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Biostratigraphy and paleoecology of the Burdigalian–Serravallian sediments in Wadi Sudr (Gulf of Suez, Egypt): comparison with the Central Paratethys evolution

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Abstract: Two main Miocene facies were recorded in the Gulf of Suez area: a deep marine and a coastal facies. The analysed sections in the Wadi Sudr area belong to the marine facies. The Lower Miocene (Burdigalian) is represented by coastal, shallow marine sediments, rich in coral, algae, gastropods and large pectinids followed by Langhian open marine sediments and Serravallian lagoonal carbonates. The open marine sediments contain well preserved planktonic and benthic foraminifers and abundant ostracods. The parts of the sections containing foraminifers have been correlated with three planktonic foraminiferal zones (*Praeorbulina glomerosa* Zone, *Orbulina* Zone and *Globorotalia praemenardii–Globorotalia peripheroronda* Zone). Two benthic ecozones were defined (*Heterolepa dutemplei–Laevidentalina elegans* Zone and *Bolivina compressa–Elphidium* spp. Zone). Two cycles of sea-level changes can be distinguished and correlated with global sea-level cycles Bur5/Lan1 and Ser1. The first (Langhian) cycle culminated in open marine sublittoral to upper bathyal well aerated sediments. The second (Serravallian) cycle was shallower, littoral suboxic sediments were overlaid by euryhaline carbonates. The studied foraminifera-bearing sediments can be correlated with the lower and Middle Badenian of the Central Paratethys. Though the area of the Gulf of Suez and the Central Paratethys were situated in different climatic zones, and influenced by different tectonic events, the main paleoenvironmental events (sea-level changes, oxygen decrease, salinity changes) are comparable. This correspondence shows that the decisive factors triggering these events were global climatic events.

Key words: Miocene, Paratethys, Egypt, Gulf of Suez, paleoecology, biostratigraphy, foraminifers.

Introduction

Due to the importance of the Miocene sediments in the Gulf of Suez as oil producing reservoirs, they have attracted the attention of geologists since the 1930s. From the paleontological view (including Miocene microbiostratigraphy), the sequences were studied by several authors, namely Macfadyen (1931), Stainforth (1949), Tromp (1949), Said & Bassiouni (1958), Souaya (1965, 1966a,b), Ansary & Andrawis (1965), Said & El Heiny (1967), Kerdany (1968), Wasfi (1969), Cherif (1972), El Heiny & Martini (1981), Andrawis & Abdel Malik (1981), Sallam (1987), Rateb (1988), Szczechura & Abd-Elshafy (1988), Haggag et al. (1990), Abd-Elshafy & Abd-Elmoneim (1992), Cherif et al. (1993), Phillip et al. (1997) Abul-Naser & Salama (1999), Ibrahim & Mansour (2002) and Strougo et al. (2006).

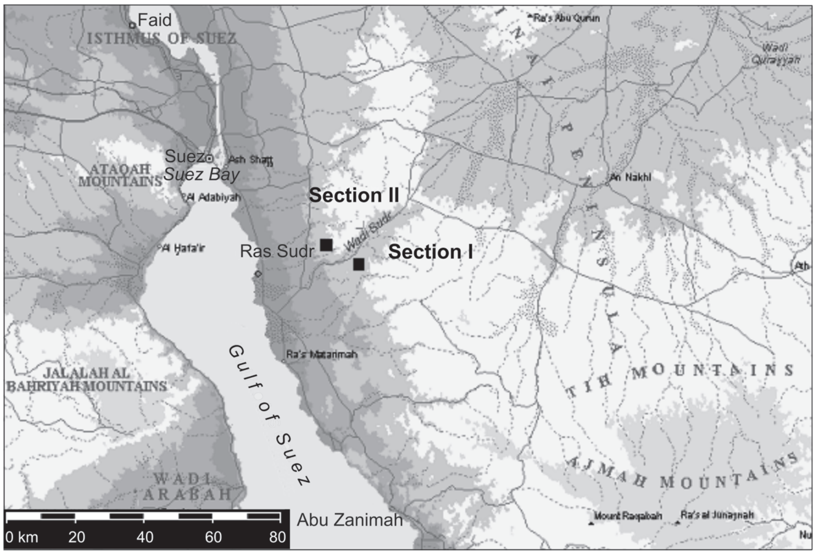

Fig. 1. Location of the studied sections.

The present study deals with the Miocene exposures lying in the eastern part of the Gulf of Suez in the area located 15–20 km southeast from Sudr city at the entrance of Wadi Sudr from the west (Fig. 1) where the Miocene deposits overlie Cretaceous–Eocene sediments.

Though many micropaleontological studies have been done on this area, this work presents biostratigraphical correlation with global planktonic foraminiferal bioevents and the first quantitative paleoecological study.

Material and methods

Material

Sixty eight rock samples were collected from two Miocene sections located on the eastern (section I, Fig. 2) and the western (section II, Figs. 3, 4) sides of Wadi Sudr. Section I, from which 38 rock samples were described, consists mainly of calcareous sandstones and claystones overlain by coralline and algal limestones rich in pectenid shells with some sandstones, claystones and conglomerates interbedded. The sequence ends with marls and claystones rich in foraminifers and ostracods. Section II, from which 30 rock samples were collected, consists mainly of marls, shales, claystones and limestones rich in foraminifers and ostracods; it ends with poorly fossiliferous, probably lagoonal limestones (Fig. 3).

Methods

Foraminifers were studied from 63–2000 μm fractions after washing of disintegrated rock samples in water. About 20 g of washed residue from every sample were checked under the stereomicroscope to pick up the main fossil groups.

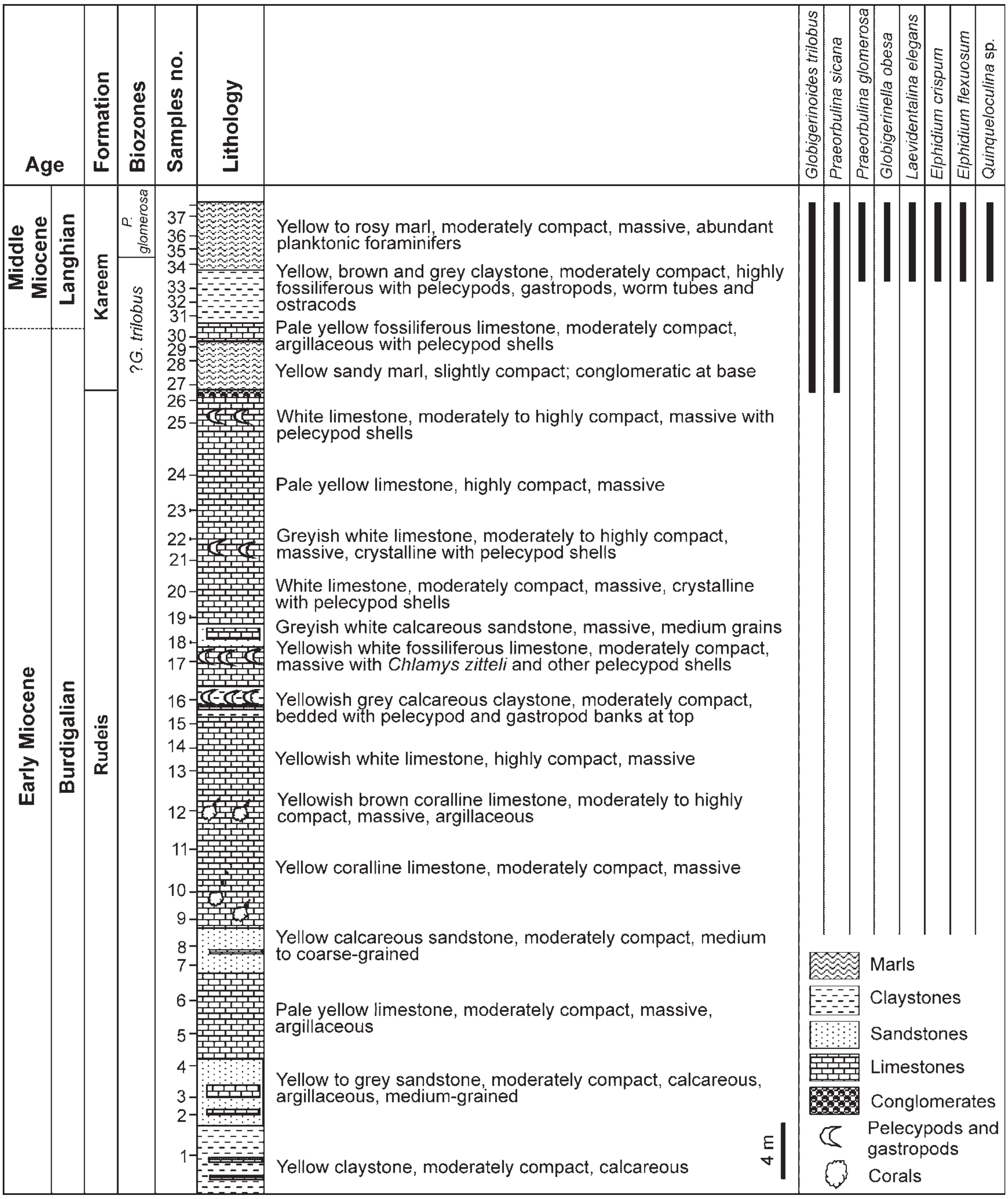

Fig. 2. Lithostratigraphy and foraminiferal distribution of the Lower Miocene rocks in south Wadi Sudr area (section I).

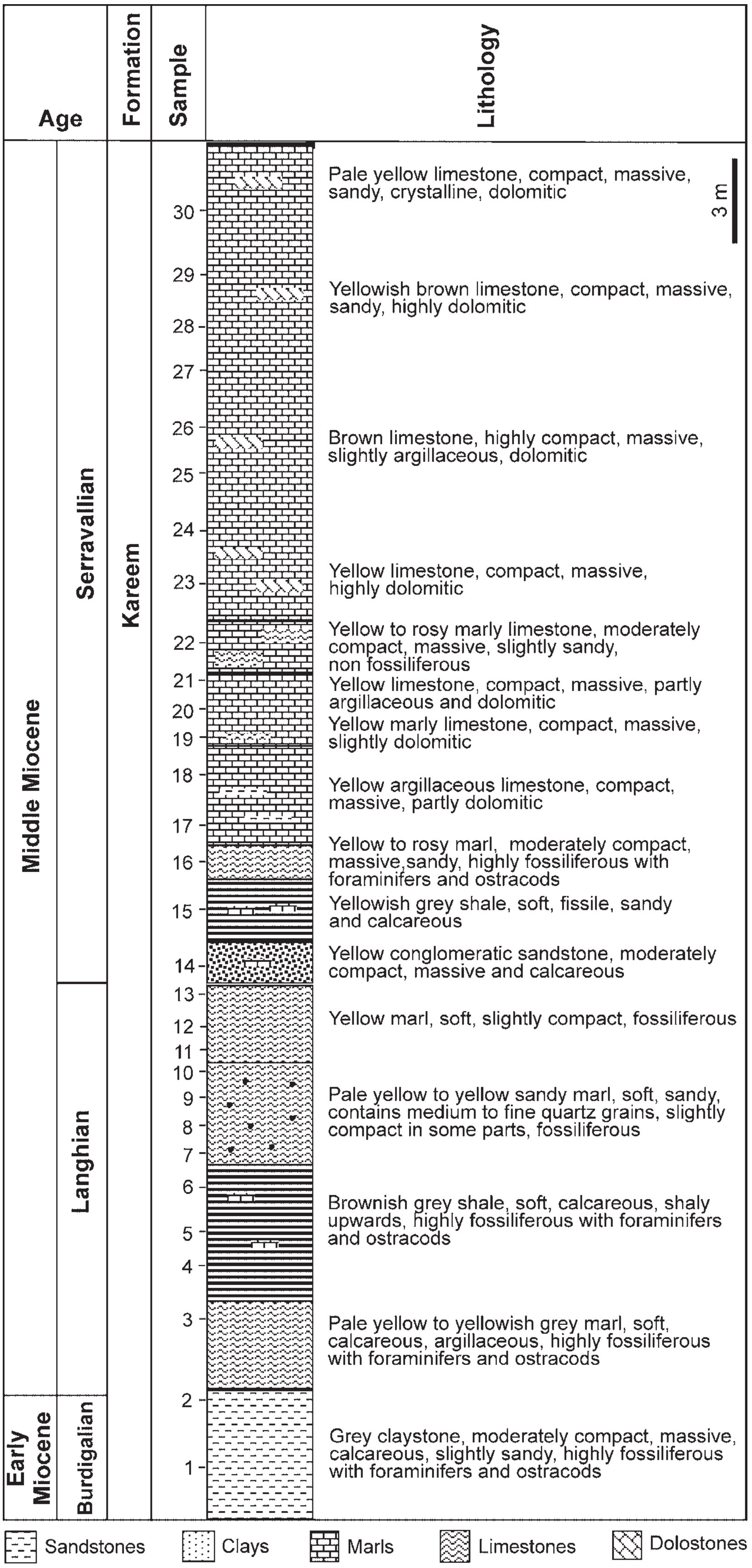

Fig. 3. Lithostratigraphy of the Lower/Middle Miocene rocks in the north Wadi Sudr area (section II).

About 200–300 specimens of foraminifers from each sample were determined (Fig. 5) and the relative abundances of taxa were calculated. The recorded foraminifers were studied and documented using a scanning electron microscope in the Department of Geology and Paleontology, Charles University of Prague.

Benthic foraminiferal faunas were grouped using Q-mode cluster analysis by the software STATISTICA (Tree Clustering; Euclidean distance). To verify results, three algorithms were used: the single linkage, Ward's method and weighted pair-group average.

The following quantitative data were used for paleoenvironmental interpretations:

(i) Abundance of foraminiferal tests in 1 g of dry sediment.

(ii) Diversity expressed as number of foraminiferal species.

(iii) Relative abundances of lagenids.

(iv) Relative abundances of infaunal species (Murray 1991, 2006; Spezzaferri et al. 2002; Báldi 2006).

(v) Relative abundances of cibicidoids.

(vi) Relative abundances of euryhaline species (*Ammonia* spp., *Elphidium* spp., miliolids; Murray 1991, 2006), their abundant occurrence may indicate oscillations of salinity.

(vii) Oxygen contents were estimated using BFOI = Benthic Foraminiferal Oxygen Index (Kaiho 1994, 1999):

$$\mathrm{BFOI} = \mathrm{O}/(\mathrm{O}+\mathrm{D})*100,$$

where O is the number of oxic indicators and D is the number of dysoxic indicators. Oxic and dysoxic indicators were classified according to Kaiho (1994, 1999), den Dulk et al. (2000); Spezzaferri et al. (2002) and Báldi (2006).

(viii) Paleodepth was estimated using the relationship between bathymetry and relative abundance of planktonic foraminifers as proposed by van der Zwaan et al. (1990). This relationship between plankton/benthos-ratio (P/B-ratio) and depth is based on the fact that availability of nutrients on the sea floor depends on depth:

$$\mathrm{Depth}\ [\mathrm{m}] = e^{\,3.58718+(0.03534\times \mathrm{Pc})},$$

where Pc is the corrected ratio of planktonic/benthic foraminifers:

$$\mathrm{Pc} = (\mathrm{P}\times 100)/[\mathrm{P} + (\mathrm{Bt}-\mathrm{Bi})],$$

where P is the number of planktonic foraminifers, Bt is the total number of benthic foraminifers and Bi is the number of deep

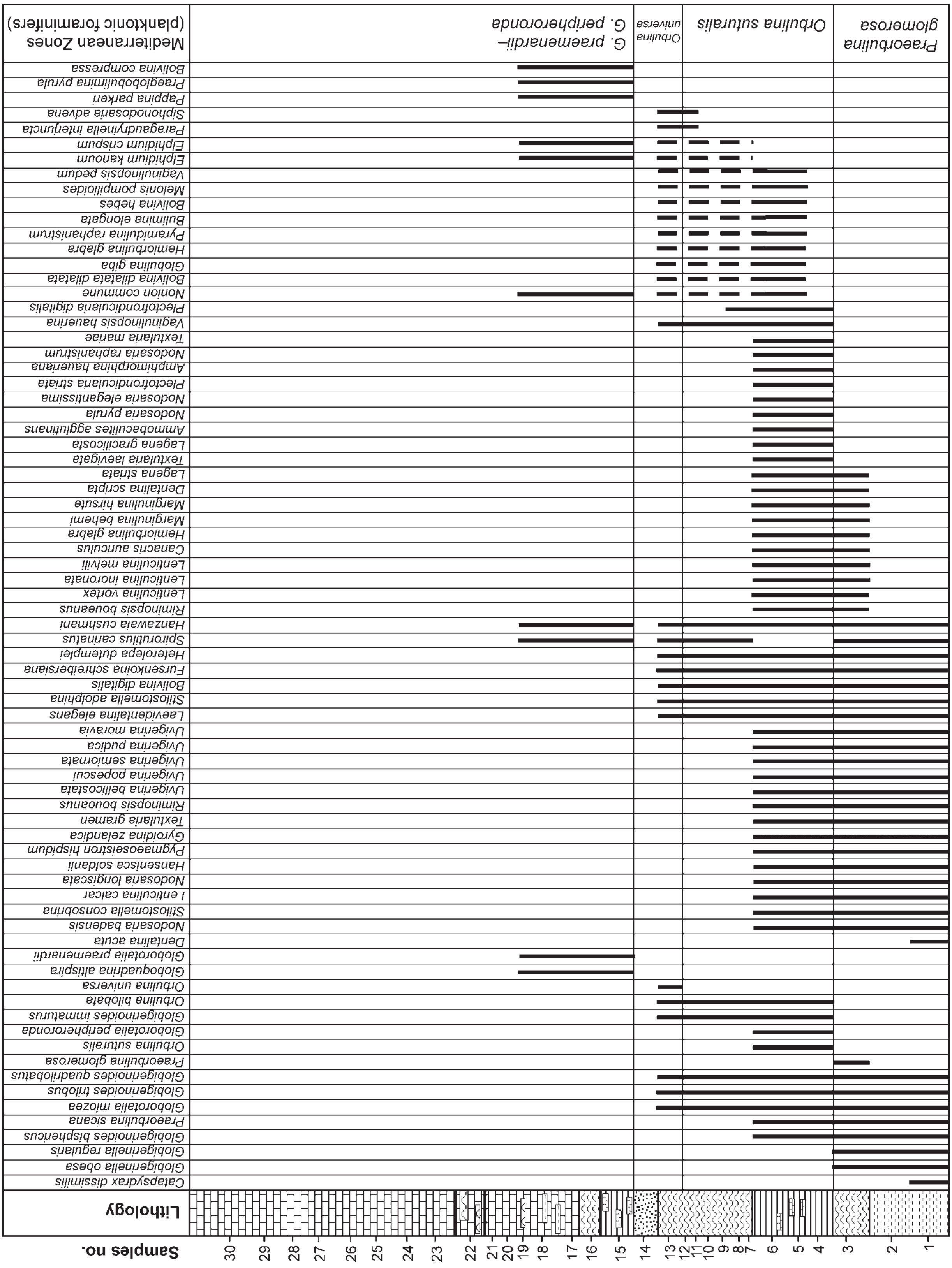

Fig. 4. Distribution of foraminiferal taxa in the Lower/Middle Miocene rocks in the Wadi Sudr area (section II).

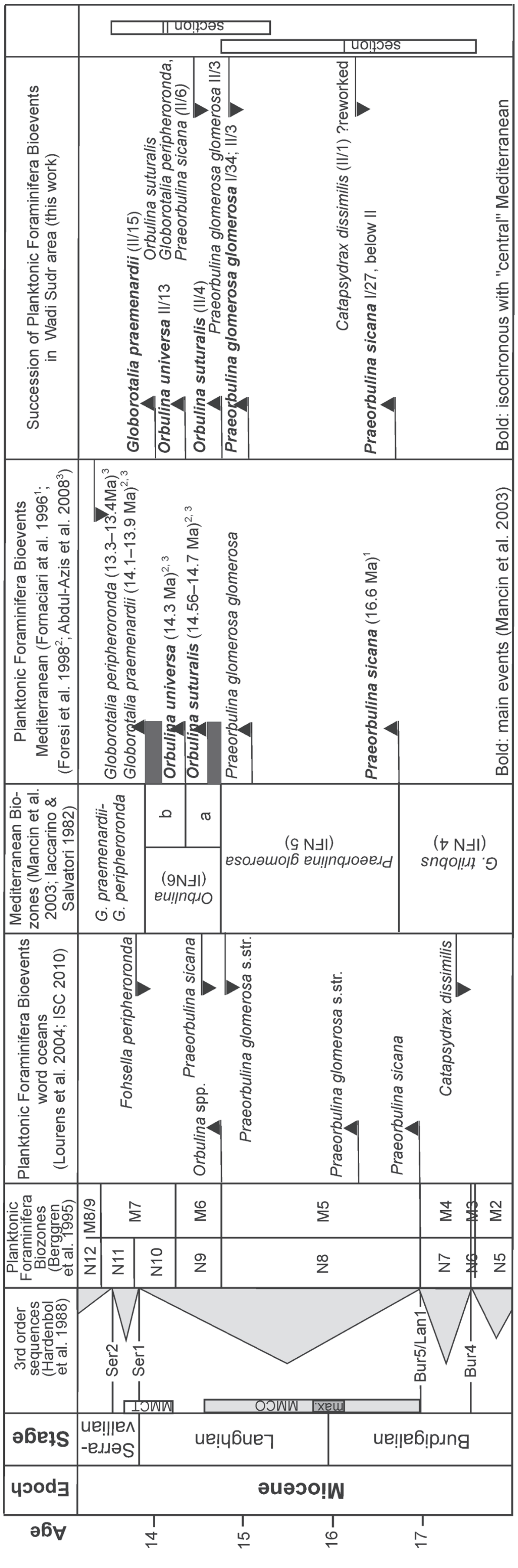

Fig. 5. Biostratigraphical correlation of the studied sections based on planktonic foraminiferal events.

infaunal species (van der Zwaan et al. 1990; van Hinsbergen et al. 2005; Báldi 2006) which are excluded from analysis because they are not directly dependent on the flux of organic matter to the sea floor. The P/B-ratio is not only influenced by depth, but also by changes in the oxygenation of bottom waters (Sen-Gupta & Machain-Castillo 1993; Jorissen et al. 1995) which may fluctuate (Kouwenhoven et al. 2003). A discrepancy between calculated paleodepths and sedimentological record has been pointed out for the Middle Miocene of the Central Paratethys (Hohenegger 2005). Therefore, calculated paleodepths were compared with paleodepths estimated from the depth ranges of some foraminiferal genera and species (Murray 1991, 2006; Hohenegger 2005).

Results and discussion

Lithology

Since Moon & Sadek (1923, 1925), the lithologies of the Miocene rocks in the Gulf of Suez have been studied by many authors, including Stainforth (1949), Sadek (1959), and Ghorab & Marzouk (1967), Said & El Heiny (1967), the National Stratigraphic Sub-Committee (1976), Grafunkel & Bartov (1977), El Heiny (1982), Hamza (1988), Saber (1991), Abd-Elmoneim (1992), Darwish & El-Azabi (1993), Abd-Elshafy & Eweda & Zalat (1996), Refaat (2002), El-Azabi (2004) and others.

According to the National Stratigraphic Sub-Committee (1976), the Miocene rocks in the Gulf of Suez are represented by two different facies:

(1) A deep marine facies, which is divided into:

(i) The lower mainly clastic Gharandal Group with its Nukhul, Rudeis and Kareem Formations; in the studied east Sudr area, Saber (1991) distinguished this group as Gharandal Formation with the lower clastic unit consisting of conglomerates, sandstones, marls and limestones; and the upper carbonate unit consisting of limestones, marls and sandstones. Mandur (2009) correlated the upper part of the Rudeis Formation with the NN4 calcareous nanoplankton Zone (17.95–14.91 Ma, Lourens et al. 2004) and the Kareem Formation with the NN5 Zone (14.91–13.65 Ma, Lourens et al. 2004).

(ii) The upper Ras Malaab Group is mainly evaporite with the Belayim, South Gharib and Zeit Formations. From the Wadi Sudr area, Saber (1991) described this group as the Ras Malaab Formation consisting of evaporites with thin claystone interbeds.

(2) A non-marine (coastal) facies which includes the Abu Gerfan, Gharamul, Gemsa and Sarbut El Gamal Formations (Ghorab & Marzouk 1967). In the study area (Wadi Sudr), Eweda & Zalat (1996) restudied the stratigraphy of the coastal facies and divided them into (i) the Abu Gerfan Formation: coarse, calcareous conglomerate alternating with gritty, coralline limestone and sandy, fossiliferous limestone interbeds and (ii) the Gharamul Formation: limestone sequence — algal coralline limestone with rare marl, sandstone and claystone intercalations.

Due to the occurrence of open marine fauna such as foraminifers, ostracods and calcareous nannoplankton, the studied Miocene exposures in Wadi Sudr can be correlated with the marine facies (Gharandal Group). Following the classification of the National Stratigraphic Sub-Committee (N.S.S.C. 1976) suggested for the eastern coast of the Gulf of Suez, the section I in Wadi Sudr belongs to the Early Miocene Rudeis Formation (samples 1–26). The upper part of section I (samples 27–38) and the whole of section II can be correlated with the Kareem Formation (Figs. 2, 3).

The Rudeis Formation consists mainly of pale yellow, moderately compact, massive, argillaceous limestone with yellow to grey, massive, calcareous, argillaceous sandstone and yellow, moderately compact, massive claystone followed by white, massive, argillaceous coralline limestone with yellowish grey, bedded, calcareous claystone containing banks of pelecypods (*Chlamys zitteli* etc.) and gastropods; the proportion of the claystone increases toward the top with two main marl beds (Fig. 2).

In the lower part, the Kareem Formation consists of pale yellow to yellowish grey, soft, highly fossiliferous marls with fissile shale intercalated, upwards sporadically slightly dolomitic or sandy. Rich foraminifers, ostracods and calcareous nannoplankton assemblages were recorded here. In the upper part, the marls are followed by yellow to brown, compact, massive, dolomitic limestones, slightly argillaceous and sandy (Fig. 3).

Fossil associations

The studied Miocene sections contain three fossiliferous horizons: (1) The lower part of section I (samples 1–26, Fig. 2) is rich in macrofossils such as algae, corals, gastropods and pelecypods (*Chlamys zitteli*) and does not contain microfossils; (2) The upper part of section I (samples 26–38, Fig. 2) and the lower part of section II (samples 1–13, Fig. 4) is rich in foraminifers and ostracods. The highest abundances of both planktonic and benthic foraminifers were recorded at the base of the second section (section II, samples 1–6, Fig. 4); (3) In the upper part of section II (samples 15–19) foraminifers and ostracods are common (Fig. 4).

In both sections, sixteen planktonic and fifty nine benthic foraminiferal species were identified (Figs. 2, 4, 10, 11). Good preservation of foraminiferal tests without abrasions, no size sorting, occurrence of both juvenile and adult specimens in samples 1–6, 11–13, 15–21 show that these assemblages are autochthonous (Holcová 1996). Rare, small and recrystallized tests in samples 7–10 are very probably reworked.

Foraminiferal biostratigraphy

The Miocene sea in the Wadi Sudr area represented a marginal, periodically isolated basin of the Mediterranean. Therefore, some biostratigraphical events may not have been isochronous to the Mediterranean ones.

In the upper part of section I and lower part of section II, the succession of the following important planktonic foraminiferal events were recorded (Fig. 5):

(1) The FO (= first occurrence) of *Praeorbulina sicana* (sample 27, section I; below the base of section II) which is correlated with boundary of M4/M5 and N7/N8 Zones. This event was dated to 17.0 Ma in the world ocean (Lourens et al. 2004). In the Mediterranean area, this event, as proposed by Bicchi et al. (1994), indicated the upper boundary of the *G. trilobus* interval Zone; Mancin et al. (2003) considered the event reliable for the definition of Mediterranean zonal boundaries; Fornaciari & Rio (1996) dated it to about 16.6 Ma. In the studied sections, the FO of *Praeorbulina sicana* corresponds to a new transgression (the base of Kareem Formation) correlatable with the Bur5/Lan1 boundary (Hardenbol et al. 1998). Therefore, the event may be isochronous in the Wadi Sudr area and in the "Central" Mediterranean.

(2) The LO (= last occurrence) of *Catapsydrax dissimilis* (sample 1, section II; Fig. 11.27–28) is dated at 17.54 Ma (Lourens et al. 2004). This species is very rare and occurs in the sample together with *Praeorbulina glomerosa*. It is probably reworked and cannot be used as a zonal marker in the studied sections.

(3 & 4) The FO and LO of *Praeorbulina glomerosa* were recorded in sample 34 of section I and sample 3 of section II (Fig. 11.24). Dating of this event differs for the oceanic realm (16.1 Ma, Berggren et al. 1995; 16.27 Ma Lourens et al. 2004) and for the Mediterranean (15.1 Ma, Abdul Aziz et al. 2008). Mancin et al. (2003) consider this event to be weakly reliable in the Mediterranean area which agrees with its later appearance in the Mediterranean (see above). The LO of *Praeorbulina glomerosa* is dated at 14.8 Ma (Lourens et al. 2004). Because the species was recorded only rarely in one sample, these events must be evaluated critically.

(5) The FO of *Orbulina suturalis* (sample 4 of section II; Fig. 11.25) is dated to 15.1 Ma (Berggren et al. 1995) or 14.74 Ma (Lourens et al. 2004, as *Orbulina* spp.) in the world oceans. For the Mediterranean it was dated to 14.7 Ma (Foresi et al. 1998) or 14.56–14.58 Ma (Abdul Aziz et al. 2008). This event is used in Mediterranean Zonation as a very good zonal marker (Fornaciari et al. 1997). In the Wadi Sudr area, the event occurred in the interval of outer shelf-upper bathyal setting in which good communication with the "central" Mediterranean could be expected. Therefore isochronity of these events in the "central" Mediterranean and the Wadi Sudr area is supposed.

(6 & 7) The LOs of *Praeorbulina sicana* and *Globorotalia peripheroronda* (sample 6 of section II) are heterochronous events in the world oceans. The LO of *Praeorbulina sicana* is dated to 14.53 Ma (Lourens et al. 2004) while the LO of *Globorotalia peripheroronda* is dated 13.80 Ma and can approximately mark the Langhian/Serravallian boundary (Lourens et al. 2004). In the Mediterranean, the event was recorded to 13.34–13.41 Ma (Abdul Aziz et al. 2008). Earlier disappearance of the species in the section studied might have been caused by deterioration of environment, because in this level more planktonic taxa (*G. bispthericus*, *O. suturalis*) also disappear.

(8) The FO of *Orbulina universa* (sample 13 of section II) defines the boundary of Zones N8/N9 or M5/M6 at 14.74 Ma (Lourens et al. 2004). In the Mediterranean, it is recorded later (about 14.3 Ma, Foresi et al. 1998; 14.3 Ma, Abdul Aziz et al. 2008) and may occur diachronously (Casolari et al. 2000). This and the following events were related to the beginning of new cycles and the probable restoration of good communication between the Wadi Sudr area and the "central" Mediterranean.

Therefore these events might occur in the Wadi Sudr area in the same time or later than in the other parts of the Mediterranean.

(9) The FO of *Globorotalia praemenardii* (sample 15, section II; Fig. 11.36–37) was recorded above a hiatus interpreted from the sedimentary record (Fig. 3). In the Mediterranean area, this event is dated to 13.90–13.92 Ma (Abdul Azis et al. 2008) or about 14.1 Ma (Foresi et al. 1998) and was recorded both above and below the FO of *Orbulina universa* (Mancin et al. 2003) which impeaches the reliability of this event.

The above mentioned bioevents and their reliability discussed above were used for correlation of the studied sections (parts with planktonic foraminifers: section I, samples 26–38; section II, samples 1–19) with the Mediterranean zonal schemes of Cita & Premoli Silva (1960), Cita & Blow (1969), Bizon & Bizon (1972), Cita (1975, 1976), Bizon (1979), Borseti et al. (1979), Iaccarino (1985), Bicchi et al. (1994), Sprovieri et al. (2002a,b), Mancin et al. (2003), Iaccarino et al. (2004) and the Miocene foraminiferal zones from Egypt of Kerdany (1968), Wasfi (1969), El-Heiny & Martini (1981), Rateb (1988), Haggag et al. (1990), Ibrahim & Mansour (2002) (Fig. 6).

The following Mediterranean planktonic foraminiferal biozones were recognized (Fig. 5):

IFN5 Praeorbulina glomerosa *Interval Zone (= M5 Zone of Berggren et al. 1995)*

Authors of the zone: Bizon & Bizon (1972); amended by Mancin et al. (2003); upper Burdigalian — lower part of Langhian.

The lower boundary (FO of *Praeorbulina sicana*; originally *Praeorbulina glomerosa* s.l. which also includes *Praeorbulina sicana* (Iaccarino 1985)) was recorded in the sample 27, section I. The upper boundary is represented by the FO of *Orbulina suturalis* (sample 4 of section I).

Because *Praeorbulina glomerosa* s.str. is rare in the studied material (in section II it occurs only in one sample), we do not use its FO for subdividing Zone M5 into the M5a and M5b Subzones (Bergreen et al. 1995).

In the Gulf of Suez area, the *Praeorbulina glomerosa* Zone was described by Kerdany (1968), El Heiny & Martini (1981) and Haggag et al. (1990).

Besides the index species, in the studied sections this zone is characterized by occurrence of the following planktonic foraminiferal species: *Globigerinella obesa*, *Globigerinoides sicanus* and *G. quadrilobatus.*

<table>
<tr><th>Age</th><th>(Kerdany 1968) Gulf of Suez</th><th>(Wasfi 1969) Gulf of Suez</th><th>(El-Heiny & Martini 1981) Gulf of Suez</th><th colspan="2">(Haggag et al. 1990) Gulf of Suez</th><th>(Ibrahim & Mansour 2002) North Western Desert</th><th>Present study</th></tr>
<tr><td rowspan="5">Serravallian</td><td rowspan="3"></td><td>Globigerinoides quadrilobatus primordius</td><td></td><td colspan="2" rowspan="2">Globorotalia mayeri</td><td>Globorotalia menardii</td><td>Globorotalia praemenardii/ Globorotalia peripheroronda altispira</td></tr>
<tr><td rowspan="2">Globigerinoides subquadratus/ G. diminutus</td><td rowspan="3">Globorotalia siakensis</td><td>Globorotalia mayeri</td><td>Hiatus</td></tr>
<tr><td rowspan="4">Orbulina suturalis/ Globorotalia fohsi periphero-ronda</td><td rowspan="3">Orbulina universa</td><td rowspan="3"></td><td rowspan="3">Orbulina universa</td></tr>
<tr><td rowspan="2">Orbulina suturalis</td><td rowspan="2">Globigerinoides sicanus/ G. transitorius</td></tr>
<tr><td rowspan="2">Orbulina suturalis/ Globorotalia fohsi peripheroronda</td></tr>
<tr><td rowspan="2">Langhian</td><td>Globoquadrina altispira/ Globorotalia fohsi peripheroronda</td><td>Globorotalia fohsi peripheroronda</td><td>Orbulina suturalis</td><td rowspan="2">Globorotalia fohsi peripheroronda</td><td>Orbulina suturalis</td></tr>
<tr><td>Praeorbulina glomerosa</td><td>Globorotalia fohsi peripheroacuta</td><td>Praeorbulina glomerosa</td><td colspan="2">Praeorbulina glomerosa</td><td>Praeorbulina glomerosa</td></tr>
<tr><td rowspan="3">Burdigalian</td><td>Praeorbulina sicana</td><td rowspan="3">Globigerinoides ruber</td><td>Globigerinoides sicanus</td><td colspan="2" rowspan="3">Globigerinoides trilobus trilobus</td><td rowspan="3">Praeorbulina sicana</td><td rowspan="3">Globigerinoides trilobus</td></tr>
<tr><td>Globigerinoides subquadratus/ G. diminutus</td><td rowspan="2">Globigerinoides trilobus trilobus</td></tr>
<tr><td>Globigerinoides trilobus</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Globigerinoides primordius</td><td rowspan="2"></td><td rowspan="2">Globigerinoides altiaperturus</td><td colspan="2">Globigerinoides altiaperturus/ Catapsydrax dissimilis</td><td>Catapsydrax dissimilis/ Globigerinoides altiaperturus</td><td rowspan="2"></td></tr>
<tr><td colspan="2">Globigerinoides primordius</td><td>Globorotalia kugleri</td></tr>
</table>

Fig. 6. Biostratigraphical correlation of studied sections with local (Gulf of Suez) planktonic foraminiferal biostratigraphy.

IFN6 Orbulina *Interval Zone*

The base of this zone can be well correlated with the base of the M6 Zone of Berggren et al. 1995 (=FO *Orbulina* spp.). Because the succession of the FOs of *Orbulina* spp. was recorded in the study material, they were used to subdivide the IFN6 Zone into two subzones.

IFN6a Orbulina suturalis *Subzone (=±M6 Zone of Berggren et al. 1995)*

Authors: Iaccarino & Salvatorini (1982); upper Langhian.

The boundaries of this subzone are defined by the FO of *Orbulina suturalis* (sample 4 of section II) to the FO of *Orbulina universa* (sample 13, section II).

In the Mediterranean area, the zone is equivalent to the *Globorotalia peripheroronda/Orbulina suturalis* Zone of Bizon & Bizon (1972), the *Orbulina suturalis* Zone of Borsetti et al. (1979) and the *Orbulina suturalis* Subzone of Iaccarino (1985).

In the Gulf of Suez, the Zone is equivalent to the *Orbulina suturalis* Zone which was recorded from the Gulf of Suez by Haggag et al. (1990), the lower part of the *Orbulina suturalis/Globorotalia fohsi peripheroronda* Zone of El Heiny & Martini (1981), the *Globorotalia fohsi peripheroronda* Zone of Wasfi (1969) and to the *Globoquadrina altispira/Globorotalia fohsi peripheroronda* Zone of Kerdany (1968).

The interval started with a turnover in the planktonic foraminiferal assemblages: *Globigerinella* spp. disappeared, while *Orbulina suturalis* (with its morphotype *O. bilobata*) appeared together with *Globorotalia peripheroronda* and *Globigerinoides immaturus*.

IFN6b Orbulina universa *Subzone (=±uppermost part of M6 Zone and lower part of M7 Zone of Berggren et al. 1995)*

Authors: Iaccarino & Salvatorini (1982).

Although Iaccarino & Salvatorini (1982) and Iaccarino (1985) correlated this zone with the Serravallian, a recent dating of the FO of *Orbulina universa* in the Mediterranean area (Abdul Azis et al. 2008) points out that the age of uppermost Langian for the subzone is more probable.

In the studied sections, only the lower boundary (=the FO of *Orbulina universa*) was recorded. This zone ends at the hiatus below the sample 14 in section II.

This zone can be approximately correlated with the *Orbulina universa* Zone, which was recorded from the Gulf of Suez by Haggag et al. (1990). It is equivalent to the upper part of the *Orbulina suturalis/Globorotalia fohsi peripheroronda* Zone of El Heiny & Martini (1981); *Globigerinoides sicanus/G. transitoria* Zone of Wasfi (1969) and *Orbulina suturalis* Zone of Kerdany (1968).

*(?)*Globorotalia praemenardii–Globorotalia peripheroronda *Subzone (=±upper part of M7 Zone of Berggren et al. 1995)*

Authors: Iaccarino & Salvatorini (1982); Serravallian.

This zone begins with the FO of the *Globorotalia praemenardii* and ends with the LO of *Globorotalia peripheroronda*. The samples 15–19 of section II could be correlated with this zone, though only very rare planktonic foraminifers occur in this interval.

In Egypt, the zone is equivalent to the *Globorotalia kugleri/Globoquadrina altiaperta globosa* Zone (Said & El Heiny 1967) in Abu Rudeis well No. 2, the *Globoquadrina altiaperta/Globorotalia fohsi peripheroronda* Zone (Kerdany 1968) and the *Globorotalia mayeri* Zone described in the Gulf of Suez (Haggag et al. 1990) and in North Western Desert (Ibrahim & Mansour 2002).

Benthic foraminiferal ecozones

The distribution of the recorded benthic foraminiferal associations revealed the presence of two local ecozones which are defined and described for the first time in the present work. The boundary between the zones (sample 14, section II) reflects a clear ecological change documented by a turnover in benthic foraminiferal faunas. At this turnover, 19 benthic foraminiferal species disappeared, and about 30 species disappeared successively below the boundary. This change is also reflected in cluster analysis (Fig. 9). Possible ecological factors that may have caused this faunal turnover are interpreted in the following subchapter.

Heterolepa dutemplei–Laevidentalina elegans *Assemblage Zone (samples 1–13, section II)*

In addition to the nominate species, this zone is characterized by *Nodosaria badensis*, *N. longiscata*, *Stilostomella consobrina*, *St. adolphina*, *Lenticulina calcar*, *L. melvilli*, *L. inoronata*, *Gyroidina danvillensis*, *G. zelandica*, *Textularia gramen*, *Riminopsis boueanus*, *Uvigerina bellicostata*, *Uvigerina semiornata*, *Uvigerina pudica*, *Uvigerina moravia*, *Bolivina digitalis*, *Fursenkoina schreibersiana* and *Lenticulina vortex*. This zone can be correlated with the *Praeorbulina glomerosa*, *Orbulina suturalis* and *Orbulina universa* planktonic foraminiferal Zones.

Bolivina compressa–Elphidium *spp. Assemblage Zone (samples 15–19, section II)*

This zone is characterized by *Elphidium flexuosum*, *Elphidium crispum*, *Paragaudryinella interjuncta*, *Siphonodosaria advena*, *Pappina parkeri*, *Praeglobobulimina pyrula* and *Bolivina compressa.* This zone can be correlated with the *Globorotalia praemenardii–Globorotalia peripheroronda* Subzone (planktonic Foraminifera).

The zones are local and cannot be correlated with the zonation of Souaya (1966a,b) based on samples from the southern part of the Gulf of Suez.

Burdigalian/Langhian and Langhian/Serravallian boundaries

The Burdigalian/Langhian boundary is dated to 15.974 Ma and lies in the M5 planktonic foraminiferal Zone above the FO of *Praeorbulina glomerosa* s.str. (Gradstein et al. 2004).

The data from Mediterranean showed a later FO of *Praeorbulina glomerosa glomerosa* (Abdul Azis et al. 2008) in comparison with the data of Lourens et al. (2004) from the oceanic realm. It agrees with the description of the succession of bioevents in the historical Langhian stratotype (Odin et al. 1997) where the Burdigalian/Langhian boundary is situated between the FOs of *Praeorbulina sicana* and *Praeorbulina glomerosa*. Because more accurate biomarkers were not recorded in the studied sections, biostratigraphically the boundary could have been determined only approximately (similarly to the historical Langhian stratotype) between the FOs of *Praeorbulina sicana* and *Praeorbulina glomerosa* (in the intervals of samples 27–34 of section I and 1–3 of section II). The lithological or ecological turnover and hiatus between the samples 25/26 (section I), which can be correlated with the Bur5/Lan1 boundary, is situated below the biostratigraphically determined Burdigalian/Langhian boundary. It agrees with correlation of the Bur5/Lan1 with the uppermost Burdigalian (Gradstein et al. 2004).

The Langhian/Serravallian boundary is dated to 13.654 Ma in the M7 planktonic foraminiferal Zone and can be correlated with the Lan2/Ser1 boundary (Lourens et al. 2004). In the Mediterranean area, the boundary is close to the FO of *Globorotalia praemenardii* (13.90–13.92 Ma; Abdul Azis et al. 2008). In the studied sections, the boundary is correlated with the beginning of the new sea-level cycle with planktonic foraminifers *Globorotalia praemenardii* (between samples 13/14 of the section II).

Paleoenvironmental analysis

The paleoecological analysis is based on a detailed quantitative study of the rich foraminiferal assemblages from section II and from the uppermost part of section I. Using

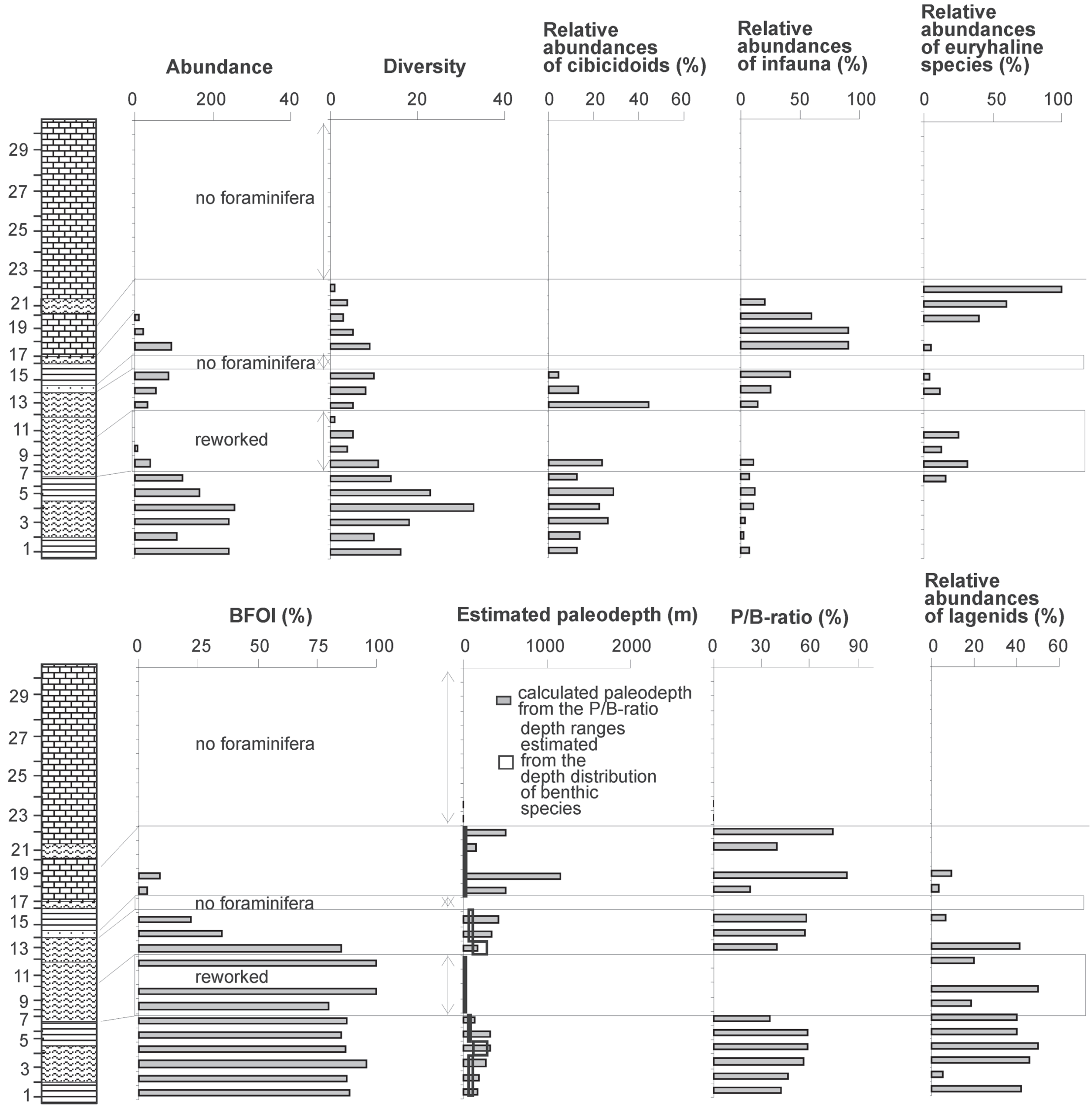

Fig. 7. Quantitative characteristics of foraminiferal assemblages from section II used for paleoecological interpretation. For explanation of calculation of the BFOI and the paleodepth see chapter Methods.

changes of quantitative characteristics of foraminiferal assemblages as well as cluster analysis and taphonomical analysis of assemblages together with lithological characteristics (Figs. 2, 3, 7, 8), two cycles were distinguished:

(1) The lower cycle can be subdivided into two intervals:

(i) The late Burdigalian/Langhian interval started with shallow-water assemblages (section I, samples 35–37) followed by rich and diversified foraminiferal assemblages dominated by lagenids and cibicidoids in samples 1–6, section II. The foraminifera indicate normal marine environment and high oxic conditions (Fig. 7). Paleodepth estimations from the P/B-ratio and from the depth distribution of taxa (Figs. 7, 8) are comparable and indicate depths of 50–100 m in the lower and upper parts of this interval and 100–300 m in the middle part (sample 4, section II). Characteristics of foraminiferal assemblage in sample 4 correspond to characteristics of high-stand assemblages summarized by Armentrout et al. (1990). Decreasing abundance and diversity of foraminiferal assemblages in samples 6–8 (section II), occurrence of reworked tests in samples 7–10 (section II) as well as appearance of euryhaline species may indicate a shallower environment. It can be corroborated by paleodepth 20–50 m estimated from depth distribution of species (Fig. 8).

(ii) The late Langhian interval starts between the samples 10/11, where diversity, abundance and P/B-ratio of foraminifer increase and reworked tests disappear. Paleodepth resulted from the depth distribution of recorded species has been estimated at 50–100 m, although calculated paleodepths from the P/B-ratio are higher but less probable (Fig. 7).

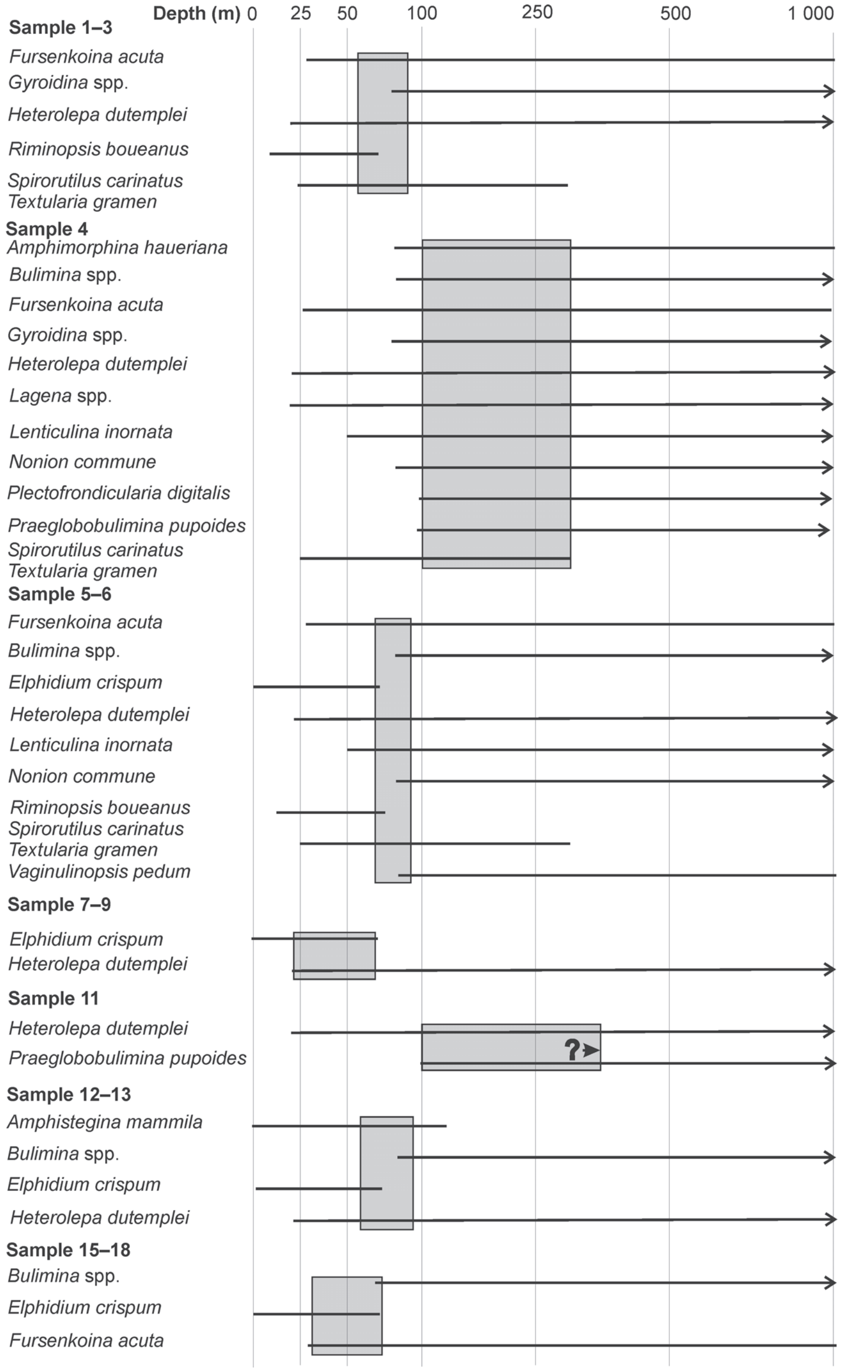

Fig. 8. Benthic foraminiferal species from section II with known depth distribution (Murray 1991; Hohenegger 2005). Grey rectangles illustrate intersection of depth ranges of foraminifers and estimation of paleodepth for separate intervals of the section.

Biostratigraphical correlation using planktonic foraminifers enables us to correlate the lower boundary of this interval (section I, sample 35) with the Bur5/Lan1 boundary (Hardenbol et al. 1998) and upper boundary (section II, sample 13) with the Ser1 boundary (Hardenbol et al. 1998).

(2) The Serravallian cycle starts with conglomeratic sandstone (sample 14, section II). Samples 15–19 are clearly distinguished using cluster analysis (Fig. 9). New foraminiferal assemblages of Serravallian age indicate suboxic conditions and probably much shallower conditions than the calculated paleodepth from the P/B-ratio (Fig. 7). The paleodepth estimated from the depth distribution of foraminiferal taxa indicates values of 20–50 m (Fig. 8). Suboxic stenohaline conditions are gradually changed to very shallow euryhaline environment at the beginning with dominance of euryhaline foraminiferal species. Later foraminifers disappear. Biostratigraphical correlation based on the FO of planktonic fo-

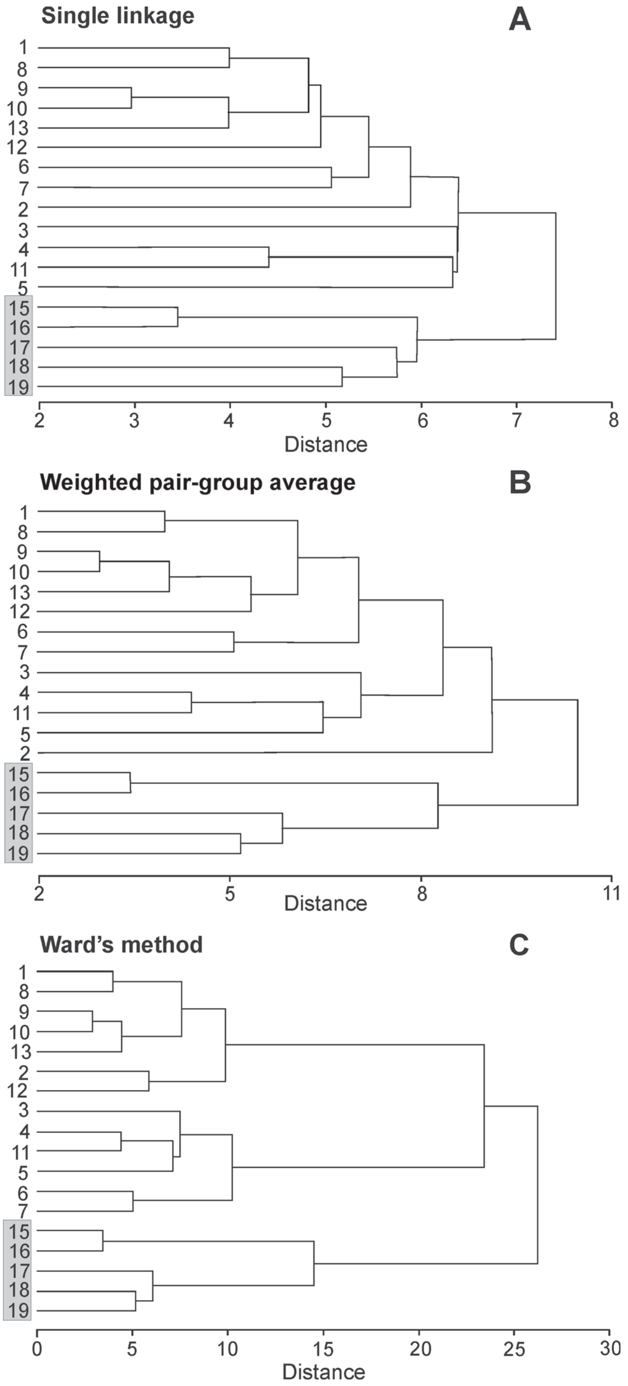

Fig. 9. Results of cluster analysis for samples from section II. Fig. A–C compares dendrograms obtained by different clustering techniques.

raminifers *Globorotalia praemenardii* enables us to correlate the base of the cycle with the Ser1 boundary (Hardenbol et al. 1998).

Comparison of the Middle Miocene evolution of the Gulf of Suez and the Central Paratethys

During the study period the Gulf of Suez formed a marginal part of the Mediterranean, while the Central Paratethys area was a chain of basins connected with the Mediterranean (e.g. Popov et al. 2004). Though these areas were separated by about 4000 km in the south-north direction (according to the paleogeographical reconstruction of Popov et al. 2004) in different climatic zones, and influenced by different tectonic events (Kováč et al. 2007), there are some similarities between the Middle Miocene evolution of these areas.

According to planktonic foraminiferal bioevents, the Langhian sediments from the Wadi Sudr area can be correlated with the Badenian sediments of the Lower and Upper Lagenidae Zones including the sediments of the Grund Formation of Austria and Moravia (Ćorić & Rögl 2004; Tomanová Petrová & Švábenická 2007; Rögl et al. 2007, 2008; Hohenegger et al. 2009a,b). In the Central Paratethys, the Lower/Middle Miocene boundary is strongly influenced by a local tectonic event: the Styrian Tectonic Phase of Stille (1924). Sedimentation gaps named the "Styrian Unconformity" characterized this boundary interval (Rögl et al. 2007; Hohenegger et al. 2009b). After this gap, a first Badenian transgression was recorded within nannoplankton Zone NN4 with rare *Praeorbulina sicana* (Hohenegger et al. 2009b). The main Badenian transgression covering all the Central Paratethys followed in the NN5 Zone with occurrence of *Praeorbulina circularis* and *Orbulina suturalis.* This large marine transgression occurred in the entire circum-Mediterranean area (Rögl & Steininger 1983; Rögl 1998, 1999; Kováč et al. 2007; Rögl et al. 2008; Hohenegger et al. 2009a,b).

In the Wadi Sudr area, sediments with *Praeorbulina* also correspond to the new transgression (the base of Kareem Formation). However, a hiatus, correlatable in both areas with the Bur5/Lan1 boundary of Hardenbol (1998), is not so pronounced as in the Central Paratethys influenced by local tectonics. In both areas, the following marine paleoenvironment is the deepest in the whole Middle Miocene and contains open marine planktonic foraminifera. The interval corresponds to the Middle Miocene Climatic Optimum (Gonera et al. 2000; Bicchi et al. 2003; Böhme 2003).

During the Middle Badenian (the interval corresponds approximately to the Langhian/Serravallian transition), communication between the Mediterranean and the Paratethys continued. A warm-temperate climate in the Early Badenian was followed by a temperature decline (Middle Miocene Climatic Transition: Gonera et al. 2000; Bicchi et al. 2003; Böhme 2003; Harzhauser & Piller 2007) and the global sea-level fall around 14.8 Ma can be correlated with the Mi3-event (Billups & Schrag 2002; Abels et al. 2005). This sea-level fall has been recorded in both areas: in the Central Paratethys (Filipescu & Girbacea 1997; Rögl 1998; Báldi et al. 2002) as well as in the Wadi Sudr area. Foraminiferal assemblages in the Pannonian Basin of the Central Paratethys suggest that during the Middle Badenian increasing food supply, decreasing oxygen level and growing stress on the sea floor occurred (Báldi 2006). These changes may be characteristic not only for the Central Paratethys: foraminiferal assemblages enable us to interpret an oxygen decrease also in Wadi Sudr area.

The following evaporite event can also be recorded in both areas. The "Wielician" Central Paratethys event is characterized by deposition of mostly sulphate facies in shallow littoral parts of the foredeep, while chloride-sulphate facies developed

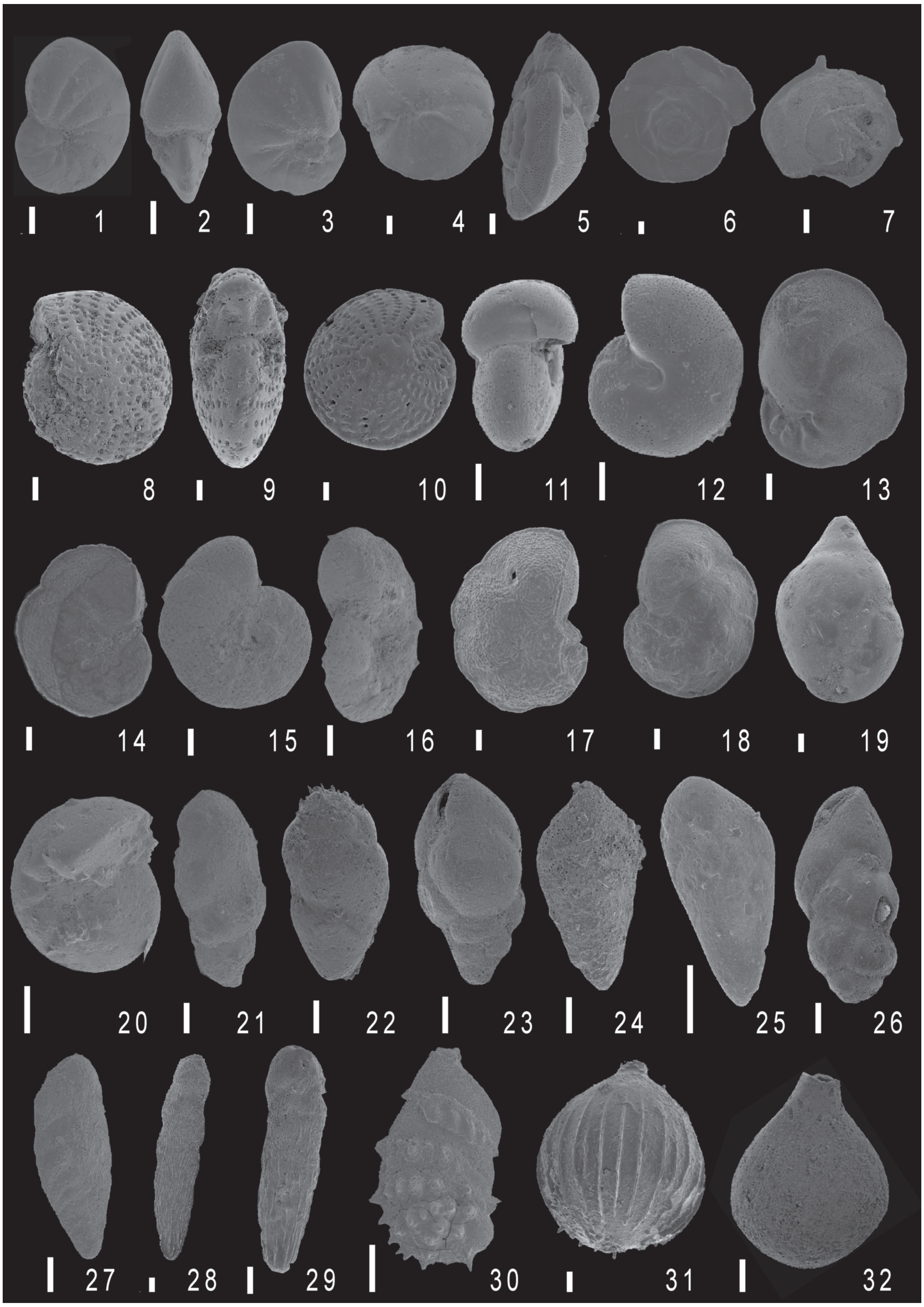

Fig. 10. **1–3** — *Nonion commune* (D'Orbigny): Sample no. 4, section II. **4–6** — *Heterolepa dutemplei* (D'Orbigny): Sample no. 5, section II. **7** — *Lenticulina calcar* (Linne): Sample no. 3, section II. **8–9** — *Elphidium crispum* (Linne): Sample no. 11, section II. **10** — *Elphidium kanoum* Hayward: Sample no. 6, section II. **11–12** — *Melonis pompilioides* (Fichtel & Moll): Sample no. 9, section II. **13–14** — *Cancris auriculus* (Fichtel & Moll): Sample no. 3, section II. **15–16** — *Riminopsis boueanus* D'Orbigny: Sample no. 5, section II. **17–18** — *Hanzawaia cushmani* (Natali): Sample no. 13, 18, section II. **19** — *Praeglobobulimina pyrula* (D'Orbigny): Sample no. 15, section II. **20** — *Hansenisca soldanii* (D'Orbigny): Sample no. 3, section II. **21** — *Bulimina elongata* D'Orbigny: Sample no. 4, section II. **22** — *Bulimina subulata* Cushman & Parker: Sample no. 8, section II. **23** — *Praeglobobulimina pupoides* (D'Orbigny): Sample no. 15, section II. **24, 25** — *Bolivina dilatata dilatata* Reuss: 24 — Sample no. 6, section II, 25 — Sample no. 12, section II. **26** — *Bulimina coprolithoides* Andreae: Sample no. 15, section II. **27** — *Bolivina dilatata maxima* Cicha & Zapletalová: sample no. 4, section II. **28–29** — *Bolivina semistriata* Hantken: Sample no. 12, section II. **30** — *Marginulina pseudodecorata* Hagn: Sample no. 3, section II. **31** — *Lagena striata* (D'Orbigny): Sample no. 4, section II. **32** — *Pygmaeoseistron hispidum* (Reuss): Sample no. 4, section II.

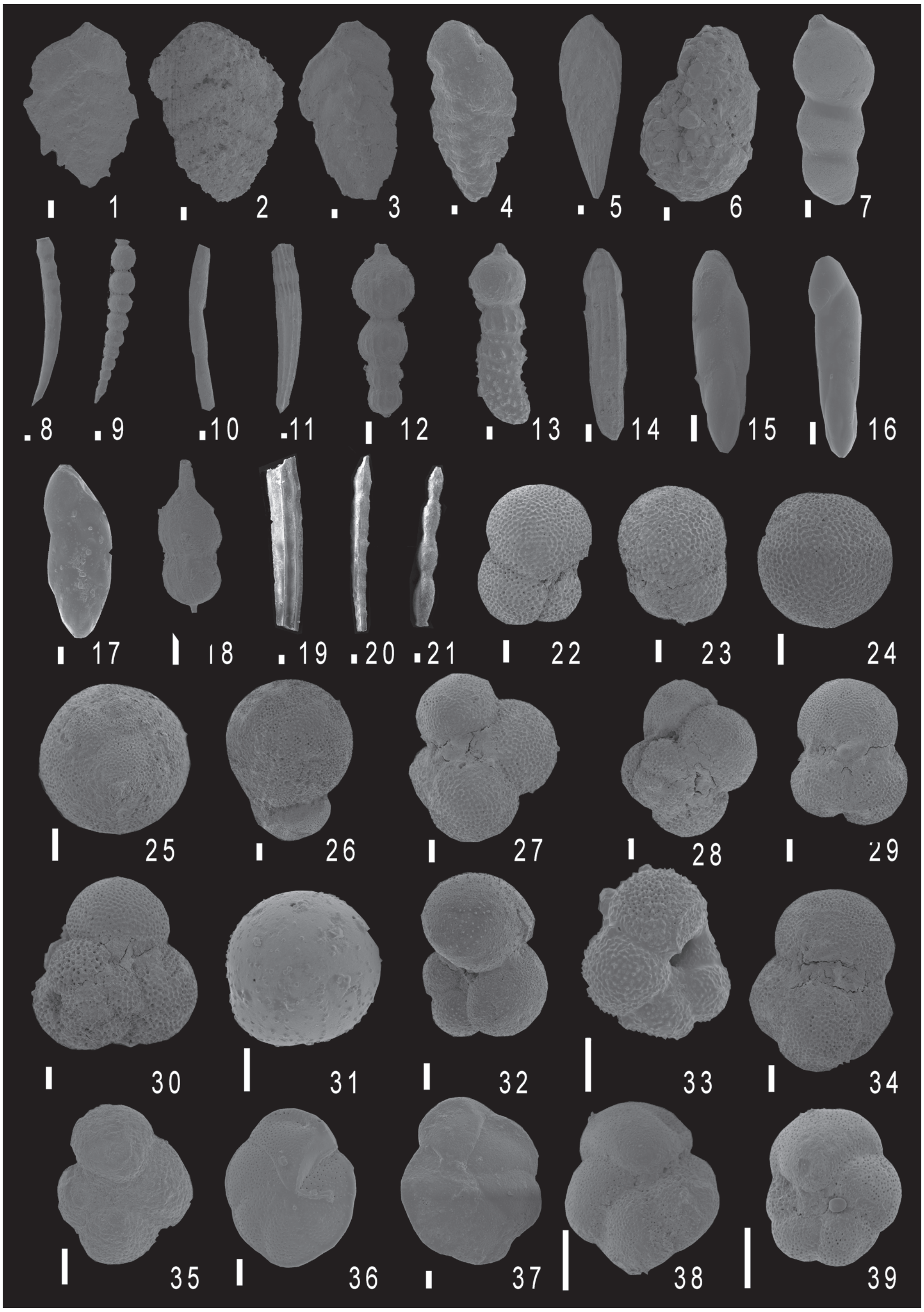

Fig. 11. 1, 3 — *Spiroplectinella carinata* (D'Orbigny): Sample no. 4, section II. **2** — *Textularia gramen gramen* D'Orbigny: Sample no. 4, section II. **4** — *Textularia mariae* D'Orbigny: Sample no. 4, section II. **5** — *Plectofrondicularia striata* (Hantken): Sample no. 4, section II. **6** — *Ammobaculites agglutinans* (D'Orbigny): Sample no. 4, section II. **7** — *Hemirobulina glabra* (D'Orbigny): Sample no. 3, section II. **8** — *Laevidentalina elegans* (D'Orbigny): Sample no. 1, section II. **9** — *Stilostomella adolphina* (D'Orbigny): Sample no. 4, section II. **10** — *Nodosaria* ex gr. *longiscata* D'Orbigny: Sample no. 4, section II. **11** — *Dentalina acuta* D'Orbigny: Sample no. 1, section II. **12** — *Amphicoryna badenensis* (D'Orbigny): Sample no. 4, section II. **13** — *Marginulina hirsuta* D'Orbigny: Sample no. 4, section II. **14** — *Plectofrondicularia digitalis* Neugeboren: Sample no. 4, section II. **15–17** — *Fursenkoina schreibersiana* (Czjzek): 15–16 — Sample no. 3, section II. 17 — Sample no. 13, section II. **18** — *Amphicoryna badenensis* (D'Orbigny): Sample no. 4, section II. **19** — *Nodosaria elegantissima* D'Orbigny: Sample no. 4, section II. **20–21** — *Nodosaria raphanistrum* (Linne): Sample no. 4, section II. **22–23** — *Globigerinoides trilobus trilobus* (Reuss): Sample no. 4, section II. **24** — *Praeorbulina glomerosa glomerosa* (Blow): Sample no. 3, section II. **25** — *Orbulina suturalis* Bronnimann: Sample no. 4, section II. **26** — *Orbulina bilobata* (D'Orbigny): Sample no. 4, section II.

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in the deepest part of the basin (Oszczypko & Ślączka 1989; Ghergari et al. 1991; Oszczypko 1997; Petrichenko et al. 1997; Andreyeva-Grigorovich et al. 1999, 2003; Bąbel 2004, 2005; Oszczypko et al. 2006). In the study area the evaporite event started with suboxic conditions gradually changing to very shallow euryhaline environment with disappearance of foraminifers.

Conclusions

The present biostratigraphical and paleoecological study of two sections in the Wadi Sudr area enriches the information about the Miocene history of the joined Gulf of Suez area. Detailed quantitative paleoecological analysis was applied in this area which enables more precisely interpretation of the paleoecological evolution of marine Middle Miocene sediments.

The following sea-level cycles have been distinguished:

(1) The Burdigalian cycle without microfauna which cannot be accurately dated biostratigraphically. During this cycle, sandstones, claystones and limestones were deposited in the lower part and coralline algal limestones in the upper part (Rudeis Formation). The limestones rich in pectinid and gastropod shells with coral colonies indicate shallow marine environments.

(2) The uppermost Burdigalian-Langhian cycle followed after a hiatus which can be correlated with the global Bur5/Lan1 sequence boundary of Hardenbol et al. (1998). In this cycle, clastic sedimentation dominates, it is represented by claystones, marls and sandy marls (lower part of Kareem Formation). Biostratigraphically, this cycle is bounded by the FO of *Praeorbulina sicana* and the LO of *Globorotalia peripheroronda*. The Langhian/Burdigalian boundary lies in the lowermost part of the cycle, upwards the cycle can be correlated with the planktonic foraminiferal zone of *Praeorbulina glomerosa* and the subzones of *Orbulina suturalis* and *Orbulina universa.* A benthic ecozone *Heterolepa dutemplei–Laevidentalina elegans* was defined in this interval. Rich and diversified foraminiferal assemblages dominated by lagenids and cibicidoids in samples 1–6 in section II indicate a normal marine, oxic environment with a maximum of paleodepth 100–300 m for the lower interval of the cycle. The upper interval is shallower (50–100 m) but a normal marine environment is expected.

(3) The hiatus which can be correlated with global Ser1 sequence boundary of Hardenbol et al. (1998) bounded Serravallian cycle starting with conglomeratic sandstones containing few foraminifers. The sandstones are followed by shales and marls containing less diversified and abundant microfauna with rare planktonic foraminifers (Zone *Globorotalia praemenardii–Globorotalia peripheroronda*). The cycle ends with dolomitic and argillaceous limestones (upper part of Kareem Formation) without biostratigraphical markers. A benthic ecozone *Bolivina compressa–Elphidium* spp. was defined in this cycle. A shallow (20–50 m) littoral, suboxic environment has been interpreted for the lower part of cycle. Section upwards, these normal marine sediments were replaced by euryhaline limestones.

The studied foraminifera-bearing interval can be correlated with the early and middle part of the Badenian of the Central Paratethys. Though the area of the Gulf of Suez and the Central Paratethys were situated in different climatic zones, and influenced by different tectonic events, the main paleoenvironmental events (sea-level changes, oxygen decrease, salinity changes) are comparable. It shows that the decisive factors triggering these events were global climatic events (the Middle Miocene Climatic Optimum followed by the Middle Miocene Climatic Transition).

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Fig. 11. ***Continuation from previous page.*** **27–28** — *Catapsydrax dissimilis* (Cushman & Bermudez): sample no. I, section II. **29–30** — *Globigerinoides quadrilobatus* (D’Orbigny): Sample no. 4, section II. **31** — *Globulina* sp., Sample no. 13, section II. **32** — *Globigerinella obesa* (Bolli): Sample no. 1, section II. **33** — *Globigerinella regularis* (D’Orbigny): Sample no. 3, section II. **34** — *Globigerinoides quadrilobatus* (D’Orbigny): Sample no. 4, section II. **35** — *Globorotalia continuosa* Blow: Sample no. 20, section II. **36–37** — *Globorotalia praemenardii* Cushman & Stainforth: Sample no. 15, section II. **38–39** — *Globorotalia* (*Fohsella*) *peripheroronda* Blow & Banner: Sample no. 4, section II.

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