e-ISSN 2580 - 0752

BULLETIN OF
GEOLOGY
Fakultas Ilmu dan Teknologi Kebumian (FITB)
Institut Teknologi Bandung (ITB)

PALEOCURRENT STUDY OF NYALINDUNG FORMATION THROUGH MOLLUSKS PALEONTOLOGICAL ASPECTS IN CI GALASAR RIVER, SUKABUMI, WEST JAVA

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Sari – Formasi Nyalindung mengandung fosil moluska dari Kelas Gastropoda dan Bivalvia yang dapat digunakan sebagai proksi lingkungan untuk studi arus purba. Studi ini menganalisis kondisi arah arus pada saat pengendapan suatu lapisan batuan sedimen dengan melihat orientasi fragmennya, atau dalam kasus ini, kandungan fosilnya. Walaupun studi ini dapat menunjukkan informasi baru mengenai lingkungan pengendapan, studi arus purba pada satuan batuan ini belum pernah dilakukan. Oleh karena itu, studi ini bertujuan untuk memberikan informasi mengenai kondisi paleogeografi yang lebih detil pada Formasi Nyalindung di daerah penelitian yang belum pernah dikaji sebelumnya. Berlokasi di Sungai Ci Galasar, Kecamatan Nyalindung, Kabupaten Sukabumi, penampang lintasan penelitian menunjukkan perlapisan fosil moluska dengan beberapa satuan stratigrafi dengan umur fosil Miosen Tengah. Analisis arus purba dilakukan di empat lokasi yang tersebar di tiga unit stratigrafi yang berbeda. Hasil studi arus purna menunjukkan bahwa menunjukkan Formasi Nyalindung di daerah penelitian terendapkan pada arah arus yang berbeda yang kemudian diinterpretasikan sebagai perubahan lingkungan pengendapan setelah disandingkan dengan data asosiasi fosil. Diukur di empat lokasi, arus menunjukkan perubahan arus purba dari bimodal, kompleks, unimodal dalam arah N 291 ° - 300 ° E, dan unimodal pada arah N 281 ° - 290 ° E. Arus bimodal bersamaan dengan keberadaan *Turritella terebra talahabensis* dan *Cypraea* sp. menunjukkan lingkungan litoral, sedangkan orientasi cangkang kompleks dengan keberadaan *Gemmula (Gemmula) granosa woodwardii*, *Dientomochilus javanus*, dan *Terebra talahabensis* menunjukkan lingkungan litoral hingga neritik yang sangat dipengaruhi oleh gelombang. Arus unimodal di N 291 ° - 300 ° E menunjukkan hubungan fosil yang serupa dengan arus kompleks menunjukkan pengaturan lingkungan yang serupa, yaitu litoral ke neritik, tetapi dengan pengaruh gelombang yang lebih rendah dan lebih banyak pada arus searah yang lebih cepat. Terakhir, arah arus N 281 ° - 290 ° E menunjukkan asosiasi fosil kerang besar yang menunjukkan lingkungan neritik dalam yang dipengaruhi oleh arus searah. Berdasarkan paleogeografi pada Miosen Tengah, arus searah yang mempengaruhi pengendapan Formasi Nyalindung diduga sebagai arus sejajar pantai.

Kata kunci: Studi Arus Purba, Paleontologi, Moluska, Formasi Nyalindung, Miosen Tengah

Abstract - *Nyalindung Formation contains mollusk fossils from the Gastropod and Bivalvia classes which can be used as proxies for paleocurrent studies. This study analyzes the condition of the current direction at the time of deposition of a sedimentary rock layer through the orientation of its fragments, or in this case, its fossil content. Though this study may provide new information about the depositional environment, studies of depositional current direction in these rock units have never been carried out. Therefore, this study aims to provide more detailed information on paleogeographic conditions of Nyalindung Formation in the research area which has never been studied before. Located on the Ci Galasar River, Nyalindung District, Sukabumi Regency, the cross-section of the research transect shows Middle Miocene mollusk fossil layers with several stratigraphic units. The paleocurrent analysis was carried out at four locations spread across three different stratigraphic units. The results show that the Nyalindung Formation in the study area was deposited in different current directions which further interpreted as changes in depositional environment after being analyzed with fossils association. Measured in four locations, the current showed changes in the ancient currents from bimodal, complex, unimodal within direction N 291 ° -300 ° E, and unimodal in N 281° -290° E direction. These changes are combined with fossils association and later interpreted as changes in depositional environment setting. The bimodal current alongside the presence of Turritella terebra talahabensis and Cypraea sp. Indicates a litoral environment. Meanwhile, complex shells' orientation with the presence of Gemmula (Gemmula) granosa woodwardia, Dientomochilus javanus, and Terebra talahabensis indicates a litoral to a neritic environment that is strongly affected by waves. The unimodal current in N 291°-300° E showing similar fossil association with complex current indicates similar environment setting, which is litoral to neritic, but with the lower influence of waves and more on faster unidirectional current. Lastly, N 281 ° -290 ° E current direction showed large bivalves fossil association which indicates inner neritic environment influenced by unidirectional current. Based on the paleogeography in Middle Miocene, the unidirectional current affecting the deposition of the Nyalindung Formation is suspected as longshore current.*

Keywords*: paleocurrent study, paleontology, mollusks, Nyalindung Formation, Middle Miocene*

1. INTRODUCTION

Bogor basin is a fore-arc basin evolving from the back-arc basin from Eocene through Quaternary (Martodjojo, 2003). Bogor basin's unique evolution can be observed through rock formation deposited in this basin along with structural and paleontology data. One of the unique features of Bogor Basin is the existent of fossil-bearing strata in the Middle Miocene named the Nyalindung Formation.

Nyalindung Formation (Aswan, et al., 2017) is a member of Bogor Basin which is known as a fossil-bearing stratum in the classes of Gastropod and Bivalves (Martodjojo, 2003). Nyalindung Formation was deposited in Middle Miocene with the stratigraphic position relatives to another unit in Bogor Basin shown in **Figure 1**. This rock unit consists of green calcareous glauconitic sandstone, claystone, marl, sandy marl, tuffaceous marl, conglomerate, breccia, and limestone (Aswan, et al., 2017).

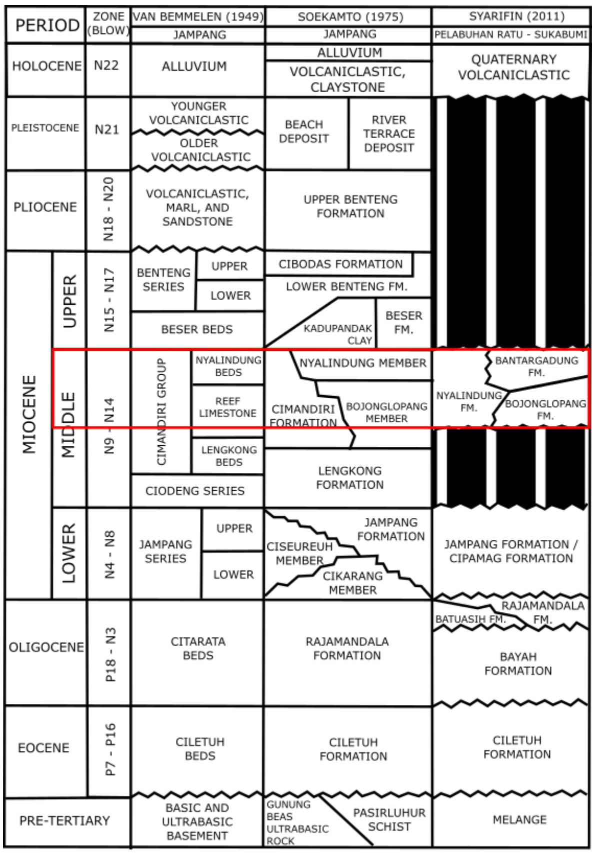

Figure 1. Nyalindung Formation Stratigraphic Position in Bogor Basin (Syarifin, 2011).

According to the stratigraphic position (Syarifin, 2011), Nyalindung Formation was deposited in Middle Miocene alongside the Bojonglopang Formation and Bantargadung Formation, above the Jampang Formation. Nyalindung Formation is distinguished from Bojonglopang Formation through the composition of volcaniclastics materials, where Nyalindung Formation consists of more volcaniclastics fragment and Bojonglopang Formation consists of Limestone. Nyalindung Formation differs itself from the Bantargadung formation through merrier fossils content, with similar lithology may be observed. Jampang Formation consists of volcaniclastics coarse to fine sedimentary rocks, which has clear distinction with Nyalindung Formation through its fossils content. Microfossils in Jampang Formation showed the age of the Early Miocene, while Nyalindung Formation showed Middle Miocene (Martodjojo, 2003).

1.1 Problem Statement

Paleontology study conducted in fossils bearing strata of Nyalindung Formation showed several depositional environment results. According to Syarifin (2011), gastropods and bivalves fossils found in this rock unit are typical for an open-sea with the swampy estuary in the east within the age of Middle Miocene, while according to Sukamto (1990) in Aswan et.al. (2008), this rock unit was deposited in shallow marine to terrestrial environments. A study in lithofacies and mollusks content showed that there were changes in sea level during the deposition of this rock unit, causing further changes in the depositional environment (Aswan & Ozawa, 2006). The most recent study conducted in Nyalindung Formation showed the importance of *Vicarya verneulli callosa,* a Middle Miocene index fossil that indicated a global sea-level rise affecting Nyalindung Formation deposition (Aswan, et al., 2017). Although many types of research regarding the Nyalindung Formation depositional environment have occurred, no further paleoenvironmental analysis has ever been conducted through mollusk fossils in this rock unit even though it is proven that the fossils fragments show some orientation that could be interpreted as paleocurrent direction (Aswan, Suparka, Rijani, Sundari, & Patriani, 2008). Paleocurrent models represent the dominant orientation of proxy in a rock bed (Selley, 1968), which may indicate the orientation of the sedimentation system, the initial dip or slope of the depositional environment, or the depositional agent current both in the regional and local region. Understanding depositional current also helps to visualize the facies distribution which later may be interpreted as environmental settings distribution, as conducted in Sandstone Body in Akpoha, Nigeria (Akana & Didei, 2017), and Catskill Deltaic Complex, in Pennsylvania and New York, the USA (Knoll, Chamberlain, & Chamberlain jr., 2017).

Fossils as paleocurrent indicators have been proven to be very helpful in a massive sedimentary layer, both in Gastropoda and Bivalvia classes. In situ gastropod shells' deposited on sedimentary rocks will have a long axis orientation that is relatively parallel to the rock layers (Allmon, 2011). Gastropods can be semi-faunally or passively buried in sediment with the aperture or shell opening facing the direction of the current being observed through recent Turritellidae from laboratory experiments. Meanwhile, biocoenoese bivalves in sedimentary rocks will show the longest axis orientation that is relatively parallel to the rock layers. The bivalve's semi-infaunal buried part of its body in the sediment with the anterior part buried under the sediment, as was observed in *Archanodon catskillensis* fossils from Pennsylvania, United States (Knoll, Chamberlain, & Chamberlain jr., 2017).

Paleocurrent study in Nyalindung Formation is considered to be very important considering that in the Middle Miocene, there was a trough that divided the island of Java and the results of this study can support the influence of the existence of the strait on the deposition of Nyalindung Formation which was deposited along the strait (Martodjojo, 2003). Thus, based on this information, local paleogeographic conditions can be determined and can complement the regional paleogeographic information of the Middle Miocene in West Java.

Since Nyalindung Formation consists of fine sandstones and carbonates with glauconite cement that are too weak to preserve sedimentary structures such as ripple mark, cross-beds, and sole-markings, abundant fossils orientation present in this rock unit are useful for paleocurrent analysis since paleocurrent can be learned through imbricated mollusk fragments (Jones & Dennison, 1970). Previous studies have been conducted in learning the paleocurrent through oriented invertebrate fossils such as gastropods, bivalves, brachiopods, and ostracods and have successfully identified the depositional current of a sedimentary stratum in recent (Allmon, 2011), Devon (Knoll, Chamberlain, & Chamberlain jr., 2017), and Ordovician (Jones & Dennison, 1970) era. In other words, mollusks' fossils exposed in sedimentary rocks do not only show the environment and age of the deposition but also indicate the depositional current in sedimentary rock.

1.2 Research Location

The research was conducted in Kertaangsana Village, Nyalindung District, Sukabumi Regency, West Java, in a 175-meter-long traverse track along Ci Galasar River (**Figure 2**). Though it is known that this area exposed abundant oriented mollusk fossils, the fossils in this particular area have not been examined thoroughly. This area was also chosen since the mollusks in this particular show significant orientation and bedding, which made the mollusks fossils eligible for paleocurrent analysis, although the abundance was not as high as outcrops exposed in other rivers such as in Ci Angsana River and Ci Talahab River.

2. DATA AND METHODOLOGY

The research was conducted through several stages, namely literature review, field observation, laboratory analysis, and reconstruction, as illustrated in the flowchart. The literature review was conducted before field observation to understand the stratigraphy and paleontology of Nyalindung Formation, mollusks' roles as paleocurrent proxy, as well as to determine the suitable research location.

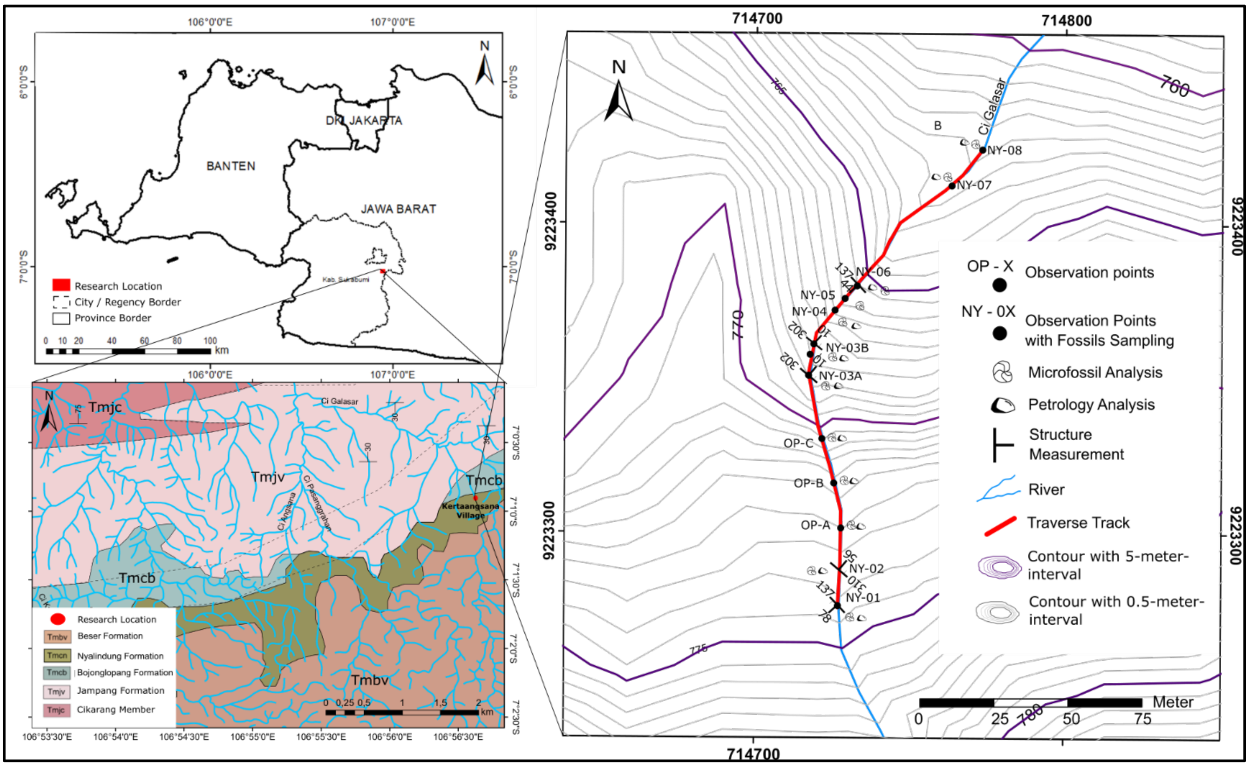

Figure 2. Research area located in Kertaangsana Village, Nyalindung District, Sukabumi Regency, along the Ci Galasar River. Within the location, there are 12 observation points.

Field observations were carried out in 12 locations along the Ci Galasar River (**Figure 2**). Sample and description of rocks samples were obtained from all locations, while fossils were obtained from nine observation points with NY prefix. Fossils shells orientation for paleocurrent analysis was conducted in NY-01, NY-02, NY-03A, NY-03B. Rock descriptions conducted in every observation point include color, condition, grain size, grain shape, packing, sorting, the composition of fragments, degree of compactness, as well as sedimentation structure when present. Fossil samples were taken as well as described based on their initial identified classes. The fossil description includes color, condition, possible types of fossilization, symmetry, the direction of shell rotation (dextral or sinistral) for gastropods, and ornamentation.

For paleocurrent analysis, shell orientation is measured by a geological compass through the orientation of the longest axis of the shell **Figure 4**. For Gastropod shells, the direction of the long axis measured is the length of the aperture to the apex. Based on this, the direction of the measurement of the longest posterior-anterior axis of the Gastropod shell will indicate the direction of the incoming current. This variable is then termed the trend variable. The slope of the longest axis will be measured to determine the inclination of the shell when it is deposited to indicate the orientation of the shell to the bedding. This variable became known as plunge. For Bivalve shells, the trend variable is defined as the direction of the long axis measured is the length of the posterior to the anterior. The slope of the longest axis will be measured to determine the inclination of the shell when it is deposited to indicate the orientation of the shell to the bedding will be termed plunge.

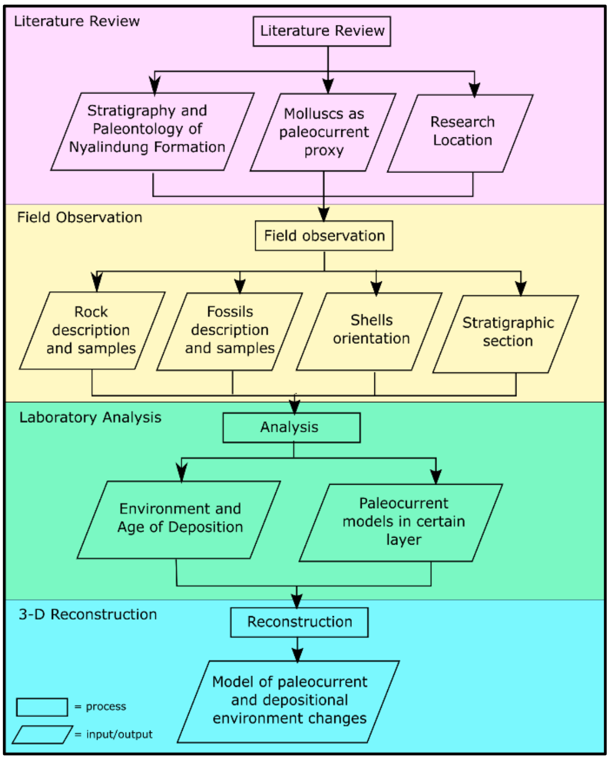

Figure 3. Flowchart diagram showing the four research stages.

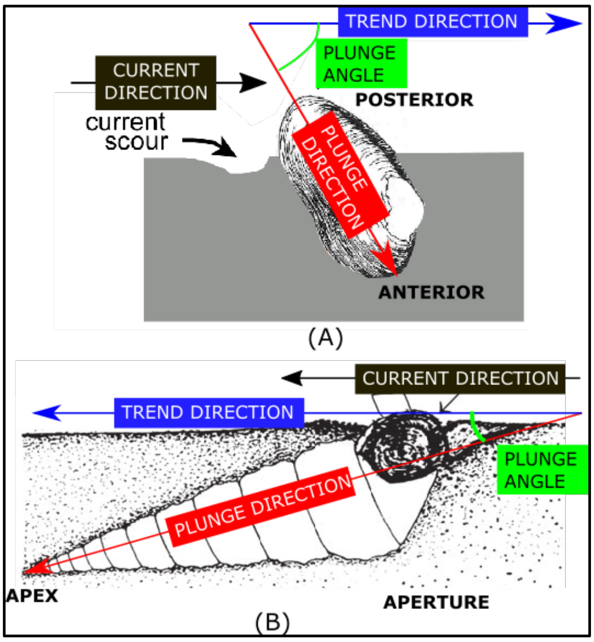

Figure 4. (A) Bivalves adjust their posterior-anterior axis parallel to the current (Knoll, Chamberlain, & Chamberlain jr., 2017), while (B) Gastropods adjusted their apical - apertural axis parallel to current (Allmon, 2011).

Laboratory analysis was conducted afterward to determine the environment and age of the Nyalindung Formation exposed in the research area and to visualize the depositional current in a particular layer. Rocks were sampled and further analyzed microscopically for their composition and their microfossil content. Petrology and microfossils analysis combined with mollusk fossils identification were elaborated to determine the overall stratigraphic section, environment changes, as well as the age of deposition. These data will later be combined with shell orientations to create paleocurrent models of Nyalindung Formation deposition afterward. The orientation of the mollusk shells that had been measured was corrected to the initial horizontal state to represent the position of the rock during deposition. The general direction of the shell orientation is presented in a rosette diagram. In this research, three types of paleocurrent models were used, which are Unimodal, Perpendicular Bimodal, Parallel Bimodal, and Polymodal. The models are illustrated in **Figure 5**. This orientation will represent the different current conditions in the past and what possible types of current affected the sedimentation. For example, bimodal with bipolar modes show a tidal current affected shore, while perpendicular bimodal style indicates river and seawater conjunction.

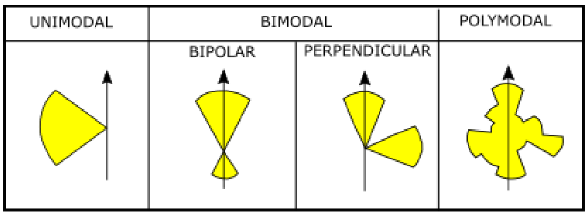

Figure 5. Paleocurrent models used in this research.

After the depositional environment, age, and current changes have been identified, 3-D models were created to illustrate changes in those parameters better. 3-D models illustrate the local paleogeography and will be compared to regional ones to determine the factors affecting depositional current in the research area.

3. RESULTS

In this section, the geological and stratigraphical conditions in the research area will be discussed in 3.1, paleontological and micropaleontological analysis in 3.2, as well as paleocurrent condition of Nyalindung Formation in the research area obtained through field observations data in 3.3.

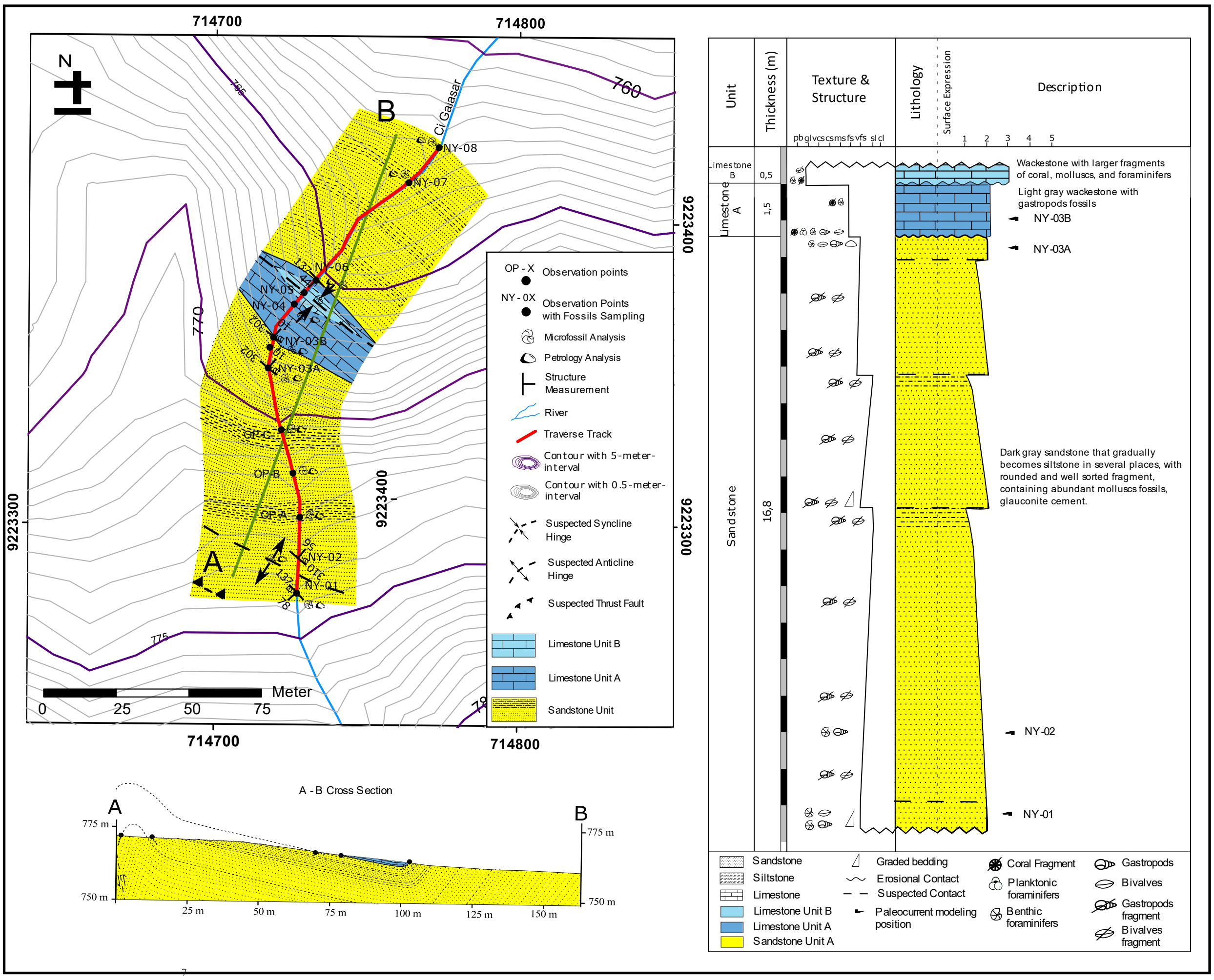

Figure 6. Geological and Stratigraphical Condition of Nyalindung Formation in Ci Galasar River Traverse Section.

3.1. Geological and Stratigraphical Condition

The Ci Galasar traverse section showed three different rock units with syncline and anticline that are suspected as a product of a thrust fault near the section **Figure 6**. Analysis in 12 observation points divided the Ci Galasar traverse section into three unofficial stratigraphic units, namely the Sandstone Unit, the Limestone A Unit, and the Limestone Unit B. Stratigraphic units of Ci Galasar traverse track can be seen in **Figure 7**.

In the cross-section of the observation path, there is a syncline and an anticline with a northwest-southeast orientation resulted from the structural restoration. The anticline limbs have strike and dip of N 137° E/78° and N 310 °E/56° as obtained from sandstone bedding in NY-01 and NY-02. The strike and dip of the layers on NY-01 and NY-02 were obtained by interpreting the field of the mollusk distribution bed. Syncline's limbs were interpreted by finding the position of N 137° E/44° and N 217° E/44° the contact of Limestone A Unit with the Sandstone Unit located NY-03A and NY-03B as well as the Limestone A Unit in NY-06.

Stratigraphically, the Sandstone Unit is deposited at the very bottom and exposed in NY-01, NY-02, OP-A, OP-B, OP-C, NY-03A, NY-07, and NY-08. The Sandstone Unit has lithological characteristics of dark-gray sandstones that gradually become siltstone in several places, with the rounded and well-sorted fragment in the size of very fine sand-silt. The fragments consisted of fossil fragments (<1mm in size), hornblende, lithic, with clay-sized matrix, glauconite cement, as well as small pyrite crystals growing in between the grains.

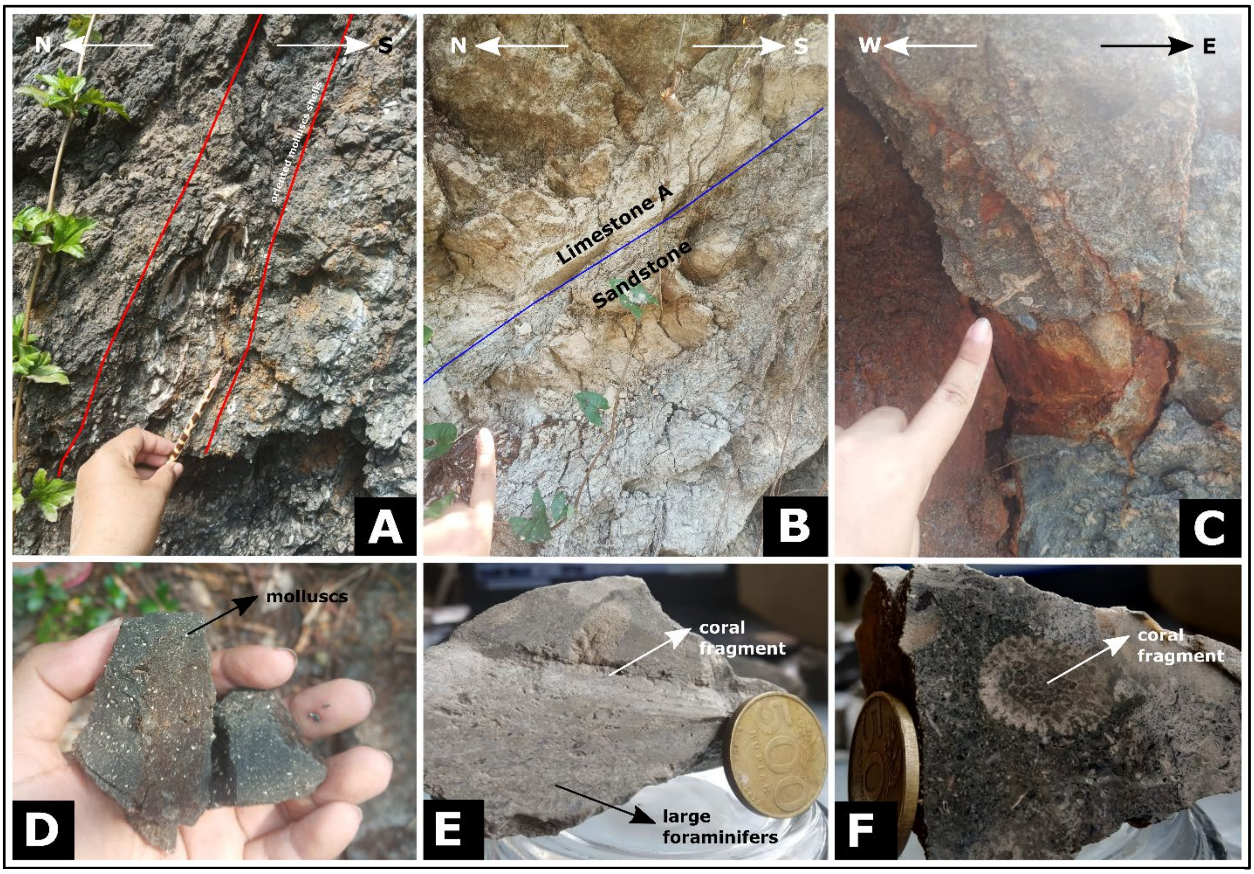

Figure 7. (A) Sandstone Unit outcrops showing parallel bed of oriented mollusks that consists of (D) dark gray sandstone; (B) contact between Limestone A and Sandstone, where Limestone A consists of (E) light gray wackestone; (C) Limestone B outcrop which consists of (F) large fragmented wackestone.

Few pyroxene fragments are indicating mafic igneous rock sources. This unit also had abundant fossils of mollusks, benthic foraminifers, and ostracods. In NY-01, NY-02, and NY-03A, mollusks fragments were found scattered in one stratum. The Limestone A Unit is deposited over the Sandstone Unit with erosional contact. These units are found on NY-03B, NY-04, and NY-06. Limestone A Unit is classified as a wackestone with neomorph micrites. In several locations, planktonic, foraminifers, mollusks, and ostracods were observed in this unit. Limestone Unit B was deposited on top of Limestone A Unit with erosional contact. Limestone Unit B is wackestone composed of coral fragments, algae, foraminifera, and mollusks fragments in the size of 5-10 mm. Micrites have undergone neomorphism in several places. This unit was exposed in NY-05. Bedding of this unit as well as sedimentary contact between Limestone A Unit and B were not found in the observation field and obtained through structural restorations of Ci Galasar River Traverse Section.

3.2. Paleontology and Micropaleontology Study of Nyalindung Formation

Paleontological studies were conducted through mollusks fossil found at nine points, namely NY-01, NY-02, NY-03A, NY-03B, NY-04, NY-05, NY-06, NY-07, and NY-08. At OP-A, B, and C, no intact fossil samples were found. From the nine observation points, 41 fossil samples were taken to be identified for environmental analysis and the depositional age of the Nyalindung Formation in the Ci Galasar River. About 35 specimens with the range size of 1 – 8 cm length were identified up to the species level and some of them are shown in **Figure 8**.

Figure 8. Some of mollusks found in Ci Galasar River Traverse Section. 1. *Chione tjikoraiensis*, 2. *Cavatodens jonkeri*, 3. *Pugilina ickei*, 4. *Nassaria* sp., 5. *Barycypraea murisimilis,* 6. *Cypraea subtetragona*, 7. *Terebra talahabensis*, 8. *Turritella terebra talahabensis,* 9. *Taxonia angsana*, 10. *Gemmula (Gemmula) granosa woodwardii,* 11. *Vicaryella martini*, 12. *Cerithideopsilla preangerensis*, 13. and 14. *Niotha talahabensis*, 15. *Dientomochilus martini,* 16. *Dientomochilus javanus*, 17. *Volema junghuhni*, 18. *Ficus* sp., 19. *Talahabia dentifera*, 20. *Melania bodjaensis,* 21. *Natica aurita*, 22. *Chelyconus socialis*, 23. *Conus odengensis,* 24. *Anazola subulata odengensis,* 25. *Lucina djunggrangensis.*

One of the mollusk fossils that are abundant in the Ci Galasar River Traverse Section is the *Gemmula (Gemmula) granosa woodwardii*, which is characterized by the presence of a long siphonal canal, nodules, and spines on each whorl of the shell. In addition, there is also a *Vicaryella martini* which also has a nodule and spine in the whorl, but does not have a long siphonal canal as in *Gemmula (Gemmula) granosa woodwardii*. Both of these taxa denote a transitional marine environment. Besides, other locality type taxa that were found in Ci

Galasar River Traverse Section are *Turritella terebra talahabensis, Dientomochilus javanus*, dan *Terebra talahabensis, Chione tjikoraiensis* dan *Cavatodens jonkeri*. Large Cypraeaidae were also found in Ci Galasar River Traverse Section, especially in NY-01 and NY-02.

Micropaleontology analysis was done through rock samples taken at 12 observation points. The results of these preparations indicated that the presence of microfossils could be found at nine points, namely NY-01, NY-02, NY-03A, NY-03B, NY-04, NY-05, NY-06, NY-07, and NY- 08. Same as mollusk fossils, microfossils were not observed at OP-A, OP-B, and OP-C. The presence of benthic microfossils dominated the presence of planktonic microfossils as observed in all nine observation points. The presence of planktonic microfossils was only found in NY-03B, NY-04, and NY-06, which are in Limestone A Unit. Microfossils found in the research area are shown in **Figure 9**.

Through microfossil observation, two taxa of planktonic foraminifera, five taxa of small benthic foraminifera, and eight taxa of marine ostracods were identified. The planktonic foraminifera found include *Globigerinoides obliquus obliquus* and *Globigerinoides subquadratus* (Bolli, Saunders, & Pierch-Nielsen, 1985). Small benthic foraminifera species found include *Ammonia* sp., *Elphidium* sp., *Nonionella* sp., and *Quinqueloculina* sp. (Loeblich & Tappan, 1988) *Ammonia* sp., *Elphidium* sp., and *Nonionella* sp. found abundantly in Sandstone Unit. *Quinqueloculina* sp. found in Limestone A Unit, while *Quinqueloculina tenagos* was discovered on Limestone Unit B. The eight genera of marine ostracods found include *Chyterella* sp.

3.3. Paleocurrent Analysis Through Mollusks' Shells Orientation

The locations chosen to model the paleocurrents are NY-01, NY-02, NY-03A, and NY-03B. That was because these four locations have an abundant distribution of mollusks so that the available data is quite representative. The measured data will be reconstructed by adjusting them horizontally to mimic the initial sedimentation condition before being statistically analyzed and plotted to rosette diagrams.

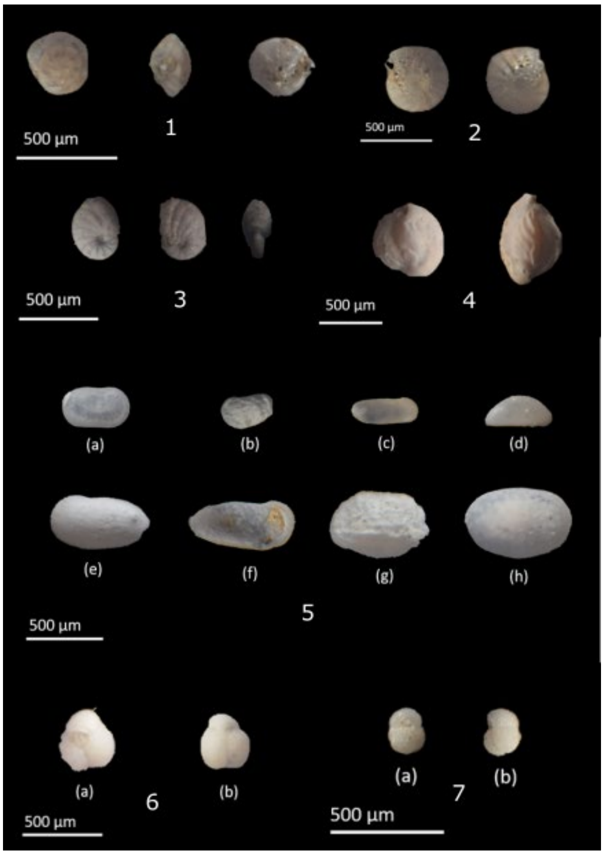

Figure 9. Microfossils found in Ci Galasar River Traverse Section. 1. *Ammonia* sp., 2. *Elphidium* sp., 3. *Nonionella* sp., 4. *Quinqeloculina* sp., 5. Ostracods, 6. *Globigerinoides obliquus obliquus*, 7. *Globigerinoides subquadratus*.

Based on the reconstruction, changes in depositional current may be observed through four locations. At NY-01, 19 shells orientation with the dominant size of 1 – 3 cm were measured. Based on summary statistics from horizontally adjusted data, the data had an average trend of N 88.6 ° E ranging from approximately N 13° E to N 217.5° E. The trend showed an average of 13.4° ranging from 1.4° to 63.1°. Rosette diagram of NY-01 showed a parallel bimodal orientation with two dominant orientations in N 21 ° -30 ° E and N 211 ° - 220 ° E. However, there are also other orientation directions with several frequencies such as N 71 ° -80 °E. At NY-02, 11 shells orientation with the range size of 3 – 8 cm were measured. Trend orientation in this observation points had an average of N 191.2˚ E ranging from N 193˚ E to N 351˚ E. Based on the rosette diagram, the orientation of the shell is classified as polymodal with a mode range of N 1 ° -10 ° E, N 171 ° -180 ° E, and N 221 ° -230 ° E. Paleocurrent in NY-03A showed a unimodal orientation with a mode range of N 291 ° -300 ° E and the sizes of molluscs are ranging from 1 – 3 cm. Based on these data, the ancient current direction of this formation has a general E-W orientation. At NY-03B, where the average of mollusks size was 3 cm, the orientation of the shell is classified as polymodal with the highest mode ranges of N281° -290°E. Though several group modes can be identified, the relative trend of the current is still E-W.

4. DISCUSSION

In this section, depositional environment and age of Nyalindung Formation in the research area will be discussed in 4.1, and paleocurrent of Nyalindung in the research area in 4.2. Stages of deposition in the Nyalidung Area based on those analyses will be conveyed in 4.3.

4.1 Depositional Environment and Age of Nyalindung Formation

In general, the lithology of the Nyalindung Formation in the Ci Galasar River Traverse Section consists of fine clastic sedimentary rocks and carbonates with many bioclastic fragments such as mollusks' shells, ostracods, planktonic foraminifers, benthic foraminifers, coral fragments, as well as sponge fragments varying in sizes and found to be either intact or in fragments. Based on different lithological textures and characteristics, three unofficial stratigraphic units were identified, which are the Sandstone Unit, Limestone A Unit, and Limestone B Unit.

The Sandstone Unit consists of very fine sandstone (Wentworth, 1922) that gradually becomes siltstone at several locations, with glauconite cement, growing pyrite crystals, as well as fossils fragments dominated by gastropods, benthic foraminifera, and ostracods. In addition, in this unit, *Turritella terebra talahabensis*, *Niotha talahabensis*, *Callista macra*, *Gemmula (Gemmula) granosa woodwardii*, *Dientomochilus javanus*, *Terebra talahabensis, Cypraea subtetragona,* and *Barycypraea murismilis* were present and indicate a shallow marine environment. This unit is under the lithological characteristics deposited on the restricted circulation shelf, which is characterized by bioclastic wackestone, litho-bioclastic sandstone, carbonate mudstone, and other fine clastic sediments with limited fossil types such as, gastropods, algae, benthic foraminifera, and ostracods (Wilson, 1975). Not only that, but the presence of pyrite crystals also shows a lowly oxygenated environment, which is consistent with restricted circulation area. Furthermore, the presence of large Cypraeaidae such as *Cypraea subtetragona* surrounded by smaller mollusks showed a high system track, which indicates the lowering of sea level in the research area (Poutiers, 1998).

Although the Upper and Lower Sandstone Unit were rich in mollusks fossils, middle Sandstone Units exposed at OP-A, OP-B, and OP-C showed only shell fragments with no intact mollusks or microfossils were found. This may indicate the depositional environment of the Sandstone Units at OP-A, OP-B, and OP-C is a transitional environment such as beaches. This is supported by the previous findings as well since the presence of larger mollusks in between smaller mollusks in NY-01 and NY-02 indicate high system track, which is consistent with the shallowing bathymetry in the Sandstone Unit deposition.

Limestone A Unit is deposited above the Sandstone Unit, characterized by matrix-supported bioclastic wackestone (Dunham, 1962) with fossil content of gastropods, pelecypods, benthic foraminifers, planktonic foraminifers, ostracods, coral, and algae. In this unit, *Talahabia dentifera*, *Chione tjikoraiensis*, and *Cavatodens jonkeri* were found. Based on the lithological texture and fossils content, the depositional environment of Limestone is suspected to be an open circulation backreef lagoon.

Limestone Unit B is characterized by wackestone (Dunham, 1962) with larger fragments of corals, foraminifers, and shells. In Limestone Unit B, only *Chione tjikoraiensis* was found. The mollusks taxa generally denote the continental exposure environment but do not explain the more specific depositional environment. Though, these characteristics are similar to open circulation back-reef lagoon lithology (Wilson, 1975), with suspected position to be near the reef-core due to larger bioclastic fragments.

Although some similarities have been found in the back-reef lagoon sediment characteristics and the stratigraphic units of Ci Galasar River traverse section, the units found in the section were not thoroughly consistent with the facies model. According to the carbonate facies model (Wilson, 1975), the color of sedimentary rocks deposited in a restricted circulation shelf is light, while the Sandstone Unit found in the research area had a dark gray color. It was also said that at open circulation lagoon, burrowing traces is very dominant, while the Limestone A and Limestone B Unit did not show similar characteristics. Though, based on fossils content and textural analysis, it is strongly indicated that the depositional environment of Nyalindung Formation is shallow – transitional marine with changes between restricted to open circulation lagoon shelf. These results provide an addition to the latest paleontology study in Nyalindung Formation that stated the depositional environment.

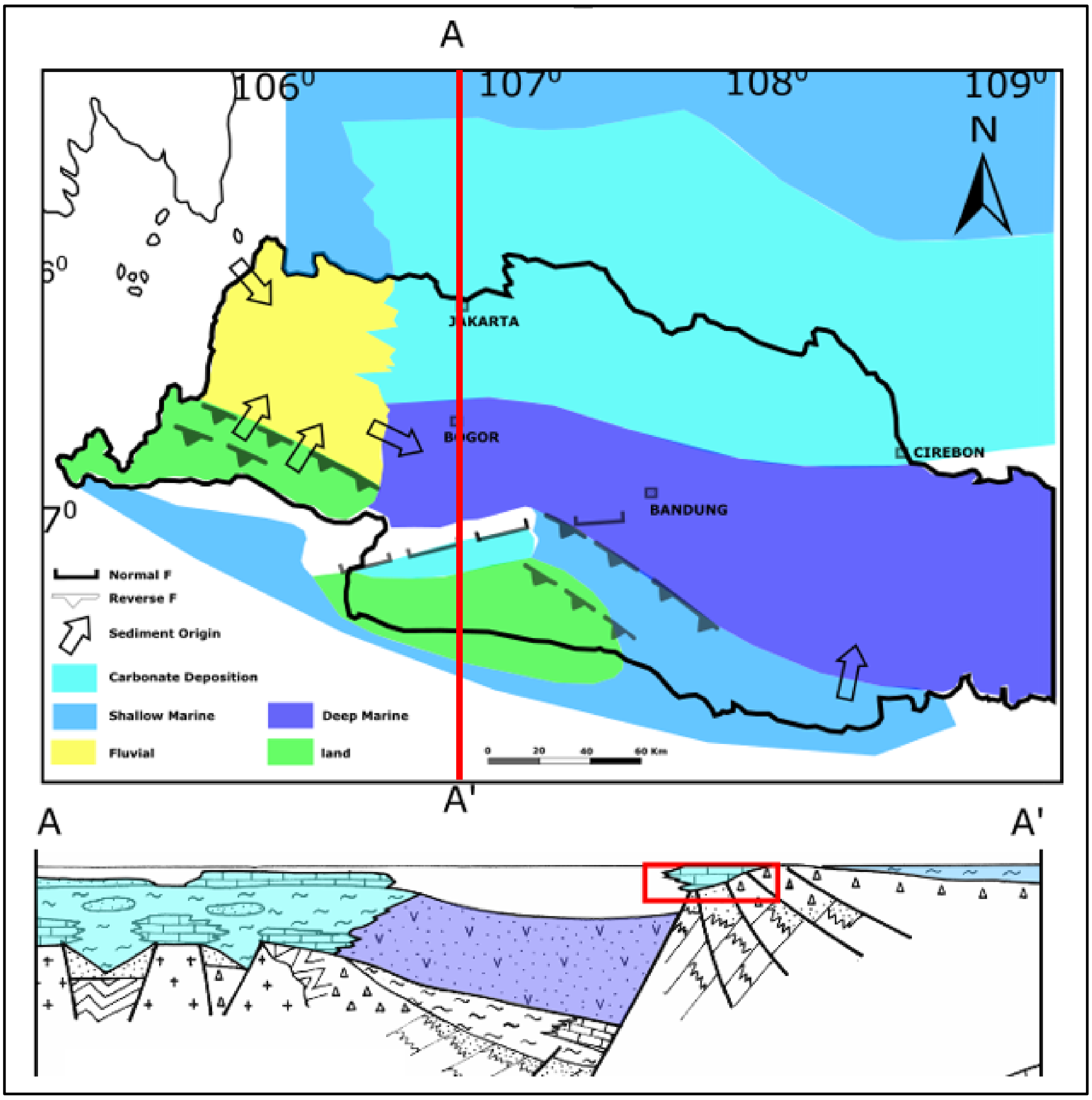

Figure 10. Paleogeography models of Middle Miocene in the research area. Research area is marked by red square.

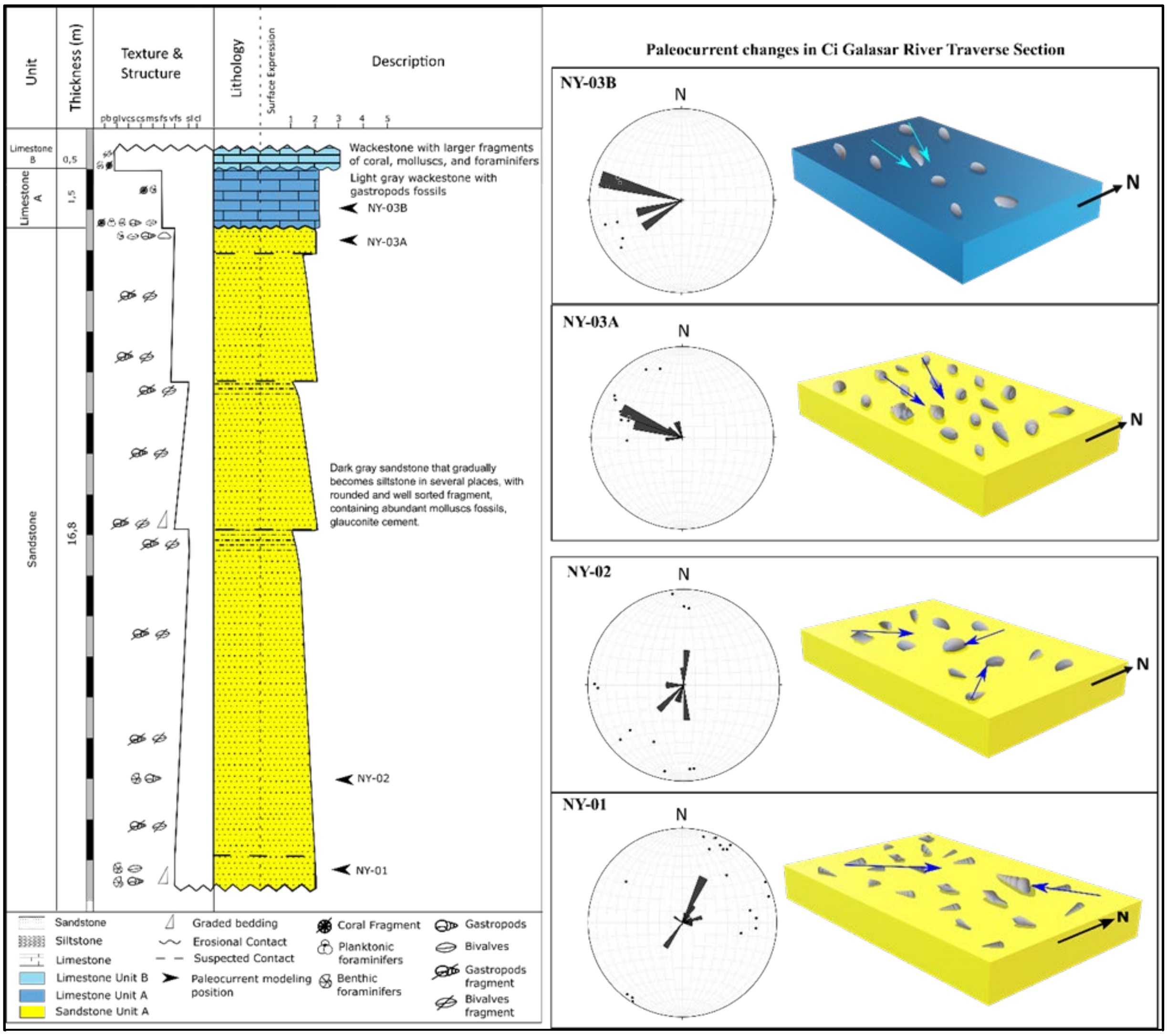

Figure 11. Paleocurrent changes during Nyalindung Formation deposition in the research area

Depositional ages of the Nyalindung Formation occurred in Middle Miocene through mollusks and microfossils analysis. Some Miocene mollusks such as *Turritella terebra talahabensis*, *Niotha talahabensis*, *Callista macra*, *Gemmula (Gemmula) granosa woodwardii*, *Dientomochilus javanus*, and *Terebra talahabensis* found in the Sandstone Unit of Nyalindung Formation showed a locality type for Middle Miocene. Though the findings were quite diverse, it is not conclusive to determine the stage of this formation. However, since the findings were quite definite to determine the age of Middle Miocene, therefore, it is safe to assume that the stage of the rock formation is in the Preangerian zone of Oostingh's Biozonation. Planktonic foraminifers, however, did not show a more specific age of deposition since the depositional ages shown by planktonic foraminifers' analysis was ranging from N6 – N14, which is equivalent to Early to Middle Miocene.

4.2 Paleocurrent of Nyalindung Formation Deposition Based on Mollusks Orientation

To visualize the current well, the Middle Miocene paleogeography model of Nyalindung Formation is adapted from Martodjojo (2003) as shown in **Figure 10**. According to Middle Miocene paleogeography models, a deep strait was flowing through in E-W orientation, with the land area located at the north and south of the strait. The suspected depositional location of the Nyalindung Formation in the paleogeography model is marked by a red square.

Based on mollusks shells orientation, there were changes in depositional current from bimodal, polymodal, to relatively E-W polymodal current. Those changes are represented in the two stratigraphic units of Nyalindung Formation, which are the Sandstone Unit and Limestone A Unit (**Figure 11**).

The Sandstone Unit showed changes not only in the depositional environment but also depositional current. At NY-01 or lower Sandstone Unit, parallel bimodal orientation indicates that tidal current plays a significant role in Sandstone Unit deposition. The presence of turritelline indicates a calmer current and was located far from the influence of rivers.

Above NY-01, the shells found in NY-02 were dominated by small gastropods and large shells of Cypraeaidae. The presence of large Cypraeaidea may indicate an environment with breaking waves or other high energy currents, such as rip current, filled with many smaller mollusks where large Cypraeaidae feed (Poutier, 1998). However, the possibility of rip current might be eliminated due to the polymodal orientation. Paleocurrent direction of NY-03A returned to unimodal direction with an orientation of N 291 ° -300 ° E. This is thought to be related to Middle Miocene paleogeography. Since the depositional environment of NY-03A was deeper than OP-C, the main current from the deep strait would affect the deposition of Nyalindung Formation more, as shown in the shells orientation and association. Therefore, the east-west relative current is suspected as the current from the deep strait.

In Limestone A Unit, only NY-03B indicates the paleocurrent of the deposition. The current direction on NY-03B then changed to N 281 ° -290 ° E dominated current with several other group modes. Though the polymodal model may be identified, the relative E-W trend is assumed to be the current direction. Considering that Limestone A was deposited in the deeper bathymetry than Sandstone Unit, the effect of strait current was stronger and showed the depositional current.

4.3 Stages of Deposition Reconstruction of Nyalindung Formation

Based on lithological texture, paleontology, micropaleontology, and paleocurrent analysis, there six sedimentation phases of the Nyalindung Formation in the research area. These phases then illustrated through 3-D block diagram in **Figure 12**. Based on the models, it is believed that there were changes in depositional current as well as the depositional environment that was probably caused by sea-level changes.

The Sandstone Unit was deposited in four phases. The lower Sandstone Unit was deposited in two different phases. This unit was initially deposited in a backreef lagoon with a bimodal current, indicating the effect of the tidal current. Then, the current started to change into polymodal oriented, which indicates a much powerful current such as breaking waves. Middle Sandstone Unit was deposited in the shallower sea with no current direction showed in this unit. The Upper Sandstone Unit was deposited in the backreef lagoon with a current direction of E – W as the effect of strait current in the Middle Miocene.

Limestone A Unit is the last unit showing a depositional current direction. Limestone A Unit consists of fine-grained wackestone with E-W current direction in backreef lagoon. This current direction is supposed to be influenced by strait current.

Lastly, Limestone B was deposited at the last stage of deposition. The depositional current of Limestone B cannot be identified, though the depositional environment is suspected to be at the backreef near the reef-core.

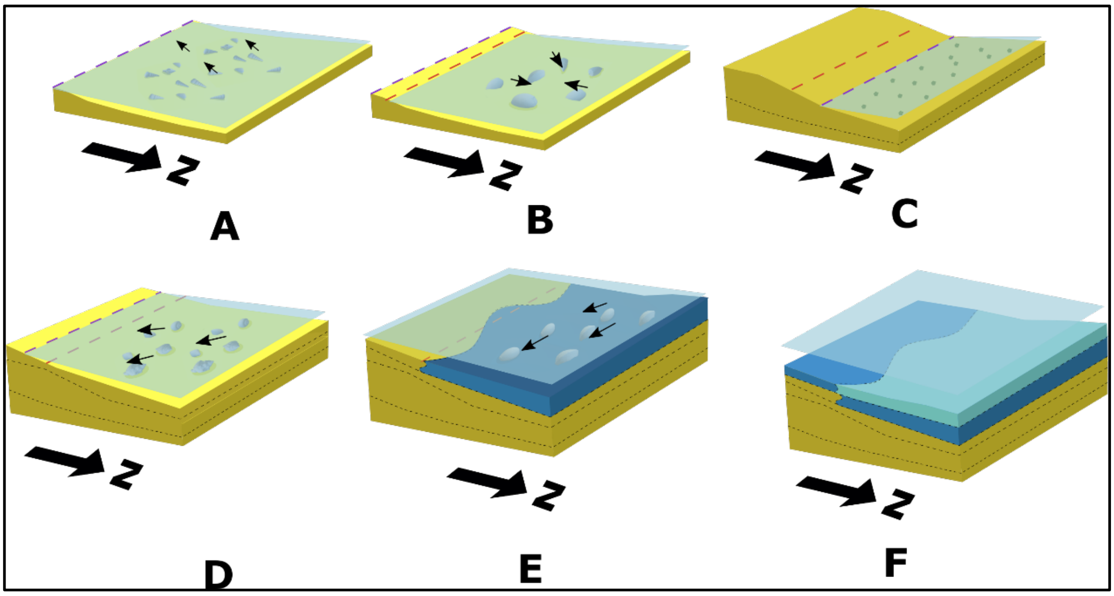

Figure 12. Six phases of Nyalindung Formation deposition in the research area. (A) Lower Sandstone Depositional Phase where the current was bimodal, (B) depositional phase of Lower Sandstone Unit where the current was polymodal, (C) Middle Sandstone Unit Deposition where the current direction was unidentified, (D) Upper Sandstone Unit deposition where the current was almost unimodal with current direction of NW-SE, (E) Limestone A deposition where the current was relatively E-W oriented, Lastly (F) Limestone B deposition where the current direction was unknown. Purple dashed-line indicate initial shoreline while red dashed-line indicate shoreline at the time of deposition.

5. CONCLUSION

According to lithology and paleontology analysis, there were changes in the environment in Nyalindung Formation observed in the research area from backreef lagoon, beach, and back to backreef lagoon. Mollusks fossils in Nyalindung Formation indicate Middle Miocene age and showed the orientation of the current during deposition. Based on mollusk orientation, four changes in the current direction during the deposition were identified. The current changes from bimodal, polymodal, unimodal N281°-290°SE, and unimodal N291°- 300°E.

ACKNOWLEDGMENT

We would like to express gratitude to family, Geological Engineering Department of ITB, and many other parties for all the supports throughout the research.

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