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Depositional Environment of the Rajamandala Formation Based on Foraminiferal Analysis from the Kemang Area, Cianjur Regency, Bogor Basin, West Java, Indonesia

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Abstract
The Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml) represent mixed siliciclastic–carbonate and carbonate deposits within the Bogor Basin. This study aims to determine the depositional environments and to evaluate the stratigraphic relationship between these two units by integrating geological mapping and micropaleontological analysis. Biostratigraphic analysis based on planktonic foraminifera indicates that both the Calcareous sandstone unit of the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml) were deposited during the Early Miocene (Zones N7–N8). Benthic foraminiferal assemblages indicate deposition within an inner–middle neritic environment for both units. Field observations document a direct contact between the two lithologies, while geological mapping shows calcareous sandstone becoming increasingly abundant toward the southwest and limestone becoming progressively dominant toward the northeast. The equivalent ages, similar depositional environments, and observed field relationships are consistent with the interpretation that the two units were deposited contemporaneously and exhibit lateral facies variation within the same shallow marine depositional system.

1. Introduction

The study area is located within the Bogor Basin, a foreland basin in West Java that formed as a consequence of the long-term subduction of the Indo-Australian Plate beneath the Eurasian Plate [1] The tectonic evolution of the basin resulted in progressive subsidence and sediment accumulation, providing favorable conditions for the development of siliciclastic and carbonate depositional systems during the Cenozoic [2] Within this basin, the Rajamandala Formation preserves carbonate platform deposits that provide an important record for evaluating facies relationships and depositional evolution [3]

The Rajamandala Formation is an important Tertiary carbonate unit that records the geological evolution of the Bogor Basin from the Oligocene to the Miocene [4] According to the regional stratigraphic framework, the Rajamandala Formation is subdivided into two members: the Limestone Member (Oml) and the Clay, Marl, and Calcareous Sandstone Member (Omc) [5] The Limestone Member is predominantly composed of massive to well-bedded limestone, whereas the Omc Member consists of clay, marl, calcareous sandstone, and conglomeratic deposits, reflecting significant lithological variation within the formation [6] Regionally, the Rajamandala Formation has been interpreted as part of a barrier reef system trending east-northeast to west-southwest, with reef-front and basin facies developed along its northern margin. Previous studies have suggested an interfingering relationship between the Omc and Oml members, indicating lateral lithological variation within the Rajamandala Formation [7] These lithological variations have been interpreted as reflecting the combined influence of tectonic activity and variations in siliciclastic sediment supply. Therefore, the lithological diversity of the Rajamandala Formation makes it an important unit for reconstructing the depositional environments of the Bogor Basin [8].

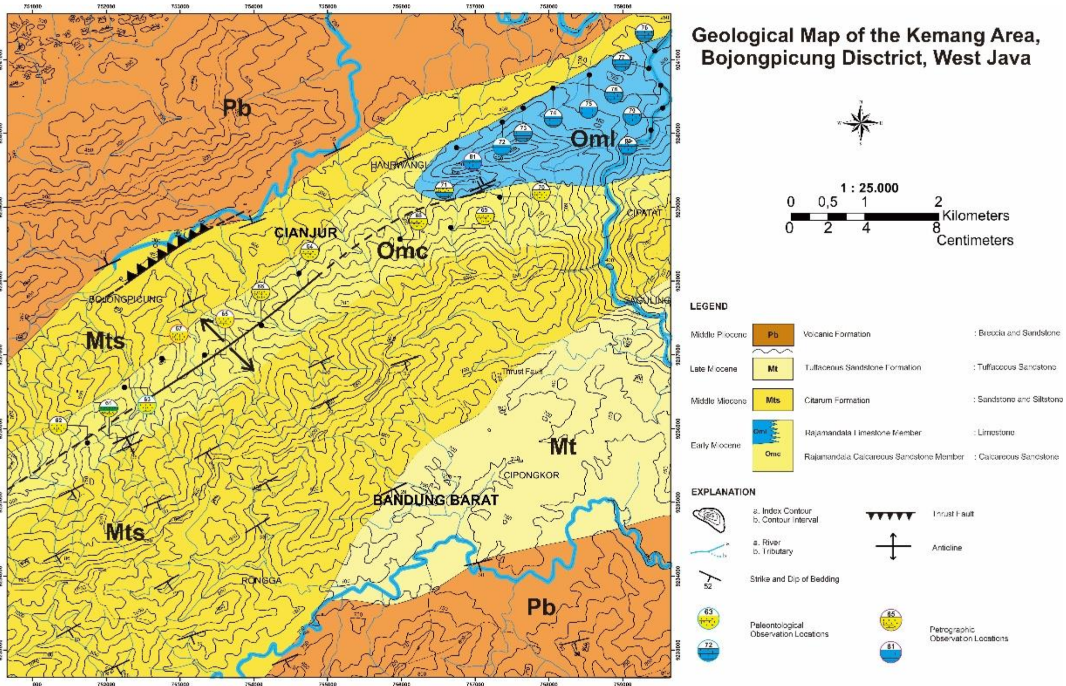


Figure 1. Geological map of the research area

Based on field mapping, the study area comprises two main formations that are stratigraphically related: the Rajamandala Limestone Member (Oml) and the Rajamandala Calcareous Sandstone Member (Omc). The Rajamandala Calcareous Sandstone Member (Omc) is characterized by calcareous sandstone lithology, whereas the Rajamandala Limestone Member (Oml) is dominated by massive limestone. The close stratigraphic position of these two units raises the question of whether they represent a conformable vertical succession or lateral facies changes through an interfingering relationship driven by bathymetric dynamics during deposition. Understanding these facies relationships depends on accurate identification of lithology and fossil content to reconstruct the depositional history reliably [9]

Paleontological analysis was conducted to identify planktonic and benthic foraminifera based on their morphological characteristics, providing a basis for determining the relative age and depositional environment of the studied units [10]. The ecological distribution of planktonic and benthic foraminifera has long been recognized as a reliable indicator for biostratigraphic correlation and paleoenvironmental reconstruction [11] Although the Rajamandala Formation has been widely investigated, the stratigraphic relationship between the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml), particularly their lateral facies relationship, remains insufficiently constrained [12] Therefore, this study integrates geological mapping and micropaleontological analyses to evaluate the relative age, depositional environment, and stratigraphic relationship of these units, providing new geological evidence for interpreting lateral facies variations within the Rajamandala depositional system [13]

2. Methodology

This study consisted of three stages, including pre-fieldwork, fieldwork, and laboratory-based petrographic and micropaleontological analyses. The pre-fieldwork stage included a literature review, interpretation of the Geological Map of the Cianjur Quadrangle [14], and planning of geological traverses to determine representative observation locations. Geological mapping was conducted at 22 outcrops, comprising 11 outcrops within the Rajamandala Calcareous Sandstone Member (Omc) and 11 outcrops within the Rajamandala Limestone Member (Oml). One representative carbonate rock sample weighing approximately 500–1000 g was collected from each unit, namely RL63 (UTM 752818 E; 9236924 N) from the Rajamandala Calcareous Sandstone Member (Omc) and RL72 (UTM 757411 E; 9240153 N) from the Rajamandala Limestone Member (Oml). Fresh, unweathered samples were selected to preserve the original microfossil assemblages. Laboratory preparation involved mechanically crushing the samples, soaking them in a distilled water H_2O_2 solution for 24 h to disaggregate the rock matrix, oven-drying them at 50°C for 2 h, and wet-sieving them through a 100-mesh (149 μm) sieve for 3 min with three repeated washing cycles before examination under a binocular stereomicroscope. Planktonic and benthic foraminifera were manually picked and identified based on their morphological characteristics following standard taxonomic procedures commonly applied in recent Indonesian micropaleontological studies [15] The relative age of each unit was determined from the narrowest stratigraphic overlap of the principal planktonic foraminiferal index taxa by integrating their First Appearance Datum (FAD) and Last Appearance Datum (LAD) according to the planktonic foraminiferal biozonation proposed [16] Petrographic analysis of representative thin sections was performed to quantify the proportions of framework grains, matrix, and cement, thereby providing complementary information on rock composition and depositional characteristics [17] Depositional environment and paleobathymetry were interpreted based on the ecological distribution of benthic foraminiferal assemblages [18] Finally, lithological observations, petrographic characteristics, and micropaleontological data were integrated to evaluate the stratigraphic relationship between the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml).

3. Results and discussions

3.1 Rajamandala Calcareous Sandstone Member

The Rajamandala Formation is one of the principal lithostratigraphic units exposed in the study area and is represented by the Rajamandala Calcareous Sandstone Member (Omc). This unit consists predominantly of calcareous sandstone. Macroscopically, the calcareous sandstone is characterized by a brownish-gray weathered surface and a gray fresh surface. It is fine-grained, well sorted, composed of rounded grains, exhibits a closed packing fabric, contains abundant carbonate material, and displays a massive sedimentary structure. The abundance of carbonate material within the sandstone suggests deposition under the influence of both siliciclastic and carbonate sediment input, indicating a mixed siliciclastic carbonate depositional system.

Based on petrographic observations of the calcareous sandstone, the siliciclastic sedimentary rock thin section examined under 40× magnification exhibits a brown color in plane-polarized light (PPL) and creamish-brown interference colors in cross-polarized light (XPL). The rock has grain sizes ranging from 0.04 to 0.73 mm (coarse silt to coarse sand), a matrix size of 0.02–0.10 mm (medium silt to very fine sand), and cement smaller than 0.01 mm. The grains are subangular to rounded with low sphericity, displaying a matrix supported fabric, well-sorted texture, floating (A8) and point (H7) grain contacts, and intragranular porosity. The rock is composed of 31% skeletal grains, 23% quartz, and 8% amphibole. The matrix is composed of 20% micrite, whereas the cement consists of 16% calcite as the cement. Based on its petrographic characteristics, the rock is classified as Sandy Allochem Limestone.

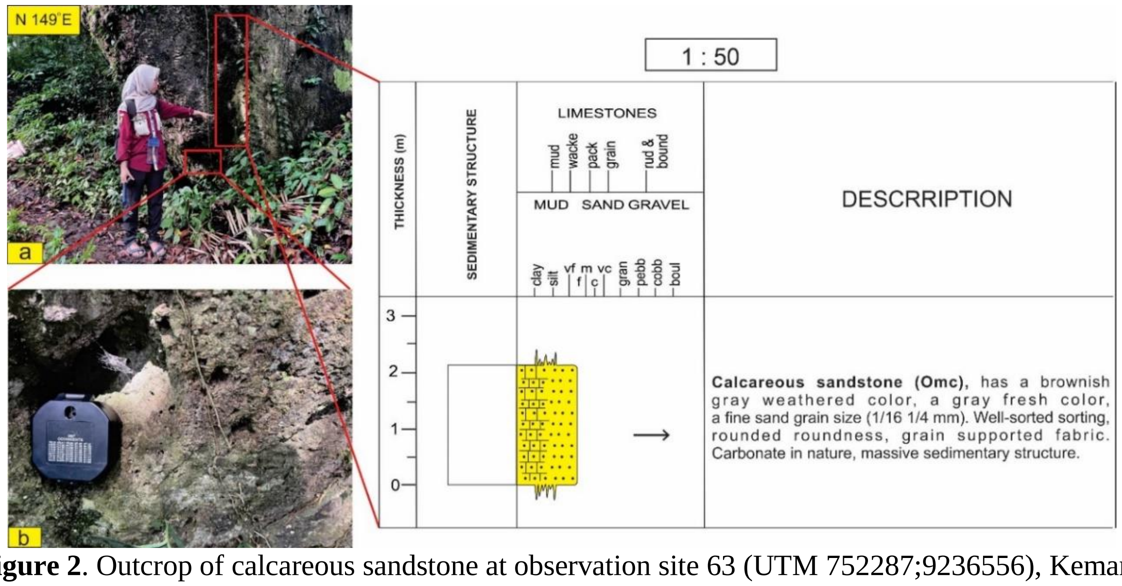


Figure 2. Outcrop of calcareous sandstone at observation site 63 (UTM 752287;9236556), Kemang Village: (A) distant view of the outcrop, (B) close-up view, and (C) outcrop profile.

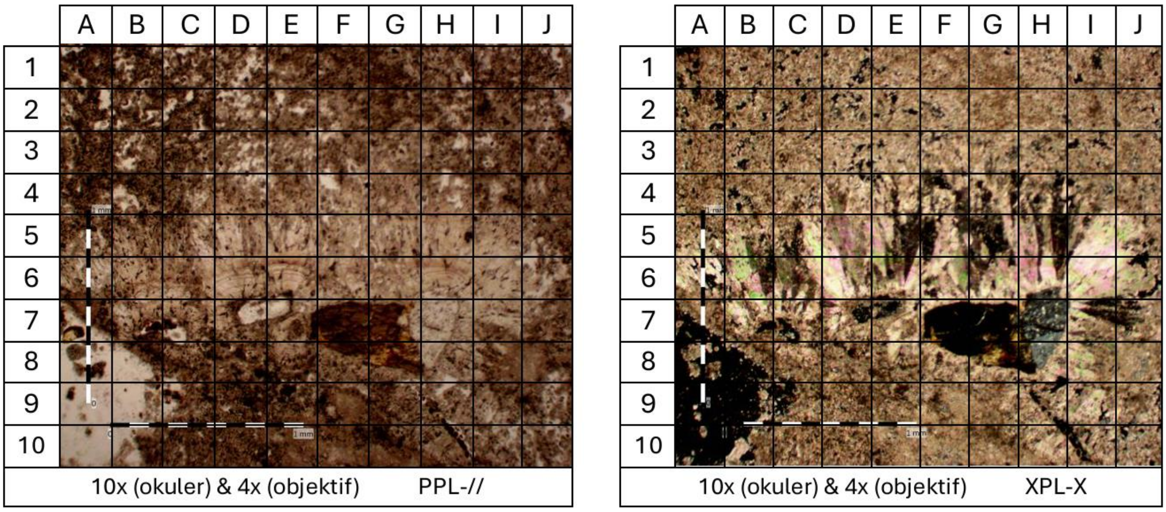


Figure 3. Thin section of Sandy Allochem Limestone from Station/RL 65 (UTM 753373; 9236994), Rajamandala Calcareous Sandstone Member (Omc).

The relative age of the Rajamandala Calcareous Sandstone Member was determined through planktonic foraminiferal biostratigraphic analysis. A total of 38 well-preserved planktonic foraminiferal specimens were identified from sample RL63, comprising *Globigerinoides diminutus* (15 specimens), *Globorotalia siakensis* (4 specimens), *Praeorbulina glomerosa* (7 specimens), *Globigerina praebulloides* (3 specimens), and *Praeorbulina transitoria* (9 specimens). Species identification was based on diagnostic morphological characteristics, including test morphology, chamber arrangement, aperture characteristics, and wall ornamentation. Biostratigraphic interpretation was carried out using the planktonic foraminiferal zonation [16]. All examined specimens are archived under sample code RL63 in the Paleontology Laboratory, Department of Geological Engineering, Universitas Sriwijaya. The identified planktonic foraminiferal assemblage provides the basis for determining the relative age of the Rajamandala Calcareous Sandstone Member in the study area.

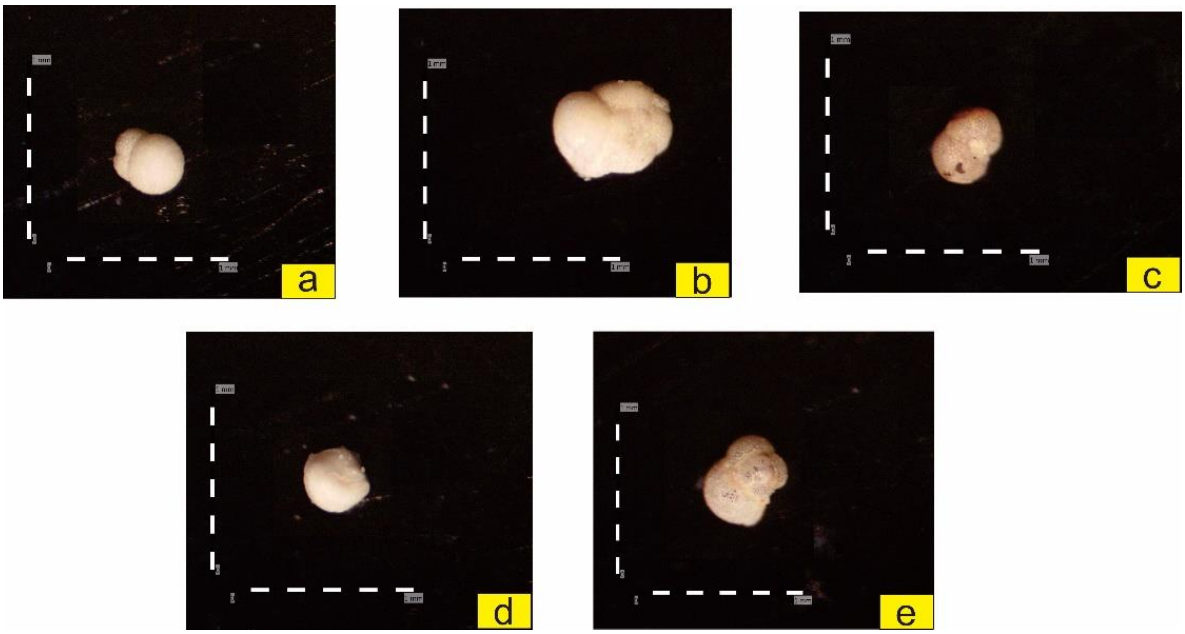


Figure 4. Planktonic Foraminiferal Fossils of the Rajamandala Calcareous Sandstone Member (Omc) (UTM 752287;9236556) : *Globigerinoides diminutus* (a) *Globorotalia siakensis* (b) *Praeorbulina glomerosa* (c) *Globigerina praebulloides* (d) *Praeorbulina transitoria* (e).

Biostratigraphic analysis of the planktonic foraminiferal assemblage indicates an Early Miocene age (Zones N7–N8) for the Rajamandala Calcareous Sandstone Member. The age assignment was established by integrating the First Appearance Datum (FAD) and Last Appearance Datum (LAD) of the identified index taxa within the planktonic foraminiferal zonation of Blow (1969). The interpreted age is constrained by the narrowest overlap of the stratigraphic ranges of the assemblage, providing a reliable biostratigraphic age assignment.

Table 1. Relative age interpretation of the RL63 Calcareous Sandstone lithology based on planktonic foraminifera [16].

Sample / Formation	: RL 63 / Omc	Rock Type	: Sedimentary Rock
Location	: Kemang Village	Age Range	: Early Miocene
Rock Name	: Calcareous sandstone	Analyse by	: Dianda Rahma Aulia

Planktonic Foraminifera (Blow, 1969)	Oligocene		Miocene										
	Late		Early					Middle					
Age ->	e.1-4		e.5					f.1		F.2		f.3	
	N2 P21	N3 P22	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14
Globigerinoides diminutus (A)													
Globorotalia siakensis (R)													
Praeorbulina glomerosa (C)													
Globigerina praebulloides (R)													
Praeorbulina transitoria (C)													

The benthic foraminiferal assemblage recovered from sample RL63 comprises Anomalinella rostrata (12 specimens), Operculina ammonoides (8 specimens), Heterostegina depressa (14 specimens), Orthoplecta clavata (3 specimens), and Tubinella funalis (13 specimens). The recovered specimens are generally well preserved and exhibit minimal fragmentation and abrasion, indicating that the assemblage has not been significantly affected by post-depositional transport or reworking. The ecological depth ranges of the identified taxa were compiled [19] and subsequently compared to evaluate their bathymetric distribution. The identified taxa show overlapping ecological depth ranges, providing the basis for subsequent paleobathymetric and depositional environment interpretations.

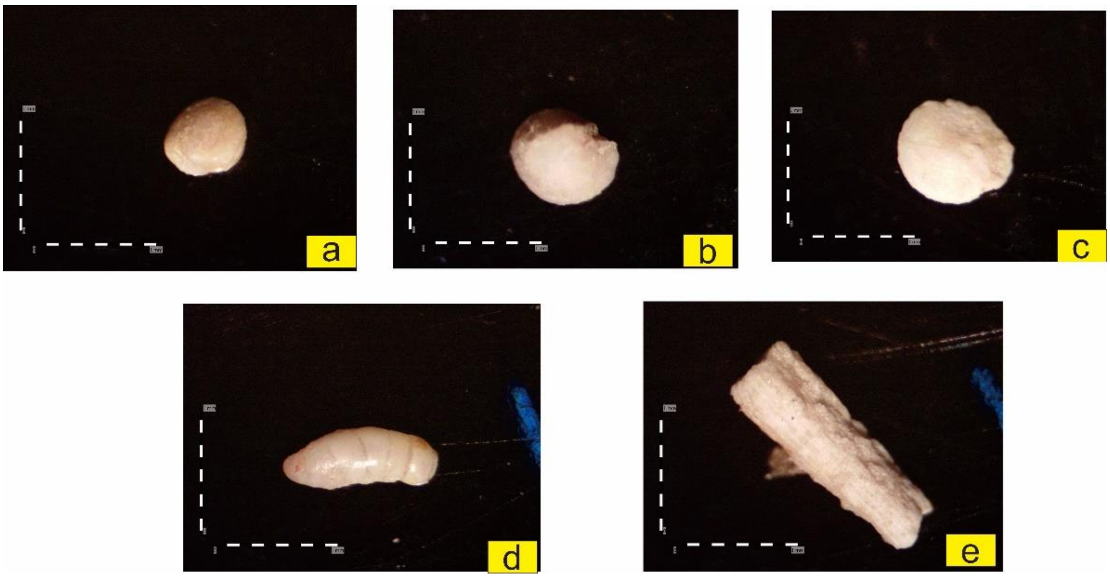
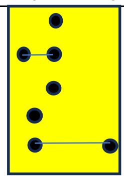


Figure 5. Benthic Foraminiferal Fossils of the Rajamandala Calcareous Sandstone Member (Omc) (UTM 752287;9236556) : *Anomalinella rostrata* (A) *Operculina ammonoides* (B) *Heterostegina depressa* (C) *Orthoplecta clavata* (D) *Tubinella funalis* (E).

Table 2. Table of Bathymetric Environment Interpretation for the RL63 Calcareous Sandstone Lithology [19].

Sample / Formation	: RL 63 / Omc	Rock Type	: Sedimentary Rock
Location	: Kemang Village	Bathymetric Environment	: Inner Neritic–Middle Neritic
Rock Name	: Calcareous Sandstone	Analyzed by	: Dianda Rahma Aulia

Bathymetric Environment, feet depth ->	Transitional	Neritic			Bathyal		Abyssal
		Inner	Middle	Outer	Upper	Lower	
Benthic Foraminifera (Barker, 1960)	0	20	100	200	500	2000	4000
Anomalinella rostrata (37 ft)							
Operculina ammonoides (16-25 ft)							
Heterostegina depressa (40 ft)							
Orthoplecta clavata (17 ft)							
Tubinella funalis (20-60 ft)							



The depositional environment was interpreted based on paleobathymetric analysis using the ecological depth ranges of the benthic foraminifera identified in the samples. The applied principle involves comparing the ecological depth ranges of the identified benthic species and determining their overlapping interval to obtain the most representative estimate of depositional depth. The ecological depth ranges of the identified taxa were compiled [19] including *Anomalinella rostrata* (37 ft), *Operculina ammonoides* (16–25 ft), *Heterostegina depressa* (18 ft), *Orthoplecta clavata* (17 ft), and *Tubinella funalis* (20–60 ft). With this approach, paleobathymetric interpretation was based on the combined benthic foraminiferal assemblage rather than on a single species. The overall ecological ranges of the assemblage indicate an estimated paleobathymetric range of approximately 16–60 ft, corresponding to an inner neritic–middle neritic depositional environment. This interpretation is consistent with the carbonate lithology and indicates deposition in a marine shelf environment.

3.2 Rajamandala Limestone Member (Oml)

The Rajamandala Limestone Member (Oml) is characterized by limestone as its dominant lithology. Macroscopically, exhibits a dark gray weathered color and a light gray fresh surface. The rock is characterized by renite grain size, well-sorted texture, and rounded grains, with massive sedimentary structure, closed packing, and a predominantly carbonate composition. The dominance of carbonate components indicates that carbonate sedimentation played an important role during the formation of this unit.

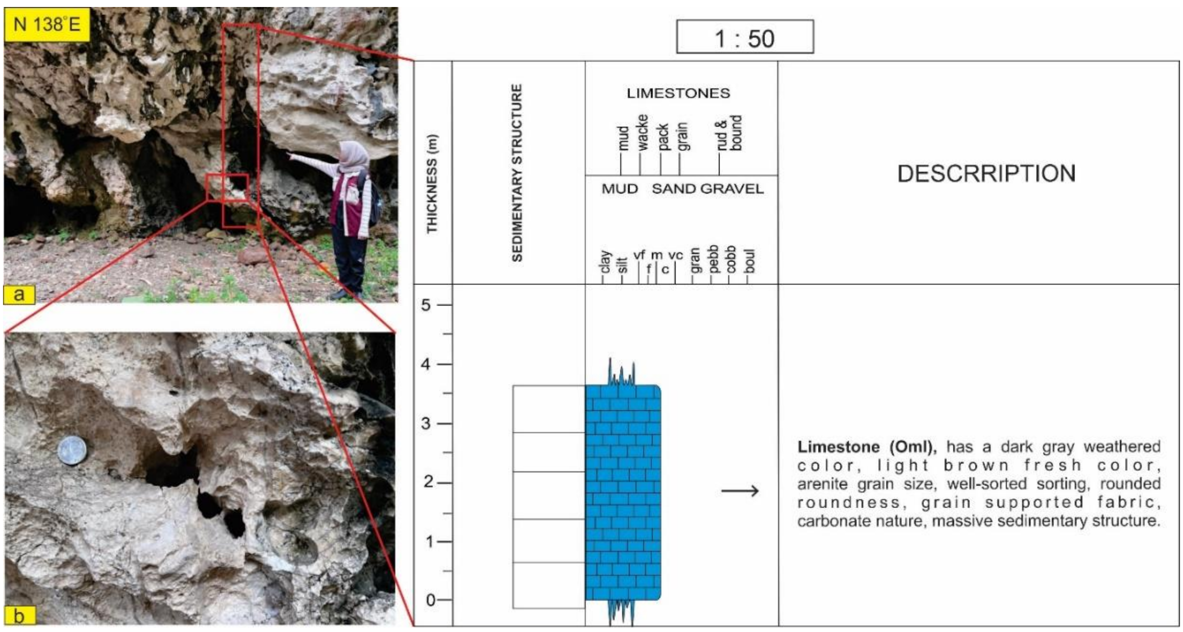


Figure 6. Outcrop of limestone at observation site 72 (UTM 757411 9240153), Rajamandala Kulon Village: (A) distant view of the outcrop, (B) close-up view, and (C) outcrop profile.

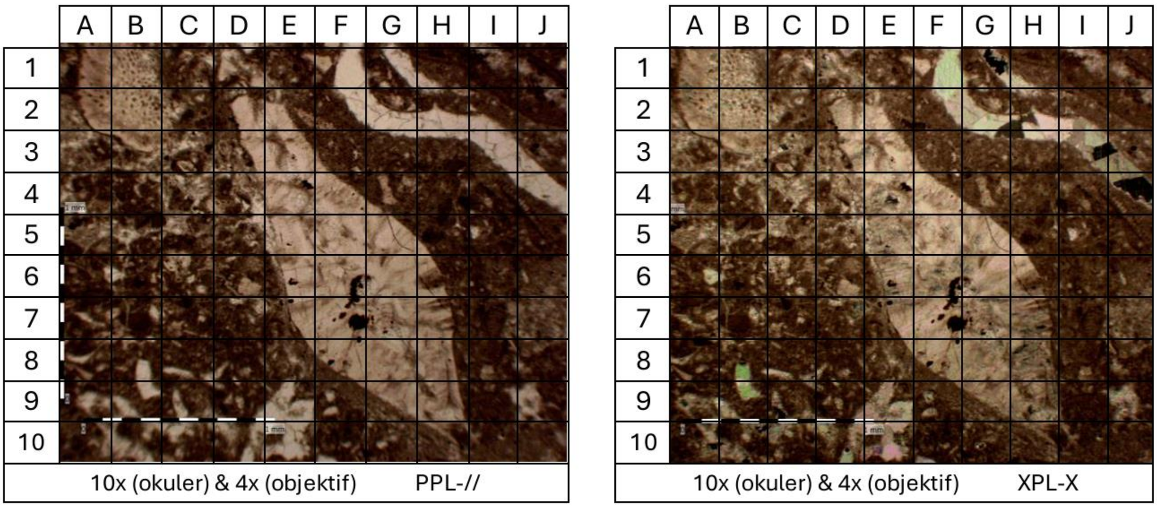


Figure 7. Thin section of Unsorted Biosparite; Packstone from Station/RL 81 (UTM 756790; 9239802), Rajamandala Limestone Member (Oml).

Based on petrographic observations, the carbonate sedimentary rock thin section examined under 40× magnification exhibits colorless characteristics in plane-polarized light (PPL) and grayish-brown interference colors in cross-polarized light (XPL). The rock has a grain size ranging from 0.02 to 2.35 mm (coarse lutite to fine rudite), a matrix size of 0.04–0.19 mm (coarse lutite to fine calcarenite), and a cement size of 0.03–0.06 mm (medium to coarse lutite). The rock is characterized by a grain-supported fabric, poor sorting, floating grain contacts (B9), and intergranular porosity. Its constituents comprise 35% skeletal grains and 15% quartz, with 28% micrite as the matrix and 22% sparite as the cement. Based on these petrographic characteristics, the rock is classified as unsorted biosparite (Packstone).

In this limestone unit, micropaleontological analysis was carried out as an important method in stratigraphic studies to determine the relative age of the rock and to interpret its depositional environment. This approach is based on the fact that planktonic foraminifera are abundant, widely distributed, and have well-defined stratigraphic ranges, making them effective indicators for biostratigraphy and paleoenvironmental interpretation. Planktonic foraminifera inhabit the open marine water column and are strongly influenced by water depth, temperature, salinity, and current circulation. Therefore, their occurrence and species assemblages record both temporal and environmental conditions during sedimentation. Based on this analysis, five species were identified from the sample RL72, namely *Globigerina sicanus* (13 specimens), *Globigerina pseudociperoensis* (7 specimens), *Globigerinoides seminulina* (10 specimens), *Globigerinoides diminutus* (11 specimens), and *Praeorbulina transitoria* (5 specimens).

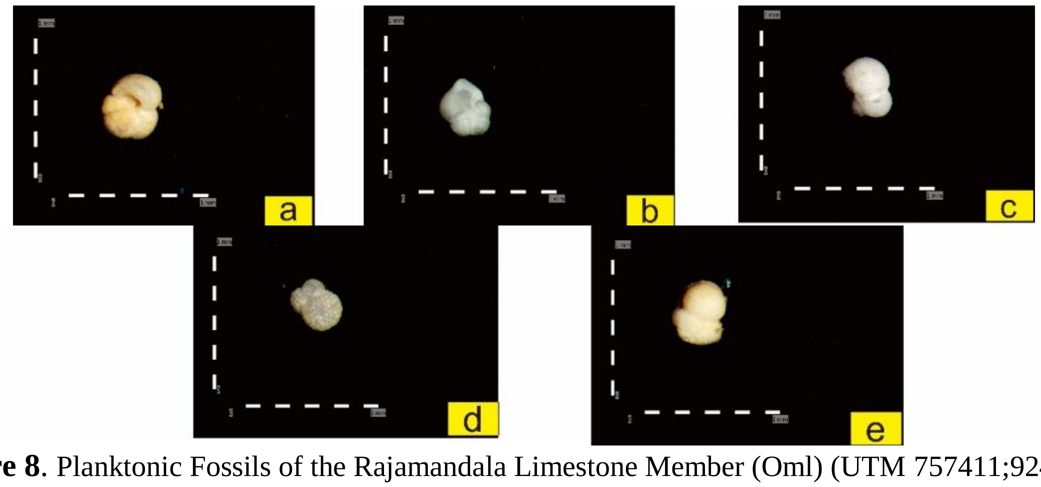


Figure 8. Planktonic Fossils of the Rajamandala Limestone Member (Oml) (UTM 757411;9240153) : *Globigerina sicanus* (A) *Globigerina pseudociperoensis* (B) *Globigerinoides seminulina* (C) *Globigerinoides diminutus* (D) *Praeorbulina transitoria* (E).

Table 3. Relative age interpretation of the RL72 Limestone lithology based on planktonic foraminifera [16].

Sample / Formation	: RL 72 / Oml	Rock Type	: Sedimentary Rock
Location	: Rajamandala Kulon Village	Age Range	: Early Miocene
Rock Name	: Limestone	Analyse by	: Dianda Rahma Aulia

Age ->	Oligocene		Miocene											
	Late		Early					Middle						
	e.1-4		e.5					f.1		F.2		f.3		
Planktonic Foraminifera (Blow, 1969)	N2 P21	N3 P22	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	
Globigerinoides sicanus (A)														
Globigerina pseudociperoensis (C)														
Globigerinoides seminulina (C)														
Globigerinoides diminutus (A)														
Praeorbulina transitoria (R)														

The relative age of the Rajamandala Limestone Member (Oml) was determined using planktonic foraminiferal biostratigraphy based on the integration of the First Appearance Datum (FAD) and Last Appearance Datum (LAD) of the identified planktonic foraminiferal assemblage within the biozonation framework of Blow (1969). The age interpretation was established from the overlap of the stratigraphic ranges of the identified index taxa. Based on this analysis, the Rajamandala Limestone Member is assigned to the Early Miocene (Zones N7–N8).

Paleobathymetric conditions were interpreted based on benthic foraminiferal fossils because these microorganisms live attached to the sediment substrate on the seafloor and are highly sensitive to local environmental changes. Benthic foraminifera possess calcareous shells, and their distribution is controlled by factors such as water depth, light penetration, current energy, substrate type and stability, and dissolved oxygen availability. Their specific ecological preferences for particular seafloor conditions make benthic foraminifera reliable indicators for paleobathymetric and sedimentary facies interpretation, as each species occupies a characteristic depth range. The identified benthic foraminiferal fossils include *Anomalinella rostrata* (14 specimens), *Elphidium craticulatum* (10 specimens), *Heterostegina depressa* (6 specimens), *Tubinella inornata* (12 specimens), and *Tubinella funalis* (15 specimens).

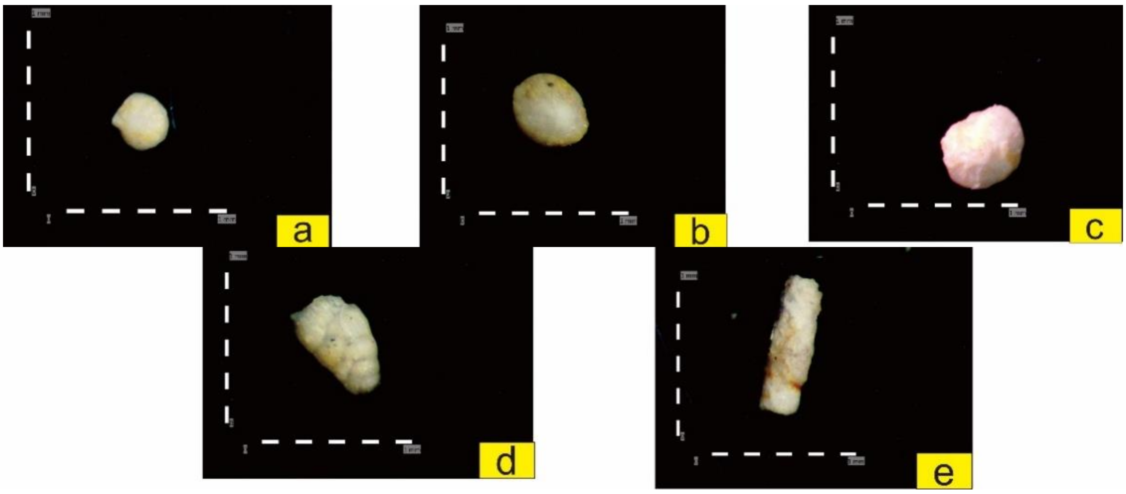
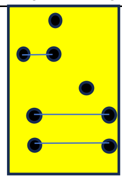


Figure 9. Benthic Fossils of the Rajamandala Limestone Member (Oml) (UTM 757411;9240153) : *Anomalinella rostrata* (A) *Elphidium craticulatum* (B) *Heterostegina depressa* (C) *Tubinella inornata* (D) *Tubinella funalis* (E).

Table 4. Table of Bathymetric Environment Interpretation for the RL72 Limestone Lithology [19].

Sample / Formation	: RL 72 / Oml	Rock Type	: Sedimentary Rock
Location	: Rajamandala Kulon Village	Bathymetric Environment	: Inner Neritic–Middle Neritic
Rock Name	: Limestone	Analyzed by	: Dianda Rahma Aulia

Bathymetric Environment, feet depth ->	Transitional	Neritic			Bathyal		Abyssal
		Inner	Middle	Outer	Upper	Lower	
Benthic Foraminifera (Barker, 1960)	0	20	100	200	500	2000	4000
Anomalinella rostrata (37 ft) *Elphidium craticulatum* (16-25 ft) *Heterostegina depressa* (40 ft) *Tubinella inornata* (20-60 ft) *Tubinella funalis* (20-60 ft)							

The paleobathymetric of this unit was determined by evaluating the dominant depth range indicated by the assemblage of benthic foraminiferal fossils identified in the limestone of the Rajamandala Limestone Member (Oml). This approach is based on the principle that each benthic foraminiferal species has a specific habitat preference within a particular depth interval, controlled by light intensity, hydrodynamic energy, substrate stability, and water chemistry. By identifying multiple species within a single sample, the paleobathymetric interpretation relies not on a single indicator but on the combined ecological preferences of the entire fossil assemblage.

Five benthic foraminiferal species were identified in this unit: Anomalinella rostrata (37 ft), Elphidium craticulatum (16–25 ft), Heterostegina depressa (40 ft), Tubinella inornata (20–60 ft), and Tubinella funalis (20–60 ft). The ecological depth ranges of these taxa were compiled based on Barker (1960) and compared to determine their overlapping bathymetric interval. The combined ecological ranges indicate a paleobathymetric interval of approximately 16–60 ft, corresponding to the inner neritic to middle neritic zones. This interpretation is based on the overlap of the ecological depth ranges of the identified benthic foraminiferal assemblage and is consistent with the carbonate lithology observed in the study area, indicating deposition in a shallow marine shelf environment.

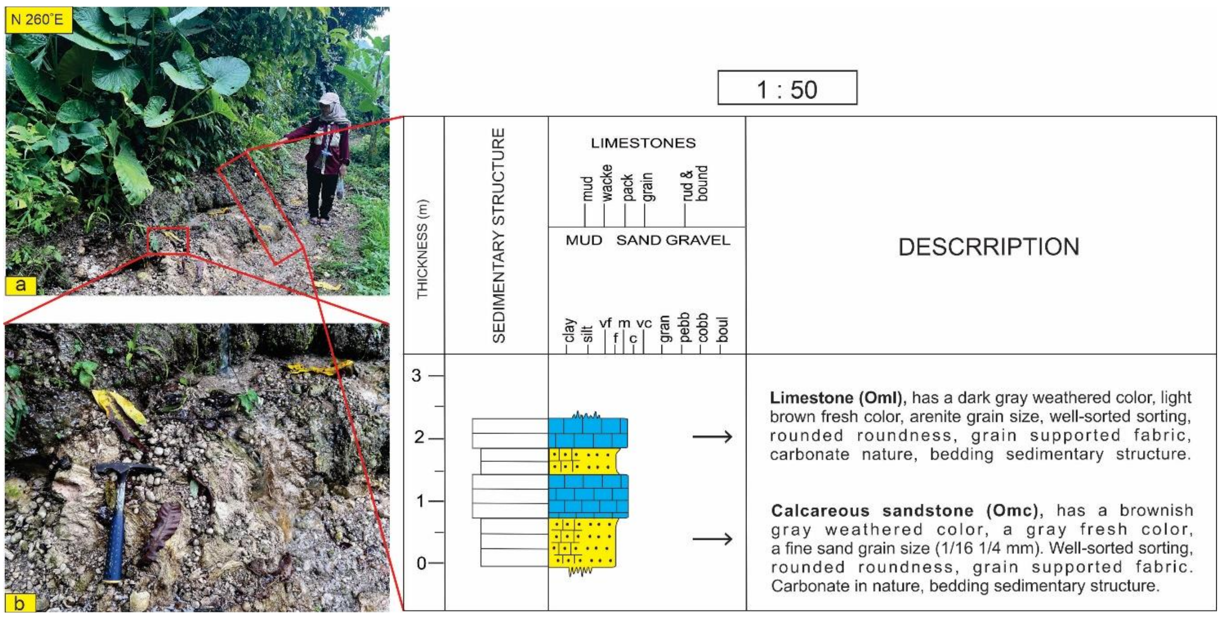


Figure 10. Outcrop Profile and Photographs from Distant (A) and Close-up (B) Observations of the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml)

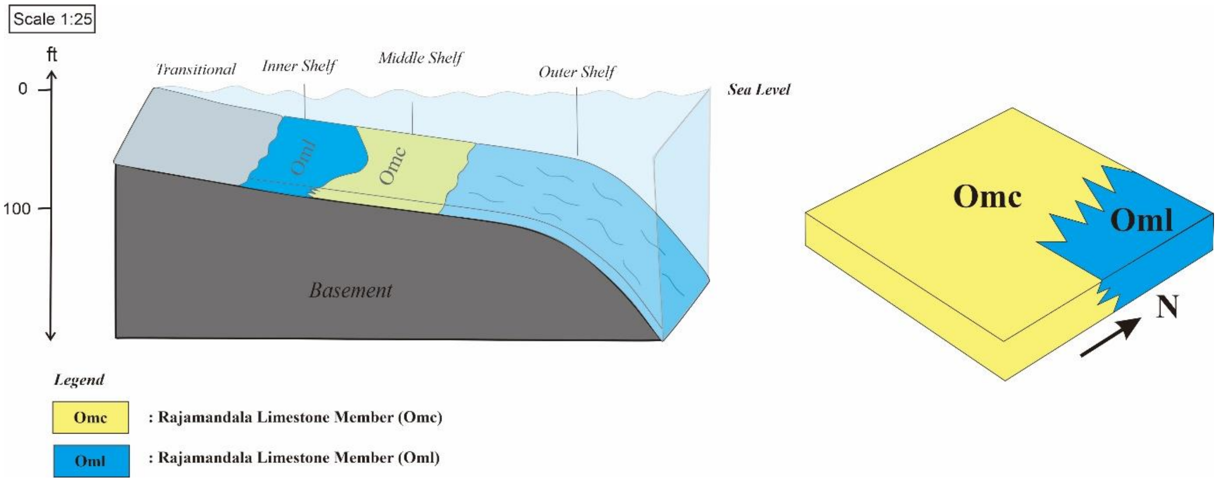


Figure 11. Illustration of the deposition of the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml).

A direct contact between the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml) was observed in the field. Paleontological analysis indicates that both units are of equivalent age, suggesting contemporaneous deposition. At the contact, a measured section records 80 cm of calcareous sandstone overlain by 70 cm of limestone, followed by 50 cm of calcareous sandstone and 40 cm of limestone, with a consistent bedding attitude of N230°E/30°. The geological map also shows a systematic lateral distribution of lithologies, with calcareous sandstone becoming increasingly abundant toward the southwest, whereas limestone becomes progressively dominant toward the northeast. The equivalent age of both units, together with the field observations and lateral lithological distribution, supports the interpretation of an interfingering facies relationship between the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml).

3.3 Depositional Environment

The reconstructed depositional history of the study area is based on the integration of micropaleontological age data, depositional environment interpretations, and field observations. The Rajamandala Calcareous Sandstone Member (Omc), represented by calcareous sandstone, is assigned an Early Miocene age and indicates deposition within an inner–middle neritic environment based on benthic foraminiferal assemblages. The Rajamandala Limestone Member (Oml), represented by limestone, is likewise dated as Early Miocene and indicates deposition within the same inner–middle neritic environment. The equivalent age and similar depositional environment of both units suggest that sedimentation occurred contemporaneously within the same shallow-marine setting. Despite sharing comparable depositional ages and paleobathymetric conditions, the two units differ in their dominant lithologies, with the Omc characterized by calcareous sandstone and the Oml dominated by limestone. Field observations documenting the contact between both lithologies, together with the systematic lateral distribution shown on the geological map, indicate spatial lithological variation across the study area. Therefore, the depositional model illustrated in Figure 11 is interpreted to represent contemporaneous lateral facies variation between the Omc and Oml units rather than successive depositional stages. This interpretation is consistent with the equivalent age, similar depositional environment, and observed field relationships of both units.

4. Conclusion

This study integrates lithological observations with planktonic and benthic foraminiferal analyses to characterize the Rajamandala Calcareous Sandstone Member (Omc) and the Rajamandala Limestone Member (Oml) in the Kemang area, Cianjur Regency. Planktonic foraminiferal assemblages indicate that both units are assigned to the Early Miocene (Zones N7–N8), while benthic foraminiferal assemblages indicate deposition within an inner–middle neritic environment. Lithologically, the Omc is represented by calcareous sandstone, whereas the Oml is dominated by limestone. Field observations document direct contact between the two lithologies and a systematic lateral lithological distribution, with calcareous sandstone becoming more abundant toward the southwest and limestone becoming more abundant toward the northeast. When considered together, these observations are consistent with the interpretation that the two units were deposited contemporaneously within the same shallow-marine depositional system and exhibit lateral facies variation. However, the proposed depositional model remains an interpretation based on the available lithological, paleontological, and field data, and further sedimentological and stratigraphic evidence is required to confirm the nature and extent of the lateral facies relationship.

Acknowledgment
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