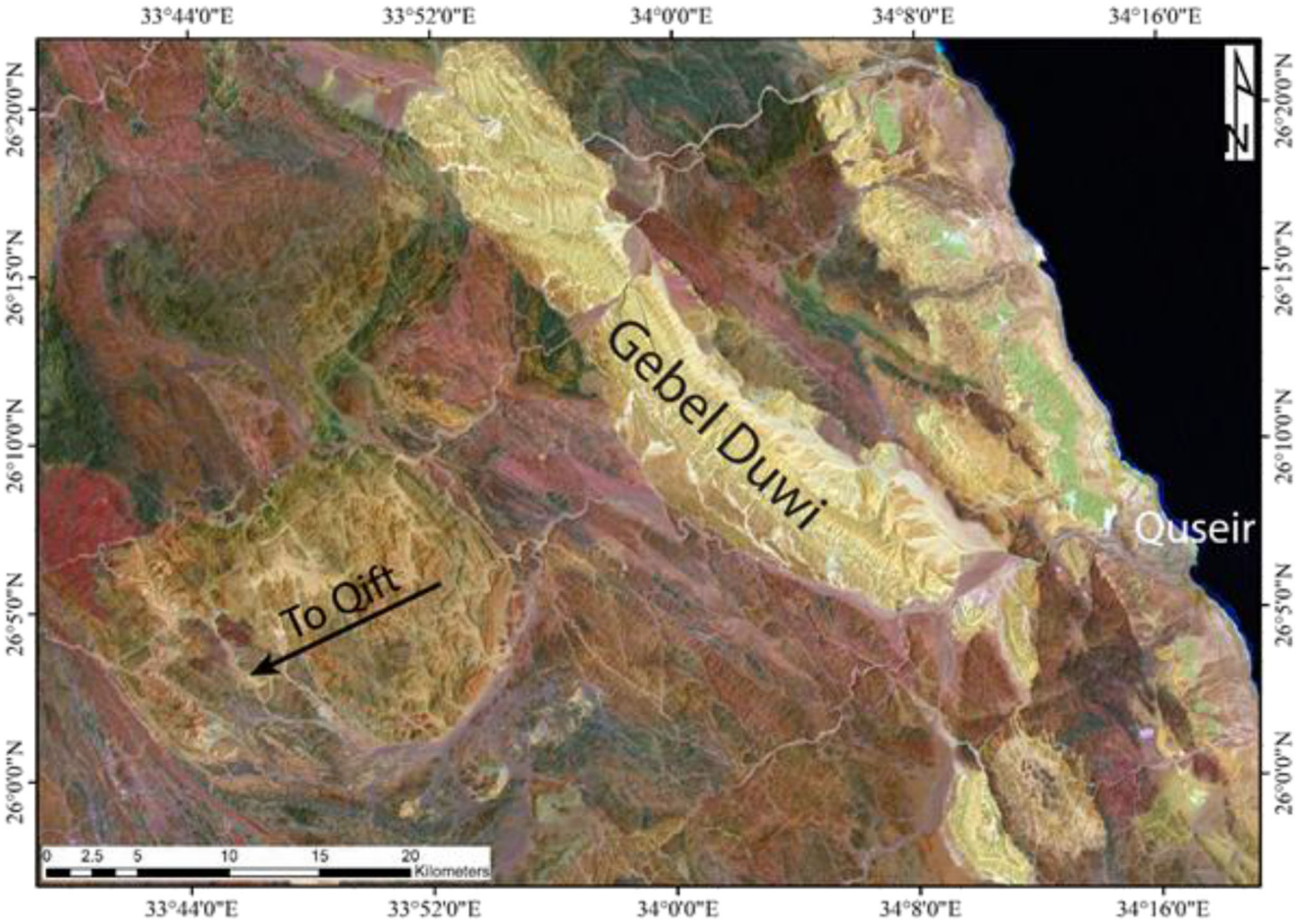

Fig. 1 Geological map of Gebel Duwi Range (modified after Khalil and McClay 2002)

do some further and more detailed paleoecological investigations.

Geological setting

The study area, 500 km south of Suez and 10 km inland from the Red Sea, along Quseir-Qeft Road, contains the largest preserved remnants of Late Cretaceous to Early Tertiary cover along the Egyptian Red Sea coast. These 600-m-thick platform sediments are preserved as outliers down faulted along trends typical of the Eastern Desert (Said 1962, 1990) (Fig. 1).

Fault trends are most prominent in the northwest-trending, 40-km-long Gebel Duwi fault block and appear to represent reactivated Precambrian structures (Khalil and McClay 2002). Red Sea–related structures began to disrupt the area in Oligocene to early Miocene time. The Cenozoic faulting hierarchy involves a pattern of northeast-tilted, northwest-trending blocks. Tilting was followed by an eastward shift of tectonic activity to form the main Red Sea basin (Akkad and Noweir 1980). A post-tilting regional erosion surface developed during mid-Miocene quiescence and has since suffered minor disruption. Possible continuations of the same tilted fault block structural style controlled by basement grain should be of interest for offshore petroleum exploration.

Upper Cretaceous epicontinental basins of the southern platform of Egypt, not deeper than 100–150 m, accumulated predominantly siliciclastic and carbonate sediment facies of marls, calcareous clays, limestones, phosphate granules, and chert. The interval of uppermost Turonian-upper Campanian is about 21 m thick of condensed phosphorite bearing succession represented by the Atcham phosphate (A-Beds) informal member of the Duwi Formation (Said 1962, 1990).

The Duwi Formation is one of the important stratigraphic units in the geology of the Cretaceous Epoch in Egypt. It is considered a marker unit of the Central and Southern Egypt. It was laid down in extremely shallow epicontinental-neritic seas which flaked the southern margin of the Tethys Ocean in Egypt (Kerdany and Cherif 1990; Glenn and Arthur 1990; El Gammal and Orabi 2019a).

Lithostratigraphy

Gebel Duwi area comprises siliciclastic Nubian facies overlain by the following formations: Quseir (Cenomanian), Duwi

(upper Cenomanian-upper Campanian), Dakhla (upper Campanian-Lower Paleocene), Tarawan (Middle to Upper Paleocene), Esna (Upper Paleocene-Lower Eocene), and Thebes (Lower Eocene) (Issawi et al. 1969).

The Duwi Formation attains 77 m thick at its type locality (Gebel Duwi Range), where Said (1962, 1990) classified locally the Duwi Formation on the basis of its mineable phosphate beds into Lower Hamadat unit (or Hamadat or C-Beds), Middle Duwi phosphate Bed (or B-Beds), and Upper Phosphate Atcham Beds (or A-Beds). El Gammal and Orabi (2019a, 2019b) studied in detail the lithobiostratigraphy of Quseir Fm. and Duwi Fm. (C-Beds and B-Beds) and assigned these formations to Cenomanian-upper Turonian, and the same authors assigned the Atcham unit (A-Beds) to upper Turonian-lower Campanian (Fig. 2).

Lithologically, the Atcham unit (A-Beds) is 20 m thick and consists of marly limestone, marl, shale beds, and a thin dolomitic oyster band near the top. The Atcham unit is capped by a conglomeratic phosphatic bed (50 cm thick); it marks the top of the all Duwi Formation section, which is overlying the Dakhla Formation.

Materials and methods

About 80 samples were collected from 21-m-thick A-Beds (Atcham Beds) at decimeter intervals, with closer sampling across the Coniacian, Santonian, and Campanian strata of the Duwi Formation at the Gebel Duwi stratigraphic section and examined to establish the biostratigraphic framework to date and detect depositional environments of the epicontinental basin of the Duwi Region (Fig. 2). The samples were disaggregated in water with diluted H_2O_2, washed through a 63-μm sieve, and dried at 50 °C. All the representative

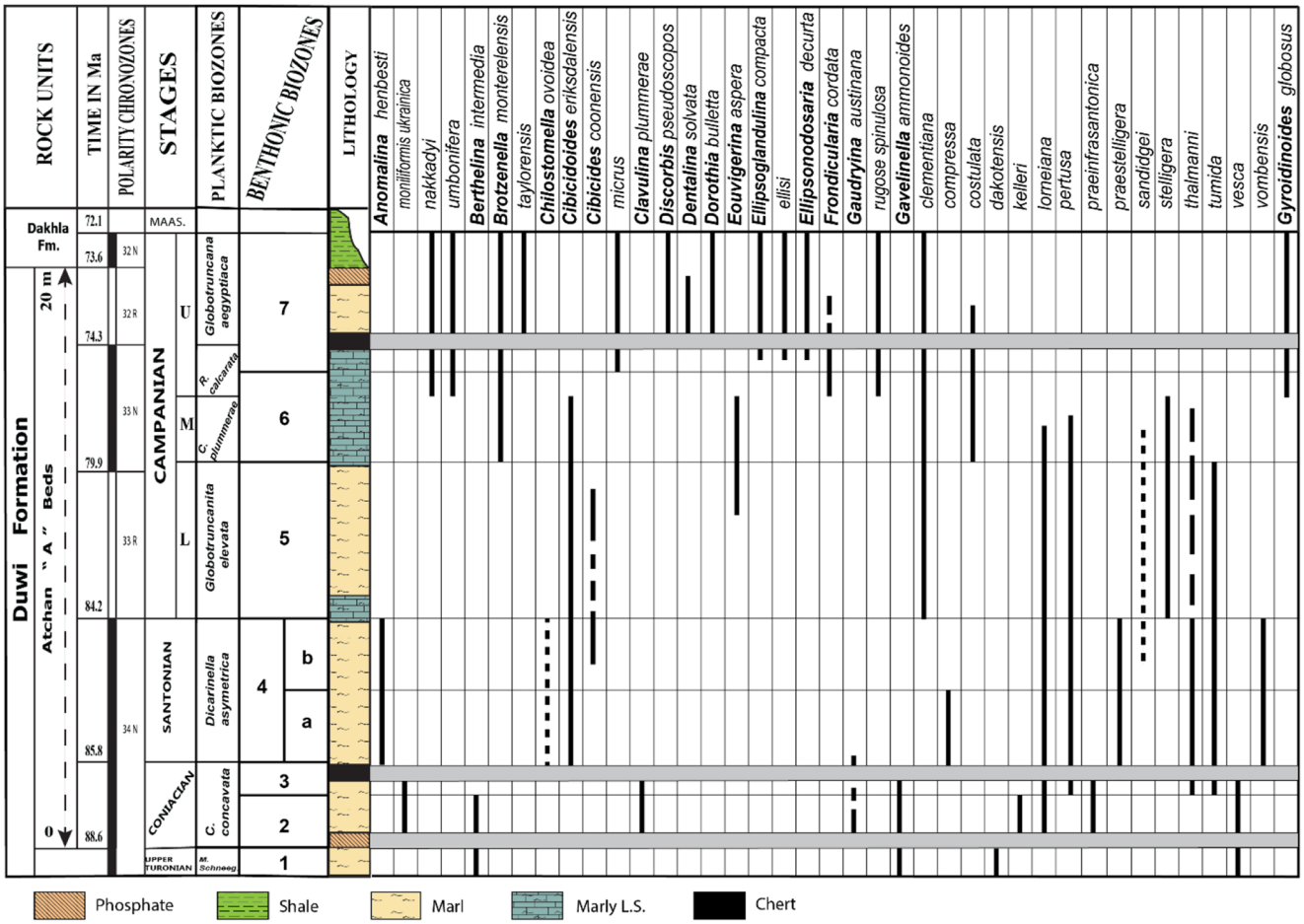

Fig. 2 Latest Turonian-Late Campanian benthic foraminiferal species distribution chart, upper part of the Duwi Formation, Gebel Duwi, Egypt. Benthonic foraminifera zones from older to younger: 1: *Gavelinella vesca*/*Gavelinella ammonites* zone; 2: *Gavelinella praeinferasantonica*/*Protostensioeina granulata* zone; 3: *Gavelinella thalmanni*/*Stensioeina exsculpta* zone; 4: *Gavelinella vombensis*/*Gavelinella praestelligera*/*Stensioein perfecta* zone, a subzone: *Gavelinella compressa*/*Stensioeina perfecta*/*Neoflabellina suturalis*, b subzone: *Gavelinella praestelligera*/*Stensioeina gracilis*; 5: *Gavelinella clementiana*/*Stensioeina pommerana* zone; 6: *Brotzenella monterelensis*/*Gavelinella costulata* zone; 7: *Brotzenella taylorensis* zone

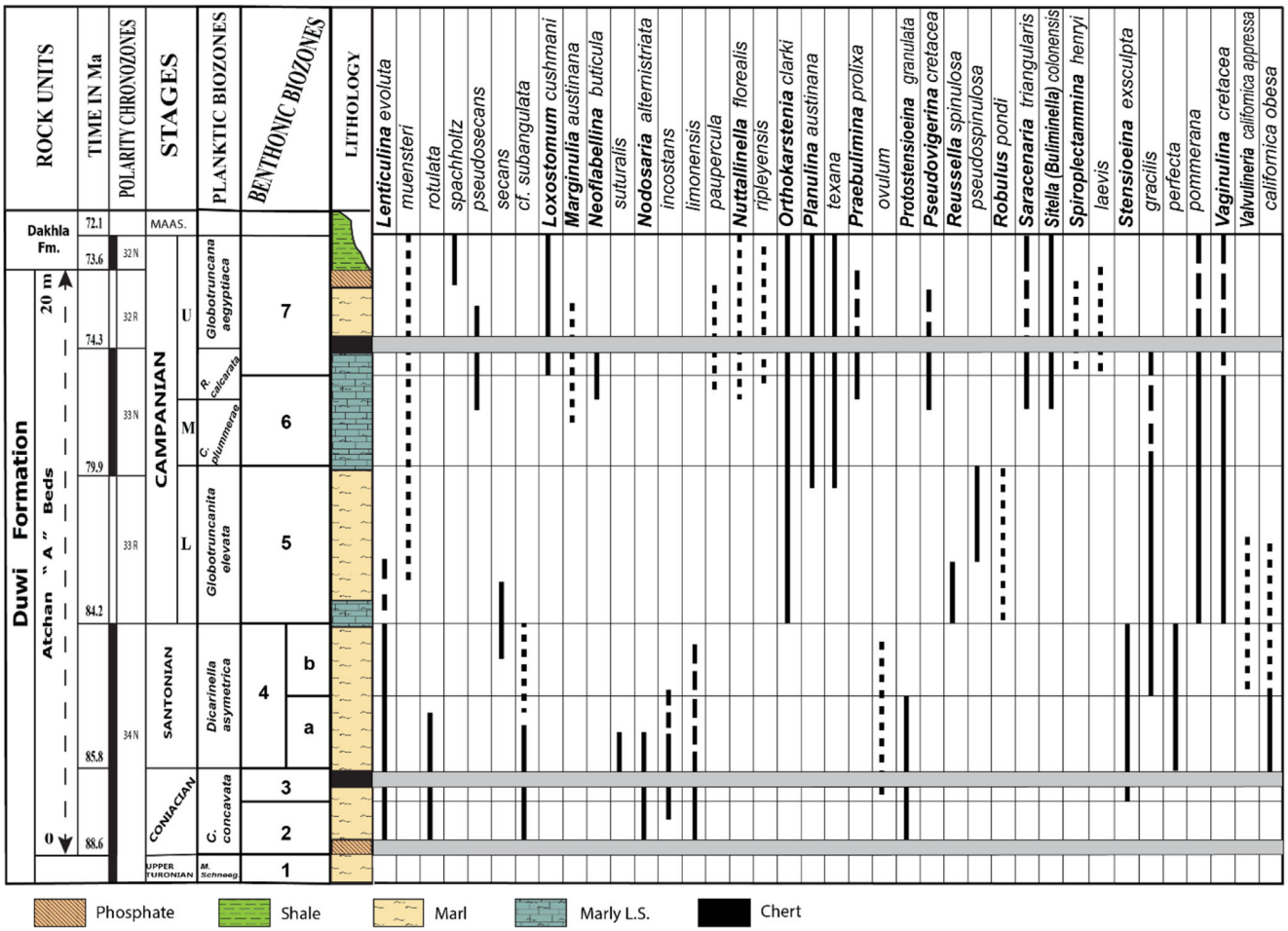

Fig. 2 (continued)

specimens were mounted on microslides for permanent record and identification.

Benthic foraminiferal biozonation (Fig. 2) is established based on the first occurrence (FO) of the taxa by the rules recommended by the North American Stratigraphic Code (NASC 1983) and International Stratigraphic Guide (Murphy and Salvador 1994).

Picked benthic specimens are grouped, identified, and scanned (SEM micrographs) using a scanning electron microscope of Alexandria University (JSM-IT200, Series Jeol) (Figs. 3, 4, and 5). The original samples are preserved with the author's collections and deposited at the Menoufia University museum collection.

Benthic foraminiferal biostratigraphy

The present work provides and establishes 7 benthic biozones and 2 subzones for the first time in the area under consideration, which correlated with the planktonic foraminiferal zonation of El Gammal and Orabi (2019a, 2019b) (Fig. 2). The suggestion benthic foraminiferal zones can be correlated with the same observation of Benyamovskiy (2008a, 2008b) and Dubicka and Peryt (2014) in Eastern, Western, and Central European provinces including Russian and south Russian basins.

The main benthic foraminiferal markers represented by the *Gavelinella*, *Stensioeina*, and *Brotzenella* genera at the Duwi section support the obtained stratigraphic subdivisions and correlation with other Tethyan sections. In general, benthic foraminiferal assemblages are flooded almost uniform through most of the stages and substages of epicontinental, evolved, diversity, and comparisons (Hart et al. 1989; Dubicka and Peryt 2014; Peryt and Dubicka 2015).

Both *Gavelinella* and *Stensioeina* genera allowed us to establish 7 benthic foraminiferal zones, where these genera have a wide biogeographical distribution covering Eastern and Western European provinces, Ukraine, Russia, southern

Russia, and others (Koch 1977; Hart et al. 1989; Olfer'ev and Alekseev 2003; Walaszczyk et al. 2004; Kopaevich et al. 2007; Olferev et al. 2007; Bailey et al. 2009; Dubicka and Peryt 2012, 2014; Bragina et al. 2016; Dubicka 2016; Dubicka et al. 2017; Vishnevskaya et al. 2018).

Benthic foraminifera of the studied interval of the Duwi Formation are rich, well preserved, and diverse of both *Gavelinella* and *Stensioeina* genera which are characterized by the complete condensed sedimentary record and correlated with the comparable planktonic foraminiferal standard zones (Fig. 2). The composition of the benthic foraminifers is very similar across the entire epicontinental European basins and Gebel Duwi section (i.e., southern Tethyan epicontinental basin) giving an opportunity of direct correlations between regions.

Gavelinella vesca/*Gavelinella ammonoides* zone

Category Concurrent range zone

Stage Upper Turonian

Definition Assemblage of *Gavelinella vesca* and *G. ammonoides* as the first appearance of upper Turonian *Marginotruncana schneegansi* zone and overlying the oyster banks of the Duwi FM.

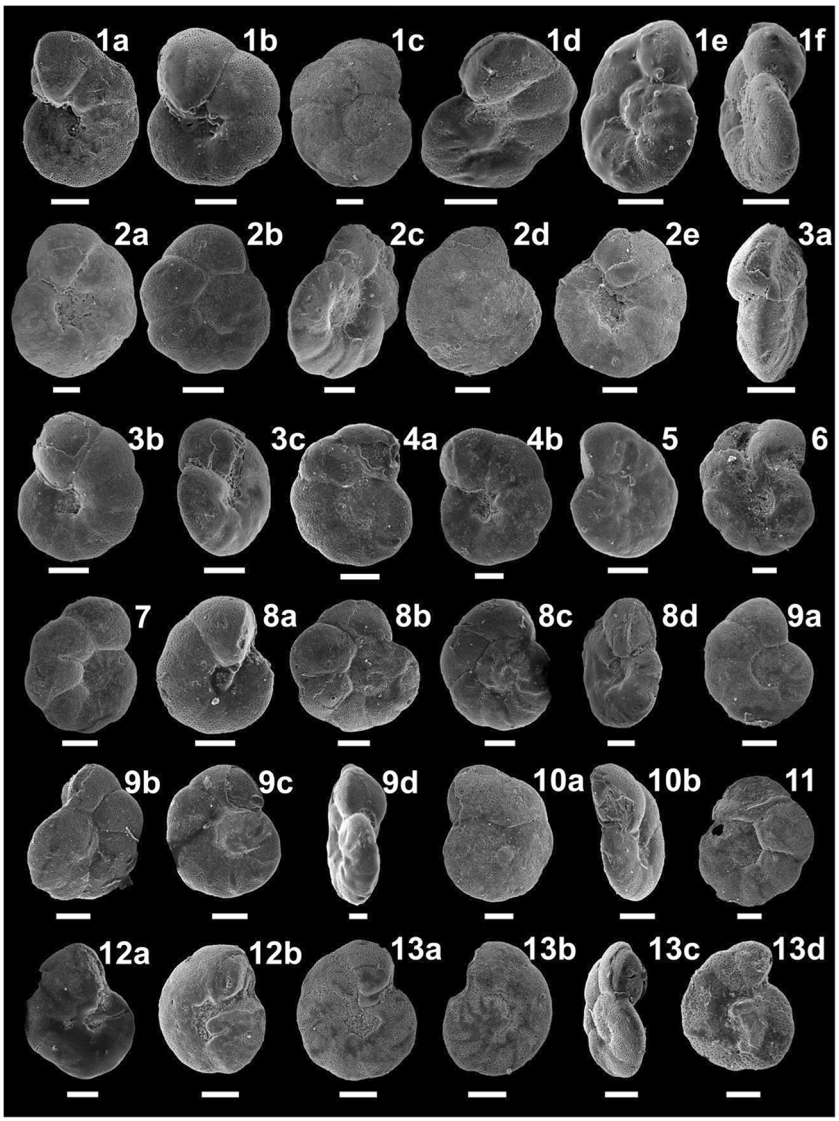

Fig. 3 Scale bar = 100 μm. (1a, b, c, d, e, f) *Gavelinella ammonoides*, (2a, b, c, d, e) *G. clementiana*, (3a, b, c) *G. costulata*, (4a, b) *G. costata*, (5) *G. compressa*, (6) *G. dakotensis*, (7) *G. kelleri*, (8a, b, c, d) *G. lorneiana*, (9a, b, c, d) *G. pertusa*, (10a, b) *G. praeinfrasantonica*, (11) *G. sandidgei*, (12a, b) *G. praestelligera*, and (13a, b, c, d) *G. stelligera*

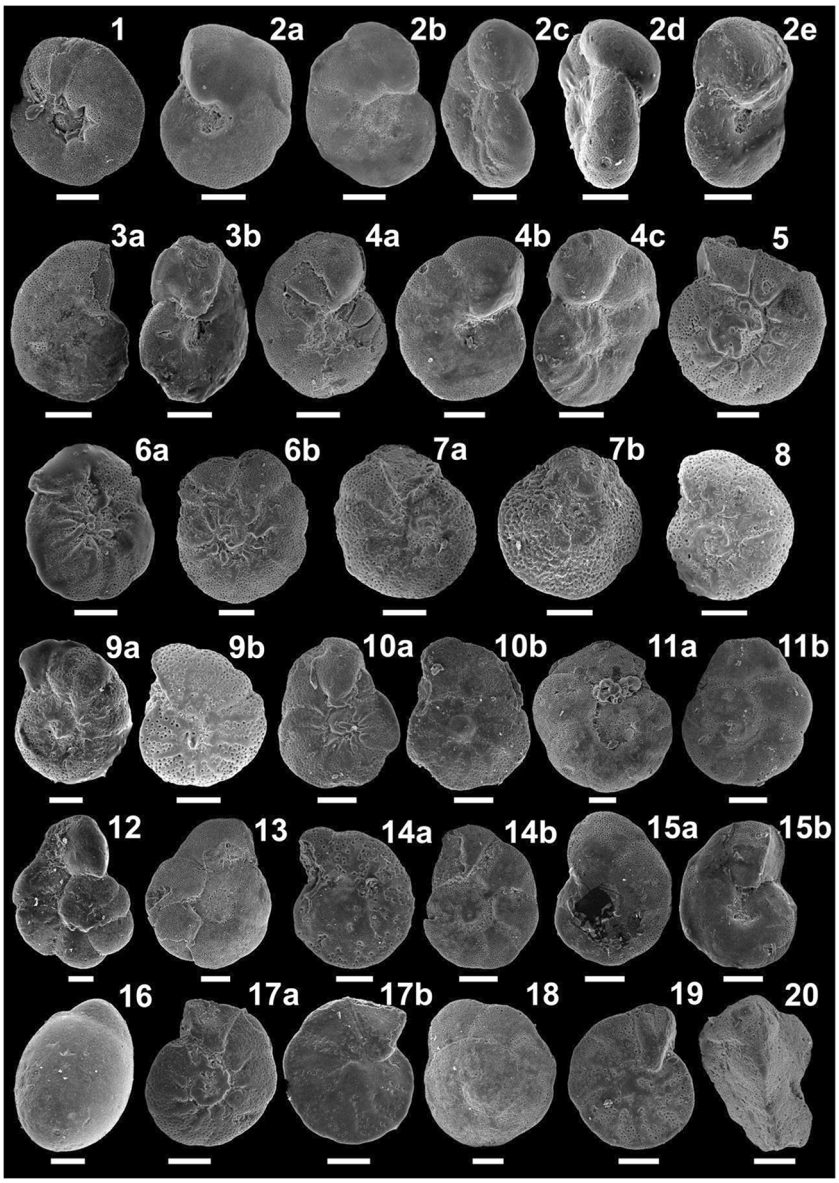

Fig. 4 Scale bar = 100 μm. (1) *Gavelinella thalmanni*, (2a, b, c, d) *G. tumida*, (3a, b) *G. vesca*, (4a, b, c) *G. vombensis*, (5) Protostensioneina granulate, (6a, b) *Stensioneina exsculpta*, (7a, b) *S. gracilis*, (8) *S. perfecta*, (9a, b) *S. pommerana*, (10a, b) *Anomalina henbesti*, (11a, b) *A. umbonifera*, (12) *Anomalinoides nakkadyi*, (13) *Berthelina intermedia*, (14a, b) *Brotzenella monterelensis*, (15a, b) *B. taylorensis*, (16) *Chilostomella ovoidea*, (17a, b) *Cibicidoides eriksdalensis*, (18) *Cibicides cooensis*, (19) *C. micrus*, and (20) *Clavulina plummerae*

Association The nominate zone plus *Berthelina intermedia*, *Gavelinella dakotensis*, and *Sitella coloensis* co-occurred with the planktonic *Marginotruncana schneegansi*, *M. paraconcavata*, *Planoheterohelix moremani*, and *Dicarinella canaliculate* assemblage.

Remarks Benyamovskiy (2008a) named this interval partially as *Gavelinella ammonoides*/*G. moniliformis* zone (LC4) of upper Turonian of the Eastern European Province (EEP). *Gavelinella ammonoides* (Reuss) is the upper Turonian form in eastern and western European provinces (Dubicka and Peryt 2014). *Berthelina intermedia* (Berthelin) is widely recorded worldwide from Albian and upper Turonian sediments (Tyszka 2006), as well as *Gavelinella vesca* (Bykova), which is of upper Turonian-Coniacian in age (Dubicka and Peryt 2014).

Gavelinella praeinfrasantonica/*Protostensioeina granulata* zone

Category Concurrent range zone

Stage Lower Coniacian

Definition First occurrence (FO) of *Gavelinella praeinfrasantonica*, *Protostensioeina granulata*, and *Gavelinella lorneiana* at the lowermost base of the Coniacian of Duwi section.

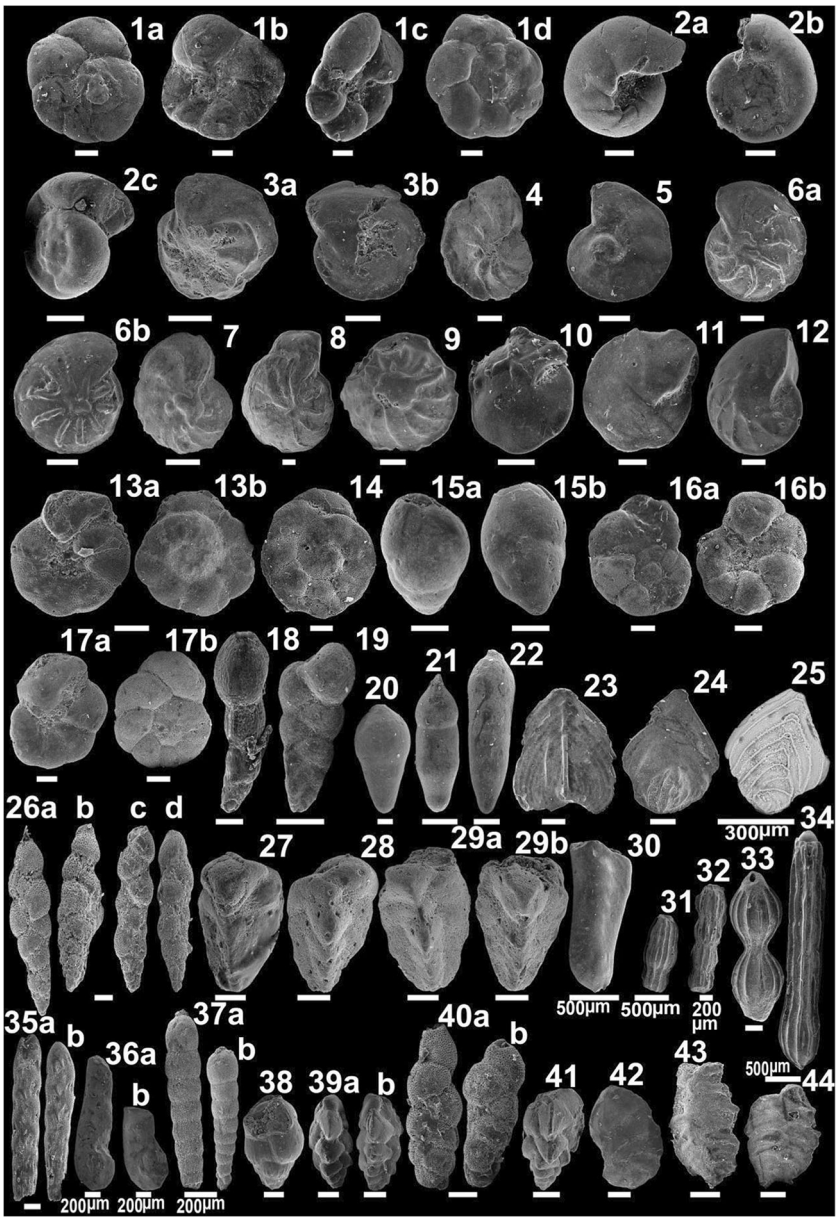

Fig. 5 Scale bar = 100 µm. (1a, b, c, d) *Discorbis pseudoscopos*, (2a, b, c) *Gyroidinoides globosus*, (3a, b) *Lenticulina muensteri*, (4) *L. pseudomamilligera*, (5) *L. pseudosecans*, (6a, b) *L. rotulata*, (7) *L. secans*, (8) *L.* cf. *subangulata*, (9) *L. evoluta*, (10) *Nuttalinella florealis*, (11) *N. ripleyensis*, (12) *Lenticulina pondi*, (13a, b) *Planulina austinana*, (14) *P. texana*, (15a, b) *Sitella colonensis*, (16a, b) *Valvulineria californica* var. *appressa*, (17a, b) *V. californica* var. *obesa*, (18) *Dentalina solvate*, (19) *Dorothia bulletta*, (20) *Ellipsoglandulina compacta*, (21) *E. ellisi*, (22) *Ellipsonodosaria decurta*, (23) *Frondocularia cordata*, (24) *Neoflabellina buticula*, (25) *N. suturalis*, (26a, b, c, d) *Eouvigerina aspera*, (27) *Gaudryina austinana*, (28) *G. rugose*, (29a, b) *Reusella pseudospinulosa*, (3) *Vaginulina cretacea*, (31) *Nodosaria alternistriata*, (32) *N. incostans*, (33) *N. pauperecula*, (34) *N. limonensis*, (35a, b) *Loxostomum cushmani*, (36a, b) *Marginulina austinana*, (37a, b) *Orthokarstenia clarki*, (38) *Praebulimina ovulum*, (39a, b) *P. prolixa longa*, (40a, b) *Pseudovigerina cretacea*, (41) *Reusella spinulosa*, (42) *Saracenaria triangularis*, (43) *Spiroplectamina henryi*, and (44) *S. laevis*

Association *Gavelinella vesca*, *G. kelleri*, and *Berthelina intermedia*

Remarks Dubicka and Peryt (2014) introduced *Protostensioeina* as a new genus of the distinct trend in the evolution of the *Stensioeina* spp., which is known from the Turonian to mid-Santonian of the European epicontinental basin. This zone is characterized by the first occurrence of rich *Gavelinella kelleri*, *G. lorneiana*, and *G. praeinfrasantonica.* The first occurrence of *Protostensioeina granulata* in the Duwi material referred to the first occurrence of Turonian age as suggested by Dubicka and Peryt (2014). Edwards (1981) considered *Gavelinella praeinfrasantonica* was evolved from the *Gavelinella vombensis* lineage. The determination of the basal Coniacian boundary based on benthic foraminifera is problematic here due to very rare benthic species at the uppermost Turonian of the Duwi Formation.

Gavelinella thalmanni/Stensioneina exsculpta zone

Category Concurrent interval zone

Stage Upper Coniacian

Definition First occurrence of *Gavelinella thalmanni* and *Stensioeina exsculpta*, *Praebulimmina ovulum*, and *Sitella colonensis* within the upper Coniacian interval of the Duwi Formation. The upper limit of this zone is marked by the first

appearance of *Neoflabellina suturalis* as marked by the Coniacian/Santonian boundary (El Gammal and Orabi 2019a).

Association This zone contains *Gavelinella vesca*, *G. praeinfrasantonica*, *G. lorneiana*, *G. ammonoides*, *Berthelina intermedia*, *Protostensioeina granulate*, *Clavulina plummerae*, some nodosariids, *Lenticulina evoluta*, *L. rotulata*, and *L.* cf. *subangulata* (Fig. 2).

Remarks Koch (1977), Bailey et al. (1983), Hart et al. (1989), Dubicka and Peryt (2014), and others detected the presence of *Stensioneina exsculpta* in the middle Coniacian of epicontinental beds of Europe. Many transitional forms of *S. exsculpta* occurred in the upper Santonian (Dubicka and Peryt 2014); in the present work, the same observation is recognized in the Duwi section.

Gavelinella vombensis/Gavelinella praestelligera/Stensioeina perfecta zone

Category Concurrent zone

Stage Santonian

Definition First occurrence of *Gavelinella vombensis*, *G. praestelligera*, *G. compressa*, *Stensioeina perfecta*, and *Neoflabellina suturalis*

Association *Gavelinella sandidgei*, *G. tumida*, *G. thalmanni*, *Cibicidoides eriksdalensis*, *Gaudryina austinana*, *G. rugosa* var. *spinulosa*, *Anomalina henbesti*, *Cibicides cooensis*, *Valvulineria californica appressa*, var. *californica obessa*, *Chilostomella ovoidea*, and *Lenticulina pseudosecans*. The lower limit of this zone is marked by the first appearance of *Neoflabellina suturalis* of the Coniacian/Santonian boundary (Fig. 2).

Remarks Olferev et al. (2007) used both *Gavelinella stelligera* and *Stensioeina pommerana* as a partial zone of upper Santonian. Dubicka in Walaszczyk et al. (2016) used the *Gavelinella vombensis/Stensioeina perfecta* zone and the *Gavelinella praeinfrasantonica* zone as the middle Santonian of extra Carpathian of Poland. Vishnevskaya et al. (2018) recorded this interval as the *Gavelinella stelligera* zone covering upper Santonian. All intervals of both *Stensioeina exsculpta* and *Neoflabellina suturalis* are the most accurate of the Santonian Stage of the Duwi section. Neoflabellinids have a wide geographical distribution in the Tethys, Boreal realm, North America, Russian platform, Western Carpathians, European provinces, Northern Spain (Lamolda et al. 2014), and Tunisia in Northern Africa (Elamri et al. 2018). *Neoflabellina suturalis* is considered here as the first best proxy zonal species for the Coniacian/Santonian boundary.

This zone can be locally divided into the following subzones as:

Lower subzone (a) *Gavelinella compressa/Stensioeina perfecta/Neoflabellina suturalis* as first appearance case of lower to middle Santonian

Upper subzone (b) *Gavelinella praestelligera/Stensioeina gracilis* (as first appearance taxon within the interval)

Gavelinella clementiana/Stensioeina pommerana zone

Category Concurrent interval zone

Stage Lower Campanian

Definition First occurrence of *Gavelinella clementiana* and *Stensioeina pommerana* with the extinctions of *Gavelinella vombensis* and *Stensioeina perfecta* of the lower zone

Association *Stensioeina gracilis*, *Lenticulina evoluta*, *L. muensteri*, *L. secans*, *Planulina austinana*, *P. texana*, *Reussella spinulosa*, *Vaginulina cretacea*, *Valvulineria californica obessa*, and *V. californica appressa* (Fig. 2).

Remarks Olfer'ev and Alekseev (2003), Olferiev and Alekseev 2005), Benyamovskiy (2008b), Dubicka in Walaszczyk et al. (2016), and Vishnevskaya et al. (2018) used *Gavelinella clementiana*, *Stensioeina pommerana*, and *Sten. gracilis* as marker species covering the early Campanian interval.

This interval zone is characterized by high flooding of the first occurrence *Orthokarstenia clarki* which is considered a good marker of the early Campanian of the Duwi section as well as the first occurrence of *Euvigerina aspera* (Bragina et al. 2016). The uppermost boundary of this zone is characterized by the extinction of most *Gavelinella* spp. as *G. Pertusa* and *G. tumida*.

The first occurrence of *Gavelinella clementiana* and *Stensioeina pommerana* was associated with extinctions of all dicarinellids (*Dicarinella concavata* and *D. asymetrica*) at the same level of the first occurrence of *Globotruncanita elevata*, together marking the Santonian/early Campanian boundary event (Fig. 6). This result is in agreement with Dubicka et al. (2017) at Bocieniec, Southern Poland, and Eastern European Platform (Vishnevskaya et al. 2018).

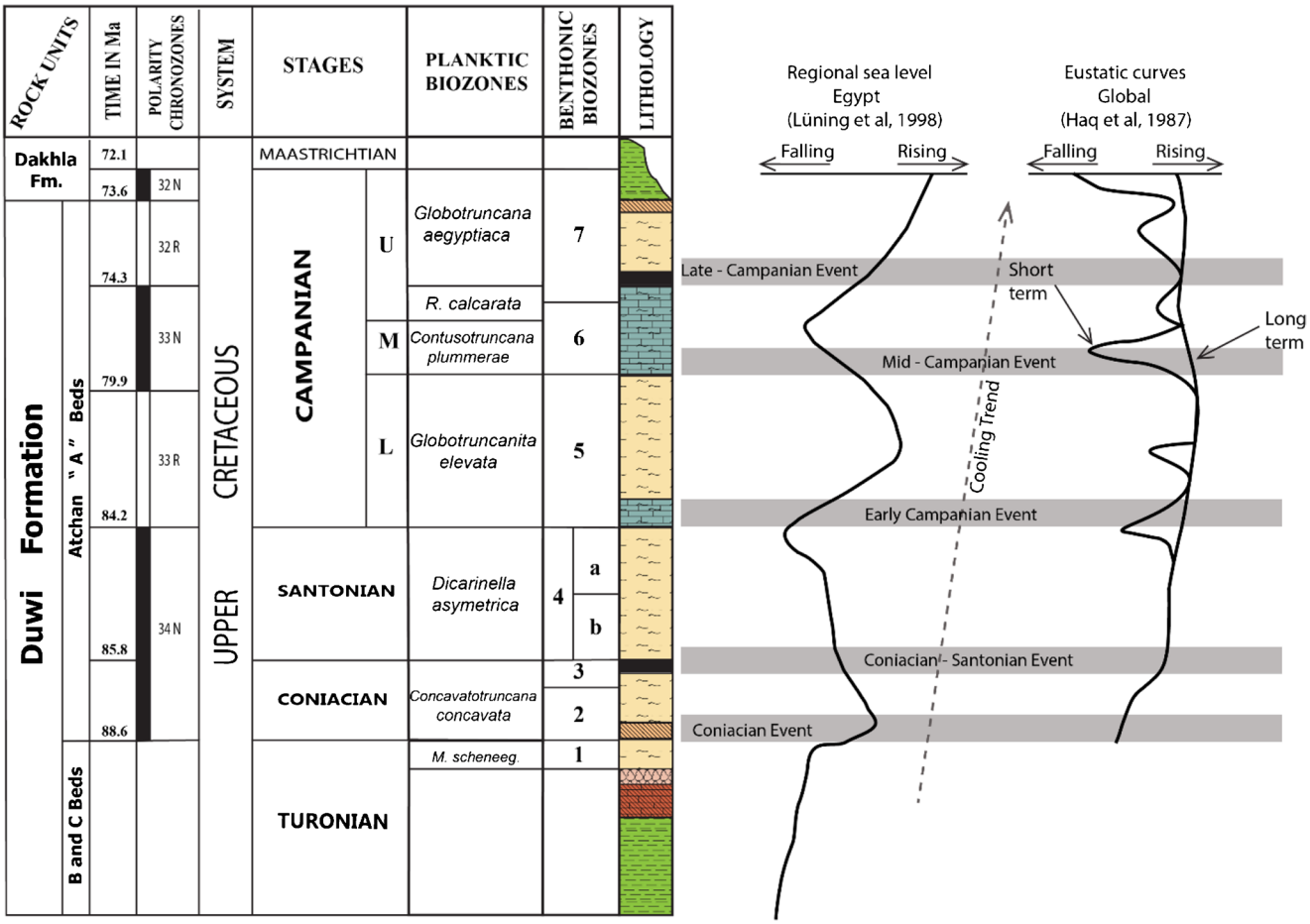

Fig. 6 Sea-level changes vs. planktonic and benthic foraminiferal biozones, chronozones and biostratigraphic events, Coniacian-late Campanian succession of the Duwi Fm., Gebel Duwi, Egypt. Time scale adopted after assuming a constant sedimentation rate, Tethyan planktonic foraminiferal zones. Peaks and troughs on the regional sea-level curves of Egypt according to Haq et al. (1987) and Lüning et al. (1998)

Brotzenella monterelensis/Gavelinella costulata zone

Category Concurrent zone

Stage Middle-upper Campanian

Definition First occurrence of *Gavelinella costulata* and *Brotzenella monterelensis* and first occurrence of *Neoflabellina buticula* and *Frondicularia cordata.*

Association First occurrence of *Neoflabellina buticula* and *Frondicularia cordata*; *Gavelinella clementiana*, *Stensioeina gracilis*, *S. pommerana*, *Gyroidinoides globosus*, *Lenticulina muenstri*, *L. spachholtz Nodosaria paupercula*, *Loxostomum cushmani*, *Nuttallinella florealis*, *N. ripleyensis*, *Orthokarstenia clarki*, *Planulina austinana*, *P. texana*, *Praebulimina prolixa*, *Saracenaria triangularis*, *Spiroplectammina henryi*, *S. laevis*, *Vaginulina cretacea*, *Anomalina nakkadyi*, *A. umponifera*, *Cibicides micrus*, *Discorbis pseudosecans*, *Dentalina solvate*, *Dorothia bulletta*, *Ellipsoglandulina compacta*, *E. ellisi*, and *Ellipsonodosaria decurta* (Fig. 2).

Remarks There is general agreement among all authors to consider the *Brotzenella monterlensis* as marker taxon of the lowermost upper Campanian of the Boreal realm and Tethyan provinces (Hart et al. 1989; Olfer'ev and Alekseev 2003; Olferiev and Alekseev 2005; Olferev et al. 2007; Benyamovskiy 2007; Walaszczyk et al. 2016; Vishnevskaya et al. 2018). The *Neoflabellina buticula* is known from the upper Campanian layers of Western and Eastern European provinces (Koch 1977).

Brotzenella taylorensis zone

Category Interval zone of the nominate taxon

Stage Upper Campanian

Definition First occurrence of *Brotzenella taylorensis* (Carsey)

Association *Neoflabellina buticula*, *Anomalina nakkadyi*, *Gyroidinoides globosus*, and *Stensioeina pommerana*

Remarks Olfer'ev and Alekseev (2003), Olferiev and Alekseev 2005), Naidin and Beniamovskiy (2006), Benyamovskiy (2007), Olferev et al. (2007), and Vishnevskaya et al. (2018) are in agreement to consider the *Brotzenella taylorensis* taxon as marking the upper Campanian. *Brotzenella taylorensis* was widespread in the Maastrichtian sediments of the East European province (Benyamovskiy 2008a). *Neoflabellina buticula* is known from the upper Campanian of Western and Eastern European provinces (Koch 1977). The disappearance of *Gavelinella clementiana* is considered a criterion for defining the Campanian/Maastrichtian boundary (Odin and Lamaurelle 2001; Beniamovski et al. 2012). *Gyroidinoides globosus* is characteristic and significant species of stratigraphic importance for upper Campanian (Bragina et al. 2016) and the *Brotzenella taylorensis* zone may be correlated with the planktonic *Globotruncana aegyptiaca* zone.

Foraminiferal morphogroups

Benthic foraminifera are sensitive to environmental changes which can be reflected in the composition of the assemblages. The distribution, abundance, and even evolution of the benthic foraminifera are controlled by several parameters such as depth, the flux of organic nutrients to the seafloor, oxygen levels of the bottom, salinity, food quality and quantity, substrate, temperature, and others (Koutsoukos and Hart 1990; Nagy 1992; Frenzel 2000; Nagy et al. 2000; Setoyama et al. 2011; Setoyama et al. 2017; Stojanova and Petrov 2018).

Because most of our samples are closely spaced, we focus on general trends rather than changes within each interpreted foraminiferal biozone. The Atchan Member or A-Beds of the upper beds of the Duwi Formation at Gebel Duwi section yielded 4 agglutinated genera and more than 30 calcareous benthic genera.

Calcareous foraminifera morphogroups

A morphogroup scheme for calcareous benthic foraminifera used in this study is after Stojanova and Petrov (2018). The greatest variety of test morphologies is observed in the Duwi section, where 6 morphogroups were described.

1. Rounded trochospiral morphogroup (RT)

   It includes trochospiral species and broadly rounded periphery: *Valvulineria*, *Berthelina*, *Anomalina*, and *Planulina*. This morphogroup comprises epifaunal active herbivores, detrivores, omnivores, and bactrivores. *Planulina* and *Valvulineria* inhabited inner shelf to upper slope environments, i.e., deep to middle shelf environments (Olsson 1988). *Valvulineria* and abundant *Gavelinella* are considered as the strongest opportunistic fauna (Tyszka 2009).
2. Plano-convex trochospiral morphogroup (PT)

   It has trochospiral tests, having a flat umbilical side and narrowly rounded to sharp periphery: *Cibicidoides*, *Cibicides*, *Discorbis*, *Gavelinella*, *Protostensioeina*, *Stensioeina*, *Brotzenella*, and *Nuttallinella*. This morphogroup is typical aerobic and eutrophic to mesotrophic environments, and most of these taxa are epifaunal forms. These taxa have been identified in the middle-outer shelf to upper slope deposits (Coccioni and Galeotti 1993; Widmark 1997; Grunert 2011). *Berthelina* and *Gavelinella* are common examples of this group.
3. Lenticular morphogroup (L)

   Species from this group display biconvex morphology with sharply angled or keeled periphery: *Lenticulina* and *Saracenaria*. This morphogroup is dominated by active deposit feeders, representing eutrophic to mesotrophic conditions and epifaunal to deep infaunal microhabitats. These taxa can be found in different environmental conditions, from sublittoral to upper bathyal and aerobic to dysaerobic conditions (Widmark 1997; Rückheim et al. 2006).
4. Tapered and cylindrical morphogroup (T/C)

   Rectilinear and straight uniserial, biserial, and triserial tests are included in this morphogroup. Species from this group display a round, oval, or triangular cross section, and parallel or subparallel sides such as *Nodosaria*, *Dentalina*, *Sitella* (*Buliminella*), *Chilostomella*, *Ellipsoglandulina*, *Loxostomum*, *Marginulia*, *Ellipsonodosaria*, *Reussella*, *Pseudovigerina*, *Vaginulina*, *Eouvigerina*, *Orthokarstenia*, and *Praebulimina*. Life position shows that they are shallow to deep infaunal, deposit feeders, and live in the neritic to upper bathyal, aerobic to dysaerobic and mesotrophic to eutrophic environment conditions (Rückheim et al. 2006; Grunert 2011). This morphogroup seems to be indicative of a well-oxygenated environment and seems to have preferred meso-eutrophic living conditions. Elongated multiserial forms are commonly found in areas with increased organic flux (Nagy et al. 1995, 1997).
5. Flattened tapered morphogroup (FT)

   The taxa of this morphogroup are characterized by an ovate to compressed cross section, and parallel to subparallel sides, and include uniserial, biserial, and palmate tests; they are represented by *Frondicularia* and *Neoflabellina*. This morphogroup is characterized by shallow infaunal detrivores and scavengers' taxa (Stojanova and Petrov 2018).
6. Agglutinated morphogroup

   The agglutinated foraminiferal taxa are rare throughout

the section such as some sporadic *Gaudryina*, *Dorothia*, *Clavulina*, and *Spiroplectammina*. The agglutinated morphogroup includes the elongated or sub-cylindrical test shape; these taxa are shallow to deep infaunal and active deposit feeders with mesotrophic to eutrophic conditions, which are present in a wide range of marine environments from inner shelf to upper bathyal (Rückheim et al. 2006). This assemblage appears to be moderately low levels of oxygen. The presence of large-sized agglutinants and low species diversity indicates constant temperature and stagnant water conditions (Haynes 1981).

Result and discussion

1. Distribution of the morphogroups and genera: Most of the benthic foraminiferal fauna that is present in Duwi Basin exists today in the shelf to upper bathyal environments. The dominating morphogroups in the most representative Duwi section (T/C, PT, RT, RP, and FT) are recorded predominantly in modern marine basins (Murray 1991; Khare et al. 1995; Alperin et al. 2011) and ancient seas (Frenzel 2000; Szydło 2005; Reolid et al. 2008; Setoyama et al. 2011, 2017) .

Assemblages in a mesotrophic, well-oxygenated environment would be characterized by a mixture of forms occupying different habitats and different feeding strategies since both organic matter and oxygen levels are high enough to support all the epifaunal, shallow, and deep infaunal forms. Various studies show that these patterns in the model can be observed in recent benthic foraminiferal assemblages (Jorissen et al. 1995; Kaminski et al. 1995; Gooday and Rathburn 1999; Heinz et al. 2001; Fontanier et al. 2005).

The population of the Duwi benthic fauna is dominated by epifaunal morphotypes of rounded trochspiral, plano-convex trochspiral, biconvex trochospiral/planispiral, flattened tapered, lenticular and tapered and cylindrical, besides agglutinated forms. The relative abundance of morphogroups in assemblages reflect environmental changes through time (Corliss 1985; Jones and Charnock 1985).

2. Uppermost Turonian-lower Santonian: Uppermost Turonian and lower Coniacian characterized by low-diversity assemblages. Several authors have studied the behavior of Recent benthic foraminiferal faunas under extreme conditions (food, oxygen), and the results show that under oxygen stress, low-diversity assemblages tend to occur, characterized by strong dominance of few species (Van der Zwaan and Jorissen 1991; Barmawidjaja et al. 1991; Sjoerdsma and Van der Zawan 1992; Sen Gupta and Machain-Castillo 1993).

The presence of *Gavelinella*, *Cibicidoides*, *Gaudryina*, *Anomalina*, *Valvulineria*, *Chilostomella*, and *Lenticulina* in the Santonian sediments. These morphogroups (PT, RT, T/C, and L) are found in aerobic and eutrophic to mesotrophic environments. Most of these taxa are epifaunal forms and active deposit feeders, and have been identified in the middle-outer shelf to upper slope deposits (Coccioni and Galeotti 1993; Widmark 1997; Grunert 2011). *Valvulineria* inhabited deep to middle shelf environments (Olsson 1988), where elongated *Chilostomella* is found in areas with increased organic flux (Nagy et al. 1995, 1997).

Benthic foraminiferal assemblages of the lower Santonian are characterized by abundant agglutinated foraminifera (*Gaudryina austinana*, *G. rugosa* var. *spinulosa*). These results refer to an increase in paleodepth from an inner shelf to an outer shelf during this interval (Nagy et al. 1995, 1997).

The abundant phosphatic grains in the upper part of the Santonian marl layers support high productivity and/or some tolerance to subsurface oxygen depletion (Polivoda et al. 2011).

In upper Coniacian, Santonian, and lower Campanian, *Lenticulina* lives within a wide range of depths in the substrate because the genus tolerates a wide range of microhabitats from epifaunal to deep infaunal (Murray 1991; Tyszka 1994).

3. Lower Campanian: The benthic foraminiferal assemblages *Orthokarstenia*, *Stensioeina*, and *Lenticulina* are rich and well-preserved in the lower Campanian indicating further deepening of the Duwi Basin. The dominant C/T morphogroup seems to be indicative of a well-oxygenated environment and has preferred meso-eutrophic trophic conditions. Elongated multiserial forms are commonly found in areas with increased organic flux (Nagy et al. 1995, 1997).

4. Middle Campanian: The flooded of *Orthokarstenia clarki* in the overall number of middle Campanian species indicate mesotrophic to more oligotrophic environmental conditions (Nagy et al. 1995, 1997). This indicates an open marine, probably outer shelf to slightly upper bathyal environment up to the late Campanian of the benthic *Brotzenella taylorensis* zone.

In the middle-upper Campanian of the Duwi section (*Brotzenella monterelensis*/*Gavelinella costulata* zone), the benthic foraminferal assemblages are of low diversity with *Spiroplectammina henryi*, *S. laevis*, and *Dorothia bulletta*. This assemblage is typical of restricted environments with dysoxic conditions. Shallow infaunal foraminifera (*Dentalina*, *Nodosaria*) live in depths of less than 5 cm (Olóriz et al. 2006). The test form is generally elongated. Very low numbers of infaunal foraminifers thriving best in environments associated with relatively high organic matter flux (Bernhard 1986) supports this interpretation.

5. Upper Campanian: The well-preserved foraminiferal assemblage and increased numbers of *Sitella*, *Vaginulina*, *Cibicides*, *Gyroidinoides*, and *Brotzenella* indicate good stratification of the water column and a tropical to sub-tropical climate during the studied upper Campanian (Leckie 1989; Huber et al. 1995). These point out to stable environmental

conditions, a stable thermocline and other parameters indicating the presence of an open marine outer shelf to slightly upper bathyal environments at least at the upper boundaries of the Duwi Formation at Gebel Duwi Basin.

The presence of *Dorothia* and *Spiroplectammina* in upper Campanian indicates marine environments from the inner shelf to upper bathyal; these faunas appear to be typical of moderately low levels of oxygen (Rückheim et al. 2006). The absence or a decrease in number of *Spiroplectammina*, nodosariids, *Pseudovigerina*, and *Reussella* in late Campanian is interpreted to indicate some cooling events associated with deep upwelling water circulation (Bejaoui et al. 2019).

Furthermore, in late Campanian, the genus *Gyroidinoides* commonly occurred in sediments of the oligotrophic well-oxygenated environment (Dubicka and Peryt 2011) as of late Campanian marker of the Duwi section (*Brotzenella taylorensis* zone), not as dysoxic bottom water conditions (Friedrich et al. 2003; Friedrich 2009).

6. The *Bolivinoides* and *Orthokarstenia* genera: Genus *Bolivinoides* are completely absent from uppermost Turonian, Coniacian to upper Campanian in the Duwi section, which coincides with Eastern and Western European provinces. The *Bolivinoides* lineages are rich and diverse in deeper zones with enough supply of nutrients and oxygen to sustain mesotrophic conditions in deeper environments (Alve and Goldstein 2003, 2010; Bejaoui et al. 2019). *Orthokarstenia clarki* is found in marly facies of the Quseir region with both *Gavelinella* and *Stensioeina*. The flooding occurrence of *Orthokarstenia clarki* through the Campanian interval of the Duwi Basin indicates middle to outer shelf to slightly deeper than 100 m. A similar case was interpreted by Kaminski and Gradstein (2005) showing *Orthokarstenia* acme zones in the modern North Atlantic water. The absence of *Bolivinoides*, *Bolivina*, and even *Bolivinopsis* genera were documented by several authors in the Maastrichtian sediments of southern Egyptian province (Hewaidy and Cherif 1984; Hewaidy 1996). Meanwhile, the Egyptian deeper northern paleogeographic province is characterized by flooding of both *Bolivinoides* and *Orthokarstenia* (El-Deeb and El-Gammal 1994, 1997).

7. *Gavelinella*, *Stensioeina*, and *Brotzenella* genera: The *Gavelinella*, *Stensioeina*, and *Brotzenella* genera of the Late Cretaceous co-occurred within the Duwi epicontinental basin. The *Gavelinella* and *Stensioeina* of the Coniacian Stage of the Duwi section together constitute up to 60% of the total benthic foraminiferal content and slightly decrease into the Santonian Stage most probably due to the Oceanic Anoxic Event (OEA3) (Fig. 6). This event is inferred and documented in the first appearance of *Dicarinella asymetrica* of early Santonian, which co-occurred with *Neoflabellina suturalis* and *Cibicidoides eriksdalensis* and extinctions to *Marginotruncana* and *Dicarinella* at the latest Santonian and Early Campanian (El Gammal and Orabi 2019a). The Late Campanian Event (LCE) (Jarvis et al. 2002; Thibault et al. 2012; Voigt et al. 2012) in many Tethyan cases may correlate with the planktonic *Globotruncana aegyptiaca* zone, which co-occurred with *Brotzenella monterelensis* and *Brotzenella taylorensis* (Fig. 6).

Concluding remarks

1. Identifications of the benthic foraminiferal assemblages (*Gavelinella*, *Stensioeina*, and *Brotzenella*) from the upper Turonian-upper Campanian successions of Gebel Duwi Range, Quseir Region, allowed the recognition of seven biozones and two subzones. The benthic foraminiferal contents are of diversified epibenthic and endobenthic taxa suggesting epicontinental inner to outer shelf depositional paleoenvironments and mesotrophic habitat.

2. Uppermost Turonian and lower Coniacian characterized by low-diversity assemblages. The behavior of recent benthic foraminifera under extreme conditions (food, oxygen) with low-diversity assemblages tend to occur, characterized by strong dominance of a few species.

3. The presence of *Gavelinella*, *Cibicidoides*, *Gaudryina*, *Anomalina*, *Cibicides*, *Valvulineria*, *Chilostomella*, and *Lenticulina* in the Santonian sediments, which belong to morphogroup plano-convex trochospiral, rounded trochospiral, tapered and cylindrical and lenticular (PT, RT, T/C, and L), is typical if aerobic and eutrophic to mesotrophic environments. Most of these taxa have been identified in the middle-outer shelf to upper slope deposits.

4. The benthic foraminiferal assemblages *Orthokarstenia*, *Stensioeina*, and *Lenticulina* are rich and well-preserved in the Early Campanian indicating further deepening of the Duwi Basin.

5. The flood of *Orthokarstenia clarki* in the overall number of middle Campanian species indicates mesotrophic to more oligotrophic environmental conditions and an open marine, probably outer shelf to slightly upper bathyal environment up to the late Campanian of benthic *Brotzenella taylorensis* zone.

6. The well-preserved foraminiferal assemblage and increased numbers of *Sitella colonensis*, *Vaginulina*, *Cibicides*, *Gyroidinoides*, and *Brotzenella*, which indicate good stratification of the water column and a tropical to subtropical climate during the studied upper Campanian.

7. The related morphotypes characterized by an abundance of the epifaunal forms and presence of some infaunal morphotypes of the well-oxygenated environment indicate a mesotrophic habitat. The Duwi benthic fauna are characterized by a mixture of forms occupying different habitats and employing different feeding strategies since both organic matter and oxygen levels are high enough to support epifaunal to deep infaunal microhabitats.

8. The Duwi Basin through the uppermost Turonian to upper Campanian increased in depth, the benthic components indicating a time of the Egyptian stable continental shelf. The gradual increase in depth had occurred with no dramatic structure or tectonic changes at least in southern Egypt.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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