Miocene Sea Surface Dynamics in the Western Equatorial Pacific Based on Calcareous Nannofossil Records

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Abstract. Calcareous nannofossil in the sediments from Ocean Drilling Program (ODP) Hole 806B in the Ontong Java Plateau have been examined to reconstruct surface water condition in the western equatorial Pacific (WEP) throughout the Miocene. By using quantitative techniques, 107 sediment samples have been prepared into nannofossil slides and observed under microscope. Changes in Reticulofenestra size variations, Discoaster relative abundance and nannofossil accumulation rates (NAR) suggest that WEP surface water was dynamic. During early to middle Miocene from 18 to 14 Ma, the surface water was warm and depleted in nutrient with deep thermocline due to warm period of the Middle Miocene Climatic Optimum. Temperature cooled, nutrient increased and thermocline shoaled at 14 Ma during the East Antarctic Ice Sheet Expansion (EAIE). Surface water warmed and thermocline deepened after 13.2 Ma as the western Pacific warm pool (WPWP) began to established. At 9 Ma, surface water suddenly changed into cooler and nutrient rich condition. The collapse of ocean stratification coincided with the onset of Asian Monsoon Intensification. Warm surface water and deep thermocline occurred again in the latest Miocene as the brief return of the WPWP during 7–6 Ma.

1. Introduction
Miocene has been recognized as a period with dynamic earth climate variability [1]. The early Miocene was a warm period toward in the middle Miocene climatic optimum (MMCO) before terminated by abrupt cooling as the permanent Antarctic ice sheet began to reestablish at ~14 Ma [1][2]. Whereas, the Late Miocene was marked by gradual cooling trend with the rise of modern climate comprising Asian monsoons intensification, C4 grass expansion and Sahara aridification toward northern hemisphere ephemeral glaciation at the uppermost of Miocene [1][3][4]. The Miocene climatic dynamics also involved changes in sea level and ocean circulation [2][5].

The western equatorial Pacific (WEP) has been a prominent region in the world’s ocean since the occurrence of an accumulation of warm surface water with deep thermocline (figure 1b) known as western Pacific warm pool (WPWP)[6]. The waxing and waning of the WPWP may contribute large impact to regional and global climate. The warm pool has established since the Miocene and was influenced by constriction of Indonesian Seaway and modulated by sea level fluctuation [7][8][9].

Calcareous nannoplankton, a group of calcite secreting phytoplankton including coccolithophores and Discoaster, is widely distributed in great abundance in world ocean surface as well as in pelagic sediments as nannofossil. Their distribution is sensitive to ecological factors such as light intensity,
nutrients, temperature and salinity thus their assemblages in the sediment can reflect the surface ocean condition [10]. The excellence of using calcareous nannofossil as a tool for paleoceanographic reconstruction have been demonstrated by numerous studies in various locations and stratigraphic ranges [11][12][13].

In this study, we reconstruct the changes in surface water stratification of the western equatorial Pacific during the Miocene, a period when the earth’s climate was dynamics. Our study relies on changes in *Reticulofenestra* size variation, *Discostear* relative abundance and nannofossil accumulation rate (NAR) at Ocean Drilling Program (ODP) Hole 806B (figure 1). We also compare our result to Site 806 planktonic and global benthic δ¹⁸O published by previous studies to clarify calcareous nannofossil respond to changing ocean and climate.

**Figure 1.** (a) Location of ODP Site 806, present day oceanographic setting along equatorial Pacific and (b) vertical temperature distribution along the equatorial Pacific with 20°C isotherm [14].

2. Modern oceanographic setting

As illustrated in figure 1a, today’s western equatorial Pacific oceanography is majorly influenced by westward flowing currents, South Equatorial Current (SEC) and North Equatorial Current (NEC) driven by easterly trade winds [15]. Underlying the SEC, there is equatorial undercurrent (EUC) that flow eastward at the depth of 150–200 m. The region is also associated with southwest equatorial Pacific boundary currents including New Ireland Coastal Current (NICU), New Guinea Coastal Undercurrent (NGCUC) and Gulf of Papua Current (GPC) [15].

The western Pacific warm pool (WPWP) is a body of warm surface water with a deep thermocline occupying most of the tropical to subtropical region of the western Pacific and Indian oceans [6]. The average annual temperature of the WPWP is >28°C (figure 1) and become the major heat source for higher latitude region [6]. The WPWP is formed by pilling up of warm surface water delivered by westward flowing equatorial currents and creates asymmetric thermocline structure across the equatorial Pacific, which is deeper in the west.

3. Calcareous nannofossil as proxy in paleoceanography

Present day center of WPWP is characterized by low productivity of calcareous nannoplankton with dominance of lower photic taxa such as *Florisphaera profunda* [16]. Whilst, the upwelling front in
WEP is high in nannoplankton productivity with abundant omnipresent species such as *Gephyrocapsa oceanica* and *Emiliania huxleyi* [16]. However, those species had not existed yet during the Miocene.

Sato and Chiyonobu [11] investigated relationship between Cenozoic ocean stratification, nutrient and sea surface temperature and calcareous nannofossil assemblages. They found that coccolith maximum size and *Discoaster* relative abundance have a positive correlation from Eocene to Pliocene interval. In upwelling region, where the surface water is rich in nutrient, coccolith productivity is high, lower photic zone taxa such as *Florisphaera profunda* and *Discoaster* are less abundant and small size of coccolith specimens is dominant. In contrast, well stratified oligotrophic condition was characterized by low coccolith productivity, domination of large size coccolith and high abundance of *Discoaster*. Schueth and Bralower [13] also mentioned that in the early Pleistocene, *Discoaster* thrived near the nutricline in the lower-photic zone of warm, stratified water masses. They added that the consequent shoaling of the nutricline associated with decrease in surface water temperature and increase in climatic variability contributed to the extinction of *Discoaster* as it reduced their living habitat significantly. Imai et al. [12] suggested that the co-occurrence of high nannofossil accumulation rate (NAR), low *Discoaster* abundance and presence of small *Reticulofenestra* may indicate a eutrophic surface water with shallow nutricline and thermocline.

4. Material and methods

This study used 107 sediment core samples recovered by Ocean Drilling Program (ODP) Leg 130 from Site 806 Hole B (00°19.1’ N, 159°21.7’ E) located in northeast flank of Ontong Java Plateau at 2520 m water depth, ranging from depth of 130.26–598.26 m below the seafloor. The lithology consists of nannofossil oozes and foraminifer nannofossil ooze at the upper part which gradually changed into nannofossil chalks and foraminifer nannofossil chalks toward the bottom part [17].

Samples were prepared into slide through suspension preparation technique for quantitative analysis following Koch and Young [18]. First, samples were powdered, weighted at 0.04 g by using microbalance and placed in a beaker glass. Distilled water (50 ml) was added by using burette pipe to dilute the powder into solution. By using a micropipette, 0.5 ml of suspension was dropped on an 18 mm cover glass and dried on a hotplate at temperature of 40°C for two hours. After the water had been completely vaporized, the cover glass was mounted to microscope slide using optical mounting medium and dried under the UV light.

Nannofossil slides were examined under an Olympus BX53-P polarized light microscope with an oil-immersion objective lens at a magnification of 1000×. Counts of 200 specimens were identified in straight transects across the slide to determine stratigraphic distribution and relative abundance. The coccolith sizes of *Reticulofenestra* were encountered during these counts and classified based on its size. Extended counting was carried out to clarify the occurrence of rare key species. Unit area counting of 10µm×18mm were done to obtain absolute abundance of nannofossil specimens.

Nannofossil accumulation rates (NAR) were calculated by following Flores and Sierro [19] as

\[ \text{NAR} = N \times d \times S \]  

where NAR is the nannofossil accumulation rate (specimens/cm²/ky); N is the number of specimens per gram of dry sediment; d is the estimated dry density (g/cm³) and S is the linear sedimentation rate (cm/ky). Whilst, nannofossil abundance in each sample were calculated as

\[ N = n \times A \times V/\alpha \times g \times v \]

where N is the number of specimens per gram of dry sediment; n the number of nannofossils counted in a scanned area; A is cover glass area (18 mm × 18 mm); V is volume of water added to the dry sediment in the beaker (50 ml), a is area of specimen counting (10µm × 18mm); g is the dry sediment weight (~0.04 g), and v is volume of mixture dropped with the micropipette (0.5 ml).
5. Results

5.1. Biostratigraphy and numerical age model
Nannofossil assemblages in the Miocene ODP Hole 806B sediments are dominated by species belong to genus Reticulofenestra. Coccolithus pelagicus and Sphenolithus abies are found throughout the section whereas Cyclicargolithus floridanus, Discoaster deflandrei, Sphenolithus heteromorphus and Sphenolithus abies are common to abundant in the lower part. Eight biodatums have been identified to divide the studied interval into nine Martini [20] standard biozones ranging from NN3 to NN12. An additional datums, LCO of Reticulofenestra pseudoumbilicus, are also used. By assigning the nannofossil biodatum numerical ages compiled by Anthonissen and Ogg [21], the studied age interval ranges from 17.95 to 5.59 Ma (Table 1), which correlate to period of early to late Miocene. Based on age to sample depth scatter plot, sedimentary rates varied between 2.45 and 4.54 cm/ky with a gradual increasing trend throughout the Miocene (figure 2).

### Table 1. Calcareous nannofossil datum and ages in ODP Hole 806B. FO: first occurrence; LO: last occurrence; LCO: last common occurrence.

| Nannofossil datums         | Age (Ma) | Depth (mbsf)  | error (m) |
|----------------------------|----------|---------------|-----------|
| LO D.quinqueramus          | 5.59     | 164.76/168.26 | 1.75      |
| FO D. berggrenii           | 8.29     | 286.76/291.26 | 2.25      |
| LCO R. pseudoumbilicus     | 8.79     | 310.26/312.26 | 1.00      |
| LO D. hamatus              | 9.53     | 331.46/335.96 | 2.25      |
| FO D. hamatus              | 10.55    | 363.56/366.56 | 1.50      |
| FO C.coalitus              | 10.89    | 374.76/378.46 | 1.85      |
| LO C. floridanus           | 13.28    | 464.76/465.36 | 0.30      |
| LO S. heteromorphus        | 13.53    | 469.86/473.56 | 1.85      |
| LCO S. belemnos            | 17.95    | 578.86/581.06 | 1.10      |

![Sedimentation rate at ODP Hole 806B during the Miocene.](image)

5.2. Reticulofenestra size variation
Throughout the Miocene, Reticulofenestra size varies between <2 µm to 11 µm (figure 3a). There are four gradual increases in Reticulofenestra size and terminated by the sudden decrease. The bottom part of studied interval prior to 14 Ma is characterized by Reticulofenestra size varied from <2-9 µm with...
two gradual increasing patterns in size mode. At 14 Ma, the size mode suddenly decreased then followed by rapid increase in *Reticulofenestra* maximum and modal size. During the interval from 13.2 to 9 Ma, there was an appearance of very large *Reticulofenestra* with size larger than 9 µm. This interval was interrupted by dramatic decrease in *Reticulofenestra* maximum size at 9 Ma. This event was followed by bimodal trend and sudden drops of maximum size at the uppermost part of studied interval.

![Figure 3](image_url)

**Figure 3.** (a) *Reticulofenestra* size variation, (b) *Discoaster* relative abundance, (c) Nannofossil accumulation rate (NAR) and estimated sea surface condition.
5.3. Discoaster relative abundance
The relative abundance of Discoaster varies throughout the studied interval, ranging from 0% to 41% (figure 3b). Prior to 14 Ma, the genus was relatively very abundant with average of 17.16%. The abundance significantly decreased after 14 Ma then gradually rise after 13.2 Ma. Sudden decrease in Discoaster relative abundance occurred again at 9 Ma, followed by interval of low abundance of Discoaster with average of 3.39%.

5.4. Nannofossil accumulation rates
Nannofossil accumulation rate at ODP Hole 806B fluctuated between 1.0 and 23.3 × 10^9 specimens/cm^2/ky during the studied interval (figure 3c). Prior to 14 Ma, nannofossil accumulation rate was averagely low, about 2.6 × 10^9 specimens/cm^2/ky. A slight increase occurred during 14–9 Ma with rates of 3.9 × 10^9 specimens/cm^2/ky in average. The accumulation rates dramatically doubled after 9 Ma with average of 7.5 × 10^9 specimens/cm^2/ky.

6. Discussion
6.1. The relationships among Reticulofenestra size variation, Discoaster relative abundance and nannofossil accumulation rate (NAR)

There are coincidences in change of Reticulofenestra size variation, Discoaster relative abundance and nannofossil accumulation rate during the studied interval in the WEP (figure 3). At 14 Ma, significant decline of Discoaster abundance occurred simultaneously with the decrease in Reticulofenestra modal size and slight increase in NAR. The dramatic drop of Reticulofenestra modal and maximum size at 9 Ma also coincided with increasing NAR and reduced Discoaster percentage. Previous studies also suggested that there is a positive correlation between Discoaster relative abundance and Reticulofenestra size variation during the Miocene [11][12]. The abundance of Discoaster decreased as the size of Reticulofenestra became smaller and vice versa. Imai et al. [12] added that decline in both parameters coincide with rise in NAR. This event marked a collapse of ocean stratification and higher surface productivity.

Changes in Reticulofenestra size variation, Discoaster relative abundance and nannofossil accumulation rates that occurred simultaneously indicate that the Miocene nannofossil assemblages in the WEP can be divided into three intervals (Fig 3). Interval 18–14 Ma is characterized by high abundance of Discoaster and large maximum size of Reticulofenestra and low NAR. Interval 14–9 Ma initiated with significant decrease in Discoaster abundance, smaller Reticulofenestra modal size and slight increase in NAR. This interval was marked by rapid growth in Reticulofenestra size toward the appearance of very large Reticulofenestra and gradual increase in Discoaster relative abundance. Whereas interval 9–6 Ma started with the dramatic decrease in Reticulofenestra size, decline in Discoaster abundance and rise in NAR. Bimodal pattern of Reticulofenestra size occurred within this interval. Variation in Reticulofenestra size, Discoaster relative abundance and NAR may suggest that sea surface of the WEP was dynamic during the Miocene.

6.2. Sea surface dynamics in the Western Equatorial Pacific during Miocene

During early to middle Miocene (18–14 Ma), photic zone of WEP was dominated by species belong to genus Discoaster. Prior to extinction in the early Pleistocene, Discoaster lived near the nutricline in the lower-photic zone of warm, stratified water masses, a similar habitat as the extant genus Florisphaera [13]. The lower photic species Florisphaera profunda dominates modern sea surface in the WPWP where SST is high, thermocline is deep and nutrient is low [16]. Therefore, the high abundance of Discoaster during the interval may suggest that ocean surface was warm and stratified with deep thermocline. Depleted nutrient in upper photic water may limit the productivity of nannoplankton and consequently decrease nannofossil accumulation on the seafloor.
The warm surface condition in the WEP coincided with the global warm period of Middle Miocene Climatic Optimum (MMCO) that peaked between 17 and 15 Ma [1][2], as shown in figure 4. During the interval, the thermocline was deep due to the absence of Equatorial Undercurrent (EUC) and weakened Equatorial Countercurrent (ECC), as both Indonesian and Central American Seaways remained open to surface circulation [7]. In addition, there was a shoaling of calcite compensation depth and enhanced dissolution throughout the water column during that might contribute to low accumulation rate of calcareous nannofossil in the western equatorial Pacific during early to middle Miocene [2][22].

Figure 4. Comparison among (a) nannofossil assemblages in this study, (b) Site 806 mixed layer (Globigerinoides sacculifer and Dentoglobigerina altispira) and thermocline (Globorotalia menardii, Globorotalia fohsi and Dentoglobigerina altispira) planktic foraminifera δ18O [9][14] and (c) global benthic δ18O [1].

A remarkable event occurred at 14 Ma when the abundance of Discoaster significantly declined that indicate WEP surface water shifted to cooler temperature, higher nutrient content and shoaling of
the thermocline (figure 3). This event likely coincided with termination of MMCO by major expansion of East Antarctic ice sheet (EAIS) that occurred between 14.7 and 13.7 Ma (figure 4c) marked by sudden increase in global benthic δ18O value [1][2]. The ice sheet expansion was also linked to pronounced equatorial upwelling reflected by high accumulation rate of opal produced by diatoms [2]. Diatoms is considered as opportunistic organisms with maximum nutrient uptake that may outcompete coccolithophores in extremely high nutrient condition [23]. This possibly become a reason why the significant decrease in Discoaster abundance was only accompanied with a modest increase in nannofossil accumulation rates.

The ocean surface warmed and the thermocline started to develop by 13.2 Ma as characterized by appearance of very large Reticulofenestra and gradual increase of Discoaster relative abundance (figure 3a). Deepening of thermocline during 10.6–9.6 Ma was also indicated by decrease in mixed layer–upper thermocline δ18O gradient (figure 3b) from planktonic foraminifera in the study site [9]. However, figure 3c exhibits an increase of global benthic δ18O value to suggest that the global climate was in cooling period [1]. It may indicate that the sea surface warming in the western equatorial Pacific was likely affected by regional change.

There was tectonic reorganization in Banda area accompanied by major sea level fall that reduced warm water transfer from Pacific to Indian Ocean through Indonesian seaway [5][8]. The restriction led into piling up of warm water mass in the WEP forming WPWP [9][24]. The waxing of warm pool was associated with the development of Equatorial Undercurrent (EUC) delivering high nutrient in deeper water eastward [9]. Depleted nutrient during the occurrence of WPWP may contribute to low nannofossil productivity as reflected by NAR record in our study site.

Another dramatical shift occurred in the late Miocene at 9 Ma as abrupt domination of small sized Reticulofenestra, decrease in Discoaster relative assemblage and rapid increase in nannofossil accumulation rates that may indicate cooler surface water, nutrient increase and collapse of surface stratification (figure 3a). Previous studies also reported SST cooling and thermocline shoaling at Site 806B to indicate the waning of WPWP [9][25]. Disappearance of WPWP with decrease in east-west SST and thermocline gradient along equatorial Pacific is similar to present day El Niño condition [9][25].

At the same time, abrupt dominance of small size Reticulofenestra also occurred in the eastern equatorial Pacific where the SST was warm and thermocline deep during the El Niño-like condition [26]. It may suggest that variation in Reticulofenestra size does not directly correspond to fluctuation in SST and nutrient content. Previous study suggested that the appearance of small Reticulofenestra interval during the late Miocene was influenced by external forcing rather than temperature and nutrient control [26]. Nevertheless, the decrease of Discoaster and rise in NAR likely correspond to SST cooling, thermocline shoaling and nutrient increase as WPWP disappeared during the late Miocene (figure 3b).

Increasing NAR coincided with increased carbonate mass accumulation rates, suggesting that productivity of nanoplankton played a major role in carbonate deposition in deep sea floor [9]. Intensification of monsoon due to Himalayan uplift during 9–8 Ma [27] has been suggested to increase precipitation and river runoff in New Guinea and increased supply of nutrient into ocean in WPWP region [28]. Weakened EUC during El Niño-like condition may also contribute to high productivity in WEP [9].

A modest decrease in NAR and increase of Discoaster abundance occurred during 7–6 Ma. Large Reticulofenestra also appeared in this short interval. It may suggest surface warming and thermocline formation in the WEP. This condition was also evidenced by increase in mixed layer – upper thermocline planktic foraminifera δ18O gradient and considered as a brief return of WPWP during the latest Miocene [9](figure 3b).

7. Conclusions
We have reconstructed early to late Miocene sea surface condition at ODP Hole 806B in the western equatorial Pacific based on Reticulofenestra size variation, Discoaster relative abundance and
nannofossil accumulation rate (NAR). Overall, *Discoaster* abundance decreased whilst NAR increased throughout the studied interval. Coincidences in decrease of *Discoaster* relative abundance, reduce of *Reticulofenestra* coccolith size and rise of NAR occurred at 14 and 9 Ma.

During early to middle Miocene, between 18 and 14 Ma, the surface water was warm and depleted in nutrient as characterized by abundant *Discoaster*, large *Reticulofenestra* and very low NAR. This warm condition is associated with Middle Miocene Climatic Optimum. Significant decrease in *Discoaster* abundance at 14 Ma suggest that sea surface cooled, nutrient increased and thermocline during the East Antarctic Ice Sheet Expansion (EAIE). The appearance of very large *Reticulofenestra* and gradual increase of *Discoaster* abundance after 13.2 Ma suggest SST warming and thermocline deepening as the WPWP began to establish. During the late Miocene at 9 Ma, there was a dramatic rise in NAR and abrupt decrease in *Reticulofenestra* size and *Discoaster* abundance indicating collapse of ocean stratification. The occurrence of cool and nutrient enriched surface water coincided with the onset of Asian Monsoon Intensification. Increasing *Discoaster* abundance and decreasing NAR between 7 and 6 Ma suggest that warm surface water and deep thermocline occurred as a brief return of the WPWP in the latest Miocene.

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