J E M T
Journal of Earth and Marine Technology
homepage URL: ejurnal.itats.ac.id/jemt

Paleosalinity and Paleoproductivity reconstruction based on Foraminifera Microfossil analysis: A case study of the Oyo Formation, Gunungkidul, Special Region of Yogyakarta, Indonesia

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Article info
Received:
Jun 20, 2026
Revised:
Jul 24, 2026
Accepted:
Jul 27, 2026
Published:
Jul 30, 2026

Keywords:
Foraminifera,
Oyo Formation,
Paleoproductivity,
Paleosalinity,
Source Rock

Abstract

The Oyo Formation in the Southern Mountains of Java represents a neritic carbonate succession rich in foraminifera. This study aims to reconstruct the paleosalinity and paleoproductivity of the Oyo Formation and to evaluate their implications for depositional conditions associated with organic matter preservation. The study was conducted through micropaleontological analysis of foraminifera from three measured sections representing the Sambipitu Formation and the lower and upper parts of the Oyo Formation in Gunungkidul Regency, Special Region of Yogyakarta. Paleosalinity was reconstructed based on the relative abundance of *Orbulina universa* and *Globigerinoides sacculifer*, while paleoproductivity was interpreted using the benthic foraminiferal epifaunal–infaunal (E/I) index. The resulting paleosalinity and paleoproductivity trends were tentatively compared with the global Middle Miocene eustatic sea-level curve of Haq et al. (1987) to evaluate the possible influence of relative sea-level fluctuations on depositional conditions. The results indicate that the Sambipitu Formation was deposited under normal marine conditions characterized by low organic matter supply and well-oxygenated bottom waters. The lower part of the Oyo Formation also records normal marine conditions, interrupted by a localized hypersaline event. The upper part of the Oyo Formation exhibits decreasing paleosalinity toward brackish conditions, accompanied by the lowest E/I index values, suggesting increased organic matter flux and relatively reduced bottom-water oxygenation. These environmental conditions may have favored enhanced organic matter preservation compared with the underlying intervals. The results provide a preliminary micropaleontological screening of depositional conditions that may be favorable for organic matter preservation and identify intervals that warrant further evaluation using complementary geochemical analyses.

1. Introduction

The stratigraphy of the Gunungkidul region in the Southern Mountains of Java records an extensive Neogene carbonate deposition overlying Paleogene volcanoclastic units. Within this regional framework, the Oyo Formation holds a critical position, stratigraphically overlying the Sambipitu Formation and underlying the reefal carbonates of the Wonosari Formation. Previous studies on the Oyo Formation have primarily focused on regional stratigraphy and depositional environments, whereas paleoecological aspects, particularly paleosalinity and paleoproductivity, have received relatively little attention. Consequently, the high-resolution oceanographic evolution of this interval remains insufficiently constrained. The Oyo Formation is stratigraphically underlain by the Sambipitu Formation, which represents an older siliciclastic–carbonate succession in the Southern Mountains of Java. Although the primary focus of this study is the Oyo Formation, the underlying Sambipitu Formation was included as a stratigraphic reference unit to provide a baseline environmental condition prior to Oyo deposition. Comparison between the Sambipitu and Oyo formations allows evaluation of paleoenvironmental changes associated with the transition from siliciclastic-dominated to carbonate-dominated sedimentation. This study focuses on reconstructing the paleosalinity and paleoproductivity within the Oyo Formation using foraminiferal microfossils. Paleosalinity conditions were estimated based on the relative abundance ratio of the planktonic species *Orbulina universa* and *Globigerinoides sacculifer*, selected due to their sensitivity to water mass changes and long stratigraphic ranges. Concurrently, paleoproductivity was reconstructed using benthic foraminiferal communities via the epifaunal–infaunal (E/I) index to evaluate the equilibrium between organic matter supply and bottom-sediment oxygenation. Based on a detailed measured stratigraphic section and laboratory analysis, this study evaluates how the variations of both parameters change stratigraphically, providing insights into their implications for the hydrocarbon source rock generation potential within the basin. Therefore, this study aims to reconstruct the paleosalinity and paleoproductivity evolution of the Oyo Formation based on foraminiferal assemblages, with the Sambipitu Formation incorporated as a stratigraphic reference to evaluate environmental changes across the Sambipitu–Oyo transition.

2. Methodology

Paleosalinity reconstruction was conducted using the relative abundance of the planktonic foraminifera *Orbulina universa* and *Globigerinoides sacculifer*. These species were selected because their ecological distribution has been reported to be sensitive to variations in seawater salinity and because both possess long stratigraphic ranges encompassing the depositional age of the Oyo Formation. *Orbulina universa* ranges from planktonic foraminiferal Zone N9–N23, whereas *Globigerinoides sacculifer* ranges from Zone N6–N23 [3]. Their wide stratigraphic distribution minimizes the possibility that changes in abundance merely reflect species appearance or extinction, allowing them to be used as paleoenvironmental indicators.

For each sample, 300 planktonic foraminiferal specimens were identified and counted [6], a count considered statistically representative for stable relative abundance analysis. The number of *Orbulina universa* and *Globigerinoides sacculifer* individuals was then converted into relative abundance before paleosalinity calculation.

The relative abundance data of the planktonic foraminifera *Orbulina universa* and *Globigerinoides sacculifer* were used to calculate paleosalinity values using a mathematical equation [10]:

$$\left\{\frac{(X_a - Y_1) - (X_2 - Y_2)}{(X_1 - Y_1)}\right\} + Y_2 = X_b \qquad (1)$$

X_a = Known fossil abundance
X_b = Target salinity (‰)
X_1 = Highest fossil abundance value
X_2 = Highest salinity boundary value (‰)
Y_1 = Lowest fossil abundance value
Y_2 = Lowest salinity boundary value (‰)

Calculations were performed separately for each species to obtain paleosalinity values based on the abundance of *Orbulina universa* and *Globigerinoides sacculifer* at each stratigraphic position. The obtained values were then categorized into the salinity range classification presented in Table 1.

Table 1. Salinity Values (‰) (Saraswati dan Srinivasan, 2015)

Kondisi Salinitas	Nilai Salinitas (‰)
Fresh Water	0-0.5
Brackish Water	0.5-30
Normal seawater	30-40
Hypersaline Water	40-80
Brine	>80

The interpolation assumes a linear relationship between species abundance and salinity within the defined salinity range. Accordingly, the estimated paleosalinity increases proportionally with increasing relative abundance between the lower and upper abundance limits. Calculations were performed separately for *Orbulina universa* and *Globigerinoides sacculifer* for every stratigraphic sample. The resulting values were subsequently classified into salinity categories [11].

The application of this method is based on the assumptions [10]: (1) the ecological response of both species to salinity remained relatively constant throughout the studied geological interval; (2) the selected species are primarily controlled by salinity within the investigated environmental setting; and (3) the observed abundance range represents the environmental variability preserved in the studied succession.

Although salinity is considered the primary controlling factor in this study, the abundance of planktonic foraminifera may also be influenced by other environmental parameters, including seawater temperature, water depth, nutrient availability, carbonate dissolution, and fossil preservation. Therefore, paleosalinity interpretation was integrated with measured section observations, petrographic characteristics, and benthic foraminiferal assemblages to reduce potential bias arising from non-salinity controls.

Epifauna		Infauna	
PLANOCONVEX TROCHOSPIRAL	*Cancris sagrum*	ROUNDED PLANISPIRAL	*Cornuspira involvens*
	Cibicidella variabilis		*Elphidium discoidale*
	Cibicides cf. *bertheloti*		*Elphidium excavatum*
	Cibicides cf. *dispars*		*Elphidium gunteri*
	Cibicidoides floridanus		*Elphidium poeyanum*
	Discorbinella bertheloti		*Haynesina germanica*
	Discorbis williamsoni		*Nonionella opima*
	Discorbis spp.		*Nonionoides grateloupi*
	Hanzawaia boweana		*Pseudononion atlanticum*
	Hanzawaia cf. *concentrica*		
	Heterolepa cf. *pseudoungeriana*		
	Lobatula lobatula	SPHERICAL	*Favulina hexagona*
	Planorbulina mediterranensis		*Hyalinonetrina gracillimum*
	Rosalina floridana		*Lagena* cf. *curvilineata*
			Lagena laevis tenuis
			Lagena striata
BICONVEX TROCHOSPIRAL TROCHOSPIRAL	*Ammonia beccarii*		
	Buccella frigida		
	Eponides repandus	FLATTENED OVOID	*Cassidulina minuta*
	Oridorsalis umbonatus		*Cassidulina* sp.
	Poroeponides lateralis		*Fissurina lucida*
			Fissurina quadricostulata
ROUNDED TROCHOSPIRAL	*Gyroidina soldanii*		
		TAPERED and CYLINDRICAL	*Amphicoryna scalaris*
			Bulimina elongata
MILIOLINE	*Biloculinella subsphaerica*		*Bulimina marginata*
	Cycloforina contorta		*Bulimina pupoides*
	Edentostomina cultrata		*Bulimina* sp.
	Lachlanellana kerimbatica		*Buliminella elegantissima*
	Miliolinella lutea		*Fursenkoina pontoni*
	Miliolinella suborbicularis		*Fursenkoina* sp.
	Miliolinella subrotunda		*Globobulimina pacifica*
	Pseudotriloculina oblonga		*Hopkinsina pacifica*
	Pyrgo elongata		*Siphogenerina raphana*
	Pyrgo nasuta		*Textularia agglutinans*
	Pyrgo ringens		*Textularia earlandi*
	Pyrgo spp.		*Textularia gramen*
	Quinqueloculina angulata		*Uvigerina peregrina*
	Quinqueloculina atlantica		
	Quinqueloculina brodermanni		
	Quinqueloculina candeiana	FLATTENED TAPERED	*Bolivina compacta*
	Quinqueloculina exculptta		*Bolivina doniezi*
	Quinqueloculina gracilis		*Bolivina lingularia*
	Quinqueloculina lamarckiana		*Bolivina pulchella*
	Quinqueloculina patagonica		*Bolivina variabilis*
	Quinqueloculina seminula		*Bolivina* sp.
	Quinqueloculina vulgaris		*Bolivinellina translucens*
	Spiroloculina depressa		*Brizalina striatula*
	Spiroloculina ornata		*Sigmavirgulina tortuosa*
	Triloculina baldai		
	Triloculina funafutiensis		
	Triloculina tricarinota		
	Triloculina trigonula		

Figure 1. Distribution of benthic foraminiferal genera (Duleba et al, 2005) [4].

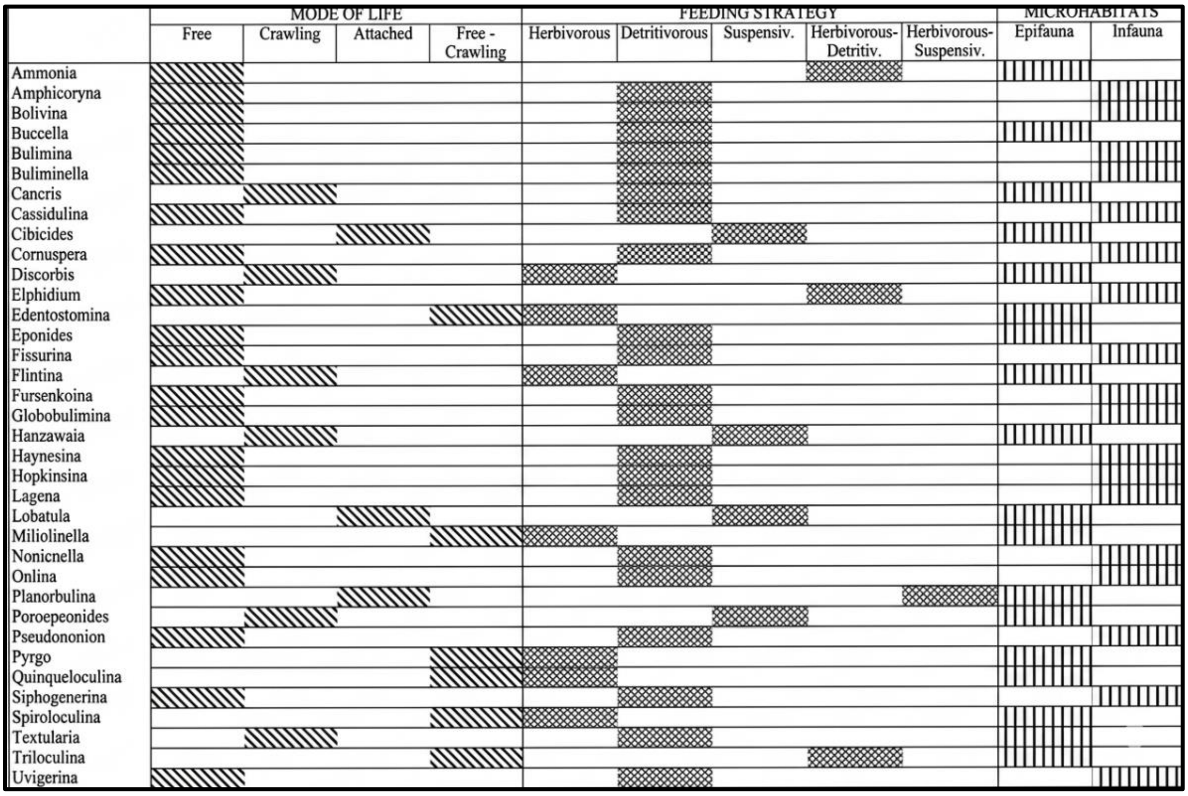

Figure 2. Distribution of benthic foraminiferal genera (Duleba et al, 2005) [4].

Because the interpolation method has not yet been calibrated against modern salinity observations from the study area, the calculated values are interpreted primarily as relative salinity trends rather than absolute salinity estimates. Consequently, the results are discussed mainly in terms of environmental tendencies, such as normal marine, slightly restricted marine, brackish tendency, or hypersaline tendency, instead of emphasizing the numerical salinity values alone.

In addition to paleosalinity, this study reconstructs paleoproductivity using benthic foraminiferal assemblages. Benthic foraminifera are widely recognized as sensitive indicators of organic matter flux to the seafloor because their microhabitat distribution responds to variations in sediment oxygenation and food availability. Epifaunal taxa generally inhabit the sediment–water interface under well-oxygenated conditions with relatively low organic matter flux, whereas infaunal taxa live within the sediment where organic matter availability is higher and oxygen concentrations are lower [2]; [13]; [8]; [14]; [9].

The benthic foraminiferal taxa identified in this study were classified into epifaunal and infaunal groups according to their preferred ecological microhabitats. Epifaunal taxa represent species living on or immediately above the sediment surface, whereas infaunal taxa represent species inhabiting shallow to deeper sediment layers [4]. The complete list of taxa assigned to each ecological group is presented in Figures 1 and 2.

For each sample, 300 benthic foraminiferal specimens were identified and counted prior to ecological classification. A minimum count of approximately 300 individuals provides a statistically representative estimate of benthic foraminiferal community composition and minimizes the effect of counting variability on ecological indices [6]. Samples containing fewer than this minimum count were not included in the E/I calculation.

Table 2. Paleoproductivity Classification Based on E/I Values (modified from Jorissen et al., 1995; Van der Zwaan et al., 1999; Murray, 2006)

E/I Value	Community Dominance	Environmental Interpretation	Trophic Level
> 0.45	Epifaunal dominant	Good oxygenation, low organic flux	Oligotrophic
0.15–0.45	Balanced community	Moderate organic flux	Mesotrophic
< 0.15	Infaunal dominant	High organic flux, low oxygen	Eutrophic

Only identifiable benthic foraminiferal specimens were included in the analysis. Fragmented specimens retaining sufficient diagnostic morphological characters were identified and counted, whereas heavily damaged or indeterminate specimens that could not be confidently assigned to an ecological group were excluded from the calculation. Likewise, specimens interpreted as reworked, based on poor preservation, abrasion, discoloration, recrystallization, or preservation inconsistent with the surrounding assemblage, were excluded from the analysis whenever recognized.

Paleoproductivity was reconstructed using the Epifaunal–Infaunal (E/I) Index, which expresses the relative dominance of epifaunal and infaunal benthic foraminifera:

$$E/I = \frac{(E - I)}{(E + I)} \quad (2)$$

E = Number of individual epifaunal benthic foraminifera
I = Number of individual infaunal benthic foraminifera

The E/I index value reflects the dominance ratio between epifaunal and infaunal benthic foraminifera. High values indicate epifaunal dominance, which is associated with good sediment oxygenation and low organic matter flux, whereas low values indicate infaunal dominance, associated with increased organic matter supply and decreased sediment oxygenation [8]; [14]; [9]. The E/I index values were then qualitatively interpreted into marine trophic levels. The paleoproductivity classification based on E/I values is shown in Table 2.

The index values of each sample were plotted against the stratigraphic position to construct the paleoproductivity curve of the Oyo Formation.

3. Results and discussions

The study area is located in Gunungkidul Regency, Special Region of Yogyakarta, which physiographically belongs to the Southern Mountains Zone of Java. The study area and the positions of the observation points are displayed on the index map presented in Figure 3. Data collection was carried out at three observation localities representing the Sambipitu Formation, the lower part of the Oyo Formation, and the upper part of the Oyo Formation using the measured section method. These three localities are designated as MS-1, MS-2, and MS-3, each representing different stratigraphic positions within the studied rock units. The geographic coordinates and administrative descriptions for each locality are as follows:
MS-1: 7°52'54.60"S, 110°30'36.20"E (Beji Village, Patuk District)
MS-2: 7°54'5.55"S, 110°34'23.08"E (Gading Village, Playen District)
MS-3: 7°54'47.65"S, 110°36'41.63"E (Kedungkeris Village, Nglipar District)

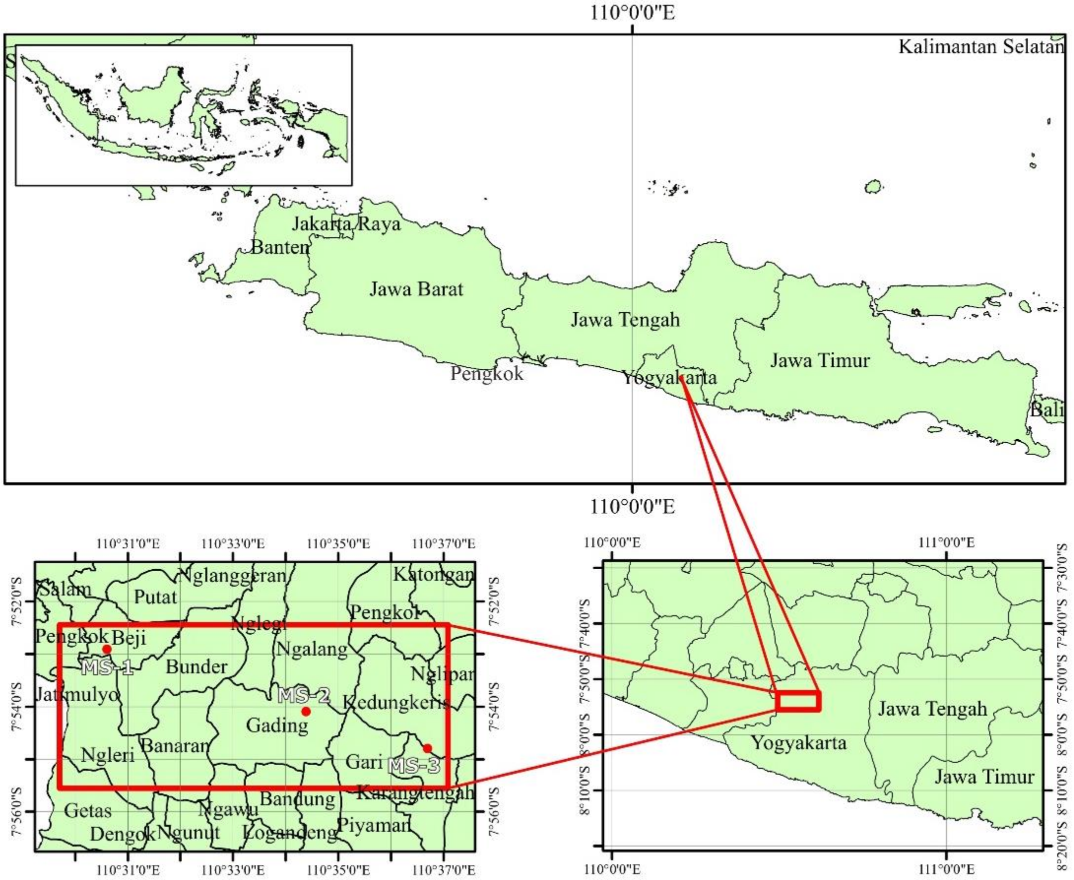

Figure 3. Index map of the study area and the distribution of observation points (MS-1, MS-2, and MS-3)

3.1. Measured Section

Stratigraphic observations were conducted along three discontinuous measured sections (MS-1, MS-2, and MS-3) to document lithological succession and establish the stratigraphic framework of the study area. Among these sections, MS-1 was included as an underlying stratigraphic reference, whereas MS-2 and MS-3 represent the main study intervals within the Oyo Formation. Correlation among the measured sections was based on the integration of (1) dominant lithological characteristics, (2) relative ages derived from planktonic foraminiferal biozones, (3) depositional environments interpreted from benthic foraminifera, and (4) field structural measurements, including bedding attitude and dip direction.

MS-1 is assigned to the Sambipitu Formation and is used as the underlying stratigraphic reference because it exhibits lithological characteristics distinct from the overlying carbonate succession and yields an older planktonic foraminiferal assemblage. In contrast, MS-2 and MS-3 represent the lower and upper intervals of the Oyo Formation, respectively, based on their comparable carbonate lithologies, depositional environments, and biostratigraphic ages.

The stratigraphic correlation is constrained using the boundary between the Sambipitu and Oyo Formations together with planktonic foraminiferal biozones as the primary correlation datums. Bedding attitudes show similar strike orientations with gentle dips toward the south, supporting a consistent stratigraphic younging direction from MS-1 through MS-2 to MS-3. Structural measurements are N073°E/12° (azimuth N162°E) for MS-1, N083°E/3° (azimuth N183°E) for MS-2, and N078°E/3° (azimuth N166°E) for MS-3.

Table 3. Summary of measured sections and analyzed samples

MS	Measured Thickness (m)	Rock Unit / Lithology	Number of Beds	Analysis Sample Code	
				Petrography	Paleontology
MS-3	90.1	Limestone	30	3(13)	3(5), 3(9), 3(13), 3(18), 3(21), 3(30).
MS-2	64.6	Limestone	16	2(2)	2(2), 2(5), 2(8), 2(12), 2(16).
MS-1	165.8	Carbonate claystone, carbonate sandstone	18	1(16)	1(3), 1(5), 1(7), 1(12) 1(16)

Because the measured sections are spatially discontinuous, the proposed succession is interpreted as a lithostratigraphic and biostratigraphic correlation rather than a physically continuous vertical section. The consistency of lithology, depositional environment, biostratigraphic ages, and bedding orientation indicates that the observed succession primarily reflects vertical stratigraphic changes rather than lateral facies variations. A summary of the measured sections, including thickness, lithology, and sample allocation, is presented in Table 3, while field outcrops are displayed in Figure 4.

Figure 4. Field photographs of the studied outcrops: (A) MS-3, (B) MS-2, and (C) MS-1

Table 4. Petrographic characteristics of the studied rock samples

Sample Number	Formation	Lithology	Petrographic Description
3(13)	Upper Oyo Formation	*Packstone*	Clastic carbonate texture; grain-supported with abraded grains and point-to-floating grain contacts. Grains range from 0.4–0.001 mm, dominated by foraminifera, skeletal fragments, and opaque minerals embedded in lime mud.
2(2)	Lower Oyo Formation	*Packstone*	Clastic carbonate texture; grain-supported with abraded grains and point-to-floating grain contacts. Grain size: 0.35–0.001 mm. Components include foraminifera, corals, skeletal fragments, quartz, plagioclase, iron oxides, and opaque minerals in a lime mud and calcite matrix.
1(16)	Sambipitu Formation	*Micritic sandstone*	Siliciclastic texture; matrix-supported with subangular-rounded grains and floating-to-point grain contacts. Grain size: 0.5–0.001 mm (very fine sand). Composed of plagioclase, quartz, K-feldspar, hornblende, iron oxides, opaque minerals, lithic fragments, clinopyroxene, calcite, skeletal fragments, and lime mud.

3.2. Petrographic Data

Petrographic analysis was conducted on representative thin sections to characterize carbonate textures, skeletal and non-skeletal components, and textural relationships that support depositional environment interpretations. Observations were made under plane-polarized light (PPL) and cross-polarized light (XPL), and representative photomicrographs are presented in Figures 5–7. Because this study primarily focuses on micropaleontological proxies, petrographic observations are intended to provide supporting sedimentological evidence rather than a detailed diagenetic assessment.

Petrographic observations are consistent with the micropaleontological results. The dominance of grain-supported packstone in the Lower and Upper Oyo Formation, together with abundant foraminiferal tests and other skeletal grains, indicates deposition in a shallow marine carbonate platform with active biological production. The occurrence of micrite suggests relatively low-energy conditions between depositional events, whereas abraded skeletal grains indicate intermittent reworking by wave or current activity. These characteristics agree with the benthic and planktonic foraminiferal assemblages, which indicate normal marine conditions and an open-marine depositional setting.

In contrast, the underlying Sambipitu Formation is characterized by a mixed siliciclastic-carbonate composition with abundant terrigenous grains, reflecting a stronger siliciclastic input than the overlying carbonate succession. This lithological transition corresponds with the micropaleontological evidence, which records the progressive establishment of carbonate-platform conditions during deposition of the Oyo Formation.

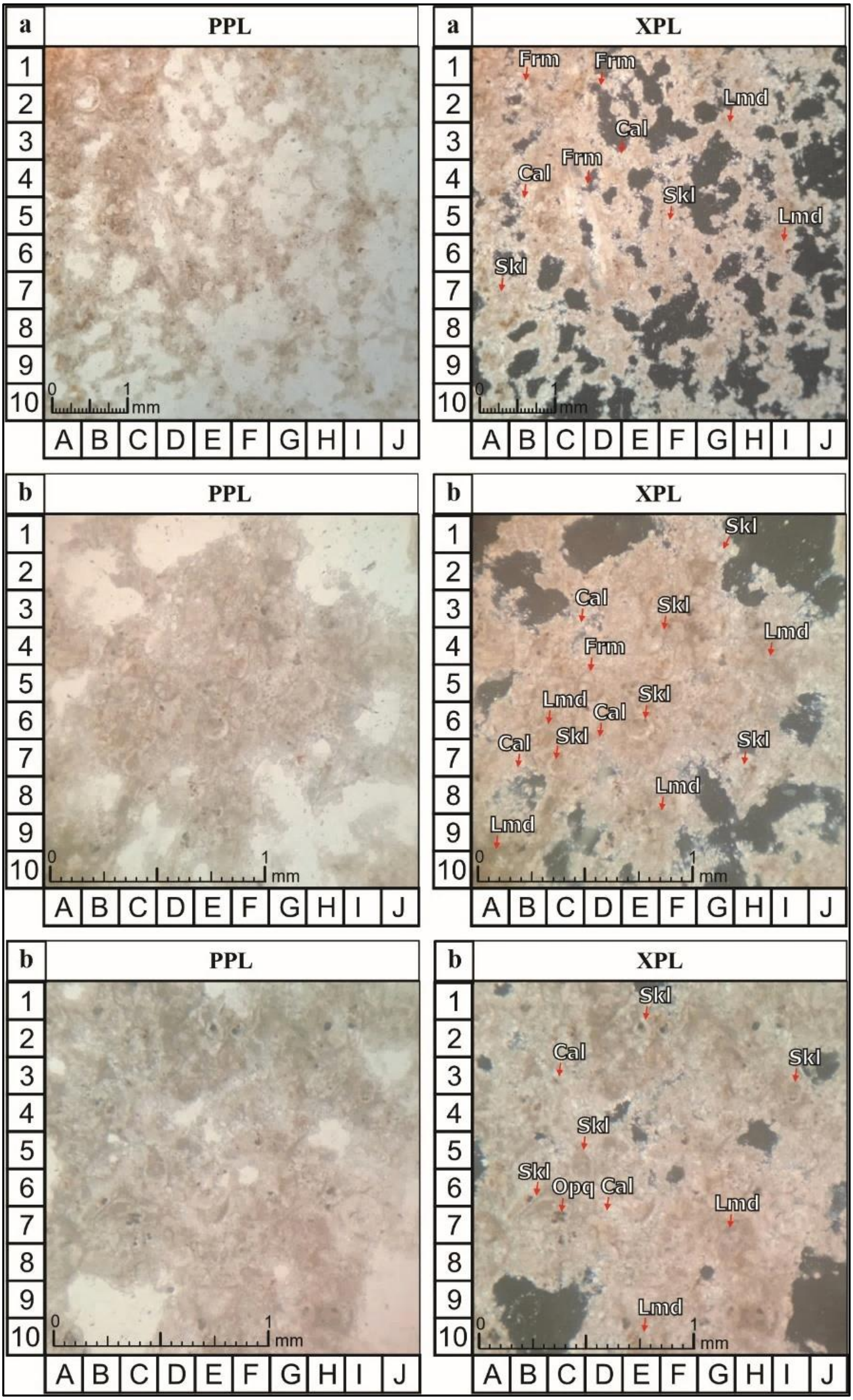

Figure 5. Photomicrograph of the upper Oyo Formation packstone thin section

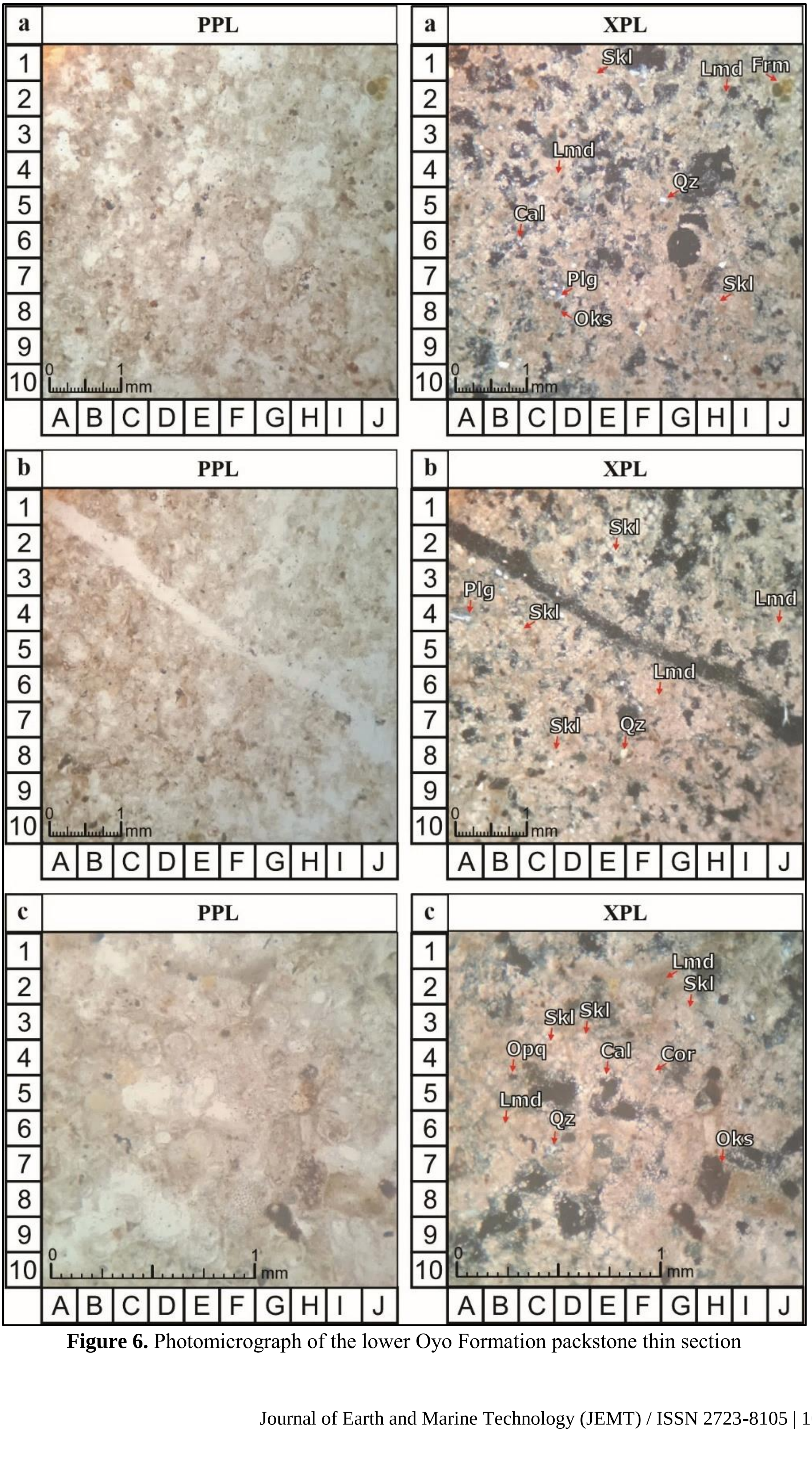

Figure 6. Photomicrograph of the lower Oyo Formation packstone thin section

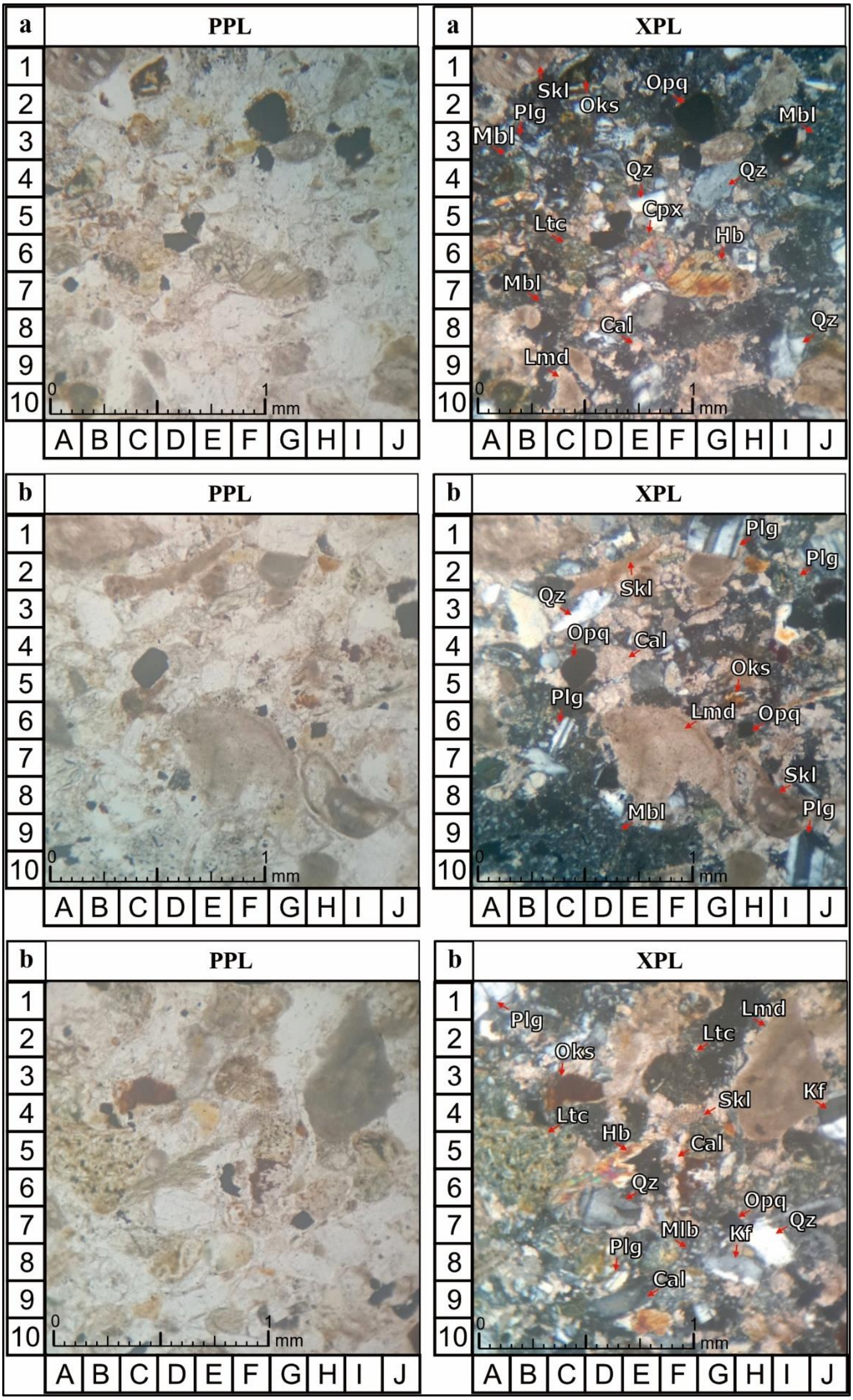

Figure 7. Photomicrograph of the Sambipitu Formation micritic sandstone thin section

3.3. Paleontologycal Data and Analysis Result

Paleontological analysis was conducted using planktonic and benthic foraminiferal assemblages from the Sambipitu Formation and the lower and upper intervals of the Oyo Formation to establish a biostratigraphic age framework and depositional depth interpretation. The obtained relative age framework provides the basis for stratigraphic correlation and interpretation of paleoenvironmental changes throughout the studied succession.

Relative age determination was performed based on the planktonic foraminiferal biozonation of Blow (1969), utilizing the first occurrence (FO) and last occurrence (LO) of diagnostic index species. The identification of age-diagnostic taxa and their stratigraphic ranges were used to constrain the relative age of each studied interval. Based on the observed planktonic foraminiferal assemblages, the Sambipitu Formation was assigned to Zone N8–N9, the lower part of the Oyo Formation to Zone N10, and the upper part of the Oyo Formation to Zone N11–N12. These biozones indicate that the studied succession was deposited from the Early to Middle Miocene.

The assigned biozones represent the most probable relative age intervals based on the available index taxa. Minor age uncertainties may remain due to the discrete occurrence of fossil specimens and the limitation of sampling resolution. However, the preservation quality and diagnostic morphological characteristics of the identified planktonic foraminifera allow reliable taxonomic determination. No significant evidence of reworked specimens, such as mixed-age assemblages, strongly abraded tests, or the occurrence of taxa inconsistent with the stratigraphic position, was observed during analysis. Therefore, the identified index species are interpreted to represent their original stratigraphic distribution.

Depositional environments were interpreted based on benthic foraminiferal assemblages [1], supported by planktonic-to-benthic (P/B) ratios according [5]. The calculated P/B ratios were subsequently converted into paleobathymetric zones [12]. The results indicate that the Sambipitu Formation was deposited in a middle to outer neritic environment, whereas the lower and upper parts of the Oyo Formation represent inner to middle neritic depositional settings. Variations in paleobathymetry reflect changes in relative depositional depth throughout the studied succession.

The combination of planktonic foraminiferal biozonation and benthic foraminiferal-based paleobathymetry provides an integrated framework for evaluating vertical environmental changes within the studied formations. These results were subsequently used as a temporal and environmental basis for interpreting variations in paleosalinity and paleoproductivity within the Oyo Formation. A summary of the relative age and paleobathymetric interpretations is presented in Table 5.

Table 5. Age and paleobathymetry summary of the Oyo and Sambipitu Formations

Sample Number	Formation	Blow (1969)	Barker (1960)	P/B Ratio	Grimsdale dan Van MarkHoven (1955)	Tipsword, Setzer dan Smith (1966)
3(13)	Upper Oyo Formation	N11- N12 (*Middle Miocene*)	Inner–Middle Neritic (0 - 100 m)	14.33 %	0 - 70 m	Inner–Middle Neritic
2(2)	Lower Oyo Formation	N10 (*Middle Miocene*)	Middle Neritic (20 – 100 m)	18.33 %	0 - 70 m	Inner–Middle Neritic
1(16)	Sambipitu Formation	N8-N9 (*Early Miocene-Middle Miocene*)	Middle–Outer Neritic (20 - 200 m)	22%	60 - 120 m	Middle–Outer Neritic

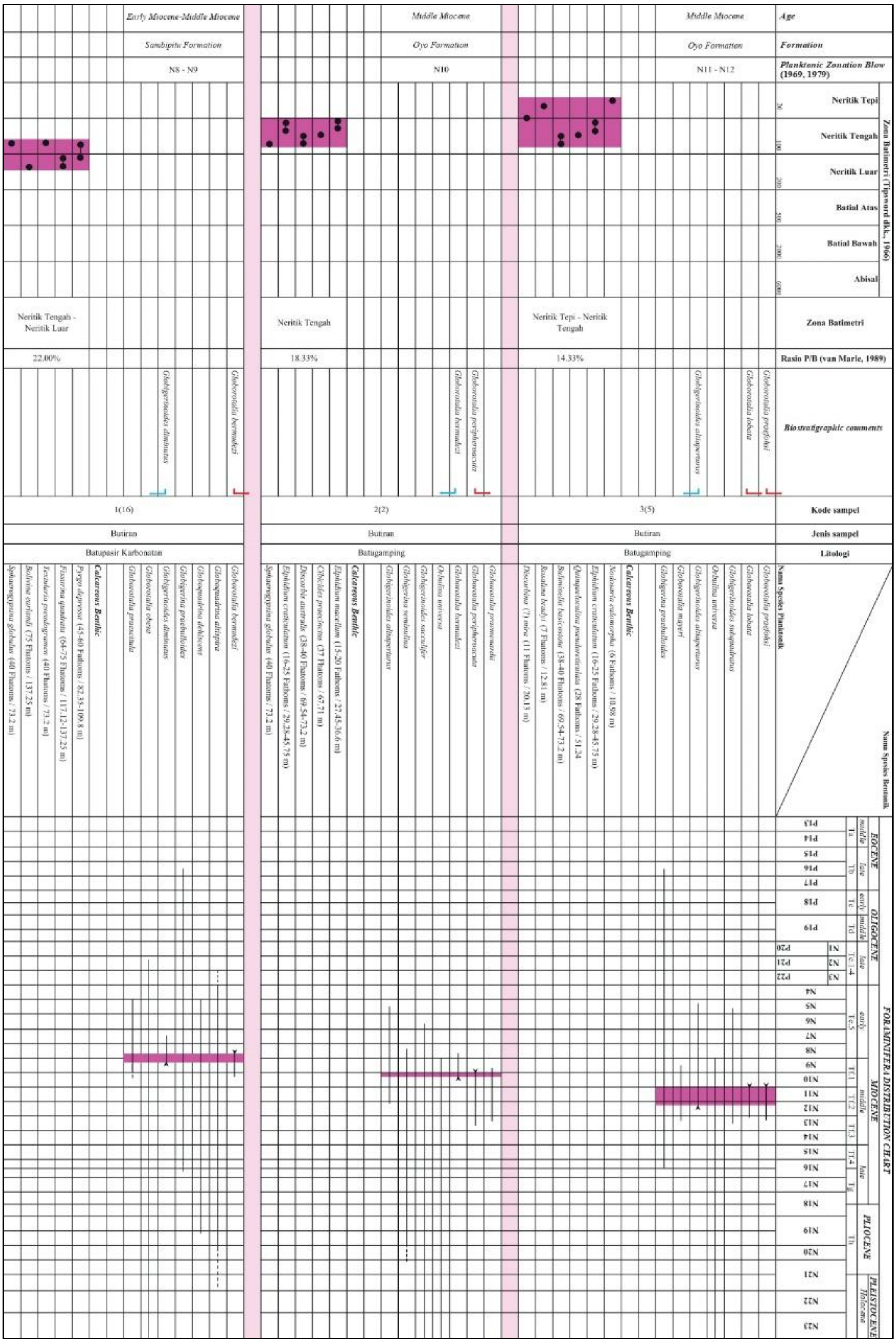

Figure 8. Relative Age and Paleobathymetric Analyses

Paleosalinity variations across the studied intervals were reconstructed qualitatively based on the relative abundances of the open-marine planktonic indicators *Orbulina universa* and *Globigerinoides sacculifer* (Figure 9), coupled with taphonomic expressions (Figure 10) and comparison with the global eustatic sea-level curve of Haq et al. (1987). The Haq et al. (1987) curve documents global eustatic sea-level fluctuations throughout the Neogene and provides a temporal framework for evaluating the potential influence of transgressive and regressive phases on paleoenvironmental evolution. Correlation with this curve was established using the biostratigraphic age constraints of the studied intervals (Middle–Late Miocene), allowing the reconstructed paleosalinity and paleoproductivity trends to be tentatively compared with contemporaneous global sea-level changes. These microecological proxies do not represent absolute chemical values but instead indicate relative changes in water-column connectivity, stratification, and evaporation–freshwater balance.

It should be noted that the reconstructed environmental changes cannot be attributed solely to global eustatic fluctuations. Variations in paleosalinity and paleoproductivity may also have been influenced by local to regional factors, including tectonic subsidence or uplift, carbonate production, sediment supply, platform morphology, and the degree of marine circulation restriction. Therefore, correlations with the global eustatic curve are regarded as tentative and are intended to provide a regional paleoenvironmental context rather than imply a direct causal relationship.

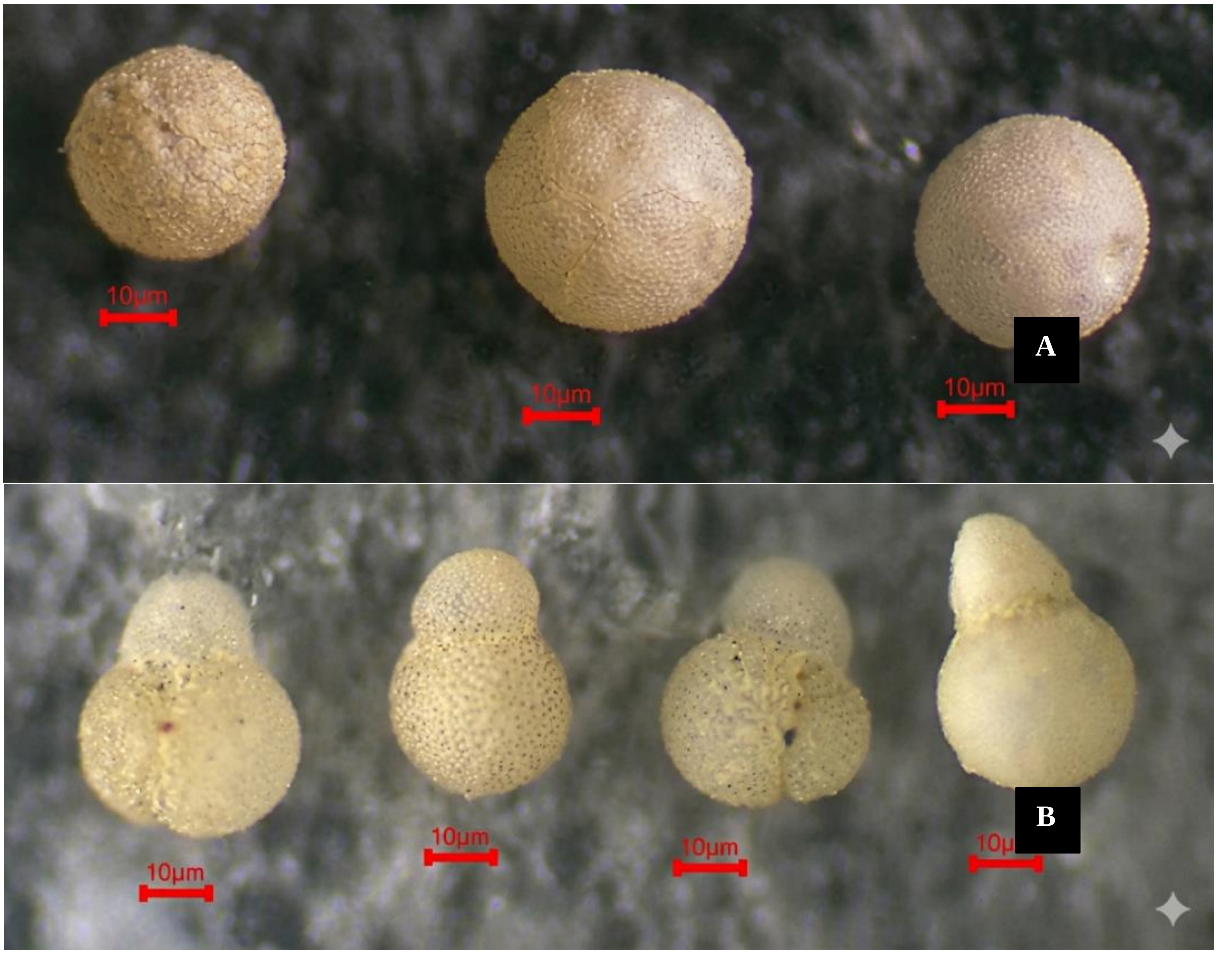

Figure 9. (A) *Orbulina universa,* (B) *Globigerinoides sacculifer* (10 µm scale bar)

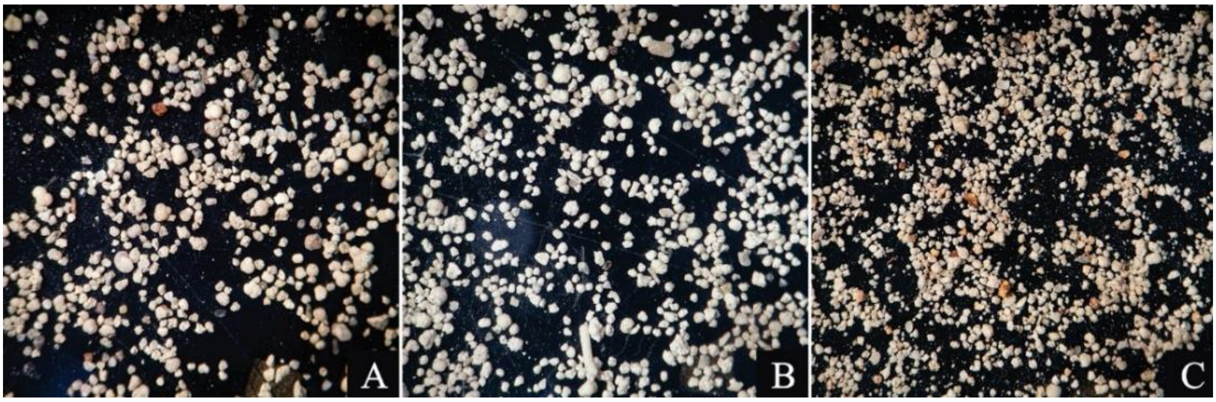

Figure 10. Photomicrograph of foraminiferal assemblages displaying variations in test taphonomy: (A) well-preserved cream-to-brown tests indicating minor oxidation; (B) well-preserved pristine white tests; and (C) tests exhibiting wall corrosion and partial dissolution due to carbonate dissolution

The results of the paleosalinity analysis based on the abundance of *Orbulina universa* for each sample are presented in Table 6 and 7. The integrated paleosalinity reconstruction from *Orbulina universa* and *Globigerinoides sacculifer*, supported by fossil appearances and lithological variations, indicates that the Oyo Formation underwent salinity variations that evolved alongside vertical stratigraphic changes and relative sea-level dynamics.

In the Sambipitu Formation (MS-1), paleosalinity remained relatively stable within the normal seawater range, associated with light-colored foraminiferal tests and good preservation. This condition reflects an open-marine environment with a relatively thick water column and effective water circulation. Robust sirculation optimized the oxygen supply to the seafloor, causing organic matter reaching the sediment to undergo decomposition and resulting in limited preservation.

Table 6. Results of paleosalinity analysis based on *Orbulina universa*

Formation	Lithology Symbol	Sample Number	Abundance of *Orbulina universa*	Salinity (‰) *Orbulina universa*	Salinity Type
Upper Oyo Formation		3(5)	4	23.00	*Brackish Water*
		3(9)	8	29.57	*Brackish Water*
		3(13)	10	32.86	*Normal Seawater*
		3(18)	9	31.21	*Normal Seawater*
		3(21)	11	34.5	*Normal Seawater*
		3(30)	10	32.86	*Normal Seawater*
Lower Oyo Formation		2(2)	18	46.00	*Hypersaline Water*
		2(5)	14	39.43	*Normal Seawater*
		2(8)	14	39.43	*Normal Seawater*
		2(12)	13	37.79	*Normal Seawater*
		2(16)	12	36.14	*Normal Seawater*
Sambipitu Formation		1(3)	9	31.21	*Normal Seawater*
		1(5)	11	34.50	*Normal Seawater*
		1(7)	10	32.86	*Normal Seawater*
		1(12)	12	36.14	*Normal Seawater*
		1(16)	11	34.50	*Normal Seawater*

Table 7. Results of paleosalinity analysis based on *Globigerinoides sacculifer*

Formation	Lithology Symbol	Sample Number	Abundance of *Globigerinoides sacculifer*	Salinity (‰) *Globigerinoides sacculifer*	Salinity Type
Upper Oyo Formation		3(5)	4	28.18	*Brackish Water*
		3(9)	2	24.00	*Brackish Water*
		3(13)	5	30.27	*Normal Seawater*
		3(18)	7	34.45	*Normal Seawater*
		3(21)	6	32.36	*Normal Seawater*
		3(30)	6	32.36	*Normal Seawater*
Lower Oyo Formation		2(2)	13	47.00	*Hypersaline Water*
		2(5)	9	38.64	*Normal Seawater*
		2(8)	8	36.55	*Normal Seawater*
		2(12)	9	38.64	*Normal Seawater*
		2(16)	7	34.45	*Normal Seawater*
Sambipitu Formation		1(3)	5	30.27	*Normal Seawater*
		1(5)	6	32.36	*Normal Seawater*
		1(7)	8	36.55	*Normal Seawater*
		1(12)	7	34.45	*Normal Seawater*
		1(16)	7	34.45	*Normal Seawater*

Moving into the lower interval of the Oyo Formation (MS-2), paleosalinity generally remained within the normal seawater range, though a temporary, localized increase in salinity developed alongside relative shallowing. The thinning of the water column increased its sensitivity to evaporation, while connectivity to the open sea was maintained. These conditions indicate that water circulation persisted and bottom-water oxygenation remained relatively good, suggesting that organic matter accumulation had not yet developed significantly.

In the upper interval (MS-3), paleosalinity shows a downward trend toward brackish conditions, accompanied by a shift toward darker fossil test colors and increased variations in preservation. This pattern reflects a shallow neritic environment increasingly influenced by terrestrial input and reduced marine connectivity. The restricted circulation allowed water-column stratification to develop, which, when coupled with an increased supply of organic matter, potentially lowered bottom-water oxygenation and relatively enhanced the preservation potential of organic matter compared to the lower interval of the unit.

Both *Orbulina universa* and *Globigerinoides sacculifer* consistently recorded paleosalinity variations with matching trends. Because both taxa represent open-marine conditions, their analytical results mutually reinforce the interpretation that paleosalinity fluctuations were primarily controlled by relative sea-level changes during deposition. Vertically, paleosalinity records an environmental transition from an open-marine setting at the bottom to a more restricted, shallow neritic environment at the top. This shift reflects a decline in open water circulation that influenced sediment oxygenation, acting as an initial controlling factor for organic matter preservation trends within the Oyo Formation. The correlation of the Oyo Formation measured sections with the paleosalinity curves and the global eustatic curve is illustrated in Figure 11.

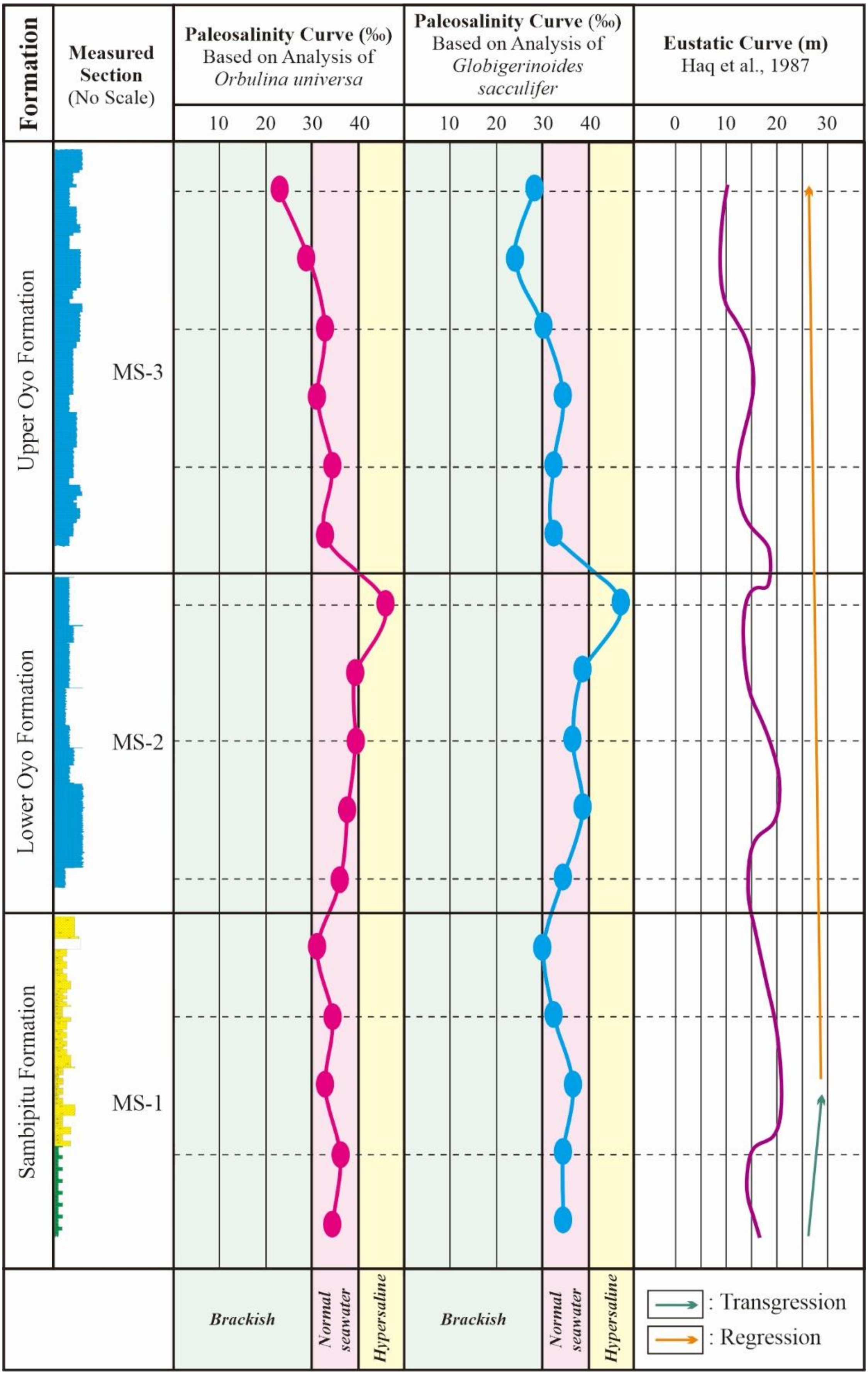

Figure 11. Pairing measured sections of the Oyo Formation (without scale) with paleosalinity and global eustacy curves Haq et al. (1987) [7].

Indicators of paleoproductivity are obtained from the analysis of benthic foraminiferal communities through the comparison of the relative abundance of epifaunal and infaunal taxa. Epifaunal foraminifera generally thrive on the seafloor with low to moderate organic matter flux (oligotrophic–mesotrophic conditions), which is characterized by a limited nutrient supply and relatively well-oxygenated bottom water. Conversely, infaunal foraminifera are associated with an increased flux of organic matter into the sediment (mesotrophic–eutrophic) because this group adapts to environments with higher food availability and lower sediment oxygenation.

Table 8 presents the grouping of dominant benthic foraminiferal genera based on epifaunal and infaunal microhabitat types used to support the interpretation of bottom-water conditions and nutrient availability during deposition, whereas Figure 12 and Figure 13 present photographs of these genera with a 10 µm scale bar.

Table 8. The dominant benthic foraminifera genus in the samples based on microhabitat type

Epifaunal	Infaunal
Cibicides	*Bolivina*
Discorbis	*Bulimina*
Lenticulina	*Buliminella*
Operculina	*Elphidium*
Planulina	*Fissurina*
Quinqueloculina	*Nodosaria*
Robulus	*Oolina*
Rosalina	*Textularia*
Sphaerogypsina	*Uvigerina*

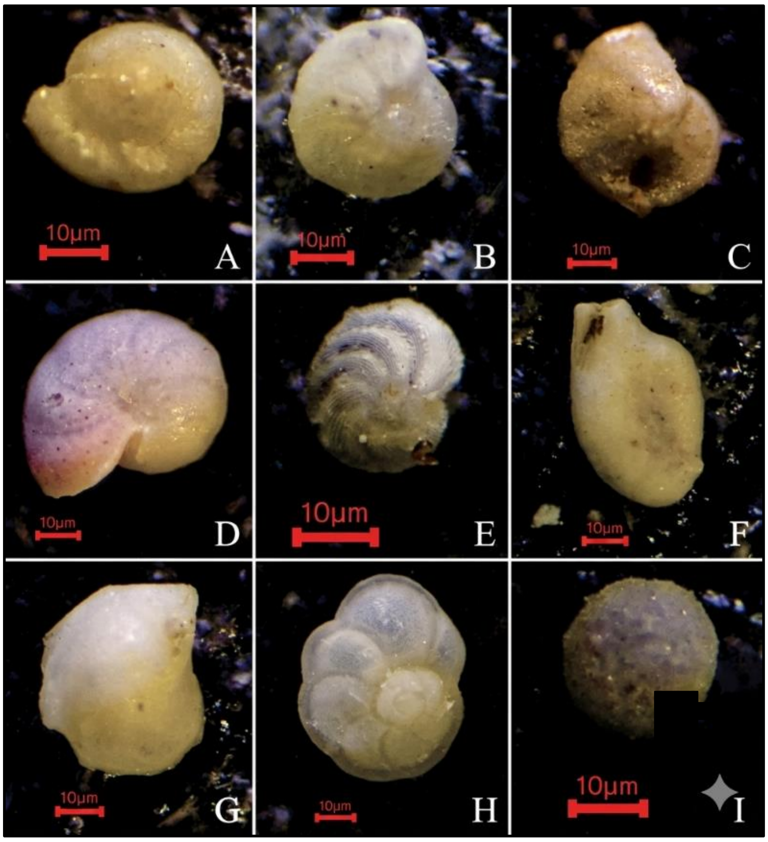

Figure 12. Epifaunal: (A) *Cibicides*, (B) *Discorbis*, (C) *Lenticulina*, (D) *Operculina*, (E) *Planulina*, (F) *Quinqueloculina*, (G) *Robulus*, (H) *Rosalina*, dan (I) *Sphaerogypsina*. 10 µm scale bar

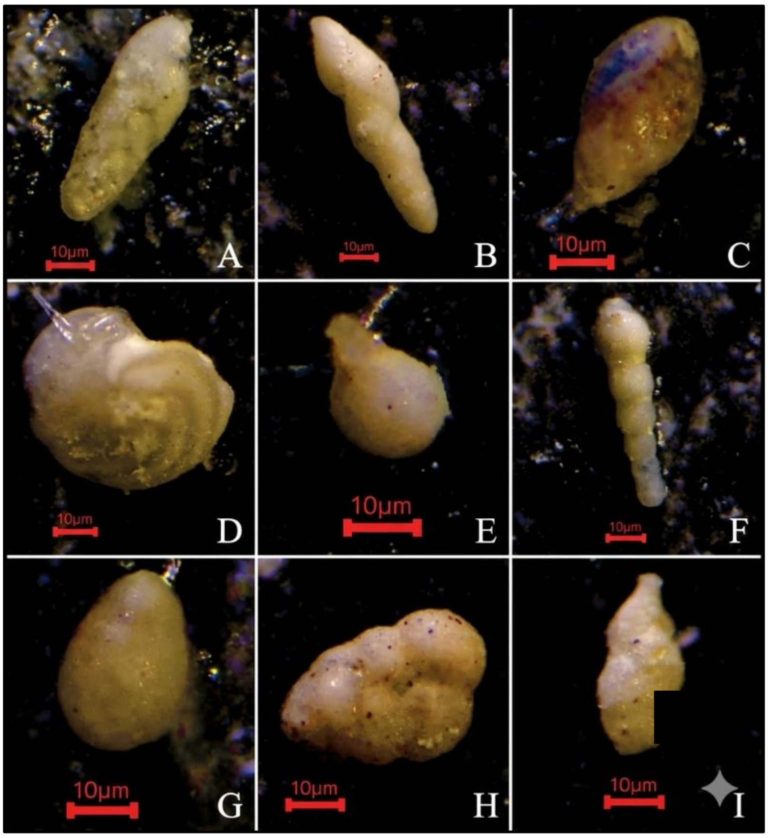

Figure 13. Infaunal: (A) *Bolivina*, (B) *Bulimina*, (C) *Buliminella*, (D) *Elphidium*, (E) *Fissurina*, (F) *Nodosaria*, (G) *Oolina*, (H) *Textularia*, dan (I) *Uvigerina*. 10 µm scale bar

The results of the paleoproductivity analysis based on the E/I index value for each sample are shown in Table 9. The paleoproductivity reconstruction of the Oyo Formation indicates a gradual upward increasing trend in the stratigraphy. This change is recorded by variations in the epifaunal–infaunal (E/I) index values, reflecting a transition in the depositional environment from an open ocean toward an increasingly restricted neritic environment.

Based on the trophic level classification, the Sambipitu Formation is characterized by oligotrophic–mesotrophic conditions, the lower Oyo Formation exhibits mesotrophic conditions, whereas the upper part develops into a mesotrophic–eutrophic state. This pattern demonstrates a gradual increase in organic matter supply throughout the stratigraphic succession.

The lower interval is characterized by an open ocean environment with oxic bottom-water conditions, resulting in a relatively limited organic matter flux and effective degradation. Entering the middle interval, the supply of organic matter begins to increase, but bottom-water oxygenation remains sufficient, so organic material preservation has not significantly developed. In the upper interval, the increased supply of organic matter, accompanied by restricted circulation, causes a decrease in bottom-water oxygenation toward suboxic conditions, thereby creating a relatively higher potential for organic material preservation compared to the underlying intervals.

Changes in the E/I index values not only record an increase in paleoproductivity but also changes in sediment oxygenation conditions. The combination of both factors controls the accumulation and preservation of organic matter within the sediment, thereby indicating a tendency toward improved organic material quality toward the upper stratigraphy of the Oyo Formation.

Table 8. Results of paleoproductivity analysis based on the E/I index

Formation	Lithology Symbol	Sample Number	Abundance of Epifaunal	Abundance of Infaunal	E/I Index	E/I Index Curve (0 – 0.5 – 1)	Paleoproductivity Class
Upper Oyo Formation		3(5)	158	142	0.053		Mesotrophic-Eutrophic
		3(9)	155	145	0.033		Mesotrophic-Eutrophic
		3(13)	170	130	0.133		Mesotrophic-Eutrophic
		3(18)	166	134	0.106		Mesotrophic-Eutrophic
		3(21)	169	131	0.126		Mesotrophic-Eutrophic
		3(30)	167	133	0.113		Mesotrophic-Eutrophic
Lower Oyo Formation		2(2)	164	136	0.093		Mesotrophic
		2(5)	178	122	0.186		Mesotrophic
		2(8)	186	114	0.24		Mesotrophic
		2(12)	191	109	0.273		Mesotrophic
		2(16)	198	102	0.32		Mesotrophic
Sambipitu Formation		1(3)	217	83	0.446		Oligotrophic-Mesotrophic
		1(5)	232	68	0.546		Oligotrophic-Mesotrophic
		1(7)	241	59	0.606		Oligotrophic-Mesotrophic
		1(12)	236	64	0.573		Oligotrophic-Mesotrophic
		1(16)	224	76	0.493		Oligotrophic-Mesotrophic

The discussion of paleosalinity and paleoproduktivity in the Oyo Formation demonstrates the correlation between relative sea-level changes, the degree of water circulation restriction, and sediment oxygenation conditions that control the accumulation of organic matter. Paleosalinity reflects the degree of openness of the aquatic system, whereas paleoproduktivity, expressed through the Epifaunal–Infaunal (E/I) Index value, reflects the magnitude of organic matter supply reaching the seafloor.

The delineation of the depositional depth environment indicates that the entire study interval remains within a neritic environment, ranging from outer neritic to inner/marginal neritic. This demonstrates that changes in the depositional environment were not controlled by a deep sea–shallow sea transition, but rather by variations in water connectivity and circulation dynamics on a shallow carbonate platform.

In the Sambipitu Formation (MS-1), the depositional environment was situated in the middle neritic to outer neritic zone. This condition indicates that connectivity with the open ocean was still well-maintained, allowing effective water circulation. Paleosalinity was relatively stable within the normal seawater range, and the E/I index value was high, dominated by epifaunal foraminifera. The oxygen supply to the seafloor was optimal, causing most of the organic matter to undergo aerobic degradation. This environment represents an open ocean with low to moderate productivity and limited organic matter preservation.

Entering the lower Oyo Formation (MS-2), the relative depth decreased toward the middle neritic zone. The relative sea-level fall caused the waters to become more restricted and weakened water mass exchange. Under these conditions, a more enclosed aquatic environment developed, which increased evaporation and led to the development of hypersaline conditions in several intervals. The E/I index value decreased, indicating an increased proportion of infaunal foraminifera. The increased flux of organic matter to the seafloor raised oxygen consumption within the sediment, causing the environment to develop toward mild suboxic conditions. Some organic matter began to be preserved, although degradation was still ongoing, so its accumulation was not yet significant.

In the upper Oyo Formation (MS-3), the environment developed toward a shallower inner/marginal neritic zone. Despite the continued relative regression, paleosalinity varied again from normal seawater to brackish. This condition indicates that the aquatic system did not become increasingly isolated, but rather experienced a reopening of water exchange pathways. The shallowness allowed for increased tidal influence and terrestrial freshwater input, causing the seawater to mix once again. The lowest E/I index value indicates the highest supply of organic matter during deposition. The increase in organic matter driven by microbial activity stimulated oxygen consumption, thereby decreasing bottom-water oxygenation toward suboxic conditions. The duller to brownish appearance of the foraminiferal tests supports the interpretation of increased organic matter content within the sediment, resulting in a greater opportunity for organic matter preservation compared to the underlying intervals.

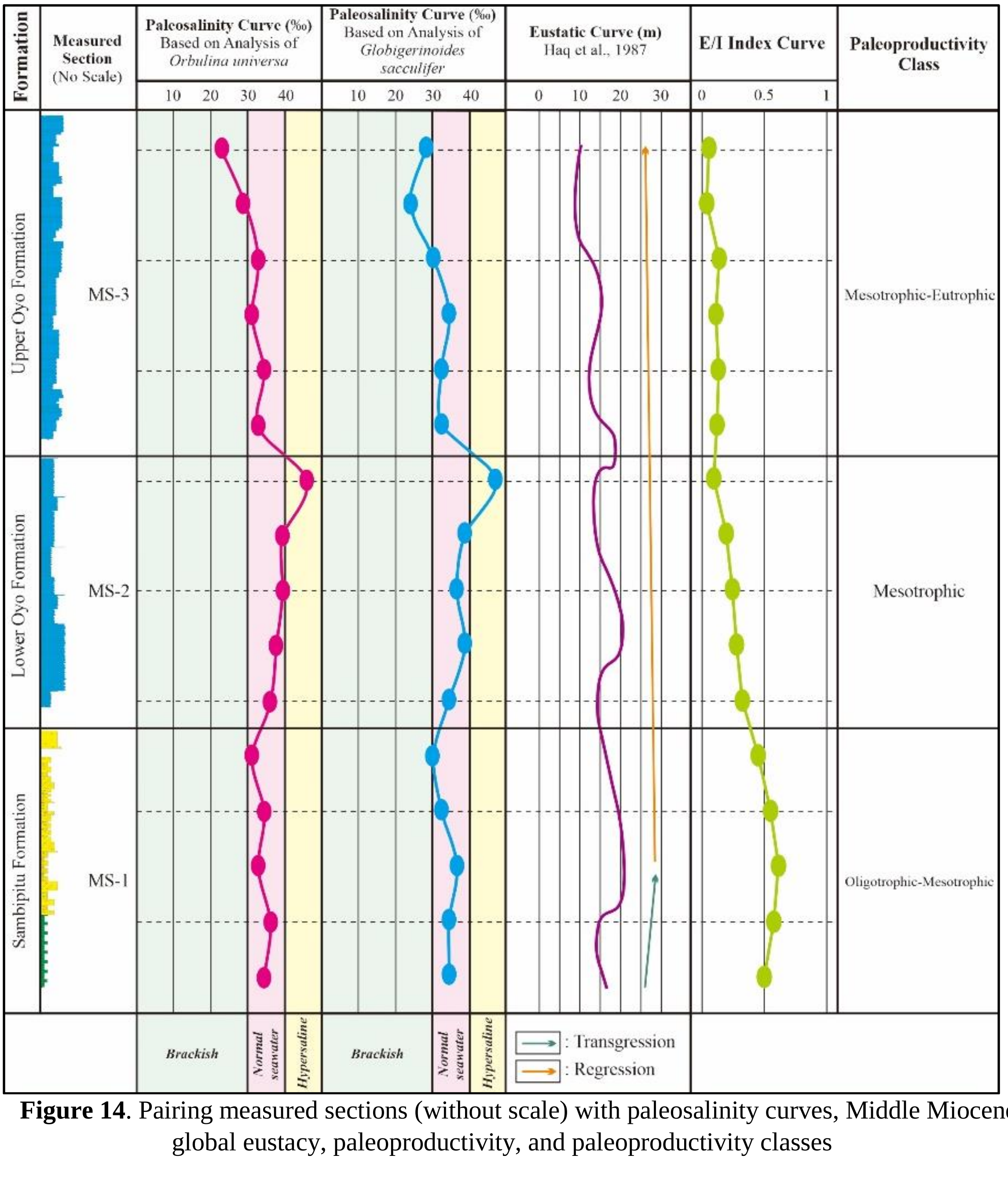

Figure 14. Pairing measured sections (without scale) with paleosalinity curves, Middle Miocene global eustacy, paleoproductivity, and paleoproductivity classes

Paleoproductivity reconstructed through the E/I index values reflects the amount of organic material reaching the seafloor. This organic matter primarily originated from the biomass of microscopic planktonic organisms that subsequently sank along with fine sediment particles. During early deposition, easily decomposable components such as proteins and carbohydrates underwent decomposition, whereas the more resistant organic fractions, particularly lipid-rich compounds, were more resilient and accumulated under low oxygenation conditions.

The accumulation of organic residue subsequently changed to early burial and mixed with the sediment matrix to form solid organic matter (kerogen). The foraminifera in this study function as indicators of the amount of organic matter reaching the seafloor, not as the source of hydrocarbon formation. Their carbonate tests only serve as constituent parts of the carbonate rocks, whereas hydrocarbons originate from the preserved soft tissues of microscopic organisms.

The lithological character of the shallow carbonate and the absence of high thermal maturity indications show that the organic matter of the Oyo Formation is still within the early diagenesis stage, specifically the stage of kerogen formation, and has not yet entered the hydrocarbon generation stage. Thus, the Oyo Formation reflects a source rock potential trend rather than a source rock that has generated hydrocarbons.

Overall, the evolution of the Oyo Formation depositional environment was controlled by relative sea-level fluctuations on a shallow carbonate platform. Variations in water openness influenced salinity, organic matter supply, and sediment oxygenation, which ultimately controlled the degree of organic matter preservation stratigraphically. Consequently, paleosalinity primarily reflects the openness of the aquatic system, whereas the capacity for organic matter preservation is more heavily controlled by paleoproductivity and sediment oxygenation conditions. The juxtaposition of the measured section with the paleosalinity curve, the Middle Miocene global eustatic curve, paleoproductivity, and the paleoproductivity class is shown in Figure 14.

3.4. Implications for Hydrocarbon Generation

The reconstruction of paleosalinity and paleoproductivity in the Oyo Formation provides insights into depositional environmental conditions that may have influenced the delivery and preservation of organic matter within the sediments. Paleosalinity reflects variations in marine connectivity and water circulation, whereas paleoproductivity, represented by the epifaunal–infaunal (E/I) index, provides an indication of the relative flux of organic matter reaching the seafloor. Together, these micropaleontological proxies provide a preliminary screening of depositional conditions that may have favored or limited organic matter preservation. However, they do not directly determine organic matter abundance, kerogen type, thermal maturity, or hydrocarbon generation potential.

The Sambipitu Formation was deposited in a middle to outer neritic setting characterized by strong open-marine connectivity and well-oxygenated bottom waters. These oxic conditions likely promoted extensive aerobic degradation of organic matter before burial, thereby reducing its preservation potential. Consequently, this interval is interpreted as representing depositional conditions that were relatively unfavorable for organic matter preservation.

In the lower part of the Oyo Formation, relatively shallower depositional conditions reduced marine connectivity and were accompanied by increased paleoproductivity. Although bottom-water oxygenation likely remained sufficient to sustain organic matter degradation, preservation may have improved compared with the underlying Sambipitu Formation. These observations suggest transitional depositional conditions in which organic matter preservation became relatively more favorable, despite the continued influence of oxidation.

The upper part of the Oyo Formation exhibits the highest paleoproductivity values together with increasingly restricted marine circulation. Reduced water exchange may have enhanced water-column stratification and increased oxygen consumption associated with organic matter degradation, leading to relatively lower bottom-water oxygen availability. These conditions may have promoted greater preservation of organic matter compared with the lower intervals. Accordingly, the upper Oyo Formation represents the interval with the most favorable depositional conditions for organic matter preservation among the studied succession.

Overall, the vertical trend from the Sambipitu Formation to the upper Oyo Formation reflects a progressive improvement in depositional conditions for preserving organic matter. The lower interval represents relatively oxic conditions with limited preservation potential, the middle interval records transitional conditions, whereas the upper interval exhibits environmental characteristics that were comparatively more conducive to organic matter preservation. These interpretations are derived from micropaleontological proxies and therefore reflect depositional environmental conditions rather than direct evidence of source rock quality.

It should be emphasized that the present study does not identify kerogen types or demonstrate the occurrence of an effective hydrocarbon source rock. Instead, benthic foraminiferal assemblages provide information on paleoproductivity, bottom-water oxygenation, marine connectivity, and the potential for organic matter preservation. Consequently, the interpretations presented here should be regarded as a preliminary screening for identifying intervals that may have been favorable for organic matter preservation, rather than a definitive assessment of source rock characteristics.

Confirmation of source rock quality requires complementary geochemical analyses that were beyond the scope of this study. Future investigations should include Total Organic Carbon (TOC) analysis to quantify organic matter abundance, Rock–Eval pyrolysis to evaluate source rock potential, Hydrogen Index (HI) and Oxygen Index (OI) to characterize kerogen affinity, Tmax and vitrinite reflectance (Ro) to assess thermal maturity, as well as organic petrography and biomarker analyses to determine the origin, composition, preservation state, and hydrocarbon generation potential of the organic matter. Integration of these datasets would provide a more robust evaluation of the petroleum source rock potential of the Oyo Formation.

This study demonstrates that micropaleontological analysis extends beyond age determination and depositional environment reconstruction by providing a valuable preliminary screening tool for evaluating depositional conditions associated with organic matter preservation. Reconstructions of paleosalinity and paleoproductivity derived from benthic foraminiferal assemblages enable the identification of stratigraphic intervals that may have experienced relatively favorable conditions for preserving organic matter, thereby providing a useful framework for prioritizing intervals for subsequent geochemical investigation.

4. Conclusion

Based on the integration of planktonic and benthic foraminiferal analysis, paleosalinity reconstruction, paleoproductivity evaluation, and depositional environment interpretation, the studied succession records environmental changes from the Sambipitu Formation to the Oyo Formation. The Sambipitu Formation (MS-1) is used as a stratigraphic reference unit, whereas MS-2 and MS-3 represent the lower and upper intervals of the Oyo Formation. Based on planktonic foraminiferal biozonation [3], the Sambipitu Formation is assigned to Zone N8–N9, the lower Oyo Formation to Zone N10, and the upper Oyo Formation to Zone N11–N12, indicating an Early to Middle Miocene age range.

Paleosalinity reconstruction based on the relative abundance of *Orbulina universa* and *Globigerinoides sacculifer* indicates a transition from relatively stable normal marine conditions in the Sambipitu Formation to more restricted conditions within the Oyo Formation. The lower Oyo Formation records normal seawater conditions with a localized hypersaline event, whereas the upper Oyo Formation shows a decreasing salinity trend toward brackish conditions, reflecting changes in marine connectivity, evaporation–freshwater balance, and circulation dynamics. These variations are interpreted as being influenced by regional depositional factors and are only tentatively correlated with global eustatic sea-level fluctuations.

Paleoproductivity reconstruction based on the epifaunal–infaunal (E/I) index demonstrates an overall increasing trend upward through the succession. The Sambipitu Formation represents relatively low organic matter supply under well-oxygenated conditions, while the lower Oyo Formation records increasing organic matter flux with continued oxidation. The upper Oyo Formation exhibits the highest paleoproductivity associated with relatively reduced bottom-water oxygenation, indicating more favorable depositional conditions for organic matter preservation compared with the underlying intervals. Integration with benthic foraminiferal assemblages, P/B ratios, and petrographic observations indicates that the succession was deposited within a neritic environment, transitioning from middle–outer neritic conditions in the Sambipitu Formation to inner–middle neritic carbonate platform conditions in the Oyo Formation.

The interpretations presented in this study are based on micropaleontological proxies that provide relative information on marine connectivity, organic matter flux, and bottom-water environmental conditions. These proxies do not directly determine organic matter richness, kerogen type, thermal maturity, or hydrocarbon generation potential. Therefore, the petroleum implications of this study should be considered as a preliminary screening of depositional conditions favorable for organic matter preservation. The upper Oyo Formation represents the interval with relatively more favorable preservation conditions; however, confirmation of source rock quality requires further geochemical analyses, including TOC, Rock–Eval pyrolysis, Hydrogen Index (HI), Oxygen Index (OI), Tmax, vitrinite reflectance, organic petrography, and biomarker analyses.

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