International Journal on Advanced Science Engineering Information Technology

Vol.9 (2019) No. 2
ISSN: 2088-5334

The Mid Miocene Climatic Optimum (MMCO) Indication at Low Latitude Sediment Case Study: The Miocene Cibulakan Formation, Bogor Basin, Indonesia

Rubiyanto Kapid[#1], Wahyu Dwijo Santoso[#], Ben Ikhsan[#], Moehammad Ali Jambak[*], Dasapta Erwin Irawan[#]

[#1]Department of Geology, Institut Teknologi Bandung, Bandung, Indonesia
E-mail:[1]ruby@gl.itb.ac.id; [1]roebiyantokapid@gmail.com

[*]Department of Geology, Trisakti University, Indonesia

***Abstract*— Middle Miocene Climatic Optimum (MMCO) is widely distributed and associated with increasing temperature and CO_2 content in the atmosphere. The effects of MMCO are identified in the mid-latitude region, with lack of examples from the low latitude areas. In this study, we aim to determine the effect of MMCO at Cibulakan Formation of Bogor Basin, Indonesia, which is situated in lower latitude. We took 58 samples from the Cibulakan Formation, which is exposed along Cileungsi River, for quantitative nannoplankton (the abundance of *Helicosphaera carteri*) analysis to mark increasing and decreasing salinity event, as they are sensitive to temperature. Temperature relates to the salinity of the seawater due to evaporation. From our analysis, we identified sea surface temperature change in Early Miocene which was presumably due to small scale Early Miocene glaciation and active tectonic during the period. The warmer temperature took place on Middle Miocene as the effect of a warm and open sea environment during Mid Miocene Climatic Optimum. Afterward, the temperature continued to rise until the late Miocene, as it had been triggered by the increasing global temperature at the Pacific Ocean and widely distributed clean water at North West Java Basin during the depositional period.**

***Keywords*— Mid Miocene Climatic Optimum (MMCO); nannoplankton; temperature changes; Cibulakan formation.**

I. Introduction

Mid- Miocene Climatic Optimum (MMCO) is one of the global climatic events during Middle Miocene, which is indicated by increasing temperature [1], [2]. The increase of temperature during such a period is often interpreted to be related to geological activity, which is followed by increasing CO_2 in the atmosphere. The impact of MMCO was widely distributed and associated with the increase of temperature by 6°C in the mid-latitude region [3]. Moreover, Antarctic vegetation in MMCO indicates the average temperature of 11°C, which is warmer than the summer period in the present day, with average annual sea surface temperature 11.5°C [3].

The change in nannoplankton population reflects the increase of temperature during MMCO as it is sensitivity to temperature change. An increase of temperature from 5oC to 8°C during the MMCO, not only affect the diversity and population of nannoplankton but also optimizes the coccolithophores evolution and its high diversity [4].

Aside to its global effect, evidence of MMCO is very limited in the tropical area. Limited knowledge of MMCO evidence and impact is due to lack of geochemical data and quantitative microfossil analysis in continuous section middle Miocene sediments, especially in Indonesia. This study aims to determine the evidence and impact of MMCO based on nannoplankton analysis in early - middle Miocene Cibulakan Formation.

A. Geology Setting

The research area is situated along Cileungsi River, Bogor, West Java within the area of North West Java Basin [5] (Figure 1 A.). This basin was formed by the collision of the Eurasian Plate with the Indian Australian Plate during Late Cretaceous to early Eocene [5, 6, 7, 8]. The Cibulakan Formation was deposited in the early – late Miocene in the back-arc basin setting [5] (Figure 1B). The stable depositional environment provided high siliciclastic sediment supplies from the continent. The change of the depositional environment in the back-arc setting was controlled by sea level changes both regional and eustasy. Drowning phase during this age had resulted in the deepening upward sequence and revealed the transition – shallow marine environment.

Generally, Cibulakan Formation consists of interbedded of claystone and sandstone, and minor limestone as intercalation [9, 10] bounded by conformity surface at the base and unconformity surface at the top by the Jatibarang and Parigi Formation respectively. [5]. Moreover, Cibulakan Formation has an interfingering connection with Jatiluhur Formation which had been deposited in the deep marine environment [11].

Sea level rise during the early Miocene had started the transgressive phase by changing the terrestrial environment of Jatibarang Formation the transitional environment [9]. The base of the Cibulakan Formation was deposited in the paralic environment and close to active delta progradation [12]. Then a transgressive phase progressed into the middle part of Cibulakan Formation and showed gradual changes from paralic environment to shallow clean water environment before eventually occupied by offshore bar sediments. At the top of them, there was claystone to bioturbated silty claystone and then calcarenite limestone [11].

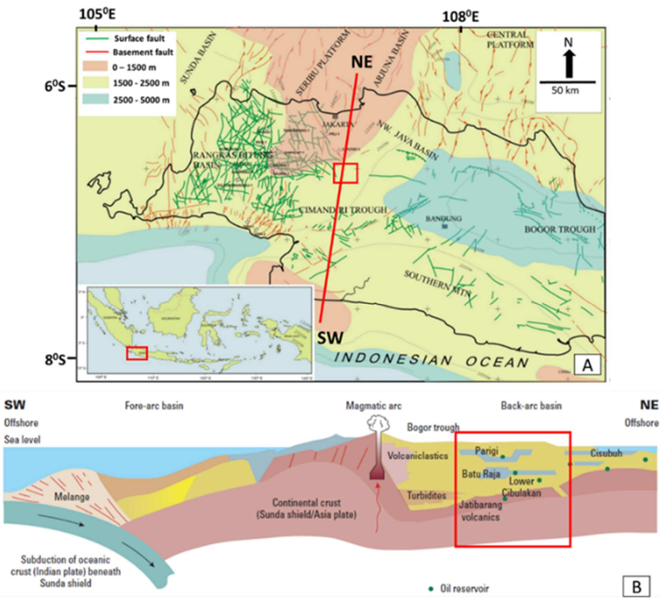

Fig. 1 (A). Structure map of West Java (Modified from [5]). The research area (red box) occupy Bogor Through. (B) Schematic cross section of West Java SW – NE (Modified from [7]). Cibulakan Formation infill back-arc basin setting in Bogor Through (red box).

II. Material and Method

The study was carried out by taking a detailed measuring section and systematic sampling. We made a five km traverse on a continuous sedimentary rock exposure, to observe sediment's dynamic and short-term changes of nannoplankton biostratigraphy (Figure 2). We obtained 58 samples, which most of them were taken from the claystone and limestone intervals of the Cibulakan Formation.

We divided the sampling strategy into three sequences:

- Samples RBK 39 – 58 were taken from Sequence I. We conducted a 5 m spacing of sampling at the top of sequence, bioclastic limestone.
- Twelve samples (RBK 38 - 26) were collected from Sequence II.
- The other 25 samples (RBK 25 - 11) were collected as Sequence III, where high-resolution sampling in interbedded claystone and sandstone was carried out at the top of this sequence, with 1.5 m spacing.

We prepared the samples using a quick smear slides method [13]. Samples were crushed, and the powder were smeared in the cover glass. The powders then were greased by Canada balsam and covered by a thin cover glass. To maintain the original composition of sediment, no material was added during preparation. We used the Field of View (FOV) method for the quantitative method [13]. Nannoplankton observation was performed in Micropaleontology Laboratory, Department of Geology, Institut Teknologi Bandung using polarization microscope Nikon Alpha shot YS2-H.

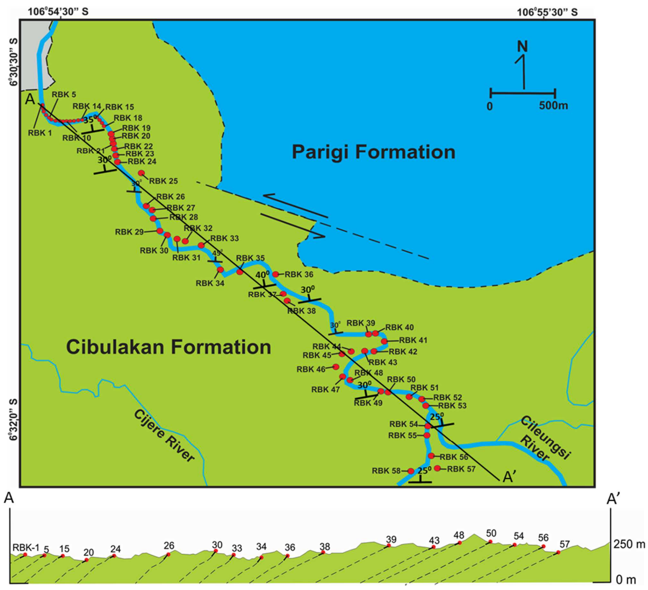

Fig. 2 Geological map (top) and cross section (bottom) of the Cileungsi River (Modified from [14]). Red dots represent the sample locations.

III. Result and Discussion

The Cibulakan Formation was deposited in the offshore environment, indicated by thick offshore shale sequences and capped by bioclastic limestone. We divided the vertical section of the formation (from bottom to top) to three sequences (Sequence I, Sequence II, and Sequence III), which bordered by bioclastic limestone.

The sequence I is characterized by 350 meters thickness of claystone, which followed by 500 meters interlamination of thin sandstone and claystone, before gradually shifting to wackestone-packstone limestone unit at the top of the sequence (Figure 3). The limestone unit contains biota fragments of coral and foraminifera to indicate transgressive environment.

Sequence II starts with 1250 m interbedded of claystones and sandstones at the bottom and followed by 3000 m of interbedded thick limestones and claystones. This sequence has more biota fragments in the limestone than in Sequence I (Figure 4), as the result of sea level rise, which is marked by intensive limestone as the cap of clastic sediment. However, Sequence III shows interbedded claystones and sandstones as the representation of regressive process (Figure 5).

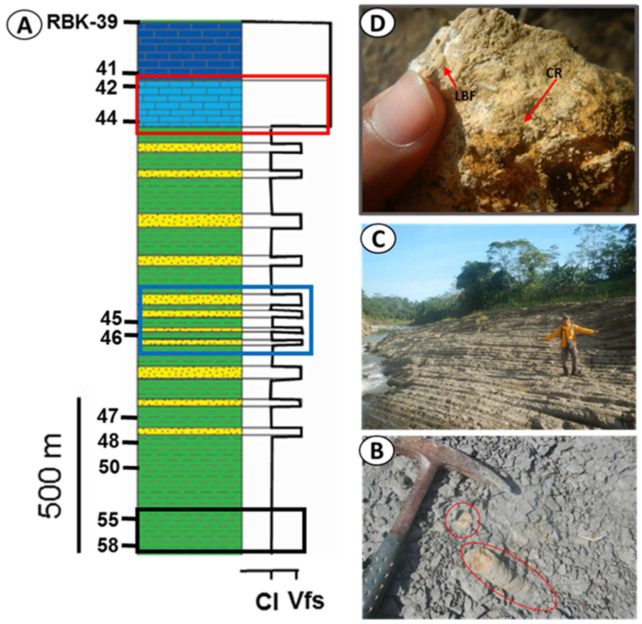

Fig. 3 Sequence I at Cibulakan Formation; (A) Section of Sequence I at Cibulakan Formation in the research area. (B) Claystone at the bottom of Sequence I with Cruziana sp. ichnofossil (location of the photograph is bordered by black box at sedimentation profile). (C) Interbedded sandstone and claystone at the middle of Sequence I (location of photograph is bordered by blue box at sedimentation profile). (D). Limestone at the top of Sequence I with coral (CR) and large benthic foraminifera (LBF) fragments (location of the photograph is bordered by red box at sedimentation profile).

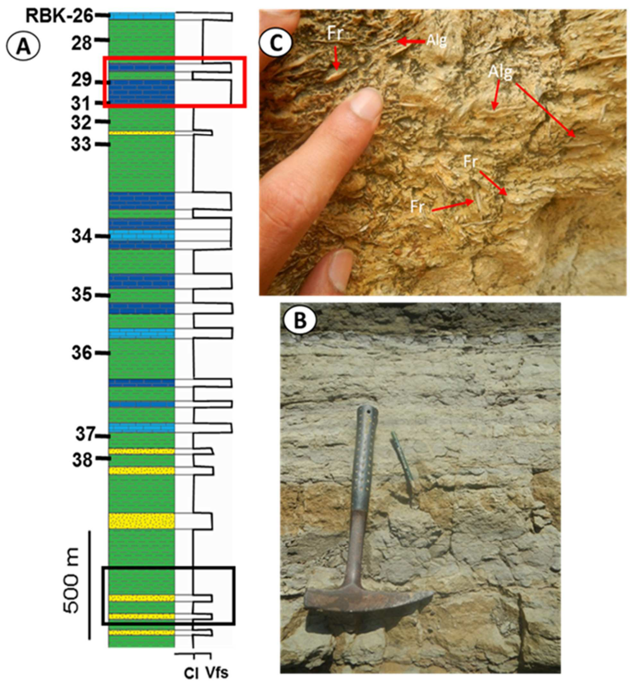

Fig. 4 Sequence II at Cibulakan Formation; (A) Section of Sequence II at Cibulakan Formation in the research area. (B) Interbedded sandstone and claystone at the middle of Sequence I (location of photograph is bordered by black box at sedimentation profile). (C). Limestone at the top of Sequence II with intensive encrusting algae (Alg) and large benthic foraminifera (Fr) fragments (location of the photograph is bordered by red box at sedimentation profile).

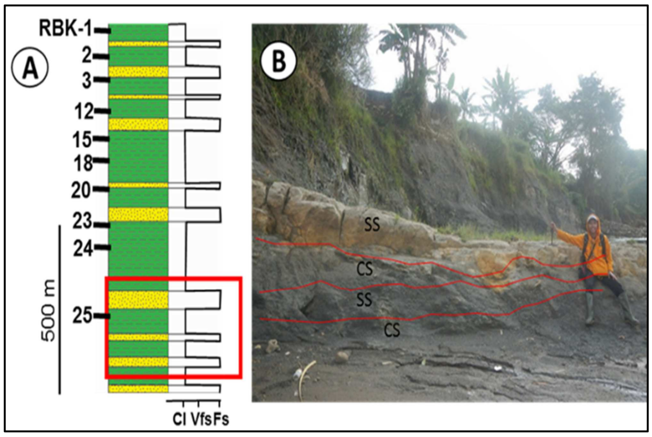

Fig. 5 Sequence III at Cibulakan Formation; (A) Section of Sequence III at Cibulakan Formation in the research area. (B) Interbedded sandstone (SS) and claystone (CS) at Sequence III (location of the photograph is bordered by red box at sedimentation profile).

Early – Late Miocene age for the Cibulakan Formation in the research area is confirmed by the nannoplankton biozones [15]. Nannoplankton biozones of Cibulakan Formation yielded much calcareous nannoplankton events. First Appearance Datum (FAD) and Last Appearance Datum (LAD) from nannoplankton fossil can be used to divide biostratigraphy event, which correlates with age and stratigraphy succession. Several nannoplankton species which act as index fossils consist of *Sphenolithus belemnos*, *Helicosphaera vederii*, *Sphenolithus heteromorphus*, *Discoaster challengeri*, *Catinaster coalithus*, and *Discoaster neohamatus* are presented in Figure 6.

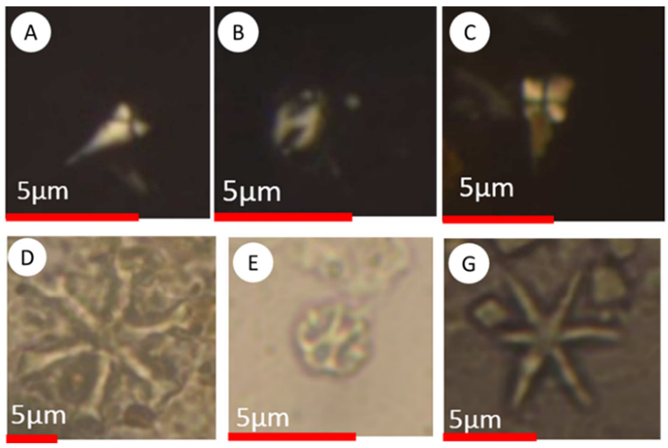

Fig. 6 Index fossils of biostratigraphy zone; (A) *Sphenolithus belemnos,* (B) *Helicosphaera vederii*, (C) *Sphenolithus heteromorphus*, (D) *Discoaster challengeri*, (E) *Catinaster coalithus,* (F) *Discoaster neohamatus.*

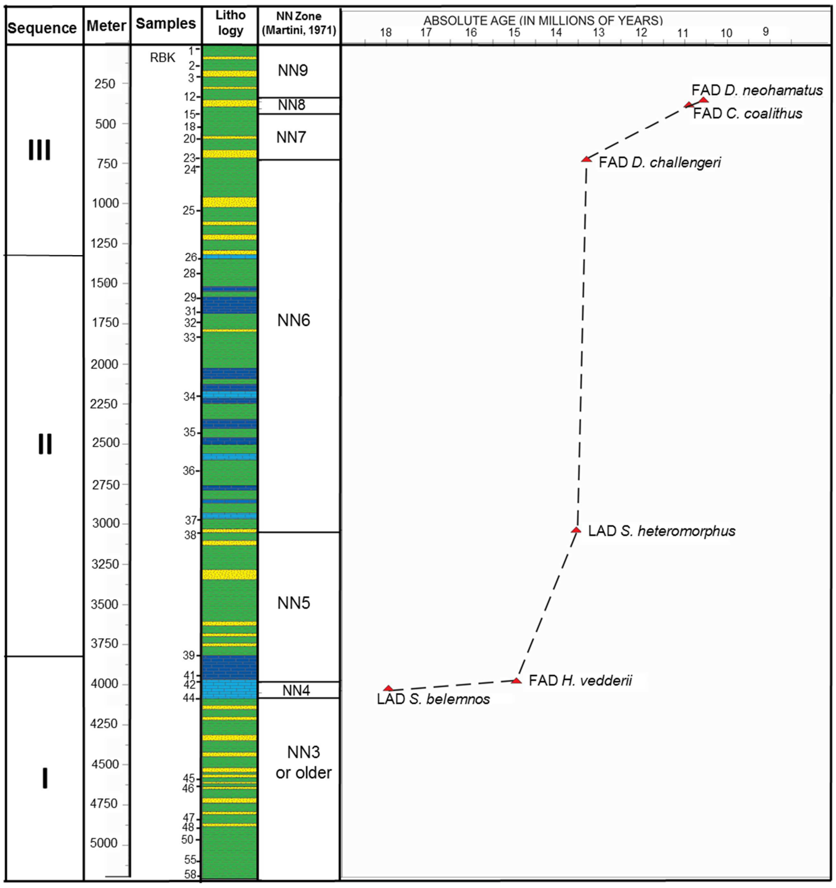

Fig. 7 Biostratigraphy zone of Cibulakan Formation in the Cileungsi River.

Figure 7 shows the biostratigraphy zones of the Cibulakan Formation; they are:

*1) Sphenolithus belemnos zone:*This zone is bordered by LAD (Last Appearance Datum) of *Sphenolithus belemnos*, in which the samples were taken in the RBK – 58 to RBK – 45 at claystone lithology. *Sphenolithus belemnos* zone equal with NN-3 [15] and relates with Early Miocene, around 17.95 mya or older [16].

2) Sphenolithus belemnos – Helicosphaera vederii zone: Partial zone is marked by interval from extinction of Sphenolithus belemnos and FAD (First Appearance Datum) of Helicosphaera vederii. This zone can be observed from RBK – 44 to RBK 42 and equal with NN – 4 [15], border of Early Miocene and Middle Miocene, around 14.91 mya [16].

3) Helicosphaera vederii - Sphenolithus heteromorphus zone: Concurrent zone is bordered by FAD (First Appearance Datum) of *Helicosphaera vederii* and extinction of *Sphenolithus heteromorphus.* This zone occupy from RBK – 41 to RBK - 39 which is equal with NN – 5 [15], Middle Miocene around 13.53 mya [16].

4) Sphenolithus heteromorphus - Discoaster challengeri zone: Partial zone is bordered by extinction of *Sphenolithus heteromorphus* and FAD (First Appearance Datum) of *Discoaster challengeri*. This zone can be observed from RBK – 38 to RBK - 23, equal with NN -6 [15], Middle Miocene around 13.27 mya [16]. Moreover, LAD (Last Appearance Datum) of *Sphenolithus heteromorphus, Discoaster brouweri* has the first appearance in this zone.

5) Discoaster challengeri - Catinaster coalithus zone: This zone is marked bythe interval from e FAD (First Appearance Datum) of *Discoaster challengeri* and FAD (First Appearance Datum) of *Catinaster coalithus*. This zone occupies RBK – 23 to RBK - 16 which is equal with NN – 7 [15], Middle Miocene around 10.89 mya [16].

6) Catinaster coalithus - Discoaster neohamatus zone: This zone is bordered by FAD (First Appearance Datum) of *Catinaster coalithus* and FAD (First Appearance Datum) of *Discoaster neohamatus*. This zone can be observed from RBK – 15 to RBK - 13, equal with NN -8 [15] which is border of Middle Miocene and Late Miocene around 10.55 mya [16].

7) Discoaster neohamatus zone: This zone is marked by FAD (First Appearance Datum) of *Discoaster neohamatus* and the extinction of *Sphenolithus moriformis*. This zone can be observed from RBK – 12 to RBK – 1, which is equal with NN -9 [15], Late Miocene age, younger than 10.55 mya [16].

Analyses of nannoplankton fluctuation has been known to be utilized as sea surface temperatures and paleosalinity indicator. These data are useful to determine the dynamic changes of depositional environment. Rising sea surface temperature is followed by blooming of nannoplankton and dropping temperature is marked by decreasing population. Rising sea temperature also associated with high salinity or hypersaline condition and vice versa. Changes in salinity is observed by comparison between *Helicosphaera carteri* and *Umbilicosphaera jafari. Helicosphaera carteri* has ellipsoid coccolith, flange end in wings, two narrow pores in central area (Figure 8A and 8B). Increasing population of *Helicoshapera carteri* represents low salinity and brackish environment [17], [18]. The similar result is revealed by

Santoso et al. [19], analyzing the high abundance population of *Helicosphaera carteri* on Late Miocene – Pliocene Sediments in North East Java Basin, Indonesia, in low salinity condition. *Umblicosphaera jafari* represents high salinity environment (>35 ppt) [17]. *Umbilicosphaera jafari* is marked by small circular species of coccolith, narrow central-area, and wide distal shield with complex suture (Figure 8C and 8D).

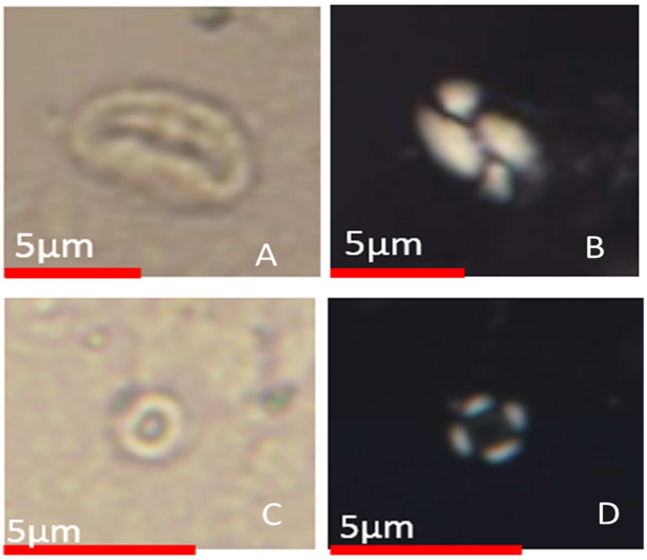

Fig. 8 Salinity Indicator.

A and B. *Helicosphaera carteri.* Photograph A in parallel nicol and Photograph B in cross nicol. C and D. *Umbilicospahera jafari*. Photograph C in parallel nicol and Photograph D in cross nicol.

Figure 9 shows the variation in temperature changes during the Early to Late Miocene represented by the Cibulakan Formation based on the analyses in this study. A period of cooling phase occurred in the Early Miocene indicated by the least abundance of nannoplankton. Sea temperature appeared to be increased in the Middle Miocene as indicated by the rise in nannoplankton population before the population bloomed in the Late Miocene to indicate the optimum sea temperature for nannoplankton growth.

Rapid changes in environment occurred in the Early Miocene (NN3 or older zone) is represented by the fluctuation nannoplankton population in relation to changes in temperature. The temperature fluctuation correlates with active tectonic related with volcanic sediment in North West Java Basin [20] and global cooling and climatic transition events on Early Miocene [21]. During Early Miocene, changes in subduction front formed at Southern Java, south of North West Java Basin [6;20], yielded prominent volcanic debris of Jatiluhur Formation which interfingers with the Early Miocene Cibulakan Formation [11]. Moreover, temperature decreased + 20C which observed from drilling project Site 747, in Indian Ocean. This event reflects a result of small scale Early Miocene Glaciation and it was confirmed by increasing of 18O isotope value of foraminifera by Billup and Schrag [21]. Based on global δ18O curve, the value of δ18O showed fluctuation trend which ranging 1.8 – 2 ‰ (Figure 9).

Increasing population of nannoplankton during Middle Miocene period (NN4 – NN7) is indicated by increase intemperature, rising sea level forming a suitable environment for nannoplanton growth [4]. This event is related to the start of a global event of Mid Miocene Climate Optimum that has been recognized to influenced population and diversification of nannoplankton. Blooming of nannoplankton in this period implies the shallow and open sea environment and warm sea [18]. Moreover, diminution decrease of volcanic activity on Middle Miocene [20] developed widely distribution of clean water and carbonate build up which provided the stable environment by nannoplankton ecology. Increasing of nannoplankton abundance fit with δ18O trend by Zachos et al. [22] (Figure 10). Between NN4 – NN7 period, the peak of nannoplankton abundance was followed by lowest value of global δ18O curve, which ranging 1.4 – 1.7 ‰. This fact indicates the abundance of nannoplankton on Middle Miocene was controlled by Mid Miocene Climatic Optimum which influences of rising of temperature.

During Late Miocene (NN8 – NN9), blooming nannoplankton continues to reach the peak of population. Increasing temperature around 40C in Pacific Ocean [23] triggered the increase of nannoplankton population. Hence, warm and shallow marine at North West Java Basin [20], [24] supported suitable local influence for nannoplankton growth during this period. This local event can be observed by development of Late Miocene Carbonate of Parigi Formation during this period.

During the Early Miocene (NN3 or older zone), salinity changes rapidly fluctuated and showed unstable environment. *Helicosphaera carteri* dominates the fossil species determined in two samples which taken at the base of Early Miocene Cibulakan Formation. This indicates that the depositional condition of Cibulakan Formation started with lower salinity environment. However, the environment changed to high salinity environment, where *Umbilicosphaera jafari* population increases at the younger samples on middle of Early Miocene. Salinity decreased at the intebedded sandstone and claystone found at the top of Early Miocene sequence. It was marked by more dominant occurrence of *Helicosphaera carteri* than *Umbilicosphaera jafari.* Salinity fluctuation on Early Miocene triggered by fluctuation of temperature on Early Miocene.

During Middle Miocene (NN4 – NN7), a stable environment can be observed during the deposition of Cibulakan Formation. High salinity marine condition was reflected by the domination *Umbilicosphaera jafari*, and showed more abundance population than *Helicosphaera carteri*. The rising temperature at the start of the Middle Miocene Carbonate Optimum (MMCO) resulted in increase in evaporation that promotes the high salinity condition.

The suitable and stable environment continued to Late Miocene (NN8 – NN9). High salinity condition was maintained, as indicated by the growing population of *Umbilicosphaera jafari* and drastic decrease of *Helicosphaera carteri* population. Such grow was controlled by high salinity condition, shallow environment, restricted area, and nearshore environment during this age [17].

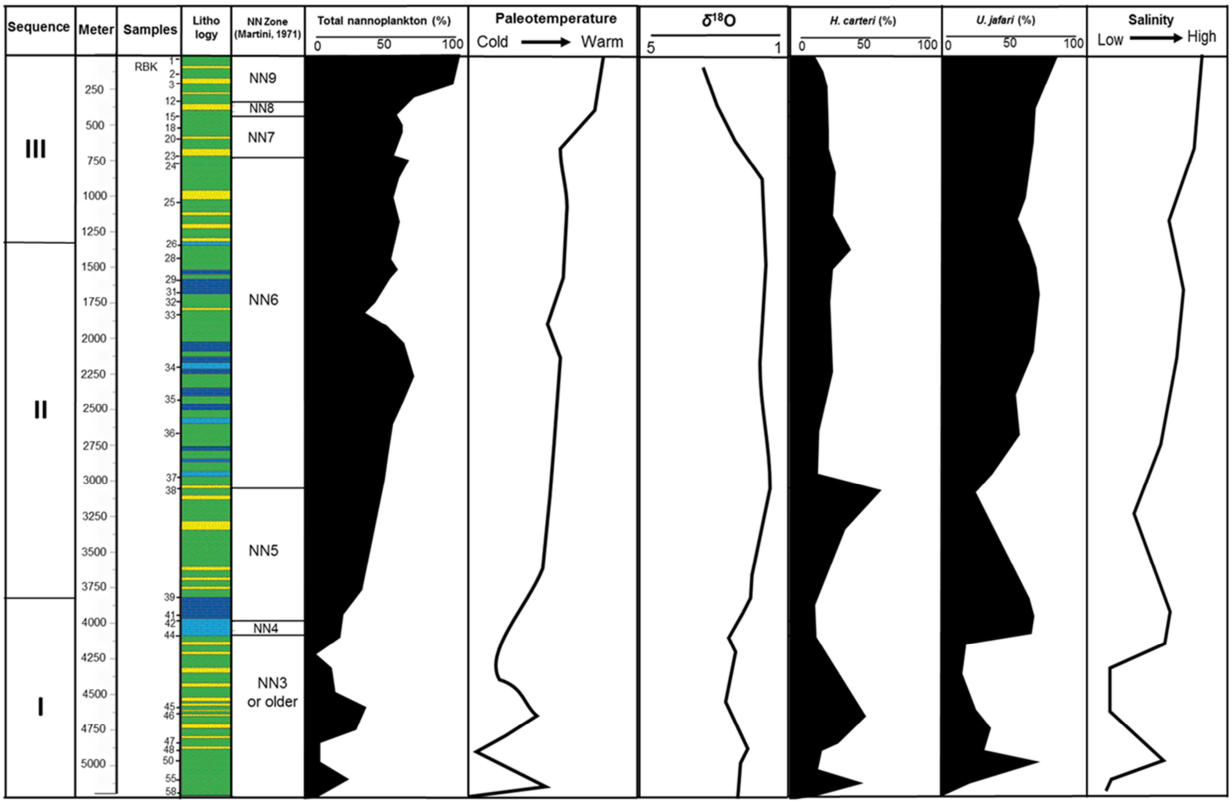

Fig. 9 The interpretation of paleotemperature and salinity of Cibulakan Formation. The reference of 18O was cited from Zachos et al. [22] curve.

IV. Conclusions

Nannoplankton population changes indicate several paleoecology changes. Nannoplankton population bloom in the Cibulakan Formation is related to the global event of Mid Miocene Climatic Optimum. This MMCO starts in the Middle Miocene before it reaches a peak in the Late Miocene. This study concludes the following:

Biostratigraphy zone of Cibulakan Formation can be divided into seven zones, namely: *Sphenolithus belemnos* zone, *Sphenolithus belemnos – Helicosphaera vederii* zone, *Helicosphaera vederii - Sphenolithus heteromorphus* zone, *Sphenolithus heteromorphus - Discoaster challengeri* zone, *Discoaster challengeri - Catinaster coalithus* zone, *Catinaster coalithus - Discoaster neohamatus* zone, *Discoaster neohamatus* zone.

Fluctuations of temperature were observed on Early Miocene which is characterized by fluctuating nannoplankton population. This event was introduced by small scale Early Miocene glaciation and active tectonic during this period. Nannoplankton population increased in the Middle Miocene as the effect of a warm and open sea during Mid Miocene Climatic Optimum. Hence, the optimum population on Late Miocene was drawn by a global temperature increase in the Pacific Ocean and widespread distribution of clean water at North West Java Basin.

Salinity changes can be detected at Cibulakan Formation deposition. During the Early Miocene, salinity rapidly fluctuates to indicate unstable environment. More stable environment recorded in the Middle Miocene is interpreted to be caused by increasing temperature and evaporation. The high salinity condition was continued into the Late Miocene and reached the maximum salinity.

Acknowledgment

This paper was funded by Institut Teknologi Bandung (P3MI) and Universitas Trisakti, in a join research scheme. The authors thank to Pak Alfend Rudyawan ST., M.Sc., and Ph.D., Geodynamic and Sedimentology Research Group and all member of Paleontology and Quartenary Geology Research Group, FITB-Institut Teknologi Bandung for all of the support. We would like to thank you to Rifky Ghifari ST., for his hard work to prepare our samples. In addition, thank you to student team for field work support from Department of Geology, Institut Teknologi Bandung and Department of Geology, Trisakti University.

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