Stratigraphic Discrimination between Kafr El-Sheikh and El-Wastani Formations in the Offshore Eastern Nile Delta, Egypt: An Integrated Geological Approach

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KEY WORDS

Pliocene; Lithostratigraphy; Biofacies; Kafr El-Sheikh\El-Wastani Boundary; Nile Delta

ABSTRACT

An integrated geological approach of biostratigraphy, paleoenvironmental analysis, seismic facies, and pore pressure data was employed to discriminate between the Kafr El-Sheikh and El-Wastani formations in the offshore eastern Nile Delta area. The foraminiferal biostratigraphic analysis of Pliocene-lower Pleistocene successions in Andaleeb-1, Temsah NW-10, Temsah NW-11, and Barboni NW-1 wells revealed that the Kafr El-Sheikh Formation is of Early Pliocene (Zanclean) age. The formation consists of pressurized shale with high to moderate brightness seismic reflectivity, gently dipping toward the north at the shoreline area and nearly horizontal reflectors northward. Locally, bright reflectors configured as channel-fan and frontal splay geometries signal episodes of turbiditic sedimentation. The formation yields foraminiferal assemblages relevant to an outer shelf-upper slope paleoenvironment; though seismic data from the Andaleeb-1 area imply deeper, basinal deposition, likely due to downslope transport of the shallower fauna by turbidity current to the basin. The overlying El-Wastani Formation shows high brightness, large foresets seismic reflectors, with extensive upper sand bodies and overpressured basal shale, and contains diverse benthic fauna typical of deltaic shelf settings. The Kafr El-Sheikh/El-Wastani formational contact south of the shoreline area shows a subaerial unconformity marked by a seismic toplap, while in the deep marine, the boundary is marked by a downlapping surface, coinciding with a remarkable shift in biofacies. Pore pressure profiles further support the boundary placement in offshore areas, showing a pressure drop across the contact. Accurate placement of this formational boundary improves stratigraphic resolution and supports safer, more effective drilling and casing strategies.

Introduction

The Nile Delta area represents a well-known gas province in the eastern Mediterranean region, noted for its numerous gas discoveries. The main commercially proven gas reservoirs are found within the turbiditic and channelized clastic units of the Pliocene sequence **(EGPC, 1994; Abd Elaal et al., 2000)**. The Pliocene-lower Pleistocene succession is subdivided into two rock units: The Kafr El-Sheikh Formation and the El-Wastani Formation, from base to top. In onshore areas, these formations are readily distinguished based on their depositional settings; the Kafr El-Sheikh Formation is typically associated with continental slope environments, whereas the El-Wastani Formation reflects shelf, deltaic conditions **(Rizzini et al., 1978)**. However, as exploration has expanded into offshore basins, particularly toward the northeastern margins, the delineation of these units has become increasingly problematic **(Rizzini et al., 1978; Abd-Allah et al., 2012; Aboul Ela et al., 2013)**. The intensive drilling for gas exploration during the last three decades, particularly in the offshore region of the Nile Delta province targeting Pliocene-lower Pleistocene sand reservoirs has revealed numerous geological challenges. In structurally high regions like the Temsah and North Port-Foad concessions, tectonic deformation driven by the salt movement of the underlying Messinian strata, as well as the inherent stratigraphic complexity in the Baltim concessions, complicate the clear determination of the Kafr El-Sheikh/El-Wastani formational boundary.

In the offshore eastern and central Nile Delta area, the thickness of Pliocene-lower Pleistocene rock units shows significant variation **(AGIP, 2001)**. The El-Wastani Formation exhibits a notable increase in thickness, primarily attributed to delta progradation, while the Lower Pliocene Kafr El-Sheikh Formation thins owing to sedimentary condensation. Additionally, increased overburden pressure affecting both formations may pose challenges during drilling operations. Also, many oil-producing sand reservoirs have been made during the past three decades, and their geological modelling and correlations have suffered from sand diachronity; in addition, the delineation of the upper and lower limits of the Pliocene rock units has been questionable in some cases.

To address these uncertainties, the present study seeks to integrate all available data, such as ditch cutting description, available core samples, well logs, seismic data, and pressure data, to comprehensively characterize the lithology, age, biofacies, seismic facies, thickness variation, and formation boundaries of the Pliocene-lower Pleistocene rock units in the study area. Specifically, our work focuses on enhancing the stratigraphic discrimination between the Kafr El-Sheikh and El-Wastani formations in offshore areas. This integrated approach aims to mitigate the aforementioned problems encountered during the drilling for gas exploration, particularly those related to stratigraphic complexity and overburden pressure variations. Detailed quantitative foraminiferal analysis is employed to reconstruct paleoenvironmental conditions and facies types, while seismic facies interpretation and pore pressure prediction further constrain formation boundaries. Together, these methods enable a more precise definition of the Kafr El-Sheikh/El-Wastani boundary.

Materials and methods

To resolve ambiguities in delineating the Pliocene-lower Pleistocene rock units in the offshore Nile Delta, a comprehensive, integrated approach was employed. Multiple datasets were combined to characterize lithology, depositional environments, seismic facies, and pore pressure variations.

Foraminiferal biostratigraphy and paleoenvironmental data

In this study, high-resolution foraminiferal biostratigraphy was conducted to analyze the Pliocene-lower Pleistocene succession in four wells (Andaleeb-1, Temsah-NW-10, Temsah-NW-11, and Barboni NW-1) in Baltim-NE, Temsah, and North Port-Foad concessions Fig. (1). A comprehensive set of 588 samples obtained from ditch cuttings was analyzed to construct continuous, detailed stratigraphic records across the studied interval in the chosen wells. Detailed laboratory procedures, including sample preparation, species identification, and quantitative analysis, follow the methodology outlined in Khalifa et al. **(2025)**. The results of foraminiferal analysis were used to generate stratigraphic charts, which visually represent the vertical distribution of biofacies data. The biostratigraphic zonation framework utilized in the current study is derived from Khalifa et al. **(2025)** (constructed based on scheme of Lirer et al. **(2019)**), which is summarized here in Fig. (3).

Paleoenvironmental analysis has been made using foraminiferal contents recorded in the studied wells. Different foraminiferal parameters have been used to delineate the depositional environments throughout the studied wells, including benthic species richness, total counted planktonic and benthic foraminifera, and the known paleobathymetric ranges of the individual benthic species and genera. To further resolve paleoenvironmental variations, Q-mode clustering analyses were applied to the relative abundances of benthic foraminiferal species in each well. This method grouped samples based on their similarities, using correlation distance and Ward linkage **(Web-based ClustVis tool; Metsalu and Vilo, 2015)** to discern natural grouping between the samples of each well based on the benthic foraminifera. This approach helps in understanding the variations in environmental conditions across different samples.

Seismic data

A total of 25 seismic lines representing a 3D seismic survey covering Abu-Madi and Baltim gas fields from south to north in the central Nile Delta area were used for seismic facies analysis, along with 5 additional 3D seismic lines traversing the studied wells in Temsah-North Port Foad fields. These datasets provided high-resolution imaging of the Pliocene-Pleistocene succession Fig. (1). This seismic data was interpreted to identify key seismic facies, such as brightness, coherency, continuity, dip degree of the reflectors, reflection termination patterns, and general structural and stratigraphic patterns.

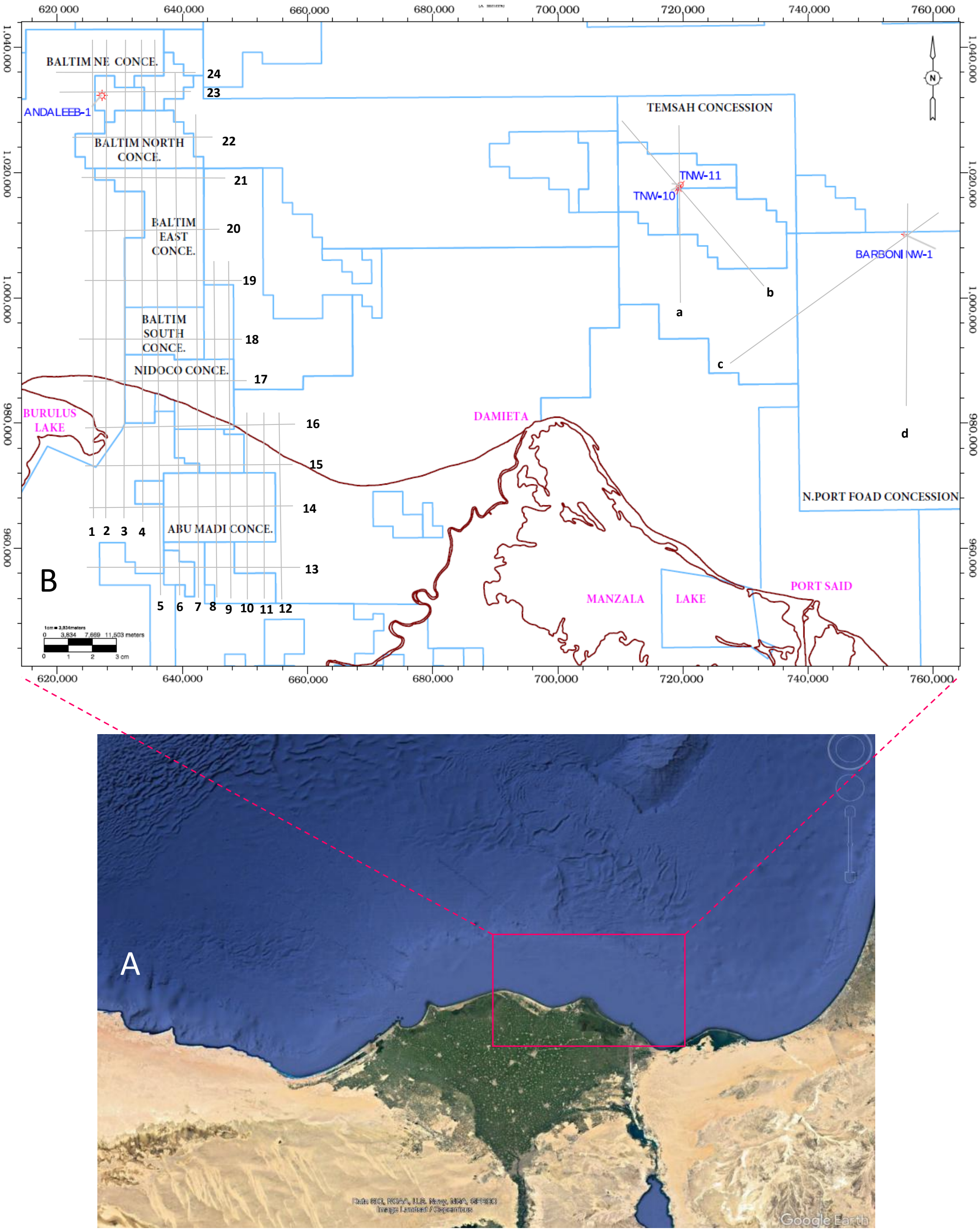

Fig. (1): Base map showing (A) the location of the studied area in the offshore eastern Nile Delta, Egypt; (B) the studied wells and the seismic lines used in this study.

Well logs and pore pressure data

Pore pressure refers to the force generated by the formation fluids or pore fluids itself **(Donaldson et al., 2002)**. There are several approaches for pore pressure estimation, including Eaton's equation, Miller's equation, and the Sonic log or Resistivity log method **(Dasgupta and Mukherjee, 2020)**. In this study, we employed the Resistivity method, incorporating a depth-dependent normal compaction trend line (NCT). While one common assumption is that shale resistivity remains constant under normal compaction, in reality, resistivity typically varies with burial depth.

Therefore, establishing an accurate NCT is crucial for reliable pore pressure prediction. Using the correlation between measured resistivity and burial depth in normally pressured formations, the following resistivity-based compaction trend equation is applied, as proposed by Zhang **(2011)**:

$$R_n = R_0 \exp(bZ)$$

where Rn denotes the shale resistivity in a normally compacted state; R0 denotes the shale resistivity at the mudline; b is a fixed coefficient; Z indicates the depth below the mudline. Inserting this Rn value into Eaton's resistivity formula allows for pore pressure computation.

Eaton's equation:

$$P_p = S - (S - P_{hyd}) (R_{log} / R_n)^{1.2}$$

Where P_p denotes pore pressure; S represents stress (usually, S_v); P_{hyd} denotes the hydrostatic pore pressure; and the n and log subscripts represent normally compacted and actual logged resistivity (R) measurements.

Abnormal pressures, either overpressure (a positive anomaly) or underpressure (a negative anomaly), indicate deviations from normal hydrostatic conditions due to variations in compaction, fluid flow, and tectonic activity. Consequently, pore pressure serves as an indicator of compaction, fluid flow, and burial history, which in turn inform formation boundary interpretations.

Integrated approach

The lithostratigraphic subdivision depends mainly on the change in lithology and biofacies characters. Sometimes, the lithologic variations between the rock units are subtle, indistinct, and hard to recognize, especially in the transitional intervals such as in the case of the current study. To overcome this, three independent datasets were integrated. These are biofacies-based paleoenvironmental interpretation, seismic reflectivity patterns, and pore-pressure anomalies into a unified stratigraphic framework. All these datasets were integrated to facilitate simultaneous analysis and cross-validation of biostratigraphic, seismic, and petrophysical information. This multi-disciplinary approach enabled a robust characterization of the lithostratigraphic framework and improved the delineation of the Kafr El-Sheikh and El-Wastani formations, thereby reducing uncertainties associated with lithologic homogeneity and complex depositional environments.

Results

Lithostratigraphy

The Pliocene-lower Pleistocene succession in the Nile Delta region has been extensively studied and classified by many authors **(IEOC, 1969, 1982; NCGS, 1976; Zaghloul et al., 1977; Rizzini et al., 1978; El-Heiny and Morsi, 1992; El-Heiny and Enani, 1996; Ismail et al., 2010; Makled et al., 2017)**. These classifications were taken into consideration in the present study.

In the Nile Delta area, the Pliocene-lower Pleistocene succession is generally subdivided into two rock units, the Kafr El-Sheikh Formation at the base and the El-Wastani Formation at the top. The lithostratigraphic characterization of the investigated rock units depends on the detailed description of cutting samples of the studied wells, microscopic examination of the washed residues, and the petrographic analysis of core plug samples from the Andaleeb-1 well (interval 2522 m-2682.5 m). Additionally, the available data, including seismic data, well logs, and mud logging data, were reviewedto provide a comprehensive understanding of the Pliocene-lower Pleistocene rock units in the study area.

Kafr El-Sheikh Formation

The Kafr El-Sheikh Formation was initially defined by IEOC (1963-1969) in an unpublished report and later adopted by Rizzini et al. **(1978)**. The Kafr El-Sheikh -1 Well (Lat. 31° 10′ 23′′ N and Long. 31° 4′ 55′′E) in the onshore Nile Delta represent the type section of this formation, with a thickness of 1458 m (depth interval: 1277 m - 2735 m). In the current study, the formation measures 1625 m in the Andaleeb-1 well, 1145 m in the TNW-10 well, and 1442 m in the TNW-11 well. This formation is represented by thick shale deposits that mainly consist of claystone and fissile shale, interbedded with some turbiditic sandstone. The claystone is moderately hard, exhibits grayish to brownish and sometimes ferruginous tint, and is almost laminated siltstone. The shale is mainly montmorillonite, kaolinite, and rare illite, exhibiting fissility, soft nature, grayish to brownish colored, sometimes ferruginous, glauconitic, and pyritic. The sandstone is mostly colorless, fine to medium-grained, mainly quartzose, sometimes arkosic and/or sublithic arenite with clay and a few carbonate matrix Fig. (2).

The Kafr El-Sheikh Formation generally exhibits abundant carbonaceous matter, mostly graphite, particularly within the lower and middle portions, as recorded in TNW-10, TNW-11, and Andaleeb-1 wells. The lower boundary of the Kafr El-Sheikh Formation directly overlies either the Messinian evaporites of the Rosetta Formation (in Temsah and North Port-Foad fields) or the Messinian sands of the Abu Madi Formation (westward at Baltim fields). The upper limit is usually cited at the appearance of thick sandstone and claystone layers of the El-Wastani Formation, corroborated by the common occurrence of shallow water foraminifera, including *Ammonia beccarii* and *Elphidium crispum*, along with the abundant occurrence of *Bulimina marginata* and *Uvigerina peregrina*. The Kafr El-Sheikh Formation yields sparse foraminiferal assemblage indicative of the *Globorotalia margaritae* and *Globorotalia puncticulata/Globorotalia margaritae* Zones **(Lirer et al., 2019; Khalifa et al., 2025)**, supporting an Early Pliocene (Zanclean) age.

El-Wastani Formation

The El-Wastani Formation was initially defined by IEOC (1963-1969) in an unpublished report for the northern Nile Delta region and was subsequently adopted by Rizzini et al. **(1978)**. The El-Wastani well no. l (Lat. 31° 24' 8.750" N and Long. 31° 35' 46.694" E) represent the type section of this formation, with a thickness of 123 m (from 1009 m to 1132 m). In the studied wells, this formation measures 1080 m in the Andaleeb-1 well, 940 m in the TNW-10 well, 943 m in the TNW-11 well, and 1000 m in the Barboni NW-1 well. It consists of thick sand with thin claystone and shale interbeds. Northward, the sandstone beds become thicker upward and pinch out into clay and shale; consequently, the claystone and shale show thickness increase toward the basin. Based on the examination of the cutting samples, the sandstone is coarse to medium-grained quartzose with few feldspars and lithic fragments. The claystone and shale are soft and silty.

The lower limit of the El-Wastani Formation is challenged in the offshore area, where thick shale beds occur at the bottom of the El-Wastani Formation. However, this lower limit can be marked by the disappearance of shallow water fauna like *Ammonia beccarii*, *Ammonia* spp., *Elphidium crispum*, and *Bulimina marginata*. The upper boundary cannot be distinguished in the offshore area based on the lithofacies and biofacies due to a lack of cutting samples; however, it can be traced from seismic data at the marine onlap of high brightness reflectors of the transgressive phase of Mit Ghamr Formation.

This formation exhibits abundant and diverse benthic foraminifera, especially shallow water species such as *Ammonia* spp. and *Elphidium crispum*, along with deep water taxa like *Bulimina marginata*, *Uvigerina peregrina*, *Gyroidina* spp., and *Cibicides* spp. However, planktonic foraminifera are very rare, with occasional occurrences of *Globigerinoides extremus*, *G. elongatus*, *Orbulina* spp., and *Globorotalia inflata*. Moreover, this formation is rich in dwarfed gastropod and pelecypod fragments, echinoid spines, and ostracods. *Globorotalia puncticulata* and *Globorotalia inflata* Zones **(Lirer et al., 2019; Khalifa et al., 2025)** were recorded from this formation, suggesting a Late Pliocene to Early Pleistocene (Piacenzian-Gelasian) age.

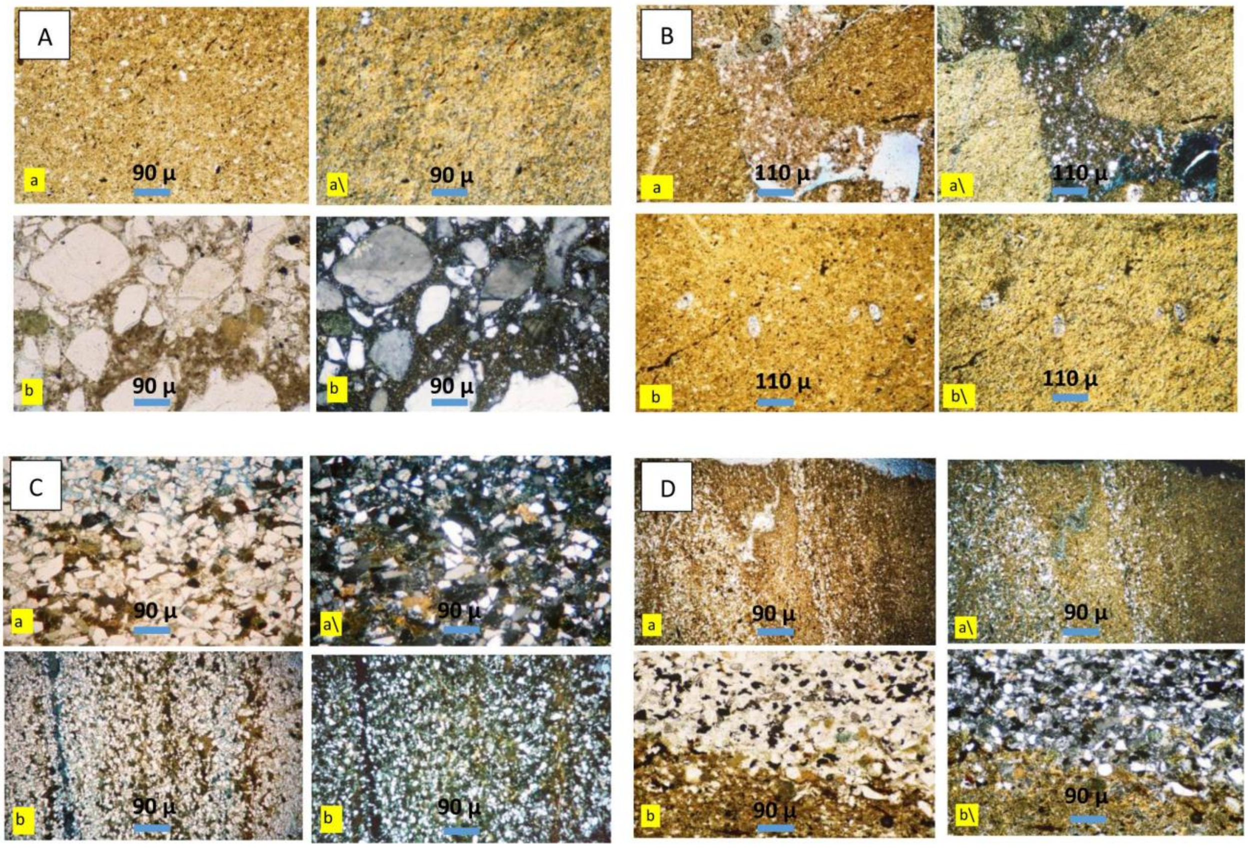

Fig. (2): Petrographic description of some core plug samples for the Kafr El-Sheikh Formation in the Andaleeb-1 well, offshore central Nile Delta area. **A:** Thin sections for core samples, at 2656m depth showing claystone (a, plane polarized light (PPL) & a\, cross nicol (CN) and 2681 m depth showing fine to medium quartz wacke with carbonate cement in the groundmass (b & b\). **B:** Thin sections for core samples, 2572m depth showing ferruginous claystone with cavities, and fractures filled with mudstone (a, PPL & a\ CN) and 2582 m depth showing microforams embedded in ferruginous claystone, the dark particles were proved (by reflected light) to be pyrite crystals (b & b\). **C:** Thin sections for core sample, 2534m depth showing cross-laminated very fine arkosic wacke sand (a, b PPL & a\, b\ CN). **D:** Thin sections for core sample, 2522m depth showing glauconitic ferruginous silty claystone dark brown color (a PPL & a\ CN) laminated with light colored glauconitic ferruginous very fine arkosic wacke sand. (b PPL & b\ CN).

Biostratigraphy and Biofacies Analysis

High-resolution foraminiferal investigation of the Pliocene-lower Pleistocene succession in the Andaleeb-1, Temsah NW-10, Temsah NW-11, and Barboni NW-1 wells, located in the offshore eastern Nile Delta, revealed six planktonic foraminiferal zones and three benthic foraminiferal zones **(Khalifa et al., 2025)**. These zones were correlated and dated utilizing the standard Mediterranean planktonic foraminiferal zonation by Cita **(1975)**, modified by Sprovieri **(1992, 1993)**, and adopted by Violanti **(2012)** and Lirer et al. **(2019)** Fig. (3). The four studied wells show different foraminiferal variations. The Andaleeb-1 well Fig. (4) represents the most complete well in the studied wells and contains good biofacies, so that its stratigraphic distribution chart, shown here, illustrates the foraminiferal biozonation and biofacies.

Our biostratigraphic data indicates that the Kafr El-Sheikh Formation is primarily of the Early Pliocene (Zanclean) age, corresponding to the NPP-1, NPP-2, and NPP-3 zones and is characterized by sparse foraminiferal assemblages. In contrast, the El-Wastani Formation, spanning the Late Pliocene (Piacenzian) to Early Pleistocene (Gelasian) age, encompasses the NPP-4, NPSP-1, and NPSP-2 zones and contains abundant and diverse benthic foraminifera. Furthermore, the established biostratigraphic framework shows the absence of the standard foraminiferal bioevents of Lirer et al. **(2019)** that subdivides the upper Pliocene (Piacenzian stage) from the study area Fig. (3). This could be attributed to significant hiatus and/or marine erosions in the offshore Nile Delta area, represented by either one amalgamated surface due to the complete missing of the Upper Pliocene in the TNW-10 well, or more than one erosive surface bounding a thin interval of Piacenzian, such as in the Andaleeb-1 well. This sedimentary interruption, approximately coincident with a notable shift in biofacies (e.g., an increase in shallow water genera like *Ammonia*, *Elphidium*, and *Bulimina* in El-Wastani Formation), likely resulted from regional tectonic events and/or sea-level fluctuations that altered the sedimentary regime Fig. (3).

Paleoenvironmental Analysis

Different foraminiferal parameters have been used to delineate the depositional environments of the studied interval throughout the studied wells, including benthic species richness, total counted planktonic and benthic foraminifera, and the known paleobathymetric ranges of the individual benthic species and genera **(Rögl and Spezzaferri, 2003; Hohenegger, 2005; Murray, 2006; Kranner et al., 2021)**. Moreover, Q-mode (sample-based) clustering of the benthic foraminifer's relative abundances data applied to discern natural grouping between the samples of each well based on the benthic foraminifera.

The upper depth limit of key benthic foraminiferal species proposed by different authors **(Van Morkhoven et al., 1986; Van Der Zwaan et al., 1990; Holbourn et al., 2013; Ayyad et al., 2023)** has been considered in the current paleoenvironmental analysis.

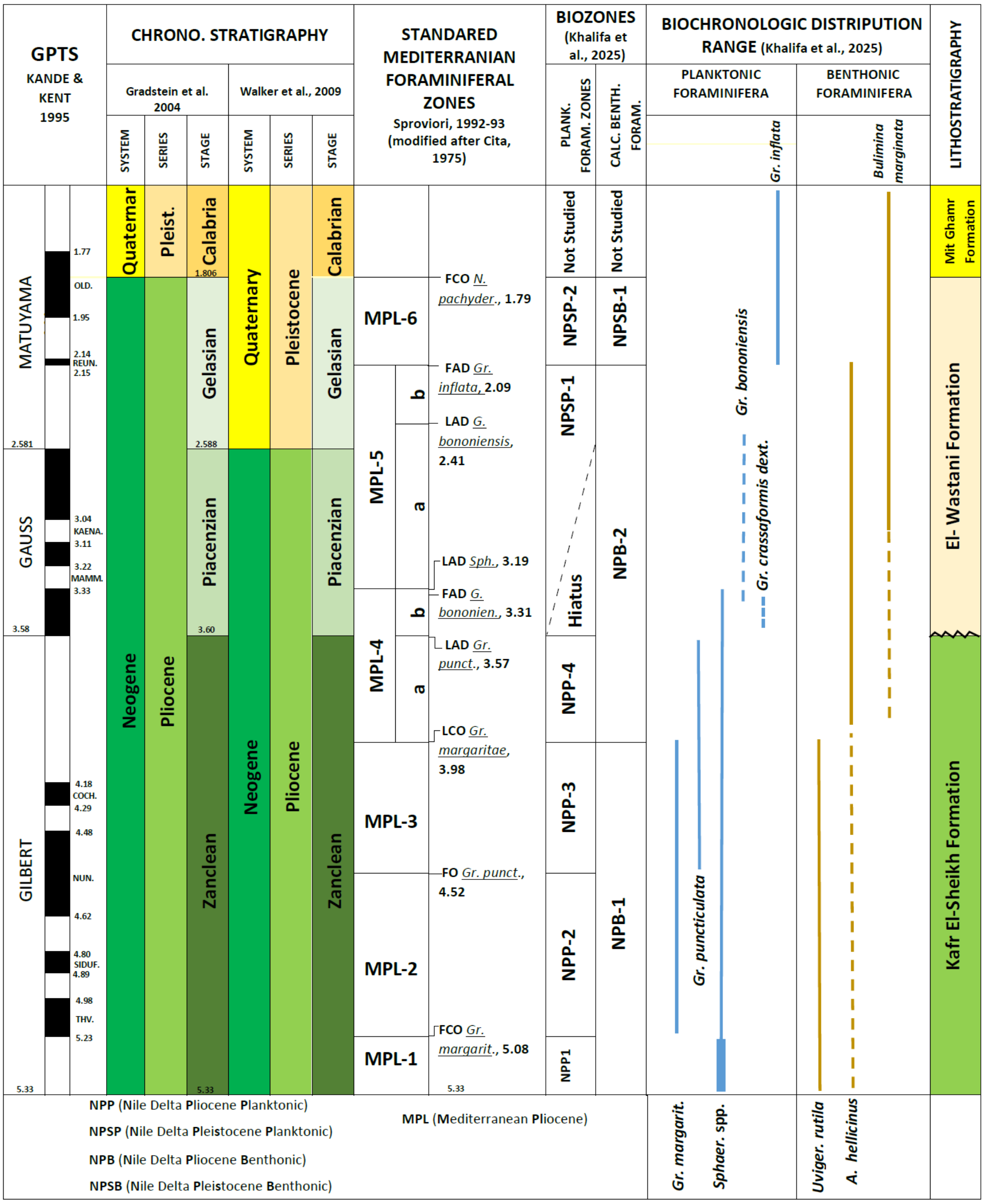

Fig. (3): Foraminiferal biostratigraphic and lithostratigraphic subdivision of the Pliocene – lower Pleistocene succession in the offshore eastern Nile Delta area (modified after Khalifa et al. **(2025)**).

Foraminiferal assemblages and biofacies

The foraminiferal biofacies analysis of the studied rock units revealed that the El-Wastani Formation exhibits a comparatively abundant and diverse foraminiferal community, while the Kafr El-Sheikh Formation yields a sparse and less diverse foraminiferal assemblage. According to the Q-mode clustering, the samples from the four studied wells are allocated into different distinct groups (termed biofacies), each with its distinct foraminiferal structure and associated paleoenvironmental interpretation (see Supplementary Figures S1-S3). Table (1) presents the summary of the Q-mode-based biofacies analyses across the studied wells, which enable us to explain the paleoenvironmental synthesis of the Pliocene units in the study area.

Paleoenvironmental Synthesis

The depositional paleoenvironments of the studied formations varied significantly across the Andaleeb-1, TNW-10, and Barboni NW-1 wells, while the TNW-11 well data excluded due to its poor foraminiferal record. The analysis is shown in Figs. (4-6).

Kafr El-Sheikh Formation

The Kafr El-Sheikh Formation generally yields a sparse and less diverse foraminiferal assemblage. Despite the generally scarce assemblage, the non-calcareous agglutinated species (*Ammobaculites* and *Haplophragmoides*) dominate in some intervals, suggesting a wide bathymetric range from shallow to deep water settings **(Murray, 2006)**. Other intervals, particularly in the middle part of the formation at the Andaleeb-1 well, are characterized by deep water taxa, including *Uvigerina* spp., *Bulimina* spp., *Gyroidina soldanii*, *Pullenia bulloides*, *Sphaeroidina bulloides*, *Cibicides* spp., and *Melonis padanum*, suggesting periodic deepening reaching up to a probably upper slope setting **(Van Morkhoven et al., 1986; Rögl and Spezzaferri, 2003; Murray, 2006; Holbourn et al., 2013)**, especially in the middle interval of the formation at the Andaleeb-1 well. Therefore, the foraminiferal-based inferred paleoenvironment fluctuated greatly throughout the formation, ranging from the inner shelf in some parts up to the outer shelf and probably upper slope settings as in the Andaleeb-1 well Figs. (4 and 5).

Alternatively, the lithological interpretation from the wireline logs, besides seismo-facies models, suggests the turbiditic nature of the Kafr El-Sheikh Formation's sand reservoirs. This turbiditic deposition may explain the presence of shallow water foraminiferal species alongside deeper species in the Kafr El-Sheikh Formation. So, the Kafr El-Sheikh Formation in the study area could be deposited in a range from the upper slope at the shoreline area to basinal environment in deep marine area such as Andaleeb-1 well area, and the presence of shallow-water species is attributed to turbidity flow.

El-Wastani Formation

The El-Wastani Formation reveals a notably rich and diverse foraminiferal assemblage. Enhanced species richness and diversity, especially in the lower half of the formation, reflect stable and favorable environments for benthic foraminifera. The occurrence of some deeper-water taxa like *Uvigerina* spp., *Pullenia bulloides*, and *Gyroidina soldanii* in certain biofacies suggests outer shelf conditions, with paleo-water depths likely reaching up to 200 m **(Boersma, 1984; Van Morkhoven et al., 1986; Rögl and Spezzaferri, 2003; Murray, 2006)**.

However, assemblage fluctuations, with intervals dominated by shallow-water indicators like *Ammonia* spp. in the Barboni NW-1 well, point to periodic sea-level changes or variations in sediment input. Overall, the paleoenvironment ranges from inner shelf to outer shelf settings. The El-Wastani Formation reveals a marked sea-level cycle of rise and fall at all studied sites, despite the lateral variation in paleoenvironment in the Andaleeb-1 well, the TNW-10 well, and the Barboni NW-1 well Figs. (4-6). This exotic difference likely reflect a combination of factors, including paleogeographic positions within the delta system, variations in sediment supply, and local structural controls. So, the paleoenvironmental interpretation of the El-Wastani Formation in the studied area ranges from shelf to slope environment in Andaleeb-1 well (considering the shallower biofacies transported by turbidity influx), with shallower conditions observed in the Temsah and North Port Foad fields than in the Baltim field.

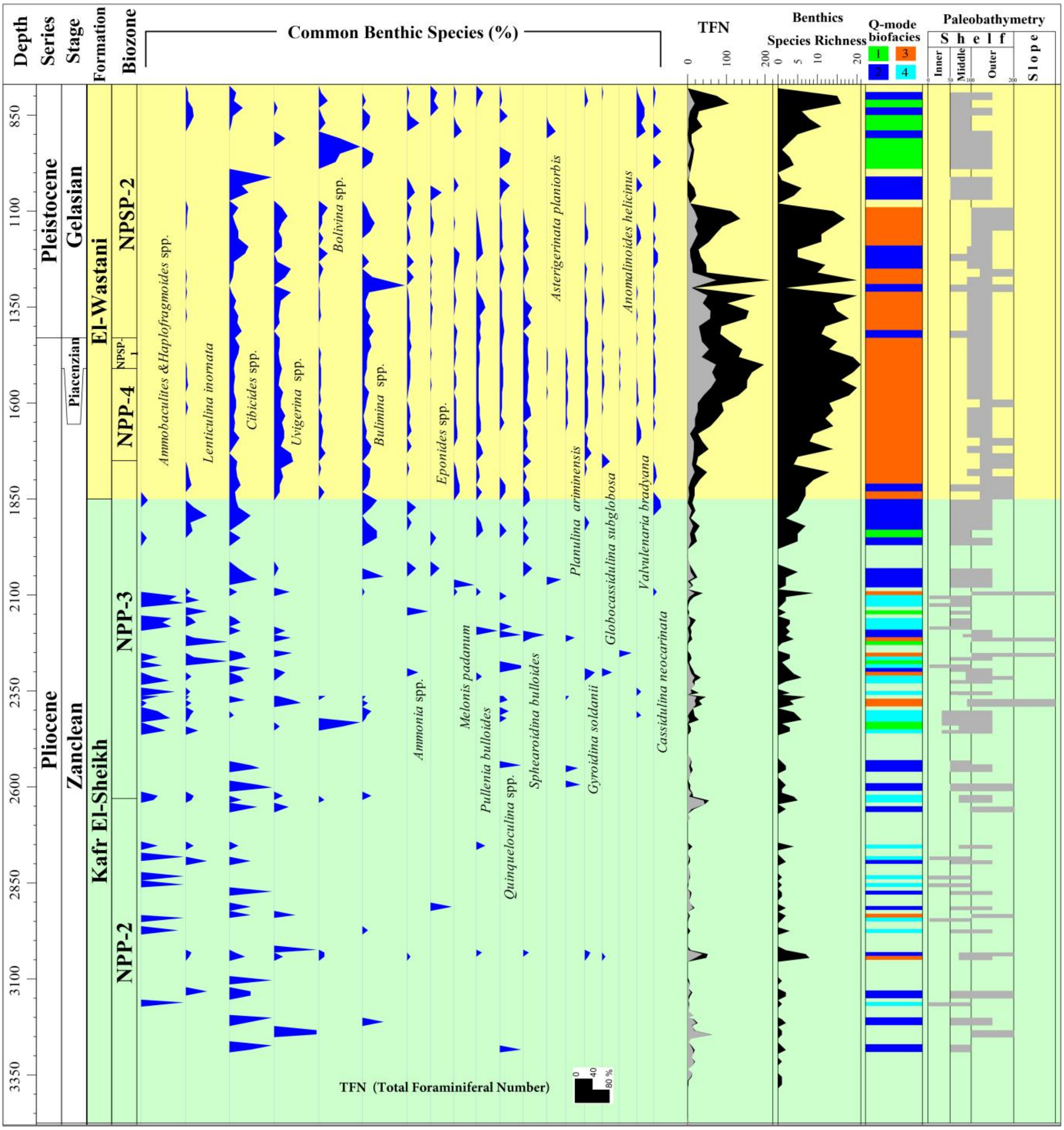

Fig. (4): Paleoenvironmental analysis of the Kafr El-Sheikh and El-Wastani formations in the Andaleeb-1 well, offshore central Nile Delta area.

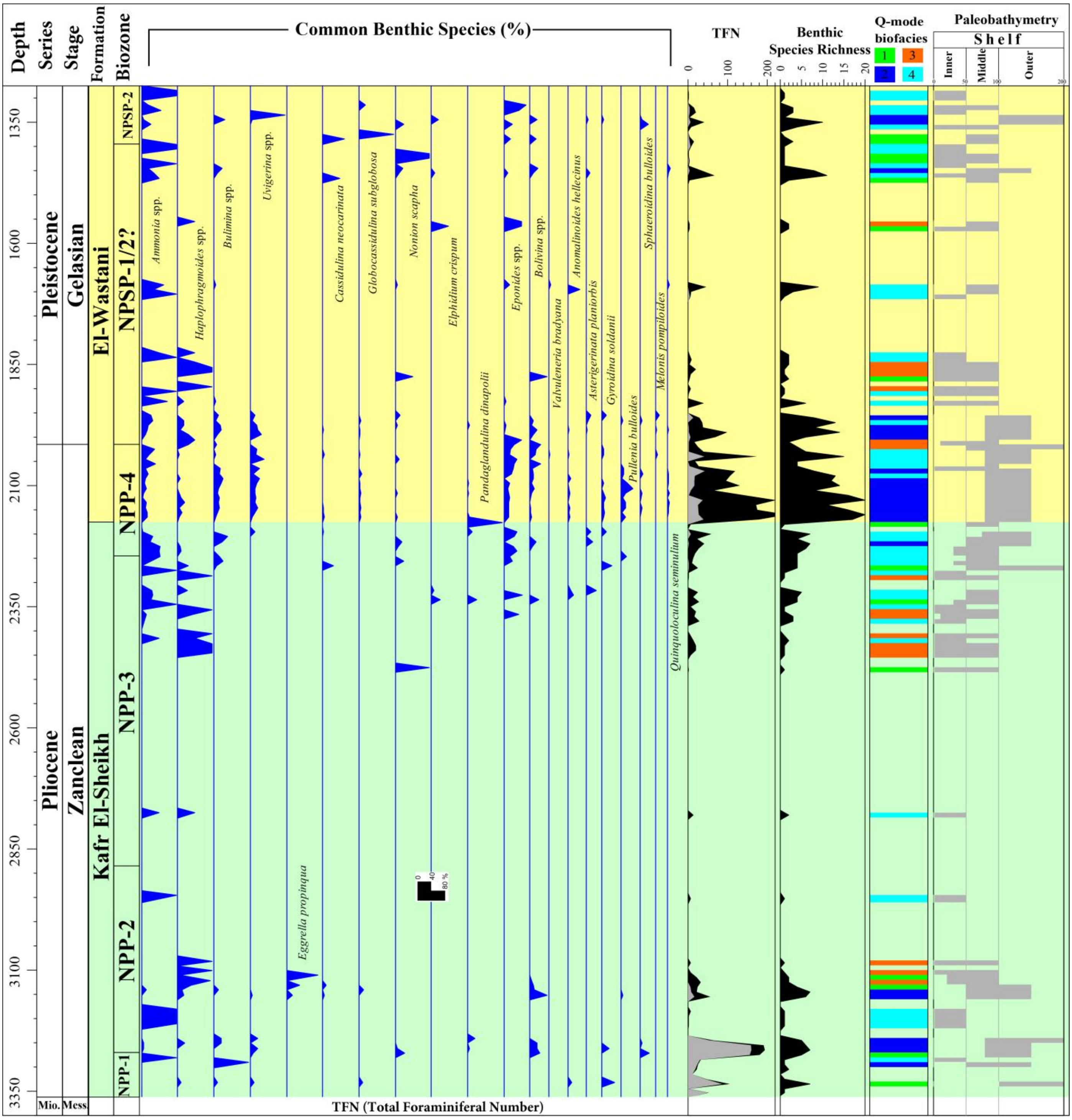

Fig. (5): Paleoenvironmental analysis of the Kafr El-Sheikh and El-Wastani formations in the Temsah-NW-10 well, offshore eastern Nile Delta area.

Table (1): Summary of Q-mode biofacies analyses across the studied wells. (See Supplementary Fig. (S1–S3) for graphical representation. Note: interpretations do not account for potential transport of shallow-water fauna to deep-water settings via turbidity currents.

Well	Biofacies	Formation	Key Benthic Foraminiferal Species	Suggested Paleoenvironment
Andaleeb-1	1	Upper Kafr El-Sheikh, upper El-Wastani	*Bolivinids*, *Lenticulina inornata*, *Bulimina* spp., *Quinqueloculina padana*	Middle-outer shelf
	2	Various levels	*Cibicides* spp., *Bulimina* spp., *Lenticulina inornata*, rare *Uvigerina* spp.	Middle-outer shelf
	3	Lower El-Wastani	*Bulimina* spp., *Lenticulina inornata*, *Uvigerina* spp., *Pullenia bulloides*, *Gyroidina soldanii*	Outer shelf
	4	Kafr El-Sheikh	*Ammobaculites*, *Haplophragmoides*, *Cibicides* spp., *Lenticulina inornata*	Wide range; Inner-shallow outer shelf
TNW-10	1	Various levels	*Nonion scapha*, *Elphidium crispum*, *Cassidulina neocarinata*, *Bolivina* spp.	Inner-middle shelf
	2	Lower Kafr El-Sheikh, lower El-Wastani	*Ammonia* spp., *Bulimina* spp., *Uvigerina* spp., *Bolivina* spp., *Pullenia bulloides*, *Gyroidina soldanii*, *Haplophragmoides* spp., *Eponides* spp.	Deep middle-outer shelf
	3	Kafr El-Sheikh, middle El-Wastani	*Haplophragmoides* spp., *Eponides* spp.	Wide range; Inner-shallow outer shelf
	4	Various levels	*Ammonia* spp., *Eponides* spp., *Haplophragmoides* spp., *Bolivina* spp., *Bulimina* spp., *Uvigerina* spp., *Nonion scapha*	Inner to middle shelf
Barboni NW-1	1	Upper El-Wastani	*Ammonia* spp., *Quinqueloculina* spp., *Elphidium crispum*	Inner shelf
	2	Lower El-Wastani	*Ammonia* spp., *Haplophragmoides* spp., *Eggerella compressa*	Inner-middle shelf
	3	Middle El-Wastani	*Bulimina* spp., *Bolivina* spp., *Eponides* spp., *Ammonia* spp., *Cassidulina neocarinata*, *Uvigerina* spp., *Pullenia bulloides*	Deep inner-shallow outer shelf

Seismic Facies

The Neogene succession in the Nile Delta and the Mediterranean Sea is generally classified into two main seismic mega-sequences, representing two main sedimentological mega-cycles: the Miocene sequence and the Pliocene-Quaternary sequence **(Rizzini et al., 1978)**. The seismic facies of the Pliocene sequence has been studied using 30 selected seismic lines covering the study area Fig. (1). Two arbitrary seismic lines are shown in Fig. (7), displaying the recognized seismic facies in the study area. In general, seismic facies of the Pliocene-Quaternary sequence show parallel to subparallel, near horizontal, and inclined seismic reflectors, which transition laterally to bright spots indicative of gas-bearing sands having the shape of sand channels, fans, and basin floor fans.

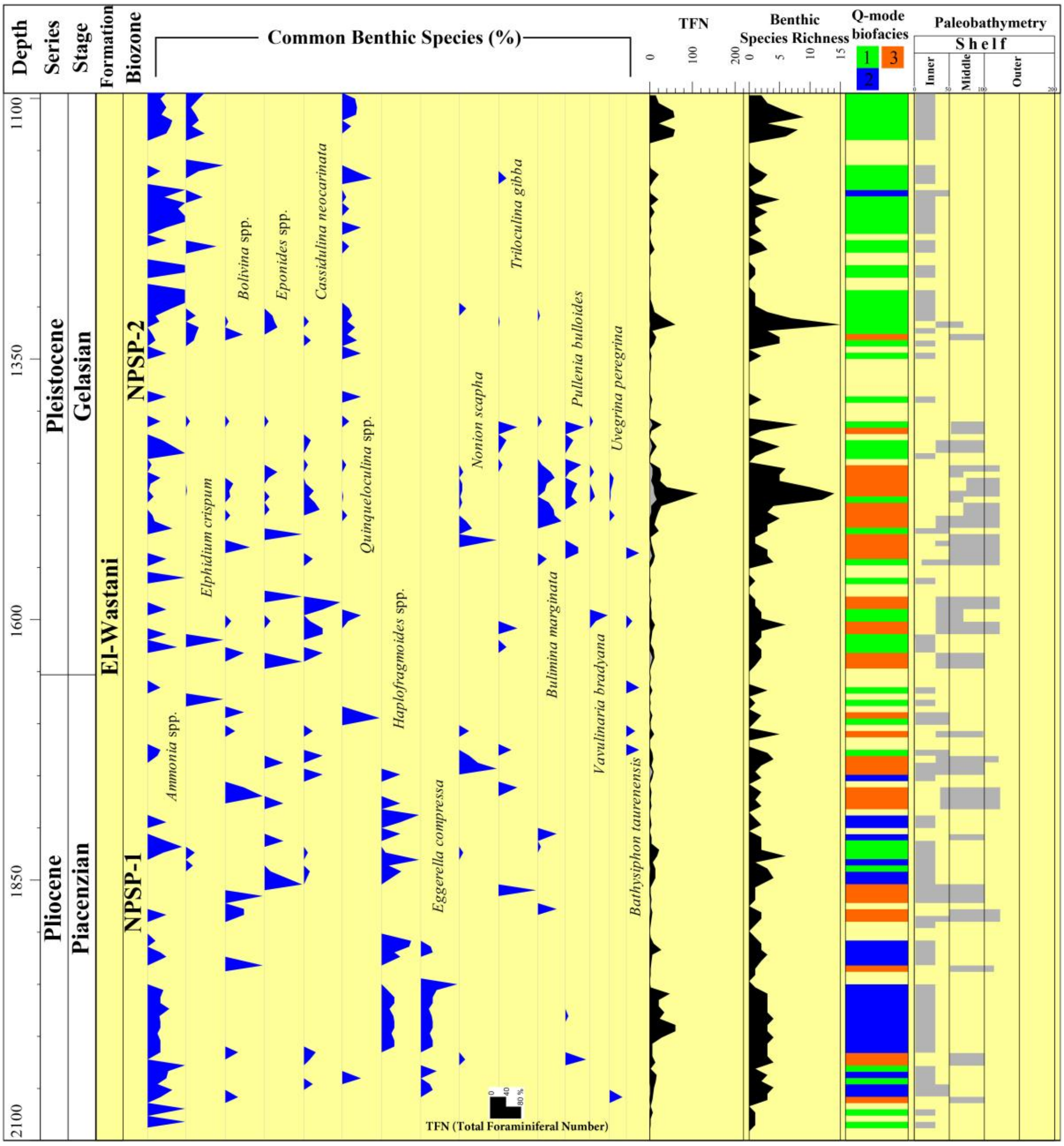

Fig. (6): Paleoenvironmental analysis of the El-Wastani Formation in the Barboni-NW-1 well, offshore eastern Nile Delta area.

Kafr El-Sheikh Formation

The seismo-stratigraphic features of the Kafr El-Sheikh Formation in the studied seismic lines exhibit high brightness reflectors at the lower part and moderate brightness, sometimes chaotic at the upper part. The reflectors are gently dipping northward at the shoreline area and nearly horizontal at the northern area indicating basinal environment, indicating slope to basinal environments. Occasional fan or channel fan form and sheet form reflectors, likely produced by turbiditic deposition, contribute to the high brightness of the reflectors Figs. (7A). In the North Port Foad and Temsah fields Fig. (7B), the brightness of the reflectors of Kafr El-Sheikh Formation is less pronounced compared to the overlying El-Wastani Formation. Moreover, listric growth faults dominate in the Kafr El-Sheikh Formation, especially those detached in the Messinian evaporites complicate the seismic facies of the Kafr El-Sheikh Formation. The Temsah and North Port-Foad fields, located at the edge of the continental shelf and upper slope areas, are highly prone to subsidence and collapse generating gravity flow deposition. In contrast, the Baltim fields exhibit only a few normal growth faults in the Pliocene section, as detected from seismic reflections. Most of these faults affect the upper part of the Miocene section and could be due to sedimentation bypassing at the shelf and upper slope settings Fig. (7).

El-Wastani Formation

The El-Wastani Formation in the offshore eastern Nile Delta area exhibits seismic facies characterized by higher brightness than the Kafr El-Sheikh Formation. The seismo-stratigraphic features, especially in Abu Madi, Nidoco, and Baltim fields in the southern part, are characterized by fluvial system progradation toward the north due to the Delta progradation. This progradational pattern is associated with extensive sand bodies in the El-Wastani Formation. While the seismic feature at the northern part (Andaleeb-1 area) indicates slope deposition, it also illustrates turbiditic influx Fig. (7A). Slope prograding is also evident in the seismic reflectivity of the southern part of the Temsah field, especially in the Karous area (well-D area in Fig. 7B), where the seismic facies is also affected by normal listric faults toward the north at the Barboni NW-1 well.

Pore Pressure Regime

The wireline logs and drilling logs (especially Resistivity and Gamma Ray logs) have been used for pore pressure analysis in the studied Pliocene-lower Pleistocene succession. Fig. (8) shows the Pore Pressure Gradient (PPG) analysis for the four studied wells: Andaleeb-1, TNW-10, TNW-11, and Barboni NW-1. The PPG curves show a pronounced increase at the basal portion of the El-Wastani Formation, forming a positive PPG anomaly that indicates pressurized shale beds. This anomaly suggests rapid burial history and high compaction at the lower portion of this formation relative to its top portion. The PPG curves show a remarkable change against the level proposed for the boundary between the Kafr El-Sheikh Formation and the El-Wastani Formation in Andaleeb-1, TNW-10, and TNW-11 wells. Across the boundary, the PPG values drop abruptly, creating a small negative anomaly consistent with the significant biofacies and paleoenvironmental change observed in our biostratigraphic analysis Figs. (4-6). This negative anomaly is absent in Barboni NW-1, suggesting it likely did not penetrate the Kafr El-Sheikh Formation, as supported by biostratigraphic results. Below this boundary, the PPG curves in Andaleeb-1, TNW-10, and TNW-11 wells start to increase again, forming a positive anomaly indicative of high pore pressure in the Kafr El-Sheikh Formation.

Discussion

Litho-Biofacies Variabilities: Controls and Implications

The study area in the offshore eastern Nile Delta exhibits great lateral variabilities, reflecting a complex interplay of depositional processes, sediment supply, and tectonic influences. This variability is not only evident in the rock record but also in the spatial distribution of foraminiferal assemblages and seismic facies, which together offer critical insights into the basin's evolution and its hydrocarbon potential. While the Kafr El-Sheikh Formation generally exhibits a sparse foraminiferal assemblage, the relative abundance and distribution of both deep-water taxa and shallow-water agglutinated species vary between the Temsah field and the Baltim field Fig. (9). In the Temsah field, thick turbiditic sands dominate the middle interval, largely barren of foraminifera. This suggests that these areas experienced episodic high-energy events, likely linked to their proximal position along the continental margin that delivered abundant coarse clastics and rapidly buried sediments. Conversely, the Baltim field shows thinly interbedded sands and shales with sparse deep-water taxa (*Bulimina* spp., *Uvigerina* spp.) and agglutinated species (*Haplophragmoides* spp.), reflecting a more stable depositional setting with less influence from turbiditic currents within distal deep shelf to upper slope conditions **(Rizzini et al., 1978; Makled et al., 2017; El-Kahawy et al., 2023)** Figs. (4 and 5).

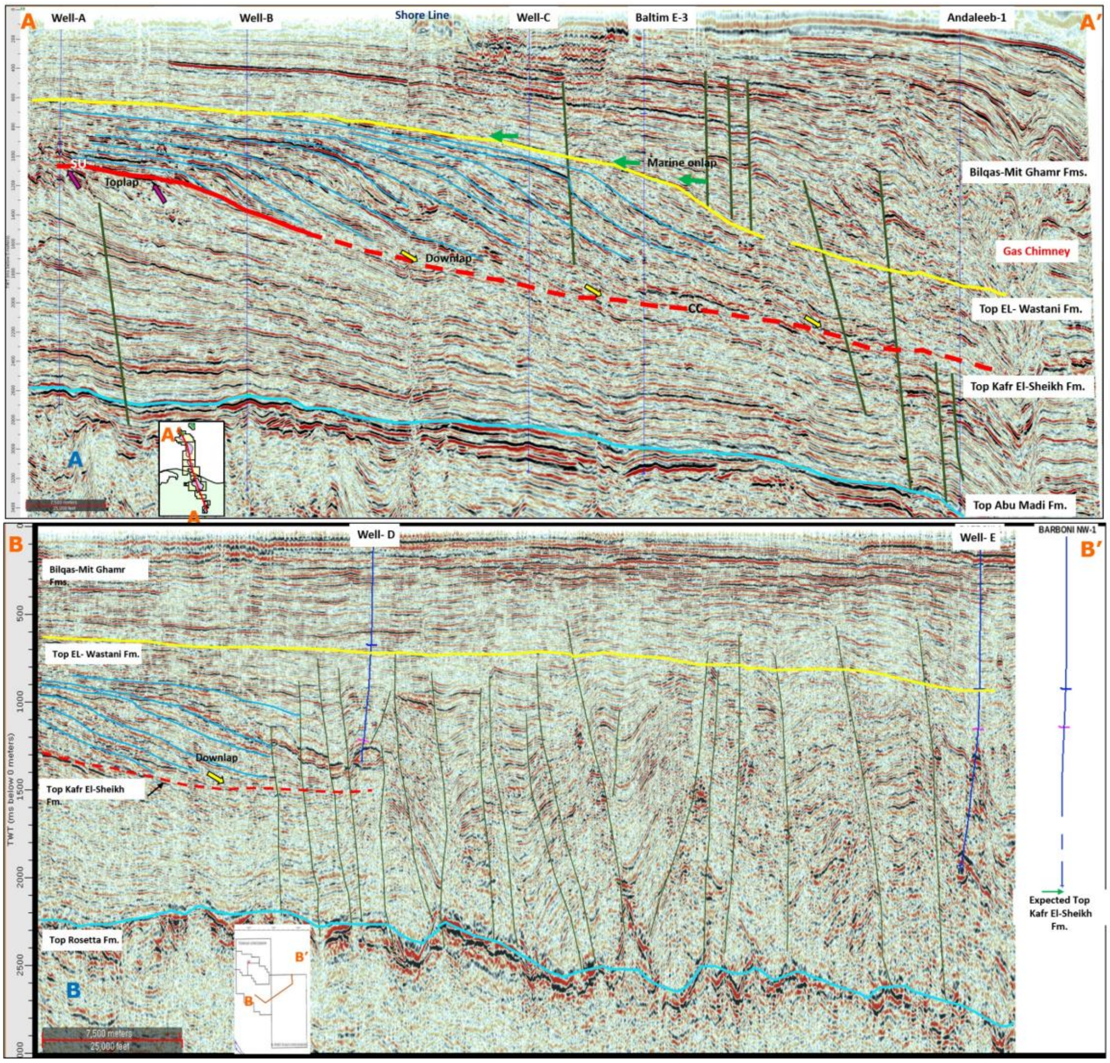

Fig. (7): Arbitrary seismic timelines illustrating the seismic facies of the Pliocene–Pleistocene succession in the offshore Nile Delta. (A) Abu Madi–Baltim Fields (central Nile Delta). (B) Temsah–North Port Fouad Fields (eastern Nile Delta). Abbreviations; SU=Subaerial Unconformity, CC=Correlative Conformity.

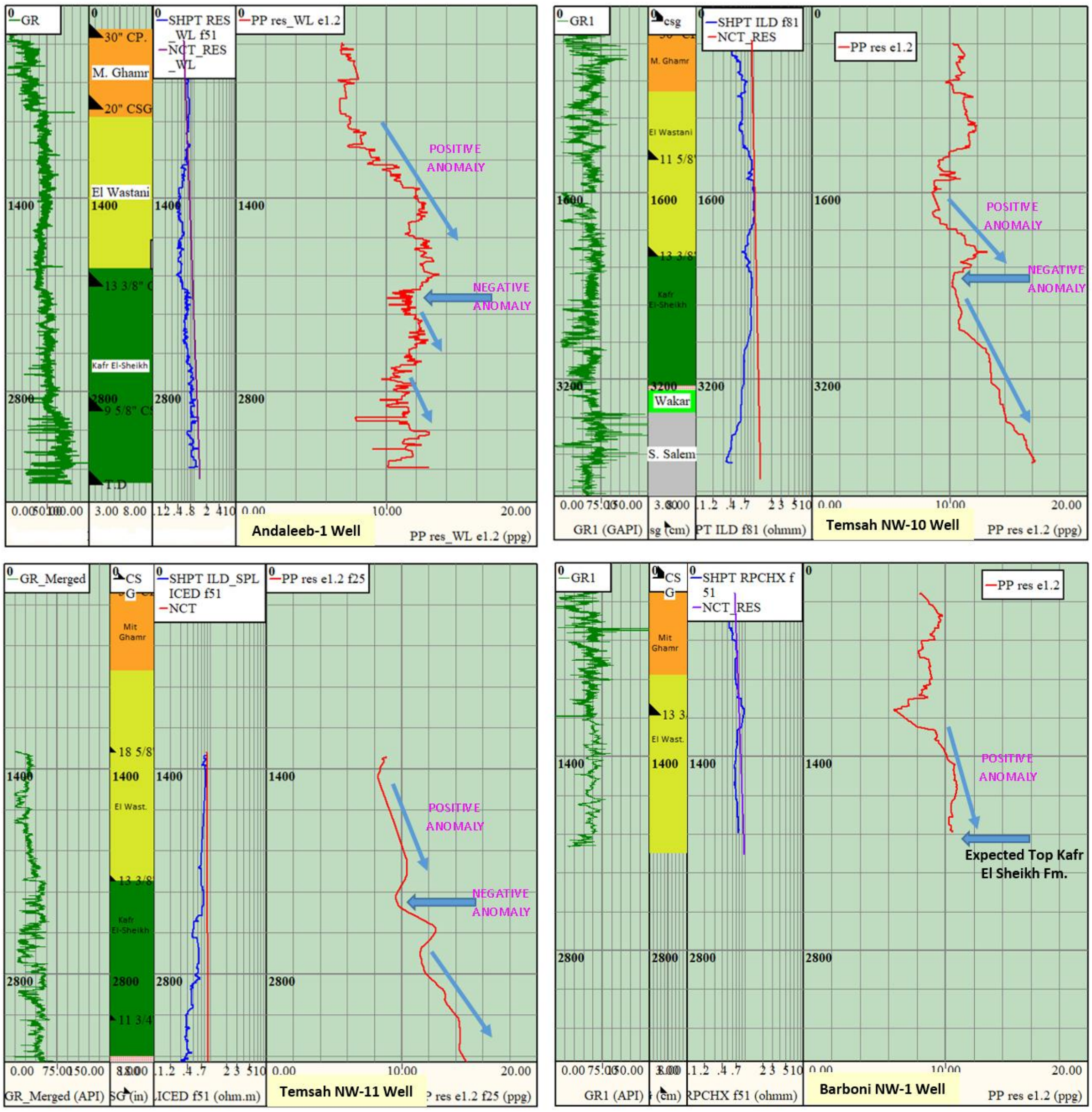

Fig. (8): PPG analysis for the Kafr El-Sheikh and El-Wastani formations in the Andaleeb-1, Temsah-NW-10, Temsah-NW-11, and Barboni NW-1 wells, offshore eastern Nile Delta area

Similarly, the El-Wastani Formation shows distinct proximal-to-distal litho-biofacies changes. At the shallower TNW-10 and Barboni NW-1 wells, the foraminiferal biofacies is dominated by shallow-to-mid water taxa (e.g., *Ammonia spp.*, *Haplophragmoides* spp., and *Eponides* spp.), and the gamma ray curves clearly indicate the presence of well-recognized thick sandy intervals. These observations suggest deposition under a higher-energy, deltaic environment with significant sand accumulation. In contrast, the Andaleeb-1 well exhibits a distinct shift in biofacies toward deep-water taxa, such as *Bulimina* spp., *Melonis padanum*, *Lenticulina inornata*, and *Uvigerina* spp., and the gamma ray log indicates a dominance of shaly and silty shales with no evidence of thick sandstone beds (Figs. 4 - 6).

The observed litho/biofacies transition indicates a lateral (likely northward) shift from high-energy deltaic deposition to low-energy basinal conditions. It also refers to variations in sediment supply along the delta margin. Increased sediment supply in proximal areas enhances the deposition of thick sandy intervals, while reduced sediment supply and lower energy conditions in more distal areas favor the accumulation of shales. This northward deepening trend within the El-Wastani Formation could be linked to delta progradation **(Sestini, 1989)**, as sea-level fluctuations and basin subsidence further influence sediment distribution.

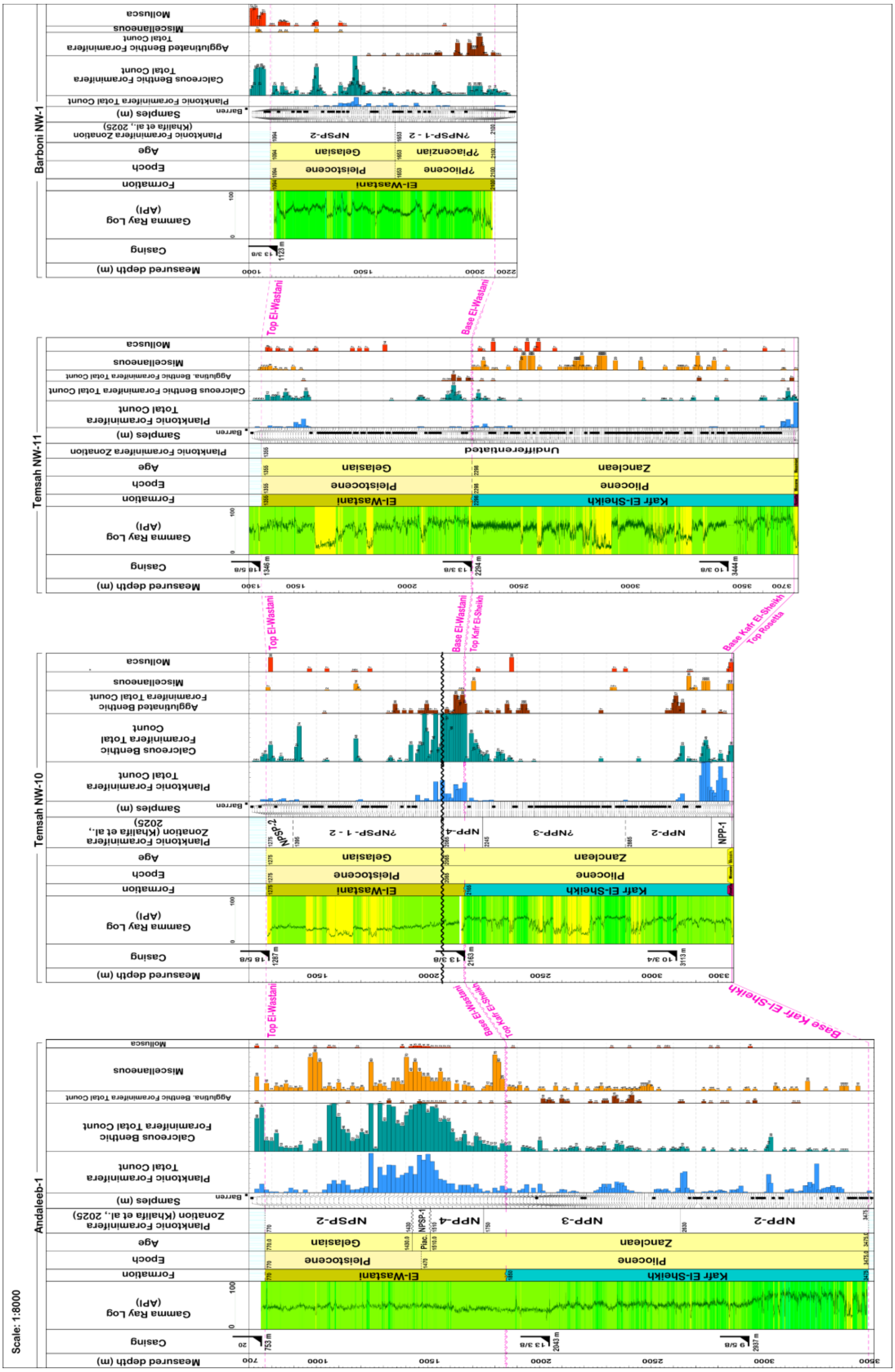

Fig. (9): Stratigraphic correlation between the four studied wells shows the litho-biofacies variations.

Interpretations of the Integrated Results

The Kafr El-Sheikh and El-Wastani formations represent key components of the Pliocene–Lower Pleistocene succession in the Nile Delta. As reported by Rizzini et al. **(1978)** and confirmed in this study, the Kafr El-Sheikh Formation comprises a thick shale sequence interbedded with some turbiditic sandstone, while the El-Wastani Formation comprises thick sandstone intercalated with thin claystone and shale Fig. (9). In the onshore Nile Delta, the boundary between these formations is marked by extensive basal sand bodies in the El-Wastani Formation **(Rizzini et al., 1978)**. Transitioning northward toward the basin (the current study area), the El-Wastani Formation thickens and becomes more shaly due to delta progradation, as shown in seismic reflections. Conversely, the Kafr El-Sheikh Formation thins out, possibly because of sediment condensation at more distal settings Fig. (7). These facies trends complicate the precise delineation of the Kafr El-Sheikh/El-Wastani formational contact. In addition, the increasing overburden pressure on both formations poses potential drilling problems. In addition, many oil-producing sand reservoirs have been made during the past three decades, and their geological modelling and correlations have suffered from sand diachronity, further emphasizing the need for accurate stratigraphic frameworks.

Our integrated analysis demonstrates that, while the biostratigraphic framework indicated major interruption of sedimentation punctuating the Upper Pliocene (Piacenzian) succession as recorded in TNW-10 and Andaleeb-1, could be associated with tectonic and/or sea level change resulted in change in sedimentary environment. Neither of these events seems to align precisely with the Kafr El-Sheikh/El-Wastani formational contact Fig. (9). Instead, the most reliable faunal marker is a sharp shift in benthic foraminiferal assemblages. Below this horizon, the benthic foraminifer reveals a sparse assemblage dominated by deep-water species (e.g., *Bulimina*, *Uvigerina*, *Pullenia*, *Gyroidina*, *Sphearoidina*, *Melonis*) with occasional incursions of agglutinated forms, indicating outer shelf to upper slope deposition influenced by turbidity flows **(Murray, 2006)**. Above the shift, the assemblage becomes more abundant and diverse, reflecting a deltaic environment Figs. (4–6). This turnover appears in the lower half of the NPP-4 Zone at TNW-10 and near the top of NPP-3 at Andaleeb-1 Figs. (4 and 9), demonstrating its consistency despite zonal offsets. The vertical offset of this biomarker relative to the planktonic foraminiferal biozones across the studied wells could be attributed to the observation that the bioevent for the NPP-4 Zone onset, i.e., the Last occurrence of *Globorotalia margaritae*, is known to have a spotty occurrence at the top of its range **(Lirer et al., 2019)**, which poses uncertainty in the level of NPP-3/4 contact **(Farouk et al., 2022; Khalifa et al., 2025)**. These challenges underscore the need to integrate biostratigraphic and paleoenvironmental analyses with seismic data to achieve a more robust subsurface interpretation.

Seismic facies analysis confirms this boundary in offshore area as a pronounced downlap surface, where large foresets of the El-Wastani prograding rest atop the nearly horizontal to gently dipping reflectors of the Kafr El-Sheikh Formation, with occasional erosional truncation and scouring across this boundary at the onshore area Fig. (7A). Such a downlap feature defines a stratigraphic boundary between the two different settings **(Mitchum et al., 1977; El-Fawal et al., 2016; Qu, 2021)**, which corroborates the findings from paleoenvironmental inferences that define a well-recognized biofacies dislocation between the two formations. Regional studies corroborate this interpretation, including work by El-Fawal et al. **(2016)** in the northern Nile Delta's post-rift megasequence and Makled et al. **(2017)** in the western Nile Delta, both of whom recognized the Kafr El-Sheikh/El-Wastani formational boundary. In the deeper, more distal areas of the Baltim NE Field (Andaleeb-1 area – Fig. (1), the progradational facies of the El-Wastani Formation transition into slope facies. This facies change, combined with the presence of normal faults and gas chimney structures, complicates tracing this boundary on the seismic sections.

Pore-pressure profiles provide a possible evidence that the Kafr El-Sheikh/El-Wastani formational boundary is interpreted as a possible unconformity surface. The abrupt PPG drop immediately below this contact Fig. (8) is likely due to the erosional removal of overburden during unconformity development, which reduced vertical stress and allowed pore fluids to expand or escape **(Xu et al., 2010; Farouk et al., 2024)**. In contrast, a positive PPG anomaly at the basal portion of the overlying El-Wastani Formation Fig. (8) indicates that rapid sedimentation outpaced fluid expulsion, trapping pore fluids and inducing disequilibrium compaction in addition to overburden-induced compaction **(Dasgupta and Mukherjee, 2020)**.

Together, these three independent lines of evidence (biofacies turnover, seismic downlap geometry, and pore-pressure anomalies) converge on a single, robust Kafr El-Sheikh/El-Wastani boundary definition that a single method could fail to achieve. Accurate placement of this formational boundary is not just a stratigraphic exercise but delivers additional geological insight and operational benefits. Geologically, it separates the prolific, oil- bearing turbiditic sands of the Kafr El-Sheikh Formation from the overlying, often non-oil-producing deltaic facies of the El-Wastani Formation at the onshore area and the dirty slope facies at the offshore area, ensuring correct reservoir correlations and more reliable field development models. From an engineering standpoint, recognizing the overpressure zone at the base of El-Wastani shales allows casing points to be set safely below this anomaly, preserving the necessary mud-weight window and enhancing drilling safety.

Conclusion

An integrated geological approach of lithostratigraphy, foraminiferal biostratigraphy and paleoenvironments, seismic facies, and pore pressure analysis has been applied for the discrimination between the Kafr El-sheikh and El-Wastani formations in the offshore eastern and central Nile Delta area, the integration between all analyses revealed the following conclusions:

- The Kafr El-Sheikh Formation is of Early Pliocene age and exhibits scarce foraminiferal biofacies, while the El-Wastani Formation is of Late Pliocene to Early Pleistocene age and contains abundant and diverse benthic foraminifera.

- In the study area, the Kafr El-Sheikh Formation was laid down in slope to basin settings, as evidenced by open marine planktonic foraminifera (*Gr. margaritae*, *Gr. puncticulata*, *Sphaeroidinellopsis* spp.) and slightly deeper benthic species (*Uvigerina rutila* and *Anomalinoides hellicinus*). In contrast, the El-Wastani Formation reflects a shallower marine setting, ranging from inner to outer shelf environments, changed to slope setting northward and is dominated by shallower benthic foraminifera such as *Ammonia beccarii*, *Elphidium crispum*, and *Bulimina marginata*. Regional variations, particularly the shallower conditions in the Temsah and North Port-Foad fields compared to the Baltim North field, were observed and highlight spatial heterogeneity in sedimentation and deltaic influence.
- Seismic interpretations reveal contrasting depositional styles between the two studied formations. The Kafr El-Sheikh Formation features high to moderate brightness and gentle dipping to nearly horizontal seismic reflectors, indicative of relatively stable, low-energy conditions. In contrast, the El-Wastani Formation displays high brightness, large progradational foresets, suggesting sedimentation that is more dynamic associated with the delta progradation.
- The pore pressure regime within the top of the Kafr El-Sheikh Formation is marked by a sudden decrease in PPG, followed by a downward-increasing trend, in contrast to the El-Wastani Formation the pore pressure regime increases in the bottom shale interbeds.
- The Kafr El-Sheikh/El-Wastani formational boundary in offshore area coincides with a stratigraphic surface contemporaneous with important paleo-event resulting sea level change, evidenced by a remarkable change in paleoenvironments, pore pressures, and seismic facies. This surface separates the progradational facies of the El-Wastani Formation from the basinal facies of the Kafr El-Sheikh Formation.

Acknowledgment

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التمييز الطباقي بين تكوينَي كفر الشيخ والوَسطاني في منطقة دلتا النيل الشرقية البحرية – مصر: منهجية جيولوجية متكاملة

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تم تطبيق منهجية جيولوجية متكاملة تشمل الدراسات الحيوية الطباقية، وتحليل البيئات القديمة، ودراسة السحنات السيزمية، وبيانات ضغط المسام، بهدف التمييز بين تكوينَي كفر الشيخ والوَسطاني في منطقة دلتا النيل الشرقية البحرية. أظهرت التحليلات الحيوية الطباقية للفورامنيفرا في آبار عندليب-١، تمساحNW-10 ، تمساحNW-11 ، وباربوني NW-1 أن تكوين كفر الشيخ يعود إلى البليوسين المبكر. يتكون هذا التكوين من طفلة مضغوطة ذات انعكاسات سيزمية (seismic reflectors) ساطعة إلى متوسطة الشدة، تميل بلطف نحو الشمال في منطقة الساحل، مع عواكس (reflectors) شبه أفقية شمالًا. تظهر محليًا عواكس سيزمية (seismic reflectors) (seismic reflectors) ساطعة على هيئة قنوات ومراوح أمامية (Frontal splay) . ويحتوي التكوين على تجمّعات من الفورامنيفرا تعكس بيئة جرف قاري خارجي إلى منحدر علوي، بينما توحي البيانات السيزمية من منطقة بئر عندليب-١ بوجود ترسيب أعمق في بيئة حوضية (basinal)، مما يشير الى انتقال الكائنات التي تعيش في البيئات الضحلة إلى البيئات العميقة عبر تيارات عكرة (turbidity currents) . أمّا تكوين الوَسطاني الأعلى فيتميز بانعكاسات سيزمية (seismic reflectors) ساطعة ذات ميول قوية (foresets) مع أجسام رملية علوية واسعة الامتداد وطفلة قاعدية مضغوطة، ويحتوي على تنوع كبير من الفورامنيفرا القاعية الدالة على بيئة دلتاوية الى بحرية ضحلة. ويُظهر الحد الفاصل بين تكوينَي كفر الشيخ والوَسطاني جنوب منطقة الساحل سطح عدم توافق (subaerial unconformity) يتميز بظاهرة التوقف العلوي(toplap) ، بينما في البيئات العميقة يتمثل الحد في سطح downlap متزامن مع تغير واضح في السحنات الحيوية. كما تدعم بيانات ضغط المسام هذا التحديد للحد الفاصل في المناطق البحرية، حيث يظهر هبوط ملحوظ في الضغط عبر السطح الفاصل. إن التحديد الدقيق لهذا الحد الطباقي يعزز من دقة التفسير الطباقي ويسهم في دعم عمليات الحفر والتغليف (casing) بشكل أكثر أمانًا وفعالية