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Paleoenvironmental Reconstruction of the Sentolo Formation Based on Paleosalinity and Paleoproductivity, South Serayu Basin, Indonesia

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Abstract
The Sentolo Formation represents one of the stratigraphic units of the Kulon Progo Mountains within the South Serayu Basin and is distinguished by the widespread occurrence of limestone. This formation is interpreted to have been deposited in marine settings ranging from neritic to bathyal environments, thereby preserving valuable palaeoceanographic information that can be used to reconstruct past ecological conditions. The distribution of foraminiferal assemblages in the Sentolo Formation is closely controlled by environmental factors, with particular species serving as proxies for ecological parameters such as palaeosalinity and palaeoproductivity. Analysis of the planktic foraminifera *Orbulina universa* and *Globigerinoides sacculifer* suggests that palaeosalinity conditions during deposition ranged from brackish to normal marine. In addition, reconstruction based on benthic foraminiferal assemblages indicates oligotrophic palaeoproductivity, as reflected by the predominance of epifaunal taxa over infaunal taxa. Brackish to normal marine salinity conditions are inferred to have promoted relatively high oxygenation, which may have limited the preservation of organic matter. The resulting low accumulation of organic material, together with evidence of oligotrophic productivity, indicates that the Sentolo Formation has limited potential as a hydrocarbon source rock.

1. Introduction

The stratigraphic succession of the Kulon Progo Mountains within the South Serayu Basin documents widespread carbonate sedimentation developed above Paleogene volcanic rocks. These carbonate deposits are represented by two stratigraphic units that accumulated during the Miocene–Pliocene, namely the Jonggrangan Formation and the Sentolo Formation [1]. The Sentolo Formation is interpreted to have been deposited under marine conditions extending from neritic to bathyal settings [2]. Previous investigations of this formation have largely emphasized depositional environments and paleoclimatic reconstructions, while its paleoecological characteristics, especially those related to paleosalinity and paleoproductivity, remain comparatively understudied. As a result, the paleoecological development of the Sentolo Formation has not yet been fully understood. Therefore, this study aims to reconstruct paleosalinity and paleoproductivity conditions within the Sentolo Formation.

Paleosalinity conditions in the study area were estimated using the planktonic foraminiferal species *Globigerinoides sacculifer* and *Orbulina universa*, whose sensitivity to salinity variations has been well documented by [3]). These species were selected due to their well-defined salinity tolerance range (23–47‰) and long stratigraphic occurrence. Variations in paleosalinity may influence nutrient distribution and oxygenation levels in marine environments, which in turn can affect paleoproductivity within the depositional basin. Additionally, the relative abundance of epifaunal and infaunal benthic foraminifera was utilized as a proxy for paleoproductivity, as their distribution is closely related to organic matter flux and oxygen availability at the sediment-water interface. The results of this study indicate that the interaction between paleosalinity and paleoproductivity within the Sentolo Formation plays an important role in reconstructing the paleoecological and paleoenvironmental dynamics that may have supported the accumulation or preservation of organic matter.

2. Methodology

The methods applied in this study include both quantitative and qualitative approaches, with data derived from measured stratigraphic sections and fossil assemblages. Data analysis in this study was conducted to reconstruct paleosalinity and paleoproductivity conditions and to perform a preliminary screening of the potential for source rock formation. The data used in this study included 300 benthic foraminifera fossils and 300 planktonic foraminifera fossils

Microfossil analysis methods, specifically the identification and quantification of planktonic and benthic foraminifera, were conducted under a binocular microscope. The analysis was conducted by determining relative abundance, species composition, and morphogroup classification (epifauna and infauna) to reconstruct age, paleobathymetry, paleosalinity, and paleoproductivity.

The samples were prepared by selecting fine-grained rock, grinding them, and treating them with a 50% Hydrogen Peroxide solution for 24 hours. Afterward, the samples were washed with water and soap until all dust residues were removed. The cleaned samples were then dried in an oven at a temperature of ±100°C for 10 minutes. Once dry, the samples were sieved using mesh sizes of 50, 80, and 100. The resulting dry residue was then sorted to separate individual foraminifera from sediment grains using fine-tipped tweezers. A total of 300 specimens per sample were sorted, following the standard practice in foraminifera research, where this number is considered representative for community analysis [4] Fossil community data were collected through the identification and counting of foraminiferal individuals from selected species, namely *Orbulina universa* and *Globigerinoides sacculifer*, which are used as salinity indicators [3], as well as benthic foraminiferal species used as proxies for paleoproductivity. These datasets constitute statistical data that can be analyzed using both descriptive and multivariate approaches to interpret paleosalinity conditions and ancient marine productivity.

Table 1. Fossil data used in each sample

Section	Sample Code	*Orbulina universa*	*Globigerinoides sacculifer*	Epifauna	Epifauna
Upper part of Sentolo Formation	ES_03_08	1	0	136	164
	ES_03_03	5	7	224	76
Middle part of Sentolo Formation	ES_02_36	9	4	224	76
	ES_02_33	5	2	221	79
	ES_02_27	7	6	124	176
	ES_02_24	4	4	126	174
	ES_02_23	10	8	286	14
	ES_02_16	1	5	220	80
	ES_02_14	2	4	270	30
	ES_02_10	1	0	245	55
	ES_02_04	2	3	50	250
Lower Part of Sentolo Formation	ES_01_49	0	0	166	134
	ES_01_41	0	2	176	124

Salinity values were calculated using a mathematical proportional equation adapted from Pinasthia (2019)[5].

$$\frac{X_a - Y_1}{X_1 - Y_1} = \frac{X_b - Y_2}{X_2 - Y_2} \quad \text{..(1)}$$

$$\left\{\frac{(X_a - Y_1) - (X_2 - Y_2)}{(X_1 - Y_1)}\right\} + Y_2 = X_b \quad \text{.. (2)}$$

X_a = observed fossil abundance value
X_b = estimated salinity value (‰)
X_1 = maximum fossil abundance value
Y_1 = minimum fossil abundance value
X_2 = upper salinity limit (‰)
Y_2 = lower salinity limit (‰)

This method assumes that the relative abundance of planktonic foraminifera is proportionally related to changes in salinity within the species' ecological tolerance range. Therefore, observed fossil abundance values can be interpolated to estimate salinity using the minimum and maximum abundance thresholds of the species, as well as the lower and upper salinity limits derived from the ecological preferences of indicator species based on [3]. This equation yields paleosalinity estimates that reflect relative salinity variations in the depositional environment, rather than direct measurements of seawater salinity.

Paleoproductivity was estimated using the Nutrient Index (NI) following [7]. The relative abundance of benthic foraminiferal epifaunal and infaunal groups was applied as a proxy for paleoproductivity. Epifaunal taxa tend to dominate assemblages under oligotrophic (nutrient-poor) conditions, whereas infaunal taxa become more abundant in environments with increased food supply or eutrophic conditions [6]. The Nutrient Index (NI) is calculated using the following equation [7]

$$NI = \frac{Hf}{Hf + Lf} \quad \text{...} \quad (3)$$

Where:

Hf: *High fertility group* (The relative abundance of benthic species indicating an environment with a high nutrient supply)

Lf: *Low fertility group* (The relative abundance of benthic species indicating an environment with a low nutrient supply.)

IN: *Nutrient Index* (%) (Indicates the level of fertility or productivity of the sedimentation environment. Higher values indicate more productive conditions; infaunal taxa become more abundant)

3. Results and discussions

This research was conducted in the Pengasih area and its surroundings, Kulon Progo Regency, Special Region of Yogyakarta, with UTM coordinates ranging from 404000 - 413000 and 9131000 – 9136000 (Figures 1 and 2). The study area is located within the Sentolo Formation of the Kulon Progo Mountains stratigraphic sequence. Furthermore, microfossil sample analysis was carried out at the Micropaleontology Laboratory, Universitas Pembangunan Nasional "Veteran" Yogyakarta.

Figure 1. Research Location in the Pengasih area, Kulon Progo Regency (Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS User Community; Esri, Maxar, Earthstar Geographics)

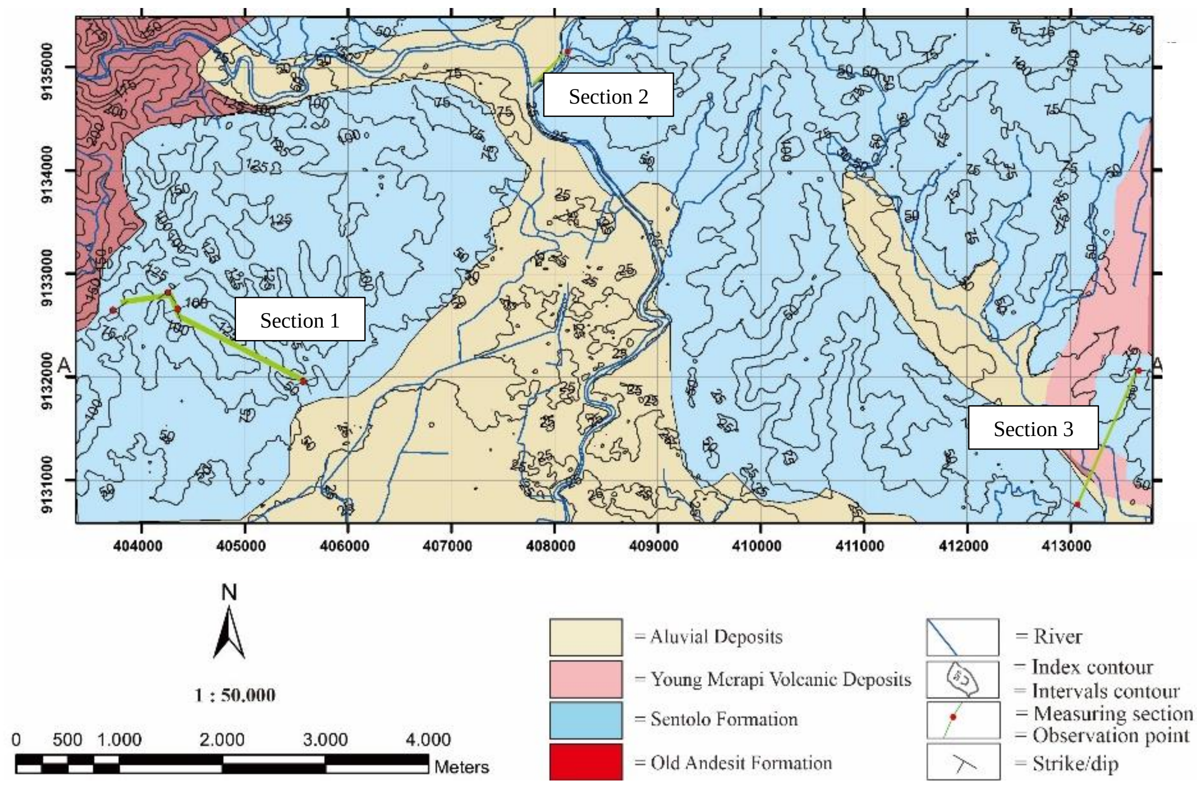


Figure 2. The map showing the sampling locations is indicated by red dots and green lines (Yogyakarta Geological Map[8])

Lithological Analysis

Analysis of rock samples indicates that the lower part of the Sentolo Formation consists of interbedded layers of packstone, wackestone, and floatstone, as evidenced by the unconformity with the Old Andesite Formation below it (Figure 3). The middle part of the Sentolo Formation is represented by Profile 5, collected at Kali Serang, where wackestone-packstone lithology dominates (Figure 4. The upper part of the Sentolo Formation is represented by two profiles with wackestone lithology (Figures 5 and 6).

Figure 3. Outcrop of the lower Part of the Sentolo Formation

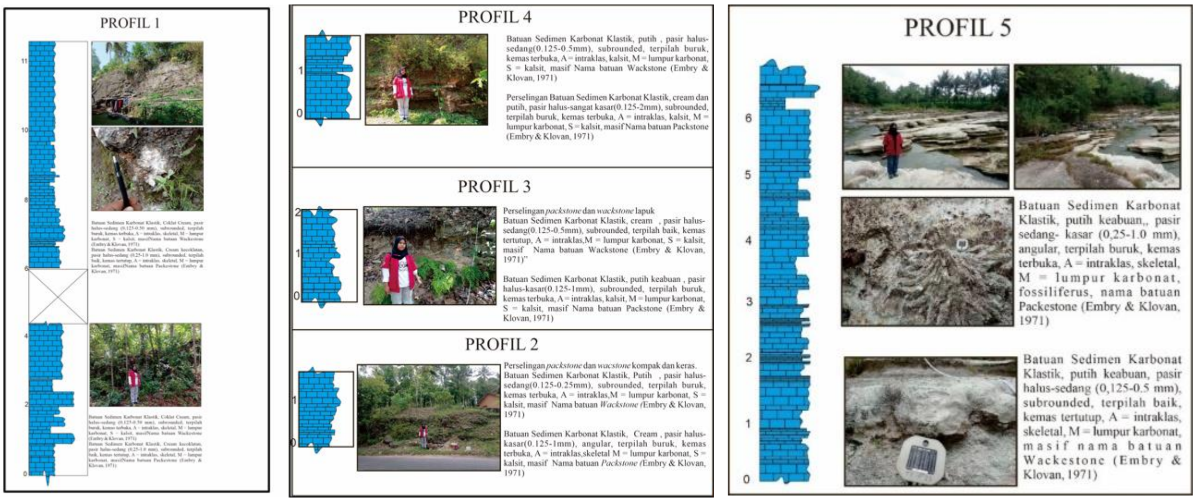


Figure 4. Lower part of Sentolo Profiles (Profiles 1, 2, 3, 4) and Middle part of Sentolo Formation Profile (Profile 5)

Figure 5. Outcrop at Profile 5 (middle part of the Sentolo Formation)

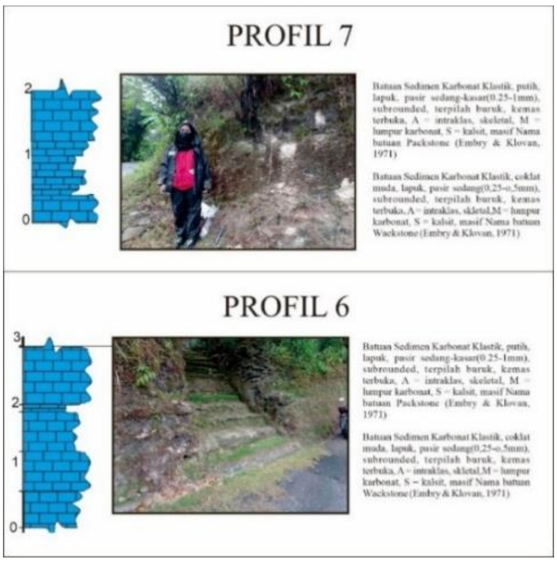


Figure 6. Profile 6-7 (Section 3) Upper part of Sentolo Formation

3.1. Microfacies Analysis

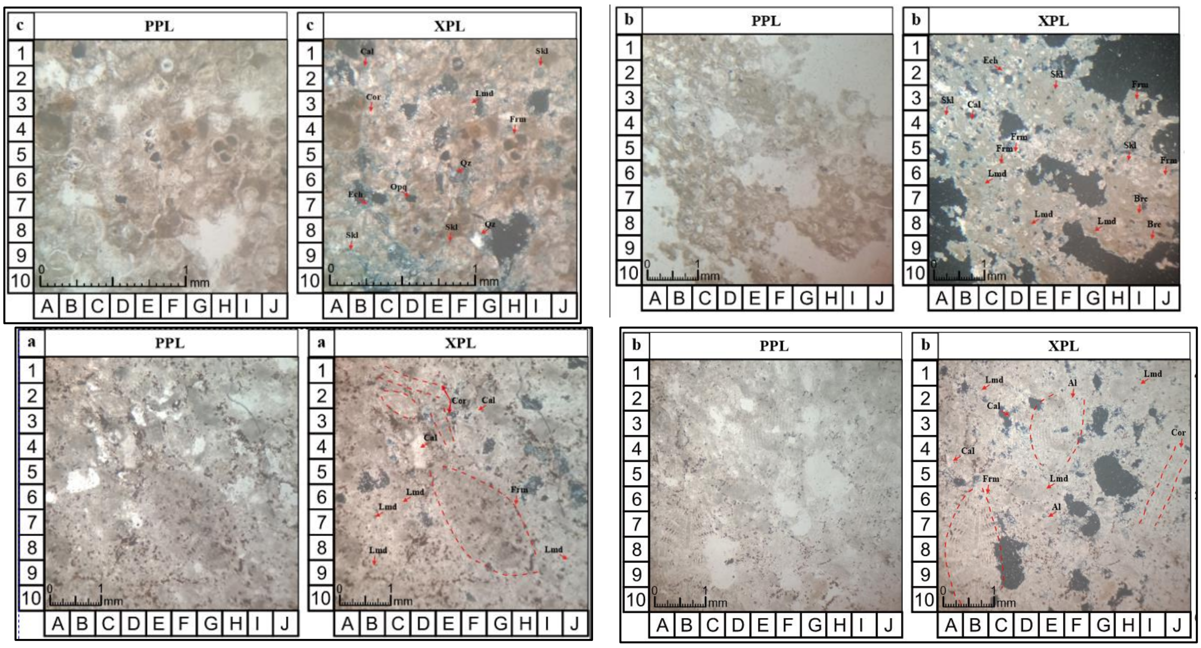
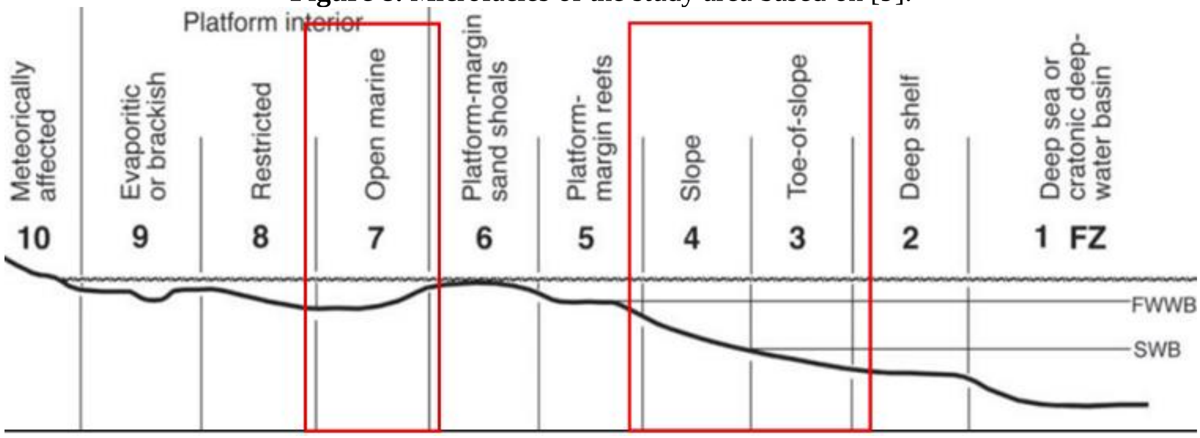


Figure 7. Thin section of the upper part of the Sentolo Formation (upper left), thin section of the middle part of the Sentolo Formation (upper right), thin section of the lower part of the Sentolo Formation (bottom left), and thin section of the lower part of the Sentolo Formation (bottom right)

Two carbonate rocks were identified based on thin-section analysis in the study area. These two lithologies are floatstone and packstone, with packstone being the dominant type. Analysis of hand-specimen rock samples also revealed a dominant presence of wackestone. (Figure 7).

Microfacies analysis of the Sentolo Formation yielded three types of Standard Microfacies (SMF). These are MFT-1, which corresponds to SMF 18; MFT-2 corresponds to SMF 5; and MFT-3 corresponds to SMF 3-For. SMF 18 indicates an open marine (F7) facies characterized by well-defined accumulations of foraminifera shells or calcareous green algae. SMF 5 represents the Slope facies (F4), which is associated with reefs. It was deposited in fore-reef and reef slope settings, or in back-reef and lagoon environments, as well as on the inner ramp. These facies are characterized by intact fossils forming depositional structures with distinctive orientations. SMF 3-For indicates the Toe of slope (FZ 3) and deep-sea water base (FZ 1) facies. These facies are characterized by the presence of pelagic foraminifera with well-preserved shells [9] (Figure 8).

Figure 8. Microfacies of the study area based on [9].



In addition to petrographic data, the facies in the middle part of the Sentolo Formation are also supported by the presence of trace fossils with Zoophycos facies, which generally indicate deep-sea conditions with a muddy substrate, located below the storm wave base, an area susceptible to oxygen stress, and characterized by slow sedimentation rates.

3.2. Paleontological Analysis Result

The benthic foraminifera in this study were divided into two groups: those with infaunal microhabitats and those with epifaunal microhabitats. This classification is based on the morphology of benthic foraminifera according to [10]. The collection of benthic foraminifera is shown in Table 2. This classification of the group is based on the morphological shape of foraminiferal microfossils. Foraminifera with an epifaunal microhabitat have a biconvex or lenticular morphology. In contrast, foraminifera with an infaunal microhabitat tend to have an elongated morphology. According to the analysis results, the benthic foraminifera assemblage in the study area is dominated by benthic foraminifera with epifaunal microhabitats at 69.3%, whereas benthic foraminifera with infaunal microhabitats account for only 30.7%.

Table 2. Table of benthic foraminifera assemblages

Infaunal Taxa (30,7%)	**Epifaunal Taxa (69,3%)**
Bolivina	*Jaculella*
Nodosaria	*Lenticulina*
Uvigerina	*Cibicidoides*
Textularia	*Triloculina*
Nonion(?)	*Clavulina*
Amphicoryna	*Spiroculina*
Vaginulina	*Lanticarinina*
Pulvinulina	*Elphidium*
Bulimina	*Miliola*

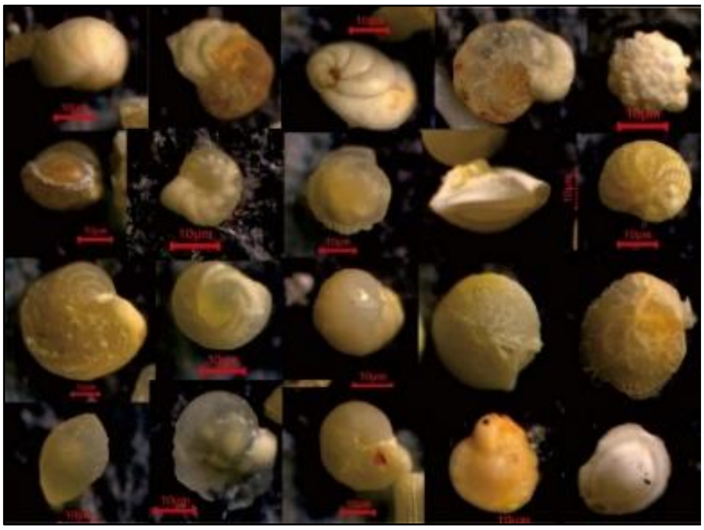


Figure 9. Assemblage of infaunal (left) and epifaunal (right) benthic foraminifera

Table 3. Age analysis results

Lintasan	AGE	Planktonic zonation Blow (1969,1979)	Biostratigraphic comr	Kode sampel/ Kedalaman (m)	Jenis sampel	Litologi	Nama Spesies Planktonik
3	Pliocene	N18-N19		ES_03_08			*Globorotalia dutertrei*
							Globigerinoides conglobatus
							Globigerina bulloides
			Globigerina riveroac				***Globigerina riveroac***
							Globigerinoides sacculifer
	Late Miocene-Plioc	N18-N19	***Globoquadrina dehiscens***	ES_03_03			***Globoquadrina dehiscens***
			Globorotalia tumida				***Globorotalia tumida***
							Sphaeroidinella subdehiscens
							Pulleniatina primalis
							Globorotalia dutertrei
							Globigerinoides ruber
2	Late Miocene-Pliocene	N18		ES_02_36			*Globoquadrina altispira*
							Pulleniatina primalis
			Globorotalia plesiotumida				***Globorotalia plesiotumida***
			Globorotalia multicamerata				***Globorotalia multicamerata***
							Globorotalia tumida
	Late Miocene-Pliocene	N18-N19		ES_02_23			*Hastigerina aequilateralis*
			Globorotalia tumida				***Globorotalia tumida***
							Orbulina bilobata
			Sphaeroidinellopsis kochi				***Sphaeroidinellopsis kochi***
							Orbulina bilobata
	Late Miocene-Pliocene	N18-N19	***Sphaeroidinella subdehisce***	ES_02_04			***Sphaeroidinella subdehiscens***
							Globigerinoides trilobus
			Globorotalia tumida				***Globorotalia tumida***
							Globigerinoides sacculifer
							Hastigerina aequilateralis
1	Late Miocene-Pliocene	N18-N19		ES_01_49			*Globorotalia tumida*
							Hastigerina aequilateralis
							Globigerinoides ruber
			Globoquadrina dehiscens				***Globoquadrina dehiscens***
							Globorotalia pseudomioceanica
							Globorotalia extremus
			Globigerinoides fistulosus				***Globigerinoides fistulosus***
	Late Miocene-Pliocene	N17-N18		ES_01_41			*Globorotalia pseudomioceanica*
							Globoquadrina altispira
			Globorotalia plesiotumida				***Globorotalia plesiotumida***
							Globorotalia extremus
							Globorotalia acostoaensis

Nama Spesies Bentonik

FORAMINIFERA DISTRIBUTION CHART

EOCENE					OLIGOCENE					MIOCENE														PLIOCENE			PLEISTOCENE	
middle		late			early	middle	late			early					middle						late						Holocene	
Ta		Tb			Tc	Td	Te.1-4			Te.5					Tf.1		Tf.2		Tf.3		Tf.4			Th				
P13	P14	P15	P16	P17	P18	P19	N1 P20	N2 P21	N3 P22	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20	N21	N22	N23

In this study, the Sentolo Formation was divided into three sections: the upper, middle, and lower sections. Each section was represented by several samples. Based on the results of age analysis using planktonic foraminifera microfossils, the Sentolo Formation in the study area was deposited during the Late Miocene to Early Pliocene. The results of the analysis are shown in Table 3.

3.3. Paleosalinity of Sentolo Formation

The results of the analysis are presented in Table 3. There are several differences in trends between salinity values based on the abundance of *Orbulina universa* and those based on the abundance of *Globigerinoides sacculifer* (Figure 10). Based on paleosalinity estimates obtained from *Orbulina universa* and *Globigerinoides sacculifer*, the Sentolo Formation exhibits considerable variations in salinity conditions throughout the studied succession (Table 4). The lower interval of the formation is characterized by relatively low salinity values, suggesting deposition under brackish-water conditions. In the middle interval, paleosalinity displays a fluctuating pattern, initially reflecting brackish conditions, followed by a gradual transition to normal marine salinity, an increase toward hypersaline conditions, and a subsequent return to normal marine conditions. In contrast, the upper interval records a shift from normal marine to brackish conditions. The average paleosalinity values inferred from *O. universa* and *G. sacculifer* are generally consistent with variations in foraminiferal morphology, particularly shell coloration. These paleosalinity patterns were further evaluated in relation to sea-level fluctuations during the Messinian–Zanclean interval based on the sea-level curve of Haq et al. (1987) [13], which was used as a reference for interpreting paleosalinity trends (Table 5).

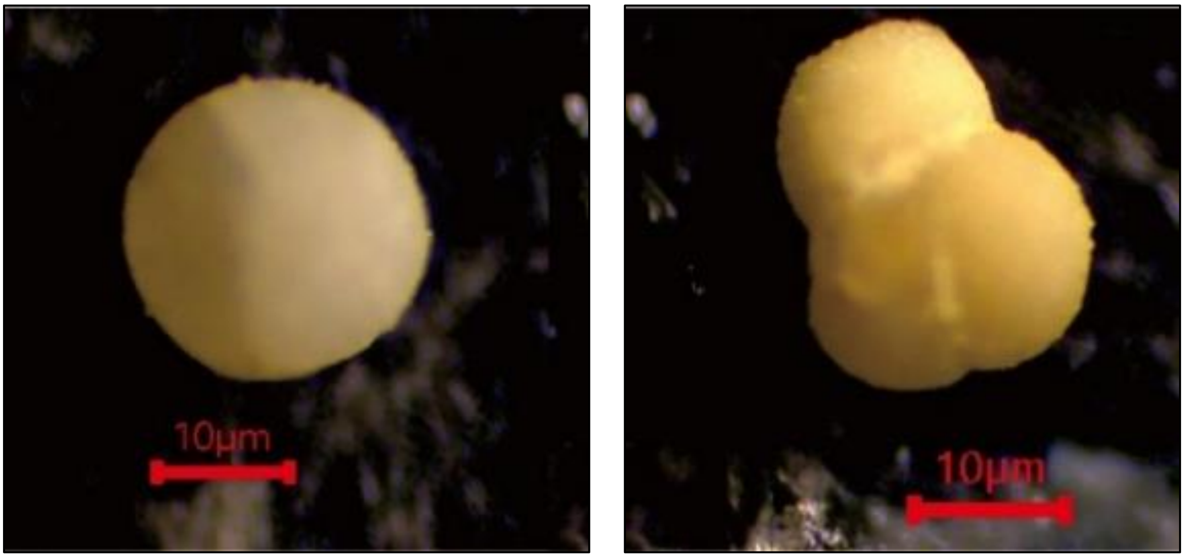


Figure 10. *Orbulina universa* (left) and *Globigerinoides sacculifer* (right)

Table 4. Results of paleosalinity analysis using *Orbulina universa* and *Globigerinoides sacculifer* fossils, along with their corresponding salinity types

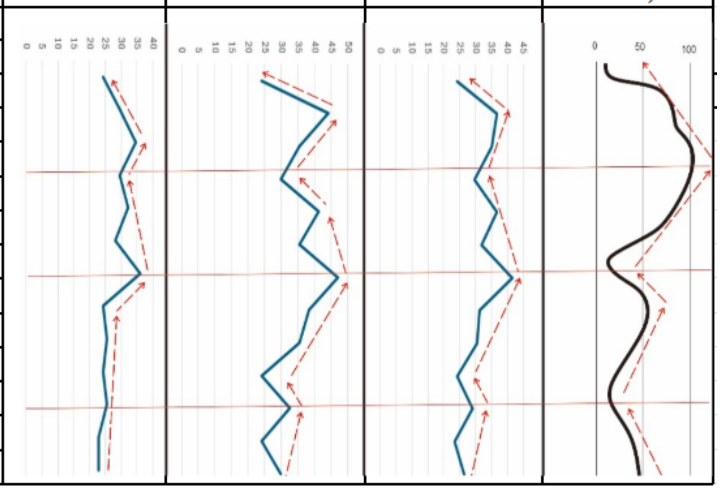
Sample	Salinity based on *Orbulina universa* (‰)	Type of water	Salinity based on *Globigerinoides sacculifer* (‰)	Type of water	Avarage salinity (‰)	Type of water
ES_03_08	24,3	*Breackish water*	24	*Breackish water*	24,15	*Breackish water*
ES_03_03	29,5	*Breackish water*	44,125	*Hypersaline water*	36,8125	*Normal Seawater*
ES_02_36	34,7	*Normal Seawater*	35,5	*Normal Seawater*	35,1	*Normal Seawater*
ES_02_33	29,5	*Breackish water*	29,75	*Breackish water*	29,625	*Breackish water*
ES_02_27	32,1	*Normal Seawater*	41,25	*Hypersaline water*	36,675	*Normal Seawater*
ES_02_24	28,2	*Breackish water*	35,5	*Normal Seawater*	31,85	*Normal Seawater*
ES_02_23	36	*Normal Seawater*	47	*Hypersaline water*	41,5	*Hypersaline water*
ES_02_16	24,3	*Breackish water*	38,375	*Normal Seawater*	31,3375	*Normal Seawater*
ES_02_14	25,6	*Breackish water*	35,5	*Normal Seawater*	30,55	*Normal Seawater*
ES_02_10	24,3	*Breackish water*	24	*Breackish water*	24,15	*Breackish water*
ES_02_04	25,6	*Breackish water*	32,625	*Normal Seawater*	29,1125	*Breackish water*
ES_01_49	23	*Breackish water*	24	*Breackish water*	23,5	*Breackish water*
ES_01_41	23	*Breackish water*	29,75	*Breackish water*	26,375	*Breackish water*

The age of each stratigraphic interval within the Sentolo Formation was determined using planktonic foraminiferal biostratigraphy. Biozonation was established based on the occurrence of age-diagnostic planktonic foraminiferal species following the standard zonation scheme. The interpreted biozones were then correlated with the global eustatic curve to evaluate whether the depositional succession corresponds to major transgressive or regressive phases during the Late Miocene–Early Pliocene. Because the age assignments are based on biozones rather than absolute numerical ages, the correlation should be regarded as approximate, and the associated age uncertainty is considered in the interpretation. Comparison with the global eustatic framework also allows evaluation of whether salinity variations occurred during periods of relative sea-level rise or fall using the halosteric effect. The effects refer to changes in the volume and density of seawater caused by variations in salinity. During low salinity, the density of seawater decreases, slightly raising the sea level. In contrast, during high salinity, the density of seawater increases, causing the sea level to drop slightly. However, these halosteric effects occur at regional to oceanographic scales and contribute only a very small fraction to sea-level variability. Therefore, they should not be interpreted as the primary control on stratigraphic sea-level changes or depositional environments. In addition to these processes, the global cooling event that occurred in the Late Miocene, when the world's climate gradually cooled down to the Late Pliocene [11], also contributed to changes in the seawater. The lower temperatures caused by the cooling event could reduce evaporation and lead to changes in the salinity gradient, particularly at the sea surface.

The analysis results show that the lower part of the Sentolo Formation shows fluctuations in salinity that are not consistent with changes in sea level due to halosteric factors. In the lower part of the Sentolo Formation, the sea level tends to decline, indicating deposition in lagoon-open marine facies. These depositional facies are interpreted as the result of relatively brackish salinity due to a higher supply of water and terrestrial material. During this event, temperatures also dropped, leading to reduced evaporation, affecting the salinity stratification in the depositional environment. The middle part of the Sentolo Formation records deposition in slope and toe-of-slope facies, indicating an increase in relative water depth. Although salinity fluctuated throughout this interval, these variations are interpreted as responses to changing oceanographic conditions rather than as drivers of sea-level change. The deepening trend is more reasonably explained by changes in relative sea level associated with regional subsidence and eustatic fluctuations. Variations in salinity during this stage may reflect changes in water-mass circulation, freshwater input, and climatic conditions that accompanied the Late Miocene cooling. In the upper part of the Sentolo Formation, the change in salinity does not align with halosteric factors. When the sea level drops, deposition occurs in the fore-reef and reef slope positions, or in the back-reef and lagoon environments. These depositional facies result in relatively brackish salinity, due to higher supply of water and terrestrial material.

Table 5. Paleosalinity controlled by the eustatic curve (Haq et al., 1987) [13]

Sample	Salinity based on *Orbulina universa* (‰)	Salinity based on *Globigerinoides sacculifer* (‰)	Avarage salinity (‰)	Eustatic Curves (Haq et al., 1987)
ES_03_08				
ES_03_03				
ES_02_36				
ES_02_33				
ES_02_27				
ES_02_24				
ES_02_23				
ES_02_16				
ES_02_14				
ES_02_10				
ES_02_04				
ES_01_49				
ES_01_41				



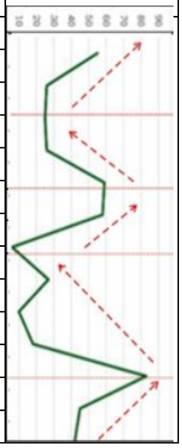
3.4. Paleoproductivity of Sentolo Formation

The distribution of benthic foraminifera in the ocean is associated with the primary productivity of the ocean. Organic matter flux, oxygen conditions, and salinity conditions are factors that can influence deep-sea paleoproductivity (Table 6). In this study, a comparison of the abundance of infaunal and epifaunal benthic foraminifera was used as an indicator of primary marine paleoproductivity. Furthermore, morphological data of foraminiferal fossils, particularly shell color, were also used to support the analysis results. The paleoproductivity index values in this study were grouped into three categories (oligotrophic, mesotrophic, and eutrophic) based on the percentage distribution of the index values across all samples. This grouping is an operational classification intended to facilitate the visualization of productivity variations among samples and does not constitute a standard paleoecological threshold.

The lower part of the Sentolo Formation indicates mesotrophic conditions. This condition is consistent with the depositional facies in an open marine-lagoon environment that results in relatively low oxygen circulation to the seafloor and a high influx of nutrients from the land. This condition leads to relatively high productivity of organic matter on the seafloor.

In the middle part of the Sentolo Formation, the depositional facies changes from backreef to slope to toe of slope. During deposition in the backreef phase, organic matter productivity can increase sharply due to nutrient influx from the land and low oxygen circulation. Then, as the facies changes to slope to toe of slope, productivity shifts to oligotrophic conditions because oxygen circulation increases and land-derived material influx decreases. This reduces the accumulation of organic matter on the seafloor
In the upper part of the Sentolo Formation, conditions are nearly identical to those in the lower part of the Sentolo Formation. The change in depositional facies from the slope environment toward the backreef results in relatively low oxygen circulation to the seafloor and a high influx of nutrients from land, leading to organic matter productivity at the seafloor under mesotrophic conditions.

Table 6. Table of paleoproductivity analysis results based on benthic foraminifera.

Section	Sample Code	Infauna	Epifauna'	Productivity Percentage	Productivity Type	Productivity Curve
Upper part of Sentolo Formation	ES_03_08	164	136	55%	Mesotrofik	
	ES_03_03	79	224	26%	Oligotrofik	
Middle part of Sentolo Formation	ES_02_36	76	224	25%	Oligotrofik	
	ES_02_33	79	221	26%	Oligotrofik	
	ES_02_27	176	124	59%	Mesotrofik	
	ES_02_24	174	126	58%	Mesotrofik	
	ES_02_23	17	286	6%	Oligotrofik	
	ES_02_16	80	220	27%	Oligotrofik	
	ES_02_14	30	270	10%	Oligotrofik	
	ES_02_10	55	245	18%	Oligotrofik	
	ES_02_04	250	50	83%	Eutrofik	
Lower Part of Sentolo Formation	ES_01_49	134	166	45%	Mesotrofik	
	ES_01_41	128	176	42%	Mesotrofik	

3.5. Discussion on the Paleosalinity and Paleoproductivity of the Sentolo Formation

The relationship between paleosalinity and paleoproductivity in the Sentolo Formation can be seen in Figure 7. When salinity levels were low (brackish), productivity was moderate to high (an inverse relationship). Brackish seawater conditions caused seawater stratification and reduced the diffusion of oxygen to the seafloor, leading to seafloor deoxygenation. A deoxygenated seafloor supports an increase in organic material, resulting in mesotrophic to eutrophic productivity levels.

Salinity in the middle part of the Sentolo Formation shows a distinct pattern. When salinity is stable at brackish-to-normal levels, productivity rises sharply to its peak. The interpretation results indicate that brackish-to-normal salinity conditions reflect the influence of freshwater from the mainland, supported by sedimentation patterns in the backreef and lagoon environments.

Brackish salinity causes stratification in the water column. This stratification inhibits vertical mixing, resulting in a reduced supply of oxygen to the seafloor. At the same time, global climate cooling occurred, as evidenced by the presence of left-coiled *Globorotalia* sp. This cooling caused surface temperatures to be lower than seafloor temperatures, leading to upwelling and an increase in nutrient supply and primary productivity at the water's surface. Increased surface productivity resulted in a greater influx of organic material to the seafloor.

The decomposition of organic matter by microorganisms on the seafloor consumes oxygen, resulting in a seafloor environment that is relatively oxygen-poor (dysoxic). This environment, characterized by high organic matter content and low oxygen levels, supports the growth of infaunal foraminifera, leading to increased productivity and a eutrophic environment. Subsequently, the salinity of the middle part of the Sentolo Formation began to increase at a steady rate. This trend is consistent with the environmental transition from a lagoon facies to toe-of-slope facies, indicating a rise in sea level. This rise in sea level is supported by conditions in the Early Pliocene, when the global climate began to warm, as evidenced by the presence of the right-coiled Globorotalia sp. Normal seawater salinity indicates environmental stability, which increases foraminifera diversity. Under these conditions, the abundance of benthic foraminifera decreased. However, epifaunal benthic foraminifera remained dominant compared to infaunal benthic foraminifera, resulting in fluctuating productivity levels with a predominance of oligotrophic productivity. Analysis of paleosalinity in the upper Sentolo Formation indicates a further decrease in salinity and an increase in productivity. This condition is similar to that observed in the lower Sentolo Formation, where the brackish environment better supports the development of benthic infaunal foraminifera that are more tolerant of salinity fluctuations. Additionally, the high abundance of benthic infaunal foraminifera indicates that organic matter is more abundant and reflects mesotrophic productivity conditions.

Regarding the relationship between salinity and productivity, changes in salinity do not necessarily imply changes in productivity. This is because productivity is not solely determined by salinity but also by the availability of nutrients and organic matter in the sediment required by organisms. However, salinity can be one of the contributing factors to changes in productivity.

3.6. Discussion on the Potential for the Formation of Oil and Gas

The evaluation of oil and gas formation potential within a sedimentary unit requires the integration of various geological, geochemical, and paleontological parameters. In this study, the primary indicators used to assess oil and gas formation potential are the abundance of foraminifera microfossils, paleosalinity, and paleoproductivity. These parameters are interrelated in controlling the accumulation of organic matter, which forms the basis for the formation of source rock.

Chemically, all organisms are composed of lipids, proteins, and carbohydrates, while higher plants also contain lignin. In the process of hydrocarbon formation, lipids play the most significant role. Lipids, including fats, waxes, terpenoids, and steroids, are the primary precursors for the formation of liquid hydrocarbons [12]. Although foraminifera are not a primary source of lipids, their abundance can reflect general ocean productivity conditions, as their presence is strongly influenced by nutrient availability and the stability of the aquatic environment. Thus, the composition and abundance of foraminifera or paleoproductivity can serve as indirect indicators of the potential for organic matter accumulation.

In addition to paleoproductivity levels, paleosalinity conditions also play a role in controlling the distribution of organisms and the dynamics of seawater circulation. Paleosalinity can indicate seawater oxygenation conditions, which influence the degree of organic matter preservation. Under high paleosalinity conditions, oxygenation levels are low (dysoxic–anoxic), allowing organic matter to be well-preserved in sediments and increasing its potential to form oil-prone Type II kerogen during the diagenesis stage. Conversely, low salinity indicates an open marine environment with relatively good water circulation. Intense circulation tends to increase oxygenation of the seafloor. When oxygen levels are high, aerobic microorganisms rapidly break down organic matter into CO_2 and other simple compounds, preventing preservation and kerogen formation.

Based on analyses of paleosalinity and paleoproductivity using foraminifera proxies and their association characteristics, the Sentolo Formation shows brackish to normal seawater salinity conditions and an average oligotrophic level of paleoproductivity. These conditions support the interpretation of an open aquatic environment with good water circulation. Open aquatic environments generally do not support effective accumulation and preservation of organic material. This is supported by data from the paleoproductivity analysis, which indicates an oligotrophic/low-productivity level. Due to the low amount of organic material, the Sentolo Formation has low potential as a source rock.

4. Conclusion

Based on the occurrence and characteristics of the planktonic foraminifera *Orbulina universa* and *Globigerinoides sacculifer*, the Sentolo Formation is interpreted to have experienced paleosalinity conditions ranging from brackish to normal marine. This interpretation is consistent with eustatic sea-level fluctuations, in which lower salinity conditions generally correspond to periods of higher sea level, whereas increased salinity tends to occur during lower sea-level stands. Paleoproductivity reconstruction further indicates that the Sentolo Formation was predominantly characterized by oligotrophic conditions. The dominance of epifaunal over infaunal benthic organisms suggests a relatively limited supply of organic matter, resulting in minimal accumulation of organic material within the sedimentary succession.

Based on the results of the discussion, the relationship between paleosalinity and paleoproductivity exhibits an irregular pattern. This is because salinity values tend to be related to conditions in the water column, whereas paleoproductivity is related to the amount of organic material in the sedimentary layers. In the relationship between salinity and productivity, changes in salinity do not always imply changes in productivity. This is because productivity is determined not only by salinity but also by the availability of nutrients and organic matter in the sediments required by organisms. However, salinity can be one of the factors contributing to changes in productivity. Paleosalinity and paleoproductivity play a significant role as indicators of hydrocarbon formation in source rocks. Brackish to normal marine salinity conditions within the Sentolo Formation reflect variable oxygenation levels, ranging from relatively low to high, which may have reduced the preservation potential of organic matter in the sediments. Furthermore, the oligotrophic paleoproductivity conditions indicate a limited supply and accumulation of organic material within the sedimentary succession. Taken together, these characteristics suggest that the Sentolo Formation has relatively low potential to function as a hydrocarbon source rock. Nevertheless, this interpretation is derived exclusively from foraminiferal proxies and therefore should be regarded as preliminary rather than conclusive evidence of source-rock quality or hydrocarbon generation potential.

Evaluation of source-rock potential requires direct geochemical analyses, including measurements of total organic carbon (TOC), Rock-Eval pyrolysis, kerogen type, and organic matter maturity. Therefore, the present results should be regarded as providing palaeoenvironmental constraints that complement, rather than replace, geochemical assessment of the petroleum system. Further research combining micropalaeontological, sedimentological, and geochemical approaches is necessary to achieve a more comprehensive assessment of the hydrocarbon potential of the Sentolo Formation.

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