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ORIGINAL PAPER

Planktic foraminiferal biostratigraphy of the Oligocene–Pliocene successions in the offshore well A1-89, Sirt Basin, Libya

Mohammed F. El Hassi[1] · Ahmed M. Muftah[2] · Esam O. Abdulsamad[2] · Belkasim K. Belkasim[3]

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Abstract

This study deals with planktic foraminiferal biostratigraphy of the Oligocene-Pliocene successions in the offshore Well A1-89 of the Sirt Basin. One hundred and forty-one ditch cutting samples covering the interval from 1050ft to 9000ft have been analyzed for this study. Fifty-five planktic foraminifera taxa belonging to seventeen genera have been identified. Ten planktic foraminiferal biozones have been recognized herein based on the integration of Bolli and Saunders's (1985), Berggren et al.(1995), Steininger et al. (GSSP 1997), and Wade et al. (2011), zonal schemes. In descending order, they are *Sphaeroidinellopsis seminulina* (Zanclean-Piacenzian); *Praeorbulina sicana* (Burdigalian-Langhian); *Globigerinoides bisphericus* (Burdigalian); *Globigerinatella* sp./*Catapsydrax dissimilis* (Burdigalian); *Globigerinoides primordius* (Aquitanian); *Paragloborotalia kugleri* (Aquitanian); *Globigerina ciperoensis ciperoensis* (Chattian); *Globorotalia opima opima* (Chattian); *Globigerina ampliapertura* (Rupelian); *Cassigerinella chipolensis/Pseudohastigerina micra* (Rupelian). The Oligocene/Miocene boundary is found to be conformable and placed at the top of the *Globigerina ciperoensis ciperoensis* Biozone. However, the Miocene/Pliocene boundary is unconformable and placed at the top of the *Praeorbulina sicana* Biozone. Additionally, the established biozones have been regionally correlated with their equivalents in Tunisia and Egypt.

Keywords Biostratigraphy · Planktic foraminifers · Oligocene · Pliocene · Sirt Basin · Libya

Introduction

The use of planktic foraminiferal biostratigraphy in the oil industry appeared in the middle of the nineteenth century in the USA and spread quickly through the main oil-producing parts of the world (Stainforth et al. 1975). This has resulted in recognition of their usefulness for precise dating, well-to-well correlations, and sedimentary basin analysis to facilitate interpretation and prediction of critical geologic structures and location of oil accumulations (Stainforth et al. 1975; Bolli and Saunders 1985; Berggren et al. 1995). The Sirt Basin in the north-central part of Libya represents the youngest sedimentary basin and has been interpreted to be an extensional continental rift basin and is referred to as part of the Tethyan rift system (Ahlbrandt 2002). There are several published studies related to the foraminiferal biostratigraphy in the onshore of Sirt Basin (e.g., Berggren 1969, 1974; Eliagoubi and Powell 1980; Muftah 1991; Duronio et al., 1991: Barbieri 1994, 1996; Ashour 1996; Tshakreen et al. 2002; Tshakreen and Gasinski 2004; Tshakreen et al. 2017; Abdulsamad et al. 2019), and most of these studies have been concentrated on the older intervals (Cretaceous and early Paleogene). On the contrary, the planktic foraminiferal biostratigraphic studies in offshore are limited in general, especially those concerning the Oligocene–Pliocene interval. Further east in Egypt some studies concerning

Responsible Editor: Attila Ciner

✉ Mohammed F. El Hassi
Hassi9010@yahoo.com

Ahmed M. Muftah
ahmed59muftah@gmail.com

Esam O. Abdulsamad
esam000@yahoo.com

Belkasim K. Belkasim
Bkb28_1981@yahoo.com

1 Faculty of Engineering Sciences, Department of Geological Engineering, University of Bright Star, Brega, Libya

2 Faculty of Science, Department of Earth Sciences, University of Benghazi, Benghazi, Libya

3 Department of Geological Sciences, Ball State University, Muncie, IN, USA

Oligo-Miocene planktonic foraminiferal biozones have been published such as (Cherif et al. 1993; Ouda 1998; Boukhary et al. 2012; Hewaidy et al. 2012, 2013; Zakaria et al. 2019). Meanwhile in Tunisia (Hooyberghs and El Ghali 1990; Riahi et al. 2010, 2015; Belayouni et al. 2012, 2013) covering the Oligo-Miocene sections. On the other hand, the Pliocene planktic biozones were studied by Ouda (1998) and Yaakoub et al. (2017) in Egypt and Tunisia, respectively. However, presently, there is a tendency to study the Oligocene, Miocene, and younger horizons at the Libyan offshore from a biostratigraphic point of view, especially after the discoveries of gas fields in the eastern Mediterranean offshore. The current study deals with the study of Oligocene to Pliocene planktic foraminifera retrieved from the Sirt Basin Offshore Well A1-89, which is located near the center of the offshore part of Ajdabiyah Trough in Sirt Basin at Lat. 31° 06′ 22″ N and Long. 19° 50′ 01.00″E (Fig. 1). The examination of the studied samples led to the recovery of many well-preserved planktic foraminifers, and this provides an excellent tool for the taxonomy and biostratigraphy approaches. The objectives of this paper are the following: (1) establishing the planktic foraminiferal biozones and correlating them with equivalent biozones recorded in Tunisia and Egypt and (2) delineating and analyzing the stage boundaries (Oligocene–Miocene and Miocene-Pliocene boundaries).

Materials, methods, and depository

The studied offshore Well Al-89 has no cores or sidewall core samples; therefore, this study has been performed based only on ditch cutting samples covering the interval from 1050 to 9000 ft. These samples are provided by the exploration division management of Arabian Gulf Oil Company (AGOCO). One hundred and forty-one samples with a 50′ apart interval form the raw material of this work. The samples are crushed gently by pestle and mortar then washed using a gentle current of tap water through a 63-µm mesh sieve (British standard mesh). The residue then was dried on a hotplate at 70 °C. Finally, the dried residue of every sample is examined under a stereoscopic microscope, and the planktic foraminifers were picked up into micropaleontological slides and then identified based on their morphologic features. Fifty-five taxa have been identified and mounted on numbered slides. Selected specimens were photographed using a scanning electron microscope (SEM) at the Department of Geoscience in the University of Indiana Pennsylvania. All foraminiferal slides including the diagnostic species are labeled and deposited in the micropaleontology section of the Department of Earth Sciences, University of Benghazi in Libya.

Lithostratigraphy

The studied succession in well A1-89 is represented by a sequence of carbonate and fine clastic rocks ranging in age from early Oligocene to early Pliocene with a total thickness of about 7950 ft. These successions were deposited in a deep marine environment, displaying different rock types and microfossils assemblages in comparison to the coeval rock units in Sirt Basin and Al Jabal al Akhdar areas, which are deposited in relatively shallower marine settings. Due to the several unmatched stratigraphic nomenclatures used in Sirte Basin and Al Jabal al Akhdar region by different oil companies and several institutes for the Oligocene and younger rock units. Therefore, the stratigraphic column of AGOCO geologists is adopted herein. This stratigraphic column is assembled using the provided data from AGOCO which included the Well-A1-89 log and ditch cutting samples (Fig. 2). This column was differentiated into the following subdivisions based on the lithological changes and fossil contents in ascending order:

Oligocene sequence

The Oligocene sequence occupies the interval from 4650 to 9000 ft, and they are subdivided into four lithological units: unit 1 (850 ft. thick) is composed of an alternation of subfissile, dark gray, medium-hard shale interbedded with calcareous claystone with a thin streak of slightly chalky limestone, grades upward into unit 2 (2400 ft. thick) which composed of gray, medium-hard, highly calcareous claystone, containing thin streaks of creamy, medium-hard argillaceous limestone at the upper part, followed by unit 3 (400 ft. thick) which composed of yellowish-green, medium-hard, argillaceous limestone. The uppermost Oligocene unit 4 (650 ft. thick) is composed of green, medium-hard calcareous claystone interbedded at the top with thick beds of greenish-gray, soft shale (see Fig. 2).

Miocene sequence

The Miocene rocks occupy the interval from 1850 to 4650 ft and rest conformably on the Oligocene sequence and subdivided into two lithological units:

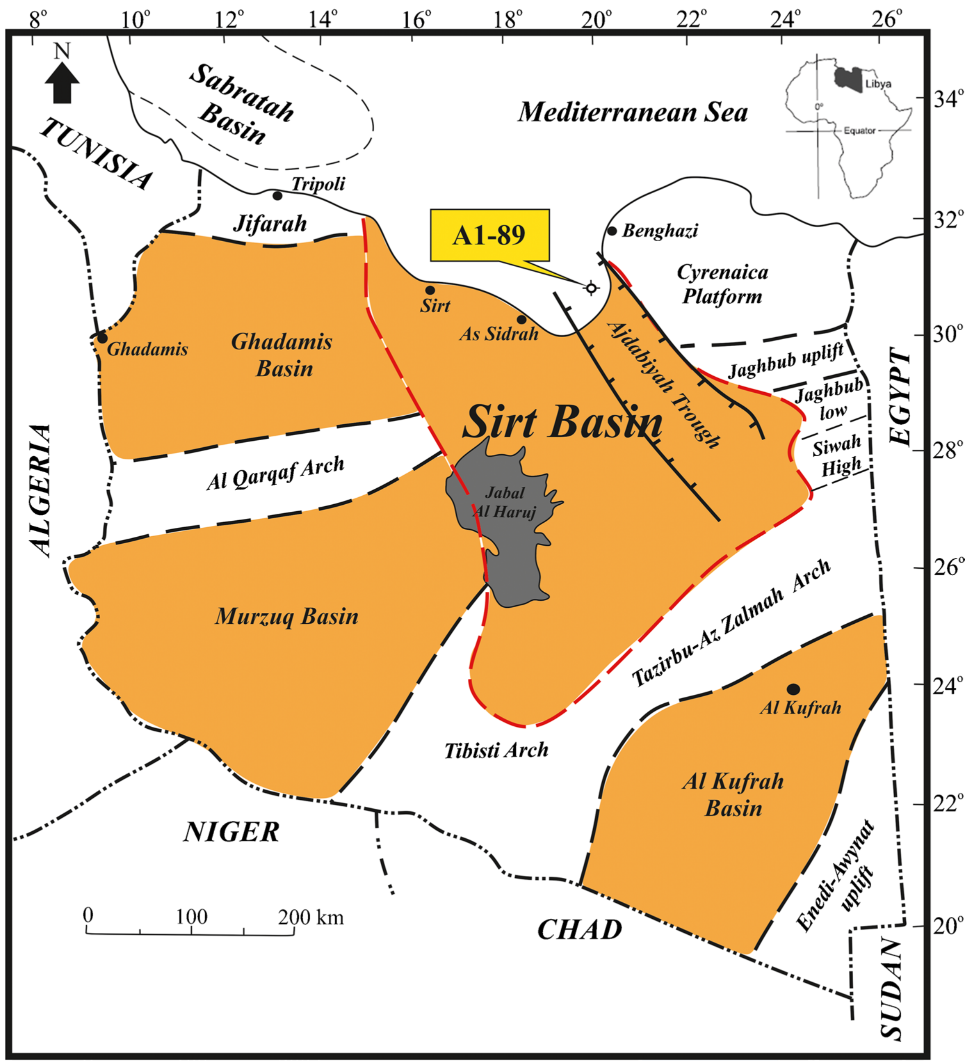

Fig. 1 Location map of the Offshore Well A1-89 and the main sedimentary basins of Libya (modified after Tmalla 1996)

unit 1 (1800 ft. thick) is composed of cream, medium-hard, argillaceous limestone interbedded with gray, medium-hard, calcareous claystone with thin streaks of gray, soft, and fissile shale. The upper Miocene unit 2 (1050 ft. thick) is composed of gray, soft to medium-hard, calcareous claystone interbedded with yellowish-brown, hard, marly, and silty dolostone (see Fig. 2).

Pliocene sequence

The Pliocene sequence spans the interval from 1050 to 1850 ft. It rests unconformably on the Middle Miocene sediments and consists of green, soft, silty, calcareous claystone interbedded with cream, soft marly limestone (see Fig. 2).

Biostratigraphy

The zonation schemes of Bolli and Saunders (1985), Berggren et al. (1995), and Steininger et al. (GSSP 1997) for the Oligocene-Early Miocene successions as well as Wade et al. (2011) and Iaccarino (1985), for younger successions, have been followed in this study due to the reported diagnostic taxa and the geographical position of the studied site. All the studied samples are ditch cuttings (i.e., collected during drilling in open hole conditions), and the contamination due to the caving problem is a major challenge in such biostratigraphic study. Therefore highest occurrence (HO) (= the first downhole appearance (FDA) of the diagnostic species was used to recognize the boundaries of each biozone. Many biostratigraphers consider the highest occurrence (HO) of diagnostic taxa

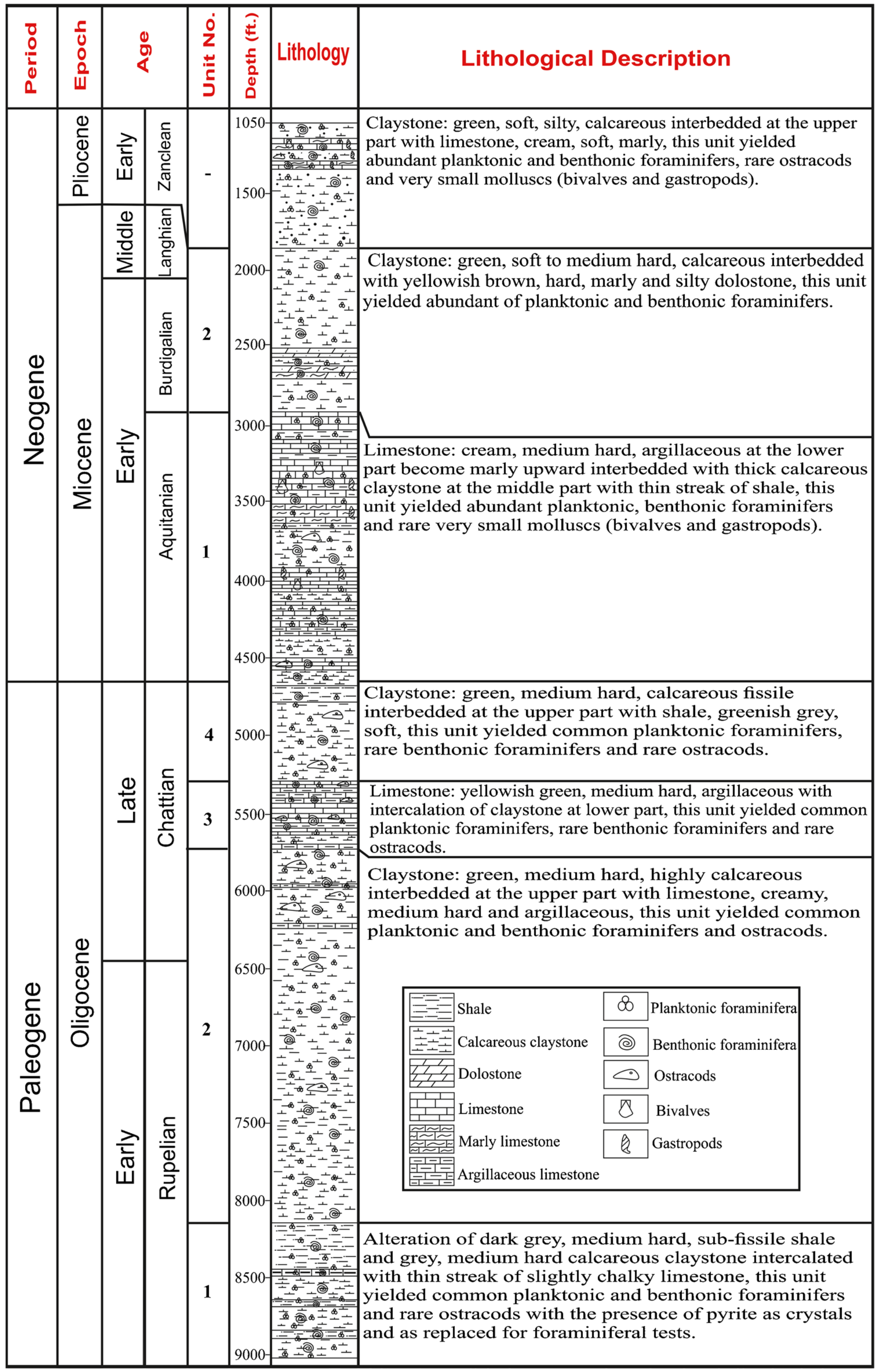

Fig. 2 The stratigraphic column of the offshore Well A1-89 (after AGOCO 1966)

more applicable and reliable for biostratigraphic analysis in ditch cuttings samples (e.g., Iaccarino and Salvatorini 1982; Lin et al. 2004; Li et al. 2007). The species of stratigraphic value are photographed and shown on (Fig. 3). The vertical stratigraphic distribution of the identified species throughout the studied succession led to the establishment of ten planktic foraminiferal biozones (i.e., four Oligocene biozones, five Miocene biozones, and one Pliocene biozone) which are illustrated in (Figs. 4 and 5). These biozones are correlated with their equivalents

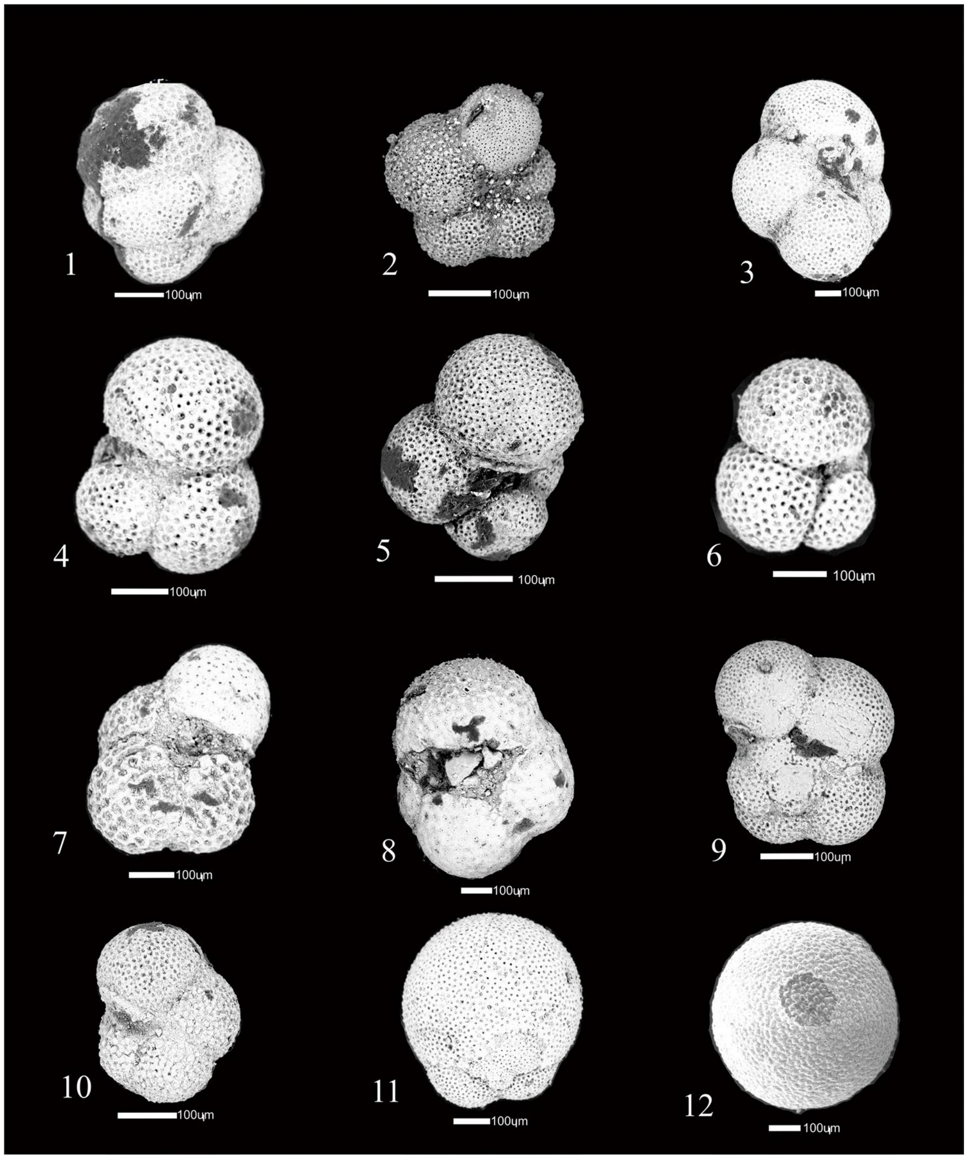

Fig. 3 *Catapsydrax dissimilis* (Cushman and Bermudez) Sample No. 28, Depth 2400′. 2—*Globigerina ciperoensis ciperoensis* (Bolli) Sample No. 57, Depth 4650′. 3—*Globigerinoides sacculifer* (Brady), Sample No. 2, Depth 1100′. 4—*Globigerinoides primordius* (Blow and Banner), Sample No. 37, Depth 2900'. 5—*Subbotina eocaena* (Gumbel), Sample No. 111, Depth 7450′. 6—*Subbotina linaperta* (Finlay), Sample No. 123, Depth 8050′. 7′—*Sphaeroidinellopsis seminulina* (Schwager), Sample No. 6, Depth 1300′. 8—*Sphaeroidinella dehiscens* (Parker and Jones), Sample No. 1, Depth 1050′. 9—*Paragloborotalia opima opima* (Bolli), Sample No. 77, Depth 5750′.10-*Paragloborotalia opima nana* (Bolli), Sample No. 58, Depth 4700′. 11—*Orbulina suturalis* (Brönnimann), Sample No. 8, Depth 1400′. 12—*Orbulina universa* (d'Orbigny), Sample No. 1, Depth 1050′

biozones recorded in the neighboring countries, "Tunisia and Egypt."

Biostratigraphy of the studied well

Sphaeroidinellopsis seminulina s.l. Acme biozone (N18) early Pliocene (Zanclean)

Definition

Interval from lowest occurrence (LO) of prominent open marine conditions in the Mediterranean after the Late Miocene salinity crisis to the LO of *Globorotalia margaritae* (Iaccarino 1985). This biozone corresponds to *Sphaeroidinellopsis* spp. Acme biozone according to earlier studies of Cita (1973, 1975, 1976).

Remarks

The upper boundary of this biozone in this study is defined at the depth 1050, and its lower boundary is defined by the highest occurrence (HO) of *Praeorbulina* spp. and covers the interval from 1050 to 1850′. This biozone is characterized by a predominance of planktic foraminifers in great diversity with excellent preservation. The associated planktic foraminiferal taxa in this biozone include *Sphaeroidinellopsis disjuncta*, *Ss. sphaeroides*, *Sphaeroidinella dehiscens*, *Orbulina*

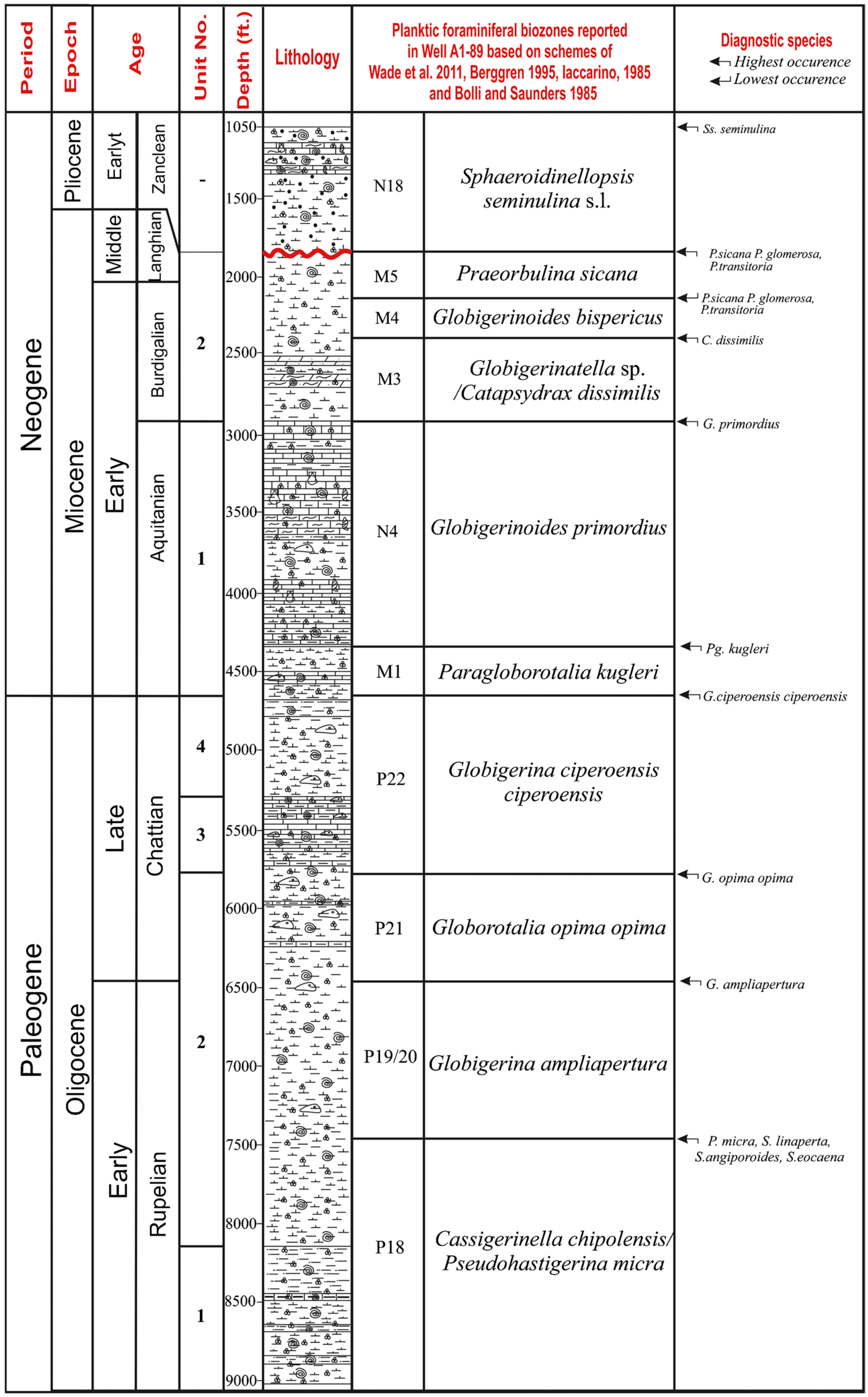

Fig. 4 The Oligo-Pliocene planktic foraminiferal biozones recognized in Offshore Well A1-89 Sirt Basin, Libya

universa, *O. bilobata*, *O. suturalis*, *Globigerinoides obliquus obliquus*, *Gds. obliquus extremus*, *Gds. sacculifer*, *Gds. trilobus*, *Gds. immaturus*, *Gds. ruber*, *Gds. quadrilobatus*, *Globigerina praebulloides praebulloides*, *Gg. praebulloides occlusa*, *Gg. falconensis*, *Globigerinita naparimaensis*, *Ggt. incrusta*, *Zeaglobigerina woodi woodi*, *Globigerinella obesa*, and *Globoquadrina dehiscens* (Fig. 5).

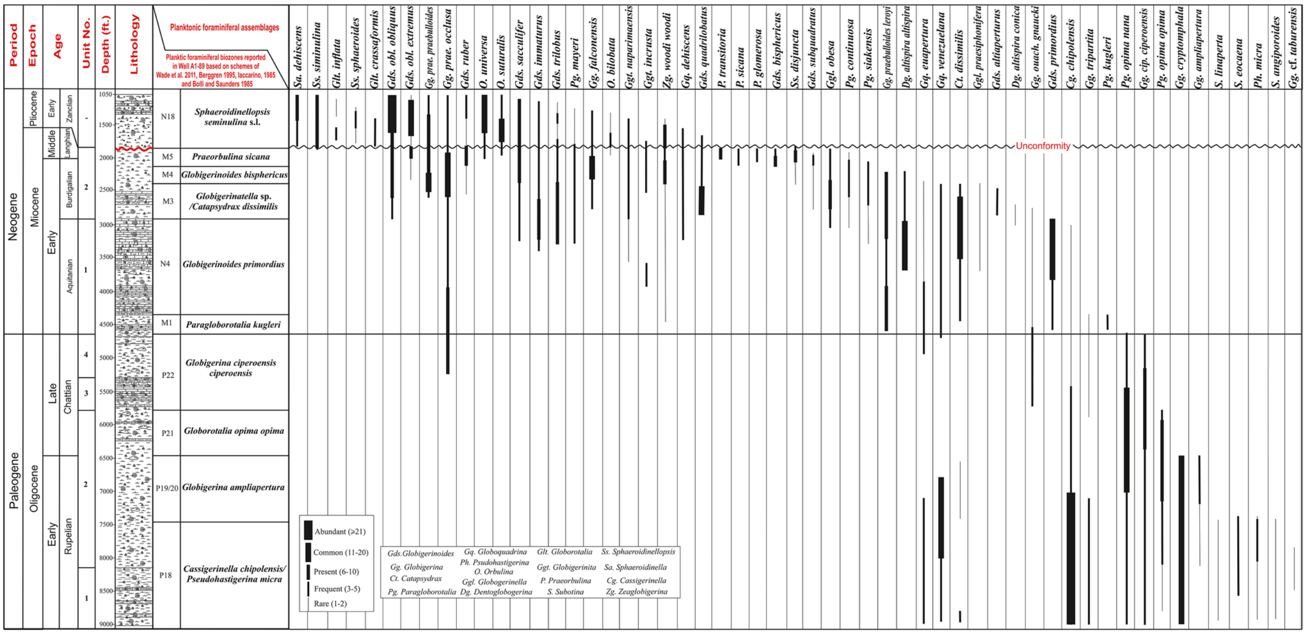

Fig. 5 Integrated biostratigraphic foraminiferal range chart of Oligocene–Pliocene successions in the offshore Well A1-89 (Bolli and Saunders 1985; Iaccarino 1985; Berggren et al. 1995; Steininger et al. 1997; Wade et al. 2011)

Geographical correlation

This biozone is equivalent to *Sphaeroidinellopsis seminulina* s.l. biozone recorded by Ouda (1998) from the Pliocene strata in the Sallum hole-1well in the northern part of the Western Desert of Egypt. However, in Tunisia, this biozone is equivalent to *Sphaeroidinellopsis* spp. Acme biozone recorded by Moissette et al. (2010) from Raf Raf Formation at Oued Galaa section in northern Tunisia.

Praeorbulina sicana lowest occurrence biozone (M5) middle Miocene (Burdigalian-Langhian)

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Definition

Interval from the LO of *Praeorbulina sicana* to the LO of *Orbulina suturalis* (Wade et al. 2011).

According to the Mediterranean biozonation scheme of Iaccarino (1985), this biozone was called *Praeorbulina glomerosa* biozone.

Remarks

The upper boundary of this biozone is defined herein, by the HO of the *Praeorbulina sicana*, *P. glomerosa*, and *P. transitoria*; however, the lower boundary of this biozone is defined by the absence of all *Praeorbulina* spp. and covers the interval from 1850 to 2150′. This biozone is characterized by a predominance of planktic foraminifers with great diversity and excellent preservation. The associated planktic foraminiferal taxa include *Praeorbulina transitoria*, *P. sicana*, *Sphaeroidinellopsis disjuncta*, *Orbulina suturalis*, *O. universa*, *O. bilobata*, *Globigerinoides obliquus obliquus*, *Gds. sacculifer*, *Gds. trilobus*, *Gds. immaturus*, *Gds. ruber*, *Gds. subquadratus*, *Gds. quadrilobatus*, *Gds. bisphericus*, *Paragloborotalia mayeri*, *Pg. siakensis*, *Pg. continuosa*, *Globigerinella obesa*, *Dentoglobigerina altispira altispira*, *Globoquadrina dehiscens*, *Globigerinita naparimaensis*, *Ggt. incrusta*, *Globigerina praebulloides praebulloides*, *Gg. praebulloides occlusa*, *Gg. falconensis*, and *Zeaglobigerina woodi woodi* (Fig. 5).

Geographical correlation

This biozone is equivalent to *Praeorbulina glomerosa* biozone of Hewaidy et al. (2013) from the lower part of the Sidi Salem Formation in the onshore Qantara-2 well and offshore wells PFMD2RBIS and Helm-1 in the eastern Nile Delta of Egypt. However, in Tunisia, this biozone is equivalent to *Globigerinoides sicanus/Praeorbulina glomerosa* biozone of Hooyberghs (1973, 1977) and Hooyberghs and El Ghali (1990) from Oued Hammam Formation at Oued Sidi Hamouda section in central Tunisia.

Globigerinoides bisphericus Partial-Range biozone (M4) early Miocene (Burdigalian)

Definition

Interval from the HO of *Catapsydrax dissimilis* to the LO of *Praeorbulina sicana* (Wade et al. 2011).

According to the Mediterranean biozonation scheme of Iaccarino (1985), this biozone is called *Globigerinoides trilobus* biozone.

Remarks

The upper boundary of this biozone is defined herein with care, by the approximate absence of *Praeorbulina sicana*, *P. glomerosa*, and *P. transitoria* due to the nature of ditch cutting samples; this boundary is approximate. The lower boundary is defined by the HO of *Catapsydrax dissimilis* and covers the interval from 2150to 2400′. This biozone is characterized by a great abundance of planktic foraminifers with great diversity and moderate to excellent preservation. The associated planktic foraminiferal taxa in this biozone include *Praeorbulina sicana*, *Globigerinoides obliquus obliquus*, *Gds. obliquus extremus*, *Gds. sacculifer*, *Gds. immaturus Gds. ruber*, *Gds. subquadratus*, *Gds. quadrilobatus*, *Paragloborotalia mayeri*, *Pg. continuosa*, *Pg. siakensis*, *Globigerinella obesa*, *Dentoglobigerina altispira altispira*, *Globoquadrina dehiscens*, *Globigerinita naparimaensis*, *Ggt. incrusta*, *Sphaeroidinellopsis disjuncta*, *Globigerina praebulloides*, *Gg. falconensis*, and *Zeaglobigerina woodi woodi* (Fig. 5).

Geographical correlation

This biozone is equivalent to the *Praeorbulina sicana* biozone of Hewaidy et al. (2013) from Qantara Formation at wells Qantara-2 and PFMD2RBIS in the eastern Nile Delta area. However, in Tunisia, this biozone is equivalent to the N6–N7 biozone of Blow (1969) recorded by Glacon and Rouvier (1967) and Belayouni et al. (2013) from Babouch Member at Babouch and Cap-Serrat areas.

Globigerinatella sp./*Catapsydrax dissimilis* concurrent-range biozone (M3) early Miocene (Burdigalian)

Definition

Concurrent range of the nominate taxa between the LO of *Globigerinatella* sp. and the HO of *Catapsydrax dissimilis* (Wade et al. 2011).

According to the Mediterranean biozonation scheme of Iaccarino (1985), this biozone is called *Globigerinoides altiaperturus/Catapsydrax dissimilis* sub-biozone.

Remarks

The upper boundary of this biozone in the present study is defined by the HO of the zonal marker *Catapsydrax dissimilis*. However, the lower boundary is defined by the highest occurrence (HO) of *Globigerina primordius* and covers the interval from 2400 to 2900′. This biozone is characterized by a super-abundance of planktic foraminifers with high diversity and excellent preservation. The associated planktic foraminiferal taxa include *Globigerinoides obliquus obliquus*, *Gds. sacculifer*, *Gds. trilobus*, *Gds. immaturus*, *Gds. subquadratus*, *Gds. altiaperturus*, *Gds. quadrilobatus*, *Paragloborotalia mayeri*, *Pg. continuosa*, *Pg. siakensis*, *Dentoglobigerina altispira altispira*, *Globoquadrina venezuelana*, *Gq. euapertura*, *Gq. dehiscens*, *Globigerina praebulloides*, *Gg. falconensis*, *Gg. ouachitaensis gnaucki*, *Zeaglobigerina woodi woodi*, *Globigerinita naparimaensis*, *Ggt. incrusta*, *Globigerinella praesiphonifera*, and *Ggl. obesa* (Fig. 5).

Geographical correlation

This biozone is equivalent to *Catapsydrax dissimilis* biozone recorded by Hewaidy et al. (2013) from Qantara Formation at offshore wells PFMD2RBIS and Helm-1 in the eastern Nile Delta area. However, in Tunisia, this biozone is equivalent to *Catapsydrax dissimilis* biozone recorded by Riahi et al. (2010) from the upper part of Zouza Member at the Balta-Bou Goutrane section in the Balta–Bougoutrane area in northern Tunisia.

Globigerinoides primordius highest-occurence biozone (N4) early Miocene (Aquitanian)

Definition

This biozone is defined in this study as the interval from the HO of *Globorotalia kugleri* to the HO of the zonal marker *Globigerinoides primordius*. On the other hand, this biozone is equivalent to the *Globigerinoides primordius* concurrent-range biozone (N4) of (Blow 1969; emended by Bolli and Saunders 1985), who defined it as interval from the LO of frequent *Globigerinoides primordius/trilobus* s.l. to HO of *Globorotalia kugleri*.

According to the Mediterranean biozonation scheme of Iaccarino (1985), this biozone was called *Globoquadrina* *dehiscens* sub-biozone of *Globoquadrina dehiscens dehiscens/Catapsydrax dissimilis* biozone.

Remarks

The upper boundary of this biozone is defined herein, by the HO of the zonal marker *Globigerinoides primordius* while the lower boundary is defined by the HO of *Paragloborotalia kugleri* and covers the interval from 2900 to 4350′. This biozone is characterized by the predominance of planktic foraminifers with high diversity, and excellent preservation. The associated planktic foraminiferal taxa include *Globigerinoides sacculifer*, *Gds. trilobus*, *Gds. immaturus*, *Paragloborotalia mayeri*, *Pg. siakensis*, *Dentoglobigerina altispira altispira*, *Globoquadrina venezuelana*, *Gq. euapertura, Globigerina praebulloides*, *Gg. falconensis*, *Gg. ouachitaensis gnaucki*, *Zeaglobigerina woodi woodi*, *Globigerinita naparimaensis*, *Catapsydrax dissimlis*, *Globigerinella praesiphonifera*, *Ggl. obesa*, and rare *Cassigerinella chipolensis* (Fig. 5). Berggren et al. (1995) claimed that this biozone is a part of *Paraglobolotaria kugleri* biozone (M1a).

Geographical correlation

This biozone is well correlated to *Globigerinoides primordius* biozone (N4) recorded by Hewaidy et al. (2012) from the upper part of the Nukhul Formation at Wadi Baba in the southwest Sinai Peninsula. However, in Tunisia, this biozone is equivalent to *Globigerinoides primordius* biozone as recorded by Riahi et al. (2010) from the upper part of Zouza Member at Tebaba and El Gassa–Msid sections in the East of Jebel Zouza in northern Tunisia.

Paragloborotalia kugleri total range biozone (M1) early Miocene (Aquitanian)

Definition

Total range of the *Paragloborotalia kugleri* (Berggren et al. 1983).

According to the Mediterranean biozonation scheme of Iaccarino (1985), this biozone was called *Globoquadrina dehiscens* sub-biozone of *Globoquadrina dehiscens dehiscens/Catapsydrax dissimilis* biozone.

Remarks

The upper boundary of this biozone is defined herein, by the HO of the zonal marker *Paragloborotalia kugleri*, and the lower boundary is defined by the HO of *Globigerina ciperoensis ciperoensis* and covers the interval from 4350 to 4650′. This biozone is characterized by a low abundance of planktic foraminifers with moderate diversity and low frequencies with moderate preservation. The associated planktonic foraminiferal taxa include *Globigerinoides primordius*, *Globoquadrina venezuelana*, *Gq. euapertura*, *Globigerina tripartita*, *Gg. praebulloides*, *Gg. ouachitaensis gnaucki*, *Zeaglobigerina woodi woodi*, *Catapsydrax dissimilis*, and *Cassigerinella chipolensis* (Fig. 5). Berggren et al. 1995 and Steininger et al. 1997 of GSSP project raised this biozone to be Aquitanian (early Miocene) rather than Chattian (late Oligocene). Herein, the *Paragloborotalia kugleri* biozone is adopted as Early Miocene following Steininger et al. (1997).

Geographical correlation

This biozone is equivalent to *Paragloborotalia kugleri* biozone, recorded by Hewaidy et al. (2013) from the lower part of the Qantarah Formation in the Qantara-2 well, offshore wells PFMD2RBIS, and Helm-1 well in the eastern Nile Delta of Egypt. However, in Tunisia, this biozone is equivalent to (N4 Zone of Blow 1969) biozone recorded by Riahi et al. (2015) from the Numidian Formation in northern Tunisia.

Globigerina ciperoensis ciperoensis highest-occurrence biozone (P22) late Oligocene (Chattian)

Definition

Biostratigraphic interval characterized by the partial range of the nominate taxon between the HO of *Paragloborotalia opima opima* and the LO of *Globorotalia kugleri* s.s (Cushman and Stainforth 1945; emended by Bolli 1957; P22 of Berggren and Miller 1988).

Remarks

The upper boundary of this biozone is defined herein, by the HO of the zonal marker *Globigerina ciperoensis ciperoensis*; however, the lower boundary is defined by the HO of *Paragloborotalia opima opima* and covers the interval from 4650 to 5750′. This biozone is characterized by a low abundance of planktic foraminifers with moderate diversity and moderate to good preservation. The associated planktic foraminiferal taxa include *Paragloborotalia opima nana*, *Globoquadrina venezuelana*, *Gq. euapertura*, *Globigerina tripartita*, *Gg. praebulloides*, *Gg. ouachitaensis gnaucki*, and *Cassigerinella chipolensis* (Fig. 5).

Geographical correlation

This biozone is equivalent to *Globigerina ciperoensis* biozone (P22), recorded by Hewaidy et al. (2014) from the lowermost part of the Nukhul Formation at Wadi Wasit section in west-central Sinai of Egypt. However, in Tunisia, this biozone is well correlated with the lower part of *Globigerina ciperoensis* biozone recorded by Belayouni et al. (2012) from the intermediate interval in the sub-Numidian succession at Zahret-Mediene area in northwestern Tunisia.

Globorotalia opima opima highest-occurrence biozone (P21) late Oligocene (Chattian)

Definition

Total range of the zonal marker *Globorotalia opima opima*, from its LO to its HO (Bolli 1957).

Remarks

The upper boundary of this biozone in the present study is defined by the HO of the zonal marker *Paragloborotalia opima opima* and its lower boundary is defined by the HO of *Globigerina ampliapertura* and covers the interval from 5750 to 6450′. This biozone is characterized by common planktic foraminifers of low diversity and moderate preservation. The associated planktic foraminiferal taxa include *Paragloborotalia opima nana*, *Globigerina ciperoensis ciperoensis*, *Gg. tripartita*, *Globoquadrina euapertura*, and *Cassigerinella chipolensis* (Fig. 5).

Geographical correlation

This biozone is well correlated with the *Globorotalia opima opima* biozone, recorded by Cherif et al. (1993) from the lower part of the Qantarah Formation at the wells Temsah-II, San El Hagar-lX, and Boughaz-l in the Isthmus of Suez and the North-Eastern reach of the Nile Delta of Egypt. However, in Tunisia, this biozone is equivalent to the *Globorotalia opima opima* biozone recorded by Riahi et al. (2010) from the lower part of Zouza Member at the Tebaba section in the east of Jebel Zouza in northern Tunisia.

Globigerina ampliapertura highest-occurrence biozone (P19-P20) early Oligocene (Rupelian).

Definition

Partial range of the zonal marker, between the HO of *Pseudohastigerina micra* and the LO of *Globorotalia opima opima* (Bolli 1957; redefined by Bolli 1966).

Remarks

The upper boundary of this biozone in the present study is defined by the HO of the zonal marker *Globigerina ampliapertura* and its lower boundary is defined by the HO of *Pseudohastigerina micra* and covers the interval from 6450 to 7450′. This biozone is characterized by an abundance of planktic foraminifers with moderate diversity and moderate preservation. The associated planktic foraminiferal taxa in this biozone include *Globigerina ciperoensis ciperoensis*, *Gg. tripartita*, *Gg. cryptomphala, Globoquadrina euapertura*, *Gq. venezuelana*, *Subbotina linaperta*, *S. eocaena*, *S. angiporoides*, *Paragloborotalia opima nana*, *Cassigerinella chipolensis*, and *Catapsydrax dissimilis* (Fig. 5).

Geographical correlation

This biozone is reported by Ouda (1998) from the lower part of the Dabaa Formation at the subsurface sections north of Qattarah depression in the northern part of the Western Desert of Egypt. However, in Tunisia, this biozone was reported by Riahi et al. (2010) from the lower part of Zouza Member at Tebaba and El Gassa–Msid sections in the East of Jebel Zouza in northern Tunisia.

Cassigerinella chipolensis/Pseudohastigerina micra Concurrent-Range biozone (P18) early Oligocene (Rupelian).

Definition

Joint occurrence of the two biozonal markers from the LO of *Cassigerinella chipolensis* to the HO of the *Pseudohastigerina micra* (Blow and Banner 1962; renamed by Bolli 1966).

Remark

It is the oldest biozone defined in the present study, and its upper boundary is defined by the HO of the zonal marker *Pseudohastigerina micra*, as well as the associated species *Subbotina angiporoides*, *S. linaperta*, and *S. eocaena.* The lower boundary, however, cannot be delineated herein. This biozone covers the interval from 7450 to 9000′. This biozone is characterized by an abundance of planktic foraminifers with high diversity and excellent preservation. The associated planktic foraminiferal taxa include *Globigerina ciperoensis ciperoensis*, *Gg. tripartita*, *Gg. cf. taburiensis*, *Gg. cryptomphala*, *Globoquadrina venezuelana*, *Gq. euapertura*, *Paragloborotalia opima nana*, *Subbotina linaperta*, *S. eocaena*, *S. angiporoides*, and *Catapsydrax dissimilis* (Fig. 5).

Geographical correlation

This biozone is equivalent to the *Pseudohastigerina* spp. biozone recorded by Ouda (1998) from the lower part of the Dabaa Formation at the subsurface sections north of Qattarah depression in the northern part of the western desert of Egypt. However, in Tunisia, this biozone is equivalent to the *Pseudohastigerina naguewichiensis* biozone (O1) recorded by Yaakoub et al. (2017) from the upper part of Souar Formation at Menzel Bou Zelfa and Jhaff sections in northeastern Tunisia.

The O/M boundary

The O/M boundary is a good example of an interval that has not undergone any significant environmental changes; also, the biotic turnover is very low (extension and organization) within all microfossils, especially in planktic foraminifera (Spezzaferri 1994). The O/M boundary worldwide lacked widely applicable correlation tools in the Chattian stratotype itself. The Aquitanian stratotype contains planktic foraminiferal assemblage suggesting foraminiferal biozone N4 and lower portion of N5 of Blow (1969). The boundary can be recognized within the top part of the foraminiferal Zone P22 of Cushman and Stainforth (1945) and Berggren et al. (1995). Many planktic foraminiferal biostratigraphers place the O/M boundary at the base of Aquitanian stage, or the first occurrence datum of the *Paragloborotalia kugleri* Interval biozone in tropical areas (Bizon and Bizon 1972; Bizon 1979; Cita and Premoli Silva 1968), and informally based on the first occurrence datum of the early Miocene *Globoquadrina dehiscens dehiscens* in Mediterranean region (Jenkins 1966, 1971; Berggren and Andurer 1973; Keller 1980; Kennett and Srinivasan 1983; Iaccarino and Salvatorini 1982; Iaccarino 1985; Di Stefano et al. 2008). However, a different point of view placed this boundary with the top of the *Paragloborotalia kugleri* biozone of Bolli (1957) at the LO of *Globigerinoides primordius* as presented by Bolli and Saunders (1985). Furthermore, the diversification of the genus *Globigerinoides* is an additional event to recognize the O/M boundary (Spezzaferri 1994). The O/M boundary in the present study placed at the top of the *Globigerina ciperoensis ciperoensis* biozone according to Berggren and Miller (1988) and Berggren et al. (1995) based on the integrated magnetostratigraphy and planktic foraminiferal stratigraphy in comparison with the eustatic sea-level chart of Haq et al. (1988). The HO of the *Globigerina ciperoensis ciperoensis* and the associated Oligocene planktic taxa defines the top of the Oligocene as it correlates with the end of Chron C6Cn2r (=23.800 Ma) proposed by (Steininger 1994; Steininger et al. 1997) that delineates the O/M boundary. However, the Miocene planktic foraminifers *Globigerinoides* and *Paragloborotalia* dominate the lower Miocene interval. This suggests that the sedimentation in Well A1-89 is continuous with no break, marking a conformable contact. However, across this boundary, remarkable changes in diversity, abundance, and preservation of foraminiferal assemblage are observed. It is obvious to mention that the Miocene foraminiferal assemblage, which typified by the occurrence of *Globigerinoides* spp. (Spezzaferri 1994) at this level was more diverse and abundant with excellent preservation than the Oligocene foraminiferal suit. Elsewhere, these changes were also reported at the O/M boundary in Egypt by Hewaidy et al. (2012, 2014) as well.

The M/P boundary

The Miocene/Pliocene (M/P) boundary, according to Cita (1975), is corresponding to the LO of the permanent open marine condition in the Mediterranean after regression and dryness of the sea. Biostratigraphically, the boundary in the tropical areas can be recognized within the top portion of the *Neogloboquadrina duetertiri* biozone at the LO of *Globorotalia margaritae* (Bolli 1957, 1966, 1970; Bolli and Premoli Silva 1973); also, the boundary is placed at the top part of *Globorotalia tumida- Sphaeroidinella subdehiscens* biozone at the LO of *Sphaeroidinella dehiscens* (Blow and Banner 1966; Blow 1969). In the temperate regions, the boundary is defined at the top of *Globorotalia conomiozea* biozone at the first evolutionary occurrence of *Globorotalia puncticulata* (Kennett 1973). During the 1960s and 1970s, many Pliocene foraminiferal biozonations of the Mediterranean have been proposed (Cita and Premoli-Silva 1968; Cita 1973; Bizon and Bizon 1972; Cita 1975; Bizon 1979; Borsetti et al. 1979; Colalongo et al. 1982; Iaccarino and Salvatorini 1982) and most of them were summarized by Iaccarino (1985). The M/P boundary in the present study is placed at the top of *Praeorbulina sicana* biozone of Wade et al. (2011). The boundary herein well A1-89 is defined by the HO of *Praeorbulina sicana* with co-occurrences of *Praeorbulina transitoria*, *Praeorbulina glomerosa*, *Globigerinoides bisphericus*, and *Orbulina suturalis*. The presence of the latter species indicates the absence of *Orbulina suturalis* (M6) biozone of Wade et al. (2011). Generally, in the Well A1-89, the M/P unconformity represents the biozones from PL2 (*Globorotalia margaritae*) to M6 (*Orbulina suturalis*) and indicates a long-term unconformity. We suggest the reason to be tectonically induced, probably linked to the events occurring in the Hellenic subduction where Cyrenaica and Sirt Basin tectonic agenda matches the geodynamic evolution of the Hellenic domain, as suggested by (Arsenikos et al. 2013).

A similar hiatus has been reported locally in the Cyrenician offshore Well A1/NC120 by Duronio et al. (1991), where the Pliocene strata rest unconformably on Middle

Miocene one with a complete absence of Late Miocene (Tortonian-Messinian), and have ascribed this hiatus to an uplifting phase affecting northern Cyrenica during the Late Miocene. This hiatus is also reported from offshore of northwestern Egypt by Ouda (1998). Furthermore, Ouda and Obaidallah (1995) report this hiatus from the Nile delta and they attribute it to the tectonic rifting of the Arabian plate from the African plate. However, in the offshore Well B1-NC35A study, Hinte et al. (1991) assumed that there was no tectonic event and the sea gradually lowered for 50 m and then suddenly dropped to more than 450 m, which later returned to normal, some movement being allowed as the result of continued compaction of the underlying section and of the isostatic effect of unloading and reloading by the water column (Hinte et al. 1991). During the Messinian salinity crisis (MSC), as defined by Hsu et al. (1973), the Mediterranean Sea shrank to a few hypersaline pools and northeastern Africa was connected to Europe by a salt desert (Hsü et al. 1973a, b). This extraordinary event allows the accumulation of thick evaporitic deposits as reported in exposures of Cyrenica in northeast Libya (El Hawat and Shelmani 1993). However, in the As Sahabi area, the large gypseum crystals infilling polygonal desiccated fractures at two stratigraphical horizons in the Lower Member (P) of the Sahabi Formation (De Heinzelin and El Arnauti 1982; Muftah et al. 2008). The evaporates are not deposited in the offshore studied well A1-89 together with underneath rocks during Serravalian and Tortonian times. Mascle and Mascle (2019) claimed the reason for this MSC is due to some parameters, including deep outflows of salty water, paleogeographical reconstruction of the Messinian basins, and their syntectonic origin. This MSC event, supported by the water balance of the Mediterranean, was quite deficient through the Strait of Gibraltar and a thick evaporite sequence.

Conclusions

1-The Oligocene–Pliocene successions in the offshore Well-A1-89 in Sirt Basin have been subjected to planktic foraminiferal biostratigraphy. Ten planktic foraminiferal biozones from Piacenzian–Rupelian have been established within the studied succession following Bolli and Saunders's (1985), Iaccarino (1985), Berggren et al. (1995), Steininger et al. (GSSP 1997), and Wade et al. (2011) zonal schemes; in descending order, they are *Sphaeroidinellopsis seminulina* s.l. biozone, *Praeorbulina sican*a biozone, *Globigerinoides bisphericus* biozone, *Globigerinatella* sp./*Catapsydrax dissimilis* biozone, *Globigerinoides primordius* biozone, *Paragloborotalia kugleri* biozone, *Globigerina ciperoensis ciperoensis* biozone, *Globorotalia opima opima* biozone, *Globigerina ampliapertura* biozone, and *Cassigerinella chipolensis/Pseudohastigerina micra* biozone.

2-The established biozones are correlated with the equivalent biozones introduced by (Hooyberghs 1973, 1977; Riahi et al. 2010, 2015; Moissette et al. 2010; Belayouni et al. 2012, 2013; Yaakoub et al. 2017), which includes *Pseudohastigerina naguewichiensis, Globigerina ampliapertura*, *Globorotalia opima opima*, *Globigerina ciperoensis*, *Globigerinoides primordius*, *Catapsydrax dissimilis*, *Globigerinoides sicanus/Praeorbulina glomerosa*, and *Sphaeroidinellopsis* spp. biozones in the Tunisian sections. However, in Egypt are correlated with the equivalent biozones introduced by (Cherif et al. 1993; Ouda 1998; Hewaidy et al. 2012, 2013, 2014), which includes *Pseudohastigerina* spp., *Globigerina ampliapertura*, *Globorotalia opima opima*, *Globigerina ciperoensis*, *Paragloborotalia kugleri*, *Globigerinoides primordius*, *Catapsydrax dissimilis*, *Praeorbulina sicana*, *Praeorbulina glomerosa*, and *Sphaeroidinellopsis spp*. biozones.

3-The O/M boundary in the present study is placed at the top of the *Globigerina ciperoensis ciperoensis* biozone of Berggren et al. (1995), as defined by the HO of the *Globigerina ciperoensis ciperoensis.* However, the Miocene planktic foraminifera (*Globigernoides* and *Paragloborotalia*) dominate the lower Miocene interval. This led to suggest that the sedimentation in Well A1-89 is continuous with no break, marking a conformable contact.

4-The M/P boundary in the well A1-89 placed at the top of *Praeorbulina sicana* biozone of Wade et al. (2011). The nature of this boundary in this study is a long-term unconformity surface as defined by the lack of almost all the middle and late Miocene biozones that were established by Wade et al. (2011). This hiatus was similarly reported by Duronio et al. (1991) in the well A1/NC120 in the offshore Cyrenica, Libya. Meanwhile, in Egypt, this hiatus was reported by Ouda and Obaidalla (1995) as well as Ouda (1998) from the Nile delta, and from northwestern offshore, respectively.

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Declarations

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

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