



Upper Cretaceous–lower Paleocene subsurface sequence, Farafra Oasis, Western Desert, Egypt: stratigraphical and paleoenvironmental inferences

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Abstract

This work presents details litho-, bio-, and sequence stratigraphy and paleoenvironmental studies on the Upper Cretaceous–lower Paleocene subsurface rocks of Sahl Baraka at Farafra Oasis, Western Desert, Egypt. Lithostratigraphically, two rock units were recognized: the Wadi Hennis (at the base) and the Khoman (at the top) formations. Ten planktonic foraminiferal zones were identified from the Khoman Formation covering the Campanian–Danian chronostratigraphic interval. Using the R-mode hierarchical cluster analyses, four benthonic foraminiferal biofacies (A, B, C, and D) were recognized. The data indicates that the sediments of the Khoman Formation were deposited in marine environments ranging from deep marine (outer neritic–upper bathyal setting) for the lower and middle parts to shallow marine one (middle–outer neritic setting) for the upper part. The Sahl Baraka area was located in a sedimentary basin subjected to three tectonic events during the Late Cretaceous–early Paleocene time which were related to the Syrian Arc Orogeny. These tectonic events interrupted the eustatic sea-level curve. The integrated data led to define three depositional sequences (sequence-1 to sequence-3) separated by three sequence boundaries (SB1–SB3) throughout the Late Cretaceous–early Paleocene time.

Keywords Upper Cretaceous -lower Paleogene · Subsurface rocks · Planktonic and benthonic foraminifera · Paleoenvironment · Sequence stratigraphy · Farafra Oasis, Egypt

Introduction

Farafra Oasis is considered one of the most famous oases located in the central part of the Western Desert, Egypt (Fig. 1). During the Late Cretaceous–early Paleogene time, the Farafra Oasis was marked by a variety of shallow and deep marine sediments with distinct lateral facies and thickness

variations (Hermina 1990; Issawi et al. 2009). This is due to the interplay between the changes of sea-level changes and tectonic activity.

The surface geology of the Farafra Oasis has attracted of several authors (e.g., Beadnell 1901; Le Roy 1953; Said and Kerdany 1961; Said 1962, 1990; Youssef and Abdel Aziz 1971; Barthel and Hermann-Degen 1981; Khalifa and

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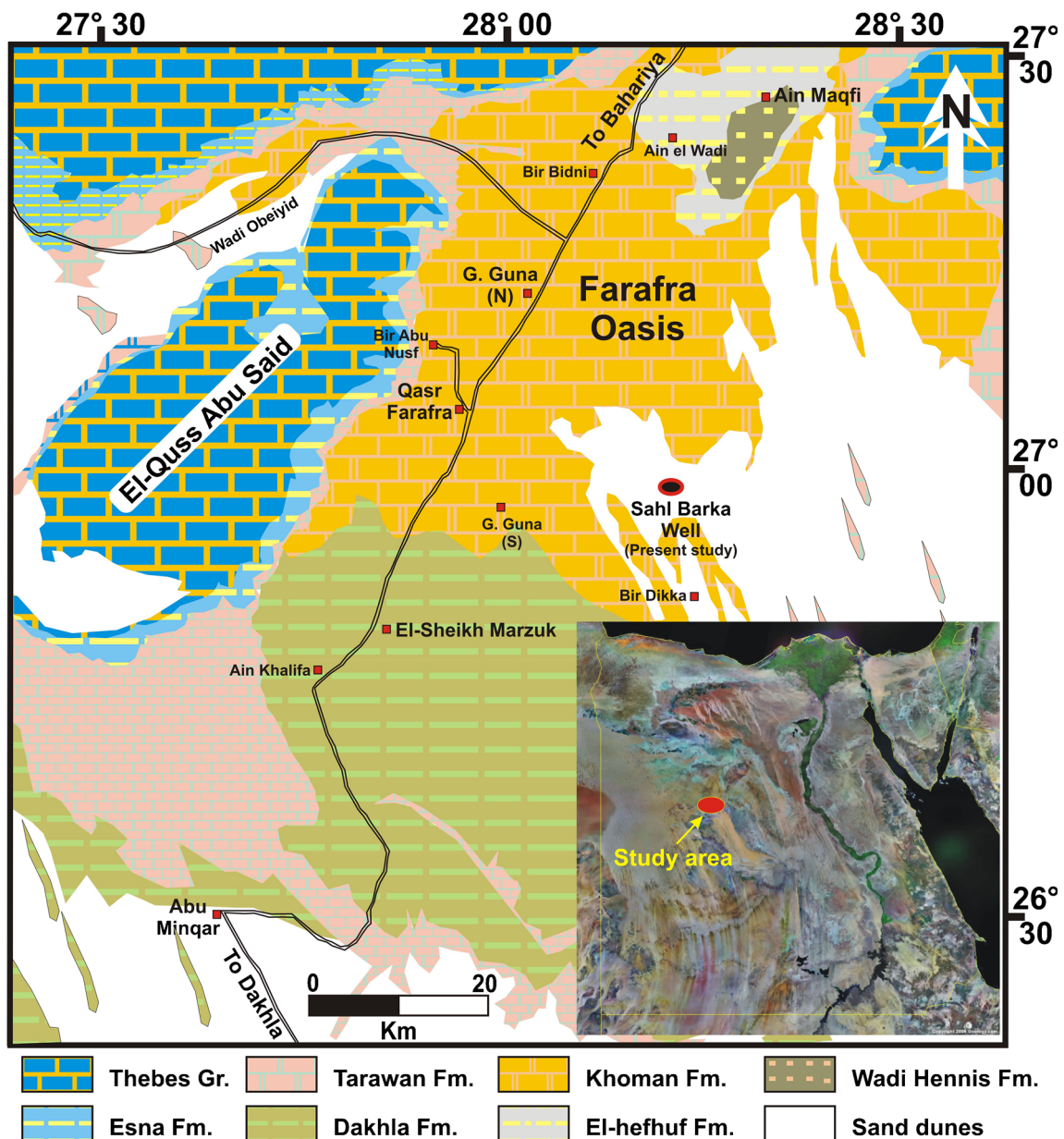


Fig. 1 Geological map of the study area (modified after Conoco 1987)

Zaghloul 1985; Strougo 1986; Hermina 1990; Abdel-Kireem and Samir 1995; El-Azabi and El-Araby 2000; Obaidalla and Kassab 2000; Keheila and Kassab 2001; El Younsy and Khalil 2005; Obaidalla et al. 2006; Hewaidy et al. 2006; Al-Kahtany 2017; Orabi et al. 2018; Faris et al. 2018; Shreif et al. 2019; El Baz 2020; Zaky et al. 2020). The Upper Cretaceous–lower Paleogene sediments at the Farafra Oasis and the surrounding areas were marked by vertical and lateral facies variations (Hermina 1990). For example, the Upper Cretaceous Khoman Formation (chalky limestone) was laterally changed toward the south into the Dakhla Formation (shale). These facies variations may be related to the syn-sedimentary tectonism as the results of the Syrian Arc Orogeny (Obaidalla et al. 2006; Faris et al. 2018). Several authors linked the

unconformity surfaces recorded in the Western Desert by the effect of the Syrian Arc Orogeny (e.g., Tantawy et al. 2001; Obaidalla et al. 2006; El-Dawy et al. 2016, 2018; Metwally and Mahfouz 2018; Faris et al. 2018; Mahfouz and Metwally 2020).

Although the Upper Cretaceous–Paleogene succession has excellent outcrops for understanding the geologic history of the Farafra Oasis, there are many questions about the nature of the subsurface rocks. The questions about the subsurface strata without satisfactory answers are the relationship between the subsurface and surface sediments and the sedimentary basin evolution. The literature survey indicates that there are no studies on the Farafra subsurface successions. The main purpose of this work is to study the geologic evolution of the

subsurface Upper Cretaceous–lower Paleocene succession at the Farafra Oasis based on high-resolution investigations of the planktonic and benthonic foraminifera to determine the age dating and the paleoenvironmental setting. This work aims also to establish the setting of depositional sequences of the studied succession.

Materials, methods, and depository

Fifty-one ditch samples were investigated (~ 3 m each interval; ~ 153 m depth) from the Sahl Baraka Well at the Farafra Oasis. Sahl Baraka Well was drilled by Al Masria Drilling Company, Egypt. It lies about 30 km southeast of Qasr Farafra (latitude 26° 56' 03" N and longitude 28° 18' 11" E; Fig. 1). The samples were defined based on their lithological characters. About 200 g of dry rock samples was disaggregated in water with few drops of diluted hydrogen peroxide (H₂O₂). Afterwards, the samples were washed through a 63 µm sieve. This procedure was repeated until foraminifera with clean surface texture are shown. The obtained residues were dried at 50–60 °C. Constant split from the dried residue was investigated qualitatively and quantitatively under a binocular stereomicroscope. The foraminiferal species were picked out, identified, and counted. The total foraminiferal numbers of planktonic (PFN) and benthonic (BFN) (individuals > 63 µm) were determined and summed to obtain the total foraminiferal number (TFN). The planktonic percentage (P/B%) was calculated and was expressed as $P/B\% = 100 \times P/(P + B)$. Species richness and diversity indices of the foraminiferal assemblages were expressed as Shannon *H* and Fisher α and calculated for benthonic foraminifera using the PAST computer software (Hammer et al. 2001). The calcareous/agglutinated percentage (C/A%) and epifaunal/infaunal percentages (E/I%) were determined to the redox conditions and the nutrient availability (Jorissen et al. 1995; Van der Zwaan et al. 1999).

Furthermore, R-mode hierarchical cluster analyses were used using the PAST computer software to group the benthonic foraminiferal taxa as assemblages related to paleoecologic inferences (Hammer et al. 2001). The scanning electron microscope (SEM, JSM 5400 LD) was used to photograph the important foraminiferal species illustrated in Figs. 2 and 3. All available data, including lithological characteristics and faunal paleoenvironmental studies, have been integrated to construct a comprehensive sequence stratigraphic framework for the studied interval which was compared with the eustatic sea-level curve (Haq et al. 1987). The materials used for this study were deposited at Assiut University, Faculty of Science, Geology Department, Assiut, Egypt (collection of Dr. Abdelhamid M. Salman).

Lithostratigraphy

The Upper Cretaceous–lower Paleocene succession in the study area was represented by two rock units: the Wadi Hennis Formation (at the base) and the Khoman Formation (at the top), which will be describing from base to top as follows:

The Wadi Hennis Formation

It was termed by Dominik (1985) to describe the clastic sequence at Wadi Hennis, northeast the Farafra Depression. The Wadi Hennis Formation composes mainly of sandstone interbeds with bituminous clays. In the present work, it composes mainly of sandstone sediments (Fig. 4). About 9 m thickness of the uppermost part of the Wadi Hennis Formation was considered. It is overlain by the Khoman Formation by an unconformable relationship. This part of the Wadi Hennis Formation is barren of both benthonic and planktonic foraminiferal taxa, which indicates that the upper part of the Wadi Hennis Formation was deposited in a continental environment may be fluvial.

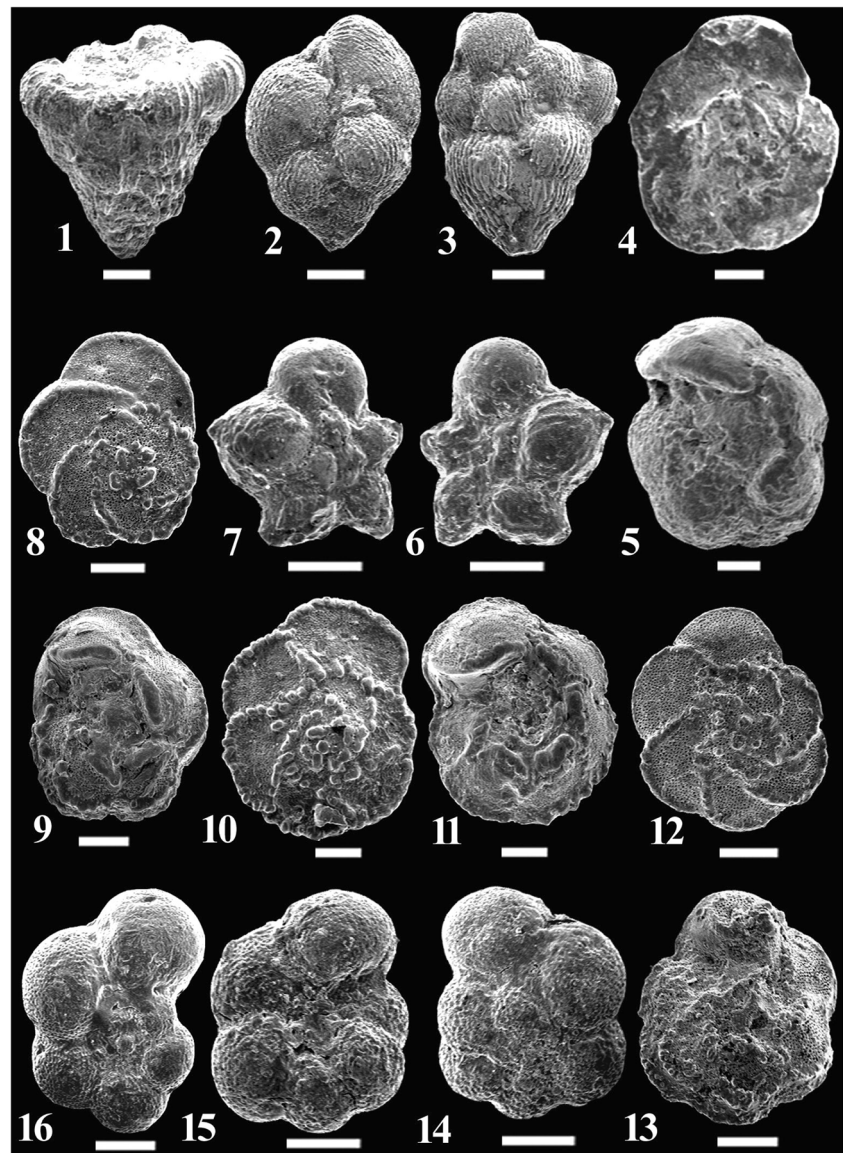
The Khoman Formation

This formation was originally introduced by Kerdany (1968) to define the open marine carbonate facies at the Ain Khoman, south of the Bahariya Oasis, Western Desert, Egypt. In the present study, the Khoman Formation is about 144 m thick and composes of snow-white chalky limestones (Fig. 4). It is interrupted by several intercalations of shale sediments: ~ 6 m thick of shale (from ~ 120–114 m depth), ~ 9 m thick of shale (from ~ 108–99 m depth), ~ 9 m thick of shale (from ~ 36–27 m depth), and ~ 9 m thick of shale (from ~ 18–9 m depth). The intercalations of shale sediments are here believed to be due to the inter-tonguing between the Dakhla Formation (shale) toward the south in the Abu Minqar and Khoman Formation (chalky limestone) toward the north at the Farafra Oasis. This is may be due to the effect of Syrian Arc Orogeny on the configuration of the sedimentary basin during the Late Cretaceous–early Paleogene time, which led to forming clastic sediments in the south and carbonate sediments in the north. The Sahl Baraka section represents the transition area between the siliciclastic sediments (shale) and carbonate sediments (chalky limestone).

Planktonic foraminiferal biostratigraphy

High-resolution planktonic foraminiferal zones were achieved to do accurate determination for the geologic age of the subsurface Upper Cretaceous–lower Paleocene succession at the Sahl Baraka area. The zonal schemes of Caron (1985) and Li and Keller (1998) for

Fig. 2 Scanning electron micrographs of the selected planktonic foraminiferal species from Sahl Baraka Well (scale bar is 100 μm): 1. *Racemiguembelina fructicosa* (Egger), sample no. 13; 2. *Pseudoguembelina palpebra* Brönnimann and Brown, sample no. 30; 3. *Pseudoguembelina hariaensis* Nederbraht, sample no. 22; 4 and 5. *Gansserina gansseri* (Bolli), sample no. 23; 6 and 7. *Plummertia hantkeninoides* (Bronnimann), sample no. 5; 8 and 9. *Globotruncana aegyptiaca* Nakkady, sample no. 29; 10 and 11. *Globotruncanita elevata* (Brotzen), sample no. 46; 12 and 13. *Globotruncana ventricosa* White, sample no. 43; 14 and 15. *Praemurica inconstans* (Subbotina), sample no. 3; 16. *Praemurica uncinata* (Bolli), sample no. 1



the Campanian and Maastrichtian ages and Berggren and Pearson (2005) for the Danian age are here applied with minor modifications. Depending on the lowest occurrence (LO) and highest occurrence (HO) of the identified index planktonic foraminiferal species, ten planktonic foraminiferal zones were identified covering the Late Cretaceous (Campanian)–early Paleocene (Danian) age (Fig. 4). These zones are summarized as follows:

Globotruncanita elevata Zone

The *Globotruncanita elevata* Zone was here defined as a Lowest Occurrence Zone (LOZ) to define the stratigraphic interval from the LO of the nominate taxon to the LO of the *Globotruncana ventricosa* White. This zone covers the lowermost part of Khoman Formation from the unconformable contact between the Wadi Hennis Formation at the base and

the Khoman Formation at the top from depth 144 m to depth 135 m (Fig. 4).

Age: early Campanian

- *Globotruncana ventricosa* Zone

This zone was here defined as a LOZ to cover the stratigraphic interval from the LO of the nominate taxon to the LO of the *Globotruncanita calcarata* (Cushman). It covers the lower part of the Khoman Formation from 135 m depth to 120 m depth (Fig. 4). It rests conformably on the *G. elevata* Zone.

Age: middle Campanian age

- *Globotruncana aegyptiaca* Zone

The *Globotruncana aegyptiaca* Zone was here defined as a LOZ to cover the stratigraphic interval from

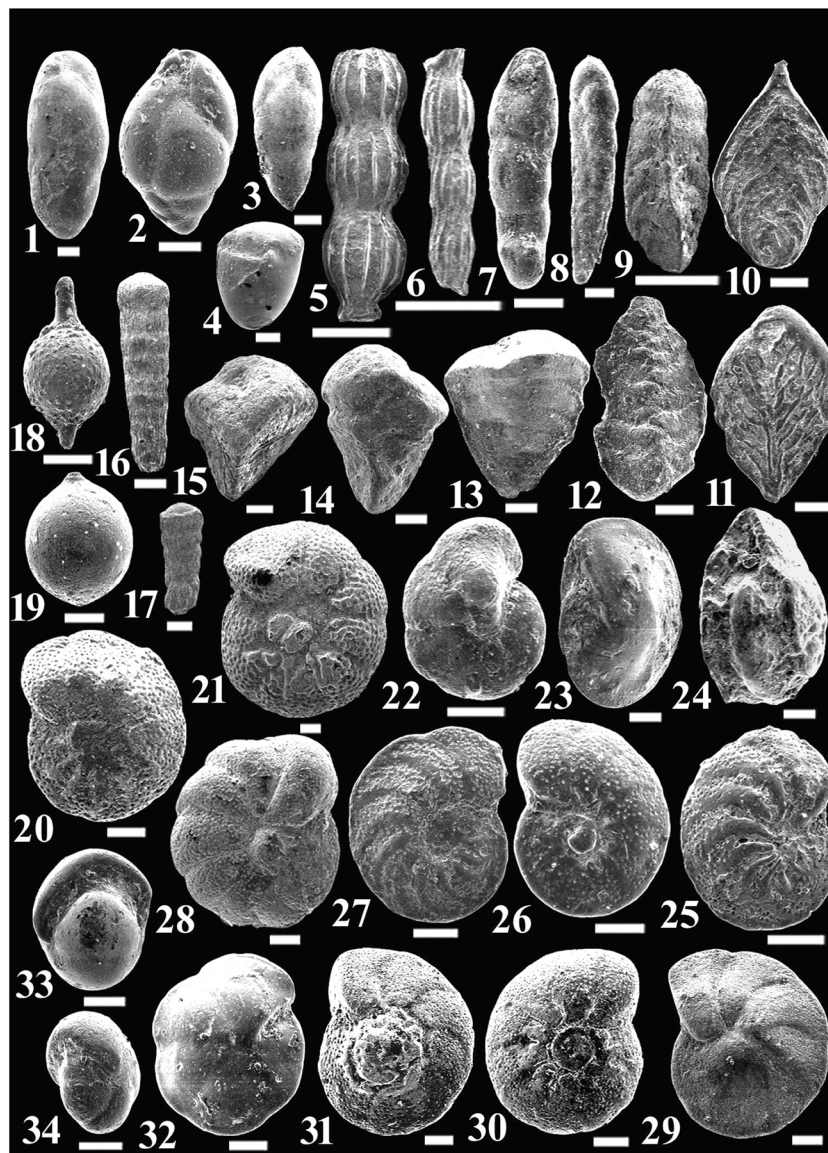


Fig. 3 Scanning electron micrographs of the selected benthonic foraminiferal species from Sahl Baraka Well (scale bar is 100 μm): 1. *Bulimina quadrata* Plummer, sample no. 19; 2. *Praebulimina reussi* (Morrow), sample no. 29; 3. *Praebulimina asper* (Cushman and Parker), sample no. 29; 4. *Allomorphina cretacea* Reuss, sample no. 31; 5. *Pyramidulina paupercula* (Reuss), sample no. 7; 6. *Dentalina delicatula* Cushman, sample no. 5; 7. *Pleurostomella subnodosa* Reuss, sample no. 13; 8. *Loxostomoides applinae* (Plummer), sample no. 29; 9. *Clavulinoides trilaterus* (Cushman), sample no. 13; 10. *Neoflabellina jarvisi* (Cushman), sample no. 46; 11. *Bolivinooides draco draco* (Marsson), sample no. 25; 12. *Spiroplectinella henryi* (Le Roy), sample no. 25; 13. *Spiroplectinella knebeli* (Le Roy), sample no. 25; 14. *Gaudryina aissana* Ten Dam and Sigal, sample no. 31; 15. *Gaudryina pyramidata* Cushman, sample no. 40; 16. *Orthokarstenia oveyi*

(Nakkady), sample no. 12; 17. *Orthokarstenia parva* (Cushman), sample no. 12; 18. *Lagena hispida* Reuss, sample no. 15; 19. *Lagena globosa* (Montagu), sample no. 15; 20. *Angulogavelinella abudurbensis* (Nakkady), sample no. 46; 21. *Angulogavelinella avnimelechi* Reiss, sample no. 46; 22. *Valvalabamina depressa* (Alth), sample no. 19; 23. *Lenticulina Midwayensis* (Plummer), sample no. 5; 24. *Lenticulina cultrata* (Montfort), sample no. 24; 25. *Anomalinooides susanaensis* (Browning), sample no. 3; 26. *Anomalinooides midwayensis* (Plummer), sample no. 23; 27. *Anomalinooides zitteli* (Le Roy), sample no. 3; 28. *Cibicidooides howelli* Toulmin, sample no. 3; 29. *Cibicidooides alleni* (Plummer), sample no. 42; 30. *Cibicidooides pseudoacutus* (Nakkady), sample no. 18; 31. *Cibicidooides pseudoperlucidus* (Bykova), sample no. 18; 32. *Eponides lotus* (Schwager), sample no. 44; 33. *Pullenia coryelli* White, sample no. 37; 34. *Pullenia cretacea* Cushman, sample no. 20

the LO of the nominate taxon to the LO of *Gansserina gansseri* (Bolli), from 120 m depth to 99 m depth (Fig. 4). The *Globotruncana aegyptiaca* Zone rests

unconformably on the *G. ventricosa* Zone due to the missing of the late Campanian *Globotruncanella calcarata* and *Globotruncanella havanensis* zones.

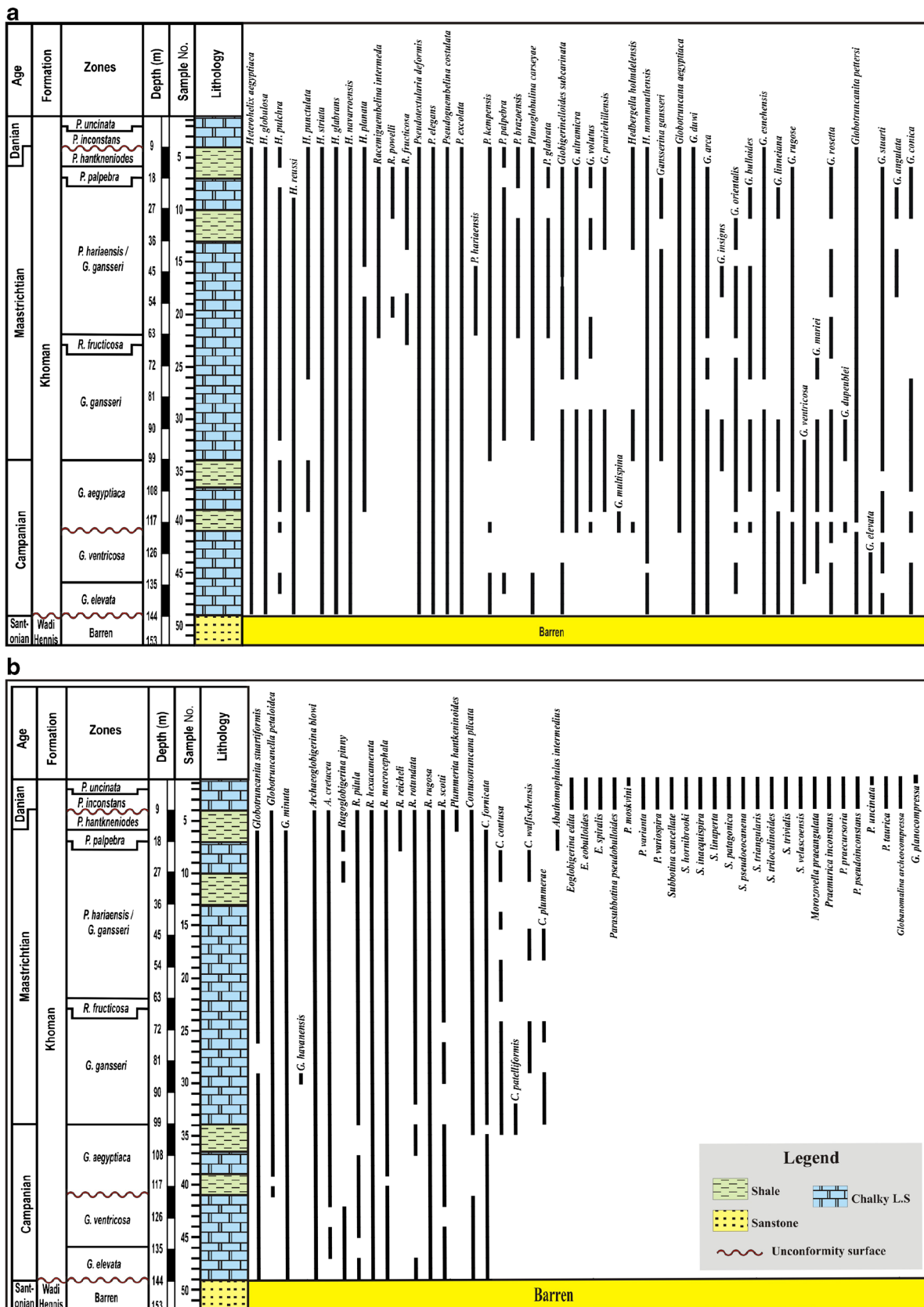


Fig. 4 Distribution chart of the identified planktonic foraminiferal species at Sahl Baraka Well

Age: late Campanian

- *Gansserina gansseri* Zone

It was here defined as a LOZ to cover the stratigraphic interval from the LO of the nominate taxon to the LO of *Racemiguembelina fruticosa* (Egger), from 99 m depth to 66 m depth (Fig. 4). The *G. gansseri* Zone lies conformably over the *G. aegyptiaca* Zone.

Age: early Maastrichtian

- *Racemiguembelina fruticosa* Zone

The *Racemiguembelina fruticosa* Zone was here defined as a LOZ to cover the stratigraphic interval from the LO of the nominate taxon to the LO of the *Pseudoguembelina hariaensis* Nederbragt, from 66 m depth to 63 m depth (Fig. 4). It is conformably rests on the *G. gansseri* Zone.

Age: early Maastrichtian

- *Pseudoguembelina hariaensis*/*Gansserina gansseri* Zone

This zone was here defined as a Concurrent-Range Zone to cover the stratigraphic interval from the LO of the *P. hariaensis* Nederbragt to the HO of the *G. gansseri* (Bolli), from 63 m depth to 18 m depth (Fig. 4). It lies conformably on the *Racemiguembelina fruticosa* Zone.

Age: middle Maastrichtian

- *Pseudoguembelina palpebra* Zone

The *Pseudoguembelina palpebra* Zone was here defined as a Partial-Range Zone to cover the stratigraphic interval from the HO of the *G. gansseri* (Bolli) to the LO of the *Plummerita hantkeninoides* (Brönnimann), from 18 m depth to 15 m depth (Fig. 4). It lies conformably over the *P. hariaensis*/*G. gansseri* Zone.

Age: late Maastrichtian

- *Plummerita hantkeninoides* Zone

This zone was here defined as a Taxon-Range Zone to cover the stratigraphic interval from the LO and HO of the nominate taxon, from 15 m depth to 9 m depth (Fig. 4). It lies conformably over the *P. palpebra* Zone.

Age: latest Maastrichtian

- *Praemurica inconstans* Zone (P1c)

This zone was here defined as a LOZ to cover the stratigraphic interval from the LO of the nominate taxon to the LO of *Praemurica uncinata* (Bolli), from 9 m depth to 6 m depth

(Fig. 4). This zone rests unconformably over the *P. hantkeninoides* Zone due to the missing of earliest Danian *Guembelitra cretacea* (P0), *Parvularugoglobigerina eugubina* (P α), *Parasubbotina pseudobulloides* (P1a), and *Subbotina triloculinoides* (P1b) planktonic zones.

Age: early Danian

- *Praemurica uncinata* Zone (P2)

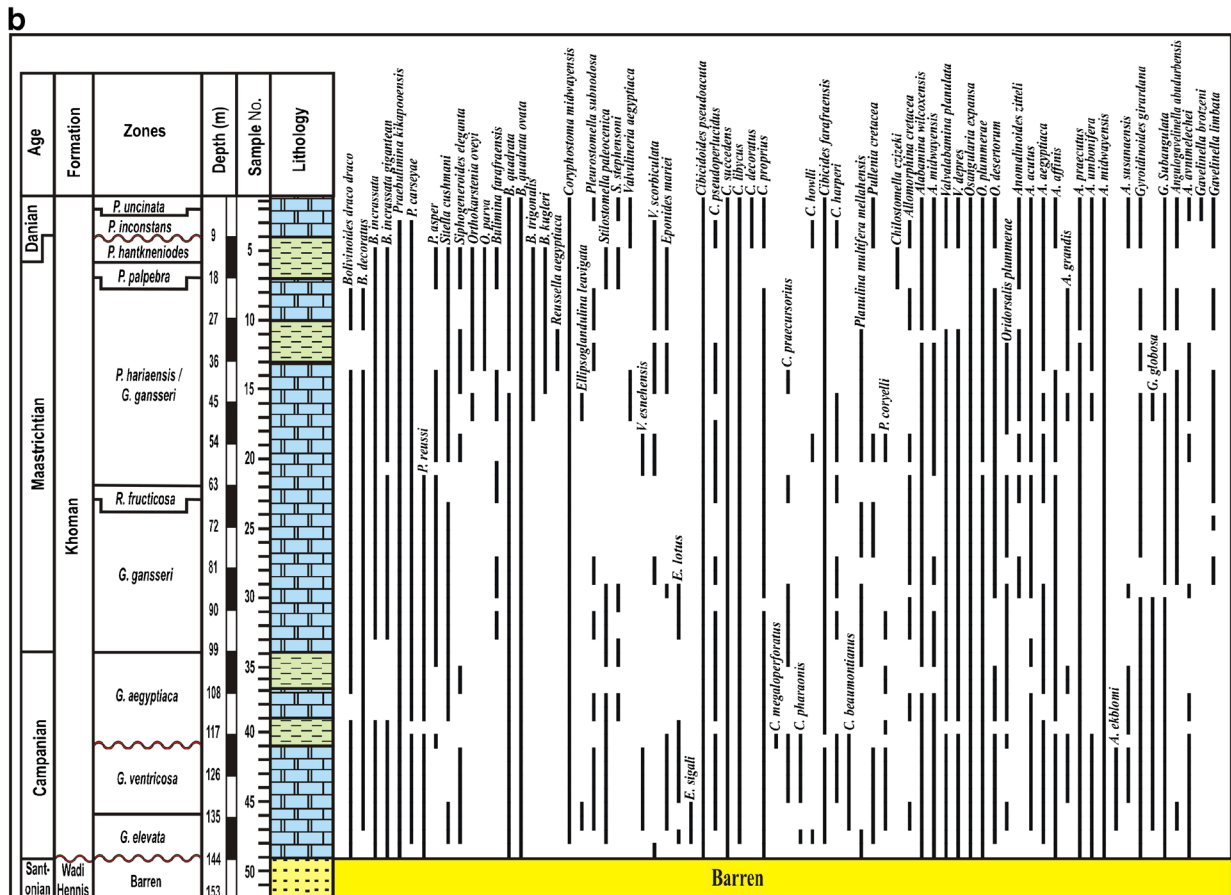
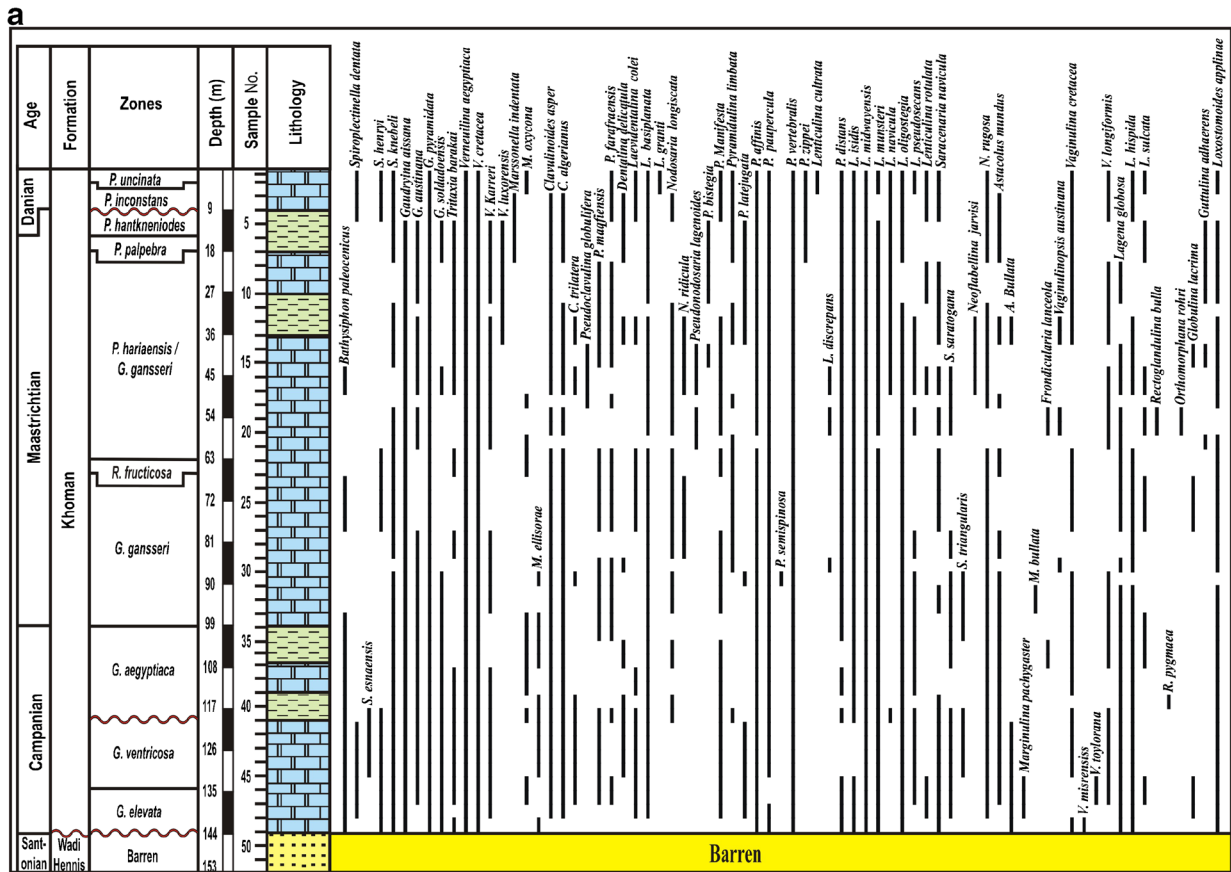
The *Praemurica uncinata* Zone was here defined as a LOZ to cover the stratigraphic interval from the LO of the nominate taxon to the LO of *Morozovella angulata* (White), from 3 m depth to the ground surface (Fig. 4). It lies conformably on the *P. inconstans* Zone.

Age: early Danian

Benthonic foraminiferal biofacies

Several authors have related the depositional depths to the faunal assemblages and individual species (e.g., Le Roy 1953; Berggren 1974a, 1974b; Berggren and Aubert 1975; Hewaidy 1984; Luger 1985; Speijer 2003; Schnack 2000; El-Dawy 2001; Sprong et al. 2012; Shreif et al. 2019). In the present study, the distribution range chart of the benthonic foraminiferal species is illustrated in Fig. 5. The R-mode cluster analyses (Fig. 6) led to identify four benthonic foraminiferal biofacies (A, B, C, and D). The dominant taxa in each biofacies were used to interpret the paleoenvironments inhabited by the biofacies assemblage (Fig. 7).

- Biofacies A has high dominance in the lower-middle Maastrichtian sequence of the study well (Fig. 7). It was characterized by high mixed epifaunal and infaunal morphogroups (e.g., *Anomalinoides affinis*, *A. midwayensis*, *A. praeacutus*, *Oridorsalis plummerae*, *Osangularia plummerae*, *Valvalabamena planulata*, *Praebulimina kikapoensis*, *Bolivinoidea draco draco*, *Lagena* spp., *Nodosariids.*, *Praebulimina carseyae*). These taxa show outer neritic–upper bathyal environment and represent mesotrophic and probably associated with low to intermediate productivity conditions. These benthonic foraminiferal assemblages consist of mixed epifaunal and infaunal morphogroups interpreted as moderately eutrophic conditions (Gooday 2003) and indicated low nutrients elements (Jorissen et al. 1995; Van der Zwaan et al. 1999).
- Biofacies (B) has very low dominance and it was characterized by the occurrence of the epifaunal morphogroups (e.g., *Cibicides decorates*, *C. farafraensis*, *Lenticulina* spp., *Pseudonodosaria* spp., *Osangularia desertorum*, *Valvulineria aegyptiaca*, *Pullina cretacea*, *Alabamina wilcoxensis*). This biofacies was interpreted as a middle



◀ Fig. 5 Distribution chart of the identified benthonic foraminiferal species at Sahl Baraka Well

neritic–upper bathyal environment and oligotrophic marine conditions with low productivity (Fig. 7).

- Biofacies (C) represents a higher occurrence within Campanian sediments. It was composed of outer neritic taxa (e.g., *Coryphostoma midwayensis*, *Siphogeneroides eleganta*, *Gaudryina* spp., *Spiroplectinella* spp., *Alabama midwayensis*, *Gyroidinoides girardana*, *G. globosus*, *Angulogivilinella avnimelechi*, *Anomalinoidea susanaensis*, *Laevidentalina* spp., *Cibicidoides libycus*, *Valvulineria esnehensis*). Thus, an outer neritic setting was inferred for this interval with increase of epifaunal morphogroups which indicate oligotrophic levels and well-oxygenated sea floor conditions.
- Biofacies (D) characterizes the upper Maastrichtian sediments (Fig. 7) including middle–outer neritic taxa (e.g., *Cibicidoides pseudoperlucidus*, *Bulimina farafraensis*, *Anomalinoidea zitteli*, *Pyramidulina* spp., *Orthokarstenia oveyi*, *O. parva*, *Bulimina ovate*, *Valvulineria scorbiculata*). These taxa show middle–outer neritic environments and were represented by mixed epifaunal and infaunal

morphogroups, suggesting oligo- to mesotrophic conditions with low to intermediate productivity.

Paleoenvironmental interpretation

According to the integration between the derived data (such as lithologic characters, quantitative and qualitative analysis of both planktonic and benthonic foraminiferal species, and R-mode cluster analyses), the succession of the studied well can be differentiated into four paleoenvironmental intervals (Fig. 7).

Santonian? interval

It represents the basal part of the studied well, namely, the uppermost part of the Wadi Hennis Formation (9 m thick of sandstone, samples 50–51). Its age was here assigned according to the stratigraphic position. This interval was characterized by a complete absence of both benthonic and planktonic foraminiferal faunal content. The sediments of the Wadi Hennis Formation are composed mainly of sandstone with some thin strikes of claystone indicate that its depositional condition was under continental (may be fluvatile) environment.

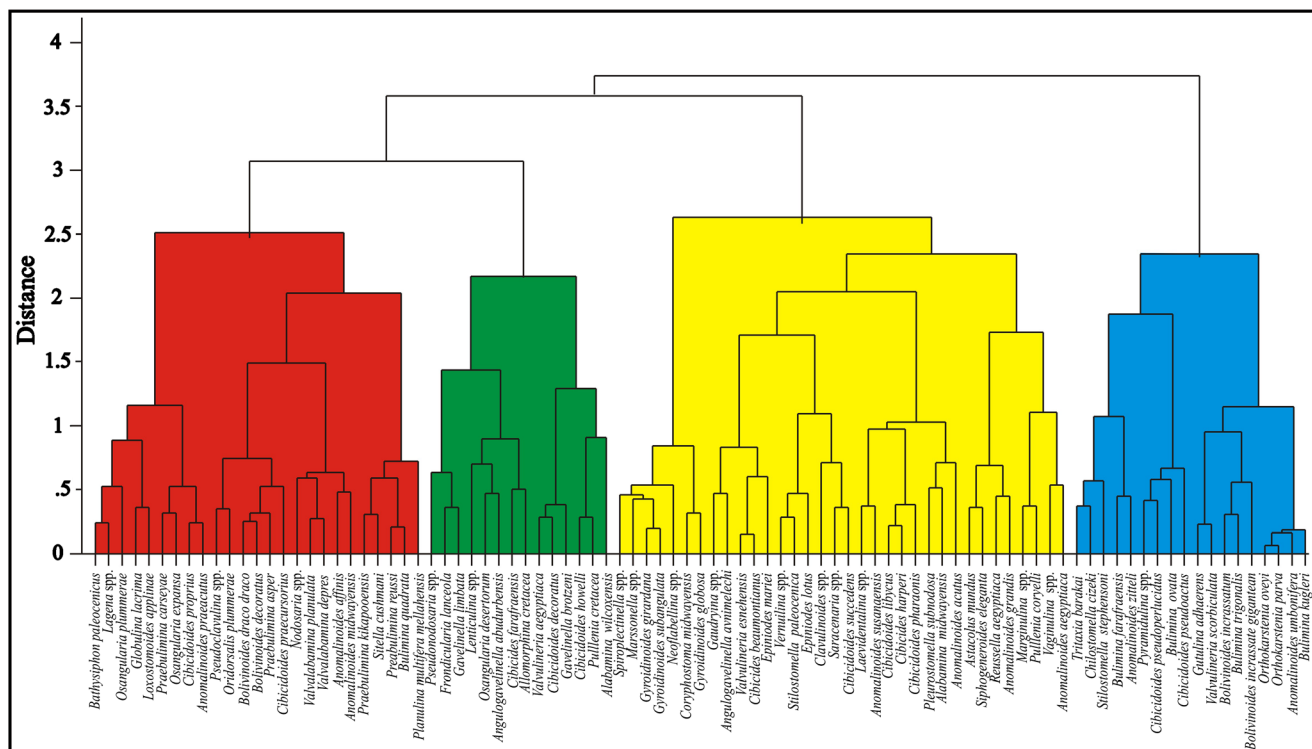


Fig. 6 Dendrogram of the R-mode cluster analysis of the benthonic foraminiferal species recorded in Sahl Baraka Well

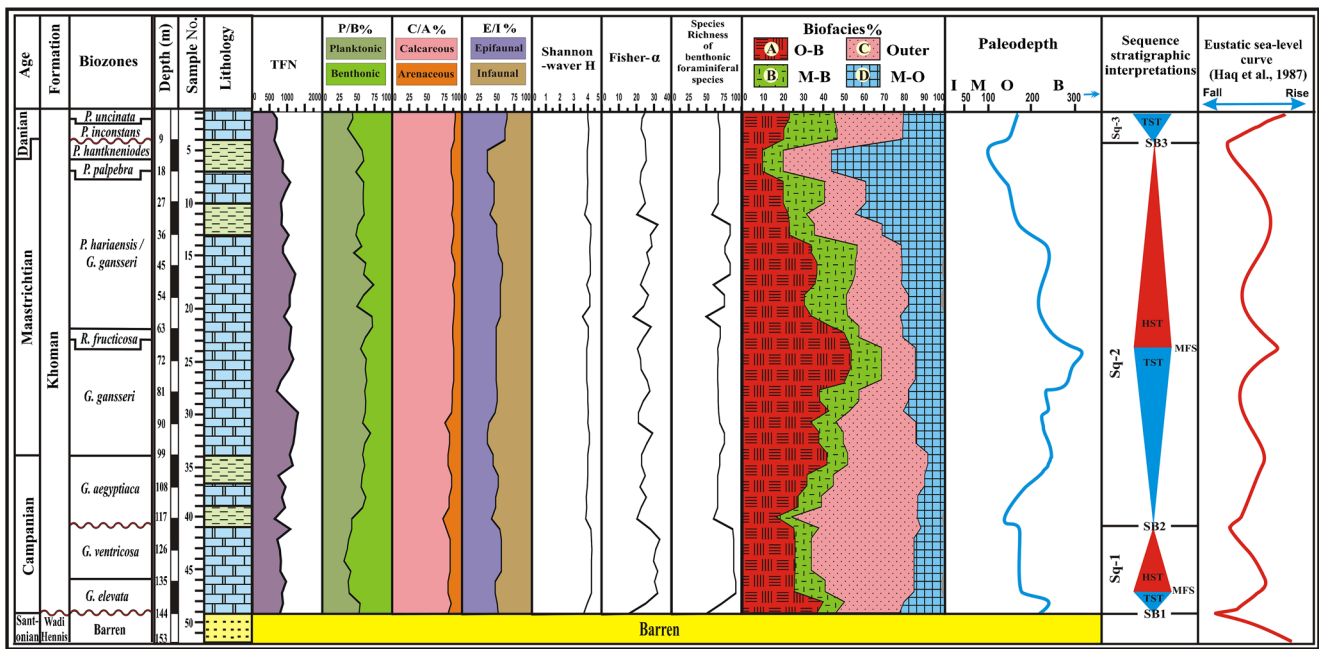


Fig. 7 General faunal indices at Sahl Baraka well, including total foraminiferal number (TFN), planktonic/benthic percentage (P/B%), calcareous/agglutinated percentage (C/A%), percentage morphogroups (E/I%), diversity and heterogeneity indices, relative abundance of the

benthonic foraminiferal depth biofacies, paleodepth and sequence stratigraphy compared with the eustatic global sea-level curve (Haq et al. 1987)

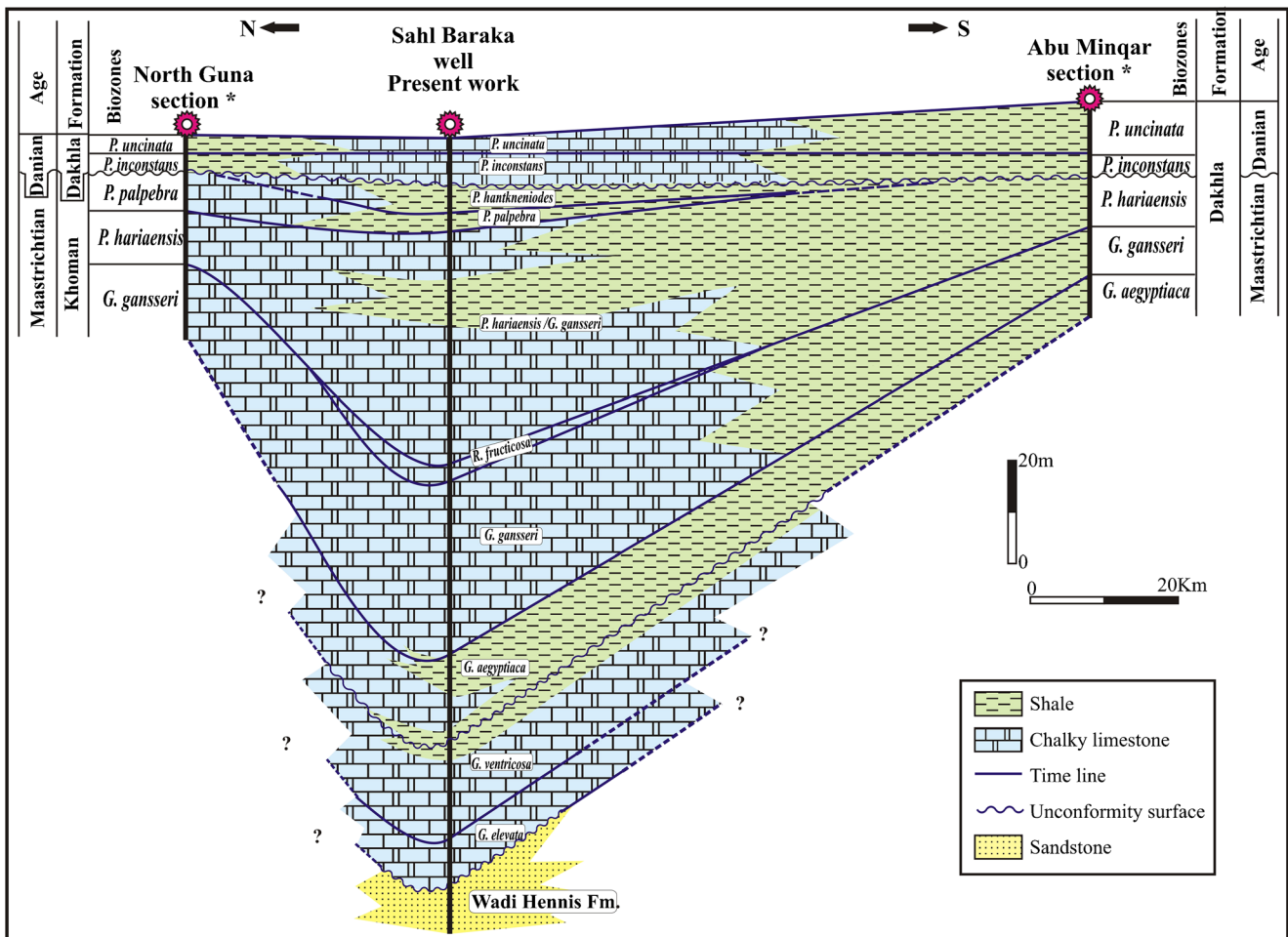


Fig. 8 Paleorelief correlation profile show the lateral and vertical facies changes in the sedimentary basin along S–N direction at Farafra Oasis, Western Desert (*Obaidalla et al. 2006)

Campanian interval

The Campanian interval occupies the lower part of the Khoman Formation composed mainly of chalky limestone with shale intercalations (~ 45 m thick, from 144 m depth to 99 m depth). This interval was covered by the *G. elevata*, *G. ventricosa*, and *G. aegyptiaca* zones. The total foraminiferal number ranges between 650 and 1161 specimens per gram dry sediment, whereas the mean value is ~ 850 specimens/g. The planktonic percentage (P/B%) increases from the base to the top, from ~ 38 to ~ 63% respectively. On the other hand, there is a decrease in the epifaunal morphogroups upwards from ~ 52 to ~ 44% and high abundance of calcareous taxa (~ 80%). The species richness of the benthonic foraminiferal species decreases upward from ~ 83 to ~ 65 species. Fisher α and Shannon H indices display higher values (~ 29 and ~ 4.1 respectively). The benthonic foraminiferal assemblage in the lower part of this interval dominates by mixed outer neritic–upper bathyal and outer neritic taxa (A and C biofacies). While the upper part shows an increase in the assemblage of the outer neritic–upper bathyal taxa (A biofacies). These data indicate an outer neritic environment for the lower part and an outer neritic–upper bathyal environment for the upper part (Fig. 7.)

Maastrichtian interval

This interval was represented by the middle and upper part of the study sequence which was composed of a thick sequence of chalky limestone with shale interbeds (~ 90 m thick, from 99 m depth to 9 m depth). It was covered by the *G. gansseri*, *R. fructicosa*, *P. hariaensis*/*G. gansseri*, *P. palpebera*, and *P. hantkeninoides* zones. The total foraminiferal number is ~ 1074 specimens which slightly decreases upward and reaches ~ 981 specimens in the uppermost part of the Maastrichtian. The benthonic foraminifera in this interval show moderate in epifaunal morphogroups (~ 46%). Calcareous taxa percentage, species richness, Fisher α , and Shannon H indices display high values (~ 87%, ~ 69, ~ 24, and ~ 4, respectively). The lower and middle Maastrichtian interval have their highest peak of A and C biofacies of an outer neritic–upper bathyal environment, while the upper part of the Maastrichtian interval has their highest peak of D biofacies of a middle–outer neritic environment (Fig. 7).

Accordingly, an outer neritic–upper bathyal environment has prevailed during the deposition of the lower and middle strata of the Maastrichtian which is a decrease in depth upward into the middle–outer neritic environment.

Danian interval

This interval comprises the uppermost part of the Khoman Formation, which mainly composes of limestone (~ 9 m

thick, from 9 m depth to the ground surface). It occupies by the *P. inconstans* and *P. uncinata* zones. The total foraminiferal numbers decrease and ~ 680 specimens/g with low P/B (~ 43%) was obtained. The relative abundance of benthonic foraminifera of this interval reflects an increase in the epifaunal morphogroups (~ 63%) with a very high abundance of the calcareous taxa (~ 90%). Also, the species richness, Fisher α , and Shannon H indices display higher values (~ 68, ~ 24, and ~ 4, respectively). Moreover, the majority of the benthonic foraminiferal fauna of this interval was represented by an equal percentage of all biofacies (A, B, C, and D). All preceding data are typically indicative of a middle–outer neritic environment (Fig. 7).

Evolution of the sedimentary basin

The Upper Cretaceous–lower Paleogene sedimentary basins in Egypt were interrupted by several syn-sedimentary tectonic events (Obaidalla et al. 2006, 2013, 2016, 2017a, 2017b, 2018; Mahfouz 2013; El-Ayyat and Obaidalla 2013; El-Ayyat and Obaidalla 2016; El-Dawy et al. 2016, 2018; Metwally and Mahfouz 2018; Faris et al. 2018; Mahfouz and Metwally 2020). In the present study, stratigraphic investigations (litho- and biostratigraphy) led to recognized three breaks throughout the Upper Cretaceous–lower Paleocene sequence which indicates that the study area was undergone to three syn-sedimentary tectonic events (I, II, and III; Fig. 8).

- Tectonic Event I: It took place at the Santonian?/Campanian boundary, which coincides with the Wadi Hennis/Khoman formational boundary. This event was very strong, because it uplifted the area during the Santonian and earliest Campanian as an aerial positive area. It was marked by the formation of fluvial clastic sediments (Sandstone of the Wadi Hennis Formation) and the lowermost part of the marine Khoman Formation was missing. This was supported by the missing of the planktonic foraminiferal assemblage of the upper part of the *Dicarinella asymetrica* Zone.
- Tectonic Event II: It was recorded within the lower part of the Khoman Formation and coincided with the middle/late Campanian boundary at the *G. ventricosa*/*G. aegyptiaca* zonal boundary. It was evidenced by the absence of the Campanian *G. calcarata* and *G. havanensis* zones.
- Tectonic Event III: It was recorded within the upper part of the Khoman Formation and coincided with the Cretaceous/Paleogene (K/Pg) boundary at the *P. hantkeninoides*/*P. inconstans* zonal boundary. It was characterized by the missing of the earliest Danian

planktonic foraminiferal zones (e.g., P0, P α , P1a, and P1b).

These tectonic events are related to the Syrian Arc Orogeny which led to the formation of a major paleohigh (due to uplift) and basin (due to subsidence) forms.

The Upper Cretaceous–lower Paleocene sequence of the study well was correlated here with the same sequence of two previous study stratigraphic sections; one lies toward the north (North Guna section, Obaidalla et al. 2006) and the another lies toward the south (Abu Minqar section, Obaidalla et al. 2006) (Fig. 8). The geometry and distribution of the sediments in the correlation profile led to understand the relative uplifted and subsidence due to the three syn-sedimentary tectonic events in the Upper Cretaceous–lower Paleocene basin. Also, this profile led to understanding the lateral facies changes from carbonate facies of the Khoman Formation toward the north to siliciclastic facies of the Dakhla Formation toward the south.

As an indicator of the paleorelief profile (Fig. 8), the Sahl Baraka area represents the depocenter of the Upper Cretaceous–lower Paleocene basin. Moreover, the correlation profile shows the lateral facies changes between the Khoman Formation toward the north and Dakhla Formation toward the south. The shale intercalations within the Khoman Formation at Sahl Baraka Well insure the inter-tonguing between the chalky limestone of the Khoman Formation and the shale of the Dakhla Formation.

Sequence stratigraphic analysis

In the present work, based on the lithological characteristics, planktonic foraminiferal biostratigraphy, benthonic biofacies, and paleoenvironmental studies, three depositional sequences (sequence-1 –Sequence-3) representing the Upper Cretaceous–lower Paleocene succession at Sahl Baraka Well were recognized (Fig. 7). The following is a detailed description of the detected sequences and their bounding surfaces:

Sequence-1

The first depositional sequence encompasses the lower part (about 27 m thick) of the Khoman Formation at Sahl Baraka Well (Fig. 7). It includes the early–middle Campanian zones (*G. elevate* and *G. ventricosa*). Sequence-1 (SQ1) was defined at the base by sequence boundary (SB1), separating the Santonian? clastic sediments (continental sandstone) of the Wadi Hennis Formation (at below) from the marine Campanian carbonate sediments of the Khoman Formation (at above). The SB1 matches with the unconformable

sequence boundary of Hermina (1990) at Dakhla and Farafra oases.

This sequence starts with a retrogradational parasequence set of mainly dominated by an outer neritic–bathyal environment of the chalky limestone sediments. This set assigned to the transgressive systems tract (TST) that reflects a relative rise of the sea level and deepening-upward cycle. In addition, it was characterized by an increase in the P/B% from base to top (from ~ 38 to ~ 63%). The transgressive deposits are followed by an outer neritic environment of the highstand systems tract (HST) due to a gradual fall in relative sea level. The boundary between the transgressive and highstand systems tracts was placed at the top of the maximum paleodepth value associated with the highest peak of total foraminiferal number and P/B% reflecting the maximum flooding surface (MFS).

Sequence-2

The second depositional sequence covers the middle part (about 108 m thick) of the Khoman Formation at the Sahl Baraka Well. It contains the late Campanian *G. aegyptiaca* Zone and the Maastrichtian *G. gansseri*, *R. fructicosa*, *P. hariaensis*/*G. gansseri*, *P. palpebera* and *P. hantkeninoides* zones (Fig. 7). Sequence-2 (SQ2) was delineated at the base by sequence boundary (SB2) that was located at the *G. ventricosa*/*G. aegyptiaca* zonal boundary within the Campanian age. The SB2 was marked by a stratigraphic break due to the missing of the *G. calcarata* and *G. havanensis* zones. It coincides with the tectonic event of Obaidalla et al. (2006) that was recorded at Naqb El Bahariya and Naqb El Sillim sections. Also, it matches with the unconformable contact given by Obaidalla et al. (2016, 2017a), Salman (2017) and Mahfouz et al. (2018) at the Eastern Desert, Egypt.

The sequence SQ2 contains a basal TST consisting of retrogradational deep marine chalky limestone and shale deposited in an outer neritic–bathyal environment during a rapid relative rise of sea level. These deposits were characterized by abundant, highly diversified, and well-preserved planktonic foraminifera and sparse benthonic foraminifera. The MFS (above the TST) coincides with the top of the *G. gansseri* zone that was characterized by the bathymetrically deepest interval, containing the maximum TFN and P/B ratio. The transgressive deposits grade upwards into a progradational HST composed of limestone and shale intercalations deposited in a middle–outer neritic environment exhibiting a pronounced decrease in the TFN and P/B% (Fig. 7).

Sequence-3

The third depositional sequence occupies the upper part (about 9 m thick) of the Khoman Formation at the Sahl

Baraka Well. It comprises the Danian *P. inconstans* and *P. uncinata* zones (Fig. 7). Sequence-3 (SQ3) was marked at the base by the basin-wide K/Pg boundary (SB3) as documented by the lack of the earliest Danian P0, P α , P1a, and P1b planktonic foraminiferal zones. It is nearly close to the sequence boundary SB1 given by Faris et al. (2018) at Farafra-Abu Minqar area, Western Desert, Egypt. In the same way, Salman (2017) traced an unconformable contact (SB3) during the K/Pg boundary that was marked by an occurrence of a conglomeratic bed as well as the absence of the earliest Danian planktonic foraminiferal zones P0, P α , P1a, and P1b.

Sequence SQ3 starts with retrogradational parasequence sets of the limestone sediments deposited in a middle–outer neritic environment. It was marked by a gradual rise in relative sea level which was interpreted as a TST.

Discussion

In the present study (Sahl Baraka well), the Khoman Formation represents almost a complete subsurface succession covering the Campanian to early Danian transition. The results and interpretations of the present study were discussed with some recent works (Fig. 9) at different localities at Farafra Oasis (e.g., NW Ain-Maqfi section of Hewaidy et al. 2006; North Gunna and Aqabaat sections of Orabi et al. 2018; South of Ain-Maqfi section of El Baz 2020; Farafra-Ain Dalla and Ain-Maqfi sections of Zaky et al. 2020). The results of this discussion can be summarized as follows:

- 1 Lithostratigraphically: the Khoman Formation is ~ 144 m thick of mainly chalky limestone intercalated with some shale beds especially in the lower and upper parts. In the comparable sections, the authors studied the upper part of the Khoman Formation (Fig. 9). The

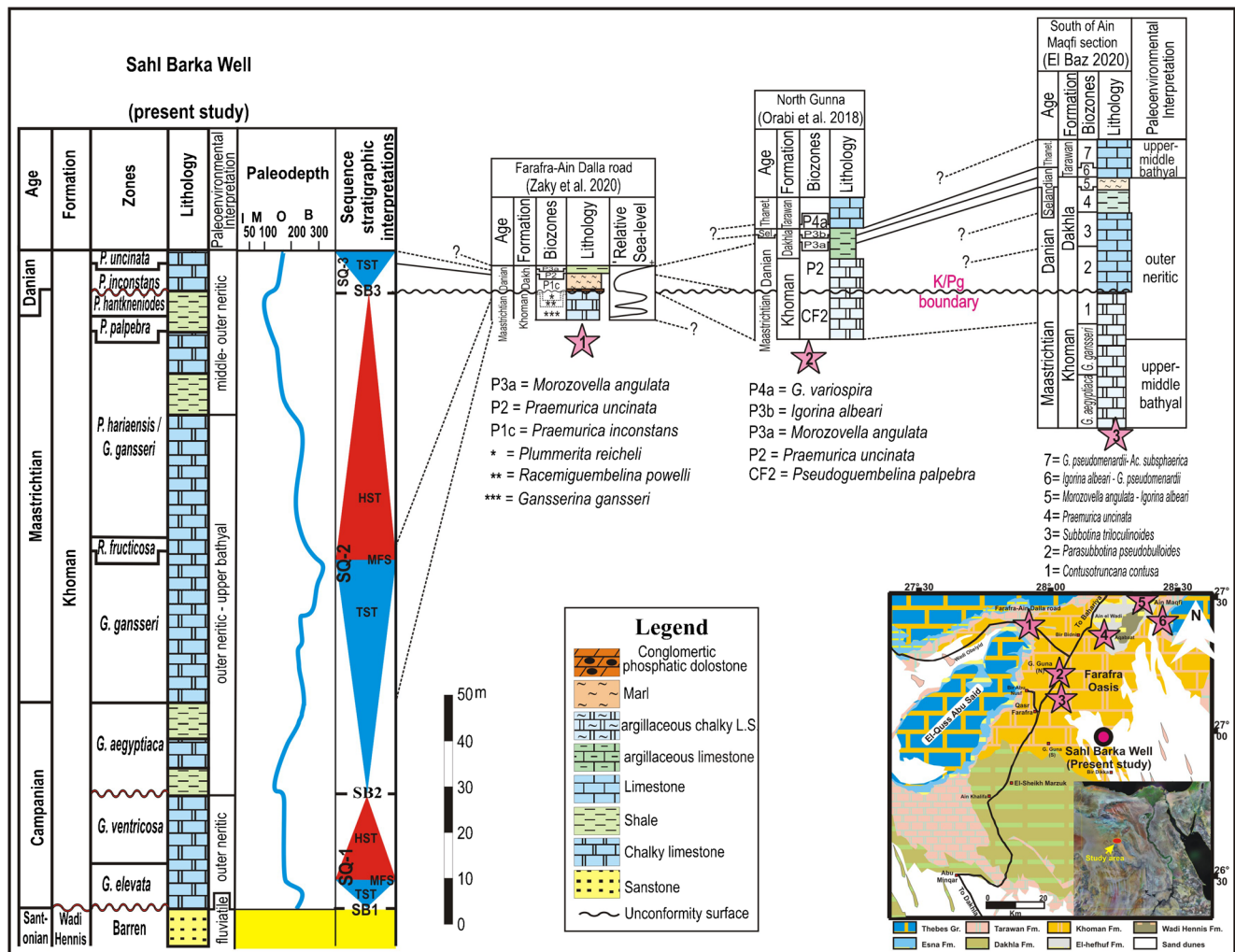


Fig. 9 Correlation of the present study with some different localities in Farafra Oasis

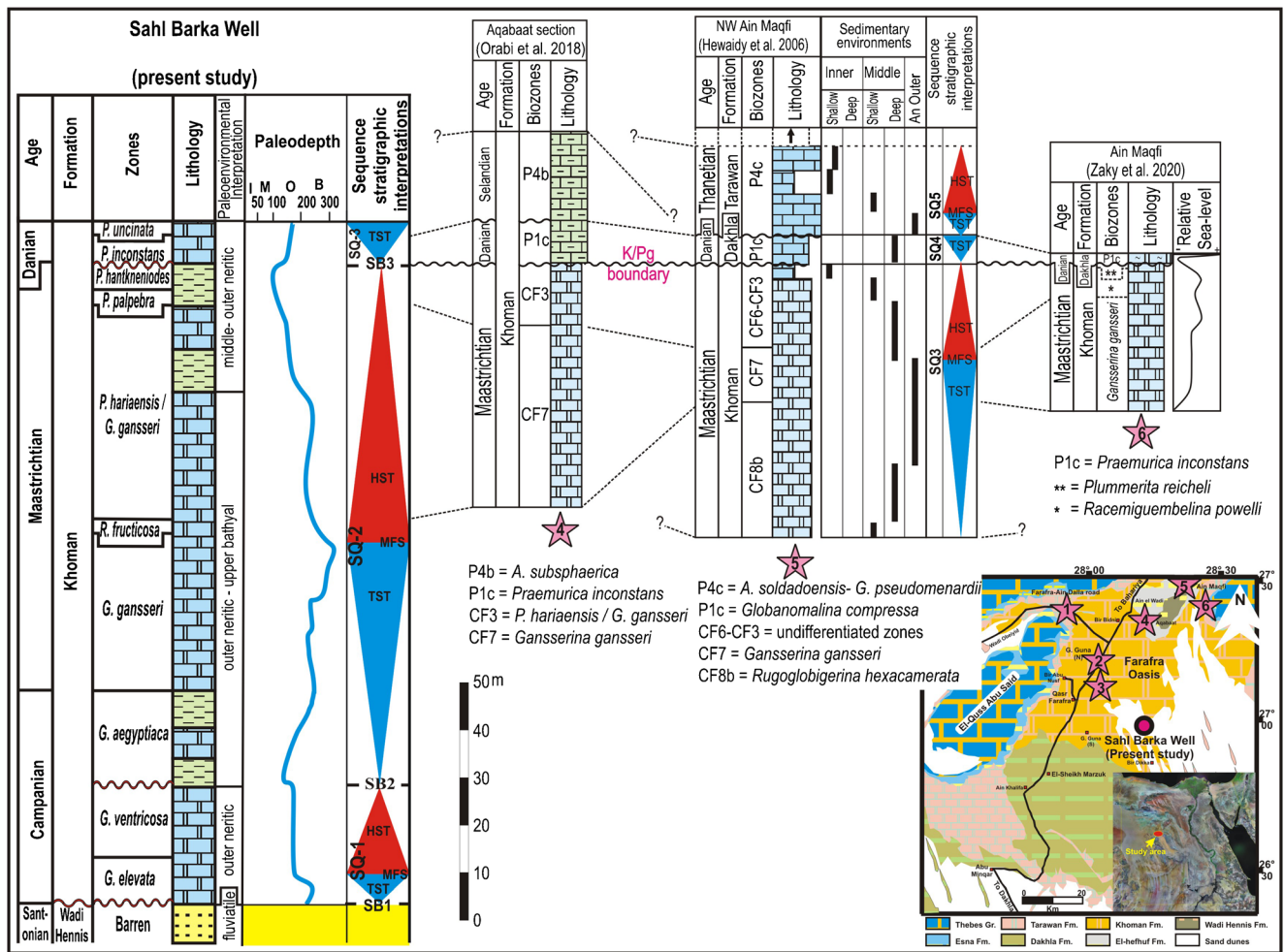


Fig. 9 (continued)

thickness of the upper part of the Khoman Formation was ~ 55 m thick at NW Ain Maqif section (Hewaidy et al. 2006), ~ 18 m thick at North Gunna, ~ 52 m thick at Aqabaat sections (Orabi et al. 2018), ~ 30 m thick at South of Ain-Maqif section (El Baz 2020), ~ 6 m thick at Farafra-Ain Dalla, and ~ 30 m thick at Ain-Maqif sections (Zaky et al. 2020). These thicknesses can be equivalent to the upper part of the study Sahl Baraka well. Contrary to the stratigraphic code, Hewaidy et al. (2006), El Baz (2020), and Zaky et al. (2020) defined the carbonate strata of the uppermost part of the Khoman Formation as a part of the Dakhla Formation (Fig. 9). They ignored the original definition of the Dakhla Formation (Said 1961) as a siliciclastic facies.

2 Biostratigraphically: ten planktonic foraminiferal zones were recorded from the Campanian–Danian interval of the subsurface succession at Sahl Baraka well. The recorded zones are correlated with those of the surface sections (Hewaidy et al. 2006; Orabi et al. 2018; El Baz 2020; Zaky et al. 2020). The

planktonic foraminiferal zones of the surface section only cover the Maastrichtian–Danian interval (Fig. 9), because these authors confirmed their studies on the uppermost part of the Khoman Formation (such as Orabi et al. 2018 at North Gunna and Aqabaat sections; El Baz 2020 at South of Ain-Maqif section; Zaky et al. 2020 at Farafra-Ain Dalla and Ain-Maqif sections).

3 The K/Pg boundary unconformably lies within the upper part of the Khoman Formation at the *Plummerita hantkeninoides/Praemurica inconstans* zonal boundary at the present study. This hiatus was evidenced by the missing of the earliest Danian P0, P α , P1a, and P1b planktonic foraminiferal zones. This is more or less conformed with the study of Orabi et al. (2018). On the other hand, this boundary was believed at the Khoman/Dakhla formational boundary by Hewaidy et al. (2006), El Baz (2020), and Zaky et al. (2020) depending on the planktonic foraminiferal zones. They (op. cit.) neglected the lithologic character of the different rock units (carbonate facies of the

- Khoman Formation and siliciclastic facies of the Dakhla Formation).
- 4 The paleoenvironmental interpretations indicate that the lower part of the Khoman Formation was deposited in an outer neritic paleoenvironmental setting which changed upward in the middle part of the formation to an outer neritic–upper bathyal paleoenvironmental setting, while the upper part of the Khoman Formation was deposited in a middle–outer neritic setting. These results were matched with the inference of Hewaidy and Strougo (2001), where they have interpreted the paleoenvironmental conditions of the Khoman Formation as an outer neritic–upper bathyal which relatively changed to shallow paleoenvironment upward at the uppermost part. El Baz (2020) inferred the Khoman Formation to be an upper–middle bathyal paleoenvironmental setting which changed upwards to an outer neritic setting during the Maastrichtian–Danian interval. On the other hand, the Maastrichtian Khoman Formation revealed an outer neritic paleoenvironmental setting at the Farafra-Ain Dalla, Ain-Maqfi, and NW Ain-Maqif sections (Hewaidy et al. 2006; Zaky et al. 2020). During the Maastrichtian–Danian transition, a shallower paleoenvironmental setting of an inner neritic was interpreted (Hewaidy et al. 2006). Zaky et al. (2020) implied an inner–middle neritic paleoenvironmental setting due to the presence of a conglomeratic phosphatic dolostone bed at the Maastrichtian–Danian transition.
 - 5 In comparison with the sequence stratigraphic interpretations, the results of Hewaidy et al. (2006) at NW Ain-Maqfi section were matched with the present work, where SQ2 and SQ3 of the present study were coincided with SQ3 and SQ4 of Hewaidy et al. (2006), while SQ1 of the present study was not recorded at NW Ain-Maqfi section (Hewaidy et al. 2006). This is because they (op. cit) studied the upper part of the Khoman Formation (Fig. 7).

Conclusion

The present work introduces stratigraphical and paleoenvironmental studies on the subsurface Upper Cretaceous–lower Paleocene strata at Sahl Baraka, Farafra Oasis, Egypt. Fifty-one ditch samples were investigated from the Sahl Baraka Well. Two rock units are defined: the Wadi Hennis Formation (uppermost 9 m thick, at base) which mainly of sandstone rocks and the Khoman Formation (~ 144 m thick, at the top) which mainly of chalky limestone sequence intercalated with four beds of shale (ranging from 6–9 m thick for each bed). High-resolution planktonic foraminiferal biostratigraphic study led to identifying ten foraminiferal zones:

Globotruncanita elevata, *Globotruncana ventricosa*, and *Globotruncana aegyptiaca* for the Campanian Age; *Gansserina gansseri*, *Racemiguembelina fructicosa*, *Pseudoguembelina hariaensis/Gansserina gansseri*, *Pseudoguembelina palpebral*, and *Plummerita hantkeninoides* for the Maastrichtian Age; *Praemurica inconstans* and *Praemurica uncinata* for the Danian Age. Four benthonic foraminiferal biofacies (A, B, C, and D) were recognized using the R-mode hierarchical cluster analyses. These biofacies were used to interpret the paleoenvironment setting dominated during this interval. The Wadi Hennis Formation (Santonian? interval) was deposited in a continental environment (may be fluvatile). During the Campanian interval, the lower part of the Khoman Formation is typically indicative of an outer neritic environment, while it indicates an outer neritic–upper bathyal environment in the upper part with oligotrophic to mesotrophic conditions and low to moderate productivity. During the Maastrichtian interval, the Khoman Formation deposits under an outer neritic–bathyal environment which changed upward to a middle–outer neritic environment with mesotrophic conditions and low to moderate productivity. During the Danian interval, the uppermost part of the Khoman Formation was deposited typically in a middle–outer neritic environment. The lithostratigraphic and biostratigraphic evidences led to recognize three hiatus which related to three syn-sedimentary tectonic events (I, II, and III) due to the effect of the Syrian Arc Orogeny.

Tectonic Event I coincided with the Santonian?/ Campanian boundary, which marked by the facies changes from the continental clastic sediments (Sandstone) of the Wadi Hennis Formation to marine carbonate sediments (chalky limestone) of the Khoman Formation. Tectonic event I led the uplifting of the Sahl Baraka area and formed an aerial positive area during the Santonian–earliest Campanian age. This event was documented by the missing of the planktonic foraminiferal assemblage of the upper part of the Santonian–early Campanian *Dicarinella asymetrica* Zone.

Tectonic Event II was took placed at the middle/late Campanian boundary, which was supported by the missing of the late Campanian *G. calcarata* and *G. havanensis* zones within the lower part of the Khoman Formation.

Tectonic Event III was at the K/Pg boundary, which was recorded within the upper part of the Khoman Formation. This event only affected the lower Danian strata, which was documented by the missing of the earliest Danian planktonic foraminiferal zones (e.g., P0, P α , P1a, and P1b).

The paleorelief correlation profile indicates that the Sahl Baraka succession represents the transition area between the clastic (shale) Upper Cretaceous–Paleocene basin toward the south and the carbonate one basin toward the north. Also, the Sahl Baraka Well may be represented by the depocenter for the Upper Cretaceous–Paleocene basin. In the framework of

the sequence stratigraphy, three sequence boundaries (SB1–SB3) have coincided with the three tectonic events that were defined the three depositional sequences (SQ1–SQ3) throughout the study well. Also, the eustatic sea-level curve shows a falling trend during these three tectonic events.

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