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Integrated Neogene to Quaternary nannofossil biostratigraphy and sedimentation rates analysis in the Cikarang sequence, North West Java Basin, Indonesia

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Abstract

Nannofossil assemblages were found throughout the Neogene to Quaternary rock sequence at Cikarang in the Northwest Java Basin, Indonesia. This study determines the biostratigraphic age, reconstructs depositional phases and calculates the sedimentary rate of the rock sequence based on lithology and nannofossil assemblages. Within this sequence, 59 nannofossil species can be identified and 14 are index fossils with easily recognizable first occurrence (FO) or last occurrence (LO). Based on these boundaries, the sequence is divided into 17 biostratigraphic zones categorized into range and interval zones. Lithology successions in Cikarang are generally composed of fine-grained clastic rocks (sandstone and claystone), clastic limestone and fossil reefs, which are deposited in various depositional environments such as deep marine, shallow marine and littoral. Sedimentation rates vary between 4.18 m/Myr to 217.87 m/Myr, reflecting the influence of tectonic activity, sea level changes and sediment supply. Unconformities are identified at the intra Miocene, as well as Mio-Pliocene and Plio-Pleistocene boundaries.

Keywords:

nannofossil; biostratigraphy; sedimentation rates; North West Java Basin

1. Introduction

Nannofossils are small marine phytoplankton fossils, generally round to semi-circular, originating from coccoliths with a layer of haptophyte cells “coccolithophorids”. Nannofossils are widely distributed in ocean sediments. Detailed biostratigraphy studies based on nannofossils are applicable to reconstruction of the basin evolution, as well as inter-basin correlations (**Bown et al. 2004; Isnaniawardhani et al. 2013; Raffi & Backman, 2022**).

Nannofossils are recognized as high-resolution biostratigraphic indicators due to their rapid evolutionary rates, wide geographic distribution and high taxonomic diversity (**Raffi, 1999; Raffi & Backman, 2022**). The first occurrence (FO) and last occurrence (LO) of a nannofossil species can often be identified globally with a temporal resolution of approximately one million years, making them valuable for refining geological timescales, particularly in marine sediments (**Gardin, 2002**). Several biostratigraphic zonation schemes have been developed in low latitude regions to interpret the Cenozoic record using nannofossils. Among the most widely referenced are those proposed by **Martini & Worsley (1970)**, **Martini (1971)**, **Okada & Bukry (1980)**, **Varol (l983)**, **Perch-Nielsen (1985)** and **Backman et al. (2012)**; each of these frameworks introduced zone numbering systems that facilitate chronological subdivision and correlation. For instance, Martini’s system uses the NP (Paleogene) and NN (Neogene) designations, which have become particularly popular in Indonesia for their clarity and ease of application (**Kapid et al. 2021**). The Neogene is divided into zones NN1 to NN21, while the Paleogene includes NP1 to NP25. Other frequently cited schemes, such as Okada & Bukry’s CN/CP system and Backman et al.’s CNM framework, have extended the utility of nannofossils through integration with multidisciplinary chronostratigraphic approaches (**Isnaniawardhani, 2015**). Recent improvements to these zonation models – through integration with tools such as magnetostratigraphy, isotope stratigraphy and planktonic foraminiferal data – have led to enhanced precision in dating and correlation (**Backman et al. 2012; Sato & Chiyonobu, 2013**). These developments have enhanced the temporal calibration of index species and strengthened the reliability of nannofossil-based stratigraphic frameworks in both regional and global contexts.

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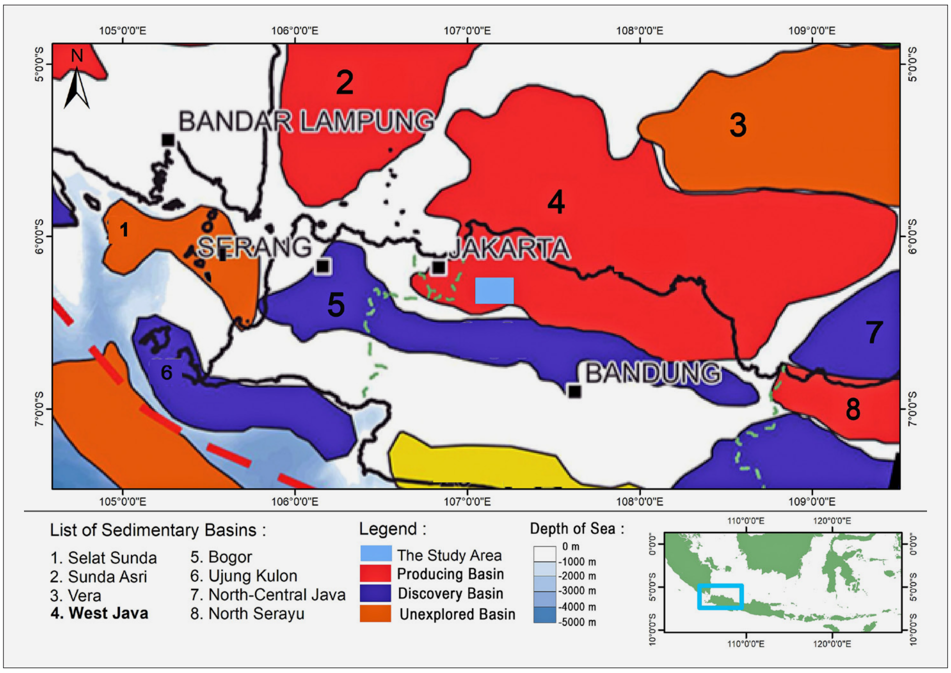

Figure 1. The position of the study area (Cikarang site), located in the North West Java Basin (**Geological Survey Center, 2022**)

Nannofossils that lived as plankton in the water column are sensitive to palaeoceanographic changes, including surface temperature, salinity, currents and nutrient levels, but are uncommonly used as bathymetric interpretation. However, when used with foraminifera analysis, the combined dataset enhances the reliability and resolution of palaeoenvironmental reconstructions more effectively than relying on either microfossil group alone (**Schiebel et al. 2004**).

The sedimentation rate of a rock sequence can be calculated using biostratigraphy analysis which provides absolute age and depositional environment data. By comparing the sediment thickness with the accumulation time interval based on the absolute age, the sedimentation rate is determined (**Gowran, 2008**). Continuous and consistent sediment sequences help to determine the position of layers accurately (**Sadler, 1981**).

As Neogene to Quaternary nannofossil assemblages are typically characterized by abundant diversification, rapid evolution, and clear recognition of their FO or LO, studies of similarly aged sediments from the North West Java Basin are expected to provide detailed marine sediment biostratigraphy. This study aims to determine the biostratigraphy, reconstruct depositional phases and calculate the sedimentation rate of the rock sequence based on Cikarang site samples.

The Cikarang site is located in the North West Java Basin, one of Indonesia's 128 sedimentary basins with rich hydrocarbon potential in volcaniclastic, carbonate and siliciclastic reservoirs with an estimated ± 2.3 BOE (Barrel Oil Equivalent) of oil and 1.17 BOE of gas (**Doust & Noble, 2008; Geological Survey Center, 2022**).

The North West Java Basin is a back-arc basin formed by subduction in southern Java (**Usman et al. 2011**). It is bordered by the Bogor Basin to the south, the Sunda Asri Basin to the west, the Vera Basin to the north, and the North Central Java Basin to the east (see **Figure 1**). The basin consists of a north-south graben system that forms sub-basins such as Jatibarang, Pasirputih, and Ciputat (**Patmosukismo & Yahya, 1974; Iskandar et al. 2019**). According to **Hamilton (1979)**, this basin is a pull-apart basin formed by a dextral strike-slip fault, with a north-south oriented structure and a west-east trending rifting opening pattern. The basin is rich in hydrocarbons, both oil and gas, stored in volcaniclastic, carbonate and siliciclastic reservoirs (**Noble et al. 1997**).

The two regions of the North West Java Basin, the onshore part in the southern area and the offshore part in the northern area (under the western Java Sea, a present-day shallow sea shelf), are influenced by dominant extensional faults with some compression (**Darman & Sidi, 2000**). The basement map shows the existence of high and low areas separated by normal faults. Three low areas are identified as the Jatibarang sub-basin, the Pasir Putih sub-basin, and the Ciputat sub-basin (**Koesoemadinata, 2020**). These sub-basins are the main half-graben-shaped sediment accommodation spaces formed by fault fractures which are then filled by Paleogene to Neogene sediments with a thickness of more than 5.500 meters. The Ciputat Sub-Basin forms the geological architecture of the study area as a result of rifting tectonics.

During the Pre-Paleogene, the area was a component of a stable continental crust which was not affected by intensive tectonic activity. The basement consists mainly of Cretaceous metamorphic rocks such as gneiss and schists, intruded by granodiorite and form as a part of locally uplifted basement rock. The granitic composition of basement rock also indicates the continental crust.

From the Pre to the Plio-Pleistocene, the development of the back-arc North West Java Basin can be divided into three main tectonic phases, namely Paleogene syn-rift stage, Neogene post-rift stage and syn-orogenic stage. During the syn-rift stage, the Jatibarang Formation consisting of basaltic/andesite lava, tuff and detrital volcanic rocks (apparently sandstone) underlies the basement within most half-grabens and is missing on most structural heights. Continued rotational movements eventually fractured the crust extending into curved to rectangular faults. Due to this faulting, topographic relief increased and coarse clastic deposits accumulated in a transitional environment. The sedimentation continued later in the Early Miocene when the Baturaja Formation was deposited during a transgression. The absence of significant tectonic activity appears to have continued. This is indicated by remnants of horst blocks separating the rift grabens that were eroded into small isolated shallow carbonate platforms on which reefs formed. The source of clastic sediment shifted from local sources to northern sources from Sundaland.

The post-rift stage is characterized by a new subduction in the south of Java Island, with west-east strike-slip faulting related to the compressive force of the Indian Plate collision. During this phase, transgression seems to have continued. Marine sedimentation is represented by outer neritic shale, sandstone, clastic carbonate and reefs of the Early to Middle Miocene Upper Cibulakan Formation (known as Mid Main Carbonate / MMS) with sediment sources from Sundaland. Shallow to mid-neritic clastic and limestone of the Parigi Formation developed during the transition from Middle to Late Miocene, which in some places develops into small carbonate build-up.

The syn-orogenic stage is marked by compression that forms a thrust fault in the southern part, such as the Pasirjadi Fault and Subang Fault, and the Pamanukan Fault in the northern area. The Late Miocene - Pliocene non-marine Cisubuh Formation, dominated by mudstone and sandstone with thin limestone in some places, was deposited during regression (**Koesoemadinata, 2020**).

2. Methods

A total of 62 samples were collected from continuous core sections of a well drilled in Cikarang, North West Java Basin, reaching a total depth of 652 m. Lithological descriptions and nannofossil assemblages were analysed directly from these core intervals. A small amount of material was scraped from the rock samples and smeared on a glass slide with a little water. The prepared samples were studied under a transmitted light microscope at 400–1000x magnification, with polarization and light contrast devices. Analyses using a Scanning Electron Microscope were performed to confirm several species.

Identification of nannofossil species was based on detailed morphological criteria and taxonomic classifications following established references, particularly those of **Perch-Nielsen (1985)**, **Young et al. (2003)** and the continuously updated online resource **Nannotax3 (https://www.mikrotax.org/Nannotax3/)**. The most frequently used and easily applied standard nannofossil biozonations are **Martini (1971)**, **Okada & Bukry (1980)** and **Backman et al. (2012)**. The nannofossil identification and biostratigraphic zone determination used in this study mainly refer to their research. The dating of FO and LO of index species was determined according to **Young (1998)**, **(Young et al. 2003)**, **Raffi et al. (2006)** and **Sato & Chiyonobu (2013)**.

A quantitative approach is commonly applied to calculate sedimentation rates based on the ratio of thickness to time interval (Shaw's method; **Gowran, 2008**). The thickness of sediment between stratigraphic layers is measured while time intervals are identified based on biostratigraphic data. The absolute age difference between the FO and LO of a species marker is used to calculate the accumulation time (**Bown & Young, 1998; Sadler, 1981**).

To obtain more accurate results in interpreting the bathymetry of the environment where the layers were formed, nannofossil data accompanied by foraminifera determination were used.

3. Results

3.1. Nannofossils Taxonomy

In core samples from the sedimentary succession of North West Java, 59 species classifying into 16 nannofossil genera were identified.

Family Braarudosphaeraceae Deflandre, 1947
- Genus *Braarudosphaera* Deflandre, 1947
  - *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, 1947

Family Coccolithaceae Poche, 1913
- Genus *Calcidiscus* Kamptner, 1950
  - *Calcidicsus leptoporus* (Murray & Blackman) Loeblich & Tappan, 1978
  - *Calcidicsus macintyrei* (Bukry & Bramlette) Loeblich & Tappan, 1978
- Genus *Coccolithus* Schwarz, 1954
  - *Coccolithus pelagicus* (Wallich) Schiller, 1930
- Genus *Coronocyclus* Hay, Mohler & Wade, 1966
  - *Coronocyclus nitescens* (Kamptner) Bramlette & Wilcoxon, 1967
- Genus *Umbilicosphaera* Boudreaux and Hay, 1969
  - *Umbilicosphaera sibogae* (Weber-van Bosse) Graarder, 1970

Family Discoasteraceae Tan, 1927
- Genus *Catinaster* Martini & Bramlette, 1963
  - *Catinaster coalithus* Martini & Bramlette, 1963
  - *Catinaster umbrellus* Bukry, 1971

Genus *Discoaster* Tan, 1927
Discoaster brouweri Tan Sin Hok, 1927
Discoaster calcaris Gartner, 1967
Discoaster deflandrei Bramlette & Riedel, 1954
Discoaster druggii Bramlette & Wilcoxon, 1967
Discoaster hamatus Martini & Bramlette, 1963
Discoaster kugleri Martini & Bramlette, 1963
Discoaster neohamatus Bukry & Bramlette, 1969
Discoaster pentaradiatus Tan Sin Hok, 1927
Discoaster quinqueramus Gartner, 1969
Discoaster variabilis Martini & Bramlette, 1963
Discoaster exilis Martini & Bramlette, 1963
Discoaster bellus Bukry & Percival, 1971
Discoaster perplexus Bramlette & Riedel, 1954

Family Helicosphaeraceae Black, 1971
Genus *Helicosphaera* Kamptner, 1954
Helicosphaera ampliaperta Bramlette & Wilcoxon, 1967
Helicosphaera euphratis Haq, 1966
Helicosphaera intermedia Martini, 1965
Helicosphaera scissura Muller, 1981
Helicosphaera sellii (Bukry & Percival) Jafar & Martini, 1975
Helicosphaera kamptneri Hay & Mohler, 1967
Helicosphaera granulate Bukry & Percival, 1971
Helicosphaera mediterranea Muller, 1981
Helicosphaera minuta Muller, 1981
Helicosphaera stalis Theodoridis, 1984
Helicosphaera philippinensis Muller, 1981
Helicosphaera oblique Bramlette & Wilcoxon, 1967
Helicosphaera rhomba (Bukry, 1971) Jafar & Martini, 1975

Family Pontosphaeracea Lemmermann, 1908
Genus *Pontosphaera* Lohmann, 1902
Pontosphaera multipora (Kamptner) Roth, 1970
Pontosphaera discopora Schiller, 1925

Family Prinsiaceae Hay & Mohler, 1967
Genus *Gephyrocapsa* Kamptner, 1943
Gephyrocapsa caribbeanica Boudreaux & Hay, 1967
Gephyrocapsa oceanica Kamptner, 1943
Genus *Pseudoemiliania* Gartner, 1969
Pseudoemiliania lacunosa (Kamptner) Gartner, 1969
Genus *Reticulofenestra*
Reticulofenestra pseudoumbilicus (Gartner) Gartner, 1969
Reticulofenestra minuta Roth, 1970
Reticulofenestra minutula (Gartner, 1967) Haq & Berggren, 1978
Reticulofenestra haqii Backman, 1978
Reticulofenestra floridana Theodoridis, 1984

Family Rhabdosphaeraceae
Genus *Rhabdosphaera* Haeckel, 1894
Rhabdosphaera procera Martini, 1969

Family Sphenolithaceae Deflandre, 1952
Genus *Sphenolithus* Deflandre, 1952
Sphenolithus abies Deflandre, 1953
Sphenolithus heteromorphus Deflandre, 1953
Sphenolithus moriformis (Bronnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967
Sphenolithus neoabies Bukry & Bramlette, 1969

Reticulofenestra pseudoumbilicus was the most dominant species. The genera *Sphenolithus* and *Coccolithus pelagicus* were found to be very abundant. *Helicosphaera kamptneri* and *Discoaster brouweri* were present in almost every interval. *Reticulofenestra floridina, Reticulofenestra minutula, Reticulofenestra minuta, Sphenolithus abies, Calcidiscus macintyrei,* and *Sphenolithus neoabies* were abundant, while other species were found in lower abundance. The whole sequence is assigned the ages of the Early Miocene to the Pleistocene (22.82 to 1.71 million years ago).

3.2. Biostratigraphy

A total of 14 index species were selected in the nannofossil-rich samples: *Helicosphaera euphratis, Discoaster druggii, Helicosphaera ampliaperta, Sphenolithus heteromorphus, Reticulofenestra pseudoumbilicus, Discoaster kugleri, Sphenolithus abies, Catinaster coalithus, Discoaster brouweri, Discoaster hamatus, Discoaster pentaradiatus, Discoaster quinqueramus, Pseudoemiliania lacunosa* and *large Gephyrocapsa oceanica* (> 4 μm). The first and last occurrence boundaries of these index species can be identified as well.

Based on the First Occurrence (FO) and/or LO (Last Occurrence) of these species, the sedimentary succession of the North West Java Basin can be grouped into 17 biostratigraphic zones starting from Early Miocene to Pleistocene (see **Table 1**).

1) *Helicosphaera euphratis* Partial Range Zone (> 652 m depth)

   A few nannofossils occur in this lowest part of sequences. Early Miocene species, *H. euphratis* (**Boesiger et al, 2017**) is found in this interval.

2) *Discoaster druggi - Helicosphaera euphratis* Interval Zone (652 m – 618.74 m depth)

   Interval from FO of *D. druggii* to LO of *H. euphratis*. FO of *D. druggii* marks the base of NN2, while LO of *H. euphratis* is close to the base of NN3 of Martini's zone or Early Miocene.

3) *Helicosphaera euphratis - Sphenolithus heteromorphus* Interval Zone (618.74 m -597.41 m depth)

DEPTH (M)	AGE	NANNOFOSSIL ZONATION: THIS STUDY	MARTINI (1971)	OKADA & BUKRY (1980)
32.00	Pleistocene	Large *Gephyrocapsa oceanica* TRZ	NN19 & younger	CN13 b & younger
44.81		*Discoaster brouweri - large Gephyrocapsa oceanica* IZ	NN19	CN13a
106.68		*Discoaster pentaradiatus - Discoaster brouweri* IZ	NN18	CN12 d
118.87		*Sphenolithus abies - Discoaster pentaradiatus* IZ	NN17	CN12 c
131.06	Late Pliocene	*Reticulofenestra pseudoumbilicus - Sphenolithus abies* IZ	NN16	CN12 a-b
155.45	Early Pliocene	*Pseudoemiliania lacunosa - Reticulofenestra pseudoumbilicus* IZ	NN15	CN11 a-b
204.22		*Discoaster quinqueramus - Pseudoemiliania lacunosa* IZ	NN12-14	CN10 a - d
320.04	Late Miocene	*Discoaster quinqueramus* TRZ	N11	CN9 a-b
338.33		*Discoaster hamatus - Discoaster quinqueramus* IZ	NN9-10	CN7-8
374.90		*Catinaster coalithus - Discoaster hamatus* IZ	NN8	CN6
411.48	Middle Miocene	*Discoaster kugleri - Catinaster coalithus* IZ	NN7	CN5 b
423.67		*Sphenolithus heteromorphus - Discoaster kugleri* IZ	NN6	CN5 a
435.86		*Helicosphaera ampliaperta - Sphenolithus heteromorphus* IZ	NN5	CN4
597.41	Early Miocene	*Sphenolithus heteromorphus - Helicosphaera ampliaperta* IZ	NN4	CN3
618.74		*Helicosphaera euphratis - Sphenolithus heteromorphus* IZ	NN3	CN2
652		*Discoaster druggi - Helicosphaera euphratis* IZ	NN2	CN1
		Helicosphaera euphratis PRZ	NN1	

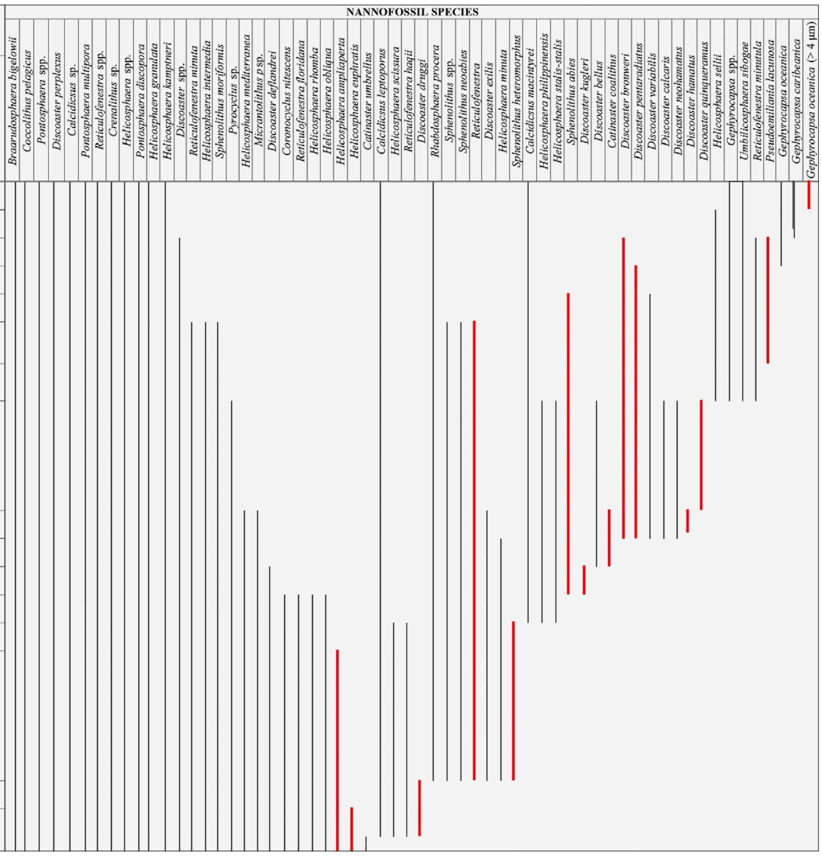

Table 1. Nannofossil biostratigraphy of Cikarang sequences in North West Java Basin
The red lines represent the index species range occurrences

Interval from FO of *H. euphratis* to FO of *S. heteromorphus*, corresponds to NN3 of Martini's zone or CN2 of Okada & Bukry's zone or CNM4-5 of Backman's zone (Early Miocene).

4) *Sphenolithus heteromorphus - Helicosphaera ampliaperta* Interval Zone (597.41 m – 435.86 m depth)

Interval from FO of *S. heteromorphus* to LO of *H. ampliaperta*, corresponds to NN4 of Martini's zone or CN3 of Okada & Bukry's zone or CNM6 of Backman's zone (Early Miocene).

5) *Helicosphaera ampliaperta - Sphenolithus heteromorphus* Interval Zone (435.86 m – 423.67 m depth)

Interval from LO of *H. ampliaperta* to LO of *S. heteromorphus*, corresponds to NN5 of Martini's zone or CN4 of Okada & Bukry's zone or CNM7 of Backman's zone (Middle Miocene).

6) *Sphenolithus heteromorphus - Discoaster kugleri* Interval Zone (423.67 m – 411.48 m depth)

Interval from LO of *S. heteromorphus* to FO of *D. kugleri*, corresponds to NN6 of Martini's zone or CN5a of Okada & Bukry's zone or CNM7 of Backman's zone (Middle Miocene). In this zone, *Reticulofenestra pseudoumbilicus* are abundant.

7) *Discoaster kugleri - Catinaster coalithus* Interval Zone (411.48 m – 374.90 m depth)

Interval from FO of *D. kugleri* to FO of *C. coalithus*, corresponds to NN7 of Martini's zone or CN5b of Okada & Bukry's zone or CNM10 of Backman's zone (Middle Miocene). In this zone, *Reticulofenestra pseudoumbilicus* are abundant.

8) *Catinaster coalithus - Discoaster hamatus* Interval Zone (374.90 m – 338.33 m depth)

Interval from FO of *C. coalithus* to LO of *D. hamatus*, corresponds to NN8 of Martini's zone or CN6 of Okada & Bukry's zone or CNM12 of Backman's zone (Late Miocene).

9) *Discoaster hamatus - Discoaster quinqueramus* Interval Zone (338.33 m – 320.04 m depth)

Interval from LO of *D. hamatus* to FO of *D. quinqueramus*, equivalent to NN9-10 of Martini's zone or CN7-8 of Okada & Bukry's zone or CNM13-18 of Backman's zone (Late Miocene).

10) *Discoaster quinqueramus* Total Range Zone (320.04 m – 204.22 m depth)

Interval range from FO and LO of Late Miocene specific taxon, *D. quinqueramus*. This zone is equivalent to NN11 of Martini's zone or C9 of Okada & Bukry's zone or CNM19 of Backman's zone (Late Miocene).

11) *Discoaster quinqueramus - Pseudoemiliania lacunosa* Interval Zone (204.22 m - 155.45 m depth)

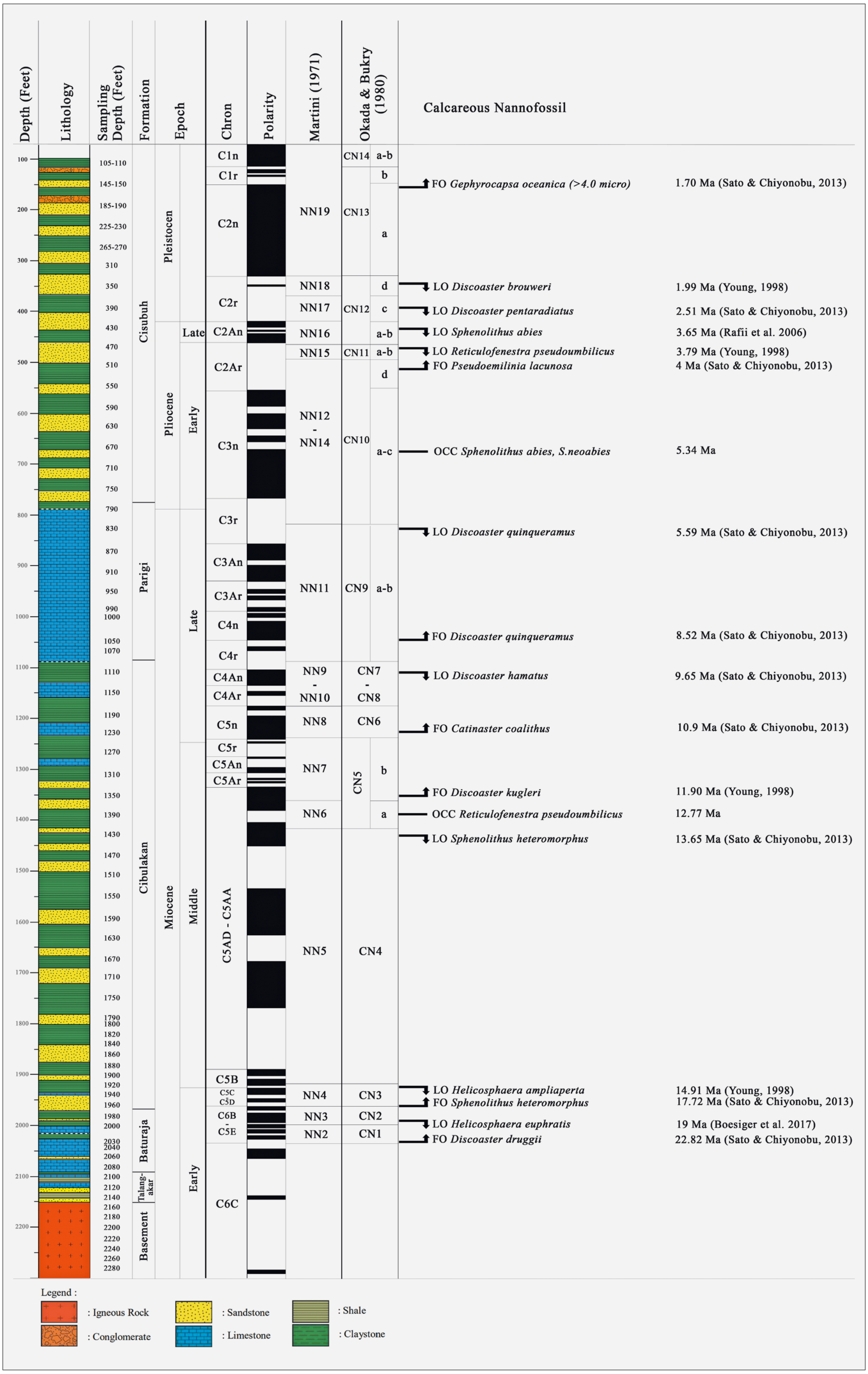

Figure 2. FO and LO dating of index species markers found in the Cikarang sequence has been proposed by **Young (1998)**, **Raffi et al. (2006)**, **Sato & Chiyonobu (2013)** and **Boesiger et al (2017)**

Interval from LO of *D. quinqueramus* to FO of *P. lacunosa*, equivalent to NN12-NN14 of Martini's zone or CN10 a-d of Okada & Bukry's zone or CNP1 of Backman's zone (Early Pliocene).

12) *Pseudoemiliania lacunosa - Reticulofenestra pseudoumbilicus* Interval Zone (155.45 m -131.06 m depth)

    Interval from FO of *P. lacunosa* to LO of *R. pseudoumbilicus*, equivalent to NN15 of Martini's zone or CN11 of Okada & Bukry's zone or CNPL2-3 of Backman's zone (Early Pliocene).

13) *Reticulofenestra pseudoumbilicus - Sphenolithus abies* Interval Zone (131.06 m – 118.87 m depth)

    Interval from LO of *R. pseudoumbilicus* to LO of *S. abies*, equivalent to NN16 of Martini's zone or CN12 a-b of Okada & Bukry's zone or CNPL4 of Backman's zone (Late Pliocene).

14) *Sphenolithus abies - Discoaster pentaradiatus* Interval Zone (118.87 m – 106.68 m depth)

    Interval from LO of *S. abies* to LO of *D. pentaradiatus*, corresponds to NN17 of Martini's zone or CN12 c of Okada & Bukry's zone or CNPL5 of Backman's zone (Pleistocene).

15) *Discoaster pentaradiatus - Discoaster brouweri* Interval Zone (106.68 m – 44.81 m depth)

    Interval from LO of *D. pentaradiatus* to LO of *D. brouweri*, corresponds to NN18 of Martini's zone or CN12 d of Okada & Bukry's zone or CNPL6 of Backman's zone (Pleistocene).

16) *Discoaster brouweri* - large *Gephyrocapsa oceanica* Interval Zone (44.81 m – 32.00 m depth)

    Interval from LO of *D. brouweri* to FO of large *G. oceanica* (>4 μm), corresponds to NN19 of Martini's zone or CN13 a of Okada & Bukry's zone (Pleistocene).

17) Large *Gephyrocapsa oceanica* Total Range Zone (< 32.00 m depth)

    Large *G. oceanica* (> 4 μm) is found in this interval. This zone is equivalent to NN20 of Martini's zone or CN13 b of Okada & Bukry's zone (Pleistocene).

Each first or last occurrence boundary of the index species, identified from the biostratigraphic analysis, is assigned with its absolute age (see **Figure 2**). These data will be used to determine the time in the sedimentation rate analysis.

3.3. Sedimentation Rate

The study of sedimentation rate will provide an overview of various factors that affect the environment such as sea level changes and tectonic activity as well as processes related to erosion and sediment supply. Through the analysis of lithology, biostratigraphy and depositional environment of vertical stratigraphic sequences from Cikarang, the manifestation of deposition and variations in sedimentation rate over the time will be described. This description can provide an understanding of the geological dynamics in the North West Java Basin from the Miocene to the Pleistocene. The sedimentation rate is calculated by dividing the thickness of the sediment interval by the geological period in meters per thousand years (m/Myr). In this study, in the NN17/CN12 zone, a sediment interval 12.19 m thick with an age range of 0.552 Ma resulted in a sedimentation rate of 23.35 m/Myr. The following is a detailed description of sediment changes along the Cikarang sequence which is divided into several depth intervals based on biostratigraphic zones descending from older to younger (see **Figure 3**).

3.3.1. Interval 652 m to 618.74 m depth

Thin layers of claystone with carbonate sediments were deposited in the transgressive phase (22.82 to 19 Ma, Early Miocene) with a sedimentation rate of about 8.7 m/Myr. Based on environmental interpretation using nannofossil data accompanied by foraminifera determination, these very fine sediments were deposited in the deep marine.

3.3.2. Interval 618.74 m to 597.41 m depth

The intercalation of claystone and sandstone was deposited during 19 to 17.72 Ma with a very low sedimentation rate (4.18 m/Myr). This phase reflects an increase in sediment supply at low energy.

3.3.3. Interval 597.41 m to 435.86 m depth

At 17.72 Ma, the depositional environment is starting to become shallower in relation to a significant increase in clastic sediment supply, with a sedimentation rate reaching 39.72 m/Myr. Fine clastic sediment layer was gradually covered by intercalated clastic and carbonate layers. This indicates a transition from deep to shallow marine. At the end of this phase, 14.91 Ma, it was covered by increasingly coarsening-upward sediments reflecting higher depositional energy.

3.3.4. Interval 435.86 m to 423.67 m depth

During the period 14.91 to 13.65 Ma (Middle Miocene), interbedded claystone and sandstone were formed in a dynamic energy shallow marine environment, with a decreasing trend in sedimentation velocity reaching 13.93 m/Myr.

3.3.5. Interval 423.67 m to 411.48 m depth

Since 13.65 to 11.90 Ma, the sedimentation rate increased slightly (13.95 m/Myr). The claystones were dominant with a few limestones which are characterized by coarsening upwards. These sediments established under the low-energy conditions with low sediment supply in a stable shallow marine environment.

3.3.6. Interval 411.48 m to 374.90 m depth

During the period of 11.90 to 10.90 Ma, basin subsidence caused the Cikarang area to become a deep marine,

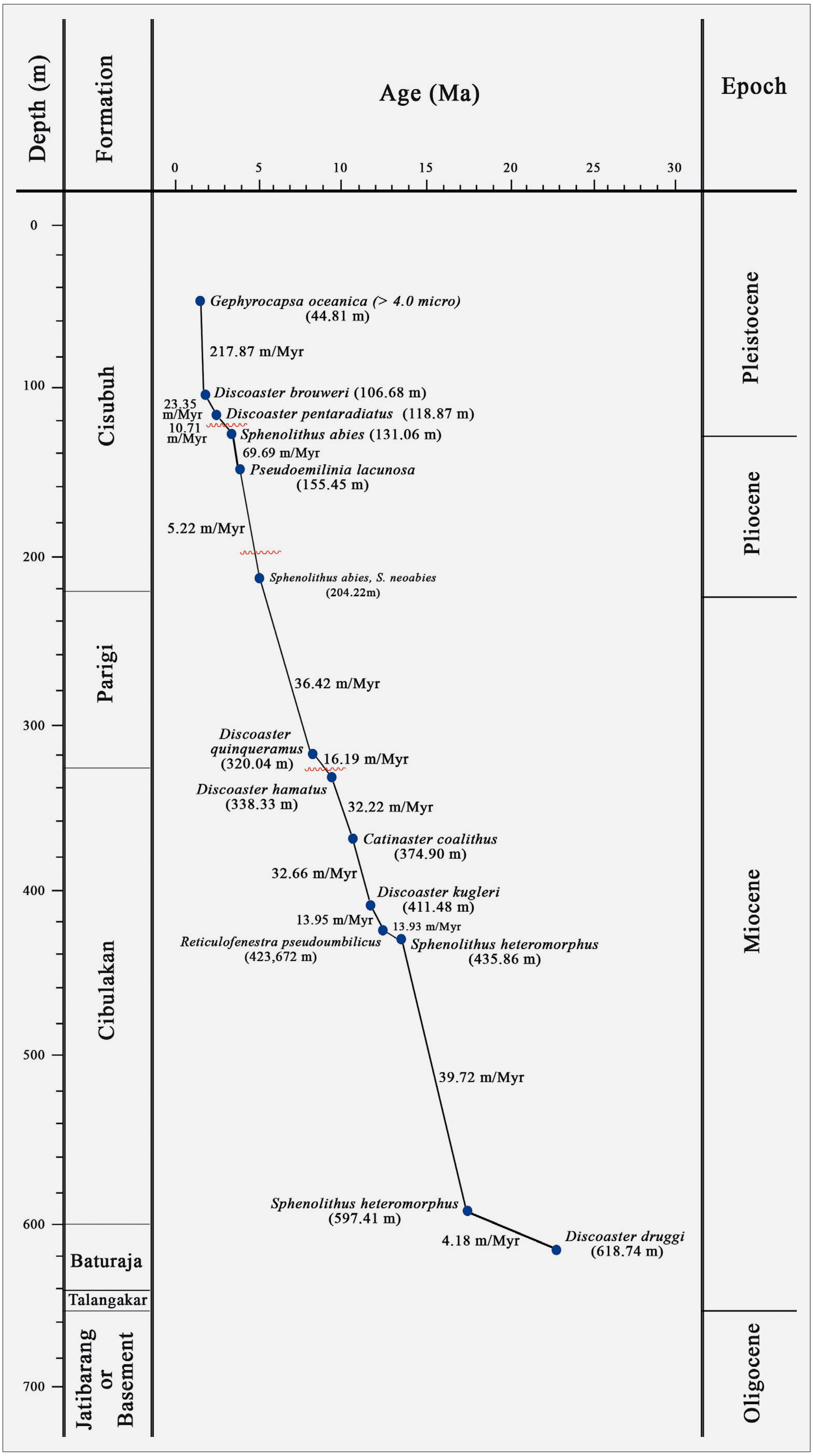

Figure 3. Age-depth plots of index species at Cikarang sequences

where clastic deposits, dominated by claystone with limestone layers, were formed. Sedimentation with the rate of 32.66 m/Myr has formed a deposit with the fining upward trend.

3.3.7. Interval 374.90 m to 338.33 m depth

Beginning at 10.90 Ma, thin layers of claystone and limestone were deposited at a sedimentation rate of 32.22 m/Myr, indicating a shallowing pattern. Approaching 9.65 Mya (Late Miocene), a coarsening-upward lithologic succession was deposited under high energy conditions.

3.3.8. Interval 338.33 m to 320.04 m depth

At the beginning of this period, 9.65 Ma, clastic deposits with limestone intercalations were formed, due to the ongoing shallowing process. An unconformity is indicated at the end of this period (Late Miocene).

3.3.9. Interval 320.04 m to 204.22 m depth

After 8.52 Ma, clastic limestone and reefs was formed in a quiet shallow marine setting, until 5.59 Mya.

3.3.10. Interval 204.22 m to 155.45 m depth

At 5.59 Ma subsidence has caused Cikarang area to become deeper, where sedimentation of fine sandstone and claystone occurred at a slow rate (5.22 m/Myr). Then gradual regression occurs. Coarse sandstone is found near the top of this interval. It indicates a depositional process in a transition zone with the sediment supply from the land. Basal Pliocene unconformity is indicated at the end of this period (4 Ma).

3.3.11. Interval 155.45 m to 131.06 m depth

During the period of 4 to 3.79 Ma, this area is characterized by an abundant supply of clastic sediments due to tectonic or erosional activity. A significant increase in sedimentation rates, up to 69.69 m/Myr, formed a sequence of sandstone and claystone in a shallow marine environment.

3.3.12. Interval 131.06 m to 118.87 m depth

Since 3.79 to 3.65 Ma (Late Pliocene), a sedimentation rate of approximately 10.71 m/Myr produced sandstone with intercalated claystone under stable transitional conditions.

3.3.13. Interval 118.87 m to 106.68 m depth

During the period of 3.65 to 2.51 Ma, sedimentation continued in shallow marine environment at an increasing rate of up to 23.35 m/Myr. Alternating claystones and sandstones formed during this phase. The high sedimentation rate indicates more dynamic conditions, with increased sediment supply, which may have been influenced by tectonic activity.

3.3.14. Interval 106.68 m to 44.81 m depth

Rapid sedimentation (217.87 m/Myr) has deposited layers of coarse sandstone and claystone. Active land progradation, tectonics, erosion and climate change influenced geological processes during 2.51 to 1.99 Ma. At the end of this period tectonic activity occurred, which lifted Cikarang into a littoral zone.

3.3.15. Interval 44.81 m to 32.00 m depth

During 1.99 to 1.70 Ma (Pleistocene), littoral sedimentation took place at a rate of 7.55 m/Myr which has deposited sandstone and conglomerate.

4. Discussion

The biostratigraphy of the North West Java Basin studied in the Cikarang sequence shows 17 biostratigraphic zones that correlate with NN1 to NN20 (CN1-CN13) in the absolute age range of 22.82 Ma (Early Miocene) to 1.70 Ma (Pleistocene). This is consistent with the regional stratigraphy of North West Java Basin according to previous researchers, including **Noble et al. (1997)** and **Koesoemadinata (2020)**. Absolute age is determined based on the first occurrence (FO) or last occurrence (LO) of index species, according to **Young (1998), Raffi et al. (2006), Sato & Chiyonobu (2013)** and **Boesiger et al. (2017)**.

The lowest part of this sequence (interval 652 - 618.74 m depth) is marked by *Discoaster druggii* which first appeared (FO) around 22.82 Ma (Early Miocene) as an indicator of warm shallow marine water at equatorial to tropical boundaries (**Aubry, 1984**). LO *Helicosphaera euphratis*, FO *Sphenolithus heteromorphus*, LO *Helicosphaera ampliaperta*, LO *Sphenolithus heteromorphus*, FO *Discoaster kugleri*, FO *Catinaster coalithus* and LO *Discoaster hamatus* characterize the boundaries of the biostratigraphic zones equivalent to NN2 to NN9 in Early to Late Miocene. The Late Miocene unconformity possibly correlated with carbonate build-up of Parigi Formation (**Koesoemadinata, 2020**). Further-more, FO and LO *Discoaster quinqueramus* characterize the base of NN11 and NN12 zone in Latest Miocene. It is followed by an unconformity that correlates to the Miocene-Pliocene boundary. FO *Pseudoemiliania lacunosa*, LO *Reticulofenestra pseudoumbilicus*, LO *Sphenolithus abies* and LO *Discoaster pentaradiatus* characterize the boundaries of the biostratigraphic zones equivalent to NN7 to NN14 in the Early to Late Miocene. An unconformity and depositional environment shifting were identified at the Plio-Pleistocene boundary (**Darman & Sidi, 2000; Hamilton, 1979**). LO *Discoaster brouweri* and FO large *Gephyrocapsa oceanica* equivalent to

NN18 and NN19 marked Pliocene period in the Cikarang area.

Each FO and LO index species were assigned with an absolute age to calculate the sedimentation rate. Overall, sedimentation rates ranging from very low (4.18 m/Myr) to high (217.87 m/Myr), which correlates with sea level fluctuation from deep marine, shallow marine to littoral. In Early Miocene (recorded in interval 618.74 to 435.86 m) sedimentation rates were low (range 4.18 to 39.72 m/Myr) indicating low sediment supply in the deep marine environment. The Middle to Late Miocene in Cikarang (interval 435.86 m to 320.04 m) is a regressive period characterized by coarsening-upward lithologic succession in shallow marine environment with sedimentation rate of 13.93 to 32.66 m/Myr, then overlain by limestone which partly forms a carbonate build-up. During the period of transgression, sedimentation rate was 5.22 m/Myr. After a brief sea level drop, there was an increase in tectonic activity that resulted in an unconformity in the basal Pliocene. The progradation phase (< 320.04 m) was marked by a significant increase in sedimentation rate reaching 217.87 m/Myr, due to the influence of tectonic activity.

5. Conclusions

Nannofossil assemblages were found throughout the Neogene to Quaternary rock sequence at Cikarang in the Northwest Java Basin, Indonesia. Within this sequence, 59 nannofossil species classifying into 16 nannofossil genera were identified: *Braarudosphaera (B. bigelowii), Calcidicsus (C. leptoporus* and *C. macintyrei), Coccolithus (C. pelagicus), Coronocyclus (C. nitescens), Umbilicosphaera (U. sibogae), Catinaster (C. coalithus* and *C. umbrellus), Discoaster (D. brouweri, D. calcaris, D. deflandrei, D. druggii, D. hamatus, D. kugleri, D. neohamatus, D. pentaradiatus, D. quinqueramus, D. variabilis, D. exilis, D. bellus* and *D. perplexus), Helicosphaera (H. ampliaperta, H. euphratis, H. intermedia, H. scissura, H. sellii, H. kamptneri, H. granulata, H. mediterranea, H. minuta, H. stalis, H. philippinensis, H. oblique* and *H. rhomba), Pontosphaera (P. multipora* and *P. discopora), Gephyrocapsa (G. caribbeanica* and *G. oceanica), Pseudoemiliania (P. lacunosa), Reticulofenestra (R. pseudoumbilicus, R. minuta, R. minutula, R. haqii* and *R. floridana), Rhabdosphaera (R. procera)* and *Sphenolithus (S. abies, S. heteromorphus, S. moriformis* and *S. neoabies)*. The most dominant species was *Reticulofenestra pseudoumbilicus* along with other species such as *Sphenolithus moriformis* and *Coccolithus pelagicus*. There are 14 index fossils with easily recognizable first occurrence (FO) or last occurrence (LO).

Based on these FO and LO, the sequence is divided into 17 biostratigraphic zones categorized into range and interval zones. FO and LO index fossils, descending from oldest to youngest, are: FO *Discoaster druggii* (22.82 Ma), LO *Helicosphaera euphratis* (19.00 Ma), FO *Sphenolithus heteromorphus* (17.72 Ma), LO *Helicosphaera ampliaperta* (14.91 Ma), LO *Sphenolithus heteromorphus* (13.65 Ma), FO *Discoaster kugleri* (11.90 Ma), FO *Catinaster coalithus* (10.9 Ma), LO *Discoaster hamatus* (9.55 Ma), FO *Discoaster quinqueramus* (8.52 Ma), LO *Discoaster quinqueramus* (5.39 Ma), FO *Pseudoemiliania lacunosa* (4.00 Ma), LO *Reticulofenestra pseudoumbilicus* (3.79 Ma), LO *Sphenolithus abies* (3.65 Ma), LO *Discoaster pentaradiatus* (2.51 Ma), LO *Discoaster brouweri* (1.99 Ma) and FO large *Gephyrocapsa oceanica* (1.71 Ma).

Through analysis of lithology characteristics, depositional environment and FO or LO of index species from vertical stratigraphic sequences, the depositional manifestation and variations in sedimentation rate over time can be identified. Lithologic successions in Cikarang are generally composed of fine-grained clastic rocks (sandstone and claystone), clastic limestone and reefs which are deposited in various depositional environments, such as deep marine, shallow marine and littoral.

Sedimentation rates vary between 4.18 m/Myr to 217.87 m/Myr, reflecting the influence of tectonic activity, sea level changes, and sediment supply. In Early Miocene (interval 618.74 to 435.86 m) the sedimentation rate was low (range 4.18 to 39.72 m/Myr) indicating the deep marine environment. From Middle to Late Miocene (435.86 m to 320.04 m) the sedimentation rate was 13.93 to 32.66 m/Myr and ended by an unconformity. Sedimentation continued at a rate of 5.22 m/Myr followed by the Mio-Pliocene unconformity. Sedimentation rate in Pliocene (< 320.04 m) reached 217.87 m/Myr influenced by tectonic activity. During the Pleistocene deposition the sedimentation rate was 7.55m/Myr. Unconformities are identified at the intra Miocene, as well as Mio-Pliocene and Plio-Pleistocene boundaries.

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SAŽETAK

Integrirana analiza neogenske do kvartarne biostratigrafije nanofosila i brzine sedimentacije u sekvenciji Cikarang, bazen Sjeverozapadne Jave, Indonezija

Zajednice nanofosila pronađene su u cijelome neogenskom do kvartarnom slijedu stijena u Cikarangu u bazenu Sjeverozapadne Jave u Indoneziji. U okviru ovoga istraživanja određena je biostratigrafska starost, rekonstruirane su faze taloženja te je izračunana brzina sedimentacije slijeda stijena na temelju litologije i zajednica nanofosila. Unutar ovoga slijeda identificirano je 59 vrsta nanofosila, a 14 su indeksni fosili s lako prepoznatljivim prvim (FO) ili posljednjim pojavljivanjem (LO). Na temelju tih granica slijed je podijeljen u 17 biostratigrafskih zona kategoriziranih u rasponske i intervalne zone. Litološke sukcesije u Cikarangu općenito su sastavljene od sitnozrnatih klastičnih stijena (pješčenjaka i gline), klastičnih vapnenaca i fosilnih grebena, koji su taloženi u različitim taložnim okruženjima kao što su dubokomorski, plitkomorski i litoralni. Brzine sedimentacije variraju između 4,18 m/Myr do 217,87 m/Myr, što odražava utjecaj tektonske aktivnosti, promjene razine mora i donosa sedimenta. Nepodudarnosti su identificirane unutar miocena, kao i na granicama miocena i pliocena te pliocena i pleistocena.

Ključne riječi:
nanofosil, biostratigrafija, brzina sedimentacije, bazen Sjeverozapadne Jave

Author's contribution

Lilian C Rieuwpassa (Postgraduate Student, Master Program in Geological Engineering, Faculty of Geological Engineering) analysed nannofossil, interpretation of both biostratigraphy and sedimentation. **Vijaya Isnaniawardhani** (Professor, Biostratigraphy) was responsible for research design, methodology, and writing of the manuscript. **Budi Muljana** (Professor, Stratigraphy) was responsible for writing and compiling the manuscript.
All authors have read and agreed to the published version of the manuscript.