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RESEARCH ARTICLE

Eocene Paleoclimatic Implications in the Bayat Basin Based on Nannofossil Distribution

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Abstract

The Middle–Late Eocene represents a critical interval of greenhouse climate evolution following the Early Eocene Climatic Optimum (EECO), yet quantitative paleoclimate records from low-latitude Southeast Asia remain scarce. This study presents a multi-proxy calcareous nannofossil-based reconstruction of surface-water conditions from the Gamping–Wungkal Formation in the Bayat Basin, southern Java. Detailed stratigraphic logging and systematic sampling along a 60 m section were combined with quantitative assemblage analysis and Scanning Electron Microscope validation. Biostratigraphic evaluation assigns the studied interval to the NP17 zone (Middle–Late Eocene). Paleoclimatic reconstruction integrates the Reticulofenestra Size Ratio (RSR), Warm-Water Index (WWI), Discoaster Abundance Ratio (DAR), and total Reticulofenestra abundance. Assemblages are dominated by medium- to large-sized Reticulofenestra and persistent Discoaster occurrences, indicating warm, oligotrophic, and stratified surface-water conditions. Despite global post-EECO cooling trends documented in mid- and high-latitude records, the Bayat data suggest sustained tropical greenhouse conditions during NP17. These findings are consistent with emerging evidence of latitudinal variability in Eocene climate evolution and establish the Bayat Basin as an important low-latitude archive for evaluating Paleogene greenhouse dynamics in Southeast Asia.

Keywords: Bayat, Eocene, Gamping Wungkal, Nannofossil, Paleoclimate

1. Introduction

1.1 Regional Physiography

The Bayat area lies within the Southern Mountains Zone of Central Java, a structurally complex region formed by interactions between carbonate platforms, metamorphic basement, and volcanic sequences. This structural complexity has significantly influenced topography, with differential erosion producing undulating hills and ridges (Surono, 2009). Recent geomorphological studies of Central Java demonstrate that tectonic uplift and erosion associated with arc-continent interactions, as well as variations in lithological resistance, strongly influence hill-valley morphology in similar Central Java terrains, highlighting the region's active landscape development (Hidayat et al., 2021).

1.2 Regional Geological Structure

Tectonically, the Bayat area lies within the northern segment of the Javanese magmatic arc, part of the broader Sunda Arc system, which developed as a consequence of the long-term subduction of the Indo-Australian Plate beneath the Eurasian Plate since the Late Cretaceous (Gallagher et al., 2024; Hall, 2011). This convergent margin generated regi onal deformation characterized by thrust faults, strike-slip faults, and fold belts trending predominantly northwest–southeast to east–west, which control lithological distribution and structural grain across southern Java. Recent tectonic syntheses further demonstrate that Java's Paleogene evolution was influenced by arc migration, slab rollback, and back-arc basin dynamics (Luan and Lunt, 2021; Lunt and Luan, 2023), processes that contributed to uplift and exhumation of Eocene carbonate units such as the Gamping–Wungkal Formation in the Bayat Basin. This structural framework provides the tectonic basis for the present-day exposure of Eocene successions and enables detailed stratigraphic and micropaleontological investigation (Figure 1).

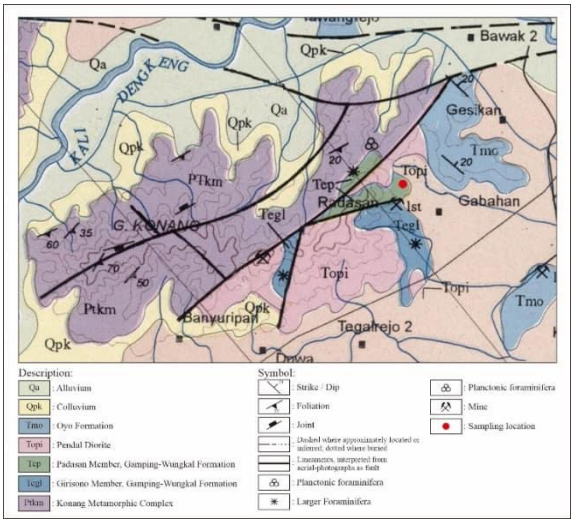


Fig. 1. Geological map of the study area (Samudra and Sutisna, 1992).

1.3 Regional Stratigraphy

The stratigraphy of the Bayat area comprises a sequence of major lithostratigraphic units from oldest to youngest (Figure 2), including the Bayat Metamorphic Complex (pre-Tertiary basement), the Gamping-Wungkal Formation (Eocene shallow-marine carbonates and claystones), the Kebo-Butak Formation (Oligocene–Miocene volcanic and

sedimentary rocks), and unconsolidated Quaternary volcanic deposits (Mulyaningsih, 2016; Surono, 2009).

Regional sedimentation patterns across Java demonstrate that Paleogene carbonate successions, like the Gamping-Wungkal, formed within broader tectono-stratigraphic frameworks influenced by dynamic subsidence, sea-level changes, and provenance shifts (Luan and Lunt, 2021; Lunt and Luan, 2023). Research on carbonate and siliciclastic deposition in eastern Java and adjacent basins underscores the role of tectonics in controlling accommodation space and sediment basin fill across the Eocene–Miocene (Gallagher et al., 2024; Hall, 2019), which supports interpretations of stratigraphic architecture in the Bayat region.

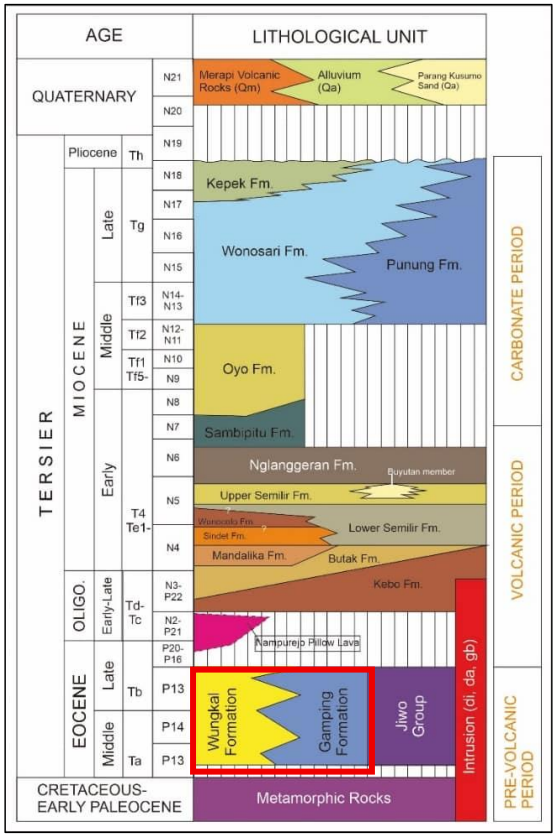


Fig. 2. Regional stratigraphy of the Southern Mountain (Surono, 2009).

The Gamping-Wungkal Formation itself contains abundant Eocene coccoliths and other microfossils, with taxa such as Reticulofenestra and Coccolithus indicating deposition in a shallow-marine environment favorable for preservation of calcareous nannofossils (Novita et al., 2014; Umiyatun et al., 2006).

The Gamping–Wungkal Formation represents one of the Paleogene carbonate successions exposed within the Southern Mountains Zone of Java. Carbonate deposition during the Eocene in Southeast Asia commonly occurred in shallow marine environments associated with carbonate platforms that formed along the margins of Sundaland under tropical greenhouse conditions. These carbonate systems were strongly influenced by the tectonic evolution of the Sunda Arc, where regional subsidence and volcanic arc activity periodically controlled sediment supply and accommodation space for carbonate accumulation. Consequently, mixed carbonate and fine-grained siliciclastic deposits such as micritic limestone, marl, and claystone are commonly preserved in arc-related basins of Southeast Asia. Similar carbonate platform developments during the Eocene have been documented in several Tethyan and Southeast Asian regions, where carbonate sedimentation occurred in warm shallow marine environments connected to open-ocean circulation (Fang et al., 2024; Luan and Lunt, 2021; Lunt, 2023).

1.4 Paleoclimate Based on Nannofossil

1.4.1 Nannofossil

Nannofossils are widely recognized as key indicators for Paleogene biostratigraphy due to their rapid evolutionary rates and sensitivity to environmental changes (Agnini et al., 2014). Previous studies in the Bayat area (Umiyatun et al., 2006) reported Paleogene taxa indicating an NP18–NP19 age range.

Furthermore, recent studies in Indonesia demonstrate that quantitative nannofossil distributions provide reliable proxies for reconstructing paleoceanographic conditions, including temperature, stratification, and productivity (Farida et al., 2024; Ratumanan et al., 2023). The integration of taxonomic composition and abundance patterns in this study therefore provides a robust basis for interpreting Eocene shallow-marine conditions in the Bayat Basin.

1.4.2 Paleoclimate

Paleoclimatic interpretation using calcareous nannofossils is commonly based on taxonomic composition, relative abundance, and quantitative indices (Agnini et al., 2014; Blaj et al., 2023; Ma et al., 2024; Menini et al., 2021).

Nannofossil taxa exhibit distinct ecological preferences. Variations in the size structure of *Reticulofenestra* reflect nutrient availability and upper-ocean conditions. Larger morphotypes are typically associated with oligotrophic and stratified waters, whereas smaller morphotypes indicate increased nutrient supply (Judd et al., 2022; Ma et al., 2024; Menini et al., 2021).

Similarly, Discoaster abundance is widely interpreted as an indicator of warm, oligotrophic, and stratified surface waters, particularly in low-latitude greenhouse settings (Judd et al., 2022; Ma et al., 2024).

Quantitative nannofossil-based indices such as Reticulofenestra Size Ratio (RSR), Warm-Water Index (WWI), Discoaster Abundance Ratio (DAR), and the relative abundance of Reticulofenestra are widely applied in Paleogene paleoceanographic studies. However, most studies do not define universal threshold values to classify these parameters into “low”, “moderate”, or “high” categories. Instead, interpretations are typically based on relative variations within individual stratigraphic sections and their ecological significance (Judd et al., 2022; Ma et al., 2024; Menini et al., 2021).

Therefore, in this study, the classification of parameter values (e.g., low or high RSR, WWI, and DAR) is interpreted in a relative sense based on internal variations between samples and supported by ecological relationships between nannofossil assemblages and surface-water conditions.

1.4.3 *Reticulofenestra* Size Ratio

The Reticulofenestra Size Ratio (RSR) was calculated as the ratio between small-sized individuals (<5 μm) and large-sized individuals (>7 μm). Variations in the size structure of *Reticulofenestra* are widely recognized as reflecting changes in surface-water nutrient availability, water-column stability, and broader paleoceanographic conditions during the Paleogene (Agnini et al., 2014; Ma et al., 2024). Quantitative morphometric studies demonstrate that dominance of large-sized morphotypes is typically associated with oligotrophic, stratified, and relatively stable surface waters. In contrast, increased proportions of small-sized morphotypes correspond

to enhanced nutrient supply and elevated productivity (Judd et al., 2022; Menini et al., 2021). Such size-structured assemblage shifts have been documented in Middle–Late Eocene records and are interpreted as reflecting regional adjustments in upper-ocean trophic conditions (Hollis et al., 2022).

1.4.4 Warm-Water Index

The Warm-Water Index (WWI) was calculated based on the relative abundance of warm-water and large-sized taxa, namely *Coccolithus pelagicus* and *Reticulofenestra umbilicus*, which are commonly associated with relatively stable and stratified surface-water conditions during the Paleogene. Variations in the abundance of large reticulofenestrids and coccolith-bearing taxa have been interpreted as reflecting upper-ocean stability and nutrient limitation in low-latitude Eocene settings (Hutchinson et al., 2021; Ma et al., 2024).

1.4.5 *Discoaster* Abundance Ratio

The Discoaster Abundance Ratio (DAR) reflects the relative proportion of Discoaster within the assemblage and is commonly used as a proxy for warm and oligotrophic surface-water conditions (Judd et al., 2022).

Previous studies have demonstrated that fluctuations in *Discoaster* abundance can be used to track variations in surface-water stability and ecological structure of coccolithophore communities. Increased representation of *Discoaster* is often interpreted as reflecting enhanced stratification and reduced nutrient supply, whereas reduced abundance may indicate relatively more dynamic or nutrient-influenced conditions (Judd et al., 2022; Menini et al., 2021).

1.4.6 Total *Reticulofenestra* Abundance

The relative abundance of *Reticulofenestra* is widely used as an indicator of paleoceanographic conditions in Paleogene marine environments. This genus represents one of the most dominant coccolithophore groups in low- to mid-latitude settings and exhibits strong sensitivity to changes in nutrient availability, surface-water stratification, and productivity (Agnini et al., 2014; Ma et al., 2024).

High relative abundance of *Reticulofenestra* is commonly associated with oligotrophic and stratified surface waters, where stable conditions favor continuous coccolithophore production. Conversely, reduced abundance may indicate increased nutrient input, higher productivity, or more dynamic water-column conditions that disrupt coccolithophore dominance (Judd et al., 2022).

1.5 Background

Reconstruction of the Eocene paleoclimate is a major topic in modern geology, as this interval witnessed significant global climate variability, including extreme warming during the Eocene Climatic Optimum and subsequent cooling toward the Eocene-Oligocene transition (Hollis et al., 2022; Hutchinson et al., 2021; Pearson et al., 2015; Westerhold et al., 2021). Recent syntheses emphasize that Middle–Late Eocene climate evolution involved complex feedbacks among atmospheric CO_2, fluctuations in carbonate compensation depth, and ocean productivity, highlighting the importance of integrating regional marine archives into globally calibrated chronostratigraphic frameworks (Westerhold et al., 2024).

Recent high-resolution Paleogene studies demonstrate that climate evolution during the late Paleogene was characterized by complex regional variability rather than uniform global change. Integrated stratigraphic and geochemical data from continental margin successions reveal short-lived cooling phases linked to carbon-cycle perturbations and atmospheric CO_2 fluctuations (Hollis et al., 2022; Westerhold et al., 2021). Across the Eocene–Oligocene Transition (EOT), coupled isotopic and calcareous nannofossil records document major paleoceanographic reorganization, including shifts in carbonate chemistry, productivity structure, and preservation dynamics (Hutchinson et al., 2021). These findings highlight that surface-water ecological responses may vary regionally and emphasize the importance of well-constrained marine archives for refining paleoclimate reconstructions.

In Indonesia, however, paleoclimate data based on nannofossils remain limited, particularly in central Java, where numerous Paleogene rock units are well exposed. One of these units is the Gamping-Wungkal Formation, which has been interpreted as a shallow-marine carbonate deposit (Surono, 2009) of Middle to Late Eocene age (Umiyatun et al., 2006) and represents a potentially important archive of paleoenvironmental change in the ancient tropical region.

Nannofossils are effective paleoclimate indicators due to their rapid evolutionary rates, broad geographic distribution, and sensitivity to changes in temperature, nutrient availability, and water-column stratification (Agnini et al., 2017). Indices such as *Discoaster* abundance, size variations of the genus *Reticulofenestra*, and changes in *Helicosphaera* abundance have been widely applied to reconstruct Paleogene shallow-marine climate dynamics. Recent Paleogene studies in Indonesia highlight the importance of nannofossil-based approaches for paleoenvironmental interpretation, as demonstrated by studies of the Tonasa Formation (Farida et al., 2024), the Nanggulan Formation (Jatiningrum et al., 2022), and the Elat Formation in Maluku (Ratumanan et al., 2023).

Previous studies in Bayat (Umiyatun et al., 2006) documented the presence of Eocene nannofossils, including *Cribrocentrum reticulatum*, *Discoaster saipanensis*, *Discoaster barbadiensis*, *Discoaster deflandrei*, *Reticulofenestra umbilica*, *Reticulofenestra hampdenensis*, *Helicosphaera compacta*, *Helicosphaera euphratis*, *Ericsonia formosa*, *Zyghrablithus bijugatus*, *Sphenolithus moriformis*, and *Sphenolithus pseudoradians*. However, no systematic attempt has been made to relate their distribution to regional paleoclimatic conditions. Previous studies documented only taxonomic occurrence and zonation. This research is the first to quantitatively integrate assemblage structure with climate-sensitive indices to reconstruct paleoceanographic conditions.

This study aims to fill this gap by analyzing nannofossil distribution in the study area, which lies within the Paleogene basin of the Southern Mountains of Java. The results are expected to contribute to the reconstruction of the Eocene paleoclimate in Java and to serve as a reference for future studies in stratigraphy, carbonate sedimentology, and micropaleontology.

1.5 Objectives

The objectives of this study are to:

1. Identify the distribution of nannofossils in the claystone of the Gamping-Wungkal Formation within the study area.
2. Determine the relative age based on nannofossil zonation.
3. Interpret Eocene paleoclimate conditions based on nannofossil abundance and diversity.

2. Material And Method

The study area is located at Watuprahu, Dusun III, Gunung Gajah, Bayat, Klaten, Central Java, Indonesia, with UTM coordinates X = 463961 and Y = 9141582 (Zone 49S)

(Figure 3). Stratigraphic measurements and sampling were conducted on well-exposed claystone outcrops with high potential for nannofossil occurrence.

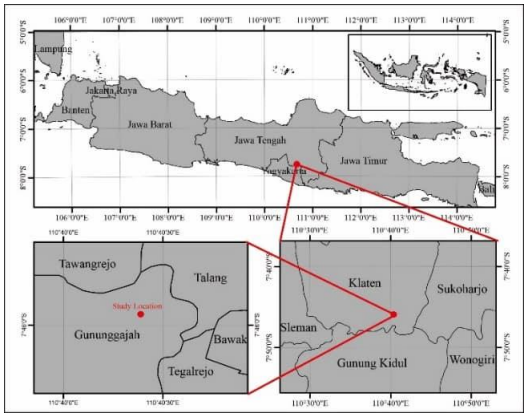


Fig. 3. Index map of the study area.

The research methods applied in this study are described as follows:

A. Measured Stratigraphic Section

A stratigraphic section approximately 60 m thick was measured in detail along the Watuprahu outcrop using a measuring tape and a geological compass. Lithological variations, sedimentary structures, and sampling positions were systematically recorded along the section. The measured stratigraphic profile, including lithological succession and sampling locations, is presented in Figure 7.

B. Sampling

Six claystone samples were collected from the measured stratigraphic section using a representative sampling approach. Sampling was conducted at regular stratigraphic intervals of several meters along the measured section, ensuring that each sample reflects variations in lithology and stratigraphic position. The selected samples specifically target claystone horizons considered suitable for nannofossil analysis. Each sample was systematically labeled, and its exact stratigraphic position was recorded during fieldwork.

C. Smear Slide Preparation

Fine-grained claystone samples were gently crushed to obtain a fine powder, suspended in distilled water, mounted on glass slides, and heated to fix the material.

D. Polarizing Light Microscope Analysis

Nannofossils were observed using a polarizing light microscope with a 40× objective magnification under both plane-polarized and cross-polarized light. Taxonomic identification was based on morphological characteristics and optical properties of the nannofossils, following standard taxonomic frameworks established by Martini (1971), Agnini et al. (2017), and Raffi et al. (2022).

Quantitative analysis was conducted using the random field counting method. Each smear slide was examined in four randomly selected fields of view. The total number of counted nannofossil specimens per sample ranged from approximately 30 to 50 individuals. Nannofossil abundance was expressed as relative abundance (%), calculated as the proportion of individuals of a given taxon relative to the total number of nannofossil individuals counted on each slide.

E. Scanning Electron Microscope (SEM) Analysis

SEM analysis was performed to obtain high-resolution images of nannofossils, confirm taxonomic identification, and document preservation states. SEM images were used as supporting data to validate observations obtained from polarizing light microscopy.

F. Relative Age Determination and Paleoclimate Analysis

Relative age determination was conducted based on Paleogene nannofossil zonation following Martini (1971). Paleoclimate interpretation was achieved by integrating several quantitative parameters commonly applied in calcareous nannofossil studies (Agnini et al., 2014; Ma et al., 2024; Menini et al., 2021), including:

1) *Reticulofenestra* Size Ratio (RSR)

$$RSR = \frac{N_{small\ Reticulofenestra}}{N_{large\ Reticulofenestra}} \quad \text{.....(1)}$$

2) Warm-Water Index (WWI)

$$WWI\ (\%) = \frac{N_{warm\ water\ taxa}}{N_{total\ nannofossil}} \times 100 \quad \text{.....(2)}$$

3) *Discoaster* Abundance Ratio (DAR)

$$DAR\ (\%) = \frac{N_{Discoaster}}{N_{total\ nannofossil}} \times 100 \quad \text{.....(3)}$$

4) Total *Reticulofenestra* abundance

$$Reticulofenestra\ (\%) = \frac{N_{total\ Reticulofenestra}}{N_{total\ nannofossil}} \times 100 \quad (4)$$

These parameters were applied to reconstruct variations in sea surface temperature, water-column stability, and surface-water productivity during the Eocene. The Reticulofenestra Size Ratio (RSR) is primarily used as an indicator of nutrient availability and productivity, where higher proportions of small-sized morphotypes generally reflect increased nutrient supply and more eutrophic conditions, while dominance of larger morphotypes indicates oligotrophic environments.

The Warm-Water Index (WWI) serves as a proxy for sea surface temperature, as it is based on the relative abundance of warm-water taxa such as Coccolithus pelagicus and Reticulofenestra umbilicus, which are typically associated with elevated temperatures in low-latitude marine settings.

The Discoaster Abundance Ratio (DAR) is widely interpreted as an indicator of water-column stability and stratification, as Discoaster taxa are commonly associated with warm, stratified, and oligotrophic surface waters. Higher DAR values therefore reflect increased stratification and reduced vertical mixing.

Finally, total Reticulofenestra abundance provides additional insight into overall surface-water conditions, including productivity levels and ecological dominance within the nannoplankton community. These interpretations are based on established ecological relationships between nannofossil assemblages and surface-oceanographic conditions (Agnini et al., 2014; Ma et al., 2024; Okada and Honjo, 1973).

3. Result and Discussions

The stratigraphy of the Bayat area is generally composed of a pre-Tertiary metamorphic rock complex, overlain by carbonate–clastic units that are regionally correlated with the Eocene Gamping-Wungkal Formation (Surono, 2009). However, at the local scale, contacts between units are indistinct, irregular, and challenging to trace laterally. Consequently, age determination of the stratigraphic units relies heavily on nannofossil biostratigraphy. The outcrop conditions and sampling traverse used for systematic claystone sampling along a 60 m measured section are shown in Figure 4.

Fig. 4. Outcrop photograph of the sampling location in the study area. The outcrop extends from south to north and has an approximate length of 60 m. Points of interest include claystone, graphite intercalations, and limestone layers, with evidence of

landslide deposits observed in the northern part of the outcrop. The white dashed line indicates the sampling traverse.

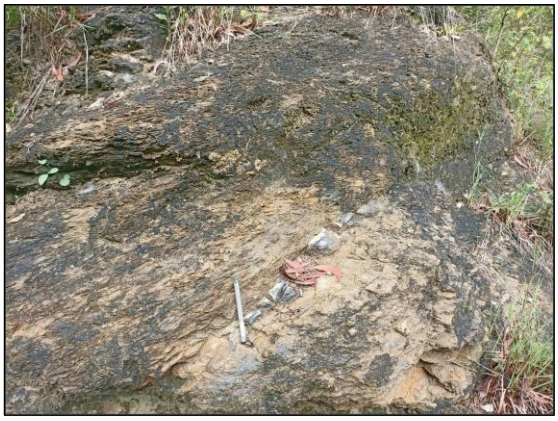


Fig. 5. Limestone unit in the study area.

3.1 Limestone Unit of the Gamping-Wungkal Formation

Along the measured section, limestone occurs only as isolated and discontinuous exposures (Figure 7), characterized by dark black coloration and a micritic texture (Figure 5). The irregular distribution of these limestones suggests that they represent remnants of the carbonate facies of the Gamping-Wungkal Formation that have undergone intense deformation and erosion. Regionally, the carbonate unit of the Gamping-Wungkal Formation is assigned to the Middle-Late Eocene (Surono, 2009) and is commonly associated with microfossil-rich shale.

3.2 Claystone Unit of the Gamping-Wungkal Formation

Claystone is the dominant lithological unit and the primary focus of this study (Figure 7). The claystone exhibits color variations ranging from reddish brown and dark brown to gray, reflecting differences in organic matter content and redox conditions (Figure 6a). Its widespread distribution and association with sandstone support its assignment to the Gamping-Wungkal Formation, within which graphite intercalations are locally observed (Figure 6b). Due to unclear stratigraphic relationships and the absence of well-defined contacts in the field, age determination of this unit is based on nannofossil analysis.

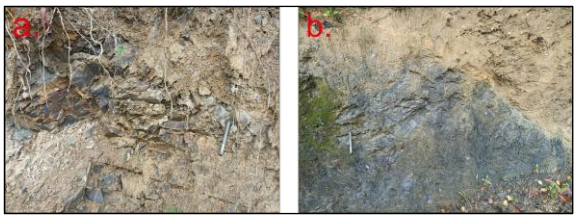


Fig. 6. Field photographs of the Claystone unit of the Gamping-Wungkal Formation in the study area. (a) claystone unit showing massive texture and brown to gray coloration; (b) graphitic claystone characterized by darker color and graphite-rich layers.

The lithological association of micritic limestone and claystone observed within the studied section suggests sedimentation under relatively low-energy marine conditions. Micritic carbonate typically forms through the accumulation of fine carbonate mud produced by planktonic organisms and microbial processes in calm-water settings. In contrast, the presence of claystone indicates the contribution of fine terrigenous or hemipelagic material settling through the water column. Such lithological characteristics are commonly associated with outer neritic to open-shelf environments along carbonate platform margins. In tropical greenhouse intervals such as the Middle–Late Eocene, these environments supported high coccolithophore productivity, leading to the accumulation of calcareous nannofossils within fine-grained marine sediments (Ghandour et al., 2023; Villa et al., 2021).

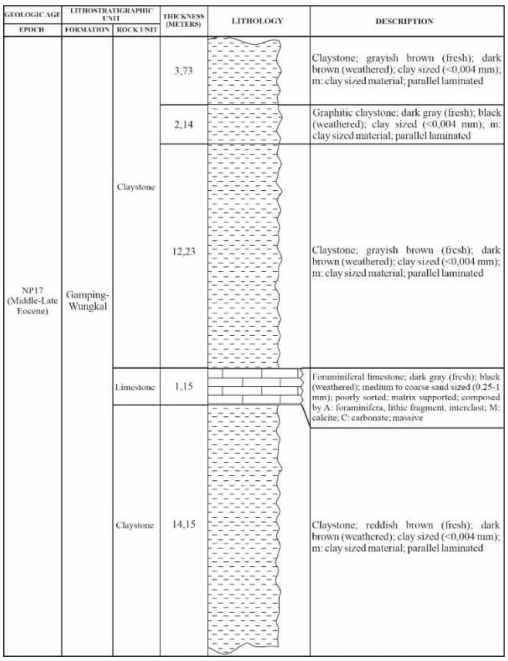


Fig. 7. Stratigraphy of the study area.

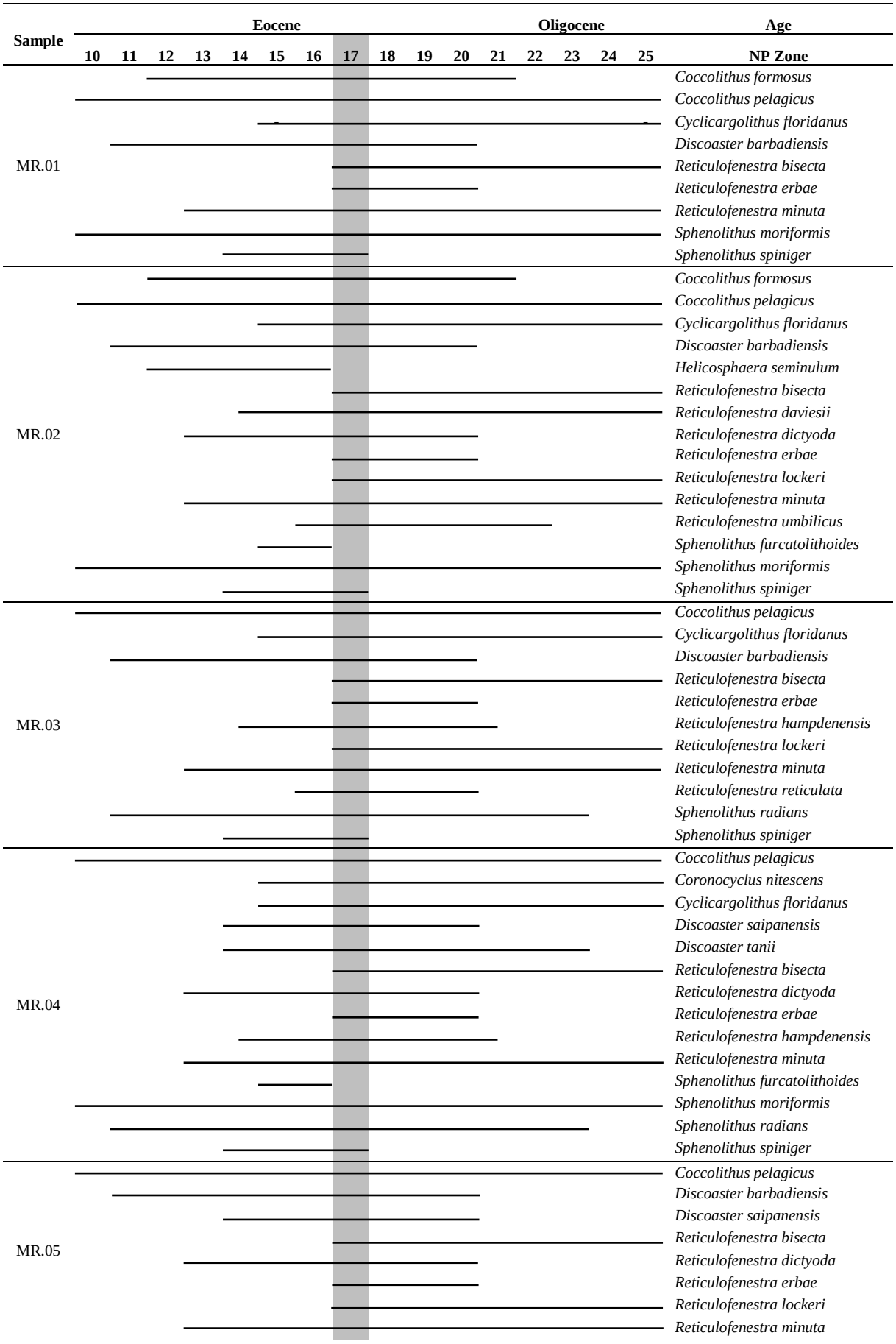
As shown in Figure 7, the measured stratigraphic section represents the corrected thickness of exposed lithological units rather than the total lateral extent of the outcrop, which reaches approximately 60 m. Vertical variations within the studied interval indicate relatively stable depositional conditions during the accumulation of the claystone-dominated succession of the Gamping–Wungkal Formation. The persistence of fine-grained lithologies and the absence of significant changes in sedimentary facies suggest continuous marine sedimentation without major shifts in depositional energy or water depth.

Sampling locations are distributed along the measured section and are indicated in Figure 7, primarily targeting claystone intervals suitable for nannofossil analysis. Minor fluctuations observed in the relative abundance of calcareous nannofossils (Table 2) likely reflect subtle variations in surface-water productivity rather than major environmental changes. Similar stratigraphic patterns have been documented in other Eocene marine successions where stable greenhouse climatic conditions promoted persistent coccolithophore productivity and continuous pelagic carbonate sedimentation (Raffi et al., 2022; Villa et al., 2021).

3.3 Nannofossil

Based on nannofossil analysis of the study area, the fossil assemblages exhibit compositional and abundance variations consistent with Martini's (1971) zonation scheme. All six samples are characterized by the dominance of *Reticulofenestra bisecta*, *Reticulofenestra erbae*, *Coccolithus pelagicus*, and the continuous occurrence of *Discoaster barbadiensis*, indicating assignment to the NP17 zone (Middle–Late Eocene) (Table 1). The relative abundance of nannofossil taxa in each sample is summarized in Table 2. Taxonomic identification and preservation assessment were conducted using light microscopy and SEM observations; representative photomicrographs are presented in Figure 8 and SEM images in Figure 9.

Table 1. Relative-age zonation table for the study area based on nannofossil distribution.



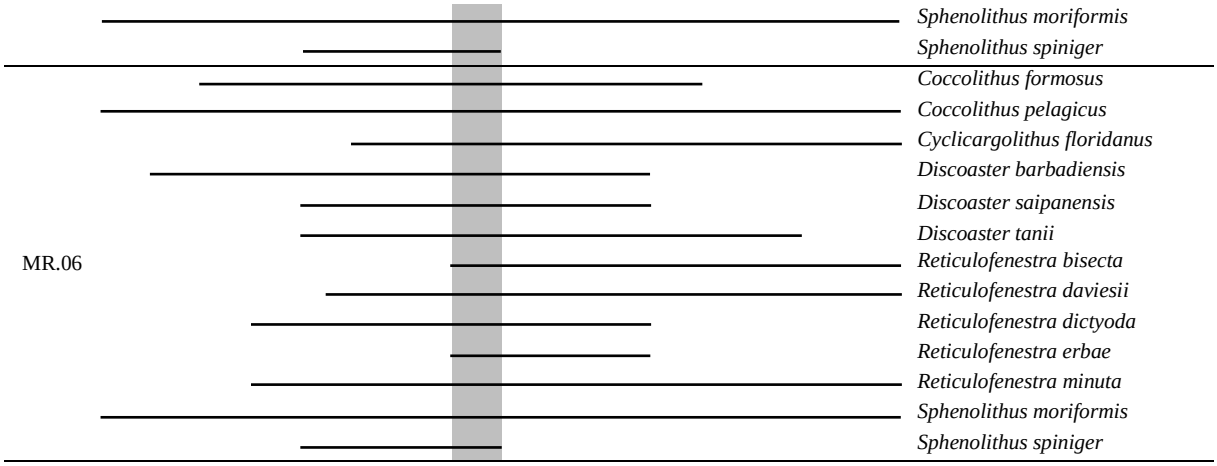


Table 2. Nannofossil abundance table of the study area.

Nannofossil	Sample					
	MR.01	MR.02	MR.03	MR.04	MR.05	MR.06
Coccolithus formosus	1	5				3
Coccolithus pelagicus	4	13	1	2	1	4
Coronocyclus nitescens				1		
Cyclicargolithus floridanus	4	4	1	2		4
Discoaster barbadiensis	2	2	1		1	6
Discoaster saipanensis				2	3	2
Discoaster tanii				1		1
Helicosphaera seminulum		2				
Reticulofenestra bisecta	10	9	7	5	7	10
Reticulofenestra daviesii		1				2
Reticulofenestra dictyoda		3		1	1	4
Reticulofenestra erbae	12	7	10	10	6	14
Reticulofenestra hampdenensis			1	1		
Reticulofenestra lockeri		1	1		2	
Reticulofenestra minuta	3	5	1	2	2	4
Reticulofenestra reticulata			1			
Reticulofenestra umbilicus		1				
Sphenolithus furcatolithoides		1		1		
Sphenolithus moriformis	5	4		5	1	5
Sphenolithus radians			1	2		
Sphenolithus spiniger	4	1	1	2	1	5

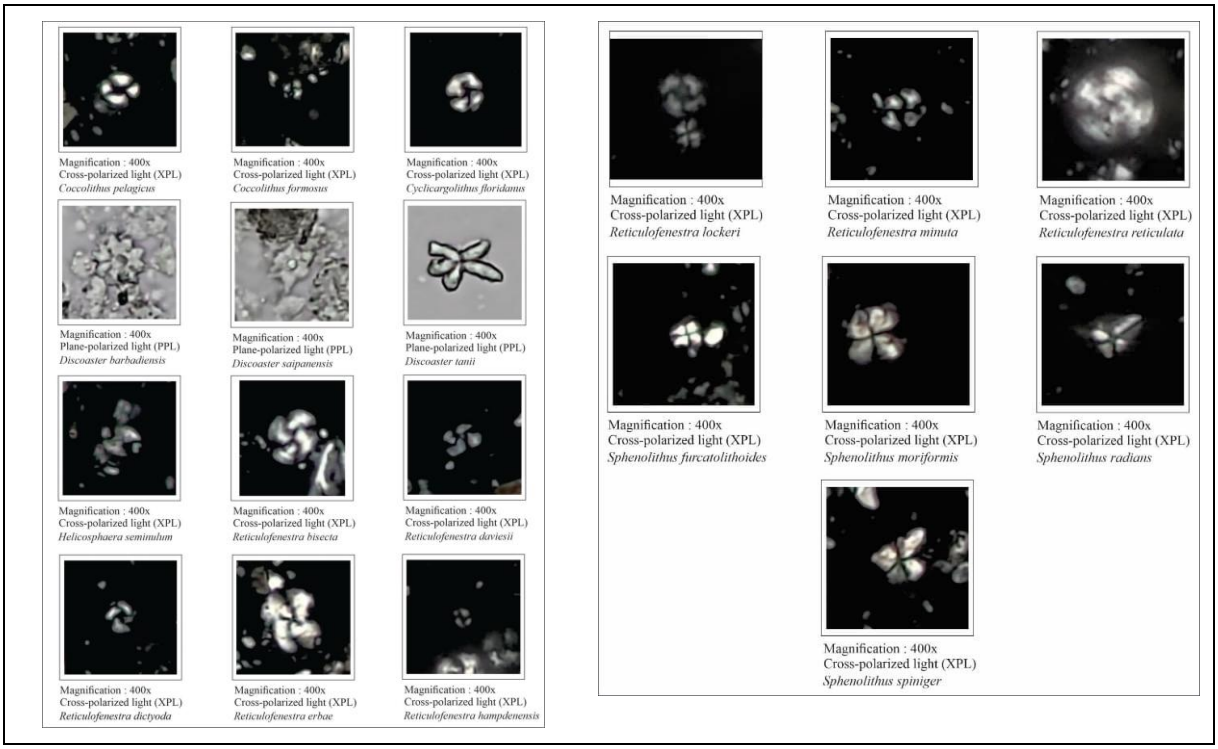


Fig. 8. Photomicrographs of nannofossil species from the study area were obtained using a polarizing microscope.

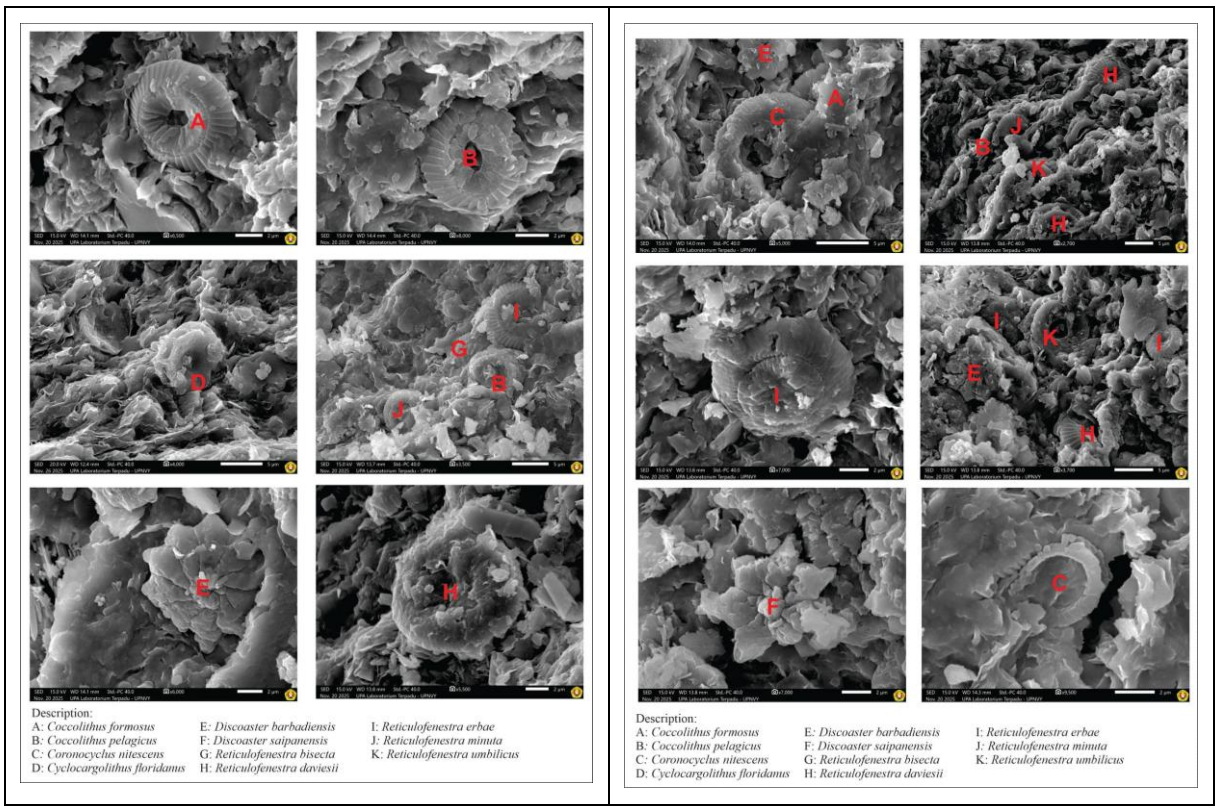


Fig. 9. Scanning Electron Microscope (SEM) images of nannofossil species from the study area.

3.4 *Reticulofenestra* Size Ratio (RSR)

Based on the abundance data of *Reticulofenestra* taxa (Table 2), all samples are dominated by large-sized species, including *Reticulofenestra dictyoda, Reticulofenestra erbae, Reticulofenestra hampdenensis, Reticulofenestra lockeri, Reticulofenestra reticulata*, and *Reticulofenestra umbilicus*. Medium-sized taxa, such as *Reticulofenestra bisecta* and *Reticulofenestra daviesii*, are also present, whereas small-sized taxa, particularly *Reticulofenestra minuta*, occur only in limited amounts. This assemblage composition indicates a dominance of large-sized *Reticulofenestra* morphotypes over small-sized forms, indicating relatively stable and nutrient-limited surface-water conditions during the NP17 interval in the study area (Table 3).

These findings are consistent with low-latitude Middle–Late Eocene marine settings characterized by enhanced upper-ocean stratification and reduced nutrient supply, conditions that favored the proliferation of larger reticulofenestrid morphotypes (Fokkema et al., 2024; Hutchinson et al., 2021).

3.5 Warm-Water Index (WWI)

In all samples assigned to the NP17 interval, the WWI is primarily controlled by the abundance of Coccolithus pelagicus, whereas *Reticulofenestra umbilicus* occurs only in limited amounts (Table 4). Elevated contributions of warm-water taxa, particularly *Coccolithus pelagicus*, indicate warm and relatively stable surface-water conditions during the NP17 interval in the Bayat Basin. These conditions are consistent with low-latitude Eocene records characterized by enhanced upper-ocean stratification and reduced nutrient supply (Fokkema et al., 2024).

3.6 *Discoaster* Abundance Ratio (DAR)

The *Discoaster* Abundance Ratio (DAR) ranges from 3.7% to 16.6% (Table 5) and shows a progressive increase from the lower to the upper part of the measured section. Samples MR.01–MR.03 (3.7–4.4%) are characterized by relatively limited Discoaster representation, whereas samples MR.05 and MR.06 (15.3–16.6%) show a more pronounced contribution of Discoaster within the assemblage.

This upward trend indicates a gradual shift in nannofossil composition, reflecting increasing influence of Discoaster-producing taxa through time. Such variations suggest changes in surface-water conditions, particularly in relation to water-column structure and ecological stability during deposition.

The persistence and increasing contribution of Discoaster throughout the section are consistent with low-latitude Middle–Late Eocene marine records, where nannofossil assemblages commonly reflect stable and stratified surface-water conditions despite broader climatic variability (Fokkema et al., 2024; Westerhold et al., 2024).

3.7 Total Reticulofenestra Abundance

Reticulofenestra constitutes a major component of the assemblage in all samples, indicating its ecological significance within the nannoplankton community during deposition (Table 6). The consistent presence and relatively strong contribution of this genus across the studied interval suggest stable environmental conditions that supported continuous coccolithophore productivity.

Such assemblage characteristics are commonly associated with stratified surface waters, where Reticulofenestra forms a dominant component of pelagic carbonate production. The observed distribution pattern therefore reflects relatively stable upper-ocean conditions rather than highly dynamic or strongly upwelling environments.

Table 3. Comparison table of Reticulofenestra as RSR indicators in the study area.

Sample	Small *Reticulofenestra* (<5 μm)	Medium *Reticulofenestra* (5-7 μm)	Large *Reticulofenestra* (>7 μm)	RSR (Small/Large)
MR.01	3	10	12	0.25
MR.02	5	10	12	0.41
MR.03	1	7	13	0.07
MR.04	2	5	12	0.16
MR.05	2	7	9	0.22
MR.06	4	12	18	0.22

Table 4. Abundance table of WWI indicators in the study area.

Sample	*C. pelagicus*	*R. umbilicus*	Total Nannofossil	WWI(%)
MR.01	4	0	45	8.9
MR.02	15	1	54	29.6
MR.03	1	0	26	3.8
MR.04	2	0	36	5.6
MR.05	1	0	26	3.8
MR.06	4	0	54	7.4

Table 5. Abundance table of *Discoaster* as DAR indicators in the study area.

Sample	Total *Discoaster*	Total Nannofossil	DAR (%)
MR.01	2	45	4.4
MR.02	2	54	3.7
MR.03	1	26	3.8
MR.04	3	36	8.3
MR.05	4	26	15.3
MR.06	9	54	16.6

Table 6. Abundance table of Reticulofenestra in the study area.

Sample	Total *Reticulofenestra*	Total Nannofossil	Percentage (%)
MR.01	25	45	55.5
MR.02	27	54	50
MR.03	21	26	80.7
MR.04	19	36	52.7
MR.05	18	26	69.2
MR.06	34	54	62.9

Based on the integrated interpretation of RSR, WWI, DAR, and total Reticulofenestra abundance, the paleoclimatic conditions of the Bayat Basin during the NP17 interval (Middle–Late Eocene) are interpreted to have been dominated by warm and stratified surface waters. The dominance of medium- to large-sized Reticulofenestra and the consistent presence of Discoaster indicate stable upper-ocean structure and limited nutrient input during deposition. (Fokkema et al., 2024; Westerhold et al., 2024).

Although the NP17 interval postdates the peak of the EECO, global syntheses indicate that low-latitude sea-surface temperatures remained relatively elevated during the Middle–Late Eocene despite progressive long-term climatic variability (Westerhold et al., 2024). The nannofossil data from the Bayat Basin, therefore, suggest that southern Java remained under a sustained warm tropical marine influence during this interval.

3.8 Implications for Low-Latitude Greenhouse Climate Dynamics

The dominance of large-sized *Reticulofenestra* and the relatively high abundance of *Discoaster* during the NP17 interval indicate that the studied section was deposited under persistently warm and stratified marine conditions. Such assemblage characteristics are typical of low-latitude Eocene environments, where stable surface waters and limited nutrient supply promoted the proliferation of oligotrophic coccolithophore communities. These observations suggest that the Bayat Basin remained under a strong tropical greenhouse influence throughout the Middle–Late Eocene.

Recent syntheses of Middle–Late Eocene climate evolution emphasize that low-latitude ocean systems maintained relatively elevated sea-surface temperatures and persistent upper-ocean stratification despite long-term global cooling trends (Westerhold et al., 2024). Integrated geochemical and micropaleontological records further demonstrate that tropical plankton communities continued to reflect greenhouse-like surface-water structures even as variability increased in higher-latitude regions (Fokkema et al., 2024; Ma et al., 2024). Such latitudinal differences in climate expression have been linked to enhanced ocean heat storage and reduced seasonal contrast in equatorial regions (Hutchinson et al., 2021).

The paleoclimatic signals obtained from the Bayat Basin are consistent with this broader framework. While several mid-latitude marine records document progressive cooling during the later Eocene (Westerhold et al., 2024), the studied section instead preserves evidence of sustained warm and oligotrophic surface-water conditions. This contrast highlights the relatively stable nature of tropical marine environments during this interval.

These findings contribute to the growing recognition that tropical marine systems did not respond uniformly to global Paleogene cooling. Instead, low-latitude regions appear to have maintained relatively stable greenhouse conditions despite increasing climatic variability elsewhere. This underscores the importance of incorporating Southeast Asian low-latitude records, such as the Bayat Basin, into global paleoclimate syntheses, which are still dominated by mid-latitude datasets from the Atlantic and Pacific oceans.

4. Conclusion

Based on nannofossil analysis of the claystone from the Gamping-Wungkal Formation. The distribution of

nannofossil assemblages is dominated by *Reticulofenestra*, *Coccolithus*, and *Discoaster*, with limited occurrences of *Cyclicargolithus* and *Sphenolithus*. The most abundant species include *Reticulofenestra bisecta*, *Reticulofenestra erbae*, *Coccolithus pelagicus*, and *Discoaster barbadiensis*.

Relative age determination based on nannofossil zonation indicates that the studied claystone unit corresponds to the NP17 zone, equivalent to the Middle-Late Eocene.

Paleoclimatic interpretation derived from the *Reticulofenestra* Size Ratio, *Discoaster* Abundance Ratio, Warm-Water Index, and total *Reticulofenestra* abundance suggests that during the NP17 interval, marine conditions were dominated by a warm climate with a relatively stable water column, reflecting the development of the Bayat Basin under tropical greenhouse climate conditions during the Middle-Late Eocene.

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