Arab J Geosci (2016) 9: 159
DOI 10.1007/s12517-015-2108-9

ORIGINAL PAPER

Integrated planktonic stratigraphy and paleoenvironments of the Lower-Middle Miocene successions in the central and southern parts of the Gulf of Suez, Egypt

Abdel-Galil A. Hewaidy[1] · **Medhat M. M. Mandur**[2] · **Sherif Farouk**[2] · **Ibrahim S. El Agroudy**[2]

Received: 16 March 2015 / Accepted: 10 September 2015 / Published online: 24 February 2016

Abstract Lower to Middle Miocene successions in three offshore wells named GS 160-2, QQ-89, and Ras Elush-2 located in the central and southern parts of the Gulf of Suez were examined for their planktonic foraminifera, calcareous nannofossil assemblages, and paleoenvironments. These successions are subdivided from older to younger into Aquitanian Nukhul, Burdigalian-Langhian Rudeis, Langhian Kareem, and Serravallian Belayim formations. The identified foraminifera includes 54 benthic species belonging to 25 genera and 47 planktonic species belonging to 11 genera, in addition to 64 calcareous nannofossil species belonging to 21 genera. The stratigraphic distribution of these assemblages suggests classifying the studied successions into seven planktonic foraminiferal and six calcareous nannoplankton biozones. The planktonic foraminiferal and calcareous nannoplankton biozones are integrated. Different environments ranging from shallow inner to outer shelf are recognized. This is based on quantitative analyses of foraminifera including benthic biofacies, planktonic/benthonic ratio, and diversity. Syn-rift tectonics played an important role in configuration of the Miocene depositional history in the Gulf of Suez region.

✉ Medhat M. M. Mandur
medhatmandur@yahoo.com

Abdel-Galil A. Hewaidy
ahewaidy50@yahoo.com

1 Faculty of Science, Geology Department, Al-Azhar University, Naser City 11727, Cairo, Egypt

2 Egyptian Petroleum Research Institute, Naser City 11727, Cairo, Egypt

Keywords Lower/Middle Miocene · Foraminifera · Calcareous nannoplankton · Biostratigraphy · Paleoenvironments

Introduction

The Miocene successions in the Gulf of Suez are characterized by their vertical and lateral facies changes due to the tectonic rift events that complicated the stratigraphic correlation. An integrated planktonic foraminiferal and calcareous nannoplankton biostratigraphy may help in establishing a more accurate correlation in that area. Among the most significant recent publications on the Gulf of Suez area are El-Heiny and Martini (1981), Andrawis and Abdel Malik (1981), Evans (1988), Haggag et al. (1990), El-Azabi (2004), Moustafa (2004), Abul-Nasr et al. (2009), Mandur (2009), Mandur and Baioumi (2011), Abed El-Naby et al. (2010), and Hewaidy et al. (2012, 2013).

The present study is an attempt to integrate the planktonic foraminifera and calcareous nannoplankton biostratigraphic classifications of the Lower to Middle Miocene subsurface successions in the Gulf of Suez region. It also sheds more light on the depositional environmental conditions which prevailed during deposition of the studied successions.

Material and methods

The material of the present work includes 187 ditch samples obtained from three wells (Fig. 1), named from north to south: GS160-2 (latitude 28° 57′ 14″ N and longitude 32° 57′ 32″ E), QQ-89 (latitude 27° 47′ 55″ N and longitude 33° 33′ 36″ E), and Ras Elush (latitude 27° 53′ 29″ N and longitude 33° 33′ 08″).

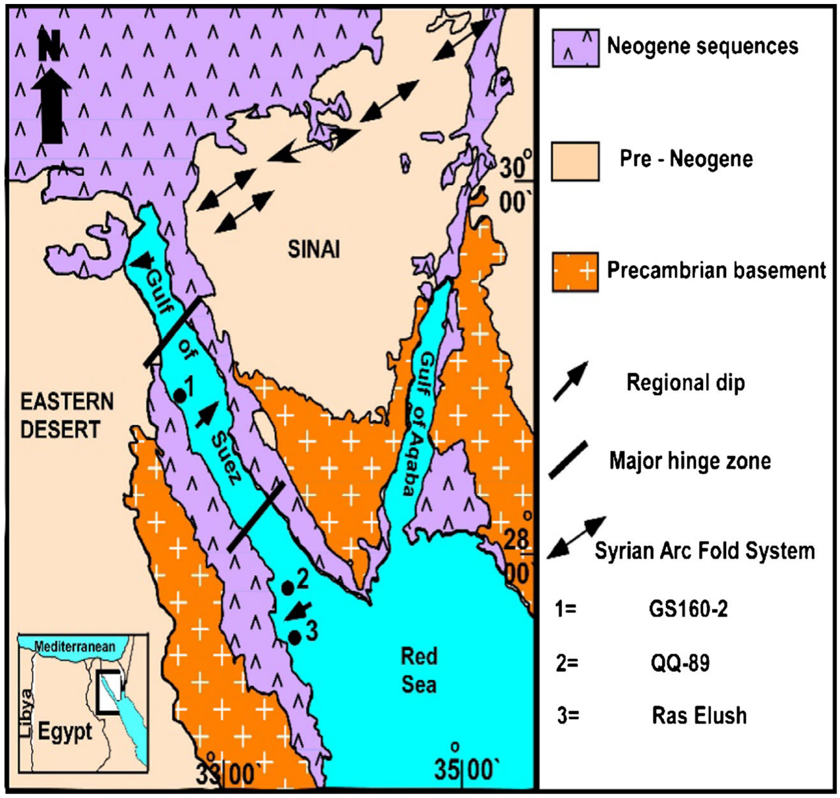


Fig. 1 Location map of the studied wells (modified after Moustafa 1976, and Salah 1994)

The obtained residues were dried, packed, and studied under binocular Olympus stereoscopic microscope. The calcareous nannofossils were separated from the studied samples and identified by using an Olympus polarized microscope with ×100 oil immersion lens. The paleoenvironments in the present study were determined based on quantitative and qualitative foraminiferal analyses. The paleoenvironmental interpretation methods are explained by several authors (Culver 1988; Armentrout 1996; Leckie and Olson 2003; Miller et al. 2008); Hewaidy et al. 2013, and Farouk et al. 2014). The planktic/benthic ratios (P/B %) is an important tool in depth zonation (Van der Zwaan et al. 1990), which is expressed as $100\times P/(P+B)$. This ratio is lowest in the shallower marine waters and generally increases with depth until the carbonate compensation depth (CCD). The planktic/benthic ratios pointed out that the inner shelf (10–50 m depth) is characterized by low planktic percentages (1–5 %) with low species diversity and high benthic percentages; the middle shelf depth (50–100 m) is characterized by 8–25 % planktonic foraminifera and higher species diversity, and the outer shelf depth (100–200 m) is marked by 30-70 % planktonic foraminiferal assemblage. The species diversity is represented by the total number of foraminiferal species, which increases away from the shore up to the middle and outer shelf depths and then decreases in deeper marine. The benthic foraminiferal groups identified in the present study are the miliolid group (*Spiroloculina*, *Quinqueloculina*, and *Pyrgo*); nodosariid group (*Nodosaria*, *Dentalina*, and *Lenticulina*); buliminid group (*Bolivina*, *Stillostomella*, *Bulimina*, *Uvigerina*, and *Rectuvigerina*); and rotaliid group (*Nonion*, *Chilostomella*, *Nonionella*, *Siphonina*, *Elphidium*, *Eponides*, and *Cibicides*).

Lithostratigraphy

The Miocene successions in the Gulf of Suez region are subdivided by many workers into several rock units (Fig. 2). In the present study, the lithostratigraphic classification of the National Stratigraphic Subcommittee of the Geological Sciences of Egypt (N.C.G.S 1976) is used. The studied Lower to Middle Miocene successions are classified into the Belayim, Kareem, Rudeis, and Nukhul formations from younger to older. The following is a brief description for these units.

The Belayim Formation

It includes the oldest part of the main Miocene evaporite cycle in the Gulf of Suez region (Ghorab 1964). It unconformably underlies South Gharib Formation and unconformably overlies Kareem Formation at its type section at Belayim well 112–12 in the Gulf of Suez area (Issawi et al. 1999). In the studied wells, the thickness of the Belayim Formation varies

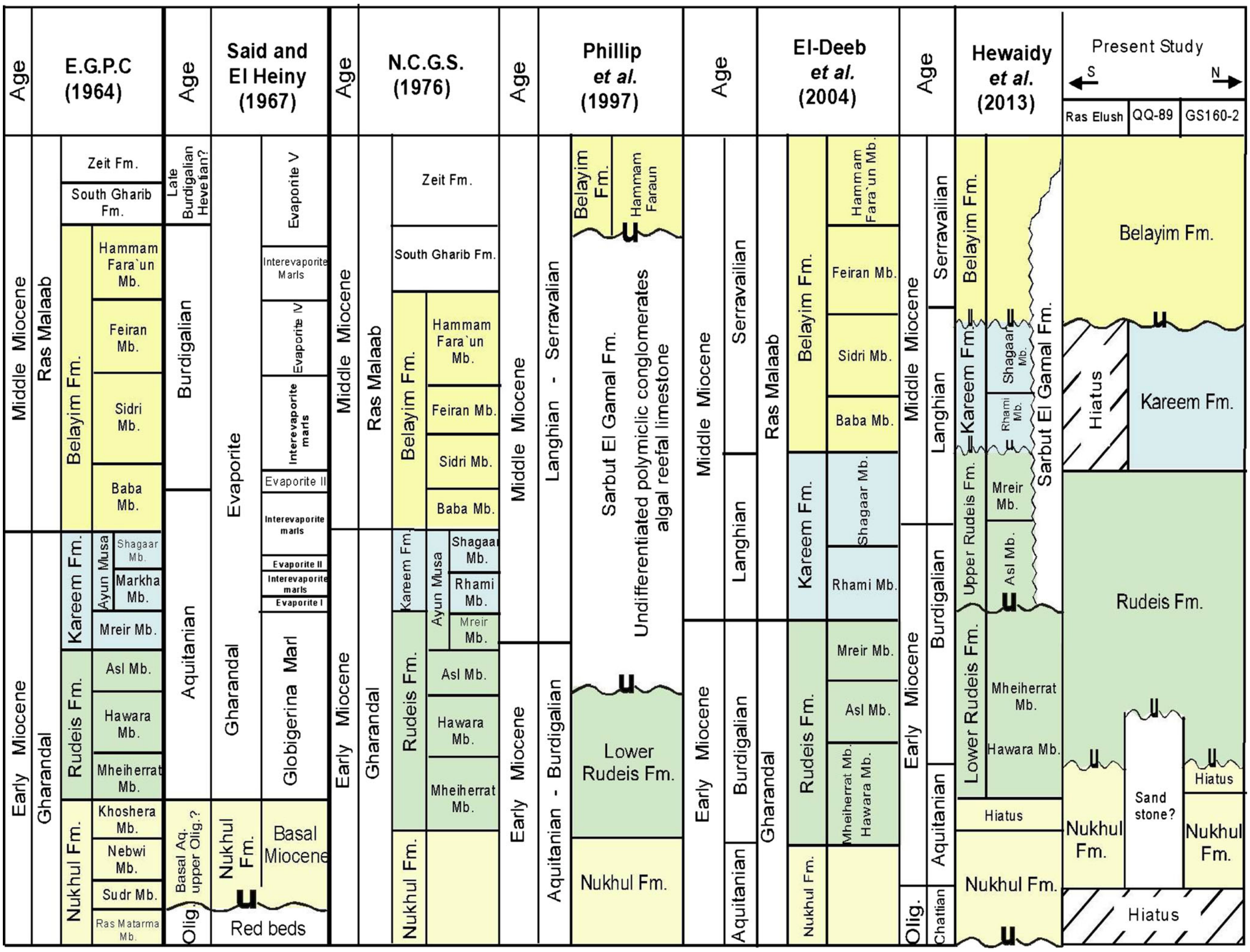


Fig. 2 Comparison of the Miocene rock units used by different authors in Egypt

from 450 ft in GS 160-2 to 280 ft in Ras Elush and is much reduced to 16 ft in the QQ-89 well. It is composed of shale and siltstone interbeded with creamy white, cryptocrystalline anhydrite (Fig. 3). It is assigned to the Serravallian age based on its microfaunal constant. The pronounced changes in thickness, facies, and the development of evaporites in the Belayim Formation are probably due to the separation of the Gulf of Suez from the Mediterranean by a structural high in the northern Gulf of Suez (Patton et al. 1994).

The Kareem Formation

The type locality of the Kareem Formation is at Gharib North well no. 2, Gulf of Suez (Ghorab 1964). In the study area, it is composed of grey to greenish, moderately hard, richly fossilliferous, shale, interbeded with white to brown, moderately hard, crystalline limestone and anhydrite (Fig. 3).

The thickness of this formation varies from place to another according to its position in the tectonic setting. In the GS 160-2 well, the Kareem Formation is about 200 ft thick, while at the QQ-89 well, the thickness of this formation is about 254 ft and is missing in the Ras Elush well southwards. It unconformably overlies the Rudeis Formation and unconformably underlies the Belayim Formation. The age of this formation is the Middle Miocene (Langhian).

The Rudeis Formation

Ghorab (1964) described the Rudeis Formation at its type locality in the Rudeis-2 well in west central Sinai as open marine sediments. In the studied wells, it is composed of shales, sandy shales, and calcareous shales rich in microfossils, with light to dark grey, brownish grey, medium to hard sandstone interbeds and occasionally thin yellowish grey massive sandy limestone streaks. The formation is

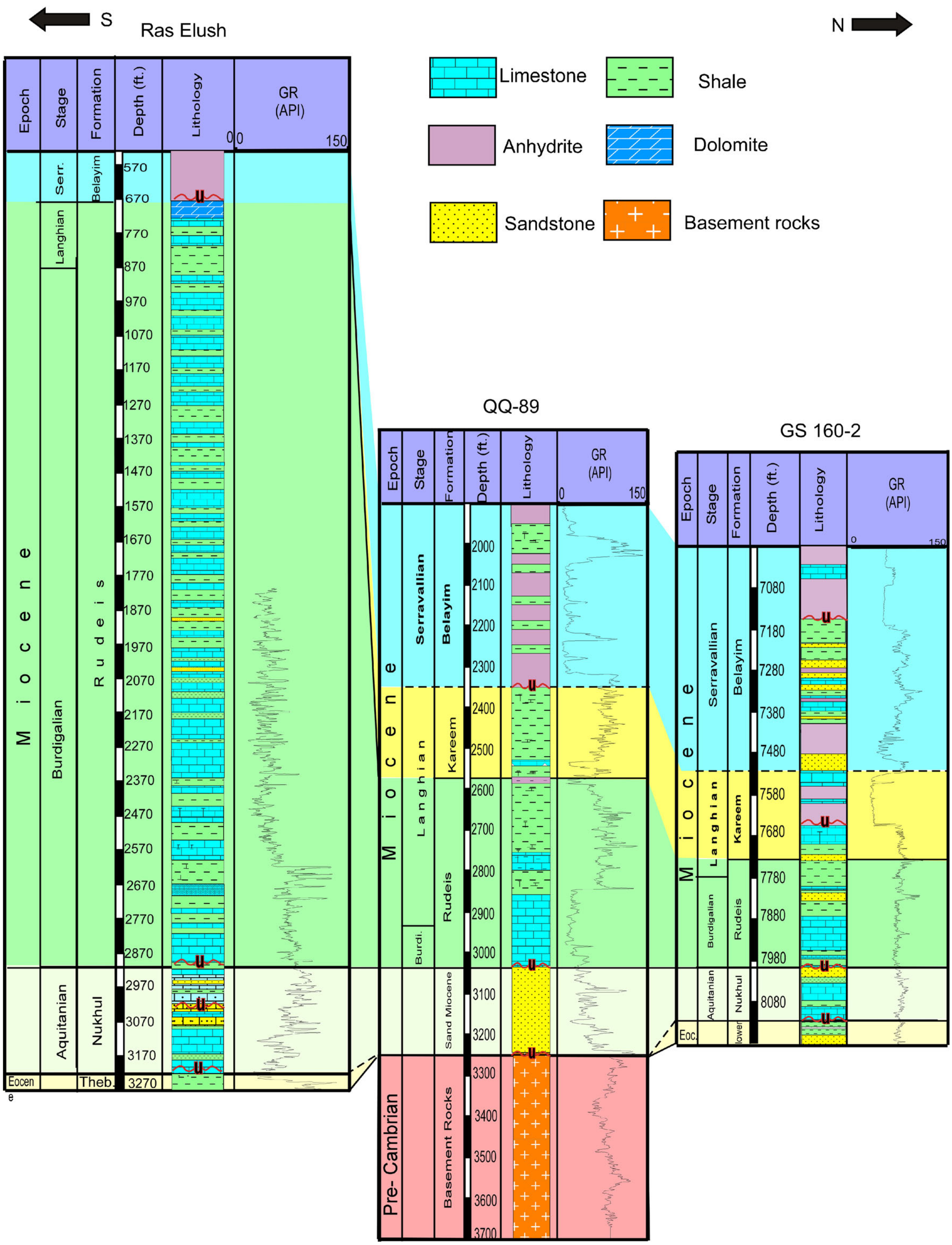


Fig. 3 Lithostratigraphic correlation chart of the Miocene successions in the studied wells

most thick (2335 ft) at the Ras Elush well; 210 ft at GS 160-2, and to about 470 ft thick at the QQ-89 well (Fig. 3). In the present study, the Rudeis Formation overlies unconformably the Nukhul Formation and underlies unconformably the Kareem Formation at GS 160-2 or unconformably the Belayim Formation at the Ras Elush well. At the QQ-89 well, the Rudeis Formation overlies unconformably the Pre-Cambrian basement paleo-high (Fig. 3). This formation is assigned to the Early Miocene (Burdigalian)–Middle Miocene (Langhian) age.

The Nukhul Formation

The Nukhul Formation at its type locality in Wadi Nukhul overlies unconformably the Oligocene Tayiba Red-Beds (Waite and Pooely 1953). At the Ras Elush well, it consists of very fine crystalline, moderately hard limestone, occasionally dolomitic and sandy limestone, interbeded with dark to greenish grey and slightly calcareous shale. In the GS 160-2 well, the Nukhul Formation consists of greenish grey shale, argillaceous sandstone, and light grey to grey, moderately hard, silty sandstone (Fig. 3). The basal Miocene sandstone recorded in the QQ-89 well is pale-yellow sandstone, fine to medium grained, moderately to well sorted, moderately hard, barren of any microplanktonic assemblages. It may be equivalent to the Nukhul Formation (Fig. 3). This formation is recorded in the Ras Elush well (about 230 ft) and GS 160-2 well (about 180 ft).

It unconformably overlies the Lower Eocene Thebes Formation and unconformably underlies the lower Miocene Rudeis Formation at the GS 160-2 and Ras Elush wells. The age of the Nukhul Formation is Early Miocene (Aquitanian).

Biostratigraphy

The biostratigraphic zonations in the present study are based on the planktonic foraminifera and calcareous nannofossil assemblages. The identified biostratigraphic units of planktonic foraminifera (Tables 1 and 2) and calcareous nannofossil (Tables 3 and 4) are correlated with other biostratigraphic units in different localities in and outside Egypt.

The examination of the Miocene successions in the studied wells has led to the identification of 47 planktonic foraminiferal species (belonging to 11 genera), 54 benthonic foraminiferal species (belonging to 25 genera), and 64 calcareous nannofossil species (belonging to 21 genera).

The vertical distributions of these microfossils enabled the subdivision of the studied succession into seven planktonic and six calcareous nannofossil biozones (Figs. 4, 5, 6, 7, 8, and 9). The most important planktonic and benthic foraminiferal and calcareous nannofossil species are shown on Plates 1, 2, and 3.

Planktonic foraminiferal biozones

The Miocene planktonic foraminiferal biozonation of the scheme of Iaccarino (1985) is used in the present study taking into consideration the revisions given by Berggren et al. (1995) and Wade et al. (2011). The Lower–Middle Miocene successions in the studied wells are subdivided into seven biozones as follows from older to younger.

Paragloborotalia kugleri (M1) Zone

Bolli (1957) introduced this zone as a total range of the nominate taxon. This zone is recorded only in the Ras Elush well from a depth of 3200 to 3100 ft (100 ft thick) (Fig. 4). This zone is marked by low diversity and moderately preserved planktonic foraminiferal assemblages. The first occurrence (FO) of *P. kugleri* (Bolli) is used to define the Oligocene/Miocene boundary (Stainforth et al. 1975; Berggren et al. 1995; Wade et al. 2011). In Egypt, due to the rarity or absence of *P. kugleri*, the Oligocene/Miocene boundary is defined by the FO of the large-sized and common occurrence of the genus *Globigerinoides* (Haggag et al. 1990; Phillip et al. 1997; Hewaidy et al. 2012; Farouk et al. 2014). On the other hand, the FO of the small- sized *Globigerinoides primordius* Blow and rare occurrence of *Globigerina ciperoensis* Bolli are considered of the Oligocene age (Ouda and Masoud 1993; Mancin et al. 2003; Kuĉenjak et al. 2006; Hewaidy et al. 2013). In the Ras Elush well, this zone is defined by the occurrence of *P. kugleri*.

G. primordius (M2) Zone

According to Blow (1969), this zone is defined as the interval from the last occurrence (LO) of *P. kugleri* (Bolli) to the LO of *G. primordius* Blow. This interval is characterized by abundant planktonic species (Figs. 4 and 6). The *G. primordius* (M2) Zone is assigned to the Aquitanian age. This zone occupies the upper part of the Nukhul Formation, in the Ras Elush well at a depth of 3100 to 2950 ft (150 ft thick), while in the GS 160-2 well it occurs between depths of 8130 to 7980 ft (150 ft) and is not recorded in the QQ-89 well (Figs. 4 and 6). It is equivalent to the *Globoquadrina binaiensis* (M2) partial-range Zone of Berggren et al. (1995) and Wade et al. (2011). It is also equivalent to the *Globoquadrina dehiscens dehiscens* subzone and lower part of the *Globigerinoides altiaperturus*/*Catapsydrax dissimilis* Zone in the Mediterranean region, by Iaccarino (1985). In Egypt, this zone is recorded from the base of the Rudeis Formation (Kerdany 1968; Andrawis and Abdel Malik 1981; El-Heiny and Martini 1981; Haggag et al. 1990; Phillip et al. 1997; Mandur 2009; Hewaidy et al. 2012).

G. altiaperturus (M3) Zone

This zone was originally established by Bolli (1957) as the interval from the LO of *G. primordius* Blow to the LO of *G. altiaperturus* Bolli. The planktonic assemblage of this zone is characterized by common occurrence of the genus *Globigerinoides*, in addition to the assemblage shown in Fig. 4. According to its content, this zone is assigned to the Burdigalian age. The *G. altiaperturus* Zone occupies the lowermost part of the Rudeis Formation at the Ras Elush well

Table 1 Comparison of planktonic foraminiferal zones in the present study with the most common zones outside Egypt

<table>
<tr><th colspan="2">Epoch</th><th>Stage</th><th>Bolli (1966)</th><th>Blow (1969)</th><th>Postuma (1971)</th><th>Stainforth et al (1975)</th><th>Kennett& Srinivasan (1983)</th><th>Bolli&Sanders (1985)</th><th>Iaccarino (1985)</th><th>Berggen et al. (1995) Wade et al. (2011)</th><th>Present study</th></tr>
<tr><td rowspan="27">Miocene</td><td rowspan="15">Middle</td><td rowspan="6">Serravallian</td><td rowspan="8">Gt. foshi fohsi</td><td rowspan="2">Gt. praefoshi(N11)</td><td rowspan="9">Gt. peripheroacuta</td><td rowspan="8">Gt. foshi fohsi</td><td rowspan="3">Ngqd. acostaensis (N15)</td><td rowspan="15">Gt. fohsi peripheroronda</td><td rowspan="4">Gt. peripheroronda</td><td rowspan="6">F. peripheroacuta (M7)</td><td>Barren interval</td></tr>
<tr><td rowspan="4">Gt peripherornda/ Gt. praemenardii (M7)</td></tr>
<tr><td rowspan="4">Gt. peripheroacuta (N10)</td></tr>
<tr><td rowspan="3">Gt. siakensis (N14)</td></tr>
<tr><td rowspan="8">O. suturalis</td></tr>
<tr><td rowspan="3">Barren interval</td></tr>
<tr><td rowspan="9">Langhian</td><td rowspan="3">O. suturalis Gt. peripheroacuta (N9)</td><td>Globigerina nepenthes (N13)</td><td rowspan="4">O. suturalis (M6)</td></tr>
<tr><td rowspan="2">Gt. lobata (N12)</td></tr>
<tr><td rowspan="3">Gt. foshi barisanesis</td><td rowspan="4">Gt. fohsi peripheroronda</td><td rowspan="2">Orbulina suturalis (M6)</td></tr>
<tr><td rowspan="5">Pr. sicana- Gtl. insueta (N8)</td><td rowspan="4">Gt. peripheroronda</td><td rowspan="3">Gt.foshi fohsi(N11)</td></tr>
<tr><td rowspan="6">P. sicana P. glomerosa (M5)</td><td rowspan="6">P. sicana P. glomerosa (M5)</td></tr>
<tr><td rowspan="4">Pr. glomerosa</td></tr>
<tr><td rowspan="3">Pr. glomerosa</td><td rowspan="3">Gt. prafoshi (N10)</td><td rowspan="5">Pr. glomerosa</td></tr>
<tr><td rowspan="4">Gtl. insueta</td></tr>
<tr><td rowspan="3">Gtl. insueta- Gds.trilobus (N7)</td></tr>
<tr><td rowspan="12">Early</td><td rowspan="7">Burdigalian</td><td rowspan="2">Gtl. insueta</td><td rowspan="2">Gtl. insueta</td><td rowspan="2">Gt. peripheroacuta (N9)</td><td rowspan="2">Pr. glomerosa</td></tr>
<tr><td rowspan="2">F. birnageae M4b</td><td rowspan="4">Globigerinoides trilobus(M4)</td></tr>
<tr><td rowspan="3">Cds. stainforthi</td><td rowspan="3">Gtl. insueta- Cds.dissimilis (N6)</td><td rowspan="8">Gds. trilobus</td><td rowspan="3">Cds. stainforthi</td><td rowspan="2">Orbulina Spp (N8)</td><td rowspan="2">Gtl.insueta</td><td rowspan="3">Gds. trilobus</td></tr>
<tr><td rowspan="2">D. venezuelana M4a</td></tr>
<tr><td>Gds. sicanus (N7)</td><td>Cds. stainforthi</td></tr>
<tr><td rowspan="4">Cds.dissimilis</td><td rowspan="4">Gqd. dehiscens (N5)</td><td rowspan="4">Cds.dissimilis</td><td>Cds. dissimilis (N6)</td><td rowspan="4">Cds.dissimilis</td><td rowspan="4">Cds.dissimilis- Gds.altiaperturus</td><td rowspan="2">Globigerinatella sp/ C. dissimilis M3</td><td rowspan="3">Globigerinoides altiaperturus (M3)</td></tr>
<tr><td rowspan="3">Gtl. insueta (N5)</td></tr>
<tr><td rowspan="5">Aquitanian</td><td rowspan="2">G. binaiensis M2</td></tr>
<tr><td rowspan="3">Globigerinoides primordius (M2)</td></tr>
<tr><td rowspan="3">Gt. kugleri</td><td rowspan="3">Gt. kugleri- Gds.primordius (N4)</td><td rowspan="3">Gt. kugleri</td><td rowspan="2">Gt. kugleri(N4B)</td><td rowspan="3">Gds. primordius</td><td rowspan="2">Gqd. dehiscens</td><td rowspan="2">G. dehiscens /'P'. kugleri M1b</td></tr>
<tr><td rowspan="2">Gt. kugleri</td></tr>
<tr><td>Gqd. dehiscens(N4A)</td><td>Gt. kugleri</td><td>Gt. kugleri M1a</td><td>Paragloborotalia kugleri(M1)</td></tr>
</table>

only from depths of 2950 to 2390 ft (560 ft) (Fig. 4). The LO of *G. primordius* and the FO of *Globigerinella obesa* are observed in this zone. It is equivalent to the *Globigerinatella* sp./ *C. dissimilis* concurrent range Zone of Berggren et al. (1995) and Wade et al. (2011).

Globigerinoides trilobus (M4) Zone

This zone is defined as the interval from the LO of *G. altiaperturus* Bolli to the FO of *Praeorbulina glomerosa* (Blow). It is assigned to the Early Miocene (Burdigalian) according to its planktonic foraminiferal assemblage (Figs. 4, 5, and 6). This zone is recorded from the lower part of the Rudeis Formation from 2390 to 850 ft (1540 ft thick) in the Ras Elush well; at the GS 160-2 well, it is recorded from depths of 7950 to 7780 ft (170 ft thick) while in the QQ-89 well it is recorded from 3050 to 2950 ft (100 ft thick) (Figs. 4, 5, and 6). This zone is equivalent to the *Globigerinoides bisphericus* (M4) partial-range Zone of Berggren et al. (1995), and Wade et al. (2011). It is subdivided into two subzones based on the LO of *C. dissimilis* and/or *Catapsydrax unicavus* and the FO of the *Globorotalia birnageae* Zone. In Egypt, this zone is equivalent to the *C. dissimilis*/*Praeorbulina sicana* (M4) Zone recorded by Hewaidy et al. (2013) and to the *G. trilobus* Zone which was recorded by many authors (Haggag et al. 1990; Phillip et al. 1997; Mandur 2004).

Praeorbulina sicanus/P. glomerosa (M5) Zone

According to Iaccarino (1985), this zone is defined as the interval from the FO of *P. sicana* De Stefani to the LO of *P. glomerosa* (Blow). This zone is characterized by

Table 2 Comparison of planktonic foraminiferal zones in the present study with the most common zones of Egypt

Stage			Formation	Member	Kerdany (1968)	Wasfi (1968)	Haggag et al (1990)	Abu Eneien (1990)	Phillip (1997)	Hewaidy et al (2012)	Farouk et al. (2014)	Present study
Miocene	Middle	Serravallian	Belayim	Hammam Faraun	O.suturalis	Gt. foshi Peripheroronda	O.universa	O. suturalis Gt. peripheroacuta	Gt.siakensis	Gt. peripheroacuta	Gt. praemenardii	Barren interval
Miocene	Middle	Serravallian	Belayim	Feiran	Gqd.altispira	Gt. foshi Peripheroronda	O.universa	O. suturalis Gt. peripheroacuta	O. suturalis	Gt. peripheroacuta	Gt. praemenardii	Gt peripheromonda/ Gt. praemenardii (M7)
Miocene	Middle	Serravallian	Belayim	Sidri	Gqd.altispira	Gt. foshi Peripheroronda	O.universa	O. suturalis Gt. peripheroacuta	O. suturalis	Gt. peripheroacuta	Gt. praemenardii	Gt peripheromonda/ Gt. praemenardii (M7)
Miocene	Middle	Serravallian	Belayim	Baba	Gt. foshi Peripheroronda	Gt. foshi Peripheroronda	O.universa	O. suturalis Gt. peripheroacuta	O. suturalis	Gt. peripheroacuta	Gt. peripheroronda	Barren interval
Miocene	Middle	Langhian	Kareem	Shagar	Gt. foshi Peripheroronda	Not recognized	O.suturalis	O. suturalis Gt. peripheroacuta	Borelis melo Zone	Gt. peripheroronda	Gt. peripheroronda	Barren interval
Miocene	Middle	Langhian	Kareem	Rahmi	Pr. glomerosa	Gds. sicanus	Pr. glomerosa	O. suturalis Gt. peripheroacuta	Borelis melo Zone	Barren interval	O. suturalis	Orbulina suturalis (M6)
Miocene	Middle	Langhian	Rudeis	Mreir	Gds. sicanus	Gds. sicanus	Gds. trilobus	Gds. trilobus	Borelis melo Zone	O. suturalis	Pr. glomerosa	Praeorbulina glomerosa (M5)
Miocene	Early	Burdigalian	Rudeis	Asl	Gds. Subquadratus	Gds. transitoria	Gds. trilobus	Gds. altaperturus	Gds. sicanus	Pr. sicana	Gds. trilobus	Globigerinoides trilobus(M4)
Miocene	Early	Burdigalian	Rudeis	Mheiherrat / Hawa	Gds. diminutus Gds. Subquadratus	Gds. Subquadratus	Cds. dissimilis	Cds. dissimilis	Gds. trilobus	Gtl. insueta	Gds. trilobus	Globigerinoides trilobus(M4)
Miocene	Early	Burdigalian	Rudeis	Mheiherrat / Hawa	Gds. diminutus Gds. Subquadratus	Gds. Subquadratus	Cds. dissimilis	Cds. dissimilis	Gds. altapperturus / Cds. dissimilis	Cds. dissimilis	Cds. dissimilis	Globigerinoides altiaperturus(M3)
Miocene	Early	Aquitanian	Rudeis	Mheiherrat / Hawa	Gds.trilobus trilobus	Gds. diminutus	Gds. primordius	Cds. dissimilis	Cds. dissimilis	Hiatus	Gds. primordius	Globigerinoides primordius(M2)
Miocene	Early	Aquitanian	Nukhul		Gds. primordius	Gds. primordius	Gds. primordius	Gqd. dehiscens dehiscens	Gds. primordius	Gds. primordius	Pgt. kugleri	Paragloborotalia kugleri(M1)

abundant planktonic species (Figs. 4, 5, and 6). It is assigned to the Middle Miocene (Langhian). The *P. sicanus*/*P. glomerosa* Zone is recognized from the upper part of the Rudeis Formation in the three studied wells in the Ras Elush well between 850 and 690 ft (160 ft thick), in the GS 160-2 well between 7780 and 7710 ft (70 ft thick), and in the QQ-89 well from 2950 to 2650 ft (300 ft thick), (Figs. 4, 5, and 6). It is equivalent to *P. glomerosa* of Iaccarino (1985). Berggren et al. (1995) classified the M5 (*Globigerinoides sicanus-Orbulina suturalis*) Zone into two subzones: *G. sicanus-P. glomerosa* (M5a) and *P. glomerosa-O. suturalis* (M5b). In Egypt, this zone could be equated to the *P. glomerosa* Zone of Kerdany (1968) in the Gulf of Suez, and Farouk et al. (2014) in the Nile Delta. This zone is correlated with the lower part of the *G. sicanus*/*Globigerinoides transitoria* Zone of Wasfi (1968), *G. sicanus* Zone of Beckmann et al. (1968) and *P. sicanus*/*O. suturalis* Zone (M5) of Hewaidy et al. (2013). It is equivalent to the *P. glomerosa* (Blow) Zone described by Bolli (1957, 1966), Stainforth et al. (1975), and Postuma (1971).

O. suturalis (M6) Zone

This zone was originally established by Blow and Banner (1966) as the interval from the FO of *O. suturalis* (Brönnimann) to the FO of *Globorotalia peripheroronda* Blow and Banner. The faunal assemblage of this zone in the present study differs from one well to another. In QQ-89, it is common and well preserved, while in GS 160-2, it is rare and poorly preserved (Figs. 5 and 6). The zone is assigned to the Middle Miocene (Langhian) age according to its planktonic foraminiferal content. This zone is recognized from the lower part of the Kareem Formation. In the GS 160-2 well, it is represented by the interval 7710 to 7640 ft (70 ft thick), while in the QQ-89 well, it is represented by the interval 2650 to

Table 3 Comparison of calcareous nannoplankton zones in the present study with the most common zonations in the world

Stage			Bramiette& Wilcoxon(1967) Martini (1971)	Muller (1978)	Okada&Bukry (1980)	Chi (1981)	Stanley& Chi (1983)	Theodooridis (1984)	Holcova (2013)	Present study
Miocene	Middle	Serravallian	*Discoaster exilis* (NN6)	*Sphenolithus heteromorphus* (NN5)	*Discoaster exilis* (CN5a)	*Cyclicargolithus foloridanus*(NN6)	*Cyclicargolithus foloridanus*(NN6)	*Eu-Discoaster exilis*	*Discoaster exilis*(NN6)	*Discoaster exilis*(NN6); Barren
		Langhian	*Sphenolithus heteromorphus* (NN5)	(cont.)	*Sphenolithus heteromorphus* (CN4)	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus*: *Helicosphera waltrane*; *Helicospher perch nielsenia*; *Discoaster singus*; *Helicosphera oblique*	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus* (NN5)
	Early	Burdigalian	*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta* (CN3)	*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta*	*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta* (NN4)
			Sphenolithus belemnos (NN3)	*Sphenolithus belemnos* (NN3)	*Sphenolithus belemnos* (CN2)	*Sphenolithus belemnos* (NN3)	*Sphenolithus belemnos* (NN3)	*Triquetrorhabdulus miliowi*	*Sphenolithus belemnos* (NN3)	*Sphenolithus belemnos* (NN3)
			Discoaster druggii (NN2)	*Discoaster druggii* (NN2)	*Triquetrorhabdulus carinatus* (NN1): *Discoaster druggii* (CN1c)	*Helicosphaera kamptneri*(NN2)	*Helicosphaera kamptneri*(NN2)	*Triquetrorhabdulus carinatus*: *Helicosphaera vedderi*	*Discoaster druggii* (NN2)	*Discoaster druggii* (NN2)
		Aquitanian	*Triquetrorhabdulus carinatus* (NN1)	*Triquetrorhabdulus carinatus* (NN1)	*Discoaster deflandrei*(CN1b); *Cyclicargolithus abisectus* (CN1a)	*Triquetrorhabdulus carinatus* (NN1)	*Triquetrorhabdulus carinatus* (NN1)	*Discoaster druggii*; *Discoaster deflandrei*		*Triquetrorhabdulus carinatus* (NN1)

2320 ft (260 ft) (Figs. 5 and 6). It could be correlated with the *O. suturalis* Zone of Iaccarino (1985), *Globorotalia lobata* Zone (N12) of Kennett and Srinivasan (1983), *Globorotalia fohsi* Zone of Bolli (1966) and Stainforth et al. (1975) and *G. peripheroronda* (M6) Zone of Hewaidy et al. (2013). It is recorded by different authors in Egypt (Haggag et al. 1990; Abu El Enein 1990; Mandur 2004).

Globorotalia praemenardii/G. peripheroronda (M7) Zone

Berggren et al. (1995) defined this zone as the interval from the FO of *G. praemenardii* Cushman and Stainforth to the LO of *G. peripheroronda* Blow and Banner. It is characterized by low abundance and poor preservation of foraminiferal assemblages (Fig. 6). It is recognized from the upper part of the Belayim Formation at the GS 160-2 well only between 7300 and 7190 ft (110 ft thick) (Fig. 6) and is assigned to the Middle Miocene (Serravallian) age according to its planktonic foraminiferal content. It corresponds to the *O. suturalis*/ *G. peripheroronda* Zone of Iaccarino (1985) and *Fohsella peripheroacuta* Zone of Berggren et al. (1995) and Wade et al. (2011) of the Serravallian age. In the Mediterranean region, Kennett and Srinivasan (1983) recorded the *Globorotalia siakensis* Zone (N15) which may be equivalent to this zone.

Calcareous nannofossil biozones

The Miocene calcareous nannofossil assemblages were studied by several workers (Bramlette and Wilcoxon 1967;

Table 4 Comparison of calcareous nannoplankton zones in the present study with the most common zonations in Egypt

Stage			Formation	Kerdany (1968)	El-Heiny& Martini(1981)	Marzouk (1998)	Sadek (2001)	Mandur (2004; 2009)	Marzouk (2009)	Soliman et al.(2012)	Present study
Miocene	Middle	Serravallian	Belayim					*Discoaster exilis* (NN6)	*Calcidiscs premaciniyrei* (MNN6); *Sphenolithus heteromorphus-R.pseudoumbilicus* (MNN6a)	Unzoned	*Discoaster exilis*(NN6); Barren
		Langhian	Kareem	*Micrantholithus vesper*	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus* (MNN5); *H.walbersdorfensis-S.heteromorphus* (MNN5b)	*Sphenolithus heteromorphus* (NN5)	*Sphenolithus heteromorphus* (NN5)
			Rudeis	*Discoaster deflandrei*		*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta* (NN4)	*S.heteromorphus-H.walbersdorfensis* (MNN5a)	*Helicosphaera ampliaperta* (NN4)	*Helicosphaera ampliaperta* (NN4)
	Early	Burdigalian			*Helicosphaera ampliaperta* (NN4)			*Sphenolithus belemnos* (NN3)	*Sphenolithus heteromorphus* (MNN4b)	*Sphenolithus belemnos* (NN3)	*Sphenolithus belemnos* (NN3)
					Sphenolithus belemnos (NN3)	*Sphenolithus belemnos* (NN3)			*H.ampliaperta-S.heteromorphus* (MNN4a); *S.belemnos-S.heteromorphus* (MNN3b)		
						Discoaster druggii (NN2)		*Discoaster druggii* (NN2)	*Sphenolithus belemnos* (MNN3a); *Helicosphaera ampliaperta* (MNN2b)	*Discoaster druggii* (NN2)	*Discoaster druggii* (NN2)
		Aquitanian	Nukhul					*Triquetrorhabdulus carinatus* (NN1)		*T.carinatus* (NN1 or 2)	*Triquetrorhabdulus carinatus* (NN1)

Kerdany 1968; Martini 1971; Muller 1978; Okada and Bukry 1980; El-Heiny and Martini 1981; Chi 1981; Stanley and Chi 1983; Theodoridis 1984; Sadek 2001; Mandur 2004, 2009; Marzouk 2009; Soliman et al. 2012; Holcovkà 2013). Six calcareous nannofossil biozones are recognized on the basis of the zonal scheme of Martini (1971). These biozones are discussed, from base to top as follows:

Triquetrorhabdulus carinatus (NN1) Zone

This zone was assigned to the Late Oligocene to Early Miocene according to its characteristic assemblage (Fig. 7). In the present study, the *T. carinatus* Zone is recorded only from the lower part of the Nukhul Formation at the Ras Elush well between 3200 and 3100 ft (100 ft thick). The absence of *Helicosphaera recta*, *Discoaster druggii*, and *Sphenolithus ciperoensis* suggests an earliest Miocene age for this zone. This zone is recorded in the Gulf of Suez (Arafa 1991; Mandur 2004, 2009), and not recorded by others (Faris et al. 2007, 2009). This is due to the major hiatus near the base of the Nukhul Formation in the region. It is equivalent to the *T. carinatus* Zone of Bramlette and Wilcoxon (1967) and Martini (1971). Also, it corresponds to the *Cyclicargolithus abisectus* (CN1a) and *Discoaster deflandrei* (CN1b) subzones of Okada and Bukry (1980). This zone is equivalent to the *T. carinatus*/*Sphenolithus belemnos* (CNM2) concurrent range Zone of Backman

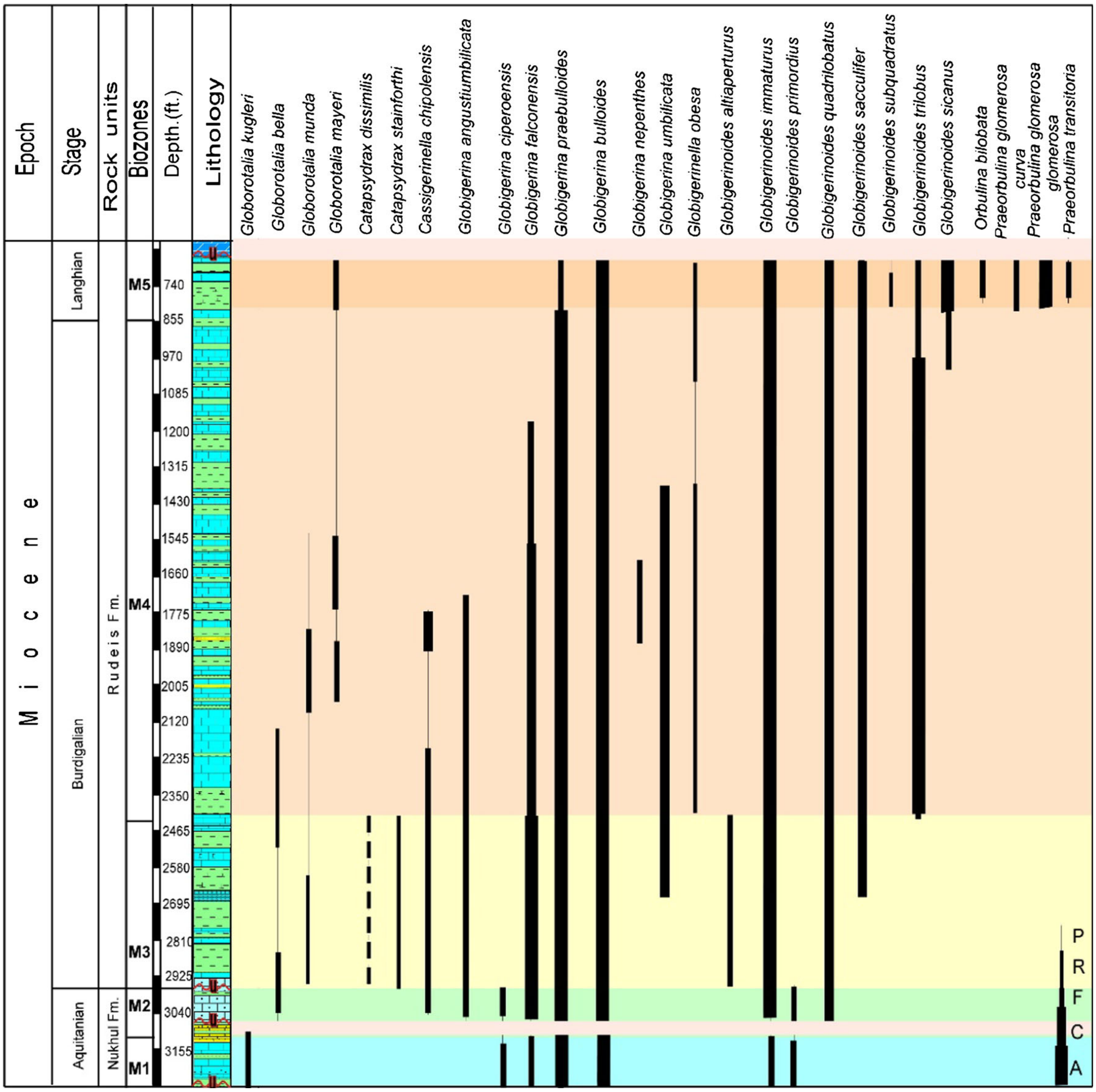


Fig. 4 Distribution chart of the planktonic foraminiferal species recorded in the Ras Elush well

et al. (2012). It equates also with *Sphenolithus delphix* of Gradstein et al. (2012) (Tables 3 and 4).

D. druggii (NN2) Zone

Martini and Worsley (1970) introduced this zone as the interval from the FO of *D. druggii* Bramlette and Wilcoxon to the LO of *T. carinatus* Martini. This zone yielded a poor nannofossil assemblage in the GS 160-2 well, while in the Ras Elush well it includes abundant assemblage (Figs. 7 and 9). It is assigned to the Early Miocene (latest Aquitanian to lower most Burdigalian). In the studied successions, this zone is recorded from the Nukhul Formation in the Ras Elush well between 3060 and 2550 ft (510 ft thick), while in the GS 160-2 well it is represented by the interval form 8130 to 7980 ft (150 ft thick). It is not recorded in the QQ-89 well as this interval is composed of barren sands (Figs. 7, 8, and 9). The FO of *D. druggii* is used to define (NN2) Zone in the zonal scheme of Martini (1971). In the studied wells, the presence of *D. druggii*, *Cyclicargolithus floridanus*, and *Calcidiscus leptoporus* refers to the NN2 Zone which is recorded by some authors in Egypt (e.g., Faris et al. 2007, 2009; Mandur 2004, 2009) (Tables 3 and 4).

S. belemnos (NN3) Zone

This zone was originally established by Bramlette and Wilcoxon (1967) and emended by Martini (1971). It is represented by the interval from the LO of *T. carinatus* Martini to the LO of *S. belemnos* Bramlette and Wilcoxon. It is assigned to the Early Miocene (Burdigalian) age based on its content from the typical Miocene nannofossil taxa, which is characterized by good preservation and common abundance (Fig. 7). This zone is recorded only from the Rudeis Formation in the

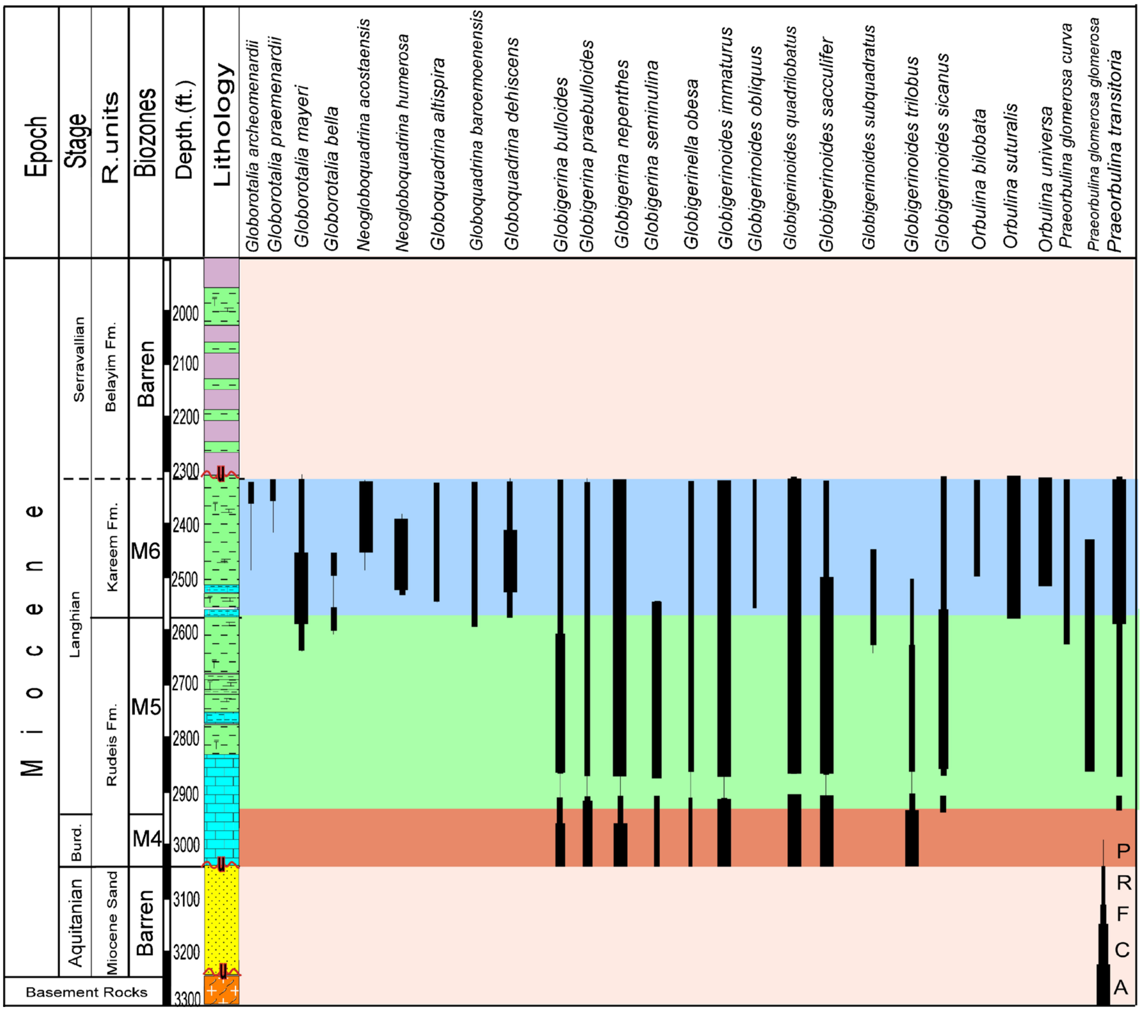


Fig. 5 Distribution chart of the planktonic foraminiferal species recorded in the QQ-89 well

Ras Elush well between 2550 and 2300 ft (250 ft thick), while this zone is not recorded in the GS 160-2 and QQ-89 wells because the Gulf of Suez was characterized by strong rifting during this time (Figs. 7, 8, and 9). This zone is equivalent to the *S. belemnos* NN3 Zone of Bramlette and Wilcoxon (1967), Bukry (1973), Backman et al. (2012), and Holcovkà (2013) (Table 3). Several workers have proposed the FO of *Sphenolilhus belemnos* as an alternative marker bioevent for the NN2/ NN3 boundary (Fornaciari et al. 1993; Fornaciari and Rio 1996; Faris et al. 2009). In the present study, the LO of this species is the marker event for the NN3/NN4 zonal boundary (Martini 1971). It is also equivalent to the *D. deflandrei* Zone of Kerdany (1968) and *S. belemnos* Zone of El-Heiny and Martini (1981), Marzouk (2009), Mandur (2004, 2009), and Faris et al. (2007, 2009) (Table 3).

Helicosphaera ampliaperta (NN4) Zone

Martini (1971) introduced this zone as the interval from the LO of *S. belemnos* Bramlette and Wilcoxon to the LO of *H. ampliaperta* Bramlette and Wilcoxon. This zone is assigned to the Early Miocene (Burdigalian)/Middle Miocene (Langhian) according to its calcareous nannofossil assemblages (Figs. 7, 8, and 9). In the present work, the *H. ampliaperta* Zone is recorded from the Rudeis Formation at the Ras Elush, QQ-89, GS160-2, and QQ-89 wells, with depths from 2300 to 600 ft (1700 ft thick), 3050 to 2650 ft (400 ft thick), and 7980 to 7700 ft (280 ft thick), respectively (Figs. 7, 8, and 9).

It is equivalent to the *H. ampliaperta* NN4 Zone of Bramlette and Wilcoxon (1967), Martini (1971), Raffi et al. (2006), and Holcovkà (2013). In the present study, *H. ampliaperta* Bramlette and Wilcoxon is abundant while *S. belemnos* disappeared. So, the LO of *H. ampliaperta* is considered a more reliable marker event for the *H. ampliaperta* Zone in the investigated subsurface sections. In Egypt, this is equivalent to the *H. ampliaperta* Zone of El-Heiny and Martini (1981), Marzouk 2009), Sadek (2001), Mandur (2009), Faris et al. (2007, 2009), and Soliman et al. (2012) (Tables 3 and 4).

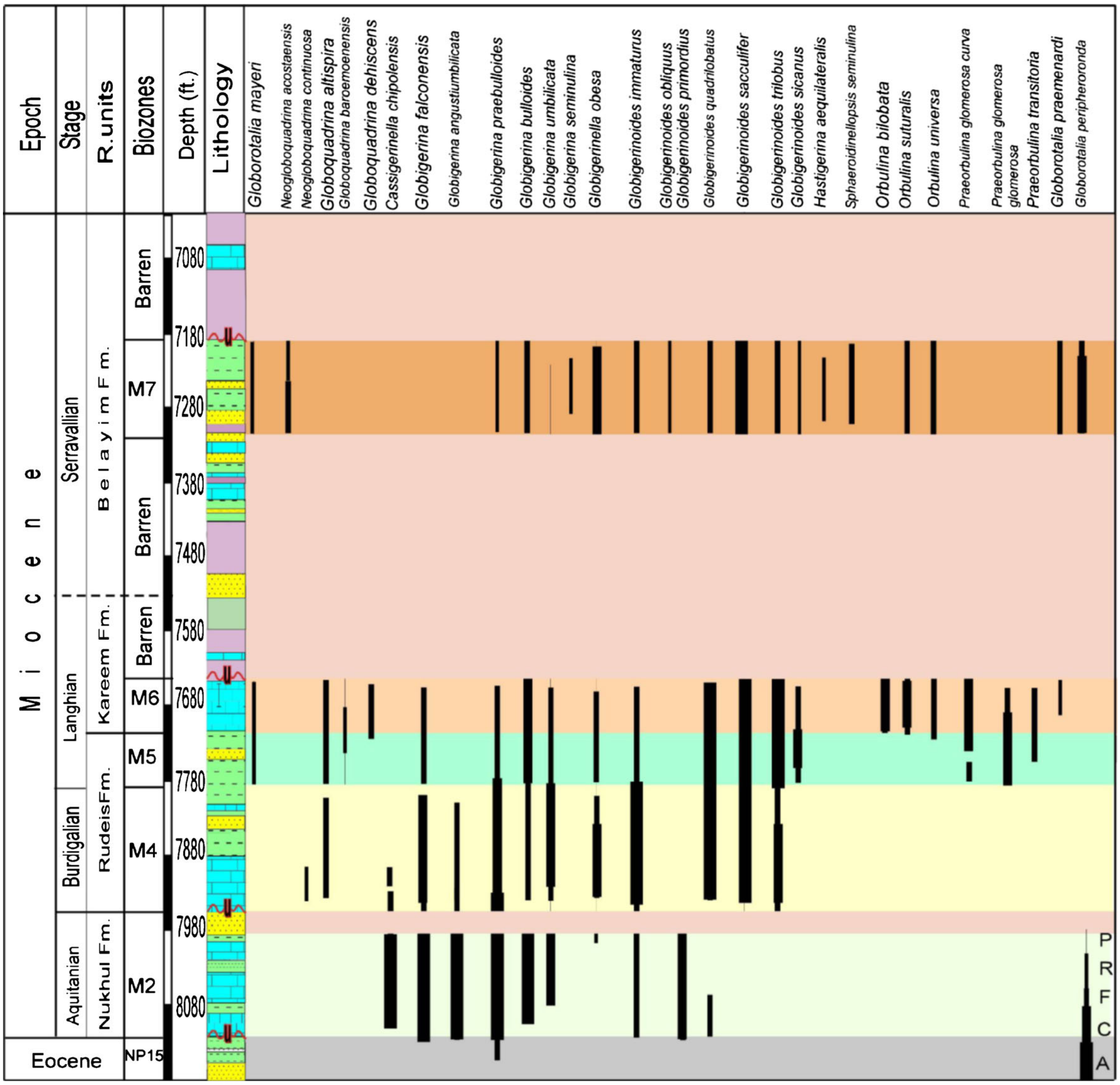


Fig. 6 Distribution chart of the planktonic foraminiferal species recorded in the GS160-2 well

Sphenolithus heteromorphus (NN5) Zone

According to Martini (1971), this zone includes the interval from the LO of *H. ampliaperta* Bramlette and Wilcoxon to the LO of *S. heteromorphus* Deflandre. It is assigned to the Middle Miocene (Langhian) age according to its calcareous nannofossil assemblage (Figs. 8 and 9). In the present study, this zone is recorded from the Kareem Formation at the QQ-89 well from depths of 2650 to 2320 ft (330 ft thick) and the GS 160-2 well from depths of 7700 to 7640 ft (60 ft thick) (Figs. 8 and 9). The LO of *S. heteromorphus* Deflandre is the marker species for the CN4/CN5a and NN5/NN6 zonal boundaries. This zone is equivalent to the *S. heteromorphus* Zone by different authors outside Egypt (Martini 1971; Bukry 1973; Okada and Bukry 1980; Maiorano and Monechi 1998; Backman et al. 2012; Holcovkà 2013) (Table 3). In Egypt, it is also recorded by Sadek (2001), Mandur (2004, 2009), Faris et al. (2007, 2009), and Soliman et al. (2012).

Discoaster exilis (NN6) Zone

The *D. exilis* (NN6) zone was introduced by Hay (1970) and emended by Martini (1974). It is represented by the interval from the LO of *S. heteromorphus* Deflandre and the FO of *Discoaster kugleri* Martini and Bramlette or LO of *C. floridanus* (Roth and Hay). It is assigned to the Middle Miocene (Serravallian) age (Fig. 9). This zone is well defined in the Belayim Formation at the GS160-2 well from depths of 7300 to 7180 ft (120 ft thick) and is not recorded from the other two wells (Fig. 9). It corresponds to the *Discoster exilis* Zone of Martini (1971), Theodoridis (1984), and Holcovkà (2013) (Table 3). In the present study, the top of the NN6 Zone is not detected due to the presence of evaporite

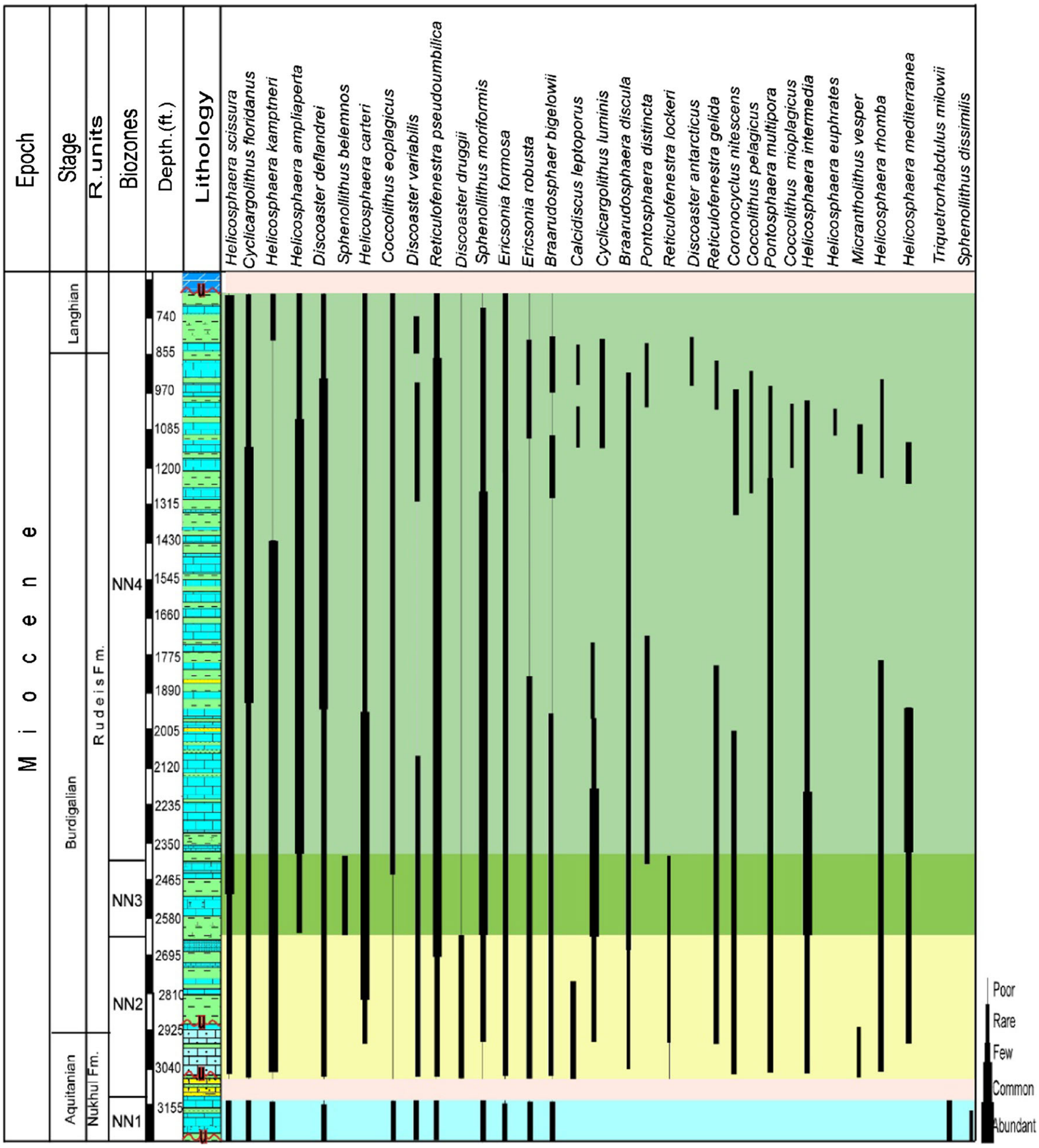


Fig. 7 Distribution chart of the calcareous nannoplankton species recorded in the Ras Elush well

deposits and absence of diagnostic taxa. It matches well with those recorded by Mandur (2004, 2009) and Marzouk (2009) (Table 4).

Stage boundaries

The stratigraphic distribution and integration of the calcareous nannofossil and planktonic foraminiferal assemblages in the Miocene successions of the Gulf of Suez region led to an accurate age assignment and correlation for these successions.

Paleogene/Neogene stage boundary

The Paleogene/Neogene Global boundary Stratotype Section and Point (GSSP) boundary is defined by the planktonic foraminifera at the base of the Aquitanian stage occurs slightly above the FO of *P. kugleri* (Gradstein et al. 2012). In the Ras Elush well, the Aquitanian stage starts at the base of the *P. kugleri* Zone, while in the GS160-2 well, the base of the Aquitanian stage is assigned to the *G. primordius* Zone recorded directly above the Middle Eocene, indicating on a major hiatus between the Paleogene and the Neogene. This was observed previously by different authors in the Gulf of Suez region (Haggag et al. 1990;

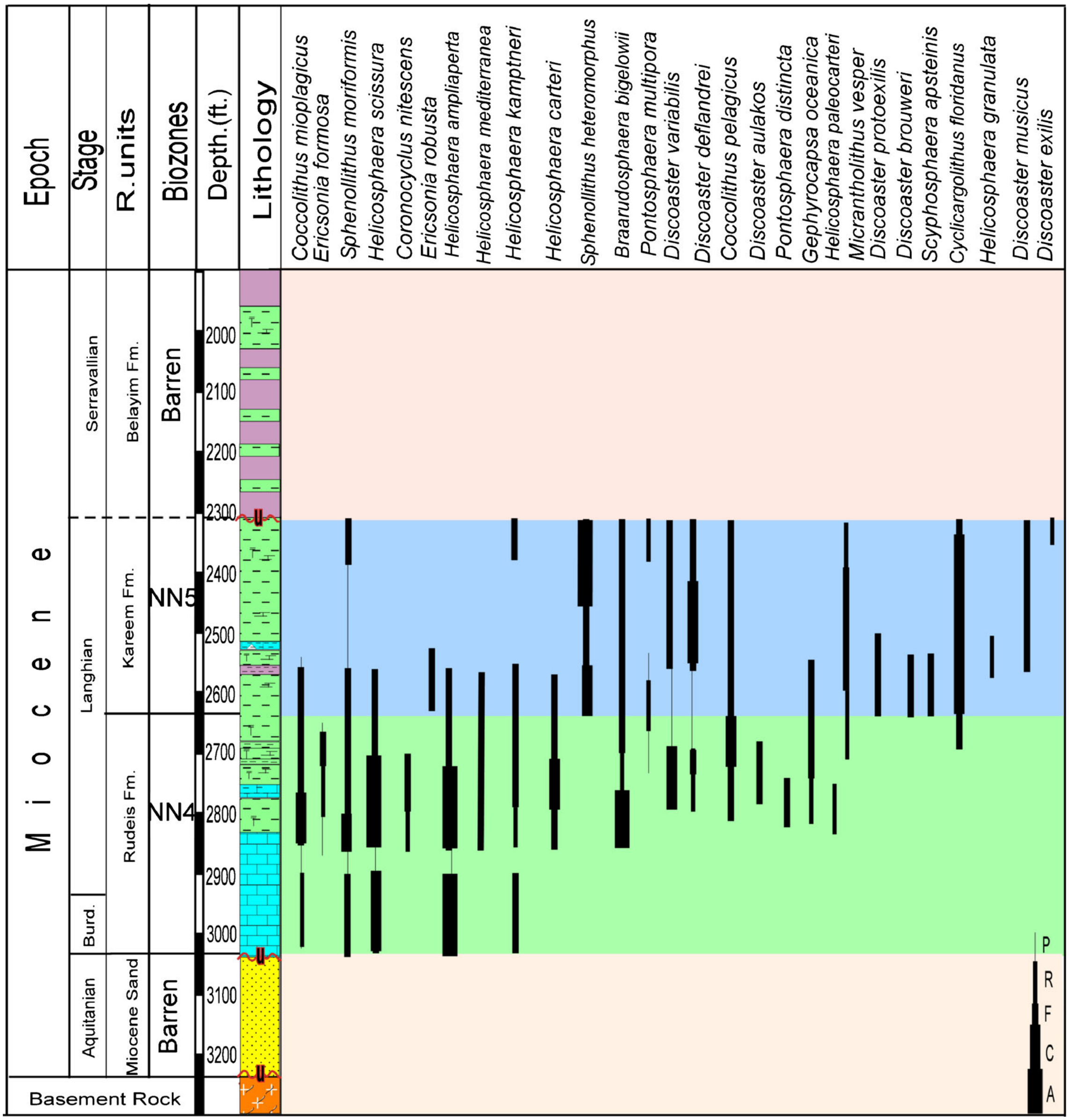


Fig. 8 Distribution chart of the calcareous nannoplankton species recorded in the QQ-89 well

Phillip et al. 1997; Mandur 2009; Hewaidy et al. 2012), indicating a major unconformity with different magnitudes. By means of calcareous nannofossil, the Paleogene/Neogene GSSP boundary is formally defined in the Lemme-Carrosio section in northern Italy at the FO of *Sphenolithus capricornutus* (Gradstein et al. 2012). Actually, this species is not recorded in the present study, but the base of the Aquitanian stage is defined by the LO of *H. recta* (Haq) and *D. druggii* (Bramlette and Wilcoxon). The Aquitanian stage unconformably overlies the Middle Eocene calcareous nannofossils NP15 Zone at the GS 160-2 well.

The Aquitanian stage is recognized at the Nukhul Formation between the planktonic foraminiferal zones *P. kugleri* (M1) and *G. primordius* (M2), which is equivalent to the calcareous nannofossil zones *T. carinatus* (NN1) and the lower part of the *D. druggii* (NN2) (Fig. 10).

Aquitanian/Burdigalian stage boundary

Until now, the GSSP Aquitanian/Burdigalian boundary is not defined (Gradstein et al. 2012). In the Gulf of Suez region, the distribution, lithology, and faunal content of the Burdigalian deposits indicate that a regional subsidence of the basin accompanied by an extensive transgression took place at the end of the Aquitanian (Ouda and Masoud 1993).

Berggren et al. (1995) proposed that the LO of *P. kugleri* can be used to define the Aquitanian/Burdigalian boundary.

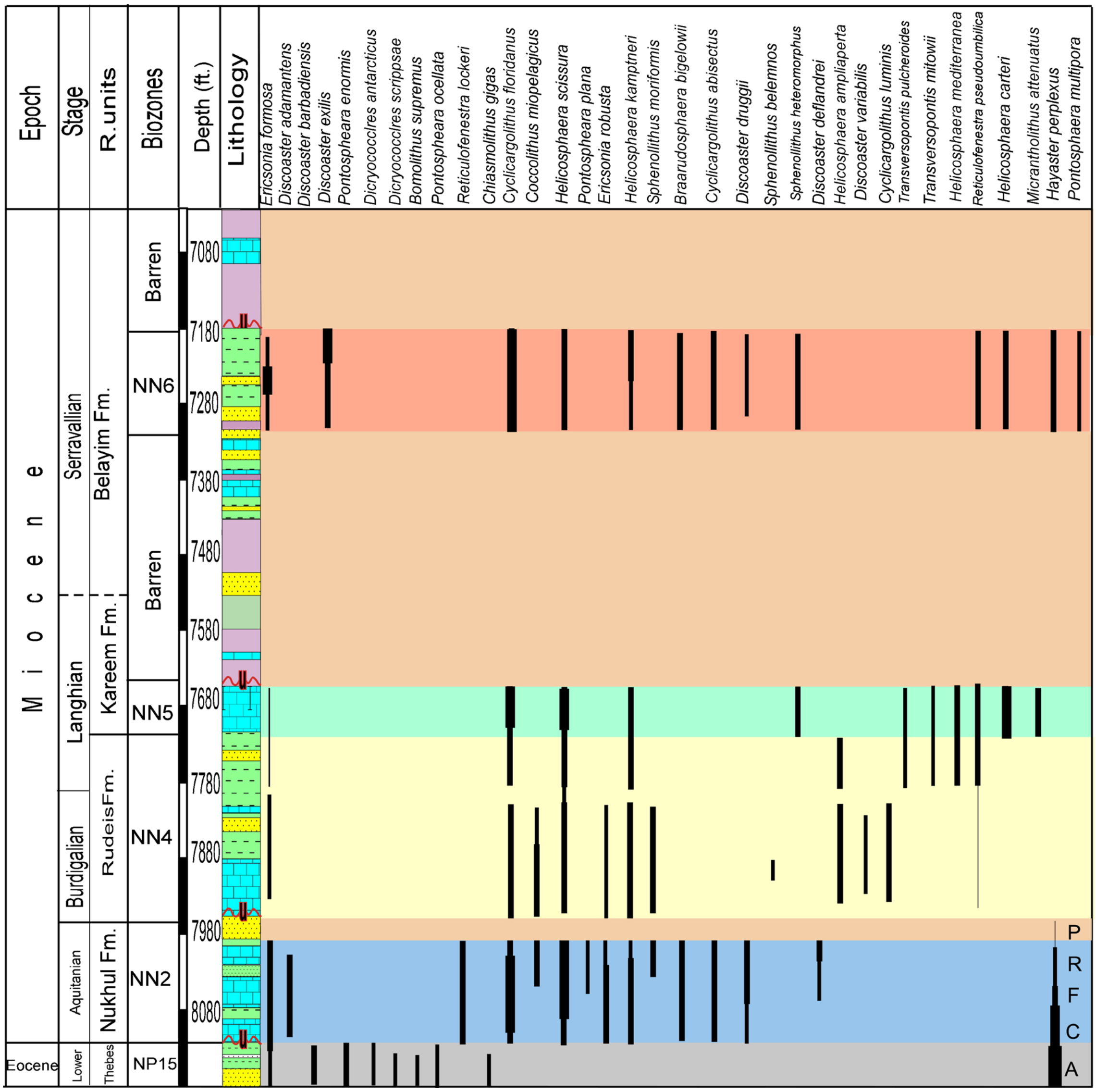


Fig. 9 Distribution chart of the calcareous nannoplankton species recorded in the GS 160-2 well

Actually, the *P. kugleri* is rarely found in the Gulf of Suez region (Hewaidy et al. 2012). They placed the Aquitanian/Burdigalian boundary at the FO *Globigerinatella insueta* and common occurrence of *C. dissimilis*. In the present study, based on the planktonic foraminifera, the base of the Burdigalian stage is delineated by the FO of *G. altiaperturus* and *C. dissimilis* near the top of the *D. druggii* Zone.

Burdigalian/Langhian stage boundary

Two potentially suitable sections for defining the Langhian GSSP are the downward extension of the La Vedova beach section in northern Italy and St. Peter's Pool in Malta (Gradstein et al. 2012). The Burdigalian/Langhian stage boundary is placed at the first appearance of *Paraeorbulina glomerosa* Blow (Iaccarino 1985; Rögl 1985; Melillo 1988; Haggag et al. 1990; Hewaidy et al. 2013). Many authors, e.g., Blow (1969, 1979), Banner and Blow (1965), Bolli (1970), Ayyad (1983), and Kennett and Srinivasan (1983) placed the Burdigalian/Langhian boundary at the first appearance of *O. suturalis* Brönnimann. On the basis of calcareous nannofossil, the Burdigalian/Langhian boundary coincides with the *H. ampliaperta* (NN4)/*S. heteromorphus* (NN5) zonal boundary (Fornaciari et al. 1996; Mandur 2009; Sadek 2001; El Deeb et al. 2004; Gradstein et al. 2012).

Marzouk (1998) placed the Burdigalian/Langhian boundary at the top of the *H. ampliaperta* (NN4) Zone. This boundary should be placed at the base of the *S. heteromorphus* (NN5) zone (El-Heiny and Martini

1981). Faris et al. (2007) recorded the Burdigalian/Langhian boundary at the base of the *Globorotalia fohsi peripheroronda* Zone by planktonic foraminifera and within the *H. ampliaperta* Zone (NN4) by calcareous nannofossil. Faris et al. (2009) placed the boundary at the base of the *O. suturalis* Zone. In the present study, the Burdigalian/Langhian boundary is recognized on the basis of planktonic foraminifera by the FO of *P. glomerosa* (Blow). By means of calcareous nannofossil, this boundary lies at the top of *H. ampliaperta* Bramlette and Wilcoxon, at the GS 160-2 and QQ-89 wells at the top of the Rudeis Formation.

The Early Langhian Kareem Formation at GS160-2 and QQ-89 includes the calcareous nannofossil *H. ampliaperta* Zone which is equivalent to the top of the *P. sicanus*/*P. glomerosa* (M5) Zone and the *S. heteromorphus* Zone matching well with the *O. suturalis* (M6) Zone.

Langhian/Serravallian stage boundary

The Serravallian GSSP was defined at the top of the transitional bed between the *Globigerina* Limestone and Blue Clay Formation in the Ras-il-Pellegrin section at Malta (Gradstein et al. 2012). On the basis of the planktonic foraminifera, the Langhian/Serravallian boundary falls within the upper part of the *O. suturalis*/*G. peripheroronda* Zone of the Mediterranean zonal scheme proposed by Iaccarino and Salvatorini (1982) which is recently emended by Iaccarino et al. (2005). In Egypt, the Langhian/Serravallian boundary by means of planktonic foraminifera is placed at the first appearance of the *Orbulina universa* Zone of Said and El Heiny (1967) or at the first appearance the *G. fohsi* and *Globorotalia peripheroacuta* zones (Hewaidy et al. 2013). The Langhian/Serravallian boundary is recognized by calcareous nannofossil at the LO of *S. heteromorphus* Deflandre (Lourens et al. 2004; Mandur 2009).

In the present study, we can expected the Langhian/Serravallian boundary between the strong vertical facies changes at the Kareem/Belayim formational boundary between interval barren below directly the FO of the calcareous nannofossil *D. exilis* Zone (NN6) and the FO of the planktonic foraminiferal *G. peripheroronda*/*G. praemenardii* (M7) in zone, which was recorded at the GS 160-2 well (Fig. 10).

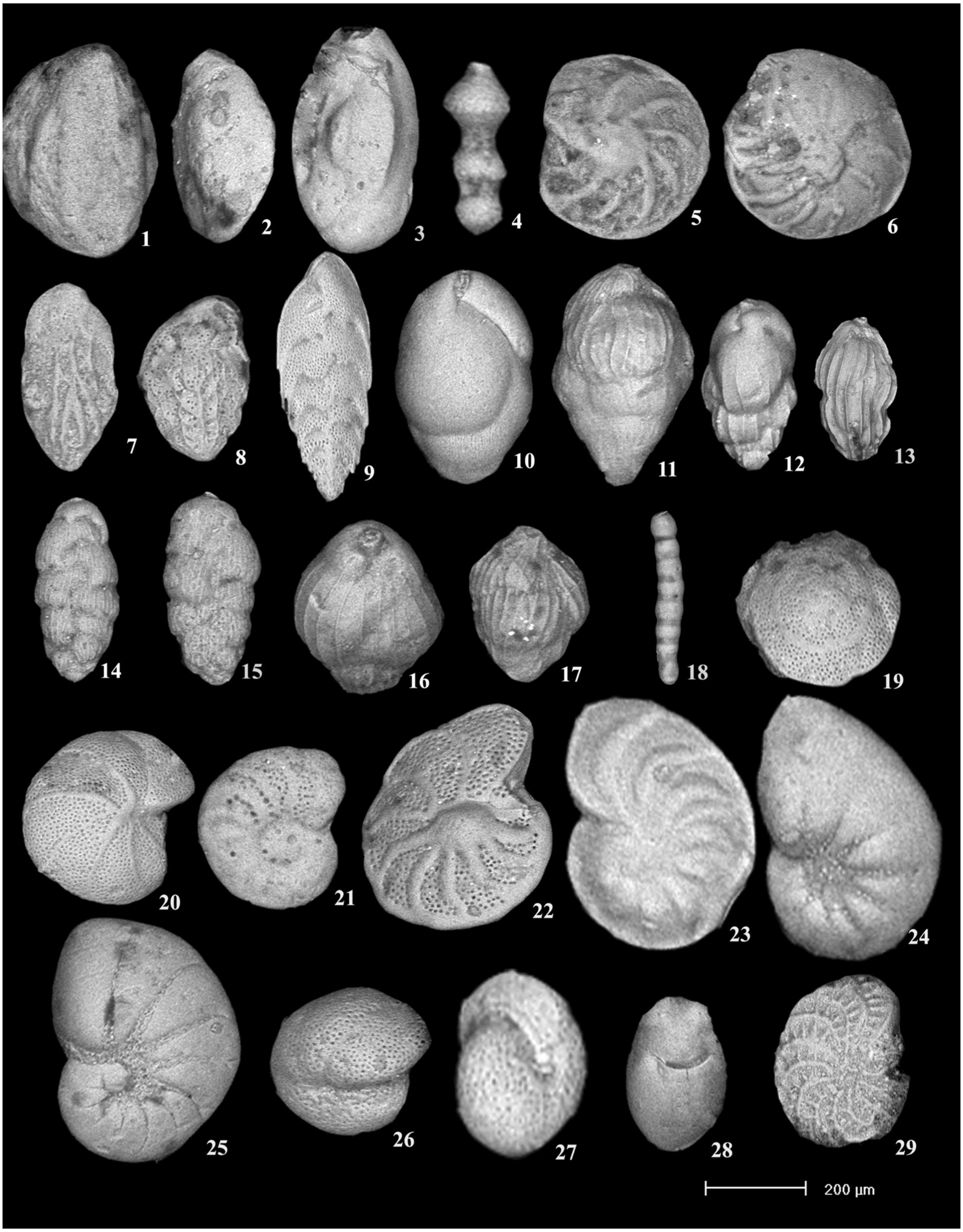
Environmental interpretations

The paleoenvironments in the present study was determined based on integrated lithologic, biostratigraphic, gamma ray log, benthic biofacies, planktonic/benthic ratio which is expressed as $100\times P/(P+B)$, abundance, and diversity parameters. These procedures are explained by several authors (Culver 1988; Armentrout 1996; Leckie and Olson 2003; Miller et al. 2008); Hewaidy et al. 2013 and Farouk et al. 2014).

Plate 1 *1 Quinqueloculina cuvieriana* d'Orbigny, 1839, QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2410 ft. *2 Quinqueloculina juleana* d'Orbigny, 1846, GS 160-2 well, Middle Miocene (Langhian), Kareem Formation, depth 7690 ft. *3 Quinqueloculina seminulua* (Linnaeus, 1758), GS 160-2 well, Early Miocene (Aquitanian), Nukhul Formation, depth 8080 ft. *4 Nodosaria soluta* (Reuss, 1851), QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2500 ft. *5 Lenticulina antipodum* (Stache, 1865), Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1470 ft. *6 Lenticulina iota* (Cushman, 1923), Ras Elush well, Early Miocene (Aquitanian), Nukhul Formation, depth 3120 ft. *7–8 Bolivina fastigla* Cushman, 1953, Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1550 ft. *9 Bolivina superba* Emiliani, 1949, Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1670 ft. *10 Bulimina pupoides* d'Orbigny, 1846, Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1770 ft. *11 Bulimina striata* d'Orbigny, 1846, QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2440 ft. *12 Uvigerina barbatula barbatula* Macfadyen, 1930, QQ-89 well, Middle Miocene (Langhian), Rudeis Formation, depth 2700 ft. *13 Uvigerina coastat* Bieda, 1936, GS 160-2 well, Early Miocene (Aquitanian), Nukhul Formation, depth 8040 ft. *14–15 Uvigerina pygmoides* Papp & Turnovsky, 1953, QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2440 ft. *16 Uvigerina striatissima* Perconing, 1955, Ras Elush well, Early Miocene (Aquitanian), Nukhul Formation, depth 3020 ft. *17 Uvigerina venusta* Franzenau, 1894, GS 160-2 well, Early Miocene (Aquitanian), Nukhul Formation, depth 8020 ft. *18 Stilostomella subspinosa* (Cushman, 1943) Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1200 ft. *19–20 Eponides repandus* (Fichtel & Moll, 1798), Ras Elush well, Early Miocene (Aquitanian), Nukhul Formation, depth 3030 ft. *21 Cibicides boueanus* (d'Orbigny, 1826), Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1510 ft. *22 Cibicides ellisi ellisi* Souaya, 1965, GS 160-2 well, Early Miocene (Burdigalian), Rudeis Formation, depth 7980 ft. 23. *Cibicides ellisi graysoni* Souaya, 1965, QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2740 ft. *24 Nonion scaphum* (Fichtel and Moll, 1798), Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1950 ft. *25 Nonionella spissa* Cushman, 1931, Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1990 ft. *26–27 Melonis pompiloides* Fichtel and Moll, 1803, Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 2940 ft. *28 Chilostomella czizecki* Reuss, 1850, QQ-89 well, Middle Miocene (Langhian), Rudeis Formation, depth 2800 ft. *29 Elphidium pustullosum* Cushman & Mcculloch, 1940, QQ-89 well, Middle Miocene, (Langhian), Rudeis Formation, depth 3030 ft

Environmental interpretation of the Nukhul Formation

The Nukhul Formation is bounded at the base by a major unconformity surface separating the syn-rift basal Nukhul Formation from the underlying pre-rift sediments of the Middle Eocene with different magnitudes related to the early clysmic tectonic rift event (Garfunkel and Bartov 1977; Evans 1988; El-Azabi



2004; Bosworth et al. 2005; Hewaidy et al. 2012). The Nukhul Formation includes two ecozones in the Ras Elush well (named as Ec-R1 and Ec-R2) intercalated with a barren interval, while the Nukhul Formation is not recorded in the QQ-89 well. In the GS-160-2 well, it includes only one ecozone (Ec-G1).

Environmental interpretation of the Nukhul Formation in the Ras Elush well

In the Ras Elush well, the Nukhul Formation is subdivided into two ecozones (Ec-R1 and Ec-R2) intercalated by a barren interval.

Ec-R1 The Ec-R1 ecozone is recorded from the lower part of the Nukhul Formation (*P. kugleri* Zone of the Aquitanian age). It consists mainly of dark shale intercalated with white limestone between 3200 and 3100 ft depth (Fig. 11). This ecozone is characterized by low diversity (8–12 species with planktic/benthic ratio of 40-60 %). It is dominated by different *Lenticulina* species (*Lenticulina antipodum*, *Lenticulina budensis*, and *L. incrustatus*), representing about 60 % of the total benthic foraminiferal groups (Fig. 12). The dominant *Lenticulina* group reflects a middle neritic environment (Reolid 2008). The assemblage of this ecozone includes in addition to the *Lenticulina* group about 40 % of other different species (*Bulimina striata*, *Bulimina elongata*, and *Rectuvigerina krachemensis*). The benthic foraminiferal associations are generally small sized, except the *Lenticulina* spp. which displays a normal size. Planktonic foraminifers include small primitive "*Globigerina* forms." Based upon the abovementioned characters, a middle neritic environment is suggested for the lower part of the Nukhul Formation in the Ras Elush well (Fig. 17).

Barren interval 1 It consists of sandstone with shale at the interval between 3100 to 3070 f. (30 f. thick) depth at Ras Elush well. The sandstone is barren of any foraminiferal tests reflecting a coastal marine environment (Fig. 11). The lithofacies characters indicate a gradual regression with increasing terrigenous influx.

Ec-R2 The Ec-R2 ecozone is recorded from the upper part of the Nukhul Formation at the Ras Elush well. This part is attributed to the *G. primordius* Zone of the Aquitanian age. It consists of limestone with shale and sand intercalations at the interval from 3070 to 2950 ft (120 ft thick) depth. It is characterized by dominant occurrence of unkeeled planktonic foraminiferal groups (*Globigerina* and *Globigerinoides*) with low diversity (18–22 species) (Fig. 11). It is characterized by dominant occurrence of the benthic foraminiferal assemblages as the *Cibicides* group 60 % (*Cibicides gibbosus*, *Cibicides dutemplei*, *Cibicides ellisi*), in addition to 30 % of *Quinqueloculina seminulua* and *Q. oblonga* and 10 % of *B. striata* (Fig. 12). *Quinqueloculina seminula* and *Quinqueloculina* spp. were recorded at water depths of 30–60 m by Gevirtz (1969) and Buck et al. (1999). A middle neritic environment is suggested for this ecozone based on the abovementioned characters (Fig. 17).

Environmental interpretation of the Nukhul Formation in the GS 160-2 well

EC-G1 Towards the tectonically paleo-low at the GS160-2 well: The EC-G1 ecozone is characterized by (1) common occurrence of unkeeled planktonic foraminifera (*Globigerina* and *Globigerinoides*), (2) high diversity of species (30–35 species), (3) dominance of the *Uvigerina* benthic foraminiferal group representing about 70 % (*U. pygmoides*, *U. asperula*, *U. semiornata*, *U. venusta*, and *U. barbatula*) in addition to 30 % of species of *Bulimina*, *Stilostomella*, and *Bolivina* (Figs. 13 and 14). It indicates an outer neritic environment for this ecozone (Fig. 17).

Barren interval 2 The upper part of the Nukhul Formation at the GS160-2 well is found barren of foraminifera. It consists of sandstone with shale at the interval between 7980 and 7950 ft depth (30 ft thick) at the GS 160-2 well. The sandstone is barren of any foraminiferal tests reflecting a coastal marine environment (Fig. 13).

Environmental interpretation of the Rudeis Formation

This formation includes two ecozones in the three studied wells, the Ras Elush well (Ec-R3 and Ec-R4), QQ-

Plate 2 *1–2 Globorotalia mayeri* Cushman & Ellisor, 1939, QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2450 ft. *3–4 Globorotalia munda* Jenkins, 1966, Ras Elush well, Early Miocene (Aquitanian), Nukhul Formation, depth 3030 ft. *5 Paragloborotalia kugleri* Bolli 1957, Ras Elush well, Early Miocene (Aquitanian), Nukhul Formation, depth 3200. *6 Neogloboquadrina humerosa* Takayanagi & Saito, 1962, QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2440 ft. *7 Globigerina ciperoensis* Bolli 1954, Ras Elush well, Early Miocene, (Aquitanian), Nukhul Formation depth 2980 ft. *8–9 Globigerina bulloides* d'Orbigny 1826 Ras Elush well, Early Miocene (Burdigalian), Nukhul Formation depth 2290 ft. *10 Globigerina nepenthes* Todd 1957, Ras Elush well, Early Miocene, (Burdigalian), Rudeis Formation, depth 1710 ft. *11–12 Globigerina seminulina* Schwager 1866 QQ-89 well, Middle Miocene (Langhian), Rudeis Formation, depth 2650 ft. *13 Globigerinella obesa* (Bolli 1957), Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 1430 ft. *14–15 Globigerinoides altiapertura* (Bolli 1957), G S 160–2 well, Early Miocene (Burdigalian), Rudeis Formation, depth 2870 ft. *16–17 Globigerinoides immaturus* (Le Roy, 1939) QQ-89 well, Middle Miocene (Langhian), Rudeis Formation, depth 2770 ft. *18–19 Globigerinoides primordius* (Blow and Banner, 1962), GS 160-2 well, Early Miocene (Aquitanian), Nukhul Formation, depth 8120 ft. *20 Globigerinoides subquadratus* Brönnimann, 1954, Ras Elush well, Middle Miocene (Langhian), Rudeis Formation, depth 800 ft. *21–22 Globigerinoides trilobus* Reuss, 1850, Ras Elush well, Early Miocene (Burdigalian), Rudeis Formation, depth 2200 ft. *23 Sphaeroidinellopsis seminulina* (Schwager, 1866), GS 160-2 well, Middle Miocene (Serravallian), Belayim Formation, depth 7260 ft. *24 Orbulina bilobata* d'Orbigny, 1846, QQ-89 well, Middle Miocene (Langhian), Kareem Formation, depth 2380 ft. *25 Orbulina suturalis* Brönnimann, 1951, QQ-89 well, Middle Miocene (Serravallian), Belayim Formation, depth 2340 ft. *26 Praeorbulina glomerosa* curva Blow 1956 Ras Elush well, Middle Miocene (Langhian), Rudeis Formation, depth 670 ft. *27 Praeorbulina transitoria* Blow 1956 Ras Elush well, Middle Miocene, (Langhian), Rudeis Formation, depth 700 ft ▶

89 well (Ec-Q1 and EC-Q2), and GS-160-2 well (Ec-G2 and Ec-G3).

Environmental interpretation of the Rudeis Formation at the Ras Elush well

Ec-R3 This ecozone is recorded only from the lower part of the Rudeis Formation (*G. altiaperturus* Zone of the Burdigalian age) at the Ras Elush well. It consists mainly of shale with about 480 ft thick from depths of 2950 to 2420 ft. It is characterized by the dominant presence of unkeeled planktonic foraminiferal genera (*Globigerina*, *Globigerinoides*, and *Catapsydrax* species). It is characterized by 55–45 % of the P/B ratio with middle diversity (22–23 species, with a total of 11–13 benthic species). The dominant benthic foraminiferal groups are *Lenticulina* and *Uvigerina* representing about 80 % (*L. antipodum*, *L. budensis L. incrustatus*, *Uvigerina striatissima*, *U. pygmoides Uvigerina fastigla*, and *U. barbatula*), in addition to 20 % of *C. dutemplei*, *Bolivina shukrii*, and *Nonion scaphum* (Figs. 11 and 12). These characters reflect a middle to outer neritic paleoenvironments (Farouk et al. 2014).

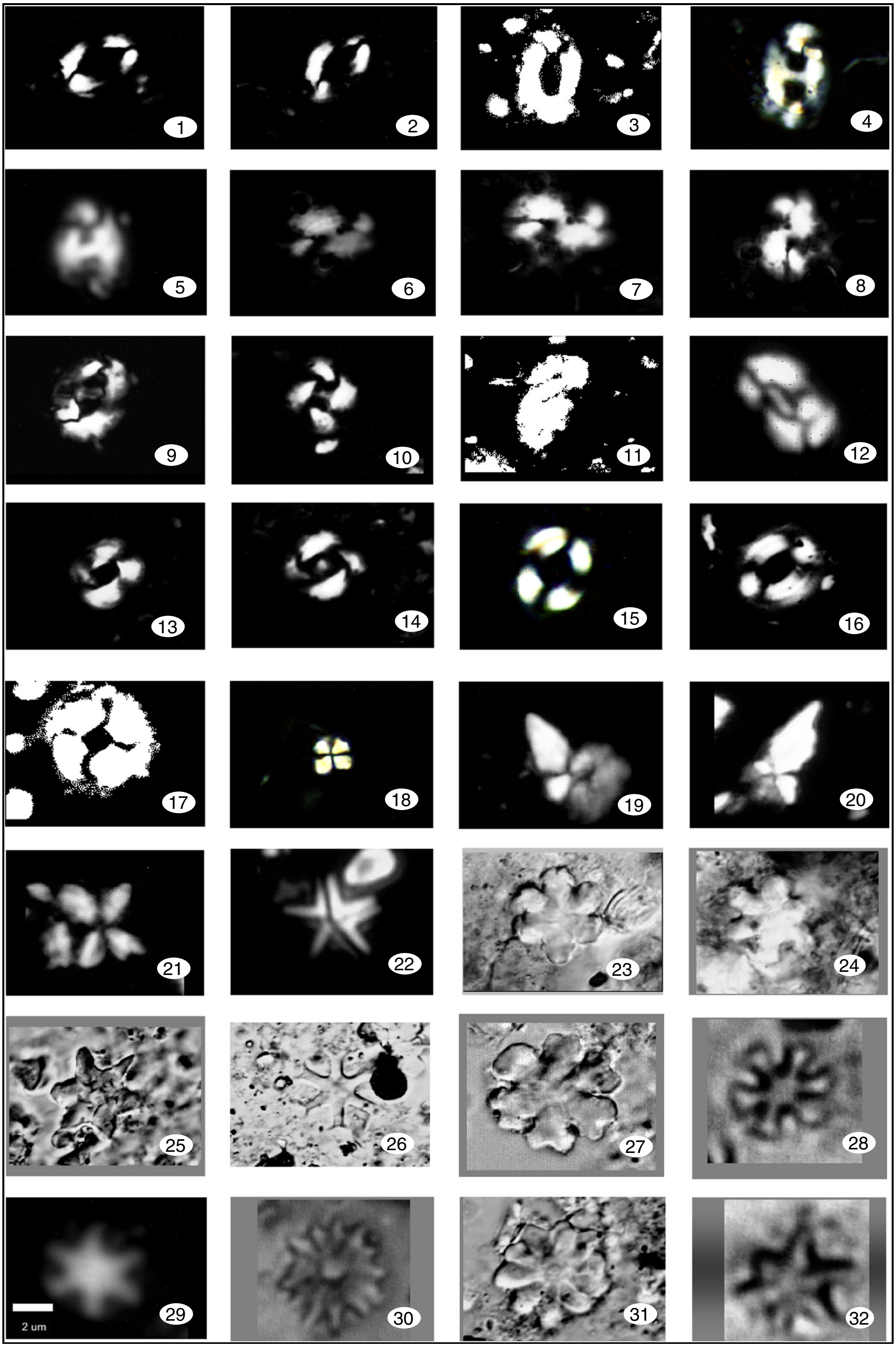
Ec-R4 This ecozone is represented by the interval from 2420 to 700 ft depth and covers the middle and upper parts of the Rudeis Formation in that well and it is equivalent to the planktonic foraminiferal zones *G. trilobus*/*Globigerinoides sicana* and *P. glomerosa*. It is characterized by (1) presence of unkeeled planktonic foraminiferal genera (*Globigerina*, *Globgerinoides*, and *Globorotalia*) with notated high abundance of *Globigerinoides sacculifer* and *G. trilobus* (65–80 %), (2) high diversity of species (70–85 species), (3) dominant occurrence of the benthic foraminiferal groups *Bolivina* and *Uvigerina* which are represented by about 75 % (*Bolivina dilatata*, *Bolivina catanensis*, *Bolivina superba*, *B. shukrii*, *Bolivina fastigla*, *B. elongata*, *U. striatissima*, *U. pygmoides*, *U. semiornata*, and *U. costata*), in addition to *B. elongata*, *B. striata*, *Lenticulina incrustatus*, *Eponides repandus*, *Stilostomella ovicula*, *S. solute*, and *Siphonina reticulate* (Fig. 12). These characters reflect an outer neritic paleoenvironment (Figs. 11 and 17).

Environmental interpretation of the Rudeis Formation in the QQ-89 well

Ec-Q1 This ecozone is recorded from the middle part of the Rudeis Formation (*G. trilobus* and lower part of *P. sicanus*/*P. glomerosa* zones of the Burdigalian to Langhian ages). It consists of white limestone, highly sandy, locally cherty, from depths of 3050 to 2850 ft. It is characterized by the presence of unkeeled planktonic foraminiferal genera (*Globigerina*, *Globgerinoides*, and *Globorotalia*) with dominant occurrence of *Globigerinoides* (75 %). The Ec-Q1 ecozone is characterized by very low diversity (3–5 benthic species) represented by the dominant occurrence of *Chilostomella czizecki* (50 %), in addition to *C. ellisi*, *Cibicides ellisi graysoni*, *Cibicides nucleates*, *C. dutemplei*, *Nodosaria soluta*, (50 %),(Fig. 16). The *Chilostomella*, and *Cibicides* assemblage with low diversity reflecting an inner shelf environment (Brunner 1992).

Ec-Q2 This ecozone is recorded in the upper part of the Rudeis Formation at the interval from depths of 2850 to 2650 ft (*P. sicanus*/*P. glomerosa* Zone of the Langhian age), which consists mainly of claystone and shale rich in microfossils. It is characterized by presence of (1) dominant unkeeled planktonic foraminiferal genera (*Globgerinoides* and *Orbulina* representing about 70–80 % of the fauna), (2) high diversity (35–45 species), (3) dominant occurrence of the benthic foraminiferal groups *Bolivina* and *Uvigerina* (*Uvigerina pygmoides*, *U. semiornata*, *U. asperula*, *U. barbatula*, *U. coastata*, *B. dilatata*, *B. superba*, *B. fasitgla*, *B. catanensis*, *B. shukrii*, and *B. superba*) (Figs. 15 and 16). The

Plate 3 *1–3 Helicosphaera ampliaperta* (Bramlette and Wilcoxon 1967) ▶ 1, GS 160-2 well, Rudeis Formation, Early Miocene (Burdigalian), depth 7700 ft. *2–3* Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 900 and 1740 ft. *4–5 Helicosphaera mediterranea* (Muller, 1981). *4* Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 2350 ft. *5* QQ-89 well, Rudeis Formation, Middle Miocene, (Langhian), depth 2590 ft. *6 Helicosphaera ampliaperta* (Bramlette and Wilcoxon 1967), GS 160-2 well, Rudeis Formation, Early Miocene (Burdigalian), depth 7700 ft. *7–8 Helicosphaera carteri* (Wallich 1877) Kamptner, 1954 7. GS 160-2 well, Kareem Formation, Middle Miocene (Langhian), depth 7680 ft. *8* QQ-89 well, Kareem Formation, Middle Miocene (Langhian), depth 2400 ft. *9–10 Helicosphaera euphratis* (Haq, 1966). *9* Ras Elush well, Nukhul Formation, Early Miocene (Aquitanian), depth 3040 ft. 10. Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 1120 ft. *11–12 Helicosphaera rhomba* (Bukry, 1971), 11. Ras Elush well, Nukhul Formation, Early Miocene (Burdigalian), depth 1200 ft. *12* Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 2250 ft. *13 Reticulofenestra pseudoumblica* (Gartner, 1967), Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 970 ft. *14 Reticulofenestra lockeri* (Müller, 1970), GS 160-2 well, Nukhul Formation, Early Miocene (Aquitanian), depth 8080 ft. *15 Ericsonia robusta* (Bramlette & Sullivan, 1961), GS 160-2 well, Nukhul Formation, Early Miocene (Aquitanian), depth 7800 ft. *16 Coccolithus miopelagicus* (Bukry, 1971), QQ-89 well, Rudeis Formation, Middle Miocene (Langhian), depth 2800 ft. *17 Ericsonia formosa* (Kamptner, 1963 Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 1660 ft. *18 Sphenolithus moriformis* (Bronnimann and Stradner, 1960) GS 160-2 well, Rudeis Formation, Middle Miocene (Langhian), depth 7900 ft. *19–21 Sphenolithus heteromorphus* (Deflandre, 1953). *19* GS 160-2 well, Rudeis Formation, Early Miocene (Burdigalian), depth 7820 ft. *20–21* QQ-89 well, Kareem Formation, Middle Miocene (Langhian), depth 2350 and 2600 ft. *22 Micrantholithus vesper* (Deflander, 1950), Ras Elush well, Kareem Formation, Middle Miocene (Langhian), depth 2600 ft. *23–25 Discoaster druggii* (Bramlette and Wilcoxon 1967), 23. Ras Elush well, Nukhul Formation, Early Miocene (Aquitanian), depth 2950 ft. *24–25* GS 160-2 well, Nukhul Formation, Early Miocene (Aquitanian), depth 8010 ft. *26 Discoaster variabilis* (Martini & Bramlette, 1963), Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 950 ft. *27 Discoaster deflandrei* (Briolette & Riedel, 1954), QQ-89 well, Kareem Formation, Middle Miocene (Langhian), depth 2400 ft. *28 Discoaster aulakos* (Gartner, 1967), QQ-89 well, Rudeis Formation Middle Miocene (Langhian), depth 2780 ft. *29 Discoaster adamanteus* (Bramlette and Wilcoxon 1967), Ras Elush well, Rudeis Formation, Early Miocene (Burdigalian), depth 1240 ft. *30–31 Discoaster barbadiensis* (Tan, 1927), GS 160-2 well, Eocene, depth 8180 ft. *32 Discoaster exilis* (Martini & Bramlette, 1963), GS 160-2 well, Belayim Formation, Middle Miocene (Serravallian), depth 7250 ft


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
2 um
30
31
32

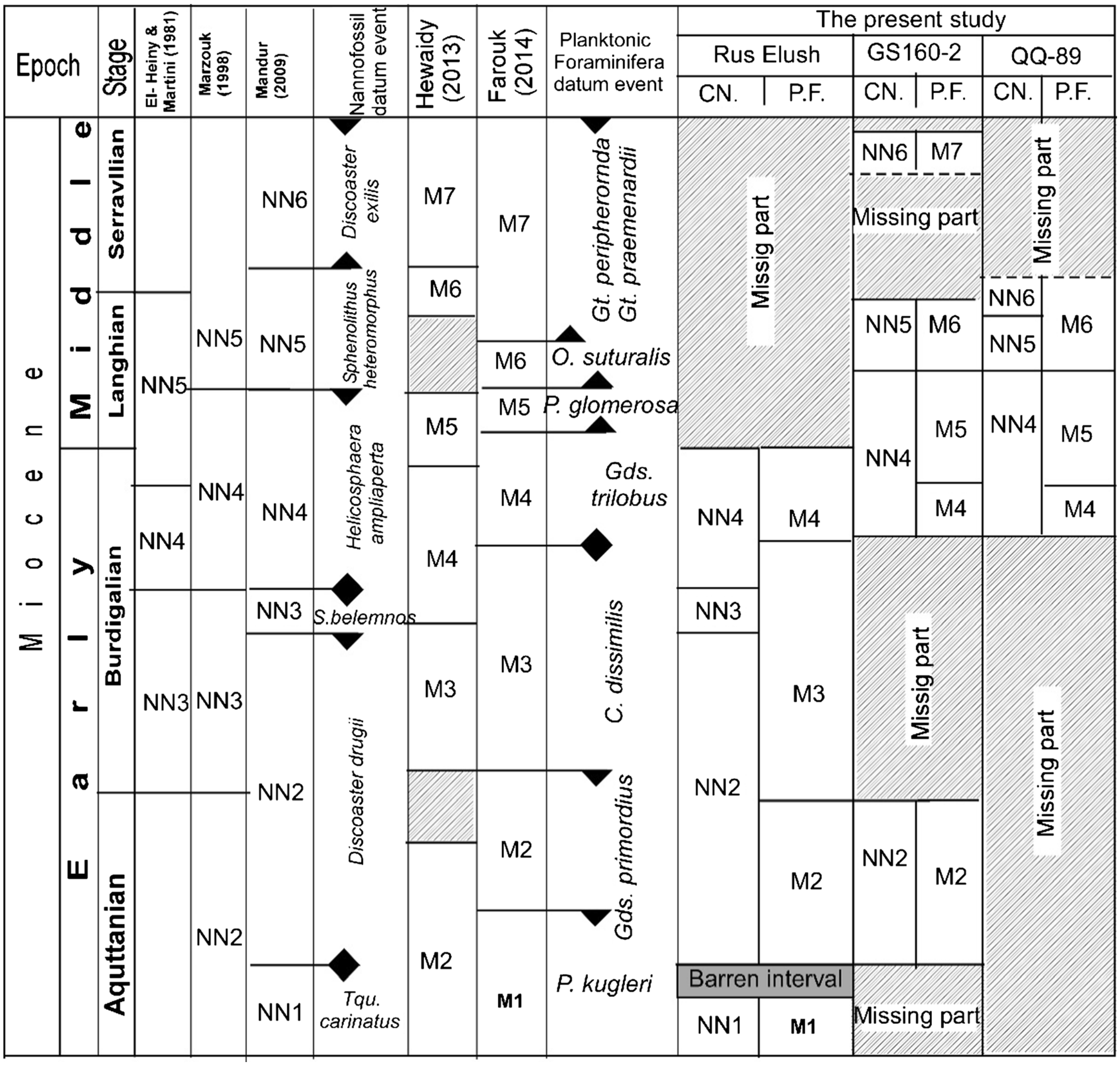


Fig. 10 Integrated biostratigraphy of the three studied wells

dominant *Bolivina* and *Uvigerina* groups reflect an outer neritic paleoenvironment (Jannink et al. 1998).

Environmental interpretation of the Rudeis Formation in the GS-16-2 well

Ec-G2 This ecozone is recorded in the middle part of the Rudeis Formation (*G. trilobus* Zone of the Burdigalian age). It consists of shale and limestone at the interval from depths of 7980 to 7830 ft. It is characterized by presence of (1) unkeeled planktonic foraminiferal genera (*Globigerina* and *Globgerinoides*); (2) the P/(P+B) ratio, reaches 65 %; and (3) high diversity of species (40–45 species), with a total of 12–15 benthic species. The dominant benthic foraminiferal group is *Bolivina* which is represented by about 75 % of the *B. dilatata*, *B. superba*, *B. arta*, *B. shukrii*, *Bolivina fastiglia* and *B. elongata*, in addition to *Uvigerina semiornata*, *Stilostomella soluta*, *S. ovicula*, and *Oolina globosa setosa* (25 %) (Fig. 14). These characters indicate an outer neritic environment for this ecozone (Figs. 13, 14, and 17).

Ec-G3 This ecozone is recorded in the upper Rudeis Formation (*P. sicana* and *P. glomerosa* Zone of the Langhian age). It consists of shale and sandstone at the interval from depths of 7830–7750 ft. It is characterized by presence of unkeeled planktonic foraminiferal genera *Globigerina*, *Globgerinoides*, *Globorotalia*, and *Orbulina*. It is dominated by *Globigerinoides* (70 %). It is characterized by the P/(P+B) ratio of (45–55 %). It has a high diversity (40–45 species, with a total of 10–12 benthic species). The dominant benthic foraminiferal species are those of the genus *Cibicides* and

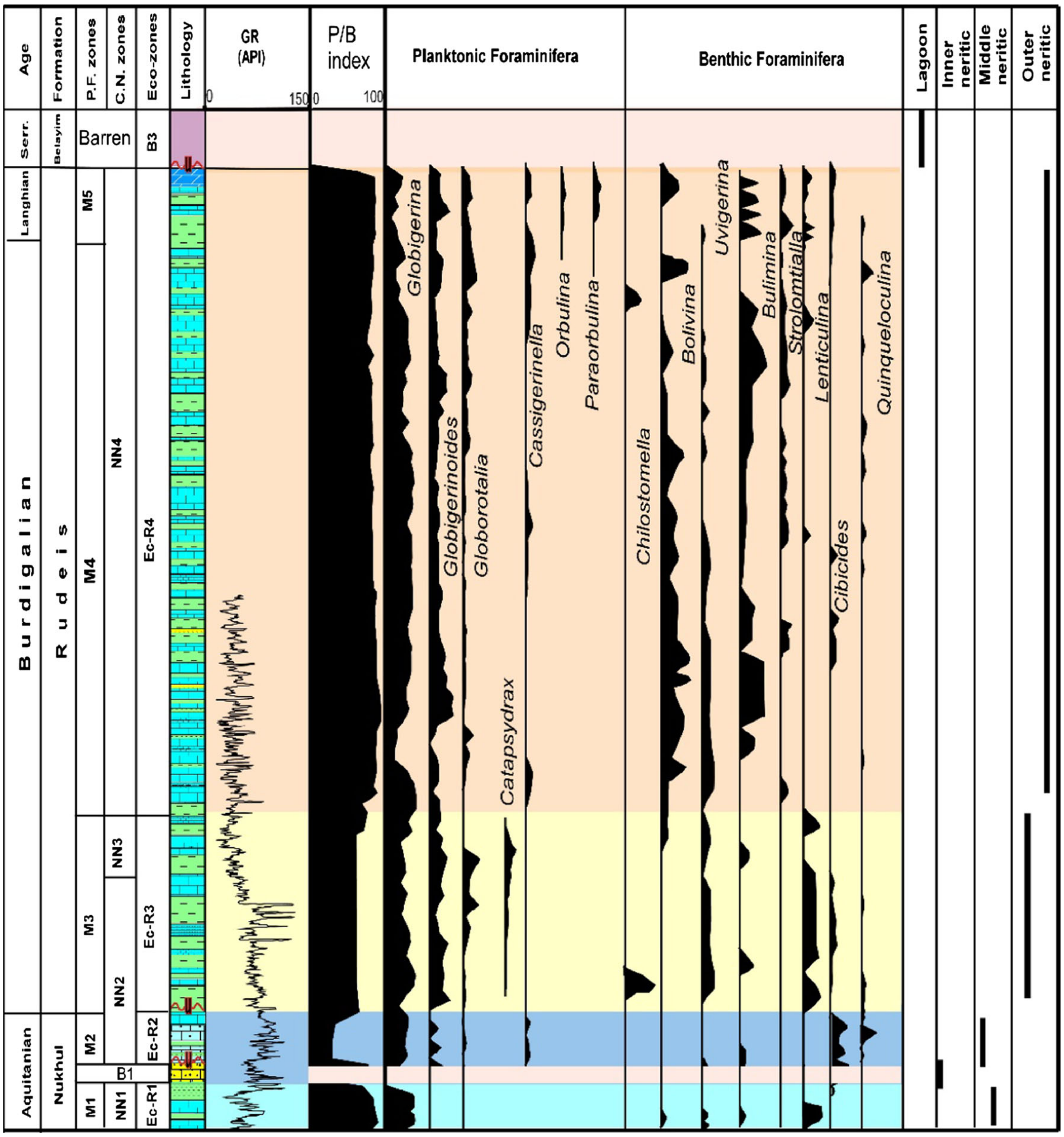


Fig. 11 Foraminiferal paleoecologic parameters and interpretation in the Ras Elush well

represented by about 75 % of *Cibicides ellisi ellisi*, *C. ellisi*, *C. ellisi graysoni*, *Cibicides boueanus*, and *C. dutemplei*, in addition to *Q. seminulua*, *Q. juleana*, *Bolivina elongate*, and *B. fastigla* representing about 25 %. These characters reflect a middle neritic environment (Fig. 14).

Environmental interpretation of the Kareem Formation

This formation includes two ecozones in the QQ-89 well (Ec-Q3 and EC-Q4), while in the GS-160-2 well, it includes one ecozone (Ec-G4). The Kareem Formation is missing in the Ras Elush well due to tectonic uplifting after deposition of the Rudeis Formation.

Environmental interpretation of the Kareem Formation in the QQ-89 well

Ec-Q3 This ecozone is recorded in the upper part of the Rudeis Formation and the lower part of the Kareem Formation (*P. sicana*/*P. glomerosa* Zone and *O. suturalis* Zone of the Langhian age). It consists of claystone and limestone with anhydrite intercalations, and represented by the interval from depths of 2650–2530 ft. It is characterized by presence of unkeeled planktonic foraminiferal genera: (*Globigerina*,

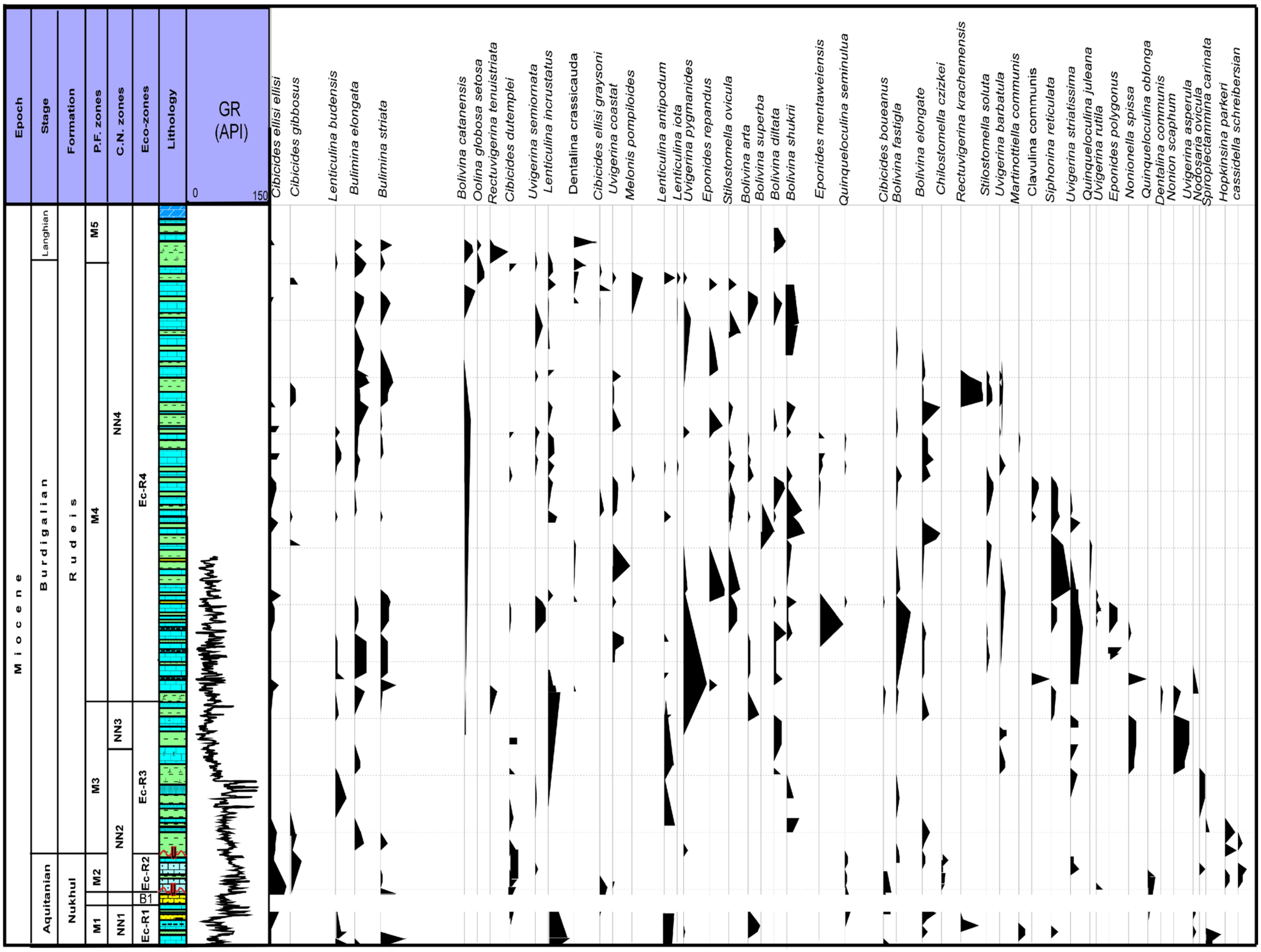


Fig. 12 Distribution and percentage of small benthic foraminiferal species across the Miocene of the Ras Elush well

Globigerinoides, *Globorotalia*, and *Orbulina*). The *Orbulina* reaches about 65 % (Fig. 15). This ecozone is characterized by (1) high diversity (50–60 species) with a total of 17–20 benthic species, (2) dominant taxa are *Cibicides* which represent about 75 % (*C. ellisi graysoni*, *C. nucleates cseguenzal*, *Cibicides tenellus*, *C. dutemplei*, *C. ellisi* and *C. boueanus*), in addition to *B. Striata*, *B. elongata*, and *Eponides procerus* (25 %) (Fig. 16). The *Cibicides* biofacies is indicative of 100-m water depth (Miller et al. 2008). The benthic foraminiferal assemblage indicates an inner to middle neritic environments (Figs. 15 and 17).

Ec-Q4 This ecozone is recorded in the upper part of the Kareem Formation (*O. suturalis* Zone of the Langhian age). It consists of claystone and siltstone and represented by the interval from 2530 to 2350 ft depth. It is characterized by presence of unkeeled planktonic foraminiferal genera (*Globigerina*, *Globgerinoides*, *Globorotalia*, *Orbulina*, and *Neogloboquadrina*). It is dominated by *Orbulina* (60 %). It is characterized by a P/(P+B) ratio of 80–90 % with high diversity (25–30 species), with a total of 11–13 benthic species. The dominant benthic foraminiferal genera *Uvigerina* is represented by about 60 % (*Uvigerina barbatula*, *Uvigerina rutila*, *Uvigerina coastat*, *U. pygmoides*, *U. semiornata*, *Uvigerina venusta*,) in addition to *S. soluta*, *Stilostomella corporosa*, *S. paleocenica*, *S. subspinosa*, *S. ovicula*, *Nodosaria catenulate*, *B. elongata*, and *B. striata*) (Fig. 16). These parameters reflect outer neritic paleoenvironment (Figs. 15 and 17).

Environmental interpretation of the Kareem Formation in the GS 160-2 well

Ec-G4 This ecozone is recorded in the lower part of the Kareem Formation (*O. suturalis* Zone of the Langhian age). It consists of siltstone and anhydrite and represented by the interval from 7750–7680 ft depth. It is characterized by presence of unkeeled planktonic foraminiferal genera *Globigerina*, *Globigerinoides*, *Globorotalia*, and *Orbulina*. It is dominated by *Globigerinoides* (60 %). It is characterized by a P/(P+B) of

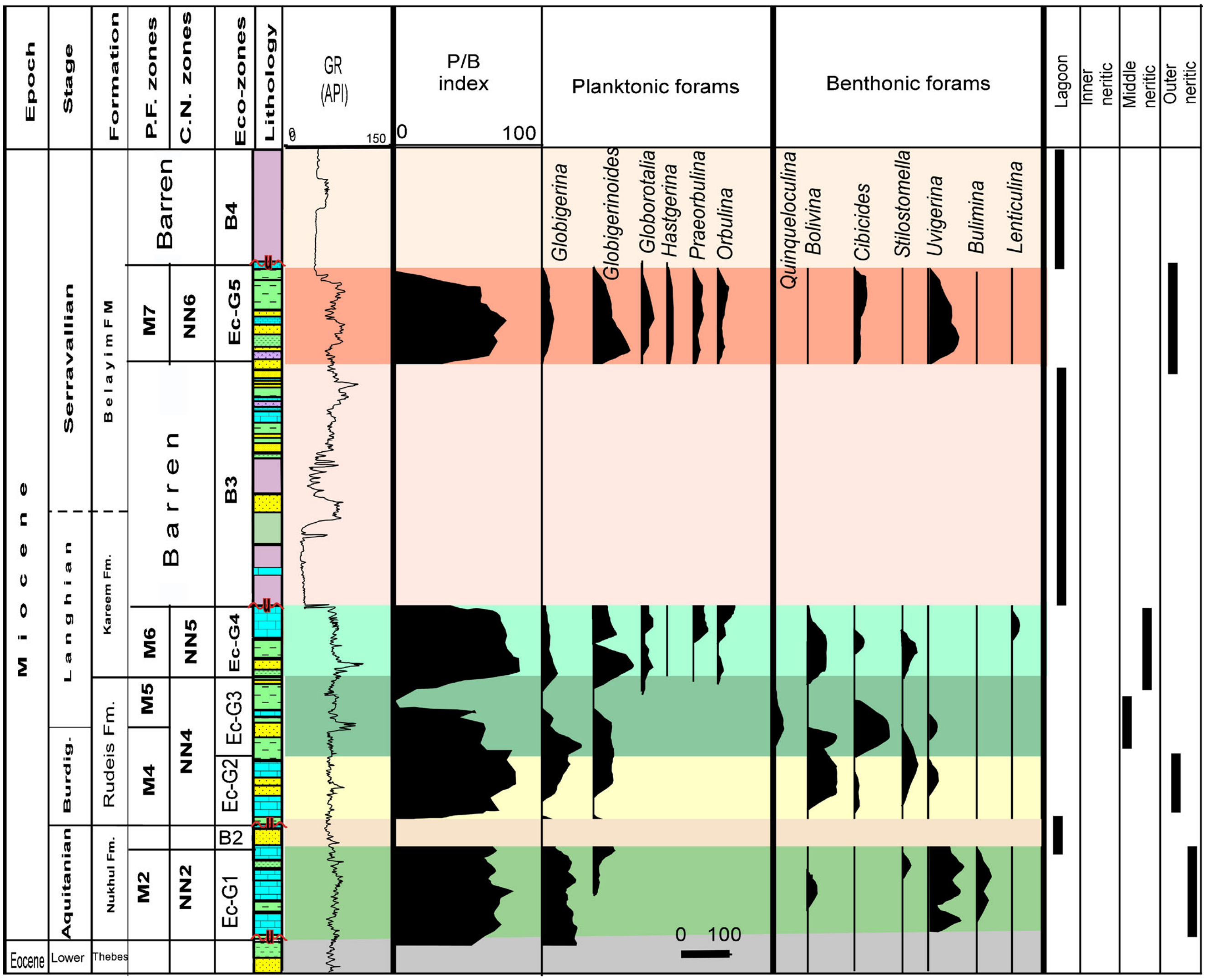


Fig. 13 Foraminiferal paleoecologic parameters and interpretation in GS160-2 well

60–70 % with low diversity (15–20 species), with a total of 10–12 benthic species. It is characterized by presence of *Bolivina* and *Stilostomella* which represent about 15 %. The dominant benthic foraminiferal genera are *Bolivina* (*B. dilatata*, *B. superba*, *B. shukrii*, *B. fastiglia*, and *B. elongata*) (50 %), in addition to *Stilostomella* (*S. solutea*, *Stilostomella verneullia*, and *S. ovicula*), *L. incrustatus*, *Lenticulina iota*, *C. ellisi ellisi*, *and N. soluta* which represent about 50 % (Fig. 14). The high P/B ratio and dominance of *Bolivina* and *Cibicides* groups reflect a middle neritic environment (Figs. 13 and 17).

Environmental interpretation of the Belayim Formation

The Belayim Formation was found barren of foraminifera in the Ras Elush and QQ-89 wells, while in the GS-160-2 well, it is subdivided into three units: a lower barren interval, middle Ec-G5 ecozone, and upper barren interval. The following is the description of these two units, the barren interval and Ec-G5:

Barren interval 3 This interval is represented by the whole Belayim Formation in the Ras Elush and QQ-89 wells or the lower part of the Belayim Formation at GS-160-2. It is represented by the whole lower part of the Belayim Formation (Serravallian age). It is represented by anhydrite and sandstone. These sediments reflect a lagoonal environment (Figs. 11, 13, and 15).

Environmental interpretation of the Belayim Formation in the GS-160-2 well

Ec-G5 This ecozone is recorded in the Serravallian Belayim Formation of the *G. praemenardii*/

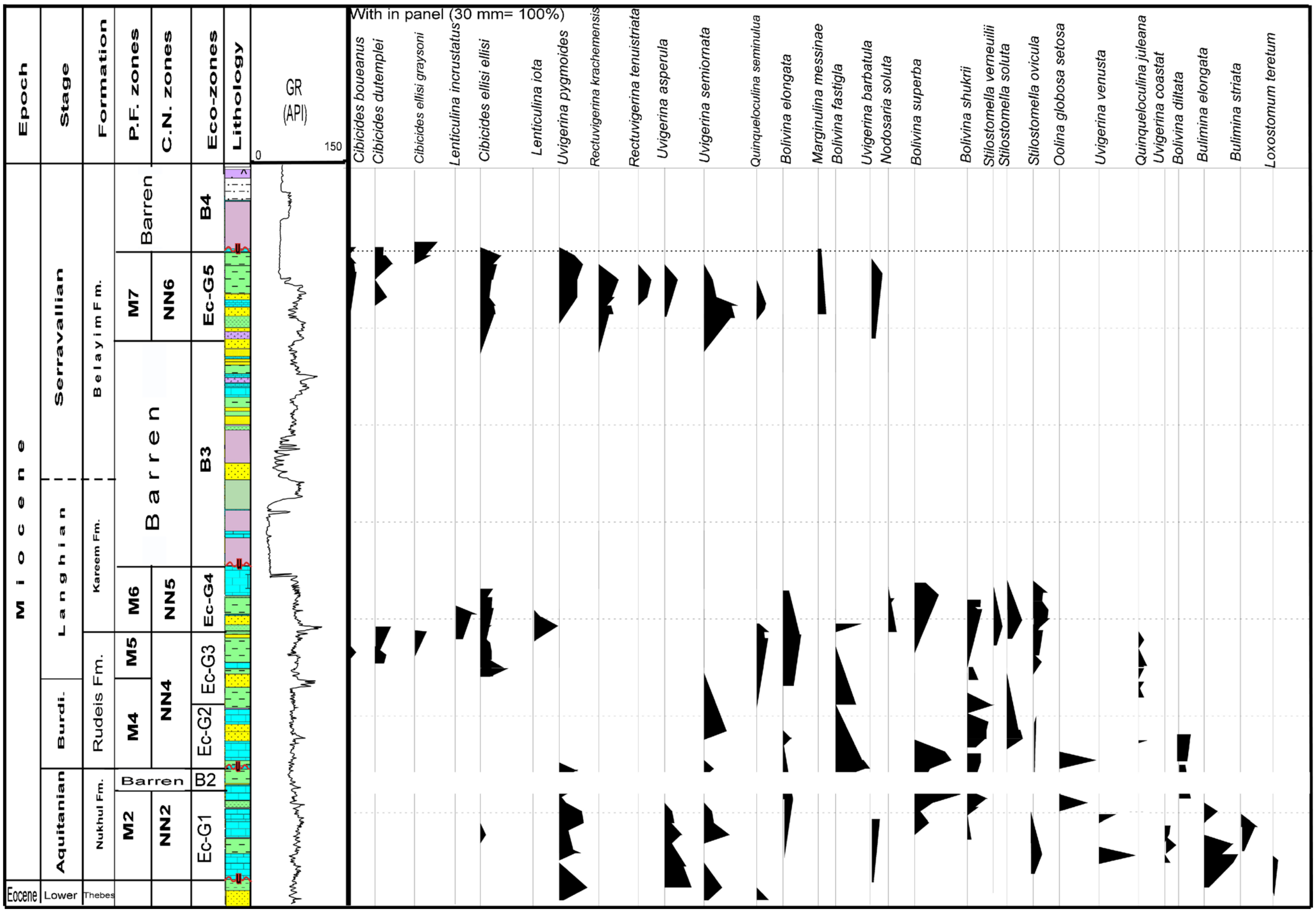


Fig. 14 Distribution and percentage of small benthic foraminiferal species across the Miocene successions of the GS-160-2 well

G. peripheroronda Zone. It consists of limestone and shale and represented by the interval between depths of 7260 and 7120 ft. It is characterized by presence of unkeeled planktonic foraminiferal genera *Globigerina*, *Globigerinoides*, *Globorotalia*, *Orbulina*, and *Hastegerina*. It is characterized by a P/(P+B) of 45 % with high diversity (22–30 species), with a total of 7–10 benthic species.

The dominant benthic foraminiferal group is *Uvigerina* (Fig. 14) representing about 60 % (*U. barbatula*, *U. pygmoides*, *U. semiornata*, and *Uvigerina asperula*) in addition to *Cibicides*, *Rectuvigeruna* which represent about 40 % (*C. ellisi ellisi*, *C. boueanus*, *C. dutemplei*, *Rectuvigeruna kraohemensis*, and *R. tenuistriata*). These parameters reflect middle to outer neritic environments (Figs. 14 and 17).

Barren interval 4 This interval is recorded from the upper part of the Serravallian Belayim Formation in the GS-160-2 well. It consists of mainly anhydrite which is completely barren of any Foraminifera genera. These sediments reflect a lagoonal environment (Fig. 13).

Summary and conclusions

Three offshore wells (GS 160-2, QQ-89, and Ras Elush) from north to south representing the subsurface Miocene successions in central and southern parts of the Gulf of Suez, Egypt, were selected to study the foraminifera and calcareous nannofossil contents and paleoenvironments. Lithostratigraphically, the lower Middle Miocene succession is classified from older to younger into Nukhul (Aquitanian), Rudies (Burdigalian-Langhian), Kareem (Langhian), and Belayim (Serravallian) formations.

The identified foraminifera includes 54 benthonic species belonging to 25 genera and 47 planktonic species belonging to 11 genera with moderate to good preservation and relatively high diversity, in addition to 64 calcareous nannofossil species. These assemblages

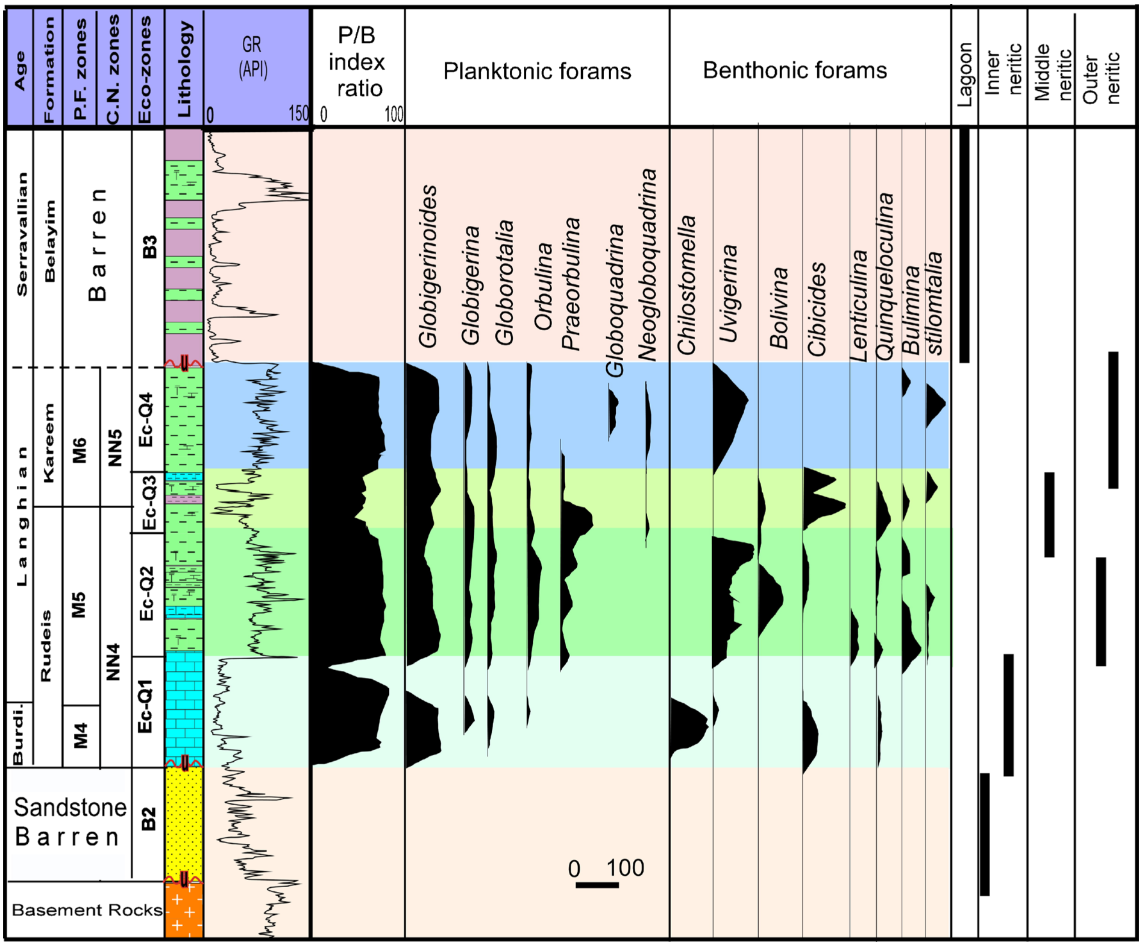


Fig. 15 Foraminiferal paleoecologic parameters and interpretation in QQ-89 well

allowed to classify the studied successions into seven planktonic foraminiferal biozones arranged from older to younger into *P. kugleri* (M1) (Early Miocene, Aquitanian), *Globigerninodes primordius* (M2) (Early Miocene, Aquitanian), *Globigerinoides altiapertura* (M3) (Early Miocene, Burdigalian), *G. trilobus* (M4) (Early Miocene, Burdigalian), *P. sicanus/P. glomerosa* (M5) (Middle Miocene, Langhian), *O. suturalis* (M6) (Middle Miocene, Langhian), and *G. praemenardii*/*G. peripheroronda* (M7) (Middle Miocene, Serravallian); in addition to six nannofossil biozones from older to younger: *T. carinatus* (NN1) (Early Miocene, Aquitanian), *D. druggii* (NN2) (Early Miocene, Aquitanian), *S. belemnos* (NN3) (Early Miocene, Burdigalian), *H. ampliaperta* (NN4) (Early Miocene, Burdigalian), *S. heteromorphus* (NN5) (Middle Miocene, Langhian), and *D. exilis* (NN6) (Middle Miocene, Serravallian).

The ranges of both planktonic foraminifera and calcareous nannofossil zones proved to match reasonably with each other. These biozones were correlated with those recorded in Egypt and in other parts of the world.

Based on the planktonic foraminifera, the Aquitanian/Burdigalian boundary in the investigated wells is delineated with the FO of *G. altiapertus* and *C. dissimilis* near the top of the *D. druggii* Zone of calcareous nannofossil. The Burdigalian/Langhian boundary is placed at the first appearance of *P. sicanus*/*P. glomerosa* planktonic foraminiferal zone. The Langhian/Serravallian boundary is recognized by the FO of the planktonic foraminiferal *G. peripheroronda*/*G. praemenardii* (M7) Zone and the FO of the calcareous nannofossil *D. exilis* Zone (NN6).

The environments of deposition of the studied units were analyzed based on the lithologic characters and faunal contents. The Nukhul Formation is recorded in the Ras Elush and GS 160-2 wells, while it is missing in the QQ-89 well. In the Ras Elush well, it is subdivided into two ecozones (Ec-R1 and Ec-R2) separated by a barren interval 1. These ecozones are supposed to be deposited in a middle neritic environment followed by a regressive phase and then back to the middle neritic environment again. In GS 160-2, the Nukhul Formation is classified into one ecozone (Ec-G1) followed by a barren

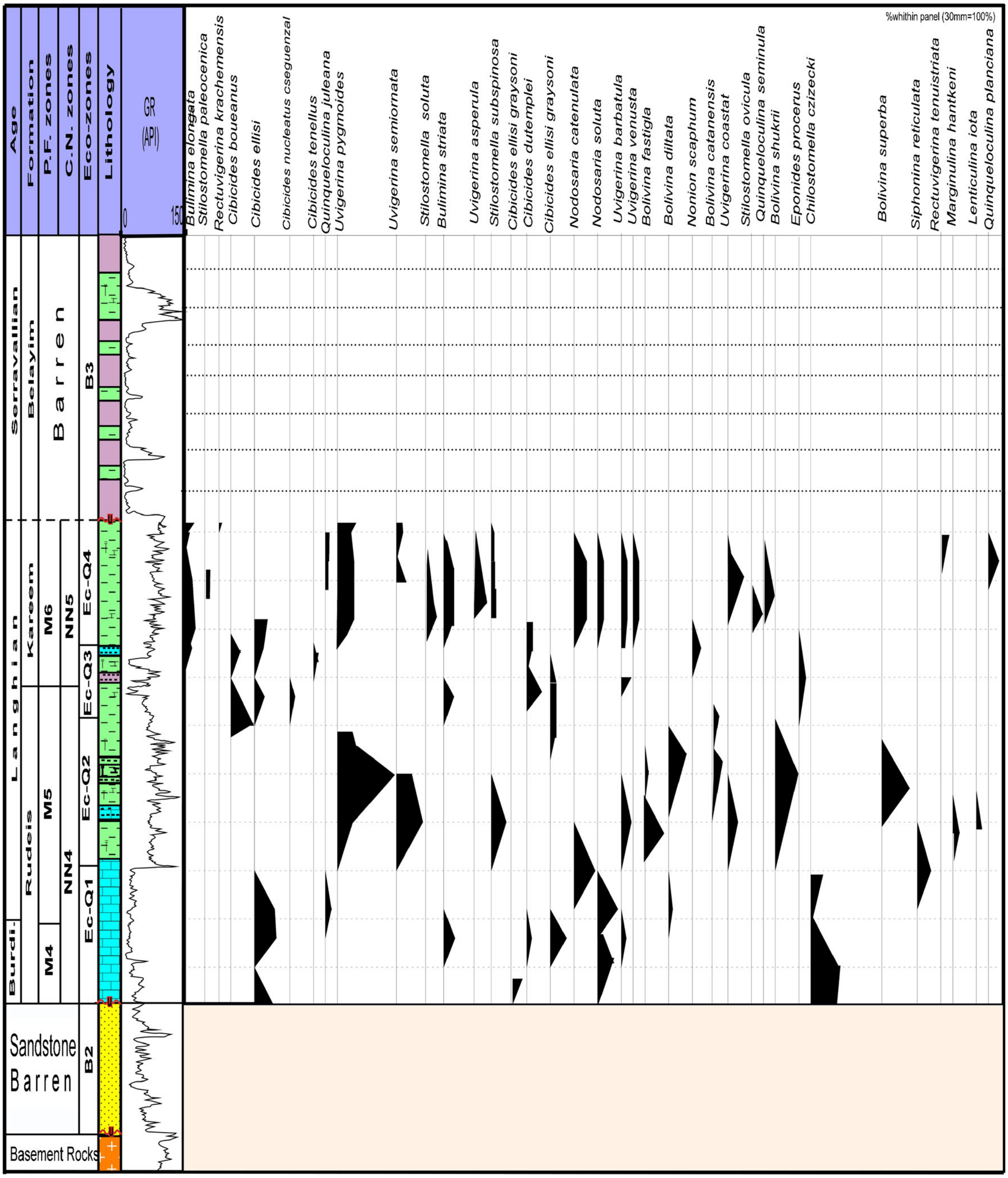


Fig. 16 Distribution and percentage of small benthic foraminiferal species across the Miocene of the QQ-89 well

interval, which were interpreted to be deposited in a deeper outer neritic environment followed by a regressive phase.

The Rudeis Formation was recorded in the three studied wells. In the Ras Elush well, it is classified into two ecozones (Ec-R3 and Ec-R4) which may be deposited in a middle to outer neritic environments. In the QQ-89 well, the Rudeis Formation is classified into one ecozone (Ec-Q1) bottomed by a barren interval which may be deposited in an inner neritic environment changed to outer neritic upwards. In the GS 160-2 well, the Rudeis Formation is classified into two ecozones (Ec-G2 and Ec-G3), which may be deposited in an outer neritic environment changed to inner to middle neritic environments at the top.

The Kareem Formation is represented in the QQ-89 and GS160-2 wells and missing in the Ras Elush well due to tectonic activity after the deposition of the Rudeis Formation. At

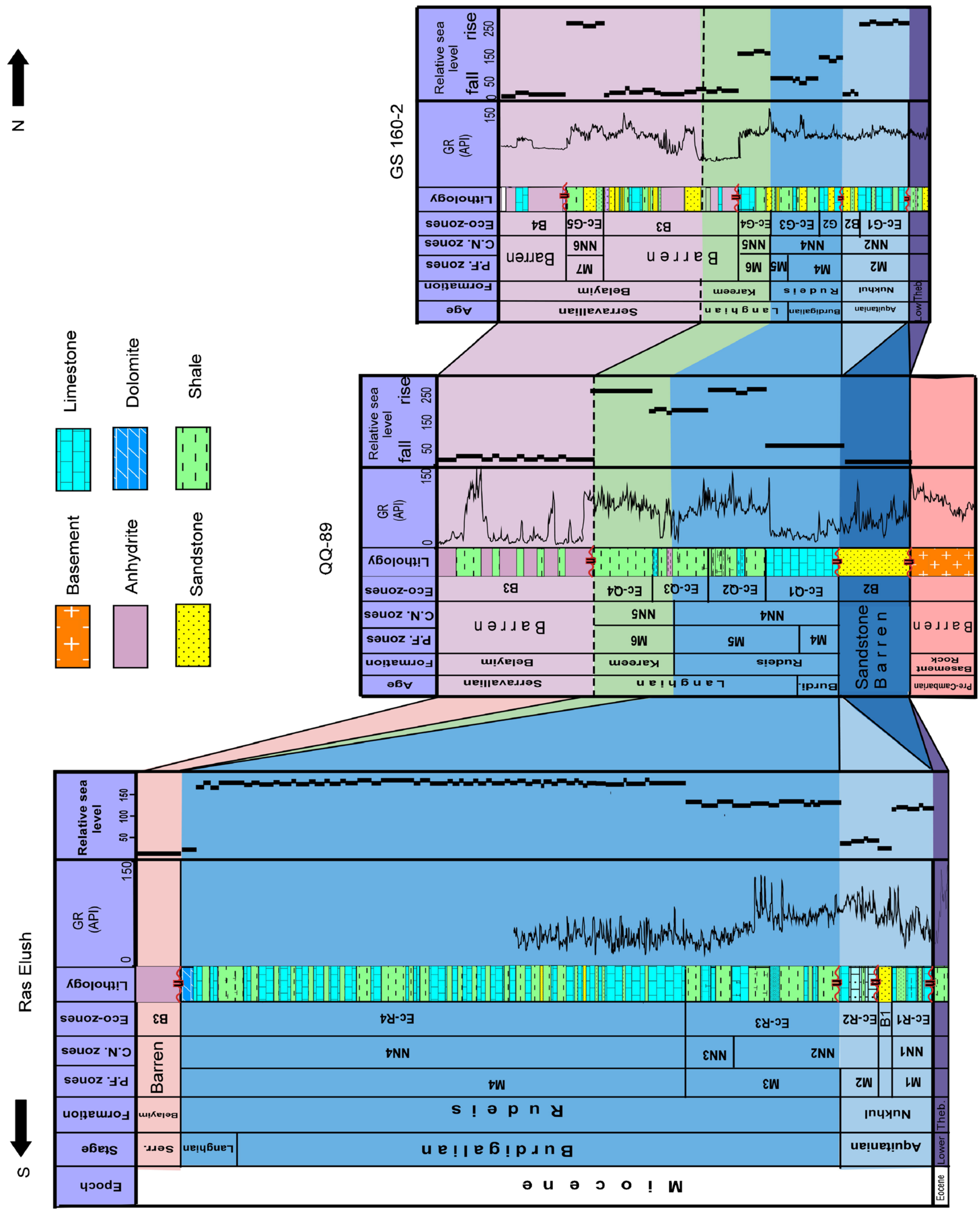


Fig. 17 Litofacies and paleoenviromental interpretations in the three studied wells

the QQ-89 well, the Ec-Q3 ecozone reflects an inner to middle neritic paleoenvironments grades to middle to outer neritic environments in the central part of the study area at the GS 160-2 well.

The Belayim Formation is detected in all the studied wells represented by a regressive phase which consists of evaporites intercalated with shale. At the GS 160-2 well, it consists of evaporites intercalated at the middle part of the Belayim Formation by deeper shale with sandstone of middle to outer neritic environments.

Acknowledgments We wish to express our thanks to the authority of the Egyptian General Petroleum Corporation (EGPC) for providing the samples. Two reviewers are thanked for the critical reading of the manuscript.

References

Abed El-Naby AM, Ghanem H, Boukhary M, Abd El-Aal M, Lüning S, Kuss J (2010) Sequence-stratigraphic interpretation of structurally controlled deposition: middle Miocene Kareem Formation, southwestern Gulf of Suez, Egypt. Geoa 15(3):129–150

Abu El Enein MA (1990) Contribution to the Miocene stratigraphy of the Nile Delta. Ph.D. Thesis, Faculty of Sciences, Geology Department, Ain Shams Univ, pp 1–186

Abul-Nasr RA, El-Safori YA, Attia SH, Maih A (2009) Stratigraphy and depositional settings of the Miocene succession in the area between Wadi Sudr and Wadi Wardan Gulf of Suez Region-Egypt. J Paleontol 9:119–144

Andrawis SF, Abdel Malik WM (1981) Lower/Middle Miocene boundary in the Gulf of Suez region, Egypt. Newsl Stratigr 10:156–163

Arafa AA (1991) Nannoplankton and planktonic foraminiferal zonation of the lower Miocene sequence in Gebel Hadahid, south west Sinai, Egypt. Egypt J Geol 35(1):275–284

Armentrout JM (1996) High resolution sequence biostratigraphy: examples from the Gulf of Mexico Pliocene and Pleistocene. Geol Soc Lond Spec Publ 104:65–86

Ayyad SN (1983) Biostratigraphic studies on subsurface Miocene sediments in North Egypt. Ph. D. Thesis, Geol Dep, Mansoura Univ, p 358

Backman J, Raffi I, Rio D, Fornaciari E, Pälike H (2012) Biozonation and biochronology of Miocene through Pleistocene calcareous nannofossils from low and middle latitudes. Newsl Stratigr 45(3): 221–244

Banner FT, Blow WH (1965) Progress in the planktonic foraminiferal biostratigraphy of the neogene. Nature 208:1164–1166

Beckmann JP, El Heiny I, Kerdany MT, Said R, Viotti C (1968) Standard planktonic zones in Egypt. First International Planktonic Conference, Geneva, pp 92–103

Berggren WA, Swisher CC, Aubry MP (1995) A revised Cenozoic geochronology and chronostratigraphy. In: Geochronology time scales and global stratigraphic correlation. Soci of Sedimentary Geol 54: 277–302

Blow WH (1969) Late middle Eocene to recent planktonic foraminiferal biostratigraphy. Proc of the First International Conf on Planktonic Microfossils, Eds: Bronnimann and P.Renz 1:199–422

Blow WH (1979) The cainozoic globigerinaceae, vol 3. E.J. Brill, Leiden, p 1413

Blow WH, Banner FT (1966) The morphology taxonomy and biostratigraphy of Globorotallia barisanensis LeRoy, Globorotalia fohsi Cushman and Ellisor, and related taxa. Micro 12(3):286–302

Bolli HM (1957) Planktonic foraminifera from the Oligocene-Miocene Cipero and Lengua formations of Trinidad, B.W.I. In: Studies in Foraminifery, Bulletin of the U.S. National Museum Vol. 215 Eds: Loeblich, A.R. Tappan, H. Beckmann, J.P. Bolli, H.M. Gallitelli, E.M.Troelsen, J.C. p. 97–123

Bolli HM (1966) Zonation of Cretaceous to Pliocene marine sediments based on planktonic foraminifera. Boletin Informativo Asociaciòn Venezolana de Geologà, Minerarà Petro 9:3–32.

Bolli HM (1970) The foraminifera of sites 23–31, Leg 4. Initial Reports of the DSDP 4:577–643

Bolli HM and Saunders JB (1985): Oligocene to Holocene low latitude planktic foraminifers. In: Bolli HM and Saunders JB (eds) Plankton Stratigraphy, 155–262

Bosworth W, Huchon P, McClay K, Abbate E (2005) The red sea and Gulf of Aden basins, in phanerozoic evolution of Africa—special volume. Afr J Earth Sci 43:334–378

Bramlette MN, Wilcoxon JA (1967) Middle tertiary calcareous nannoplankton of the Cipero Section Trinnidad. Tulane Studies in Geol Paleo 5:93–131

Brunner CA (1992) Paleoenvironment and biostratigraphy of foraminifers at sites 794, 795, 796, and 797 in the Japan Sea. Deep Sea Drilling Project Sci Rese 127:187–224

Buck K, Hilary C, James A, Jr A (1999) Paleoenvironmental evidence for latest Pleistocene sea-level fluctuations on the New Jersey outer continental shelf: combining high-resolution sequence stratigraphy and foraminiferal analysis. Mar Geol 154:287–304

Bukry D (1973) Low-latitude coccolith biostratigraphic zonation. Initial reports of the DSDP 15:487–494

Chi WR (1981) Nannofossils. Exploration and Development Research Center, China, p 407

Culver SJ (1988) New foraminiferal depth zonation of the northwestern Gulf of Mexico. Palaios 3:69–85

Egyption General Petroleum Corporation Stratigraphic Committee, (E.G.P.C) (1964) Oligocene and Miocene rock stratigraphy of the Gulf of Suez region. Report of the Stratigraphic Committee, 142 p

El Deeb WZM, El Ashwah A, Mandur MM (2004) Planktonic Foraminifera and Calcareous nannoplankton biostratigraphy of the lower and middle Miocene sequence in Wadi Gharandal, southwest Sini, Egypt. Egypt. Egypt J Pet 13:105–122

El-Azabi MH (2004) Facies characteristics, depositional styles and evolution of the Syn-rift Miocene sequences in Nukhul-Feiran area, Sinai side of the Gulf of Suez rift basin, Egypt. Sedimentology Egypt 12:69–103

El-Heiny I, Martini E (1981) Miocene foraminiferal and calcareous nanno-plankton assemblages from the Gulf of Suez Region and correlation. Géol Mediterr 2:101–108

Evans AL (1988) Neogene tectonics and stratigraphic events in the Gulf of Suez rift area, Egypt. Tectonoph 153:235–247

Faris M, Samir AM, Shabaan M (2007) Calcareous nannofossil biostratigraphy of the subsurface Miocene sequence, northeast Nile Delta, Egypt, 5th International Conference on the Geol of Africa 1:1–31

Faris M, Samir AM, Shabaan M (2009) Calcareous nannofossil biostratigraphy of the lower and middle Miocene sequence in the Gulf of Suez area, Egypt. 6th International Conference on the Geology of Africa VII: 17–44

Farouk S, Ziko A, Eweda S, Said AE (2014) Subsurface Miocene sequence stratigraphic framework in the Nile Delta, Egypt. J Afr Earth Sci 91:89–109

Fornaciari E, Rio D (1996) Latest Oligocene to early middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. Micr 42(1):1–36

Fornaciari E, Backman J, Rio D (1993) Quantitative distribution patterns of selected lower to middle Miocene calcareous nannofossils from the Ontong Java Plateau. Proc Ocean Drill Program Sci Results 130: 245–256

Fornaciari E, Di Stefano A, Rio D, Negri A (1996) Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. Micr 42(1):37–63

Garfunkel Z, Bartov Y (1977) Tectonics of the Suez Rift. Bull Geol Surv Israel 71:1–45

Gevirtz JL (1969) Palaecology of benthonic foraminifera and associated microorganisms of the continental shelf off Long Island, New York. Ph.D. Dissert. Rensselaer Polytechnic Institute, Troy, p 93

Ghorab MA (1964) Oligocene and Miocene rock stratigraphy of the Gulf of Suez region. Egyptian General Petroleum Company, Start. Committee, Cairo, pp 1–142

Gradstein FM, Ogg JG, Schmitz MD, Ogg GM (2012) The geologic time scale, Elsevier 1:1–1033

Haggag MA, Youssef I, Salama GR (1990) Stratigraphic and phylogenetic relationships of Miocene planktonic foraminifera from the Gulf of Suez, Egypt. M.E.R.C, Ain Shams University. Earth Sci 4: 22–40

Hay WW (1970) Calcareous nannofossils from cores recovered on Leg 4. Initial Reports of the DSDP 4:455–501

Hewaidy AA, Farouk S, Ayyad HM (2012) Nukhul Formation in Wadi Baba, southwest Sinai Peninsula, Egypt. Geoa 17:103–120

Hewaidy AA, Farouk S, Ayyad HM (2013) Foraminifera and sequence stratigraphy of Burdigalian-Serravallian succession on the eastern side of the Gulf of Suez, southwestern Sinai, Egypt. Neues Jb Geol Paläontol Abh 2:151–170

Holcovkà K (2013) Morphological variability of the Paratethyan Oligocene–Miocene small reticulofenestrid coccolites and its paleoecological and paleogeographical implications. Acta Palaeontol Pol 58(3):651–668

Iaccarino S (1985) Mediterranean Miocene and Pliocene planktonic foraminifera. Plankton Stratigraphy. Cambridge Univ Press, pp 283–314.

Iaccarino S, Salvatorini G (1982) A framework of planktonic foraminiferal biostratigraphy for Early Miocene to Late Pliocene Mediterranean area. Paleontology Stratigraphic, Evol 2:115–125

Iaccarino S, Premoli Silva I, Biolzi M, Foresi LM, Lirer F, Petrizzo MR (2005) Practical manual of Oligocene to middle Miocene planktonic foraminifera. Eds. International School on Planktonic Foraminifera 4th course. Mar Geol 95:1–16

Issawi B, El Hinnawi M, Francis M, Mazhar A (1999) The phanerozoic geology of Egypt, a geodynamic approach. Egyptian Geological Survey, Special Publication

Jannink NT, Zachariasse WJ, Van der Zwaan GJ (1998) Living (Rose Bengal stained) benthic foraminifera from the Pakistan continental margin (North Arabian Sea). Deep Sea Ras I(45):283–1513

Kennett BA, Srinivasan MS (1983) Neogene planktonic foraminifera. A phylogenetic Atlas, p 61

Kerdany MT (1968) Note on the planktonic zonation of the Miocene in the Gulf of Suez Region U.A.R. Proceeding of the Committee of Mediterranean Neogene Stratig 35:157–166

Kuĉenjak MH, Fućek VP, Slavković R, Mesić I (2006) Planktonic foraminiferal biostratigraphy of the late Eocene and Oligocene in the Palmyria area, Syria. Geol Croat 59:19–39

Leckie RM, Olson HC (2003) Foraminifera as proxies of sea-level change on siliciclastic margins. Society for Sedimentary Geol 75: 5–19

Lourens L, Hilgen F, Shackleton NJ, Laskar J, Wilson D (2004) The Neogene Period. In: Gradstein FM, Ogg JG, Smith AG (eds) A geologic time scale. Cambridge University Press, Cambridge, pp 409–452

Maiorano P, Monechi S (1998) Revised correlation of early and middle Miocene calcareous nannofossil events and magnetostratigraphy from DSDP site 563 (North Atlantic Ocean). Mar Micropaleontol 35:235–255

Mancin N, Pirini C, Bicchi E, Ferrero E, Gigliola V (2003) Middle Eocene to middle Miocene planktonic foraminiferal biostratigraphy for internal basins (Monferrato and northern Appennines). Micro 49(4):341–358

Mandur MM (2004) Stratigraphical and paleontological studies on some Miocene successions of southwest Sinai, Egypt. Unpublished Ph.D. Thesis, Ain Shams Univ, pp. 1–220

Mandur MM (2009) Calcareous nannoplankton biostratigraphy of the lower and middle Miocene of the Gulf of Suez, Egypt. Aust J Basic Appl Sci 3(3):2290–2303

Mandur MM, Baioumi A (2011) Planktonic Foraminifera Biostratigraphy of the Lower and Middle Miocene successions of the Gulf of Suez, Egypt. International J of Academic Rese 3(4):91–102

Martini E (1971) Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. (Ed.). Proceedings of the Second International Conference on Planktonic Microfossils Roma, Tecn 2:739–785

Martini E (1974) Nannoplankton-Untersuchungen in Oligozànen Alagerungen zwischen Clij und Heuedin (NW Siebenburgisches Becken, Rumanien). N Jb Geol Paläont (Monatsh) 1:18–37

Martini E, Worsley T (1970) Tertiary calcareous nannoplankton from the western equatorial Pacific. Proc Ocean Drill Program Sci Results 7: 1471–1507

Marzouk A (1998) Nannofossil biostratigraphy of the subsurface Miocene sections in the Ras Budran Area, Gulf of Suez, Egypt. Neues Jb Geol Paläontol Abh 209(2):19–40

Marzouk A (2009) Nannofossil biostratigraphy of Miocene section from two wells in the Gulf of Suez, Egypt. Paleontology, Strat, Fazi 532(17):101–127

Melillo AJ (1988) Neogene planktonic foraminiferal biostratigraphy, ODP Leg 101, Bahamas. In: Austin JA Jr, Schlager W et al Proceedings of the Ocean Drilling Program, Scientific Results, Col 101: 3–45

Miller KG, Browning JV, Aubry MP, Wade BS, Katz ME, Kulpecz AA, Wright JD (2008) Eocene-Oligocene global climate and sea-level changes: St. Stephens Quarry, Alabama. Geol Soc Am Bull 120: 34–53

Moustafa AG (1976) Block faulting in the Gulf of Suez, 5th EGPC. Exploration, Seminar, Cairo 1:1–36

Moustafa AR (2004) Exploratory notes for the geologic maps of the eastern side of the Suez rift (Western Sinai Peninsula). AAPG/Datapages, Inc.GIS Series, Egypt, p 33

Muller C (1978) Neogene calcareous nannofossils from the Mediterrannean Leg 42 A of the DSDP. Proc Ocean Drill Program Sci Results 42:727–751

N.C.G.S (National Committee of Geological Sciences) (1976) Miocene rock stratigraphy of Egypt. Egypt J Geol 18(1):1–59

Okada H, Bukry D (1980) Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation. Mar Micropaleontol 5:321–325

Ouda K, Masoud M (1993) Sedimentation history and geological evolution of the Gulf of Suez during the Late Oligocene. Miocene. Geol Soc Egypt 1:47–88

Patton TL, Moustafa AR, Nelson RA, Abdine SA (1994) Tectonic evolution and structural setting of the Suez Rift. In: London (ed) Interior rift basins.Tulsa, Oklahoma, vol 59. American Association of Petroleum Geologists, Memoirs, pp 7–55

Phillip G, Imam MM, Abdel Gawad GI (1997) Planktonic foraminiferal biostratigraphy of the Miocene sequence in the area between Wadi El-Tayiba and Wadi Sidri, west central Sinai, Egypt. J Afr Earth Sci 25(3):435–451

Postuma JA (1971) Manual of planktonic foraminifera- Amsterdam, Elsevier Publishing, p. 420

Raffi I, Backman J, Fornaciaric E, Heiko PD, Rioc D, Lourense L, Hilgene F (2006) A review of calcareous nannofossil astrobiochronology encompassing the past 25 million years. Quat Sci Rev 25:3113–3137

Reolid M (2008) Taphonomic features of Lenticulina as a tool for paleoenvironmental interpretation of mid shelf deposits of the Upper Jurassic Prebetic Zone, Southern Spain. Palaios 23(7):482–494

Rögl F (1985) Late Oligocene and Miocene planktonic foraminifera of the central paratehys. In : Bolli, H.M., Saunders, J.B. and Perch-Neilsen, K. (eds.) Plankton Stratigraphy. Cambridge Univ. Press, pp 315–328

Sadek S (2001) Biostratigraphic contribution to the Miocene formations (Gharandal Group), North Hammam Fara'un area, Sinai, Egypt. J Paleontol 1:253–261

Said R, El Heiny I (1967) Planktonic foraminifera from the Miocene rocks of the Gulf of Suez region, Egypt. Cushman Laboratory Foram Rese 18(l):14–26

Salah M (1994) Geology of the northwestern Rad Sea with special emphasis on the petrology, sedimentology and hydrocarbon potential of the Miocene Kareem Formation. Unpublished Ph. D. Thesis. Cairo University, pp 1–166.

Soliman A, Stjepan C, Martin JH, Werner EP, El Beialye YE (2012) Lower and middle Miocene biostratigraphy, Gulf of Suez, Egypt based on dinoflagellate cysts and calcareous nannofossils. Palyn 36(1):38–79

Stainforth RM, Lamb JL, Luterbacher H, Beard JH, Jeffords RM (1975) Cenozoic planktonic foraminiferal zonation and characteristics of index forms. University of Kansas Paleo Contr 62:1–425

Stanley SL, Chi WR (1983) Neogene nannoplankton biostratigraphy in Taiwan and tectonic implications. Petr Geol of Taiwan 19:93–147

Theodoridis SA (1984) Calcareous nannofossil biozonation of the Miocene and revision of the helicoliths and discoasters. Micr 32: 1–271

Van der Zwaan GJ, Jorissen FJ, De Stigter HC (1990) The depth dependency of planktic/benthonic foraminiferal ratios: constraints and applications. Mar Geol 95:1–16

Wade BS, Pearson PN, Beggren WA, Palike H (2011) Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. Earth Sci 104:111–142

Waite ST, Pooely RW (1953) Report on the Nukhul Formation-unpblished Report G.R. Egypt. General Petrolum Co-operation, Egypt, p 952

Wasfi SM (1968) Miocene planktonic foraminiferal zones from the Gulf of Suez region, Egypt. 3rd African Micr, pp 461–476