

Pliocene-Lower Pleistocene high-resolution foraminiferal biostratigraphy of offshore eastern Nile Delta area, Egypt

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A B S T R A C T

This study presents a high-resolution foraminiferal biostratigraphic analysis of three Pliocene-Lower Pleistocene successions encountered in the Andaleeb-1, Temsah-NW-10, and Barboni-NW-1 wells, drilled for gas exploration in the offshore eastern Nile Delta. The studied successions were divided into two rock units from base to top: The Kafr El-Sheikh Formation and the El-Wastani Formation. The studied successions are characterized by scarce planktonic foraminiferal records in most parts, while benthonic foraminifera are more abundant and diverse, particularly in the top portion of the investigated sections. The biostratigraphic analysis of the recorded foraminiferal assemblages suggests six planktonic foraminiferal zones and three benthonic foraminiferal zones based on marker species consistent with Mediterranean basin standards. The planktonic zones, in ascending order, are the NPP-1 (Nile Delta Pliocene Planktonic) Zone, NPP-2 Zone, NPP-3 Zone, NPP-4 Zone, NPSP-1 (Nile Delta Pleistocene Planktonic) Zone, and NPSP-2 Zone. The three benthonic zones, also in ascending order, are the NPB-1 (Nile Delta Pliocene Benthonic) Zone, NPB-2, and NPSB-1 (Nile Delta Pleistocene Benthonic) Zone. However, the reliability of some bioevents used to define the zonal boundaries was challenged by the scarcity and patchy distribution of certain marker species in the study area. The *sphaeroidenellopsis* acme, a key marker for the NPP-1 Zone, could only be tentatively recognized in one well because the bottom Pliocene is not encountered in the other two wells. The limited occurrences of *Globorotalia bononiensis*, the marker species for the subdivision of the standard Mediterranean MPL-5 Zone, complicated the correlation of the NPSP-1 Zone with the Mediterranean standard zonation. As a result of bio-zonation, an unconformity surface was recorded between the Lower Pliocene (Zanclean stage) and the Lower Pleistocene (Gelasian stage) due to totally or partially absence of Piacenzian stage. The onset of the Gelasian stage (Lower Pleistocene) is marked by the progradation of the Nile Delta, which led to the development of nutrient-rich, shallow marine environments, supporting a relatively diverse and abundant benthonic foraminiferal assemblage.

Keywords:

Pliocene-Lower Pleistocene
Biostratigraphy
Foraminifera
Nile Delta
Egypt

1. Introduction

The Nile Delta, located in northern Egypt, has emerged as a significant gas province with numerous gas and condensate discoveries primarily in its Pliocene turbiditic and channelized clastic units (Abd Elaal et al., 2000). Intensive drilling over the past three decades, especially in offshore regions, has targeted Pliocene sand reservoirs under the cut-and-fill play concept, revealing the substantial economic potential of the region. However, these efforts have also highlighted a range of geological challenges, primarily stemming from the diachronicity of the sand reservoirs, which complicates stratigraphic correlation. These challenges are particularly pronounced in structurally complex areas

such as the North Port-Foad and Temsah concessions, where the movement of Messinian salt layers beneath the Pliocene strata has further complicated reservoir modeling. Also, in stratigraphically complex areas such as the Baltim-North East concession, many stratigraphic problems and difficulties have arisen during modeling for hydrocarbon exploration. Most of these challenges are primarily owed to delta progradation and bypassing of sedimentation from the African continental shelf to the basin, besides the high sedimentation rate that prevailed in the Baltim concessions during the Pliocene-Pleistocene time.

The Nile Delta area is characterized by a central uplift known as Oligo-Miocene high which trends NW-SE and divides the true Tertiary Delta province into two distinct basins: the eastern and western basins

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(IEOC, 1982; Egyptian General Petroleum Corporation, 1994). An additional structural feature, the E-W trending hinge zone, further subdivides the Nile Delta into northern and southern blocks (Said, 1990). The focus of this study lies within the northern block, specifically in the offshore eastern Nile Delta area (Fig. 1), where the Pliocene succession consists of two main lithostratigraphic units: the Kafr El-Sheikh Formation and the overlying El-Wastani Formation. These formations represent distinct depositional environments, with the Kafr El-Sheikh Formation linked to continental slope conditions and the El-Wastani Formation associated with neritic settings (Rizzini et al., 1978). Moving northward towards the basin, there is a notable increase in the thickness of Pliocene-Pleistocene rock units, particularly in the El-Wastani Formation, mainly due to delta progradation. In contrast, the thickness of the Lower Pliocene Kafr El-Sheikh Formation decreases, due to sediment condensation. Consequently, the overburden pressure over both the Kafr El-Sheikh Formation and the El-Wastani Formation (lower part) increases, potentially leading to drilling problems.

Detailed biostratigraphic analysis, particularly using foraminiferal assemblages, provides a cost-effective and reliable tool to address these stratigraphic and structural complexities. High-resolution foraminiferal biostratigraphy enables more accurate stratigraphic correlations and offers insights into paleoenvironmental conditions, supporting geological modeling in areas with complex structures and stratigraphy, such as the Nile Delta. This approach is especially valuable in reducing exploration risks by improving reservoir correlation and prediction in hydrocarbon exploration. The biostratigraphy of the offshore Delta area of Egypt was the target of many previous studies, including those of Viotti and Mansour (1969); Abd El Kerim et al. (1984); Andrawis et al. (1984); AGIP (2001); Ismail et al. (2010); Aboul Ela et al. (2013); Boukhary et al. (2016); and Makled et al. (2017a), with most concentrating on the western Nile Delta. In contrast, the current study is concerned with the biostratigraphic analysis of the subsurface Pliocene-Lower Pleistocene sections in the offshore eastern and central Nile Delta area (Fig. 1). It aims to provide a high-resolution biostratigraphic framework for the Pliocene-Lower Pleistocene successions based on a quantitative analysis of the planktonic and benthonic foraminiferal contents.

2. Materials and methods

For this study, the Pliocene-Lower Pleistocene successions in three wells were micropaleontologically studied using high-resolution foraminiferal biostratigraphy. The studied wells are Andaleeb-1, Temsah-NW-10 and Barboni-NW-1 which are located in Baltim-NE, Temsah and North Port-Foad concessions, respectively (Fig. 1). All available cutting samples obtained from those wells were studied to produce high-resolution records. A total of 588 ditch-cutting samples were examined, covering complete and continuous Pliocene and Lower Pleistocene sections across the three wells. These samples were taken at 5–10 m, with some exceptions where samples were taken every 20 m in shallower depths.

For each sample, approximately 100 g were boiled with sodium hydroxide and hydrogen peroxide, then washed and sieved through a sieve of mesh number 200 under a jet of water. The washed residue was dried in an oven at < 40 °C and settled in a small plastic fresh tube, labeled by the sample depth and well name. The identification of the foraminifera species was based on the species definition provided by Blow (1969); Cita (1975); Bolli and Saunders (1985); Iaccarino (1985); Jenkins (1985); AGIP (1982); Loeblich and Tappan (1988); and Hewaidy et al. (2013a and b).

The analysis of the samples began at the top, and all foraminiferal forms in each sample being identified, which is more convenient when ditch-cuttings are used to avoid contamination from caving. The biostratigraphic zonation is discussed from older to younger to align with bioevents in geologic time. Standard regional and modern biozonation schemes for the Mediterranean basin were applied (Cita, 1975; Sprovieri, 1992, 1993), with additional correlations made to Nile Delta

biozonation schemes (e.g., Aboul Ela et al., 2013; Makled et al., 2017a). Changes in both species composition (relative abundances of planktonic vs. benthonic taxa) and community structure (species richness) were quantified for each sample, and taxa were grouped by their depth-habitat preferences. These metrics provided the quantitative basis for our palaeoecological reconstructions, allowing us to infer shifts in water depth, nutrient levels, and depositional regimes.

Distribution stratigraphic range charts for the identified planktonic and benthonic foraminiferal species and their biostratigraphic zonation are presented and integrated with Gamma-Ray (GR) logs, casing points, and lithostratigraphic subdivisions. Moreover, a type-slide representing all the recorded species and subspecies was prepared, and the most significant species were photographed using SEM. The material described in this study, including cutting samples and slides of the picked foraminiferal species, is deposited in the collection of the first author (Mahmoud F. Khalifa, Belayim Petroleum Company, Nasr City, Cairo, Egypt).

3. Results

3.1. Foraminiferal biostratigraphy

The detailed examination of the foraminiferal contents of the Pliocene-Lower Pleistocene successions in three wells in the offshore area of the Egyptian Nile Delta give 50 planktonic and 60 benthonic species (Figs. 2 and 3). The vertical range of these species (Figs. 6–8) was used to establish 6 planktonic and 3 benthonic foraminiferal zones. These zones are discussed and correlated with the equivalent zones in- and out-side Egypt (Fig. 4).

3.1.1. Planktonic foraminiferal zonation

The Pliocene-Lower Pleistocene successions in the study area have been classified into six planktonic foraminiferal zones. This classification is based on the zonal scheme originally proposed for the Mediterranean region by Cita (1975) and later modified by Sprovieri (1992, 1993), with additional reference to regional studies in the Nile Delta by Aboul Ela et al. (2013) and Makled et al. (2017a).

Each of these zones is defined by chronostratigraphically dated (Walker and Geissman, 2009) bioevent markers (first, last or common occurrences of standard planktonic species; Figs. 4 and 5). From bottom to top, the six planktonic zones are, 4 Pliocene and 2 Pleistocene zones. The Pliocene zones are from base upwards: NPP-1 (Nile Delta Pliocene Planktonic) Zone, NPP-2 Zone, NPP-3 Zone, NPP-4 Zone, while the Pleistocene zones are from base upwards: NPSP-1 (Nile Delta Pleistocene Planktonic) Zone and NPSP-2 Zone. Below is the description of the aforementioned planktonic zones (Figs. 6–8).

3.1.1.1. NPP-1 Zone. NPP-1 is defined as an Acme Zone of *Sphaeroidenellops* spp., occurring in the basal part of the studied Pliocene interval. The lower limit of this zone is marked by the reappearance of planktonic foraminifera following the Messinian Salinity Crisis (5.33 Ma), indicated by a prominent *Sphaeroidenellops* acme, which indicated by a prominent the return of open marine conditions. The upper boundary is marked by the first common occurrence (FCO) of *Globorotalia margaritae* (5.08 Ma). The proper age of this zone is the Early Pliocene (Zanclean). This zone is recognized just above the Messinian evaporites in the Temsah-NW-10 well. In other wells, the zone is not observed, as they do not extend deep enough to intersect the Pliocene-Miocene boundary. This zone is rich in species of the genus *Sphaeroidenellops*, including *Sphaeroidenellops disjuncta*, *S. dehiscense*, and *S. praedeheiscense* (Fig. 7). Our NPP-1 Zone is correlated with MPL-1 Zone of Cita (1975), Sprovieri (1993) and Violanti (2012) in the Mediterranean region, as well as the *Sphaeroidenellops* Acme Zone of Aboul Ela et al. (2013) and the *Sphaeroidenellops seminulina* Acme Zone of Makled et al. (2017a) in the offshore western Nile Delta area (Fig. 4).

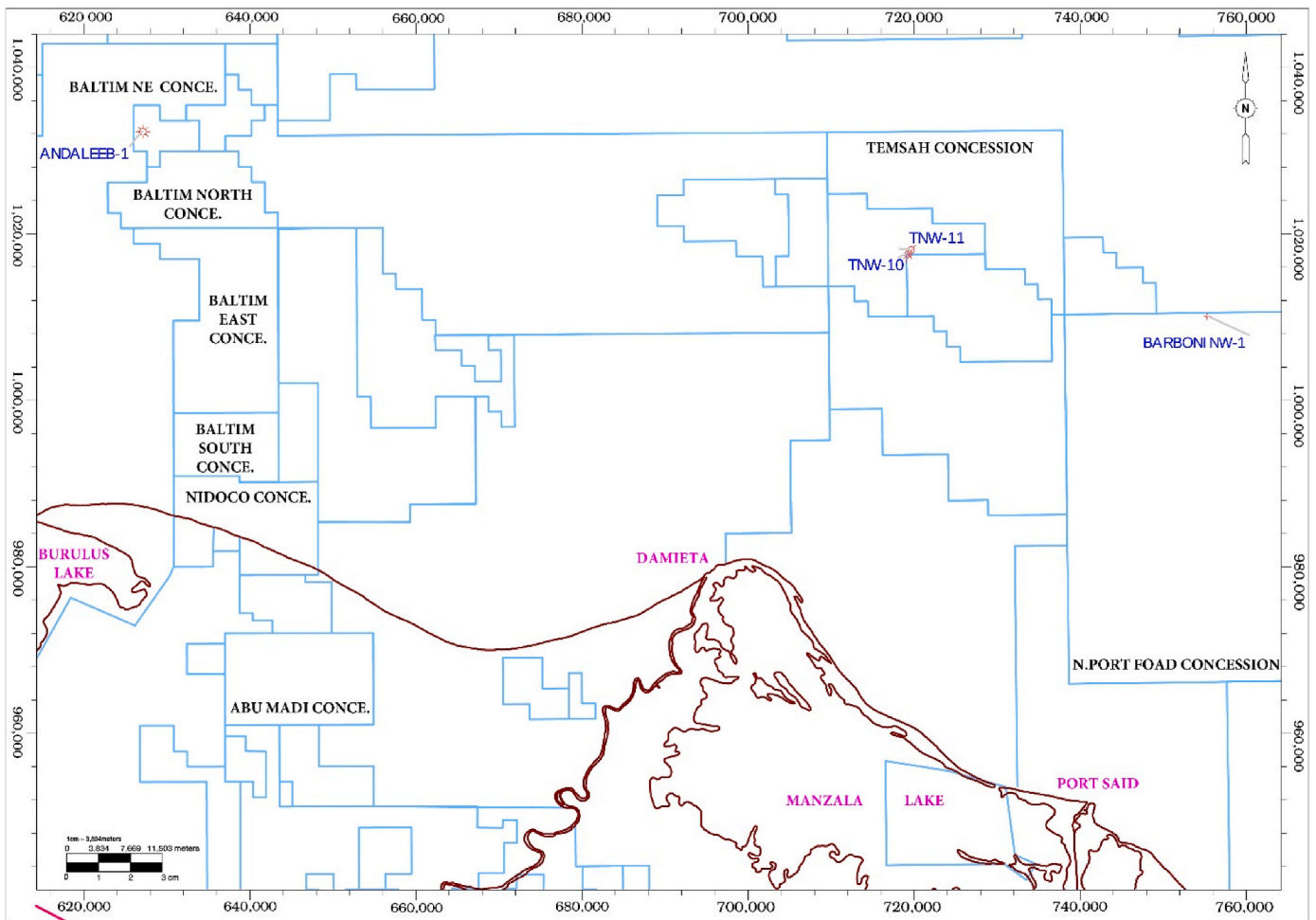
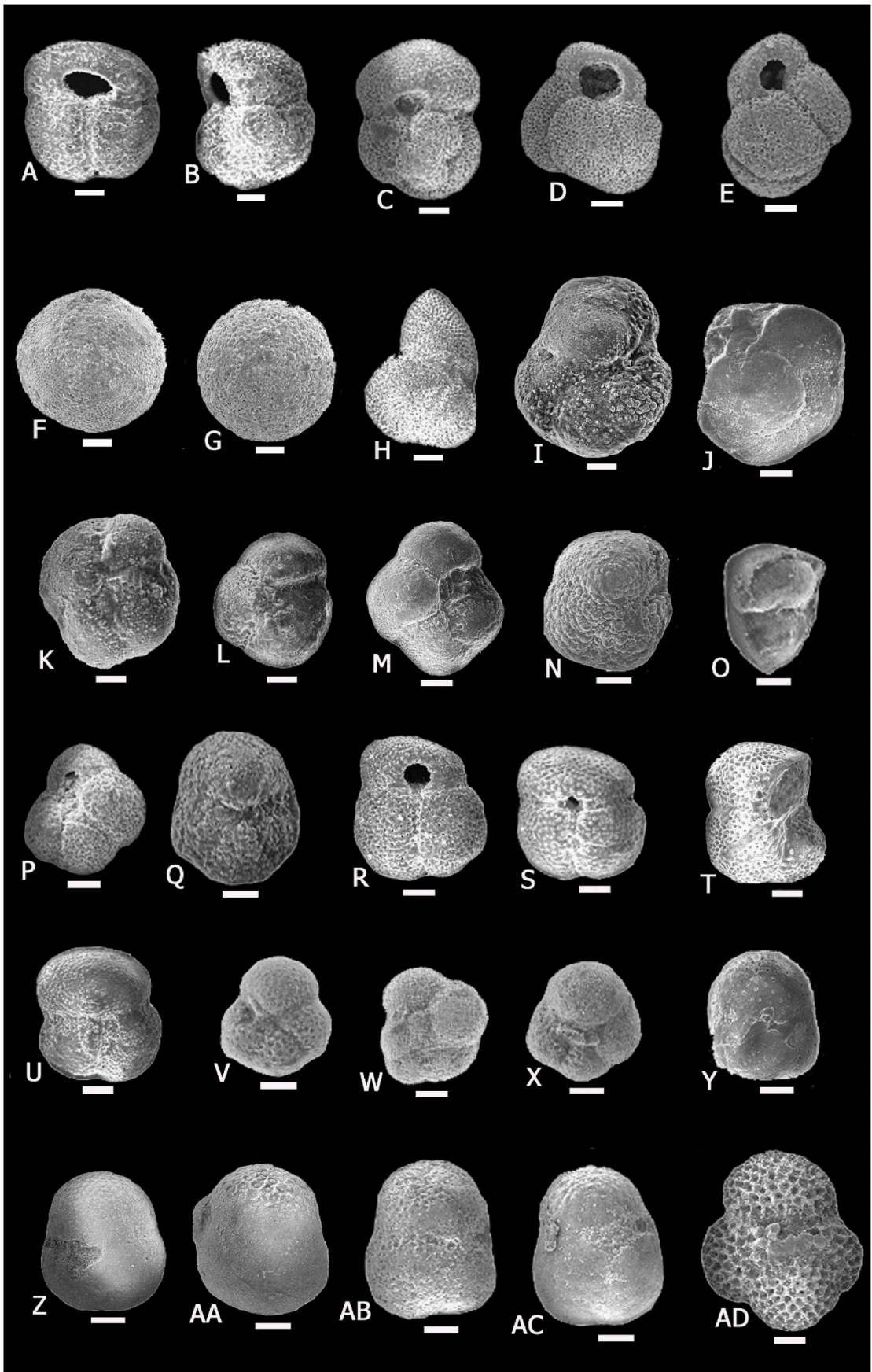


Fig. 1. Base map displaying the location of the investigated wells in the offshore eastern Nile Delta area, Egypt.



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Fig. 2. Scanning electron micrographs showcasing a selection of planktonic foraminiferal species. All the scale bars are equal to 200 μm . A, B- *Globigerinoides seigliei* (Permudez and Bolli); Lower Pleistocene, El Wastani Formation, Andaleeb-1 well, C- *Globigerinoides ruber* (d'Orbigny); Lower Pleistocene, El Wastani Formation, TNW-10 well, D, E- *Globigerinoides extremus* (Bolli); Lower Pleistocene, El Wastani Formation, Andaleeb-1 well, F- *Orbulina suturalis* (Bronnimann); Lower Pliocene, Kafr El Sheikh Formation, TNW-10 well, G- *Orbulina universa* (d'Orbigny); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, H- *Globigerinoides sacculifer* (Brady); Lower Pleistocene, El Wastani Formation, Andaleeb-1 well, I-k- *Globorotalia margaritae* (Bolli and Bermudez); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 and TNW-10 wells (J-dorsal view with broken last chamber & K- ventral view with incomplete last chamber), L, M- *Globorotalia puncticulata* (Deshayes); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, N- *Globorotalia crassaformis* dext. (Galloway and Wissler); Middle Pliocene, El Wastani Formation, Andaleeb-1 well, O- *Globorotalia tosaensis* (Takayangi and Saito); Upper Pliocene, El Wastani Formation, Andaleeb-1 well, P- *Globorotalia* cf. *bononiensis* (Dondi); Middle Pliocene, El Wastani Formation, Andaleeb-1 well, Q- *Globorotalia* cf. *aemiliana* (Colalongo and saroni); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, R, S- *Globigerinoides elongatus* (d'Orbigny); Lower Pleistocene, El Wastani Formation, Andaleeb-1 well, T, U- *Globorotalia inflata* (d'Orbigny); Lower Pleistocene, El Wastani Formation, Andaleeb-1 well, V-X- *Neogloboquadrina acoastaensis* (Blow); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 and TNW-10 wells, Y- *Sphaeroidinella dehiscens* (Parker and Jones); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, Z, AA- *Sphaeroidinellopsis paenedehiscens* (Blow); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, AB, AC- *Sphaeroidinellopsis seminulina* (Schwager); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, AD- *Sphaeroidinellopsis disjuncta* (Finlay); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well.

3.1.1.2. **NPP-2 Zone.** The NPP-2 Zone is an Interval Zone, defined at its base by the FCO of *Globorotalia margaritae* (5.08 Ma) and at its top by the first occurrence (FO) of *Globorotalia puncticulata* (4.52 Ma). This zone is dated as Early Pliocene (Zanclean). The NPP-2 Zone is recorded in the Andaleeb-1 and Tamsah-NW-10 wells (Figs. 6 and 7). The onset of the NPP-2 Zone features the occurrence of several planktonic species, including *Globigerinoides extremus*, *Gs. seigliei*, *Gs. elongatus*, *Sphaeroidinellopsis paenedehiscens*, *Orbulina suturalis*, *O. universa*, *Globigerina apertura*, *G. eamesi*, *G. nepenthes*, *Neogloboquadrina acoastaensis*, and *Globigerinita glutinata*. It is correlated with the MPL-2 Zone of Cita (1975), Sprovieri (1993), and Violanti (2012) in the Mediterranean region, as well as the *Globorotalia margaritae* Interval Zone of Aboul Ela et al. (2013) and the *Globorotalia margaritae* Interval Zone of Makled et al. (2017a) in the offshore western Nile Delta area (Fig. 4).

3.1.1.3. **NPP-3 Zone.** The NPP-3 Zone is a Concurrent Range Zone (CRZ) defined by FO of *Globorotalia puncticulata* (4.52 Ma) at its base and the last occurrence (LO) of *Globorotalia margaritae* (3.98 Ma) at its top. NPP-3 belongs to the Early Pliocene (Zanclean) in age. In the Andaleeb-1 well, the NPP-3 Zone is well-documented, with a clear presence of both *Globorotalia puncticulata* and *Globorotalia margaritae*. However, in the Tamsah-NW-10 well, these markers appear infrequently (see Figs. 6 and 7). The species composition within this zone is similar to that of the preceding NPP-2 Zone. This zone is correlated with the MPL-3 zone of Cita (1975), Sprovieri (1993), and Violanti (2012) in the Mediterranean region. It is correlated with the *Globorotalia puncticulata* - *Globorotalia margaritae* Zone of Aboul Ela et al. (2013) and the *Globorotalia puncticulata* - *Globorotalia margaritae* Zone of Makled et al. (2017a) in the offshore western Nile Delta area (Fig. 4).

3.1.1.4. **NPP-4 Zone.** This zone is an Interval Zone, with its base marked by the LO of the *Globorotalia margaritae* (3.98 Ma) and its top at the last appearance datum (LAD) of *Globorotalia puncticulata* (3.57 Ma). The age of this zone is of Early Pliocene age, specifically the top of Zanclean. This zone is well documented in Andaleeb-1 and Tamsah-NW-10 wells, although the marker species (*Globorotalia puncticulata*) are sparse in the Tamsah-NW-10 well (Figs. 6 and 7). This zone is correlated with the MPL-4a Subzone of Sprovieri (1993) and Violanti (2012) in the Mediterranean region. Also, it is correlated with the *Globorotalia puncticulata* Interval Subzone of Aboul Ela et al. (2013) and *Globorotalia puncticulata* Zone of Makled et al. (2017a) in the offshore western Nile Delta area (Fig. 4).

The top limit of this zone exhibits the simultaneous LADs of *G. puncticulata* and *Sphaeroidinellopsis* spp. (Figs. 6 and 7) This co-occurrence suggests the omission of the MPL-4b Subzone in both wells, pointing to a possible stratigraphic gap corresponding likely to the Upper Pliocene interval.

3.1.1.5. **NPSP-1 Zone.** This zone is an Interval Zone, with its lower limit traced at the LAD of *Globorotalia puncticulata*, while its top is cited at the

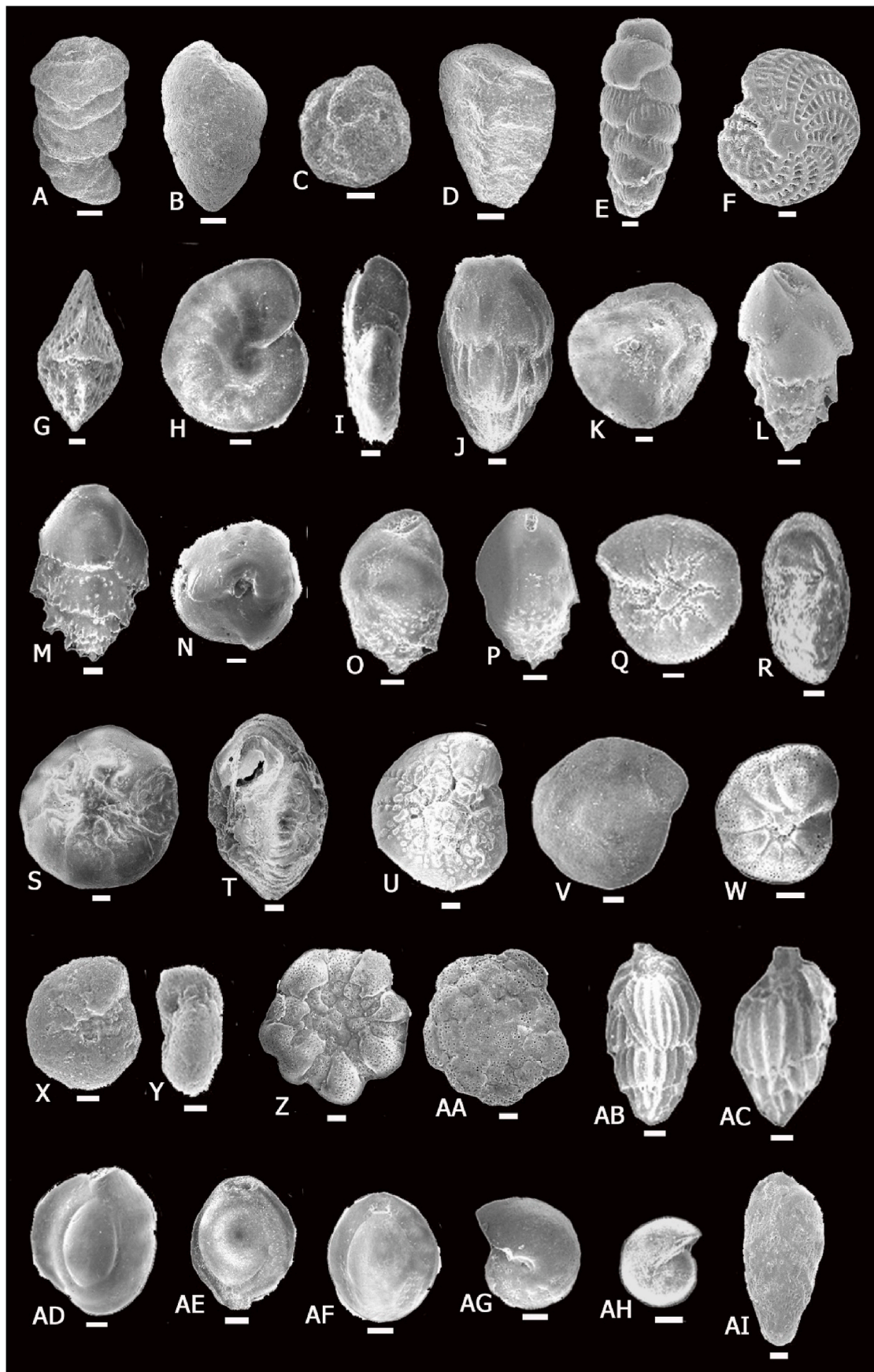
first appearance datum (FAD) of *Globorotalia inflata* (2.09 Ma). This zone is dated mainly as of the Early Pleistocene (Gelasian); its age may occasionally be extended down to the Late Pliocene (Piacenzian) based on the hiatus magnitude. It is recorded from the Andaleeb-1 well, with a questionable record in the Tamsah-NW-10 well, and in the Barboni-NW-1 well, the bioevent markers are extremely scarce (Figs. 6–9). It is characterized by the common occurrence of *Gs. elongatus*, *Gs. extremus*, *Gs. seigliei*, and rare occurrence of *Globorotalia crassaformis* with dextral coiling at its bottom. This zone is correlated with the entire MPL-5b Subzone and parts of MPL-4b and the MPL-5a Subzones of Sprovieri (1993) and Violanti (2012) in the Mediterranean region. Additionally, it is correlated with the *Globorotalia planispira* Subzone and *Globigerinoides elongatus* Zone of Aboul Ela et al. (2013) and the *Globorotalia aemiliana* Zone of Makled et al. (2017a) in the offshore western Nile Delta area (Fig. 4). Generally, this zone is very thin, as the study area may be affected by long period of uplifting and erosion at the Late Pliocene-Early Pleistocene time (Fig. 9).

3.1.1.6. **NPSP-2 Zone.** This zone is an Interval zone, with its lower limit defined by the FAD of the *Globorotalia inflata* (2.09 Ma), while its top is defined by the FCO of *Neogloboquadrina pachyderma*, which is not reached in the studied wells. This zone is dated as of the Early Pleistocene (Gelasian) age. It is recorded in the Andaleeb-1 and Barboni-NW-1 wells, whereas the FAD of *Globorotalia inflata* is uncertain in the Tamsah-NW-10 well (Figs. 6–8). It is characterized by an increase in the density of *Globigerinoides sacculifer*, *Gs. elongatus*, *Gs. extremus*, and *Gs. seigliei*. This zone is correlated with the MPL-6 Zone of Sprovieri (1993) and Violanti (2012), which is recorded in the Mediterranean region. It is also correlated with the *Globorotalia inflata* Interval Zone of Aboul Ela et al. (2013) and the lower portion of the *Globorotalia inflata* Interval Zone of Makled et al. (2017a) in the offshore western Nile Delta area (Fig. 4).

3.1.2. Benthonic foraminiferal zonation

60 benthonic foraminiferal species were identified from the Pliocene-Lower Pleistocene interval in the studied wells. This fauna was used to build a benthonic foraminiferal zonal scheme for the studied interval. Three calcareous benthonic foraminiferal zones are suggested: NPB-1 (Nile Delta Pliocene Benthonic) Zone, NPB-2 Zone, and NPSB-1 (Nile Delta Pleistocene Benthonic) Zone (Fig. 5). These benthonic zones are described from bottom to top as follows.

3.1.2.1. **NPB-1 Zone.** The NPB-1 Zone is characterized by the Total Range of *Uvigerina rutila* in the studied wells. It covers the combined interval of the NPP-1, NPP-2 and NPP-3 planktonic zones in the present study. Accordingly, the NPB-1 Zone is dated as Early Pliocene (Zanclean) (Fig. 5). This age assignment agrees with other relevant studies that consider the presence of *Uvigerina rutila* as a good benthonic foraminiferal marker for the lower Pliocene. Notably, its LAD is observed nearly at the top of the lower Pliocene at several Mediterranean localities (Boersma, 1984; Berggren and Miller, 1989; Sprovieri and



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Fig. 3. Scanning electron micrographs showcasing a selection of benthonic foraminiferal species. All the scale bars are equal to 200 μm . A- *Ammobaculites* sp.; Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, B- *Karrerriella bradyi* (Cushman); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1 well, C- *Haplophragmoides cf indentatus* (Voloshinova); Pliocene-Lower Pleistocene, Kafr El Sheikh-El Wastani formations, Andaleeb-1, Barboni NW-1 wells, D- *Textularia* sp.; Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1, TNW-10 wells, E- *Hopkinsina* sp.; Lower Pliocene, Kafr El Sheikh Formation, TNW-10 well, F, G- *Elphidium cispum* (Linne'); Lower Pleistocene, El Wastani Formation, Barboni NW-1 well, H, I- *Anomalinoidea hellicinus* (Costa); Lower Pliocene, Kafr El Sheikh Formation, Andaleeb-1, TNW-10 wells, J, K- *Uvigerina rutila* (Cushman and todd); Lower Pliocene, Kafr El Sheikh Formation, TNW-10 and Andaleeb-1 wells, L-N- *Bulimina marginata* (d'Orbigny); Lower Pleistocene, El Wastani Formation, Barboni NW-1 and Andaleeb-1 wells, O, P- *Bulimina basispinosa* (Tedeschi and Zanmatti); Lower Pleistocene, El Wastani Formation, Barboni NW-1 and Andaleeb-1 wells, Q, R- *Ammonia beccarii* (Linne'); Lower Pleistocene, El Wastani Formation, Barboni NW-1 well, S, T- *Ammonia inflata* (Seguenza); Lower Pleistocene, El Wastani Formation, Barboni NW-1 well, U, V- *Ammonia papilosa* (d'Orbigny); Lower Pleistocene, El Wastani Formation, TNW-10 well, W- *Valvulineria bradyana* (Fornasini); Pliocene-Lower Pleistocene, Andaleeb-1 well, X, Y- *Ammonia tepida* (Cushman); Lower Pleistocene, El Wastani Formation, TNW-10 well, Z, AA- *Planorbulina mediterranensis* (d'Orbigny); Lower Pleistocene, El Wastani Formation, TNW-10 well, AB, AC- *Uvigerina peregrina* (Cushman); Lower Pleistocene, El Wastani Formation, Andaleeb-1 and TNW-10 wells, AD- *Quinqueloculina vulgaris* (d'Orbigny); Pliocene-Lower Pleistocene, El Wastani Formation, TNW-10 and Andaleeb-1 wells, AE- *Fissurina quadricostulata* (Reuss); Lower Pleistocene, El Wastani Formation, Andaleeb-1 well, AF- *Pyrgo depressa* (d'Orbigny); Lower Pleistocene, El Wastani Formation, TNW-10 well, AG- *Melonis pombiloides* (Fichtel and Moll); Lower Pleistocene, El Wastani Formation, Barboni-NW-1 well, AH- *Pullenia bulloides* (d'Orbigny); Lower Pleistocene, El Wastani Formation, TNW-10 well, AI- *Brizalina cf cataensis* (Seguenza); Pliocene-Lower Pleistocene, TNW-10 well.

| CHRONOSTRATIGRAPHY | | MEDITERANEAN STAND. FORAMINIFERAL ZONES | | FORAMINIFERAL BIOEVENTS | NILE DELTA FORAMINIFERAL ZONES | | | | | | | | | | | | |
|------------------------|---------------------------|---|---------------------------------|---------------------------------|---|----------------------------------|-------------------------|----------------------------------|---|---|---|-----------------------------------|-------|---------------------------------|-----------------------|-----------------------|------------------------------|
| Gradstein et al., 2004 | Walker and Geissman, 2009 | Cita, 1975 Sprovieri, 1992, 1993 | Iaccarino, 1985 | | Rizzini et al., 1978 | Andrawis et al., 1984 | Aboul Ela et al., 2013 | Boukhary et al., 2016 | Makled et al., 2017 | This Work | | | | | | | |
| PLIOCENE | PLEISTOCENE | CAL. | <i>G. cariacensis</i> | <i>G. cariacensis</i> | FAD <i>G. cariacensis</i> 1.75 FCO <i>N. pachyderm.</i> s. 1.79 | Undefined | Undefined | Undefined | <i>Gr. inflata</i> | <i>Gr. inflata</i> | Not studied | <i>Bulimina marginata</i> (NPB-3) | | | | | |
| | | | MPL - 6 | <i>Gr. inflata</i> | FAD <i>Gr. inflata</i> 2.09 | | | | | | | | NPS-2 | | | | |
| | | GELASIAN | MPL - 5b | <i>Gr. aemiliana</i> | LAD <i>Gr. bononiensis</i> 2.41 LO <i>N. atlantica</i> 2.41 FO <i>N. atlantica</i> 2.72 | <i>Gr. crassaformis</i> | <i>Gr. crassaformis</i> | <i>Globigerinoides elongatus</i> | <i>Gr. aemiliana</i> | <i>Gr. aemiliana</i> | NPS-1 | | | | | | |
| | | | MPL - 5a | | LAD <i>Sphaer.</i> spp. 3.19 | | | | | | | | NPP-4 | | | | |
| | | | PIACENZEAN | | MPL - 4b | | | | | | | | | FAD <i>Gr. bononiensis</i> 3.31 | <i>Gr. aemiliana</i> | <i>Gr. aemiliana</i> | <i>Gs. obliquus extremus</i> |
| | MPL - 4a | LAD <i>Gr. puncticulata</i> 3.57 | | NPP-3 | | | | | | | | | | | | | |
| | ZANCLEAN | MPL - 3 | | | <i>Gr. puncticulata</i> - <i>Gr. margaritae</i> | LCO <i>Gr. margaritae</i> 3.98 | <i>Gr. puncticulata</i> | <i>Gr. margaritae evoluta</i> | <i>Gr. puncticulata</i> - <i>Gr. margaritae</i> | <i>Gr. puncticulata</i> - <i>Gr. margaritae</i> | <i>Gr. puncticulata</i> - <i>Gr. margaritae</i> | | NPP-2 | | | | |
| | | MPL - 2 | <i>Gr. margaritae</i> | FO <i>Gr. puncticulata</i> 4.52 | <i>Gr. margaritae</i> | <i>Gr. margaritae margaritae</i> | | | | | | | | <i>Gr. margaritae</i> | <i>Gr. margaritae</i> | <i>Gr. margaritae</i> | NPP-1 |
| | | MPL - 1 | <i>Sphaeroidinellopsis acme</i> | FCO <i>Gr. margaritae</i> 5.08 | | | | | | | | | | | | | |

Fig. 4. Comparison between the Pliocene-Lower Pleistocene planktonic foraminiferal zonal schemes proposed in the current study and previous zonations in the Nile Delta and Mediterranean regions, alongside the Gradstein et al. (2004) and Walker and Geissman (2009) chronostratigraphic frameworks, highlighting the differing approaches to Gelasian stage assignment.

Hasegawa, 1990; Violanti, 2012). This zone is recognized in the Andaleeb-1 and Tamsah-NW-10 wells, while it is not encountered in the Barboni-NW-1 well (Figs. 6 and 7). It is characterized by moderate occurrence of benthonic foraminiferal record.

3.1.2.2. *NPB-2 Zone*. This zone is an Interval Zone of *Anomalinoidea hellicinus*, defined between the LO of *Uvigerina rutila* at the base and the LO of *Anomalinoidea hellicinus* at the top. Based on the defining criteria, it corresponds to the *Anomalinoidea hellicinus* Interval Zone of Colalongo and Sartoni (1979). The present NPB-2 Zone covers the combined interval of the NPP-4 and NPS-1 planktonic zones in the present study. Accordingly, this Zone spans from the Late Pliocene to the Early Pleistocene age (Fig. 5). This age assignment agrees with other relevant studies that traced the LO of *Anomalinoidea hellicinus* within the MPL-5 Zone (Ambrosetti et al., 1987; Sprovieri and Hasegawa, 1990;

Violanti, 2005, 2012). The NPB-2 Zone is recorded in all studied wells and is characterized by an obvious abundance foraminiferal record (Figs. 6-8).

3.1.2.3. *NPSB-1 Zone*. This zone is an Interval Zone of *Bulimina marginata*. Its lower limit in the study area is cited at the FCO of *Bulimina marginata* and/or the LO of *Anomalinoidea hellicinus*. The top boundary of this zone was not reached in our study due to the lack of cutting samples. The top of the NPSB-1 Zone could be placed at the FO of *Hayalena balthica* which was suggested by Aboul Ela et al. (2013) and Makled et al. (2017a) in offshore western Nile Delta area. This zone is correlated with the NPS-2 planktonic Zone in the present study, and is primarily assigned to the Early Pleistocene (Gelasian) age (Fig. 5). This zone is recorded in all the studied wells and is characterized by high abundance and high diversity of benthonic assemblage, including *Bulimina* spp.,

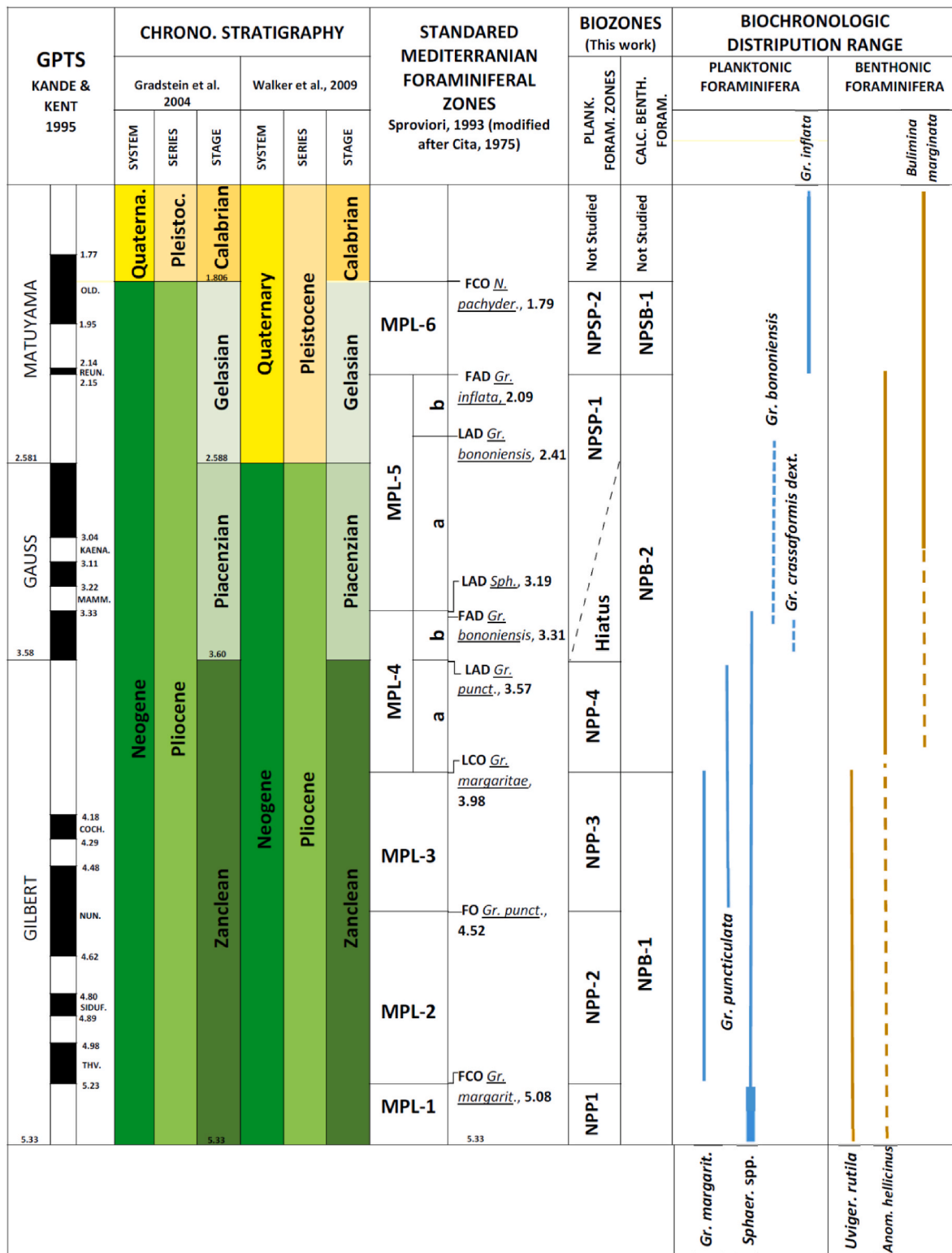


Fig. 5. Foraminiferal biostratigraphic classification for Pliocene-Lower Pleistocene succession in the offshore eastern Nile Delta area.

Ammonia spp., *Elphidium crispum*, and *Uvigerina peregrina* (Figs. 6–8).

3.2. Composition and structure of the benthonic foraminiferal assemblages

The benthonic foraminiferal record varies greatly across the studied Pliocene-lower Pleistocene interval. The lower Pliocene interval is

characterized by a patchy and less diverse benthonic assemblage, with dominance of agglutinated species such as *Cyclammina* spp. and *Haplophragmoides* spp. in most intervals. These agglutinated species are intermittently accompanied by calcareous taxa such as *Cibicides* spp., *Bolivina* spp., *Cibicides* spp., *Eponides* spp., and *Quinqueloculina* spp. Additionally, some intervals yield some deep-water species, including *Bulimina elongata*, *Bulimina striata*, *Cassidulina neocarinata*, *Melonis*

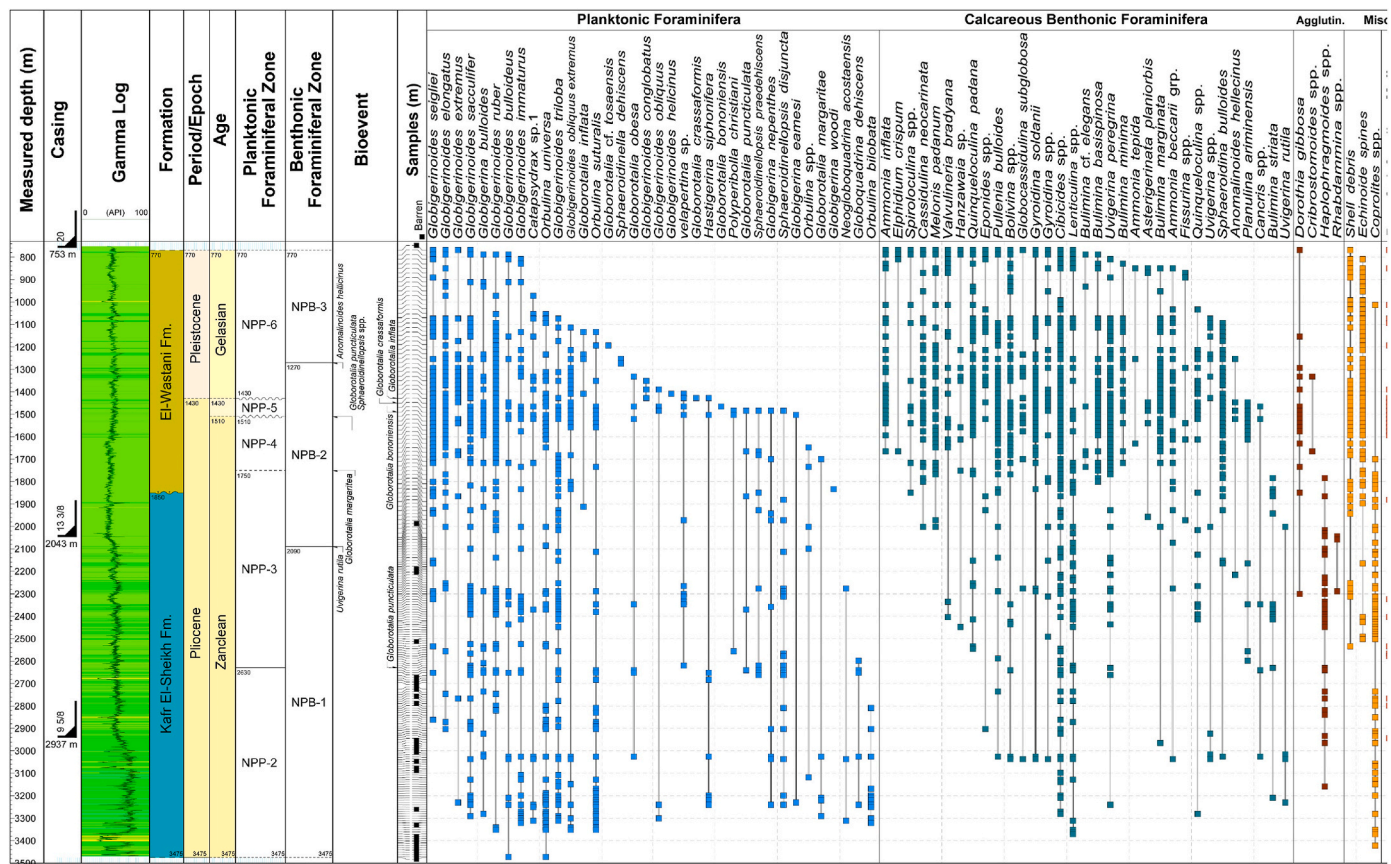


Fig. 6. Stratigraphic range chart of the identified foraminiferal species in the Andaleeb-1 well.

pombiloides, *Pullenia bulloides*, *Uvigerina rutila*, *Uvigerina peregrina*, and *Gyroidina soldanii* (Figs. 6 and 7). In contrast, the Lower Pleistocene displays a markedly abundant and more diverse benthonic foraminiferal assemblage. Common taxa in this interval include *Bulimina marginata*, *Bulimina basispinosa*, *Ammonia beccarii*, *Ammonia inflata*, *Elphidium crispum*, *Valvulineria bradyana*, *Cassidulina neocarinata*, and *Uvigerina peregrina*. This shift in benthonic foraminifera is also coupled with a significant decrease in the relative abundance of planktonic foraminifera (Figs. 6–8).

4. Discussion

Given the low abundance of foraminiferal fauna in the bottom section, the *Sphaeroidenellopsis* acme, a key marker for the MPL-1 Zone in the Mediterranean (Violanti, 2012; Lirer et al., 2019), is recorded only in the Temsah-NW-10 well, while the other two wells did not encounter this zone. Additionally, its record depends only on a tentative relative acme compared to the occurrence of *Sphaeroidenellopsis* spp. in the surrounding stratigraphic layers, both below and above. The non-recognition of a such pronounced and well-defined acme in the present study could be owed to the high sedimentation rate and/or other environmental factors, likely diminishing its reliability as a biostratigraphic marker in such a context (Violanti, 2012).

Furthermore, the FCO of *Globorotalia margaritae*, FO of *Globorotalia puncticulata*, and LCO of *Gr. margaritae*, which are considered here as markers for the base of the NPP-2, NPP-3, and NPP-4 zones, respectively, emerge as particularly reliable events (Lirer et al., 2019), consistently recognized across the Andaleeb-1 and Temsah-NW-10 wells (Figs. 5 and 6). The delineation of the LCO of *Gr. margaritae* (the base of the MPL-4 Zone; Lirer et al., 2019) is challenging due to the rarity of *Gr. margaritae*. Consequently, we adopted its LO as a replacement marker for defining the onset of the present NPP-4 Zone. While the LO is a later event than

the LCO, offering a more practical reference point in conditions where *Gr. margaritae* is scarce and exhibits a patchy distribution (Aboul Ela et al., 2013; Makled et al., 2017a).

The simultaneous occurrence of the LADs of *Globorotalia puncticulata* and *Sphaeroidenellopsis* spp. indicates the absence of the MPL-4b standard Subzone, as noted in the Andaleeb-1 and Temsah-NW-10 wells (Figs. 4 and 5). The *Globorotalia bononiensis*, the marker for subdividing the Mediterranean MPL-5 Zone into two subzones (MPL-5a and MPL-5b) (Sprovieri, 1992; Violanti, 2012; Lirer et al., 2019), reveals a very rare record in our study, with a complete absence in the Temsah-NW-10 well and only a single occurrence in the Andaleeb-1 well (Figs. 6 and 7). This rarity, consistent with other studies from the Nile Delta (Abdou et al., 1984; Aboul Ela et al., 2013; Makled et al., 2017a), suggests that *G. bononiensis* may not serve as a reliable stratigraphic marker in this region.

Furthermore, the single occurrence of *G. bononiensis* complicates the interpretation of its stratigraphic position, whether representing its FAD or LAD. Consequently, correlating the interval attributed herein to NPSP-1 with either subzone of MPL-5 is challenging. Regardless, these observations likely suggest a significant unconformity between the Pliocene and the Pleistocene. In Andaleeb-1, this hiatus partially omits the Piacenzian, while in Temsah-NW-10 the Piacenzian is completely missing. Such hiatus complicates the identification of the Pliocene/Pleistocene boundary and raises important questions regarding the nature of this transition in the eastern Nile Delta area. The inferred hiatus likely reflects global sea-level changes driven by the onset of major Northern Hemisphere glaciations (Miller et al., 2005). Such sea-level fluctuations could have led to periods of non-deposition or erosion in the Nile Delta region.

The benthonic foraminiferal zonation proposed in this study closely aligns with other relevant schemes established in the western Nile Delta (Makled et al., 2017a) and other Mediterranean localities, including

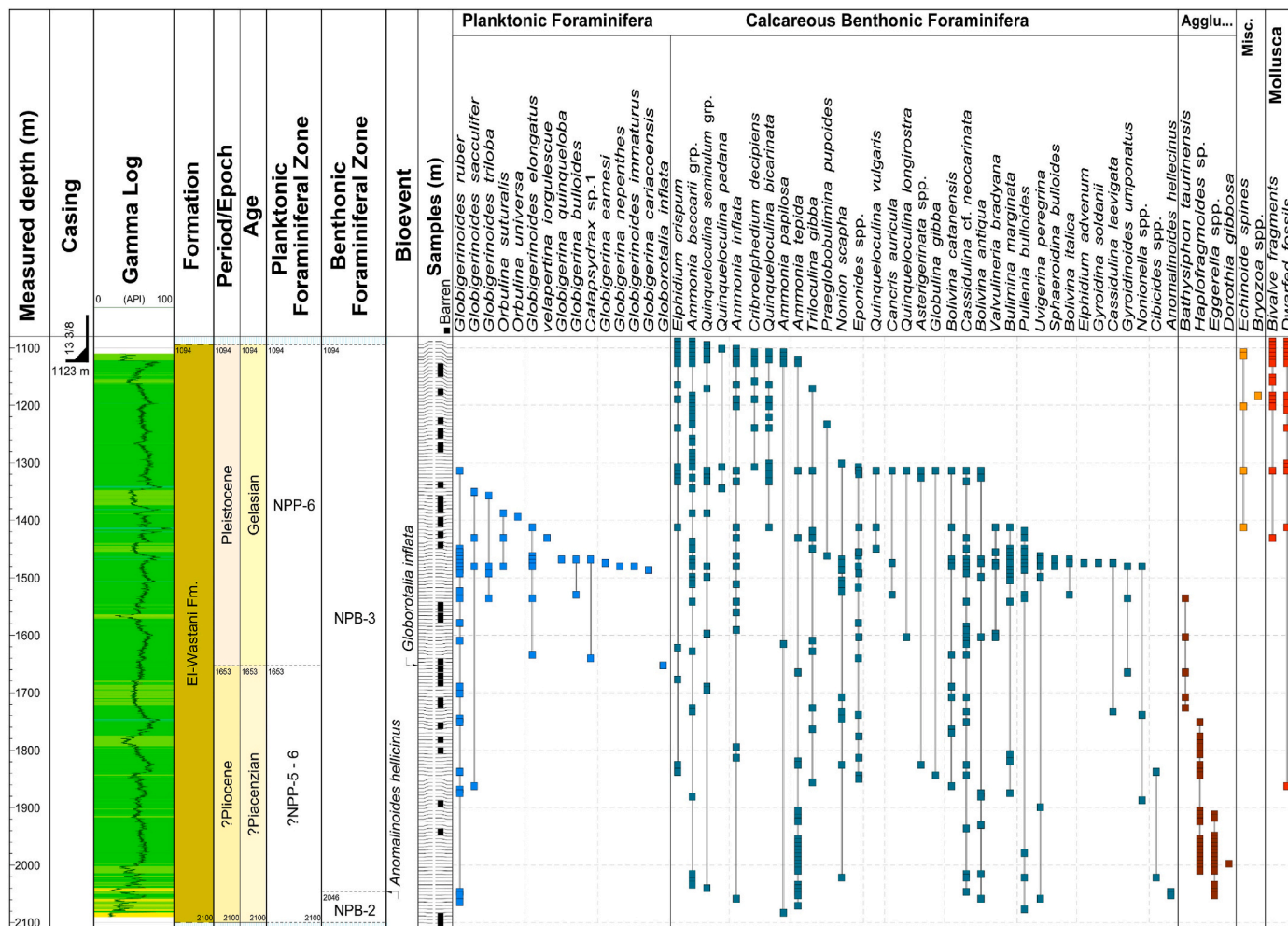


Fig. 8. Stratigraphic range chart of the identified foraminiferal species in the Barboni-NW-1 well.

consistent with earlier paleobathymetric estimates for the Kafr El-Sheikh Formation (Rizzini et al., 1978; Makled et al., 2017b). Conversely, the Lower Pleistocene interval shows a transition to more stable and shallower marine conditions, as indicated by the rich and more diverse benthonic assemblage, including *Bulimina* spp., *Ammonia* spp., *Elphidium crispum*, and *Uvigerina peregrina* (Figs. 6–8). This assemblage composition suggests a predominately shelf setting with enhanced nutrient availability and oxygenation (Makled et al., 2017b). Supporting this interpretation of shallower marine conditions is the observed decline in planktonic foraminiferal abundance toward the Pleistocene, with many species restricted to the Pliocene and disappearing near the topmost Pliocene interval (Figs. 6 and 7). Collectively, these foraminiferal shifts likely reflect the progradation of the Nile Delta during this period (Sestini, 1989), where advancing deltaic sediments caused significant environmental changes. These changes, in turn, favored the proliferation of diverse benthonic foraminiferal assemblages in more nutrient-rich and oxygenated conditions.

Moreover, many agglutinated foraminiferal species and dwarfed fossils along with macro-faunal debris flow and carbonaceous matter, were recorded in the shale interbeds within the sandstone intervals (interpreted from GR log) in both Pliocene and lower Pleistocene successions (Figs. 5–7). These turbidity currents likely contributed to the sparse record of foraminiferal fauna in most parts of the studied successions, as they may have disrupted benthonic habitats and led to the rapid deposition and burial of foraminiferal assemblages.

5. Conclusions

This paper deals with the foraminiferal biostratigraphic analysis of the Pliocene-Lower Pleistocene successions in the Andaleeb-1, Tamsah-NW-10 and Barboni-NW-1 wells located in offshore eastern Nile Delta area.

1. Six planktonic foraminiferal zones were recognized in the Pliocene-Lower Pleistocene successions in the offshore eastern Nile Delta area (NPP-1, NPP-2, NPP-3, NPP-4, NPS-1, and NPS-2) and three benthonic foraminiferal zones (NPB-1, NPB-2, and NPS-1).
2. The identified six planktonic zones are correlated well with the standard Mediterranean planktonic foraminiferal zones MPL-1, MPL-2, MPL-3, MPL-4a, MPL-5? and MPL-6, respectively. In the proposed benthonic zonal framework, the NPB-1 is identified as a Total Range Zone of *Uvigerina rutila*, covering NPP-1 to NPP-3; NPB-2 is an Interval Zone defined from the LO of *Uvigerina rutila* to the LO of *Anomalinoidea hellicinus*, corresponding to NPP-4 and NPS-1; and NPS-1 is marked at its bottom by the LO of *Anomalinoidea hellicinus*/FCO of *Bulimina marginata* and is correlated with NPS-2.
3. The reliability of some bioevents used to define these zones was found to be affected by the scarcity and uneven distribution of key marker species in the eastern Nile Delta.
4. The Upper Pliocene (Piacenzian stage) is either totally or partially absent in the study area, due to the thinning of NPS-1 and/or absence of some parts in the NPS-1 Zone. This likely suggests a significant unconformity separating between the Pliocene and the

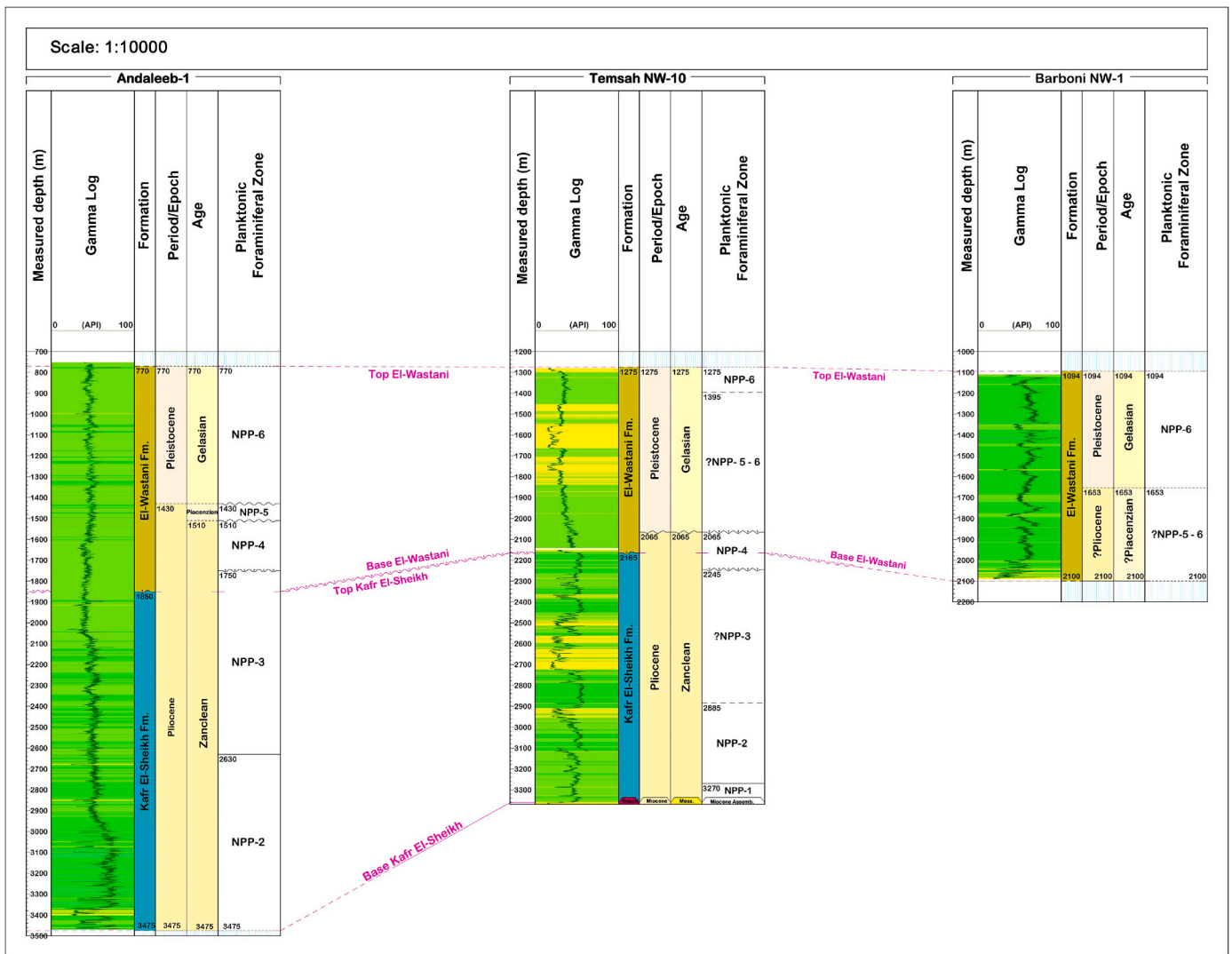


Fig. 9. Stratigraphic correlation between the three studied wells.

Pleistocene, suggesting regional tectonic or sea-level changes that may have impacted the sedimentary record. The onset of the Gelasian stage (Pleistocene) features the increased progradation of the Nile Delta, which led to the creation of nutrient-rich marine environments that supported a diverse and abundant benthonic foraminiferal assemblage.

CRediT authorship contribution statement

Mahmoud F. Khalifa: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdel Galil A. Hewaidy:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Amr Talaat:** Writing – review & editing, Data curation, Conceptualization. **Youssef Bazeen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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