SEDIMENTATION RATES AND CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY OF THE NANGGULAN FORMATION, KULON PROGO, INDONESIA

TINGKAT SEDIMENTASI DAN BIOSTRATIGRAFI NANNOFOSIL FORMASI NANGGULAN, KULON PROGO, INDONESIA

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ABSTRACT: The Nanggulan Formation is the oldest sedimentary rock of Paleogene age that was deposited in the eastern part of the Southern Central Java Basin. A total of 103 nannofossil samples were taken from two traverses in the study area, i.e., the Watupuru and Jetis Routes. Based on the biodatum identified from the nannofossil samples, the biostratigraphy of the rock formation is divided into five zonations, namely the upper part of Zone NP16, Zone NP17, the lower part of Zone NP18, the upper part of Zone NP22, and the lower part of Zone NP23, expanding from 41.1 Ma to 32.2 Ma of age (Middle Eocene to Early Oligocene). Only Zone NP17 is identified as a complete zone, whereas the other four are observed as partial. The fluctuation of global sea level is believed to be an influence on the deposition of the Nanggulan Formation. The sedimentation rate and the change of nannofossil species shows a decrease of oligotrophic (Sphenolithus) and an increase of eutrophic (Reticulofenestra) taxa, especially in small reticulofenestrids (Reticulofenestra spp.). This occurrence suggests a shift in the environmental conditions from an oligotrophic condition around 41.1 Ma to a eutrophic one, particularly after 40.40 Ma. The enhanced eutrophication in the Watupuru and Jetis Routes was caused by an increasing terrigenous input in 40.40 Ma and after, consequently providing nutrient availability on the water surface. This interpretation is supported by the increase in the sedimentation rate when sea level slightly decreased in 40.40 Ma.

Keywords: Nanggulan formation, calcareous nannofossil, biostratigraphy, sedimentation rate

***ABSTRAK**:* Formasi Nanggulan merupakan sedimen berumur Paleogen dan endapan sedimen paling tua di Jawa bagian timur yang diendapkan di Cekungan Jawa Tengah Selatan. Sebanyak 103 sampel nannofosil diambil dari dua lintasan di Formasi Nanggulan: Watupuru dan Jetis. Berdasarkan biodatum yang diidentifikasi dari sampel nannofosil, biostratigrafi Formasi Nanggulan dibagi menjadi 5 zonasi. Terdapat empat zona kisaran sebagian dan satu zona kisaran sebagai berikut: Zona NP16 bagian atas, Zona NP17, Zona NP18 bagian bawah, Zona NP22 bagian atas dan Zona NP23 bagian bawah. Berdasarkan studi biostratigrafi, Formasi Nanggulan diendapkan pada umur 41,1 juta tahun sampai dengan 32,2 juta tahun (Eosen Tengah hingga Oligosen Awal). Menurut distribusi lithofasies secara horizontal, pengendapan Formasi Nanggulan dipengaruhi oleh fluktuasi muka air laut. Laju sedimentasi dan perubahan nannofosil juga dianalisis dalam penelitian ini. Adanya pengurangan taksa oligotrofik (*Sphenolithus*) dan peningkatan taksa eutrofik (*Reticulofenestra*) terutama *Reticulofenestra* berukuran kecil (*Reticulofenestra* spp.) menunjukkan adanya perubahan kondisi lingkungan dari oligotrofik pada umur 41,1 juta tahun menjadi eutrofik pada umur 40,40 juta tahun. Peningkatan eutrofik di rute Watupuru dan Jetis diakibatkan oleh adanya penambahan material darat hasil erosi pada umur 40,40 juta tahun dan setelah umur 40,40 juta tahun sehingga meningkatkan ketersediaan nutrisi di permukaan laut. Interpretasi ini didukung oleh adanya peningkatan laju sedimen ketika permukaan air laut sedikit menurun pada umur 40,40 juta tahun.

Kata Kunci: Formasi Nanggulan, nanofosil gampingan, biostratigrafi, kecepatan sedimentasi

INTRODUCTION

The Nanggulan Formation is reported by Van Bemmelen (1949) and Rahardjo et al. (1977) as Paleogene sedimentary rock. It is known as the oldest sediment of the eastern part of Java that was deposited in the Southern Central Java Basin (Satyana, 2005). The formation outcropped locally in Watupuru and Jetis River in Nanggulan sub-regency, Kulon Progo Regency, Yogyakarta Special Province, approximately 30 kilometers to the west of Yogyakarta (Figure 1). The age of the Nanggulan Formation ranges from Middle Eocene to Early Oligocene (Purnamaningsih and Pringgoprawiro, 1981; Rahardjo et al. 1995; Lelono, 2000; and Widagdo et al., 2016), based upon its microfossil analysis. The lithology in the Nanggulan Formation comprises foraminifera, mollusks, as well as pollen and spores. However, derived from several studies regarding biostratigraphy that have been done in the Nanggulan Formation, calcareous nannofossils are rarely used. The previous studies using calcareous nannofossils in the Nanggulan Formation was carried out by Okada (1981), followed by Lunt and Sugiatno (2003) and Saputra and Akmaluddin (2015).

Through a new high-resolution calcareous nannofossil biostratigraphy and a paleoceanographic interpretation derived from detailed lithostratigraphy and calcareous nannofossil data, as well as sedimentation rates, this study aims to reconstruct the paleoceanographic condition of the Nanggulan Formation within the range of its depositional age.

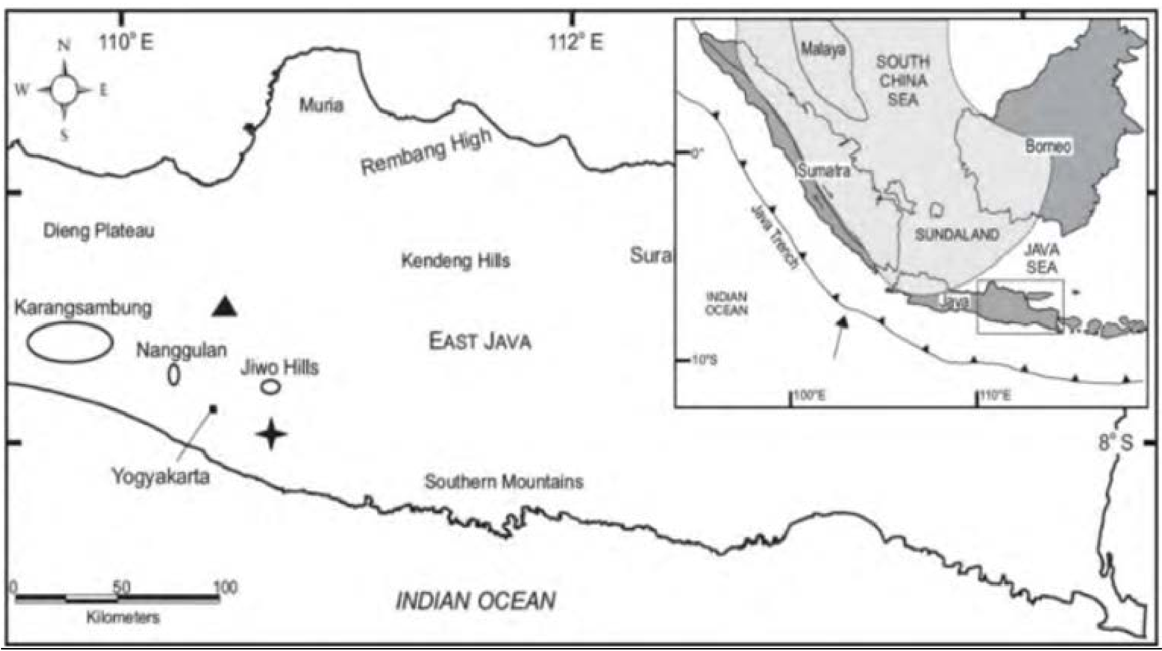

Figure 1. Study area located in the Nanggulan Area. Significant Paleogene sites in the eastern part of Java (Smyth et al. 2008) are marked with ellipse.

sandstones with intercalated lignites, sandy siltstones, claystones with limonite concretions, intercalated marls and limestones, and tuffaceous sandstones. According to Purnamaningsih and Pringgoprawiro (1981), the upper part of this formation consists of marls and calcareous sandstones that are also known as the Seputih Member. The Nanggulan Formation is also a part of the Nanggulan Anticline, which extends relatively north-northeast to south-southwest.

Much extensive research projects have been done in the Nanggulan Formation with regard to sedimentology, geological structure, and palaeontology. According to Saputra and Akmaluddin (2015), the Nanggulan Formation is known for its high variety and good preservation of fossils. Among the varieties of fossils that can be found in this formation include calcareous nannofossil, large benthic foraminifera, benthic

MATERIAL AND METHODS

A total of 103 samples were taken from two traverses: the Watupuru and Jetis Routes. Sampling in the Watupuru Route was accomplished using intervals of ~9 m on average; whereas in the Jetis Route, the sampling was carried out at intervals of ~3 m. Samples for calcareous nannofossil analysis were obtained from fine-grained sedimentary rocks, i.e., claystone, siltstone, sandy siltstone, and very fine sandstone.

Smear slides were prepared from unprocessed sediment samples following the standard technique by Bown and Young (1998) and then were observed under the polarized microscope with immersion oil at 1000x - 1500x magnification. In this study, calcareous nannofossils from each slide were analyzed using a semi-quantitative method. For each smear slide, at least 200 specimens were counted and identified based upon Perch-Nielsen (1985), Farinacci (1969), and Bown (1998) to comprehend the distribution and relative abundance of nannofossil taxa presented in the smear slide. Two to three additional long traverses were scanned to identify the presence of rare taxa or key species for biostratigraphic study. By this means, the calcareous nannofossil zonation is determined after the standard zonation of Martini (1971), Fornaciari et al. (2010), Agnini et al. (2014), and Fioroni et al. (2015) for deducing their absolute age. The sedimentation rate calculation was attained from the age versus thickness/depth cross-plot diagram.

RESULTS

Watupuru Route

The Watupuru Route extends from northwest to southeast, consisting of 18 outcrops exposed along the Watupuru River. The total thickness of the outcrops is estimated at around 207 m with an average strike-dip orientation of 215/13.80 NW (Figure 2).

a. Lithofacies

The lithology found along this route (Figure 3) can be divided into lower, middle, and upper parts. The lower part of the route consists of a thin coal bed intercalation, fine to

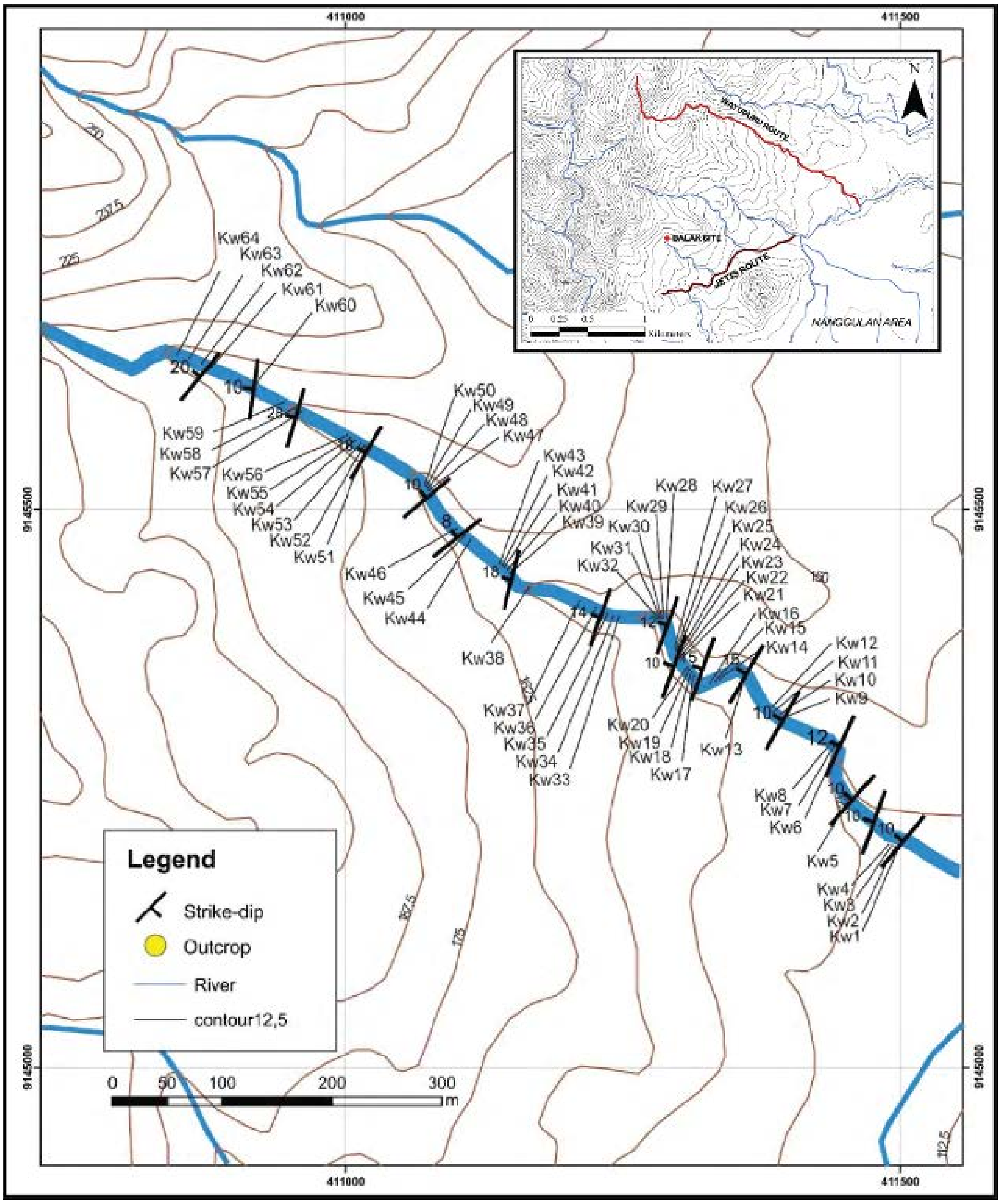

Figure 2. Sample distribution of the Watupuru Route with strike-dip orientation.

very fine sandstones, siltstones, and sandy siltstones. The coal is a lignite type with a thickness of 20 cm and has a black color and a dull luster. The fine sandstone has dark bluish gray to light gray colors with a thickness of around 30 cm to 80 cm. The sedimentary structures present in the sandstones are normal grading, blocky, hummocky cross-stratification, and parallel lamination. The siltstone shows a massive structure with a thickness varying from 30 cm to 120 cm with minor bioturbation and contains mollusks and foraminifera fossils.

The lithology in the middle part of the Watupuru Route generally consists of siltstones with occasional intercalations of sandstones. The siltstone has a dark greenish to bluish-gray color and a massive structure with a thickness of more than 1 m. The bioclast consists of mollusks and foraminifera fragments and is increasing upward. A secondary structure such as concretion is present. The sandstone is generally fine to very fine-grained with a thickness varying from 15 cm to 1 m and contains bioclasts of mollusks and foraminifera with

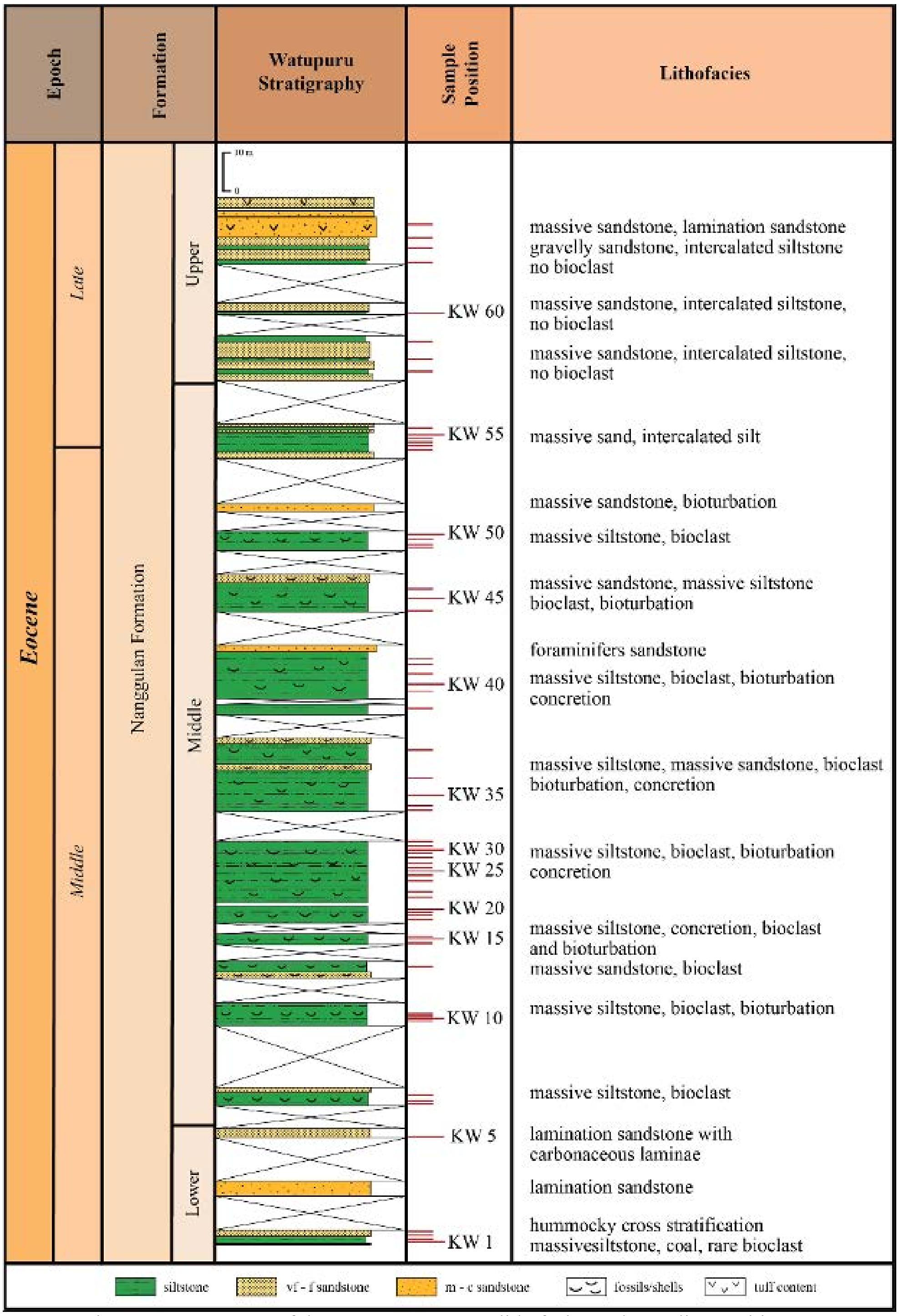

Figure 3. Summary of the Watupuru Route's lithofacies and sampling positions

minor bioturbation. Aside from that, there is also a 2-m-thick coquina-type foraminiferal sandstone with a substantial number of foraminiferal bioclasts.

There is a change of lithology pattern in the upper part of the route. The siltstones are decreasing and sandstones with coarser grains are more dominant. The sandstone is generally medium to coarse-grained with a dark gray color, showing a change in composition. At the uppermost part of the route, gravelly sandstone is present and the bioclast is scarce.

b. Biostratigraphy

The biostratigraphy of this route begins at Zone NP16, which is a partial range zone. The bottom boundary of this zone cannot be identified. The zonal boundary between Zone NP16 and Zone NP17 is detected in the middle part of the section, which is marked by the last occurrence of *Chiasmolithus solitus*. *Dictyococcites bisectus* is also present within this zone. However, the occurrence is delayed until later. The top boundary of Zone NP17 is marked by the last occurrence of *Sphenolithus spiniger*, the last occurrence of *Sphenolithus furcatolithoides*, and the last occurrence of *Chiasmolithus gigas*. Agnini et al. (2014) and Okada & Bukry (1980) marked the boundary between Zone NP17 and Zone NP18 using *Chiasmolithus gigas* as the biodatum, separating the Middle Eocene and the Late Eocene. However, in this study, the presence of this species is not reliable to take into account due to Zone NP18 being a partial range zone with an undefined top boundary. There is no record of nannofossil occurrence in most samples above KW-60 (Figure 4).

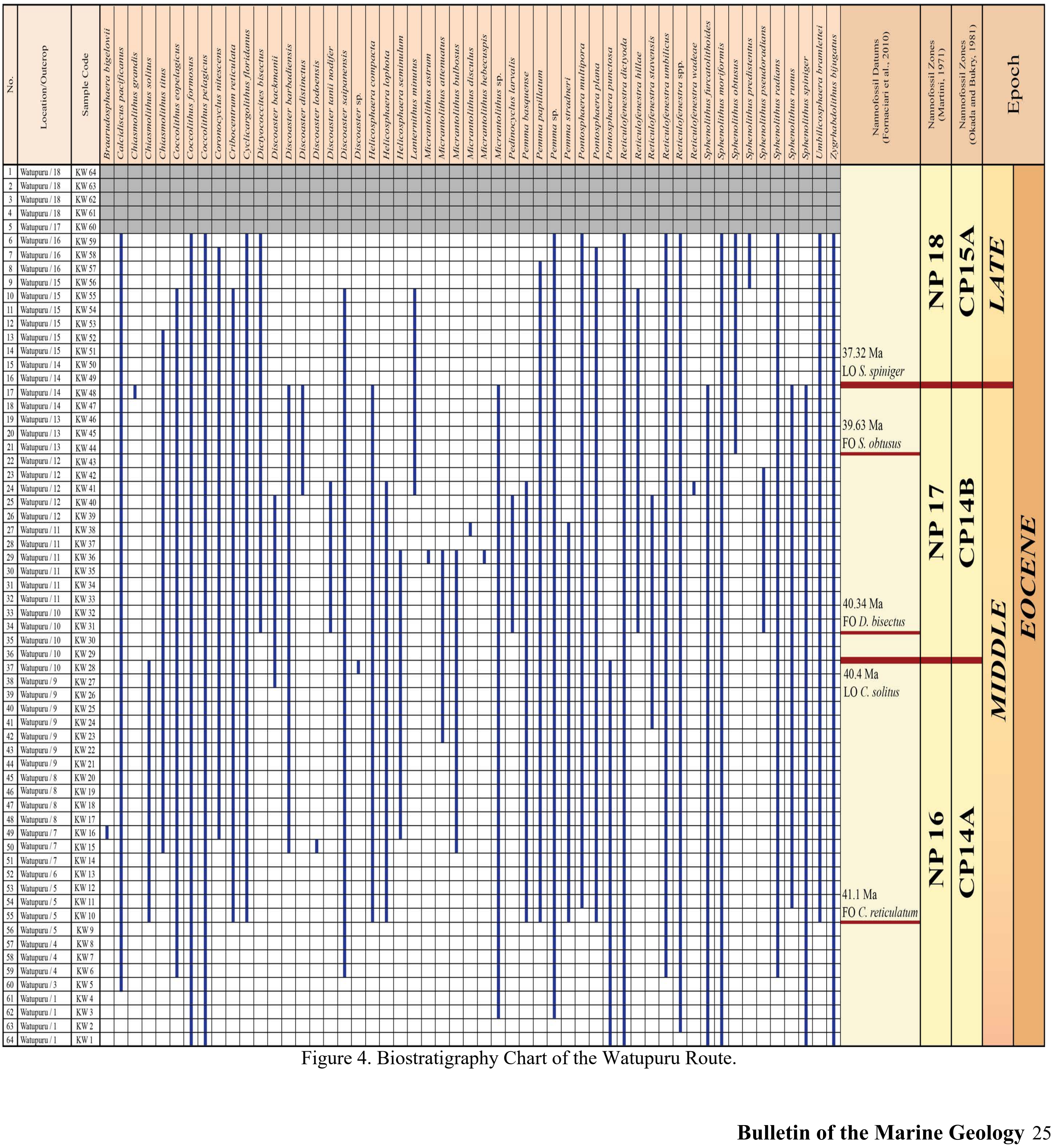

Figure 4. Biostratigraphy Chart of the Watupuru Route.

Table 1. Biodatums and numerical ages used in biostratigraphy study in the Watupuru Route.

Biodatum	Position (Interval)	Age (Ma)			
		Fioroni et al. (2015)	Agnini et al. (2014)	Savian et al. (2013)	Fornaciari et al. (2010)
LO *Sphenolithus spiniger*	137.5 m	-	37.32	-	-
FO *Sphenolithus obtusus*	117 m	39.0	-	-	39.63
FO *Dictyococcites bisectus*	79 m	39.0	40.34	-	-
LO *Chiasmolithus solitus*	77 m	38.7	-	40.40	38.40
FO *Cribocentrum reticulata*	45 m	41.3	42.37	-	41.1

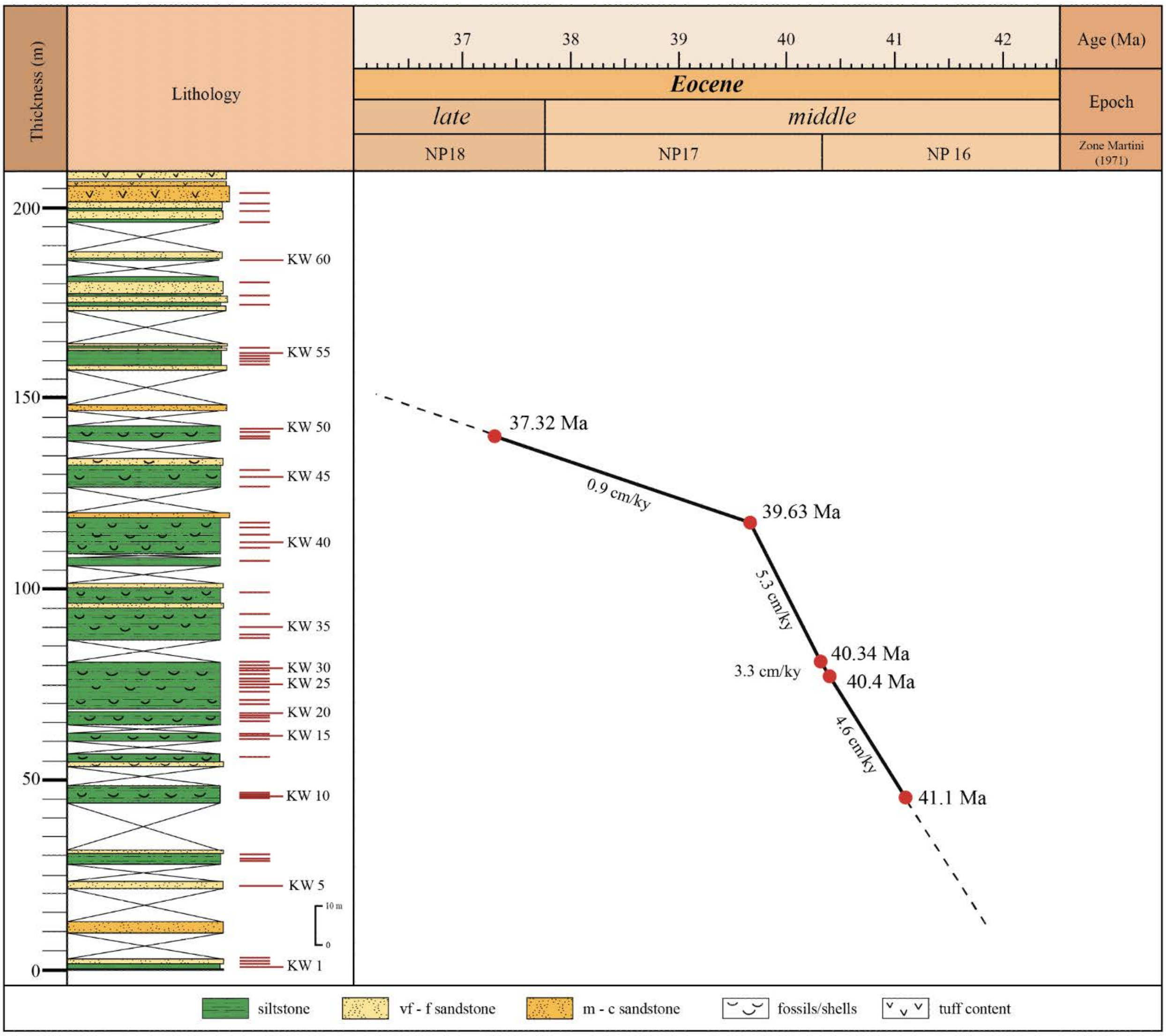

Figure 5. Age versus depth/thickness cross-plot of the Watupuru Route and its sedimentation rates.

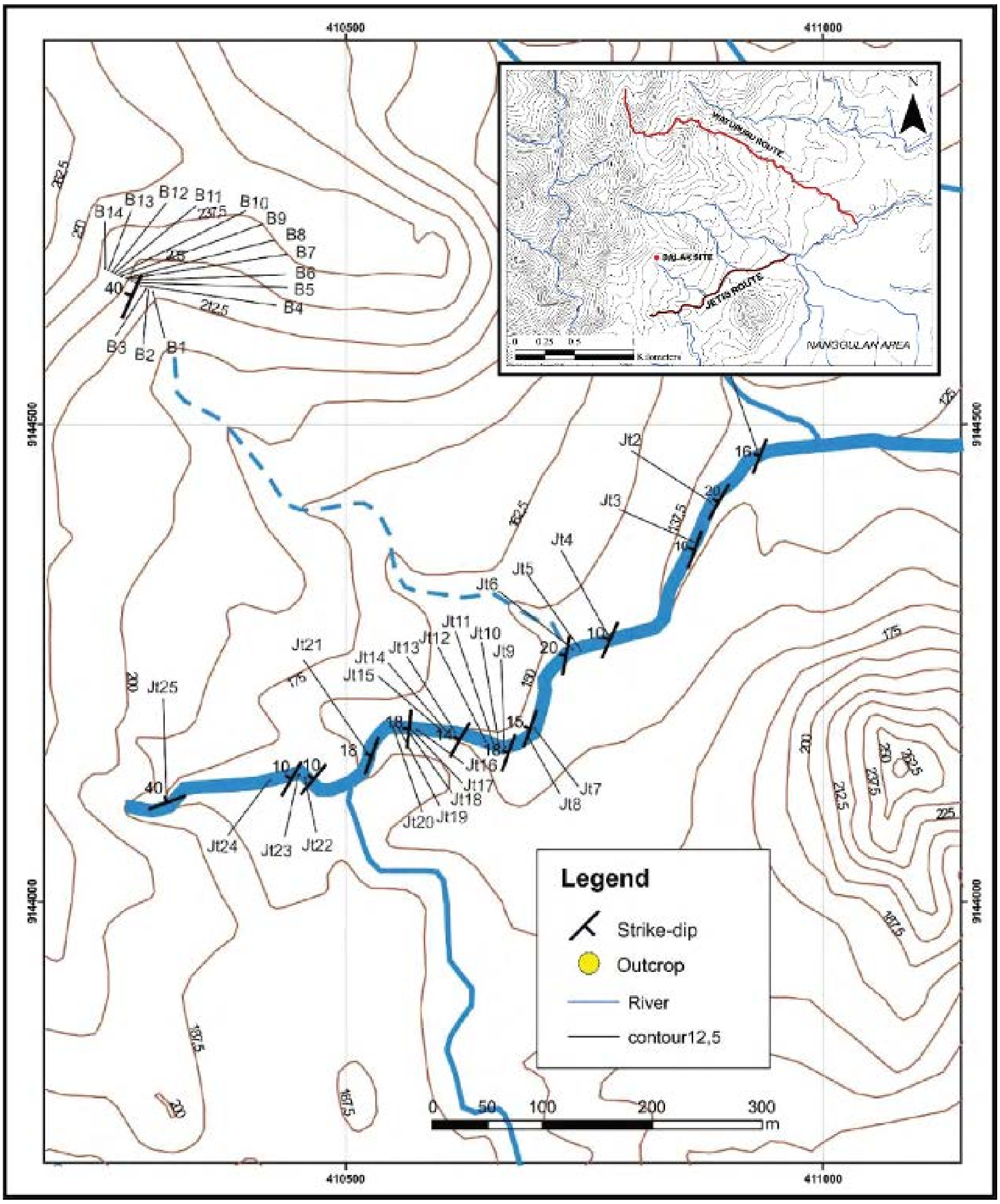

Figure 6. Sample distribution of the Jetis Route with strike-dip orientation.

c. Sedimentation Rate

In accordance with the biodatum identified by calcareous nannofossils taken from the Watupuru Route (Table 1), the sedimentation rates for this section differ, showing four depositional sequences (Figure 5). The first sequence is the 45–77 m interval with the sediment accumulation rate of 4.6 cm/kyr in the age period ranging from 41.1 Ma to 40.40 Ma. The second sequence is the interval of 77–79 m accumulated between 40.40 Ma and 40.34 Ma and has the sediment accumulation rate of 3.3 cm/kyr. The third sequence starts from 79 m to 117 m positions dated 40.34 Ma to 39.63 Ma and reveals the sedimentation rate of 5.3 cm/kyr. The last sequence is in the interval of 117 m to 137.5 m, deposited from 39.63 Ma to 37.32 Ma with the sedimentation rate of 0.9 cm/kyr. The average sedimentation rate of the Watupuru Route is 3.5 cm/kyr, approximately.

Jetis Route

The Jetis Route lengthens from the northwest to southeast, consists of 19 outcrops in which 18 of them are exposed along the Songgo River and Seputih River in Jetis Village and the one outcrop is in Balak (Figure 6). The total thickness of this route is estimated at about 197 m with average strike-dip orientation of 189/17.50 NW.

a. Lithofacies

The lithofacies summary of the Jetis Route is shown in Figure 7. The route is divided into lower, middle, and upper parts. The lower part of the Jetis Route comprises sandstone-siltstone intercalations. The condition of this part is weathered; thus, some sedimentary structures are not clearly recognizable. The sandstones are generally fine to very fine-grained with light greenish to bluish-gray colors. Their thicknesses vary from 40 cm to 1.5 m. The sedimentary structures noticed in this part are massive structures and laminations. The sandstones contain bioclasts of mollusks and foraminifera with minor bioturbations. The siltstones have dark greenish to bluish-gray colors, and the sedimentary structure of massive structures. Their thicknesses vary from 30 cm to 1 m. Mollusks and foraminifera bioclasts, as well as some minor bioturbations, can be found in the siltstones. The

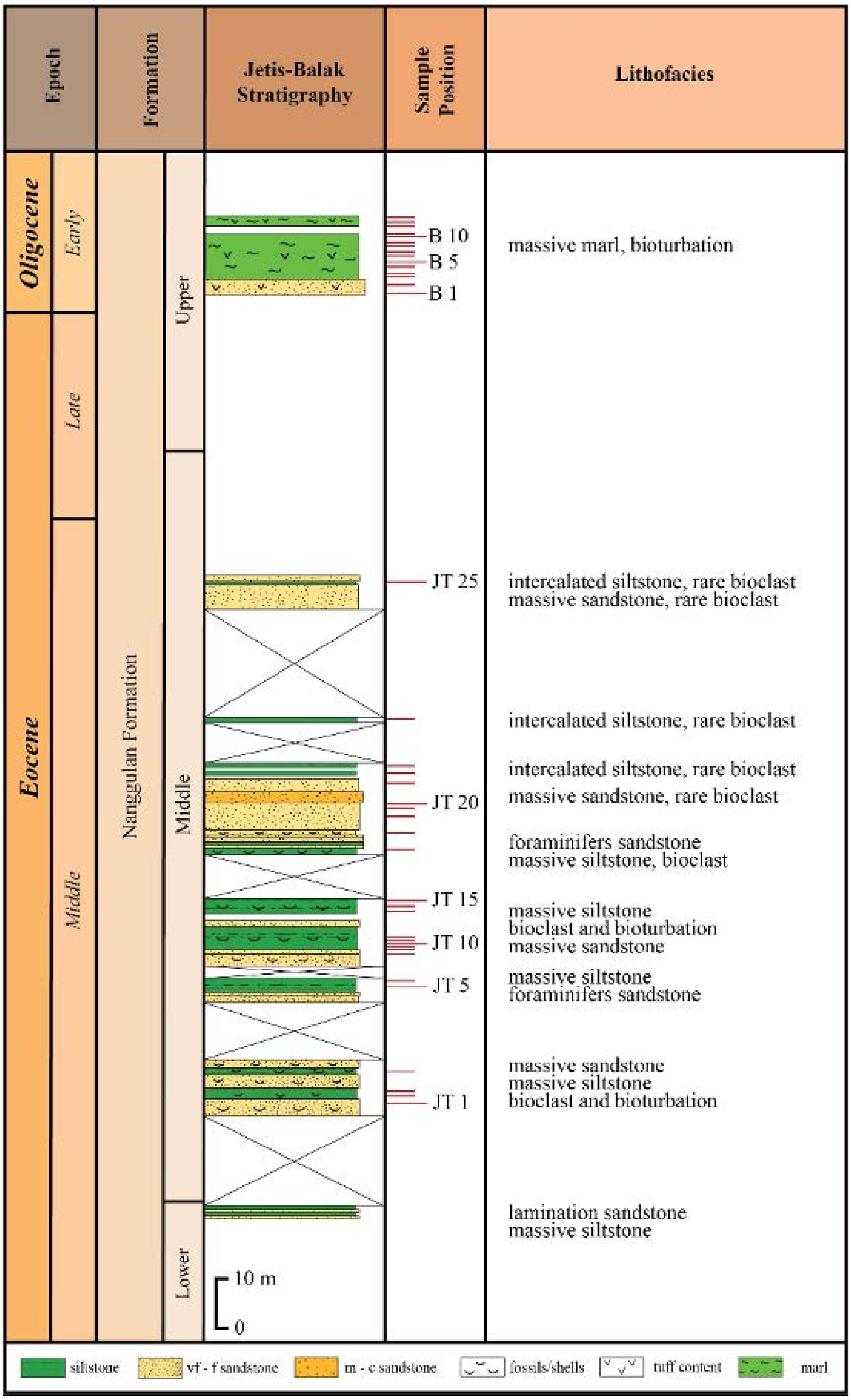

Figure 7. Summary of the Jetis Route's lithofacies and sampling positions

secondary structure of concretions is present in both lithofacies.

The lithofacies in the middle part of the Jetis Route are fairly similar to those in the lower part. However, the occurrence and thickness of the siltstones alternated with sandstones are gradually increasing. In general, the sedimentary structure is massive with minor bioturbations. Concretion is present in both sandstone and siltstone. There is also coquina-type foraminifera sandstone present with a considerable amount of bioclasts, mainly of larger benthic foraminifera, such as *Discocyclina*. The coquina is dark green in color and matrix-supported, with medium sand as the matrix. This type of sandstones develops as of about 1 m-intercalations between the sandstones and siltstones in two of the outcrops.

The upper part of the Jetis Route generally consists of bedded sandstones with intercalations of siltstones. The sandstone is dark gray in color, mostly fine to medium-grained. However, coarse sandstone is also present in some outcrops. The sandstone is massive, laminated, or normal graded with minor bioturbations. The bioclasts are sparse in sandstones. Siltstone appears as intercalations showing massive or blocky structure and commonly has dark greenish to bluish-gray colors with few bioclasts.

The youngest part of this route, the Balak Site, is exposed along the slope of Menoreh Hill, around 500 m to the north of the river. Between the last sampling site of the Jetis Route and the Balak Site, there is no outcrop exposed in the vicinity, which then is interpreted as a gap of time. This site is considered a part of the Jetis Route due to its near-by location and possesses a similar strike-dip orientation in general. The Balak Site consists of marlstones and limestones in gray to white colors. They are rich in carbonate material, and bioturbations are also present. There are no bioclasts or rock fragments found in the outcrop. Their sedimentary structure is mostly massive with the grain size of very fine sand or silt.

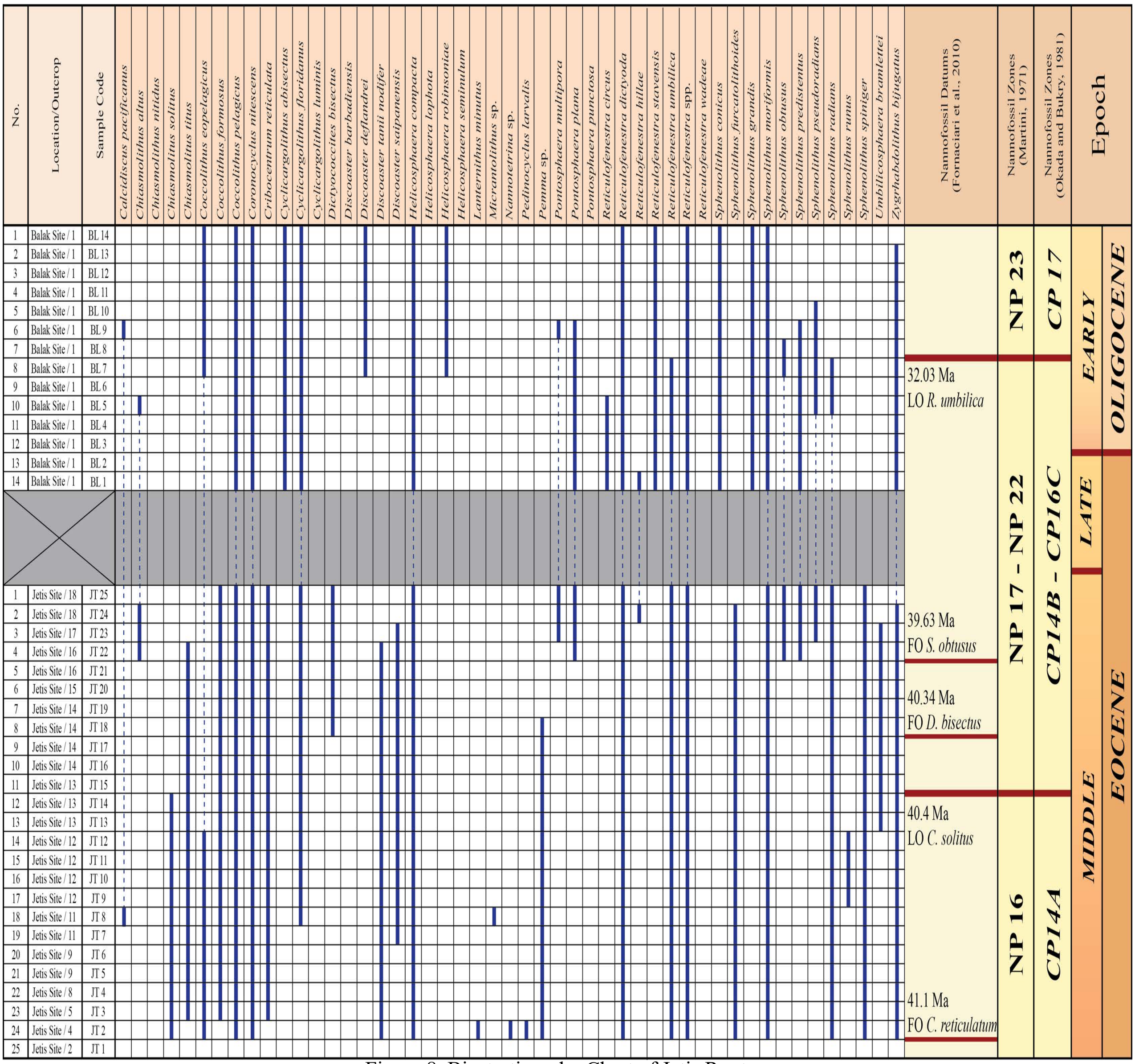

Figure 8. Biostratigraphy Chart of Jetis Route.

Table 2. Biodatum and numerical age used in Jetis Route biostratigraphy study.

Biodatum	Position (Interval)	Age (Ma)			
		Fioroni et al. (2015)	Agnini et al. (2014)	Savian et al. (2013)	Fornaciari et al. (2010)
LO *Reticulofenestra umbilica*	198.5 m	31.05	32.02	32.30	-
FO *Sphenolithus obtusus*	92.4 m	39.0	-	-	39.63
FO *Dictyococcites bisectus*	83.4 m	39.0	40.34	-	-
LO *Chiasmolithus solitus*	57.6 m	38.7	-	40.40	38.40
FO *Cribocentrum reticulata*	25.3 m	41.3	42.37	-	41.1

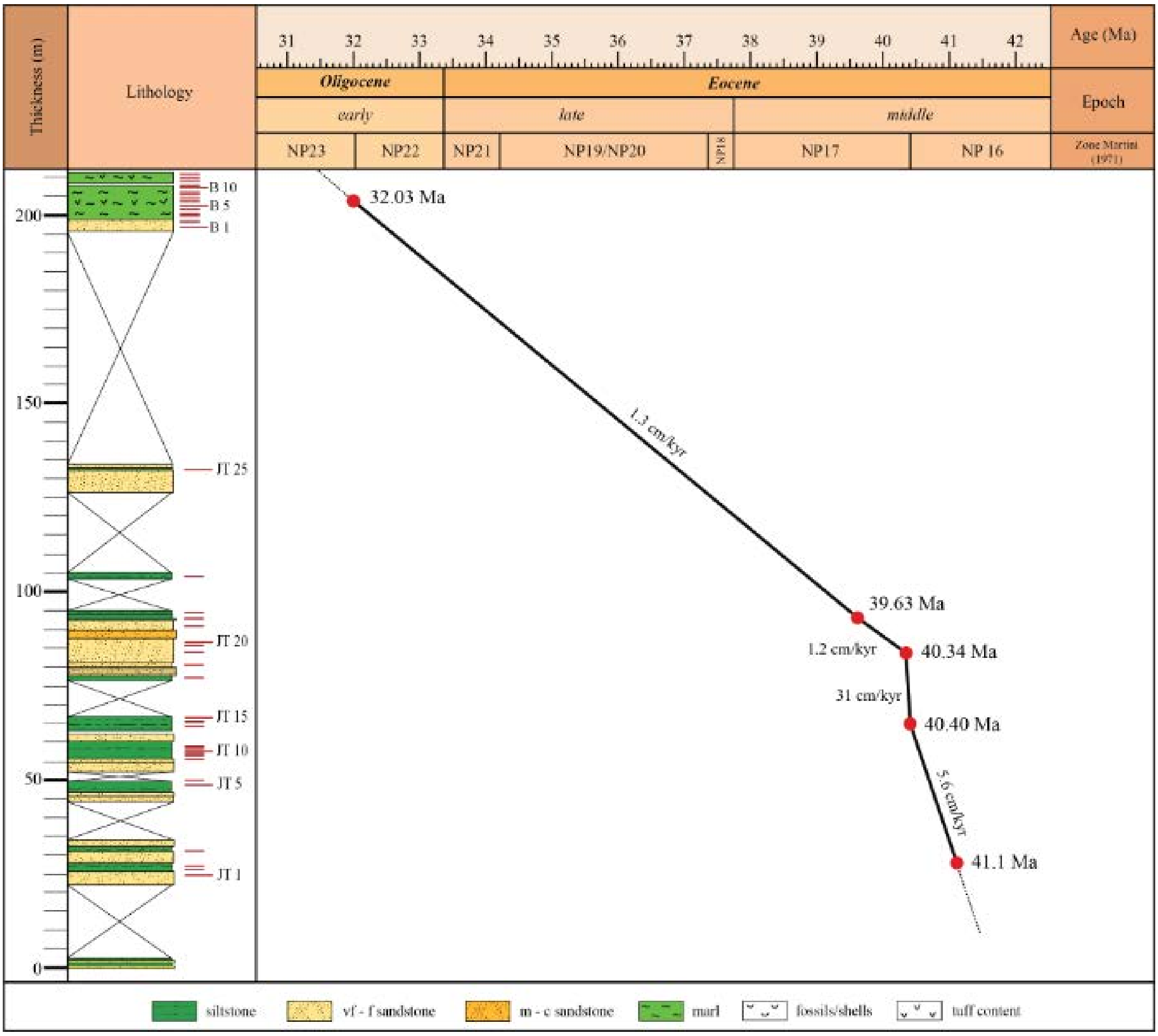

Figure 9. Age versus depth/thickness cross-plot of the Jetis Route and its sedimentation rates.

b. Biostratigraphy

There are two calcareous nannofossil zones identified in the Jetis Route and two additional zones identified in the Balak Site (Figure 8). The Jetis Route's biostratigraphy starts from Zone NP16, indicated by the first occurrence of *Cribocentrum reticulatum*, which is also used as an additional biodatum to characterize the lower part of Zone NP16. The zonal boundary between Zone NP16 and Zone NP17 is observed in the middle part of the section of the Jetis Route, identified by the last occurrence of *Chiasmolithus solitus*. In this section, the first occurrence of *Dictyococcites bisectus* characterizes the base of Zone NP17, whereas the first occurrence of *Sphenolithus obtusus* characterizes the upper part of Zone NP17. Zone NP17 is considered a partial zone since its top boundary cannot be identified.

Between the Jetis Route and the Balak Site, there is a 60 m lithological gap shown by no outcrops present in the upper part of the section. At the Balak Site, the zonal boundary of NP22/NP23 is determined by the last occurrence of *Reticulofenestra umbilica*, hence resulting in NP22 and NP23 as two partial zones. There is only one biodatum identified in this section, indicating a much younger age of Early Oligocene.

c. Sedimentation Rate

Based on the biodatum identified from calcareous nannofossil samples of the Jetis Route (Table 2), the sedimentation rates of this section is divided into four sequences (Figure 9).

The first sequence is from 41.1 Ma to 40.4 Ma, encompassing from 25.3 m to 64.8 m with a sediment accumulation rate of 5.64 cm/kyr. The second sequence is between 40.4 Ma and 40.34 Ma and is situated at 64.8 m to 83.4 m with a sedimentation rate of 31 cm/kyr. The third sequence is located at 83.4 m to 92.4 m, dated 40.34 Ma to 39.63 Ma, and has a sedimentation rate of 1.26 cm/kyr. The fourth sequence's age is 39.63 Ma to 37.7 Ma and was discovered at 92.4 m to 198.5 m, showing a sedimentation rate of 1.39 cm/kyr. The average sedimentation rate of the Jetis route is circa 9.82 cm/kyr.

DISCUSSION

Biostratigraphy of Nanggulan Formation

The biostratigraphy study shows that the Nanggulan Formation was deposited in the Middle Eocene to Early Oligocene, or according to the biozonation of Martini (1971), is equal to NP16 to NP23. It is also equal to CP14A-CP17 which was based on Okada & Bukry (1980), or to CNE15-CNO3, assumed by Agnini et al. (2014) (Figure 9). The result corresponds with the age of the Nanggulan Formation suggested by Purnamaningsih & Pringgoprawiro (1981), Lunt & Sugiatno (2003), and Marliyani (2005). There are three calcareous nannofossil zones identified from the Watupuru Route, namely as follows:

Figure 10. Biostratigraphic correlation of the Jetis, Balak, and Watupuru Routes.

a. *Chiasmolithus solitus* Partial Range Zone

This zone is marked by *Chiasmolithus solitus*'s last occurrence at the top and an undefined bottom border. The zone is represented by samples KW1 to KW28 and is equivalent to NP16 of the zonal division by Martini (1971), as indicated by the first occurrence of *Cribocentrum reticulata* in the lower part.

b. *Chiasmolithus solitus* - *Sphenolithus spiniger* Range Zone

This zone discloses the last occurrence of *Chiasmolithus solitus* as the bottom border and the last occurrence of *Sphenolithus spiniger* as the top one. The zone is determined from samples KW29 to KW48, in which the first occurrences of *Dictyococcites bisectus* and *Sphenolithus obtusus* are observed, equivalent to NP17 according to Martini (1971).

c. *Sphenolithus spiniger* Partial Range Zone

This zone reveals the last occurrence of *Sphenolithus spiniger*, setting a border at the bottom. However, the top border is unclear. The zone is defined by samples KW49 to KW64 and is equivalent to NP18, consistent with Martini (1971).

Based on results from the Jetis and Balak Routes, there are three calcareous nannofossil zones that can be distinguished as follow (figure 10):

a. *Chiasmolithus solitus* Partial Range Zone

The zone is marked by *Chiasmolithus solitus*'s last occurrence at the top border with an undefined bottom one. This zone is represented by samples JT1 to JT14 and equivalent to NP16 by Martini (1971), supported by the first occurrence of *Cribocentrum reticulata* in the lower part of this zone, similar to the Watupuru Route.

b. *Chiasmolithus solitus* - *Reticulofenestra umbilica* Range Zone

The zone is identified by the last occurrence of *Chiasmolithus solitus* at the bottom border of the Jetis Route and the last occurrence of *Reticulofenestra umbilica* at the top border of the Balak Route. The first occurrences of *Dictyococcites bisectus* and *Sphenolithus obtusus* are also found within the zone. This zone is equivalent to NP17-NP22 according to Martini (1971); however, no outcrop reveals in the middle part, showing a data gap like in the upper part of the Jetis Route. This zone is represented by samples JT15 to JT25 and BL1 to BL7.

c. *Reticulofenestra umbilica* Partial Range Zone

The zone is typified by the last occurrence of *Reticulofenestra umbilica* at the bottom border with an undefined top border. This zone is represented by samples BL8 to BL14 and is equivalent to NP23 as described by Martini (1971).

Lithological Changes and Sedimentation Rates

In accordance with the Watupuru and Jetis-Balak Routes, the overall grain size of the facies is decreased in the northward direction, i.e., from dominated sandstone in the Jetis Route to dominated siltstone in the Watupuru Routes. Along with the decreasing grain size, the total thickness of the succession is also increased northerly, indicating the source of sediment supply possibly comes from the direction of the Jetis Route. In consideration of the lithofacies of its depositional environment, the Watupuru Routes is interpreted as an offshore transitional deposition while the Jetis Route is interpreted as a shoreface area. This depositional environmental change suggests that water depth also increases northward in the direction of Watupuru Routes.

a. Sequence before 41.1 Ma

The distribution of lithofacies in the Watupuru Routes was coal, massive siltstones, laminated sandstones, and hummocky cross-stratified sandstones. The variation suggests an increase in water depth from the backshore area into the offshore transition-area. The sandstone and siltstone contained bioclasts of mollusks and foraminifera, while the lithofacies in the Jetis Route are mostly dominated by lamination of sandstone and siltstone.

b. Sequence 41.1 Ma to 40.40 Ma

Between 41.1 Ma and 40.40 Ma, the Watupuru Route has a sedimentation rate of 4.6 cm/kyr and is characterized by the fining-upward pattern. The distribution of siltstone facies is gradually increasing upward and becoming dominant, with occasional layers of fine to very fine-grained sandstone intercalations. In the Jetis Route, the fine to very fine-grained sandstones decrease in quantity, while the massive siltstones increase, alternating with fine to very fine-grained sandstone. The sedimentation rate is 5.6 cm/kyr. The sandstone and siltstone facies also contain bioclasts, consisting of mollusks and foraminifera. The foraminifera sandstones also appear in this section for the first time, possibly as a result of storm events. The overall fining-upward pattern suggests a stable increase in water depth. The low sedimentation rate possibly indicates a low sediment supply along with the extension tectonic period in the Nanggulan region (Prasetyadi, 2008) that contributed to an increase in accommodation.

c. Sequence 40.40 Ma to 40.34 Ma

This period is characterized by a second occurrence of foraminifera sandstones in the Jetis Route with a sedimentation rate of 31 cm/kyr; whereas in the Watupuru Route, massive siltstones are dominant with a sedimentation rate of 3.3 cm/kyr. The coarsening-upward pattern is observed in the Jetis Route, suggesting a decrease in water depth in the upper part of this sequence. Considering the increase in the sedimentation rate as the water depth decreased, the weathering and erosion of exposed outcrops might also intensify, resulting in more

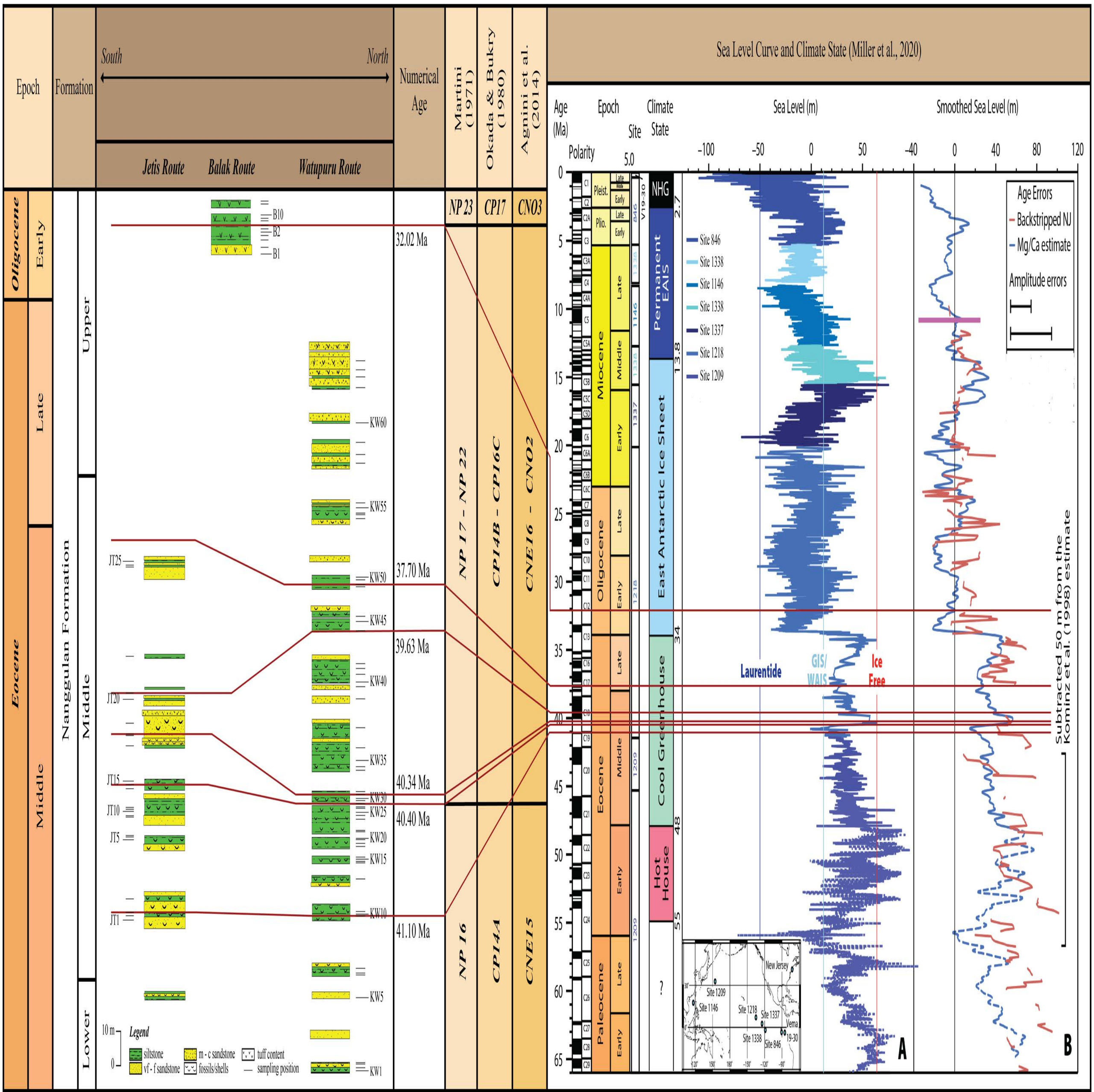

Figure 11. Correlation between the Nanggulan Formation's depositional history and the global sea-level curve after Miller et al. (2020)

sediment supply to deposit, particularly in the Jetis Route. Meanwhile, the increase in sediment supply in the Watupuru Route did not seem to affect the deeper environment.

d. Sequence 40.34 Ma to 39.63 Ma

This period was characterized by an increase in sandstone facies upward in the Watupuru Route with a sedimentation rate of 5.3 cm/kyr. The sandstone facies appear in between the massive siltstone facies that gradually increase upward. Meanwhile, the sedimentation rate of the Jetis Route is 1.2 cm/kyr. The fine to very fine-grained sandstone facies appear dominantly in the base of this sequence, and then abruptly change into a coarse to medium-grained sandstone. The overall pattern in each route is coarsening upward, suggesting a decrease in water depth. There is a significant decrease in sedimentation rate in the Jetis Route, whereas the sedimentation rate of Watupuru Route increases compared to the previous period. This change possibly indicates that the sediment accommodation of the Jetis Route is significantly decreasing, and the deposition of the sediment is directed to the deeper environment, causing the sedimentation rate of the Watupuru Route to increase.

e. Sequence 39.63 Ma to 37.32 Ma

Within this period, the sedimentation rate in the Watupuru Route is 0.9 cm/kyr. The sandstone facies found in this route also appear increasingly, along with decreasing bioclast content. In overall, grain size becomes coarsening-upward, i.e., from fine to very fine-grained sandstones to coarse to medium-grained sandstones. The third appearance of foraminifera sandstone facies in this sequence indicates a considerable shallower environment in the Watupuru Route. Meanwhile, the appearance of the sandstone facies in the Jetis Route becomes frequent toward the upper part.

f. Sequence after 37.32 Ma

After 37.32 Ma, the appearance of sandstone facies in the Watupuru Route become more frequent. The fine to very fine-grained sandstone facies appeared frequently upward, alternating with coarse to medium-grained sandstone. In the Jetis Route, there are no lithofacies documented after 37.32 Ma. The uneven distribution after 37.32 Ma suggests a significant change in depositional environment. The lithofacies association in the Watupuru Route indicates a shallower environment from upper to lower shoreface, revealing a coarsening-upward pattern toward the end of this sequence.

g. Sequence around 32.03 Ma

In the Jetis Route, this period is characterized by a deposition of marlstone, which indicated an offshore environment. This sequence is entirely separated from the lower sequence due to no outcrop recorded here. There is a

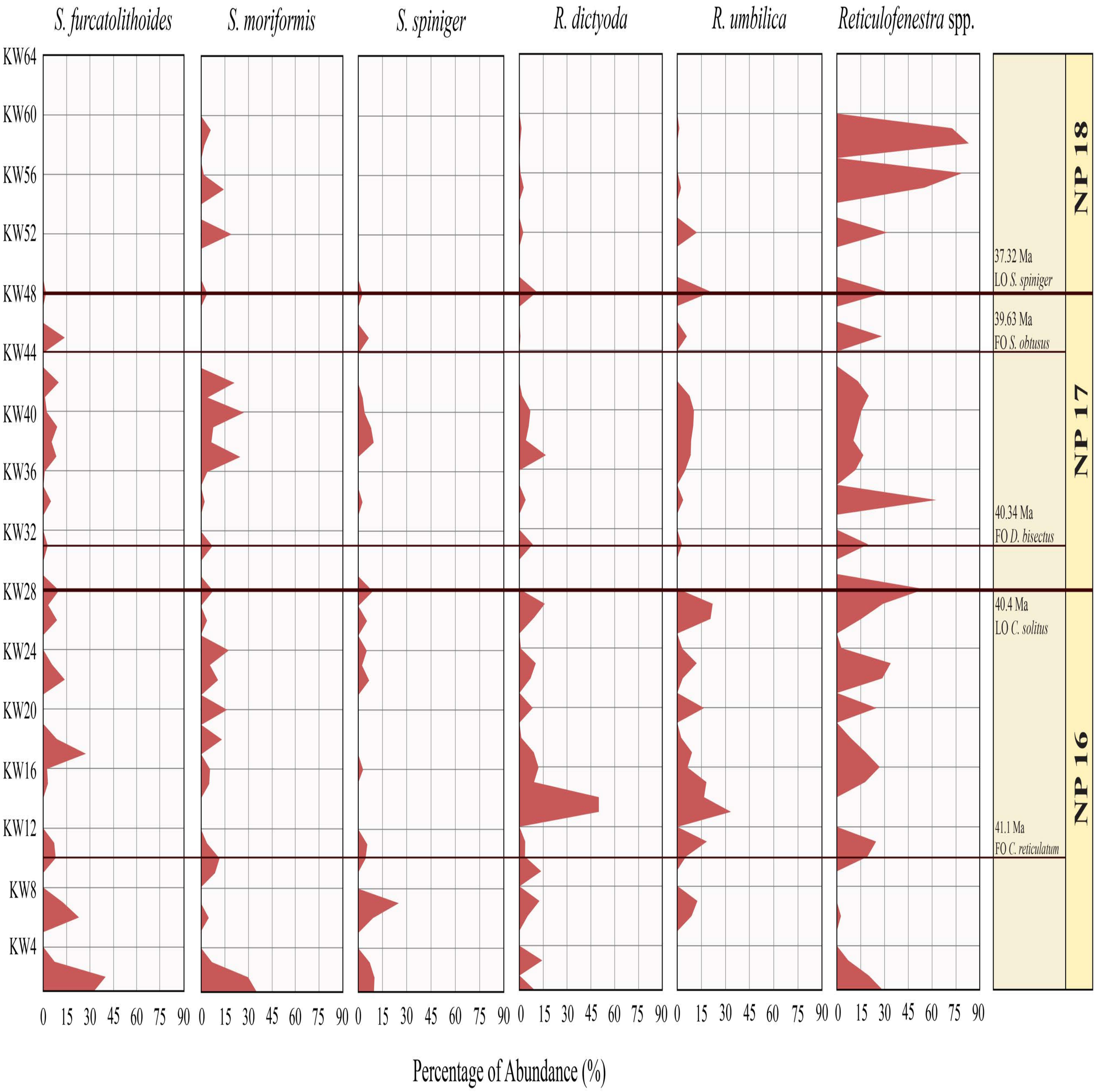

Figure 12. The abundance percentage in *S. furcatolithoides, S. moriformis, S. spiniger, R. dictyoda, R. umbilica,* and *Reticulofenestra* spp. in the Watupuru Route.

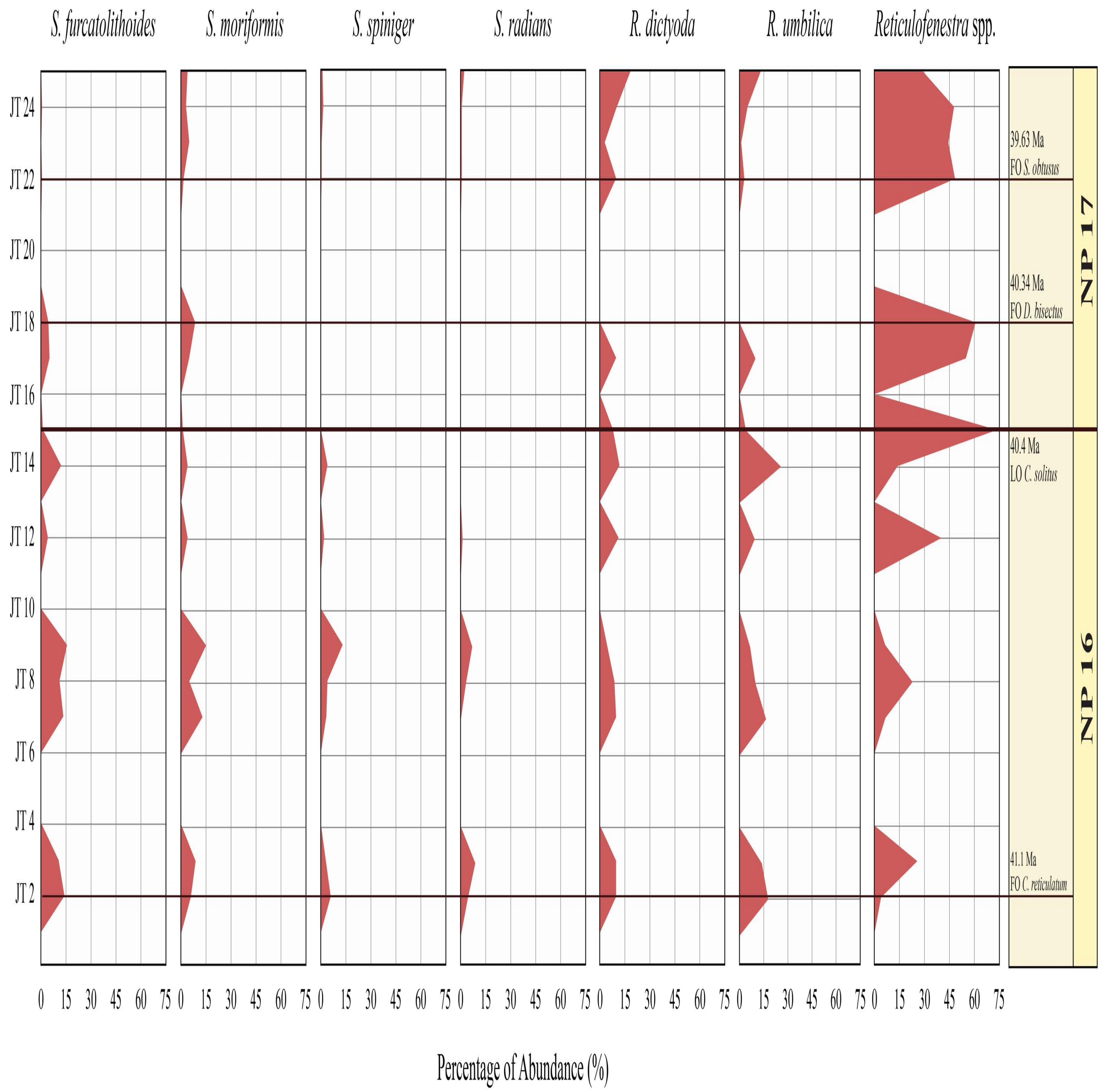

Figure 13. The abundance percentage of *S. furcatolithoides, S. moriformis, S. spiniger*, *R. dictyoda, R. umbilica,* and *Reticulofenestra* spp. in the Jetis Route.

5.29 Ma time gap between the sequence of the Watupuru Route and the sequence in the Jetis Routes. From the period of 39.63 Ma to 32.03 Ma, the sedimentation rate is 1.3 cm/kyr in Jetis Route. The marl shows a slight reduction in grain size from fine to very fine sand to silt-clay size, suggesting an increase in water depth. There is no bioclast content found in this sequence.

The changes in the depositional environment within the study area are interpreted as a result of sea-level fluctuations, suggesting that the deposition of the Nanggulan Formation has been greatly affected by the sea level changes. To confirm this interpretation, the correlation between the Nanggulan Formation's depositional history and the relative sea-level curve was made by utilizing the global sea level curve proposed by Miller et al. (2020) (Figure 11).

From the correlation, it is confirmed that there were significant fluctuations in sea level during the deposition of the Nanggulan Formation. The global sea-level curve showed two cycles of sea-level rise and fall happening during the depositional period, which closely influenced the changes of depositional environment within the study area. Before 41.1 Ma, global sea level rose until 40.7 Ma period before slightly falling toward 40.4 Ma. As a result, the lithofacies show a fining-upward pattern below 40.4 Ma. During the period of 40.4 Ma to 40.34 Ma, global sea level fell slightly, indicated by a coarsening-upward pattern in the Jetis Route and the decrease of siltstone facies in the Watupuru Route. From 40.34 Ma to 39.8 Ma, sea level was relatively stable but then slightly rose from 39.8 Ma to 39.63 Ma. In the Watupuru Route, the sandstone facies slightly increased but were still dominated by siltstone. In the Jetis Route, the fine to very fine-grained sandstone facies were deposited consistently and then the intercalation of siltstone appeared before 39.63 Ma, confirming the rise of sea level at the upper part of the section.

Within the period of 39.63 Ma to 37.32 Ma, global sea level slowly decreased until 38.7 Ma and then rose slightly to 37.32 Ma. The lithofacies show a coarsening upward pattern, confirming sea level change. In the Watupuru route, the siltstone facies occur alternately with sandstone facies. Meanwhile, there is a slight increase of siltstone intercalations alternated with sandstone facies in the Jetis Route toward the upper part. After 37.32 Ma, global sea level continued to rise. However, the change in lithofacies does not reflect the sea level change. In the Watupuru route, the lithofacies after 37.32 Ma appeared to be dominated by sandstone facies with a coarsening-upward pattern. The distribution of lithofacies and the rising of sea level lead to the interpretation that the sedimentation rate possibly outpaced the rate of sea level rise. In a short period around 32.02 Ma, sea level rose slightly. The fining-upward pattern in the Balak Site possibly related to this sea level change. However, the lack of outcrop distribution inclines this part to be separated completely from the rest of the deposition in the Jetis and Watupuru Routes, although the interpretation might not possibly be accurate.

Indication of environmental changes from nannofossil data

In the Watupuru Route, from 41.1 Ma to 40.40 Ma, there was a slightly increase of percentage abundance from *Reticulofenestra* taxa (Figure 12), especially small *Reticulofenestra* (*Reticulofenestra* spp.). Meanwhile, *Sphenolithus* thrived before 41.1 Ma and their abundance gradually decreased until 40.40 Ma, suggesting a shift from oligotrophic to eutrophic condition at age 41.1 Ma - 40.40 Ma. *Sphenolithus* is taxa that prefers oligotrophic and warm-water condition (Aubry, 1998; Bralower, 2022; Gibbs et al. 2004; Villa et al. 2008; Toffanin et al. 2011; Imai et al. 2015), while small *Reticulofenestra* is considered to be an indicator of eutrophic environment (Takahashi & Okada, 2000; Kameo, 2002; Balleeger et al. 2012; Imai et al. 2015; Hendrizan, 2016) because small placoliths typically flourish in high-productivity areas (Okada and Honjo, 1973; Winter et al. 1994; Okada, 2000; Hagino and Okada, 2000; Toffanin et al. 2011). Small *Reticulofenestra* (*Reticulofenestra* spp.) continued to thrive, especially in Zone NP18. However, *R. dictyoda* and *R. umbilica* decreased after 40.4 Ma. *Sphenolithus* slightly increased in the middle of Zone NP17 before decreasing again after 37.32 Ma.

In the Jetis Route, the percentage abundance of *Reticulofenestra* taxa did not change significantly from 41.1 Ma to 40.40 Ma. However, small *Reticulofenestra* (*Reticulofenestra* spp.) drastically increased in 40.40 Ma and continued to thrive from then on (Figure 13). On the other hand, *Sphenolithus* taxa started thriving from 41.1 Ma. Their abundance decreased slightly before 40.40 Ma and drastically decreased after 40.40 Ma. During and after 40.40 Ma, the low abundance of *Sphenolithus* taxa and the increase of eutrophic taxa, such as *Reticulofenestra,* may be driven by enhanced eutrophy since the sphenoliths prefer oligotrophic and warm-water conditions. The calcareous nannofossil change after 39.63 Ma in the Jetis-Balak Routes cannot be interpreted due to lack of outcrop data.

We suspect that the enhanced eutrophy in the Jetis and Watupuru Routes was caused by the increasing terrigenous input in and after 40.40 Ma, thus providing nutrient availability on the water surface. This interpretation is supported by the abrupt increase in sedimentation rates in the Jetis Route before and after 40.40 Ma, which is from 5.6 cm/kyr to 31 cm/kyr. However, the sedimentation rate in the Watupuru Route is slightly decreased in that age, from 4.6 cm/kyr to 3.3 cm/kyr. It is also confirmed from sea level change that the increase in sedimentation rates was likely influenced by sea level fall in the age of 40.40 Ma to 40.34 Ma.

CONCLUSIONS

Based on the biodatum identified in the study area, the biostratigraphy of the Nanggulan Formation is divided into five zonations following the standard zonation by Martini (1971). There are four partial zones and one complete one, stated as follows: the upper part of Zone NP16, Zone NP17, the lower part of Zone NP18, the upper part of Zone NP22, and the lower part of Zone NP23. Based on the biostratigraphy study, the Nanggulan Formation was deposited at the age of 41.1 Ma to 32.2 Ma (Middle Eocene to Early Oligocene).

According to the horizontal distribution of lithofacies, the depositional environment of the Nanggulan Formation became shallower southward in the Jetis Route and shifted to a deeper environment northward in the Watupuru Route. The deposition of the Nanggulan Formation is strongly believed to be greatly influenced by the fluctuation of global sea level according to sea level change correlation.

The decrease of oligotrophic taxa (*Sphenolithus*) and the increase of eutrophic taxa (*Reticulofenestra*), especially small reticulofenestrids (*Reticulofenestra* spp.), suggest that there was a shift of the environment condition from oligotrophic in around 41.1 Ma to eutrophic condition after 40.40 Ma, particularly. The enhanced eutrophy in Jetis and Watupuru Route is believed as a result of increasing terrigenous input in and after 40.40 Ma, thus providing nutrient availability in the water surface. This interpretation is supported by the increase in the sedimentation rate when sea level slightly decreased at 40.40 Ma.

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