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Age and Depositional Environment of Sampolakosa Formation Calcarenite Base on Foraminiferal Fossil Analysis

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ABSTRACT

The Sampolakosa Formation in Buton Island, Southeast Sulawesi, Indonesia, is predominantly composed of packstone calcarenite, which is brownish white when fresh and brown when weathered, and contains 57.8% skeletal grains, 34.3% micrite, 6.1% sparry calcite, and 1.8% pores/voids. Petrographic analysis indicates a grain-supported fabric, reflecting deposition in a moderate-energy environment capable of accumulating bioclasts while retaining a micrite matrix. Planktonic foraminiferal assemblages, including Globorotalia plesiotumida, Globorotalia acostaensis, and Globorotalia mayeri, constrain the age of the formation to the Late Miocene (~11–6 Ma), consistent with its stratigraphic position overlying the Tondo Formation and underlying the Wapulaka Formation. Benthic foraminifera, such as Cibicides lobatulus, Lagena sp., Bolivina sp., and Chrysalidina gradata, indicate deposition on a shallow to middle shelf (5–100 m) within a warm, clear tropical carbonate shelf characterized by moderate bottom-water energy, active currents, and generally well-oxygenated conditions with locally reduced oxygen levels. The combination of grain-supported packstone and micrite retention suggests deposition below the fair-weather wave base but influenced by occasional high-energy events, representing a transition from nearshore to middle shelf under relatively stable seabed conditions. These findings provide a robust framework for the biostratigraphy and paleoenvironmental reconstruction of the Sampolakosa Formation, contributing to regional stratigraphic correlations and insights into carbonate depositional systems.

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1. INTRODUCTION

The Sampolakosa Formation is a significant stratigraphic unit within the geological framework of Buton Island, Southeast Sulawesi, Indonesia. It constitutes part of the syn-orogenic to post-orogenic sedimentary succession that records the tectonic and depositional evolution of the region during the Late Neogene (Arifin & Naibaho, 2016; Arisona, Praja, & Okto, 2022). The formation is characterized predominantly by marl (napal) of light gray color, thickly bedded, with intercalations of sandy limestone bearing foraminifera fossils in its middle and upper portions (Arisona et al., 2022; Suyanto & Utomo, 2014). The Sampolakosa Formation conformably overlies the Tondo Formation and is unconformably overlain by the Wapulaka Formation (Arifin & Naibaho, 2016; Sulaeha, Masri, & Hasria, 2021; Suyanto & Utomo, 2014). Its distribution is among the most extensive on Buton Island, making it a critical unit for understanding the geological history of the region (Arifin & Naibaho, 2016).

Previous geological investigations have assigned the Sampolakosa Formation a Late Miocene to Early Pliocene age, with deposition interpreted to have occurred in neritic to bathyal environments (Arisona et al., 2022; Suyanto & Utomo, 2014). The formation is notable for containing abundant planktonic foraminifera of the Globigerinae group, as well as molluscan fossils characteristic of deep marine settings (Arifin & Naibaho, 2016). Furthermore, oil and asphalt seepages have been documented within this formation at several localities, underscoring its relevance to hydrocarbon exploration (Arifin & Naibaho, 2016; Arisona et al., 2022; Widarsono et al., 2023). The Sampolakosa Formation, together with the Tondo Formation, constitutes a major host for asphalt accumulations on Buton Island, with the distribution area of the Sampolakosa Formation alone estimated at approximately 1,182 km² (Widarsono et al., 2023).

Foraminiferal fossil analysis is a well-established and powerful tool for biostratigraphy and paleoenvironmental reconstruction. Planktonic foraminifera, owing to their wide geographical distribution, high species diversity, and rapid evolutionary rates, serve as excellent biostratigraphic markers for dating marine sedimentary sequences (Asis, Tahir, Musta, & Jasin, 2018; Permana, Pramumijoyo, Akmaluddin, & Barianto, 2020; Praptisih, Putra, & Nugroho, 2022). In contrast, benthic foraminifera are sensitive indicators of water depth, substrate conditions, oxygen levels, and nutrient availability, making them invaluable for paleobathymetric and paleoecological interpretations (Drınıa, Antonarakou, & Louvari, 2016; Permana, Pramumijoyo, & Akmaluddin, 2020; Taha, 2023). The integration of both planktonic and benthic foraminiferal data enables a comprehensive reconstruction of depositional environments, from shallow neritic to deep bathyal settings (Fakhruddin, 2019; Salama, Sayed, Saber, & El-Gaied, 2021).

Foraminiferal fossil analysis is a fundamental tool for constraining the age and interpreting the depositional environment of carbonate and calcarenitic formations worldwide (Kobawila, Elenga, & Ngatse, 2021; Maryunani, Kapid, Djuhaeni, Santoso, & Irawan, 2021; Okpala, Osisanya, Ighrakpata, Saleh, & Ibitoye, 2022). This study aimed to identify the age and depositional environment of the calcarenite of the Sampolakosa Formation based on foraminiferal fossil analysis. Additionally, this study identified rock types based on petrographic analysis using the point-counting method.

2. METHOD

2.1. Field Sampling

The study area is located at 122°52′20” E longitude and 5°23′40” S latitude and is administered under the Winning Village, Pasarwajo District, Buton Regency, Southeast Sulawesi Province. Samples were collected from calcarenite outcrops exposed within the natural asphalt (asbuton) mining area, with sampling conducted by collecting one representative sample for each distinct lithology identified in the outcrop.

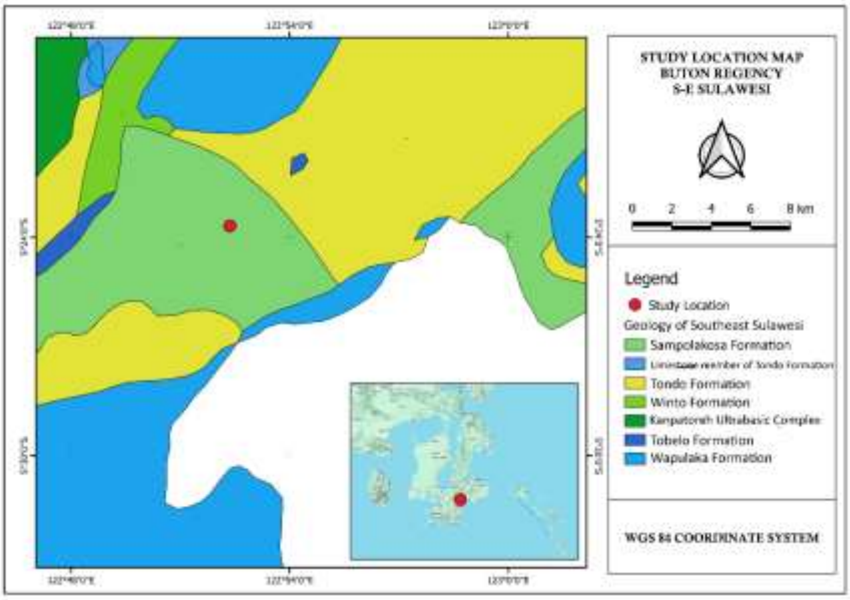


Figure 1. Map of the research location

2.2. Micropaleontological Analysis

Micropaleontological analysis was conducted to identify the types of fossils contained in the rock. The microfossil analysis was carried out at the Paleontology Laboratory, Faculty of Engineering, Universitas Hasanuddin. The micropaleontological analysis of foraminifera followed standard methods widely employed in foraminiferal biostratigraphy and paleoecology (Asis et al., 2018; Ištuk et al., 2023; Praptisih et al., 2022). The samples to be analyzed were first prepared by crushing them into fine particles. The samples were then placed in a container and mixed with a solution consisting of 15% hydrogen peroxide (H_2O_2) and 85% water and left to stand for three days. This step aimed to remove materials coating the samples. Afterward, the samples were washed and dried. . The residues were oven-dried at temperatures below 60°C. The dried samples were then sieved using mesh sizes of 297 µm, 177, and 149 µm.

Foraminiferal specimens were selected from the washed residues using a binocular microscope. Well-preserved specimens were selected for taxonomic identification based on established taxonomic and biostratigraphic classifications. The classification and stratigraphic distribution of planktonic foraminiferal species were determined using standard planktonic foraminiferal zonation and taxonomic references commonly applied in biostratigraphic and paleoenvironmental studies (Asis et al., 2018; Fakhruddin, 2019; Permana et al., 2020). Benthic foraminiferal identification was conducted using established benthic foraminiferal taxonomic references and was supported by previous studies related to foraminiferal classification and paleoenvironmental interpretation (Al-Saad & Ibrahim, 2002; Permana et al., 2020).

Foraminiferal identification was performed using established taxonomic references and classification systems commonly applied in micropaleontological studies (Al-Mashakbeh, 2020; Liu et al., 2020). The planktonic foraminiferal zonation approach is widely used as a biostratigraphic framework for determining the relative age of marine sedimentary rocks based on diagnostic fossil assemblages (Lucas & Ononeme, 2020). This approach subdivides geological time into numbered biozones by considering the first and last occurrences of diagnostic planktonic foraminiferal species (Akaerue et al., 2022; Igbinigie & Aigbadon, 2024; Lucas & Ononeme, 2020).

2.3. Petrographic Analysis

Petrographic analysis was conducted at the Sample Preparation Laboratory, Faculty of Engineering, Hasanuddin University. The samples were prepared using the thin-section method. Standard petrographic thin sections were prepared at approximately 0.03 mm (30 µm) and examined under transmitted polarized light microscopy. Observations were performed using a polarized light microscope (Nikon Eclipse LV100N POL). Point counting was used to quantify skeletal and non-skeletal grains, micrite, and sparite. The point-counting procedure involved establishing a systematic grid across the thin section and identifying the mineral or component present at each grid intersection point under the microscope, with a total of 1000 points per thin section. The points were evenly distributed (25 × 40 grid = 1000 points). Petrographic analysis of the thin sections was conducted to determine the limestone type according to the Dunham classification (mudstone, wackestone, packstone, and grainstone)..

3. RESULTS AND DISCUSSION

3.1. Lithological Characteristics

Field observations and petrographic analysis indicate that the Sampolakosa Formation in the study area is predominantly composed of calcarenite, as shown in Figure 2. The calcarenite observed in this study is brownish-white in fresh condition and brown when weathered. The rock exhibits a clastic texture with coarse sand-sized grains. Foraminiferal fossils are present within the calcarenite and can be observed under a microscope.

Figure 2. Outcrop of calcarenite

Based on the 1000-point counting results from the thin section of TR1C-001 sample, the composition consists of approximately 57.8% skeletal grains (allochems), 34.3% micrite (matrix), 6.1% sparry calcite, and 1.8% pores/voids. The dominance of skeletal grains over micrite indicates that the rock framework is grain-supported, with grains commonly in contact, while micrite is still significantly present, filling the intergranular spaces as the matrix. Referring to the carbonate textural classification proposed by Dunham, these characteristics meet the criteria of a packstone, defined as a grain-supported carbonate rock that still contains micrite. Therefore, this thin section can be classified as a packstone, which generally reflects a moderately energetic depositional environment, energetic enough to accumulate bioclasts but not strong enough to remove all carbonate mud (Figure 3).

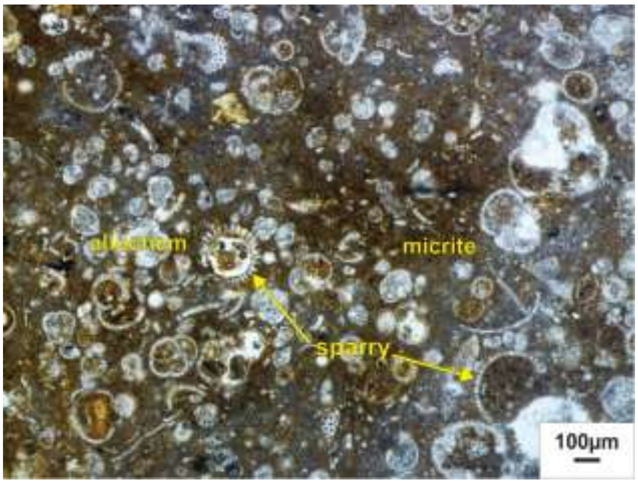


Figure 3. Thin section of calcarenite sample (TR1C-001) (crossed nicols, 5× objective lens)

The intergranular spaces are filled with sparry calcite cement, and the grains are in mutual contact, forming a rigid supporting framework that indicates a grain-supported fabric. The strong dominance of skeletal grains further confirms that the rock texture is grain-supported. This condition is consistent with previous studies of the Sampolakosa Formation, which reported that the limestone types composing this unit include packstone, wackestone, and crystalline varieties (Arisona et al., 2022). Packstone facies is distinguished from wackestone by its grain-supported fabric, where skeletal and non-skeletal grains are commonly in mutual contact (Arisona et al., 2022; Asharun et al., 2021).

3.2. Biostratigraphic Age Determination

Biostratigraphic analysis revealed the presence of diagnostic planktonic foraminiferal assemblages within the Sampolakosa Formation. The identification of zone-diagnostic species, including their first and last occurrence patterns, provided the basis for determining the relative age of the studied calcarenite. The combined occurrence of selected planktonic foraminiferal species allows the rock age to be constrained within a specific Neogene biostratigraphic interval, particularly when correlated with standard planktonic foraminiferal zonation used in previous studies (Martín-Martín et al., 2022).

The fossils analyzed for determining the rock age are planktonic foraminifera. Micropaleontological analysis indicates that the calcarenite contains the planktonic foraminiferal species Globorotalia plesiotumida, Orbulina universa, Globorotalia menardi, Sphaeroidinelopsis subdehiscens, Globorotalia acostaensis, Globorotalia mayeri, Orbulina bilobata, and Globigerina bulloides.

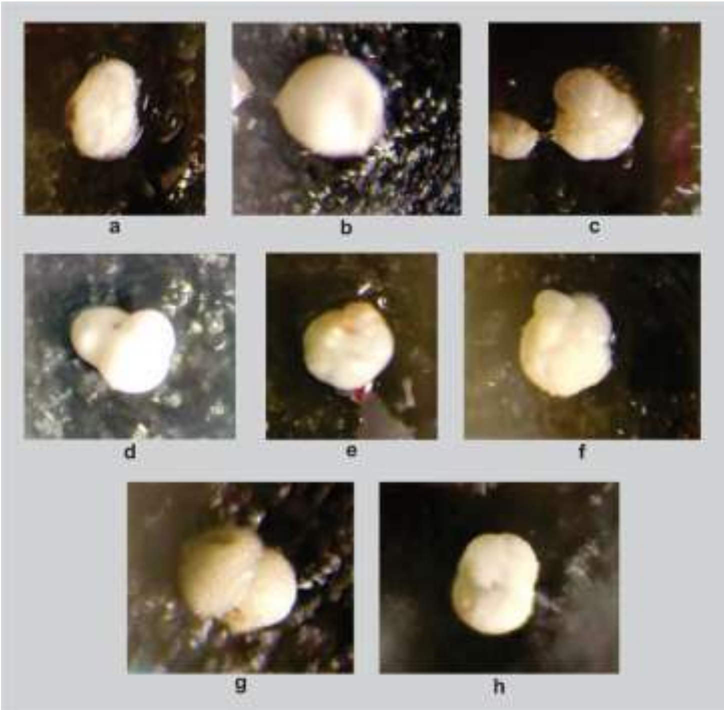


Figure 4. Planktonic foraminiferal fossils; a) *Globorotalia plesiotumida*, b) *Orbulina universa*, c) *Globorotalia menardii*, d) *Sphaeroidinelopsis subdehiscens*, e *Globorotalia acostaensis*, f. *Globorotalia mayeri*, g. *Orbulina bilobata*, h. *Globigerina bulloides*

Globorotalia plesiotumida is a planktonic foraminiferal species with a well-constrained stratigraphic range from the Late Miocene to the Early Pliocene. Its first occurrence is dated at approximately 8.6 Ma, while its last occurrence is dated at approximately 3.8 Ma in the Early Pliocene (Nugraha et al., 2023; Permana et al., 2020). The occurrence of this species is therefore useful for constraining the age of the studied calcarenite within the Late Miocene to Early Pliocene interval. In this study, the presence of *Globorotalia plesiotumida* supports the interpretation that the Sampolakosa Formation calcarenite belongs to the Neogene marine succession and provides an important biostratigraphic indicator for age determination (Nugraha et al., 2023; Permana et al., 2020).

Orbulina universa is a planktonic foraminiferal species with a broad stratigraphic range, extending from the Middle Miocene to the Holocene (Kobawila et al., 2021; LeKieffre et al., 2020). This species has been recorded in several Neogene to Quaternary intervals, including the Late Miocene, Pliocene, Pleistocene, and Holocene, indicating that it has a long temporal distribution and limited value as a narrow age marker when used independently (Lam & Leckie, 2020; Wycech et al., 2024; Spooner et al., 2020; Kiss et al., 2023). As an extant species, *O. universa* also occurs in modern open-ocean environments, reflecting its wide ecological tolerance and continued presence in marine planktonic foraminiferal assemblages (Balestra et al., 2021; Gautam et al., 2021).

Globorotalia menardii is a planktonic foraminiferal species with a broad stratigraphic range that extends from the Middle Miocene to the present. Although its temporal distribution is relatively long, this species has important biostratigraphic significance, particularly in the Neogene marine successions (Kobawila et al., 2021; Carvajal-Chitty & Navarro, 2021; Meilland et al., 2020). Its most diagnostic occurrences are commonly associated with the Late Miocene to Early Pliocene interval, making it useful as a supporting species for constraining the age of the studied calcarenite when interpreted with other planktonic foraminiferal assemblages (Targhi et al., 2021; Tournadour et al., 2021).

Sphaeroidinellopsis subdehiscens is a planktonic foraminiferal species that has been used as an important biostratigraphic marker in Miocene successions. In Indonesian basins, the first appearance of this species has been associated with the base of Zone N13 at approximately 11 Ma, indicating its significance for Middle to Late Miocene age interpretation (Isnaniawardhani et al., 2018). Other studies have placed its occurrence within broader Miocene to Lower Pliocene biozones, including intervals ranging from N14 to N19, suggesting that this species can support age determination when interpreted together with other diagnostic planktonic foraminifera (Kurniasih et al., 2021; Clark & BouDagher-Fadel, 2020). In South Sulawesi, *S. subdehiscens* has also been recorded in zones extending from the upper Middle Miocene to the Pliocene, further supporting its relevance for regional biostratigraphic correlation (Leroux et al., 2020).

Globorotalia acostaensis, which is now commonly referred to as *Neogloboquadrina acostaensis* following taxonomic revision, is a planktonic foraminiferal species with a stratigraphic range extending from the Late Miocene to the Pliocene (Kobawila et al., 2021; Pearson et al., 2023; Ulfah et al., 2023). Its first appearance datum is calibrated at approximately 9.83 Ma, placing its origin within the Late Miocene, particularly the Tortonian stage (Chen et al., 2024; El-Kahawy et al., 2023; Ulfah et al., 2023). This species has also been reported from Neogene biozones equivalent to the Late Miocene interval, making it a useful index fossil for supporting age interpretation in the studied calcarenite (Matsumaru & Yagi, 2022). The occurrence of *Globorotalia acostaensis* in this study strengthens the interpretation that the Sampolakosa Formation calcarenite was deposited during the Late Miocene, especially when evaluated together with other diagnostic planktonic foraminiferal species (Aguirre et al., 2022; De Ruig, 2025; El-Kahawy et al., 2023; Kobawila et al., 2021; Ulfah et al., 2023).

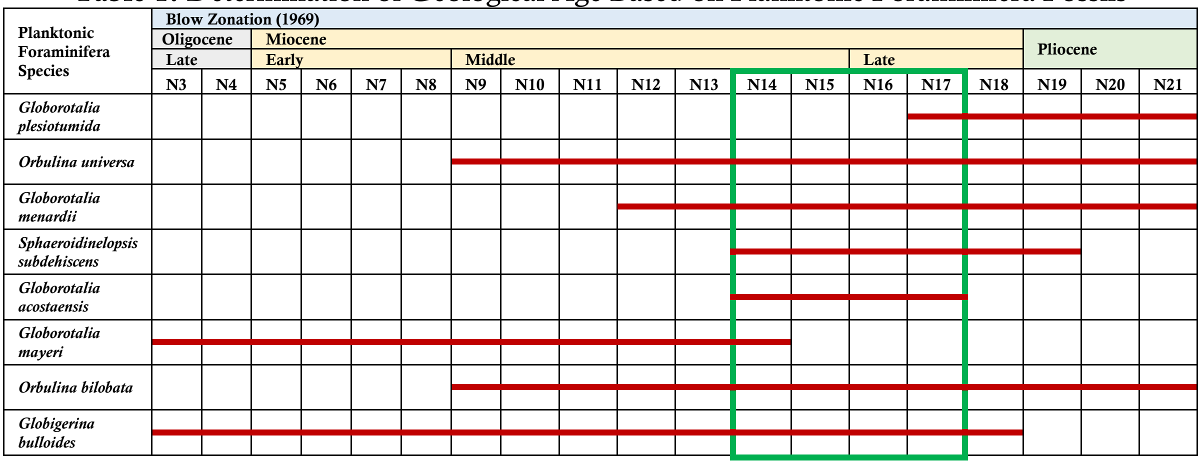
Globorotalia mayeri is a planktonic foraminiferal species commonly associated with Middle to Late Miocene marine successions in the Indo-Pacific region. Its stratigraphic occurrence has been reported across several Neogene biostratigraphic intervals, including records from the Early to Middle Miocene zones and occurrences within the *Globigerina nepenthes* Zone (Gaspersz et al., 2021; Kobawila et al., 2021). The last appearance datum of this species was calibrated to approximately 10.46 Ma, placing its disappearance near the transition from the Late Middle Miocene to the Early Late Miocene (Chen et al., 2024). Therefore, the occurrence of *Globorotalia mayeri* in the studied sample provides an important biostratigraphic constraint and supports the interpretation of a Miocene age when considered with other diagnostic planktonic foraminiferal species.

Orbulina bilobata is a planktonic foraminiferal species with a broad stratigraphic range from the Miocene to the Recent (Jovanovic et al., 2020). The genus *Orbulina* first appeared during the Middle Miocene, and its occurrence has been widely used in Neogene biostratigraphic interpretation (Kirkham et al., 2020; Maniscalco et al., 2023). *O. bilobata* has been documented in Langhian deposits together with *O. universa*, as well as in Badenian and Serravallian–Tortonian successions (Husain, 2023; Kirkham et al., 2020; Sremac et al., 2022). This species has also been recorded in Quaternary and Recent sediments, indicating that it has a long temporal distribution and limited value as a precise age marker when used independently (Gebhardt et al., 2023; Jovanovic et al., 2020). Therefore, the presence of *O. bilobata* in the studied calcarenite is best interpreted as supporting evidence for a Miocene or younger age when evaluated together with other diagnostic planktonic foraminiferal species (Husain, 2023; Jovanovic et al., 2020; Kirkham et al., 2020).

Globigerina bulloides is a planktonic foraminiferal species with a broad stratigraphic range, extending from the latest Oligocene or Early Miocene to the present, depending on the taxonomic concept applied (Fabbrini & Foresi, 2019; Kajita et al., 2020). This species has been recorded in Miocene sediments from several regions, including the Badenian of the Paratethys and the Middle Miocene of Croatia, where it occurs as an abundant component of planktonic foraminiferal assemblages (Godbillot et al., 2022; Kajita et al., 2020; Manoj et al., 2020). Its occurrence has also been documented in Miocene to Recent sediments from various ocean basins, indicating a long temporal distribution and broad ecological tolerance (Mulitza et al., 2021). Therefore, the presence of *Globigerina bulloides* in the studied calcarenite is not sufficient as a precise age marker when used independently; however, it supports a Neogene age interpretation when evaluated together with more diagnostic planktonic foraminiferal species.

The rock age was determined using planktonic foraminiferal biostratigraphy referenced to the Blow Planktonic Foraminiferal Zonation, based on diagnostic biochronological events. The last occurrence (LO) of Globorotalia mayeri marks the end of the Middle Miocene, indicating that the sample must be younger than this interval. The presence of Globorotalia plesiotumida confirms a Miocene–Pliocene range without significantly narrowing the age. The principal constraint is the occurrence of the index fossil Globorotalia acostaensis, which is globally recognized as characteristic of the Late Miocene. The intersection of these three bioevents is only consistent within zones N14–N17, allowing the rock to be reliably assigned a Late Miocene age (approximately 11–6 Ma) in accordance with standard international biostratigraphic correlation practices that emphasize FO/LO events and index fossils. The geological age determination of the rock is presented in Table 1.

Table 1. Determination of Geological Age Based on Planktonic Foraminifera Fossils



This age assignment is consistent with previous regional geological studies that interpreted the Sampolakosa Formation as having Late Miocene to Early Pliocene ages (Arisona et al., 2022; Suyanto & Utomo, 2014).

Biostratigraphic data from this study refine the age of the limestone intercalations within the Sampolakosa Formation. The presence of key index species allows correlation with global planktonic foraminiferal zonation and provides a robust chronostratigraphic framework for the formation. The Late Miocene to Early Pliocene age is further supported by the stratigraphic position of the Sampolakosa Formation, which conformably overlies the Tondo Formation (Middle Miocene to Late Miocene) and is unconformably overlain by the Wapulaka Formation (Plio-Pleistocene) (Arifin & Naibaho, 2016; Arisona et al., 2022; Pedoja et al., 2018; Sulaeha et al., 2021; Suyanto & Utomo, 2014).

There is some discrepancy in previous studies regarding the precise age of the Sampolakosa Formation. One interpretation referred to this formation as Quaternary in age based on seismic stratigraphy from the waters south of Buton Island, whereas onshore micropaleontological studies generally assigned the formation to the Tertiary, particularly the Late Miocene to Pliocene interval (Arifin & Naibaho, 2016; Arisona et al., 2022; Pedoja et al., 2018; Suyanto & Utomo, 2014). This discrepancy may reflect differences between offshore seismic stratigraphic interpretation and onshore biostratigraphic evidence, or it may indicate lateral facies and age variations within the formation. Based on the foraminiferal assemblages identified in this study and their correlation with previous micropaleontological investigations, the Sampolakosa Formation is more consistently interpreted as having a Late Miocene to Early Pliocene age (Arisona et al., 2022; Pedoja et al., 2018; Suyanto & Utomo, 2014).

3.3. Depositional Environment

The depositional environment of the calcarenite was determined using micropaleontological analysis of benthic foraminiferal fossils. The analysis of the calcarenite identified five benthic foraminiferal species: Cibicides lobatulus, Lagena sp., Textularioides inflata, Chrysalidina gradata, and Eponides tenera (Figure 5).

Figure 5. Benthic foraminiferal fossils in the sample include a) *Cibicides lobatulus*, b) *Lagena sp.*, c) *Bolivina sp.*, d) *Chrysalidina gradata*, and e) *Eponides tenera*

Cibicides lobatulus is a benthic foraminiferal species commonly associated with shallow-water inner-to-middle shelf environments. This species has been reported from nearshore to continental shelf settings, particularly on sandy substrates and in areas influenced by moderate bottom-water energy (Maryunani et al., 2021; Hempel & Flemming, 2021). Its occurrence in water depths ranging from shallow seagrass environments to approximately 50 m indicates that *C. lobatulus* is useful for interpreting shallow marine depositional conditions (Buosi et al., 2020; Hudáčková et al., 2020; Hempel & Flemming, 2021). Therefore, the presence of *Cibicides lobatulus* in the studied calcarenite supports deposition in a shallow shelf environment with relatively active bottom currents and stable substrate conditions.

Cibicides lobatulus has a broad thermal tolerance and can occur in cold, temperate, and warm marine environments. In high-latitude settings, this species is associated with cold-water conditions and strong bottom currents, whereas in temperate to warm marine settings, it has been reported from environments with higher seawater temperatures (Chatterjee et al., 2023; Devendra et al., 2022; Hempel & Flemming, 2021; Aiello et al., 2021). This wide ecological tolerance indicates that *C. lobatulus* has a cosmopolitan distribution and is not restricted to a narrow temperature range (Buosi et al., 2020). Therefore, in this study, the occurrence of *Cibicides lobatulus* is more appropriately used as an indicator of shallow marine shelf conditions, stable substrates, and active bottom-water movement rather than as a specific temperature indicator.

Lagena sp. is a benthic foraminifer with a wide bathymetric distribution, ranging from shallow neritic to deeper marine settings. In shallow marine environments, *Lagena* has been reported from neritic zones and inner-shelf settings, indicating its relevance for paleobathymetric interpretation when associated with other benthic foraminiferal taxa (Maulia & Idarwati, 2023; Orabi et al., 2024). However, this genus has also been documented in bathyal environments and deeper marine assemblages, suggesting that its occurrence alone is insufficient to define a narrow depositional depth (Giraldo-Gómez et al., 2022; Noucoucouk et al., 2023). On continental shelf settings, *Lagena* species may occur across broad depth gradients, with assemblage composition varying according to water depth and environmental conditions (Goeting et al., 2023; Chatterjee & Ghosh, 2023). Therefore, in this study, the presence of *Lagena* sp. is interpreted as supporting evidence for a marine shelf environment, particularly when considered together with other benthic foraminiferal species identified in the calcarenite.

Temperature is a key environmental factor that covaries with depth in controlling benthic foraminiferal distributions, including Lagena sp. (Goeting et al., 2023). Oxygen isotope analyses of benthic foraminifera on the Brunei shelf confirmed that cooler temperatures at greater depths are positively correlated with species distribution patterns (Goeting et al., 2023). In Arctic settings, Lagena sp. is associated with cold-water conditions (sea surface temperatures of 3–6°C) (Chatterjee & Ghosh, 2023). In Pliocene assemblages of northwestern France, Lagena-bearing faunas were linked to overall cooling of temperatures (Margerel, 2023).

Bolivina sp. is most commonly associated with neritic depositional settings. In the Niger Delta, Bolivina scalprata miocenica occurs within the Ammonia beccarii biofacies, indicative of shallow to inner neritic paleoenvironments (Asadu & Oghotuoma, 2023). Similarly, Bolivina sp. co-occurs with other calcareous benthic foraminifera, such as Lenticulina inornata and Uvigerina sparsicostata, in inner-to-middle neritic settings (Fajemila, Olayiwola, & Obidiya, 2022; Joshua et al., 2022). The occurrence of Bolivina and Poritextularia species has been specifically used to interpret inner-shelf environments (Fajemila et al., 2022). In middle Eocene successions in Egypt, a high abundance of Bolivina spp. was associated with outer-shelf settings (Sayed, Heinz, Abd El-Gaied, & Wagreich, 2023).

Chrysalidina gradata d'Orbigny is a foraminifer associated with shallow-water platform environments. Stratigraphic studies indicate that it inhabited shallow inner-to-middle-ramp environments. In the Mishrif Formation, southern Iraq, C. gradata occurs in the Pseudolituonella reicheli–Chrysalidina gradata Concurrent Biozone in shallow carbonate ramp settings (Mohajer, Afghah, Dehghanian, & Abyat, 2022; Schlagintweit & Simmons, 2022). In the Sarvak Formation, Zagros Basin (SW Iran), it characterizes interval zones associated with carbonate ramp microfacies (Solak, Taslı, & Koç, 2021). Paleotemperature data are unavailable, but its Cenomanian association with Tethyan platforms implies warm tropical to subtropical waters (Mohajer et al., 2022; Mohsin, Mohammed, & Alnajm, 2023; Solak et al., 2021).

The association of Cibicides lobatulus, Lagena, Bolivina, and Chrysalidina gradata indicates deposition in a shallow shelf environment (inner to middle shelf, approximately 5–100 m water depth) with fine- to moderately coarse-grained carbonate–siliciclastic sandy substrates, moderate bottom-water energy, active currents, and generally well-oxygenated bottom conditions with locally reduced oxygen. C. lobatulus reflects nearshore stable substrates and currents; Lagena indicates depth and temperature gradients; Bolivina suggests quieter neritic zones with more reducing conditions; and C. gradata supports warm, shallow carbonate waters within the photic zone.

3.4. Depositional Setting

The integration of lithological, micropaleontological, and petrographic data indicates that the Sampolakosa Formation was deposited in a marine environment. The depositional setting is interpreted as a shallow inner-middle shelf (approximately 5–100 m water depth) developed on a warm, clear, moderately energetic carbonate shelf with fine- to moderately coarse sandy substrates, active bottom currents, and generally well-oxygenated conditions, locally tending to slightly reduced oxygen levels. This interpretation is supported by the association of Cibicides lobatulus, Lagena, Bolivina, and Chrysalidina gradata, which collectively indicate nearshore to middle-shelf carbonate conditions within the photic zone.

The grain-supported nature of the packstone indicates that bioclastic grains, including foraminiferal tests, were concentrated by wave or current action to the point of mutual grain contact, whereas the retention of the micrite matrix suggests deposition below the fair-weather wave base but above the storm wave base, or in settings where intermittent high-energy events concentrated grains while background sedimentation contributed fine carbonate mud (Ahmad et al., 2020; Rajabi, Senemari, & Tehrani, 2023).

4. CONCLUSIONS

The Sampolakosa Formation in the study area is mainly packstone calcarenite, brownish white when fresh and brown when weathered, consisting of 57.8% skeletal grains, 34.3% micrite, 6.1% sparry calcite, and 1.8% pores/voids. Dominant skeletal grains indicate a grain-supported fabric, while micrite fills intergranular spaces, reflecting deposition in a moderate-energy setting that accumulated bioclasts without removing all micrite. Planktonic foraminiferal analysis indicates a Late Miocene age, approximately 11–6 million years ago, confirmed by Globorotalia plesiotumida, Globorotalia acostaensis, and Globorotalia mayeri under Blow (1969) zonation, consistent with its position above the Tondo Formation and below the Wapulaka Formation. Deposition occurred on a shallow to middle shelf, approximately 5–100 m deep, in warm carbonate waters, below fair-weather wave base but influenced by occasional high-energy events.

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