INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Sedimentation Rate During Miocene to Pleistocene Related with Nannofossil Biostratigraphy, in Banyuurip, Kedewan, Rembang Zone, East Java Basin, Indonesia

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Manuscript received: July, 13, 2021; revised: April, 5, 2022;
approved: June, 22, 2023; available online: November, 3, 2023

Abstract - The researched area is located in Rembang Zone, North East Java Basin. The Rembang Zone is one of the largest basins in Indonesia. In this area, there are many oil wells that today are still actively producing. The research concerning the content of microfossils in marine sedimentary outcrops is needed to determine the rate of sedimentation in a basin. The method is basically based on the result of stratigraphic measurements of two sections with a distance of 2,743.7 m. Sedimentation rate is the average thickness ratio to the average time interval. The sections have a good outcrop and a continuous stratigraphic sequence from Miocene (Wonocolo, Ledok, and Mundu Formations) to Pleistocene (Lidah Formation). Samples taken in the section consisted of fourty-one samples of marls and shales. The results of the analysis show eighteen genera with fifty-seven species of nannoplankton. While the resulting biostratigraphic zone can be arranged into eleven zones consisted of two partial, one range and eight interval zones. The development of sedimentation rate (RoS) of studied area consists of ten periods, those are (1) CNM15 Zone/Late Miocene of Ledok Formation at a depth of 427.8 - 322.4 m, and has a sedimentation rate (RoS) of 11.46 cm/ky, (2) CNM16-CNM20 Zone/Late Miocene to Early Pliocene, Ledok Formation at a depth of 322.4 - 279.3 m and has a RoS of 1.54 cm/ky, (3) Mundu Formation is CNPL2 Zone/Early Pliocene at a depth of 279.3 - 223 m and has a RoS of 5.41 cm/ky, (4) CNPL3 (Early Pliocene) Zone at a depth of 223 - 148.4 m and has a RoS of 33.91 cm/ky, (5) CNPL4 Zone (Middle Pliocene) at a depth of 148.4 - 82.7 m and has a RoS of 5.09 cm/ky. (6) Zone of CNPL5 (Middle-Late Pliocene) at a depth of 82.70 - 53.1 m and has a RoS of 21.14 cm/ky, (7) CNPL6 Zone/Late Pliocene at a depth of 53.1 - 52.0 m and has a RoS of 0.24 cm/ky, 8). CNPL7 Zone/Late Pliocene to Early Pleistocene at a depth of 52.0 - 33.8 m and has a RoS 8.27 cm/ky, (9). CNPL8 Zone (Early Pleistocene) at a depth of 33.8 - 26.4 m and has a RoS of 1.14 cm/ky, (10) CNPL9 Zone? (Early Pleistocene) at a depth of 26.4 - 12.5 m and has a RoS of 1.7 cm/ky. The relatively faster sedimentation rate of the CNPL3 is due to the faster subsidence and maximum sediment supply. During the development of sedimentation rate, there are two unconformities, namely (1) after the CNM20 Zone resulting in a sedimentation interval during CNPL1 and (2) after CNPL6 (Late Pliocene).

Keywords: sedimentation rate, biostratigraphy, Rembang Zone, Banyuurip

How to cite this article:
Choiriah, S.U., Haty, I.P., and Kaesti, E.Y., 2023. Sedimentation Rate During Miocene to Pleistocene Related with Nannofossil Biostratigraphy, in Banyuurip, Kedewan, Rembang Zone, East Java Basin, Indonesia. *Indonesian Journal on Geoscience*, 10 (3), p.349-361. DOI: 10.17014/ijog.10.3.349-361

Introduction

Background

The researched area lies in Banyuurip and its surrounding area, Kedewan Subregency, Bojonegoro Regency, East Java Province. Geographically, it is located at UTM coordinates 576000mE–581000mE and 9215500mN–9219500mN. On the RBI Map (Indonesian Landscape), it is included into 1506–534 Malo sheets (Figure 1).

Figure 1. Researched area (Kedewan, Bojonegoro).

North East Java Basin consists of Rembang and Kendeng Zones, divided into seven physiographic units (Bemmelen, 1949) (Figure 2). The researched area is part of Rembang Zone, North East Java Basin, which is one of the largest basins in Indonesia. In this area, many oil wells are still actively producing up to now. The reservoir quality in Cepu Fields appears to change in the stratigraphic age with the Miocene having better reservoir quality than the Oligocene one. Banyuurip has the best reservoir quality (Zaiza *et al*., 2018).

There are only a few researches on sedimentation rates based on the outcrop samples. Firmansyah *et al.* (2019) have researched relative

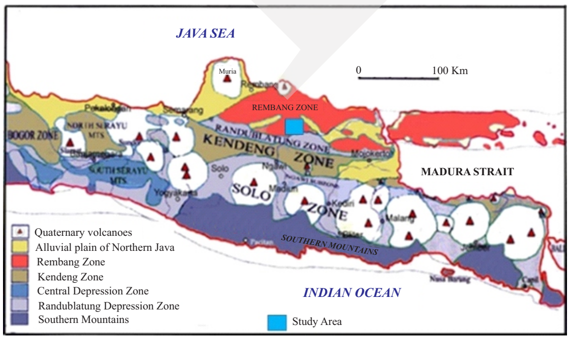

Figure 2. Physiography of East Java Basin (modified from Van Bemmelen, 1949).

sedimentation rates based on types of benthic foraminifera and distribution patterns of benthic foraminifera of Sasak Pasaman Beach, West Sumatra, using a purposive sampling method. The results show that distribution pattern of benthic foraminifera tends to clump, and it is not clear what sediment rate is in the studied area. In his paper, it is stated that there are two forms of sedimentation rates, relative and absolute (Firmansyah *et al.*, 2019).

A research on the sedimentation rate was once carried out by Marine Geology Research and Development Centre (2010), using the 210Pb sediment isotope method in Muara Tanjung Api-api, south Sumatra. The sampling was conducted on recent sediments at depths of 17 - 30 cm and 190 - 210 cm with sediment ages of 11.54 and 22.45. The average sedimentation rate results are 2.03 cm/year (at 0 - 0.3 m below the sea surface) and 8.9 cm/year (up to a depth of 2.1 m below the sea surface) (Raharjo, 2010). Biostratigraphic studies of nannofossils and sedimentation rates have been carried out in Indonesia in Watupuru Section. Nanggulan Formation (Eocene) results show that the average sedimentation rate was 3.5 cm/kyr (Jatiningrum *et al.*, 2022).

Until now, there is more research on sedimentation rates based on subsurface data, such as drilled well data, mud logging, well logging data, core data from coring results, and seismic data. Subsurface study is essential to assist the burial history. The outcrop study also can be carried out to interpret the burial history as performed in the present study.

This study aims to determine the sedimentation rate based on age data (biostratigraphy) of the Miocene-Plistocene age in Kedewan Sections. These sections have marine sediment, a good outcrop, and a continuous stratigraphic sequence from Miocene (Wonocolo, Ledok, and Mundu Formations) to Pleistocene (Lidah Formation).

A sedimentation rate is the ratio between thickness of sediment at a specific time (Choiriah *et al.*, 2020). Regarding the sedimentation rate, microfossils play a role in determining the age duration. The thickness of sediment is determined based on layer dimensions from the lower to the upper boundaries of the biostratigraphic zone. Thus, microfossils can be used to determine sedimentation rates.

Stratigraphy

Rembang Zone is dominated by carbonate and siliciclastic sedimentary rocks. These sediments were deposited in a marine environment of different facies. The offshore area of Java Sea is generally occupied by a sedimentary shelf area composed mainly of carbonates (Pringgoprawiro, 1983) (Figure 3).

Stratigraphically, the studied area (Kedewan) older to younger are Wonocolo Formation, Ledok Formation, Mundu Formation, and Lidah Formation (Figure 3). The lithology in this zone comprises sandstone and carbonate with alternating marl and claystone. Rembang Zone has

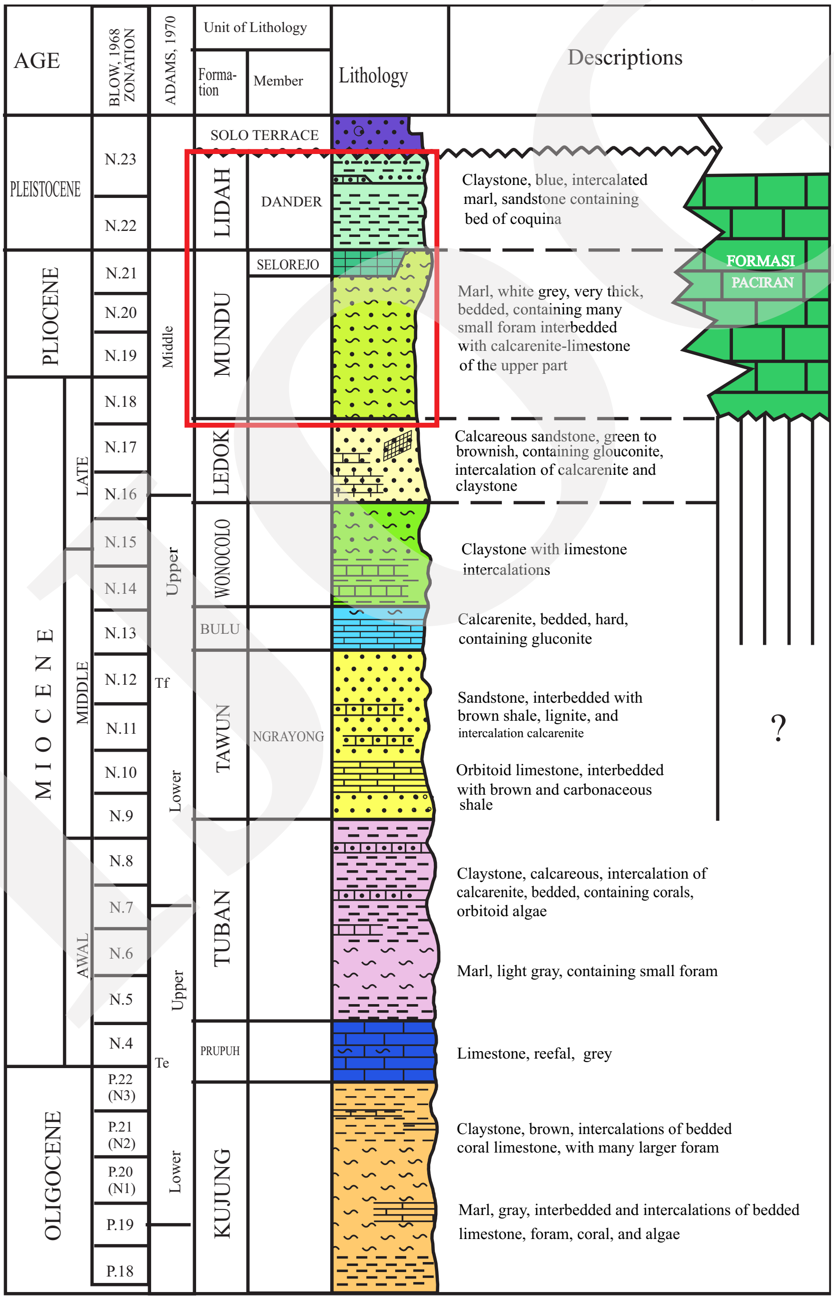

Figure 3. Stratigraphy of Rembang Zone and the studied area (red box) (modified from Pringgoprawiro, 1983).

a larger capacity for coarse-grained sediments than fine-grained sediments, with a slower rate of sedimentation than the basin subsidence rate.

Methods and Materials

The research used geological field mapping observation and stratigraphic measurements as the methods. The stratigraphic measurements were carried out through two sections with a distance of about 2,743.7 m. Selected section has good outcrops and a continuous stratigraphic sequence from Miocene (Wonocolo, Ledok, and Mundu Formations) to Pleistocene (Lidah Formation). Samples taken were fourty-one, which were fine-grained sedimentary rocks (marl, shale), carbonaceous, with a distance of 5 - 20 m, the presence of fine-sized lithological change was recognized.

Sample preparation was carried out using smear slide method, which used objective glasses, then determined by a polarizing microscope at 1000x magnification. Binocular white light microscopes equipped with parallel and cross nicol, and nannotax3 determination (http://www.mikrotax.org/ Nannotax3/index) were used to determine fossil contents. Whilst species were identified using taxonomic remarks by Gartner (1981), Perch-Nielsen (1985), and Nannotax3 website. Biostratigraphy determination used was based on nannoplankton biozonation according to Backman *et al*. (2012). Fourty-one samples were analyzed using a polarizing microscope, while SEM analysis carried out on five samples, was used to observe very small nannofossil species that were difficult to observe using the polarizing microscope. SEM could determine the first occurrence/base of the datum and the last occurrence/top. Position of the datum was converted to an absolute age, used to calculate the sedimentation rate of each biostratigraphic zone. The datum and absolute age utilized the classification of Backman *et al.* (2012). This classification is more detailed, so that the resulting sedimentation rate is also more detailed.

The sedimentation rate was calculated based on the thickness difference of the biodatum (depth of bottom zone–depth of top zone) divided by the absolute age difference between the base zone and the top zone (meter/million age). McGowran (2008) also calculated the sedimentation rate based on the ratio of the average thickness to the mean time interval. Continuous and stable sedimentation is essential data that can be used to determine the position of the nannofossil biodatum.

Value of the sedimentation rate is indicated by a graphic model determined by calculating the estimated age difference (biostratigraphic datum) converted by the absolute age (x-axis) to the depth difference (y-axis). Thus, the calculation of the sedimentation rate is highly dependent on the nannofossil datum. Despite these limitations, several relatively constant/stable sedimentation intervals were separated by hiatus, mass flow, or condensed intervals as shown in depth and age graph plots (Figures 4a and b).

Lithostratigraphy used in this study follows the regional stratigraphy of Pringgoprawiro (1983). Based on the geological map (Choiriah *et al*., 2021) the studied area is occupied by four units, those are Marl Unit of Wonocolo Formation, Limestone Unit of Ledok Formation, Marl Unit of Mundu Formation, and Claystone Unit of Lidah Formation (Figure 5).

Result and Analysis

Stratigraphic measurement was only carried out through three units, namely the Limestone Unit of Ledok Formation, Marl Unit of Mundu Formation, and Calcareous-claystone of Lidah Formation (Figure 6).

1. Limestone/Calcarenite Unit of Ledok Formation. The dominant lithology is calcarenite (sand-size limestone) with repeating marl and shale, calcareous- sandstone, massive layered sedimentary structures, and mega cross-bedding. This unit contains glauconite mineral. Thickness of the area is 207.2 m. This

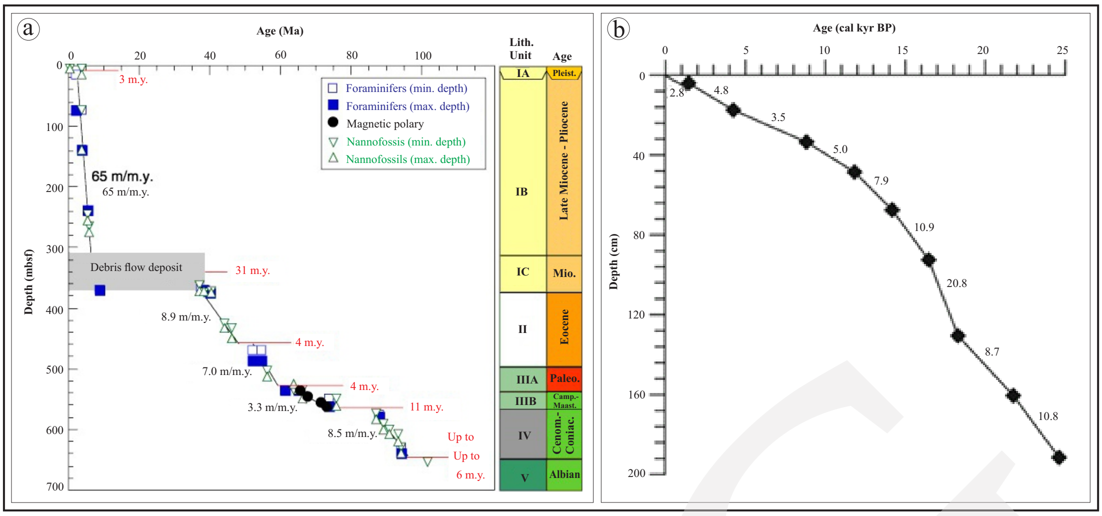

Figure 4. Model of sedimentation rate. a). (depth ages) based on foraminifera and nannofossil data (http://www-odp.tamu.edu/publications/207_IR/ chap_08/c8_7.htm (Choiriah *et al.*, 2021); b). Depth versus calibrated radiocarbon age (absolut age) and linear sedimentation rate (LSR) plots of core BoB-88. The LSR are listed for each interval in cm/kyr. (Jingrui *et al.*, 2020).

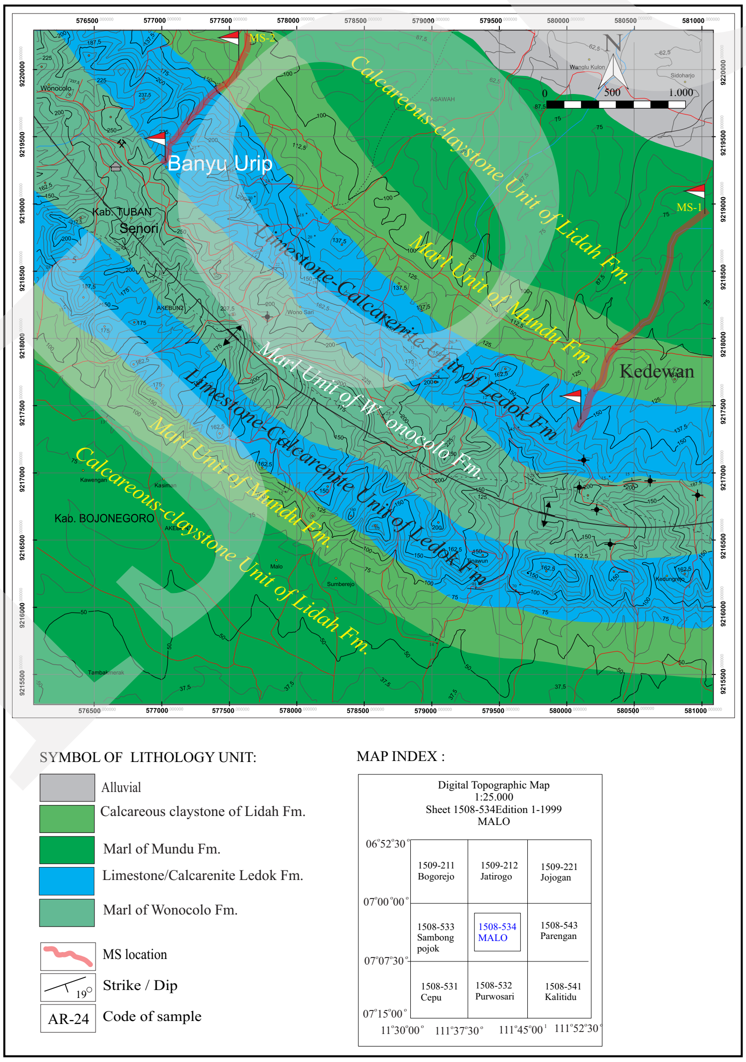

Figure 5. Geological map of Kedewan area, Bojonegoro, East Java, Indonesia (Choiriah *et al.*, 2021).

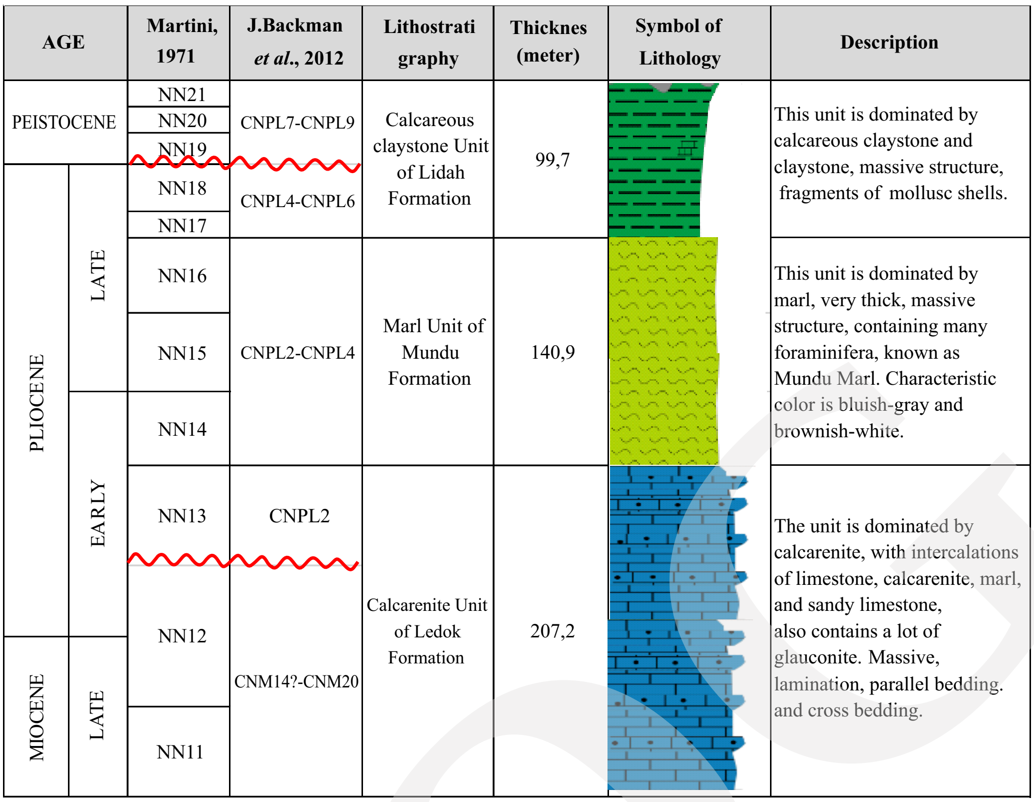

Figure 6. Stratigraphy of Kedewan, Bojonegoro (Choiriah *et al*., 2020) .

unit is of Late Miocene CNM14 to CNM20 (Backman *et al*., 2012). According to Choiriah *et al*. (2020) the unit is NN10–NN12 (Martini, 1971), and the environment is marine with a depth of 100 m–200 m or Outer Neritic (Tipsword *et al*., 1966). The stratigraphic relationship between Ledok limestone/calcarenite unit and Marl Unit of Mundu (above) is an unconformity. This is indicated by the first occurrence/base of *Ceratolithus acutus* (5.36Ma) and the first occurrence of *Ceratolithus rugosus* (5.08Ma) that was found in the same sample (Figure 7).

2. Marl Unit of Mundu Formation. The dominant lithology is massive thick marl rich in foraminifera. This unit has a thickness of 140.9 m with the age of Early to Late Pliocene CNPL2 to CNPL6 (Backman *et al*., 2012). This unit was formed in the deep sea at depths ranging from 200 to 2,000 metres in the Upper to Lower Bathyal zone (Choiriah et al., 2020). The stratigraphic relationship between the Marl unit of Mundu and the calcareous-claystone unit of Lidah Formation (above) is an unconformity. This is indicated by the base of *Gephyrocapsa caribbeanica* (1.71Ma) and the top of *Pseudoemiliania lacunosa* (1.9Ma) found in the same samples.
3. Calcareous-Claystone Unit of Lidah Formation. It is dominated by massive calcareous-claystone, and the presence of mollusk shell fragments. The thickness is more than 99.7 m from Late Pliocene to Early Pleistocene CNPL7 to CNPL9 (Backman *et al*., 2012). Choiriah et al. (2020) determined that this unit was deposited in the Outer Neritic to Upper Bathial zone, at a depth of 200 to 500 metres. In this unit, there is unconformity which is indicated by the base of *Gephyrocapsa caribbeanica* (1.71Ma) and the top of *Pseudoemiliania lacunosa* (1.9Ma) found in the same sample.

Biostratigraphy

Analysis of nannofossils from 41 samples shows there are 19 genera with 51 species.

FORMATION	UNIT OF LITHOSTRATIGRAPHY	AGE	ZONE OF NANNOFOSSIL (J.BACKMAN *et. al.*, 2012)		Number of Samples	DEPTH (metre)	BIOSTRATIGRAPHY OF NANNOFOSSILS: SPECIES OF BIODATUM	ZONE	ZONE OF NANNOFOSSIL BIOSTRATIGRAPHY
LIDAH	CALCAREOUS CLAYSTONE	MIDDLE PLIOCENE - LATE PLIOCENE	CNPL4-CNPL9	CNPL9 ?	41	4,1		Partial Zone of CNPL9	Partial Zone of *Emiliania huxleyi*
					40	12,5	*B.Emiliania huxleyi*		
				CNPL8	39	20,3	*B.Gephyrocapsa oceanica*	Interval Zone of CNPL8	Interval Zone of *Gep.oceanica*-Emiliania
					38	26,4			
				CNPL7	37	33,8	*B.Gephyrocapsa caribbeanica*	Interval Zone of CNPL7	Interval Zone of *Discoaster brouweri-Gephyrocapsa caribbeanica*
					36	38,1			
					35	42,2			
					34	47,4			
				CNPL6	33	49,6	*T.Discoaster brouweri*	Interval Zone of CNPL6	Interval Zone of *Discoaster pentaradiatus - Discoaster brouweri*
					32	8,6			
					31	20,8			
					30	33,7			
					29	42,7			
				CNPL5	28	53,1	*T.Discoaster pentaradiatus*	Interval Zone of CNPL5	Interval Zone of *D.surculus - Discoaster pentaradiatus*
					27	67,1			
				CNPL4	26	82,7	*T.Discoaster surculus*	Interval Zone of CNPL4	Interval Zone of *Reticulofenestra pseudoumbilicus - Discoaster surculus*
					25	99,7			
MUNDU	M A R L	EARLY - MIDDLE PLIOCENE	CNPL2-CNPL4		24	118,4			
					23	135,9			
				CNPL3	22	148,4	*T.Reticulofenestra pseudoumbilicus*	Interval Zone of CNPL3	Interval Zone of *Discoaster asymmetricus - Reticulofenestra pseudoumbilicus*
					21	155,9			
					20	164,6			
					19	175,3			
					18	183,5			
					17	189,7			
					16	198,3			
					15	209,4			
					14	220,8			
					13	230,5	*B.Discoaster asymmetricus*		
				CNPL2	12	240,6		Interval Zone of CNPL2	Interval Zone of *Ceratholithus rugosus-D.asymmetricus*
LEDOK	LIMESTONE /CALCARENITE	LATE MIOCENE - EARLY PLIOCENE	CNM14-CNPL2		11	256,3			
					10	279,3	*B.Ceratholithus rugosus*		
				CNM20 - CNM16	9	301,4		Range Zone of *CNM16-CNM20*	Interval Zone of *D.surculus-Cer.rugosus*
					8	322,4	*B.Discoaster surculus*		
				CNM15	7	351,4		Interval Zone of *CNM15*	Interval Zone of *Reticulofenstra pseudoumbilicus-Discoaster surculus*
					6	372,6			
					5	380,9			
					4	391,6			
					3	410,0			
					2	427,8	*B.Reticulofenestra pseudoumbilicus*		
				CNM14?	1	447,8		Partial Zone of CNM14	Partial Zone of *R.pseudoumbilicus*

Notes: ⋏ B (Base of Biodatum) and Y T (Top of Biodatum) ∿∿∿ Unconformity

Figure 7. Nannofossil biostratigraphy of Kedewan (Choiriah *et al.*, 2020) .

The biostratigraphic zone can be arranged into 11 zones consisting of 2 partial zones, 1 range zone, and 8 interval zones (Figures 7, 8, and 9) described as follows.

1. Partial Zone of CNM14 or Partial Zone of *Reticulofenestra pseudoumbilicus.* Zone: Boundary of the bottom zone is unknown, and the top boundary is the base of *Reticulofenestra pseudoumbilicus* (8.8 Ma) with the estimated age is more than 8.8 Ma (Late Miocene).
2. Interval Zone of CNM15 or Interval Zone of *Reticulofenestra pseudoumbilicus–Discoaster surculus.* Zone: Base of *Reticulofenestra pseudoumbilicus* (8.8Ma) and base of *Discoaster*

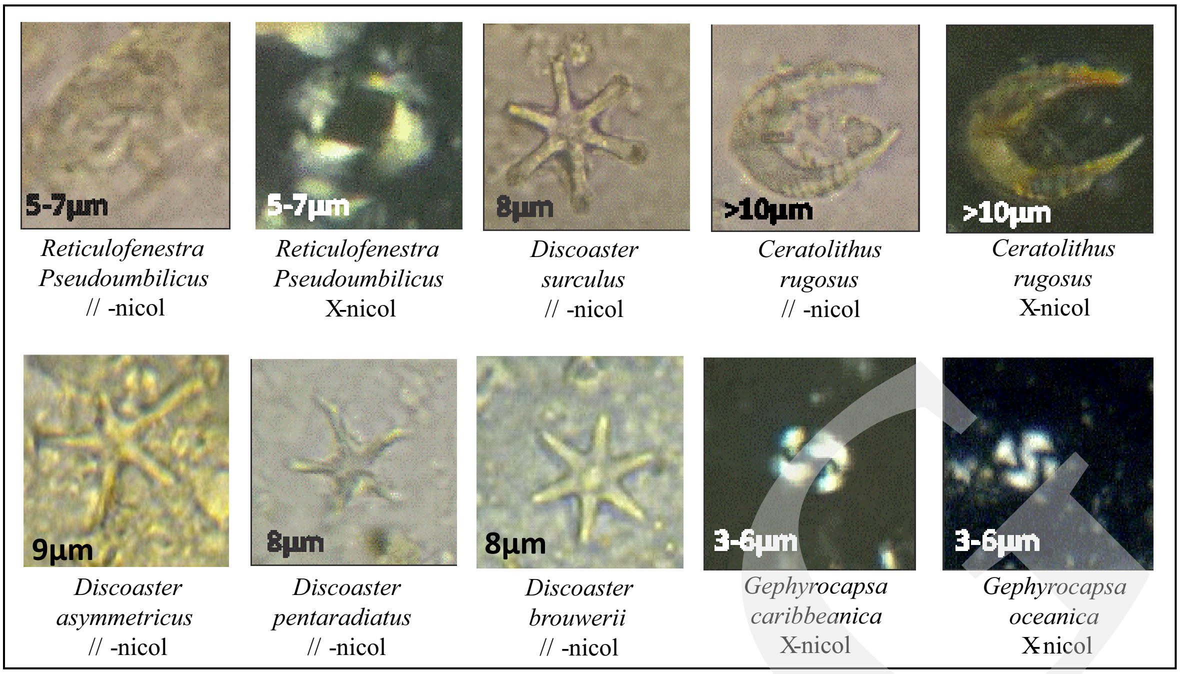

Figure 8. Photomicrographs of nannofossil index (this research).

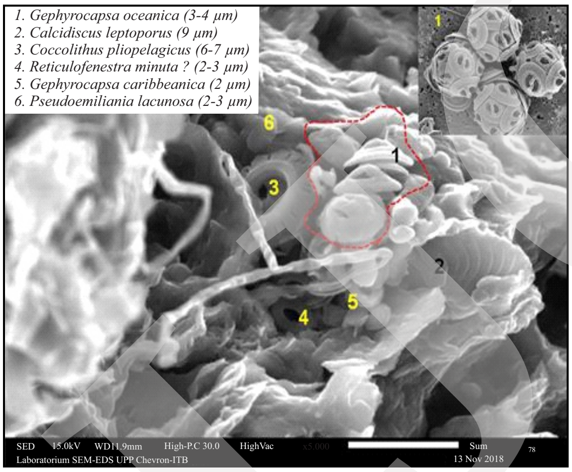

Figure 9. Photomicrographs of SEM of nannofossil index (*Gephyrocapsa*).

surculus (7.88 Ma) with the estimated age is 8.8 Ma to 7.88 Ma (Late Miocene).

3. Range Zone of CNM16–CNM20/CNPL1? or the range zone of *Discoaster surculus–Ceratolithus rugosus.* Zone: Base of *Discoaster surculus* (7.79 Ma) and base of *Ceratolithus rugosus* (5.08 Ma) with the estimated age is 1.93 Ma to 1.26 Ma (Late Pliocene to Early Pleistocene).
4. Interval Zone of CNPL2 or Interval Zone of *Ceratolithus rugosus–Discoaster asymmetricus.* Zone: Base of *Ceratolithus rugosus* (5.08 Ma) and base of *Discoaster asymmetricus* (4.04 Ma) with the estimated age is 5.08 Ma to 4.04 Ma (Early Pliocene).
5. Interval Zone of CNPL3 or Interval Zone of *Discoaster asymmetricus–Reticulofenestra pseudoumbilicus.* Zone: Base of *Discoaster asymmetricus* (4.04 Ma) and top of *Reticulofenestra pseudoumbilicus* (3.82 Ma) with the estimated age is 4.04 to 3.82 Ma (Early Pliocene).
6. Interval Zone of CNPL4 or Interval Zone of *Reticulofenestra pseudoumbilicus–Discoaster surculus*. Zone: Top of *Reticulofenestra pseudoumbilicus* (3.82 Ma) and top of *Discoaster surculus* (2.53 Ma) with the estimated age is 3.82 Ma to 2.53 Ma (Middle Pliocene).
7. Interval Zone of CNPL5 or Interval Zone of *Discoaster surculus– Discoaster pentaradiatus.* Zone: Top of *Reticulofenestra pseudoumbilicus* (3.82 Ma) and top of *Discoaster pentaradiatus* (2.39 Ma) with the estimated age is 3.82 Ma to 2.39 Ma (Middle Pliocene to Late Pliocene).
8. Interval Zone of CNPL6 or Interval Zone of *Discoaster pentaradiatus–Discoaster brou-*

weri. Zone: Top of *Discoaster pentaradiatus* (2.39 Ma) and top of *Discoaster brouweri* (1.93 Ma) with the estimated age is 2.39 Ma to 1.93 Ma (Late Pliocene to Early Pleistocene).

9. Interval Zone of CNPL7 or Interval Zone of *Discoaster brouweri–Gephyrocapsa caribbeanica* or interval zone of *Discoaster brouweri–Gephyrocapsa oceanica*. Zone: Top of *Discoaster brouweri* (1.93 Ma) and base of *Gephyrocapsa caribbeanica* (1.71 Ma) with the estimated age is 1.93 Ma to 1.71 Ma (Early Pleistocene).
10. Interval Zone of CNPL8 or Interval Zone of *Gephyrocapsa caribbeanica – Gephyrocapsa oceanica.* Zone: Base of *Gephyrocapsa caribbeanica* (1.71 Ma) and top of *Gephyrocapsa oceanica* (1,06 Ma) with the estimated age is 1.71 Ma to 1.06 Ma (Early Pleistocene) (Figure 9)
11. Partial Zone of CNPL9 or Partial Zone of *Emiliania huxleyi*. Zone: Base of *Emiliania huxleyi* (0.24 Ma) and top boundary are unknown.

Sedimentation Rate

Data from three different fields in the Cepu block suggest that relatively high sedimentation rates occurred during the Oligocene Chattian (28.4−23.03) Ma. Much lower sedimentation rates predominated during Miocene Aquitanian (23.03–20.43) Ma and lower Burdigalian (10.43 −15.97) Ma, and again higher sedimentation rates prevailed in the upper Burdigalian (Zaiza *et al*., 2018). Luan and Lunt., (2022) do not state the exact value increase in the sedimentation rate at the beginning of Sequence J120 (Late Pliocene).

The development of sedimentation rate (RoS) at Banyuurip, Kedewan, Rembang Zone, started from Late Miocene (CNM14 ?/CNM15) to the upper boundary of (Pleistocene/CNPL10). The result is ten periods of change in sedimentation rate (Table 1 and Figure 10), those are:

1. CNM15 Zone/Late Miocene at a depth of (427.8–322.4) m with the RoS of 11,46 cm/ky.
2. CNM16-CNM20 Zone (Late Miocene-Early Pliocene) at a depth of 322.4−279.3 m with an estimated sedimentation rate of 1.54 cm/ky, because it is a hiatus boundary at 279.3 m depth. At a depth of 279.3 m, there is an unconformity boundary of the CNPL1 Zone, which is marked by FO/base of *Ceratolithus rugosus* (5.08Ma) and FO/base of *Ceratolithus acutus* (5.36 Ma) as reworked fossils.
3. CNPL2/Early Pliocene Zone at a depth of (279.3−223) m with the RoS of 5.41 cm/ky.
4. CNPL3 (Early Pliocene) Zone at a depth of 223−148.4 m with the RoS of 33.91 cm/ky.
5. CNPL4 Zone (Middle Pliocene) at a depth of 148.4−2.7 m with the RoS of 5.09 cm/ky.
6. CNPL5 Zone (Middle to Late Pliocene) at a depth of 82.70−53.1 m with the RoS of 21.14 cm/ky. These results follow the results of previous studies, which stated that there was a rapid increase in the sedimentation rate in Late Pliocene (Luan and Lunt, 2022).
7. CNPL6 (Late Pliocene) Zone at a depth of (53.1−52.0) m with the RoS of 0.24 cm/ky.
8. CNPL7 Zone (Late Pliocene to Early Pleistocene) at a depth of 52.0−33.8 m with the RoS of 8.27 cm/ky. The depth of 33.8 m is Late Pliocene to Pleistocene boundary (CNPL8) where an unconformity was found, indicated by the first occurrence of the base of *Gephyrocapsa caribbeanica* (1.71 Ma) in the same rock sample.
9. CNPL8 Zone (Early Pleistocene) at a depth of 33.8−26.4 m with the RoS of 1.14 cm/ky.
10. CNPL9 Zone? (Early Pleistocene) at a depth of 26.4−12.5 m with the RoS of 1.7 cm/ky.

Sedimentation rate in the CNPL3 Zone (Early Pliocene) at a depth of 223−148.4 m, has a very high RoS of 33.91 cm/ky. At that time there was a subsidence in Rembang Basin characterized by the deposition of Marl Mundu in the deep sea environment with sediments as thick as 700 m (Husein, 2015). The relatively faster sedimentation rate is due to the faster subsidence and maximum supply of sediment. The development of the basin in the researched area occurred in two uplift processes, namely after Late Miocene (CNM20/unconformity-1) and Late Pliocene (CNPL6/unconformity-2).

Table 1. Biostratigraphy and Sedimentation Rate of Kedewan Area

NO	AGE	Zonation of Nannofossil			Top		Bottom		Thickness (m)	Duration (m.y.)	LSR*	
		Martini (1971)	Okada & Bukry (1980)	Backman *et al.* (2012)	Depth (mbsf)	Age (Ma)	Depth (mbsf)	Age (Ma)			(m/m.y.)	(cm/k.y.)
1	Early Pleistocene	NN19	CN13b-CN14a	CNPL9 ?	12.50	0.24	26.40	1.06	13.90	0.82	16.95	1.70
2	Early Pleistocene	NN19	CN13b	CNPL8	26.40	1.06	33.80	1.71	7.40	0.65	11.38	1.14
3	Late Pliocene-Early Pleistocene	NN19	CN13a	CNPL7	33.80	1.71	52.00	1.93	18.20	0.22	82.73	8.27
4	Late Pliocene	NN18	CN12d	CNPL6	52.00	1.93	53.10	2.39	1.10	0.46	2.39	0.24
5	Middle to Late Pliocene	NN16-NN17	CN12b-CN12c	CNPL5	53.10	2.39	82.70	2.53	29.60	0.14	211.43	21.14
6	Middle Pliocene	NN16	CN12a	CNPL4	82.70	2.53	148.40	3.82	65.70	1.29	50.93	5.09
7	Early Pliocene	NN14-NN15	CN11b	CNPL3	148.40	3.82	223.00	4.04	74.60	0.22	339.09	33.91
8	Early Pliocene	NN13	CN10c-CN11a	CNPL2	223.00	4.04	279.30	5.08	56.30	1.04	54.13	5.41
9	Late Miocene	NN11-NN12	CN9a-CN10a	CNM16-CNM20	279.30	5.08	322.40	7.88	43.10	2.80	15.39	1.54
10	Late Miocene	NN10	CN8b	CNM15 ?	322.40	7.88	427.80	8.80	105.40	0.92	114.57	11.46

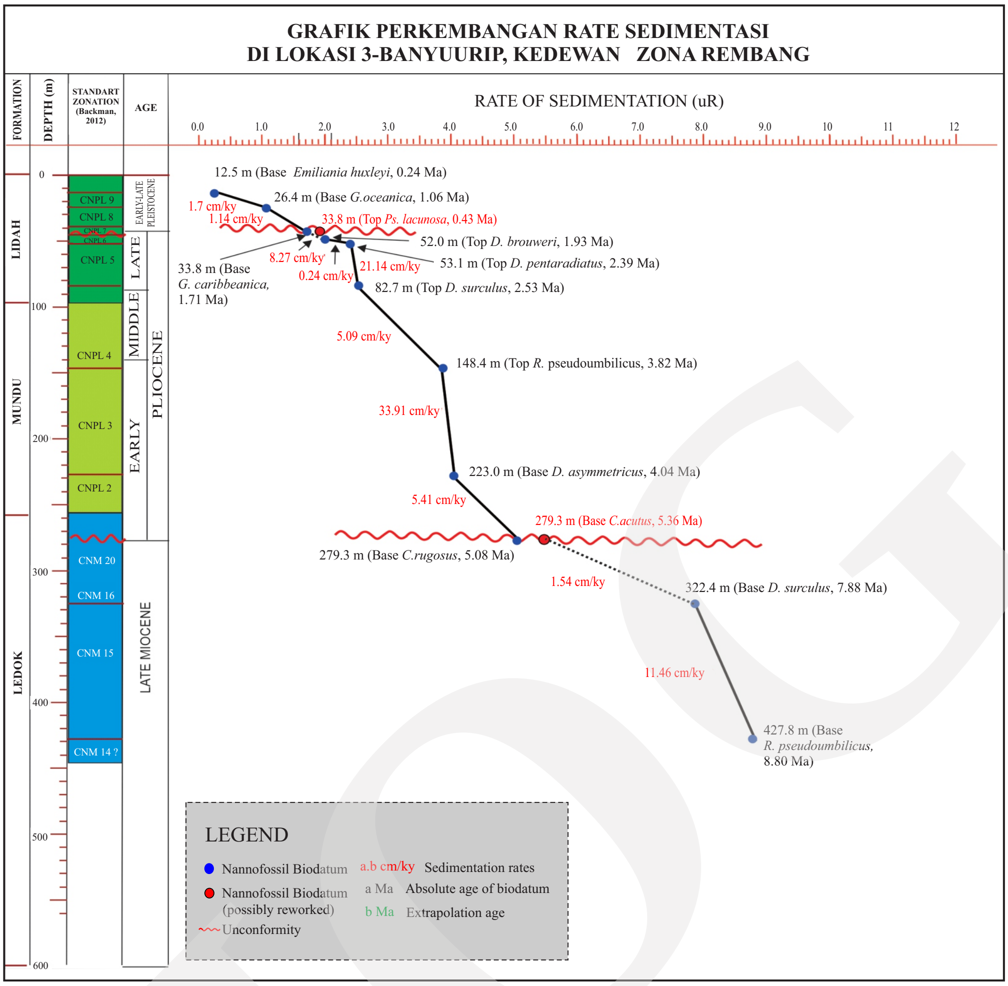

Figure 10. Sedimentation rate of the researched area.

Conclusions

Local stratigraphy of the researched area is composed of four units. Older to younger they are Wonocolo Marl Unit, Ledok Formation, Mundu Formation, and Lidah Formation. The measurement section is composed of three units, that are Limestone Unit of Ledok Formation, Marl Unit of Mundu Formation, and Calcareous-claystone Unit of Lidah Formation.

The biostratigraphic zone can be arranged into 11 zones consisting of 2 partial zones, 1 range zone, and 8 interval zones. These zones are (1) Partial Zone of CNM14/ *Reticulofenestra pseudoumbilicus,* (2) Interval Zone of CNM15 or *Reticulofenestra pseudoumbilicus–Discoaster surculus*, (3) Range Zone of CNM16–CNM20/ CNPL1/*Discoaster surculus-Ceratolithus rugosus,* (4) Interval Zone of CNPL2/*Ceratolithus rugosus–Discoaster asymmetricus,* (5) Interval Zone of CNPL3/*Discoaster asymmetricus–R. pseudoumbilicus,* (6) Interval Zone of CNPL4/*R. pseudoumbilicus-D.surculus,* (7) Interval Zone of CNPL5/*Discoaster surculus – Discoaster pentaradiatus,* (8) Interval Zone of CNPL6/ *Discoaster pentaradiatus– Discoaster brouweri,* (9) Interval Zone of CNPL7/*Discoaster brouweri–Gephyrocapsa caribbeanica*/*Discoaster brouweri–Gephyrocapsa oceanica,* (10) Interval Zone of CNPL8/*Gephyrocapsa caribbeanica–Gephyrocapsa oceanica,* (11) Partial Zone of CNPL9 / *Emiliania huxleyi.*

In the development of sedimentation rate (RoS) from Late Miocene (CNM15) to Pleistocene (CNPL9) there are ten periods of change. The sedimentation rates are: (1) CNM15 Zone

(Late Miocene) is 11.46 cm/ky, (2) CNM16-CNM20 Zone (Late Miocene-Early Pliocene) is 1.54 cm/ky, (3) CNPL2 Zone (Early Pliocene) is 5.41 cm/ky, (4) CNPL3 (Early Pliocene) Zone is 33.91 cm/ky, (5) CNPL4 Zone (Middle Pliocene) is 5.09 cm/ky, (6) CNPL5 Zone (Middle-Late Pliocene) is 21.14 cm/ky, (7) CNPL6 Zone (Late Pliocene) is 0.24 cm/ky, (8) CNPL7 Zone (Late Pliocene to Early Pleistocene) is 8.27 cm/ky.

Previous researchers concluded that Late Pliocene to Pleistocene sedimentation rates were approximately 850 m/My or 8.5 cm/ky (Luan and Lunt, 2022). (9) CNPL8 Zone (Early Pleistocene) is 1.14 cm/ky, (10) CNPL9 Zone (Early to Middle Pleistocene) is 1.7 cm/ky. The highest sedimentation rate is in The CNPL3 Zone (Early Pliocene) Zone which is 33.91 cm/ky, with a sediment thickness of 74.6 m.

An unconformity is found in Late Miocene (Top of CNM20) and CNPL1 Zone (hiatus/sedimentation interval), and Early to Middle Pleistocene (Top of CNPL6).

Acknowledgements

The authors thank LPPM UPN Veteran Jogjakarta and Research Rembang Team, Geological Engineering, Faculty of Mineral Technology UPN "Veteran" Yogyakarta.

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