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Cenozoic Basin History of the Cepu Area Based on Calcareous Nannofossil Biostratigraphy in Eastern Java, Indonesia

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Abstract*— We studied in detail the nannofossil biostratigraphy of Lasem-1, Kalijati-1, Kedungtuban-1, and Ngimbang-1 wells located in Cepu Area, Eastern Java, Indonesia. Our result indicates that a total of four unconformities are traceable in the Oligocene to Pliocene sequence in this area. Unconformity 1 is situated in the Oligocene/early Miocene boundary, which is traceable in all wells, is characterized by the missing interval from NN1 to NN3 zone of the early Miocene. Unconformity 2 is correlated to the early middle Miocene, which is found in Kedungtuban-1 well. Nannofossil zone NN6 is not present in this well. Unconformity 3, which is characterized by missing the interval NN8 of the early late Miocene, is traceable to Kedungtuban-1, Dander-1, and Ngimbang-1 wells. Among the wells, the sediments from NN6 to NN8 is not present in Ngimbang-1 well. Unconformity 4, which is the biggest unconformity found in this area, is situated in the lower Pliocene base. In this area, the lower Pliocene NN14 sediment is distributed above the unconformity 4. The time gap of unconformity 4 is the biggest in Lasem-1 and Kalijati-1, located in the western area. The interval, NN6 to NN13 of middle Miocene to lowest Pliocene, is missing in Lasem-1 well, and the interval NN5 to NN13 (part) is not distributed in Kalijati-1 well. These results indicate that the LST (Low Stand Systems Tract) above the unconformities 1 and 2 are situated in the center of the studied area (Kedungtuban-1 and Dander-1 wells), and LST above unconformity 3 is found in the eastern area located in out of the sedimentary basin (Ngimbang-1 well). In contrast with LSTs of the Miocene, the location of LST above unconformity 4 moves to the western area. The thickest sandstones, which are reservoir rocks of this oil field, is correlated to the early Pliocene LST and Transgressive Systems Tract above the unconformity 4.

***Keywords*— Biostratigraphy; calcareous nannofossil; East Java basin; cenozoic.**

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I. INTRODUCTION

The East Java Basin is one of the Indonesia prolific petroleum sedimentary basins. The geology of this area, which is mainly composed of Paleogene to Neogene Systems, has been studied mainly for clarifying the petroleum system [1]–[3]. Although several biostratigraphic frameworks have been studied based on larger and smaller foraminifera [4]–[6], many bio- and chronostratigraphic problems remain in this area. For example, some unconformities were found in the sequence of Paleogene to Neogene, but the precise age correlation and the scale of the time gap are not clear yet. These problems strongly influence research on the reconstruction of the Petroleum system in the basin.

Recently, Sato *et al.* [7] published a new opinion on the chronostratigraphy of the basin based on calcareous nannofossil biostratigraphy. In the previous report, the stratigraphy of DDR-1 well, located in the East Java basin, had been correlated to the Eocene to Quaternary without unconformities (PERTAMINA, 1982). Nobody raised questions about this correlation and geological framework. In such a situation, Sato *et al.* [7] examined detailed calcareous nannofossil biostratigraphy of DDR-1 well and detected four big unconformities from the Miocene to Pliocene sequence. They also showed that the reservoir sandstones were formed just above the unconformity. This result means that problems remained regarding the detailed bio-chronostratigraphy of the basin and should be clarified from high-quality biostratigraphy.

The Cepu area is located in East Java, Northern Slope tectonic provinces [3] (Fig. 1). The sediments of the basin are composed of the Eocene to Pliocene Series [1]. Although many research papers have been published on the geological framework of this area, some confusing lithostratigraphic units, especially “Formation” and “Member” remain between the papers [3]. For this reason, we tentatively use the “Formation” name only in figures 3,4,5,6, according to the PERTAMINA report.

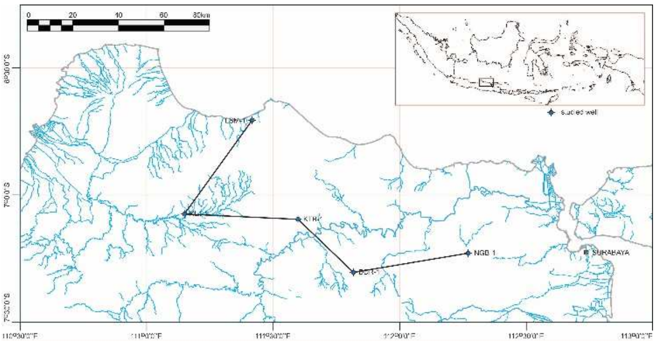

Fig. 1 Location map of the study area and exploration wells.

The Oligocene to early Miocene is composed of the Ngimbang, Kujung, and Prupuh Formations, which consist of limestone. The early Miocene series, which are characterized by limestone, marl, and siltstone, are Tuban and Tawun Formations. The Tuban Formation, mainly composed of siliciclastic rock of incised valley fill, is interpreted as lowstand systems tract [3]. The middle Miocene to Pliocene series is Ngrayong, Bulu, Wonocolo, Ledok, and Mundu Formations. The Bulu Formation is characterized by limestone. Wonocolo and Ledok Formations are respectively composed of calcareous mudstone and sandy mudstone [1]. Mundu Formation, which is poor in macrofossil, consists of extremely rich microfossil sandstone as Globigerina ooze [3].

We studied in detail the Cenozoic calcareous nannofossil biostratigraphy of the exploration wells located in the Cepu area, Eastern Java, Indonesia. Based on the nannofossil biostratigraphy, we determine and revise the geological age of the sequences of the wells to make firm the time scale and characteristics of detected unconformities. From these facts, we clarify the relationship between unconformities and global climatic events. Finally, we summarize the geological framework and the basinal history of the Cepu Area.

II. MATERIAL AND METHOD

A total of four wells located in the Cepu area are studied (Fig. 1). Additionally, we use the nannofossil data of Dander-1 well [7] for discussion in this study. Among them, Kalijati-1, Kedungtuban-1, Dander-1, and Ngimbang-1 wells are situated in East-West direction. Lasem-1 and Ngimbang-1 wells are located on the edge of the sedimentary basin.

Cutting samples and a few core samples are used for the preparation of calcareous nannofossils. The samples are collected about a 20m interval. The nannofossil preparation is made by the smear slide method. Small tips of cutting samples from studied wells are picked up and crushed for making powder using mortar. A small amount of sample powder is placed on the cover glass. A little amount of water is dropped on the powder and spread over the cover glass using the toothpick. After dry on the hot plate, drop the mounting adhesive on the sliding glass and put the cover glass. Put the preparation into the ultraviolet lightbox for about five minutes, then complete.

Zeiss Axio-imager is used for the identification of nannofossils. For identification, we used 1200X and 1600x magnification and observed under the polarizing light. The study is limited to qualitative analysis. All species found in the preparation are listed, and “first” and “last” occurrence datum of key species is carefully identified. The reworked specimens are also checked (open circle in figures).

Nannofossil biostratigraphy and datum used in this study are shown in Fig. 2 [8], [9]. Nannofossil datum indicated by 1 to 22 in Fig. 2, is useful for correlation and determination of the geological age in this area. Based on the characteristics, we carefully checked and identified the horizon of nannofossil datum in the sequences for correlation of the wells and detecting the unconformities in this study.

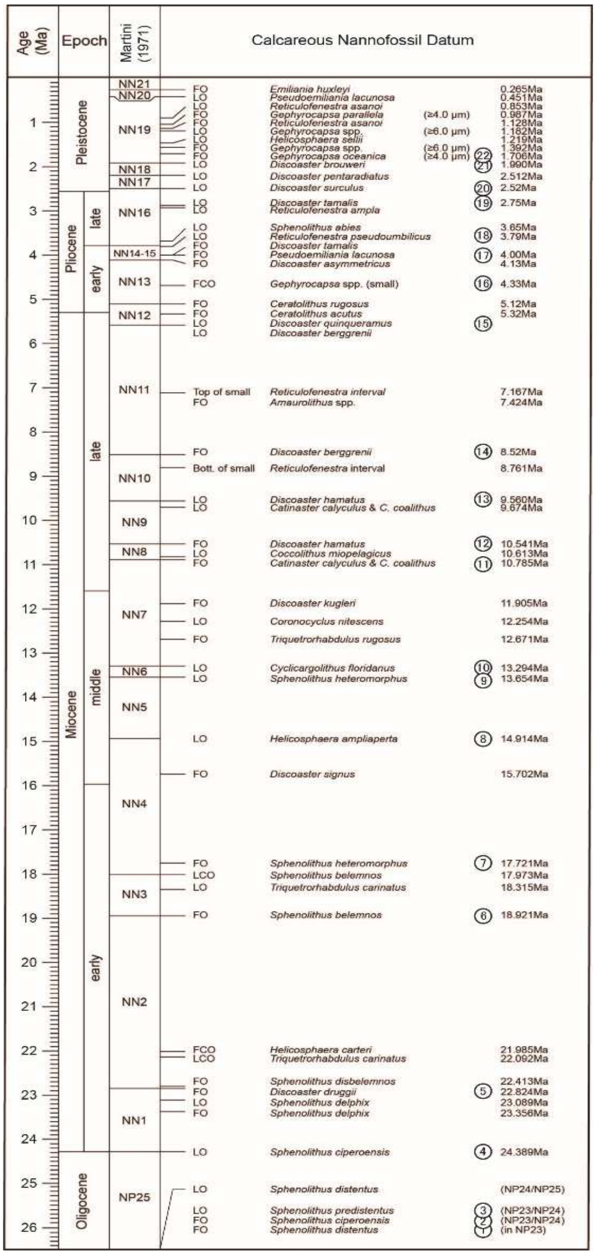

Fig. 2 Latest Oligocene to recent Calcareous Nannofossil datum used in this study [8], [9]. The encircled number from 1 to 22 in the figure indicates the datum used for correlation in this study.

III. Result and Discussion

A. *Calcareous Nannofossil Biostratigraphy*

Calcareous nannofossils abundantly occur in samples except for some limy and muddy intervals. Although the specimens are moderate to well preserved throughout the section, some specimens are overgrowth. Reworked specimens from the early Miocene series are sometimes found in the Pliocene series.

Lasem-1: The lithology of the sequence is characterized by limestone in lower depth from 2050m down to 2950m (total depth). Although the sandstone facies, which is identified as Ngrayong Formation, is present between 850m and 1100m, a total of the sequence is characterized by siltstone facies with marl.

Nannofossil assemblages are characterized by the abundant occurrence of *Reticulofenestra* spp. (Fig. 3). The lower photic zone species, *Discoaster*, occurs commonly to rare. The key species listed in Fig. 2 are continuously found in the sequence. Top of *Reticulofenestra pseudoumbilicus,* which last occurs in the early and late Pliocene boundary (NN15/NN16 boundary of Martini zonation), is situated in 620m/640m. *Pseudoemiliania lacunosa* first occurs in the late early Pliocene, is found from 1100m to the top. The abundant occurrence of small *Gephyrocapsa,* which indicates the early Pliocene to Quaternary, is also present in and above samples of 1100m. The samples from 1120m to 1160m are barren. The sequence from 1180m to 1320m is characterized by the occurrence of the key species of middle Miocene NN5 Zone, *Sphenolithus heteromorphus,* and *Cyclicargolithus floridanus*. The top of *Helicosphaera ampliaperta,* which defines the NN4/NN5 boundary of the early/middle Miocene boundary, is situated in 1340m. The interval from 1420m to 2020m is rarely the occurrence of nannofossils. Samples from 2040m to 2610m, which are composed of limestone, are barren nannofossil. The interval from 2630m to 2650m, which consists of siltstone interbedded in Limestone facies, is characterized by *Sphenolithus ciperoensis,* which indicates the Oligocene NP24 to NP25 zone. *Sphenolithus distentus* last appeared in NP24/NP25 boundary, is not found in this section.

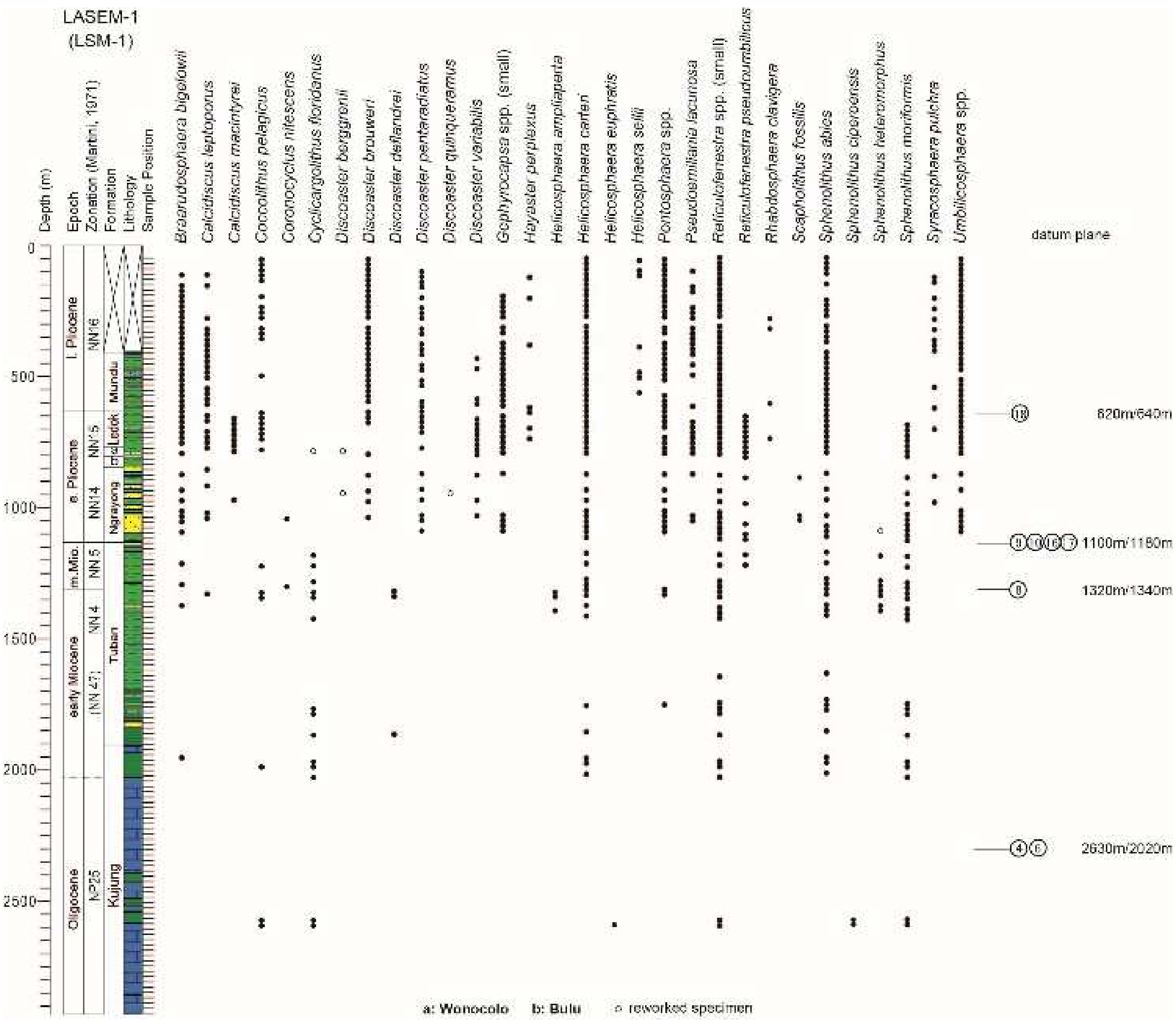

Fig. 3 Calcareous Nannofossil biostratigraphy of Lasem-1 well.

From these facts, the sequence of this well is correlated as follows (Fig. 3). From top to 620m/640m is correlated to the late Pliocene of NN16 based on the presence of Datum 18 (listed in Fig. 2). The section from 620m/640m to 1100m/1180m is in the early Pliocene of NN14 to NN15. Datum 9, 10, 16, 17 indicate the age from the middle Miocene to early Pliocene (NN6 to NN14) are present in 1100m/1180m. This evidence indicates that the big unconformity between the middle Miocene to early Pliocene is present in 1100m/1180m. The sequence from 1100m/1180 down to 2630m/2020m is correlated to early Miocene of NN4 to NN5 based on datum 7 and 8 in 1400m/1420m and 1320m/1340m, respectively. The sequence below 2020m is correlated to the late Oligocene of NP25, based on the presence of Datum 4 to 6 at 2630m/2020m. These results show that the sequence of the latest Oligocene to early Miocene is missing in this well.

Kalijati-1: Nannofossil assemblages are studied using about 20m interval cutting samples from 50m down to 2710m. The lithology of the sequence from top to 2500m is mainly composed of siltstone. In the middle part of the sequence from 900m to 1600m is characterized by interbedding of limestone and sandstone. Furthermore, below 2500m, the lithology of the sequence is limestone with some siltstone layers.

Although nannofossils are rare to barren in the interval between 1950m and 2530m, well-preserved nannofossils abundantly occur in the well (Fig. 4). The assemblages are characterized by the abundant occurrence of small *Reticulofenestra*. Lower photic zone species, *Discoaster* rarely occurred/common in the section.

Reticulofenestra pseudoumbilicus, which last appeared in the NN15/NN16 boundary of the early and late Pliocene boundary, is found in the top sample. The bottom of *Pseudoemiliania lacunosa,* which is situated in the latest early Pliocene in NN15, is present in 790m. The depth between 1370m and 1390m is characterized by the presence of four data between middle Miocene to early Pliocene, such as the bottom of common occurrence small *Gephyrocapsa* (NN13), top of *Cyclicargolithus floridanus* (NN6/NN7 boundary), *Sphenolithus heteromorphus* (NN5/NN6 boundary), and of *Helicosphaera ampliaperta* (NN4/NN5 boundary). The depth 2630m/2650m is characterized by the presence of the first occurrence of *Sphenolithus heteromorphus* situated in lower NN4 and the last occurrence of Sphenolithus ciperoensis, which indicates the top of the Oligocene, NP25.

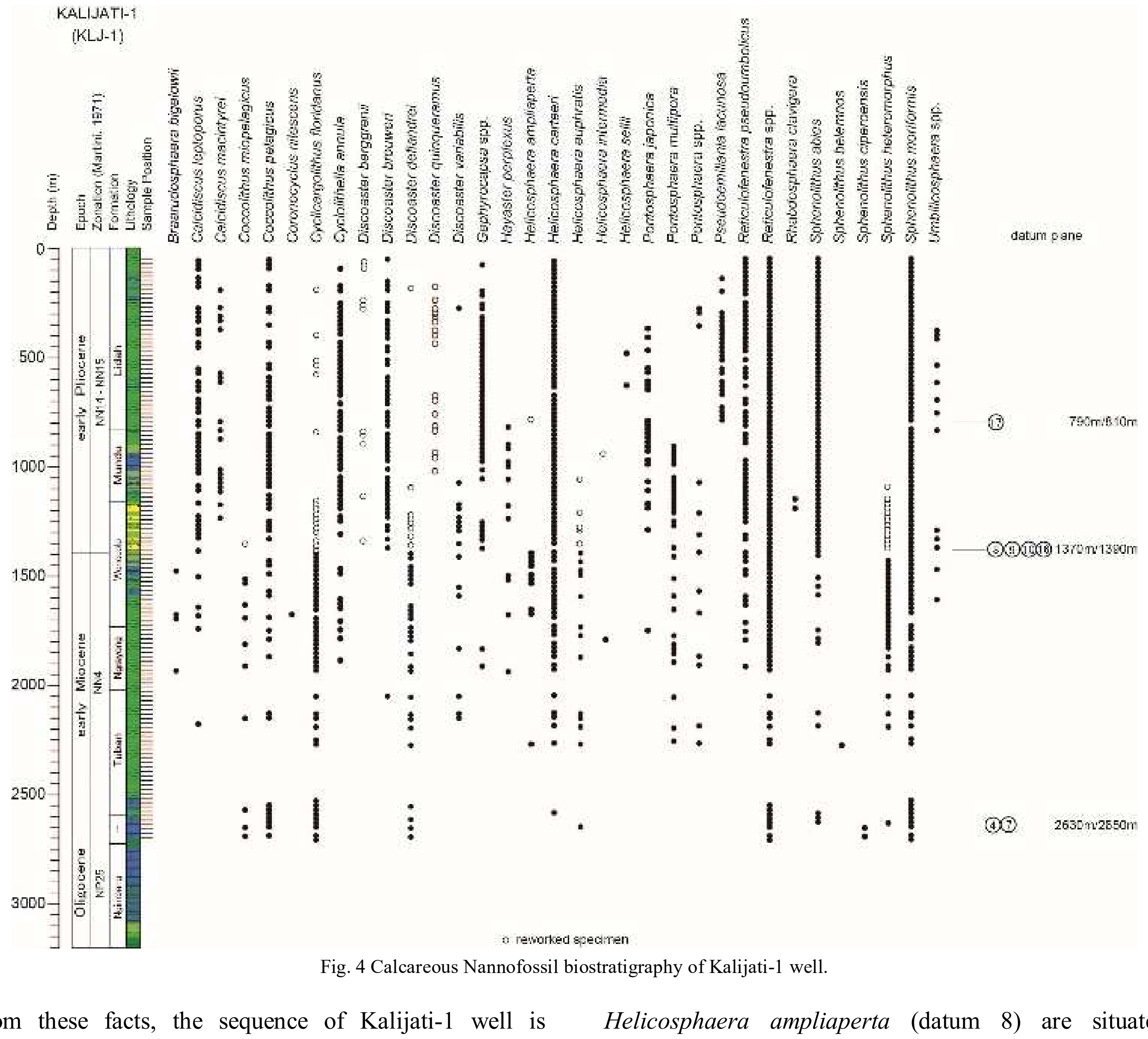

Fig. 4 Calcareous Nannofossil biostratigraphy of Kalijati-1 well.

From these facts, the sequence of Kalijati-1 well is correlated as follows (Fig. 4). The section from top to 1370m is the early Pliocene of NN14 to NN15. The first occurrence of *Pseudoemiliania lacunosa,* which is situated in upper NN15 (datum 17), is present in 790m/810m. Four datum planes are shown by the frequent occurrence of *Gephyrocapsa* (datum 16), last occurrences of *Cyclicargolithus floridanus* (datum 8), *Sphenolithus heteromorphus* (datum 9), and *Helicosphaera ampliaperta* (datum 8) are situated in 1370m/1390m. This evidence indicates that the unconformity between late early Miocene and early Pliocene (NN5 to NN13) is present on this horizon. The early Miocene datum, the first occurrence of *Sphenolithus heteromorphus* (datum 7) and the Oligocene/Miocene boundary datum, last occurrence of *Sphenolithus ciperoensis* (datum 4) are present in the same horizon as 2630m/2650m. The early Miocene unconformity from NN1 to NN3 is shown in the depth 2630m/2650m.

The additional characteristics are present in the sequence of this well. The samples from the early Pliocene interval from top to 1370m contain a lot of reworked specimens from lower Miocene to upper Miocene, such as *Cyclicargolithus floridanus*, *Discoaster berggrenii*, *Discoaster quinqueramus*, *Helicoshpaera ampliaperta*, *H. euphratis*, and *Sphenolithus heteromorphus*. This evidence indicates that the lower Miocene to upper Miocene sediments distributed in this area were outcropped in the early Pliocene.

Kedungtuban-1: The 20m interval samples from 50m to 3210m are examined in this well. Siltstone facies with marl characterize the lithology of the sequence. In the middle part, between 1050m and 1650m are present of interbedded sandstone. The lowest interval below 2760m is composed of limestone.

Although the nannofossils are found abundantly in samples, samples from the limestone facies, 2750m to 3210m, are rare to barren nannofossils (Fig. 5).

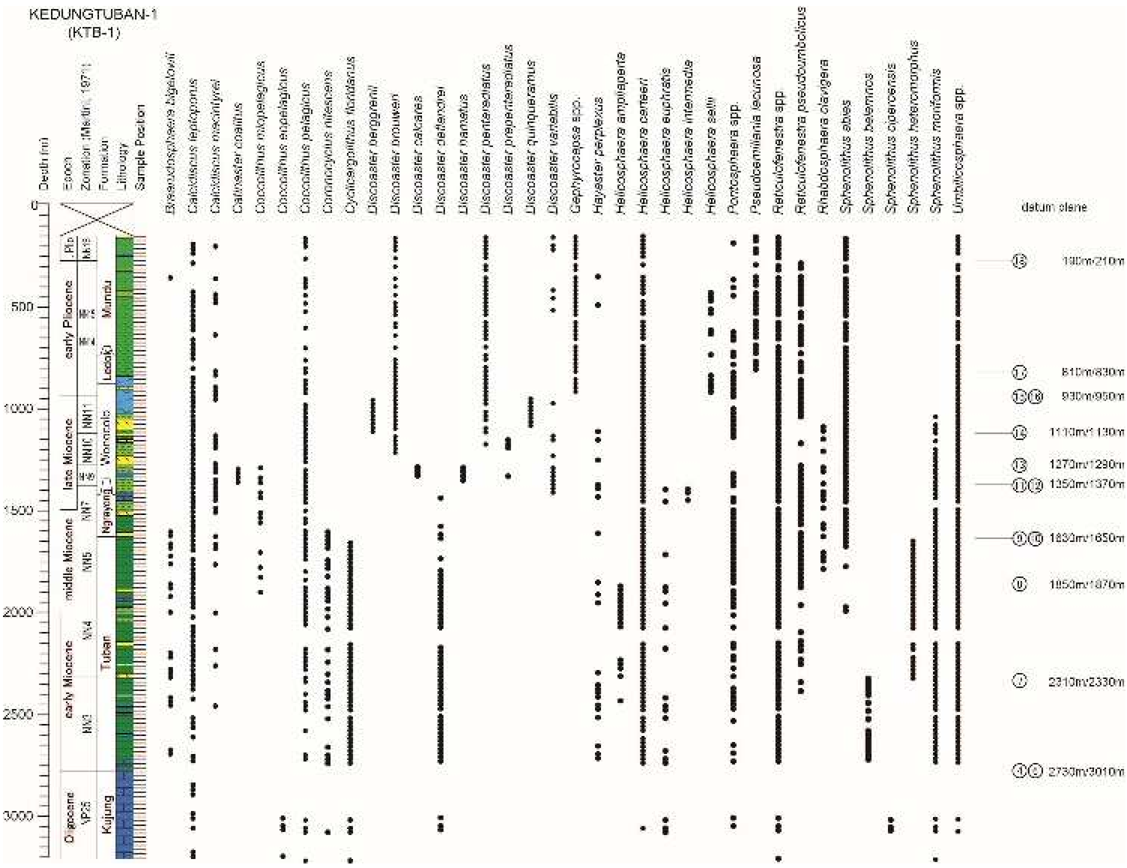

Fig. 5 Calcareous Nannofossil biostratigraphy of Kedungtuban-1 well.

Reticulofenestra pseudoumbilicus, which last appear in NN15/NN16, occur from 210m down to 2190m. The late early Pliocene to late Quaternary key species of *Pseudoemiliania lacunosa* is found in and above the depth 810m. Bottom of the frequent occurrence of *Gephyrocapsa*, generally present in early Pliocene of NN13, and top of both *Discoaster berggrenii* and *D. quinqueramus*, which indicates NN11/NN12 boundary, are recognized in 930m/950m. The bottom of *D. berggrenii,* which defines the NN10/NN11 boundary, is situated in 1110m/1130m. The occurrence of late Miocene key species, *Discoaster hamatus*, is limited in the interval between 1270m/1290m and 1350m/1370m. The first occurrence of *Catinaster coalitus*, which indicates the NN7/NN8 of late Miocene, is also situated in 1350m/1370m, which is the same depth of the first occurrence of *D. hamatus*. The top of *Cyclicargolithus floridanus* and *Sphenolithus heteromorphus*, which define the middle Miocene datum of NN6/NN7 and NN5/NN6 boundaries, are found in 1630m/1650m. The important datum for determining the age of early Miocene, the last occurrence of *Helicosphaera ampliaperta,* and the last occurrence of *Sphenolithus belemnos*, are found in 1850m/1870m and 2290m/2310m. The first occurrence of *Sphenolithus heteromorphus,* which is situated in the early Miocene, is also situated in 2310m/2330m. Nannofossil assemblages change drastically between the sequences above and below 2730m/3010m. The assemblages between 2310m and 2730m are characterized by the occurrence of *S. belemnos,* which indicates the early Miocene. On the other hand, the sequence below 3010m contains the Oligocene nannofossils, *Sphenolithus ciperoensis*. *S. distentus*, marker species of late Oligocene, is not found throughout the section.

From the facts above, the sequence of Kedungtuban-1 well is correlated as follows (Fig. 5). The interval from 50m to 190m is correlated to the NN16 late Pliocene. Top of *Reticulofenestra pseudoumbilicus* (datum 18: NN15/NN16 boundary) is situated in 190m/210m. The interval between 210m to 810m is assigned to early Pliocene. The bottom of

Pseudoemiliania lacunosa (datum 17) is present in 810m/830m. Samples 950m to 1110m and 1130m to 1270m are respectively correlated to NN11 and NN10 of the late Miocene based on the presence of datum 14. Based on the results, both datum 15 and 16 are situated in the same depth of 930m/950m. It indicates that the latest Miocene to early Pliocene NN12 to NN13 interval is missing in this well. Furthermore, datum 11 and 12, first occurrences of *Catinaster coalitus* and *Discoaster hamatus,* are present in the same depth as 1350m/1370m. This evidence also indicates that the NN8 of the late Miocene sequence is not present in this area. The last occurrences of both *Cyclicargolithus floridanus* (datum 10) and *Sphenolithus heteromorphus* (datum 9) are found in the same depth at 1630m/1650m. Datum 8, last occurrence of *Helicosphaera ampliaperta*, datum 7, the first occurrence of *S. heteromorphus*, are respectively situated in the depth 1850m/1870m, 2310m/2330m. *Sphenolithus belemnos*, which defines the NN3 of early Miocene, is found from 2290m to 2730m. Therefore, the intervals of 1650m to 1850m, 1870m to 2270m, and 2290m to 2730m are correlated to NN5, NN4, and NN3 of early to middle Miocene. Samples from 3010m down to bottom samples are NP25 of the late Oligocene. This result shows that the NN1 to NN2 of the lowest Miocene is missing in this well.

Ngimbang-1, which is located in the out of the basin, was drilled into 3260m. The upper sequence above 1420m is mainly composed of siltstone and marl with thin sandstone layers. The sediments below 1420m are characterized by dominant of marl and limestone. The siltstone and sandstone formations are also rarely found in the sequence.

Calcareous nannofossils dominantly occur in the sequence (Fig. 6).

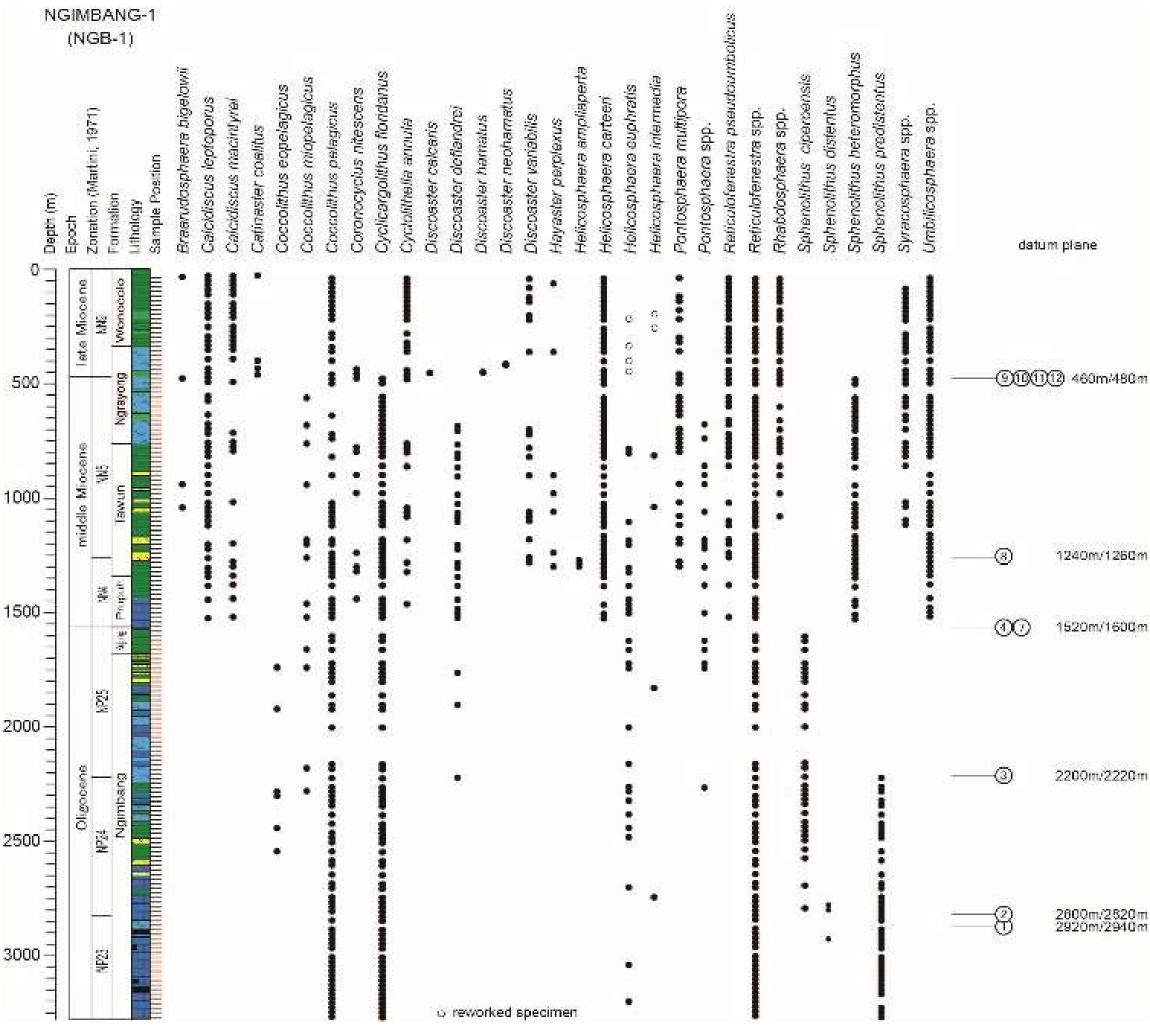

Fig. 6 Calcareous Nannofossil biostratigraphy of Ngimbang-1 well.

The sediments from 40m to 460m are characterized by the occurrences of *Catinaster coalitus* and *Discoaster hamatus,* which are respectively marker species of NN8 to NN9 of the middle Miocene. Both last occurrences of *Cyclicargolithus floridanus* (NN6/NN7) and *Sphenolithus heteromorphus* (NN5/NN6) are found in samples from 480m. The *Helicosphaera ampliaperta* last occurred in the NN4/NN5 boundary of early Miocene, is present below 1260m. The changes in nannofossil assemblages characterize the depth of 1520n/1600m. From the sequence below 1600m, the assemblages are composed of Paleogene nannofossil species. *Sphenolithus ciperoensis*, key species of NP24 to NP25, is occurred between 1600m and 2800m. *Sphenolithus predistentus,* which is last occurred in NP24 of late Oligocene, is present in and below 2220m. The first occurrence of *Sphenolithus distentus*, situated in NP23 of late Oligocene, is found in the sample from 2920m.

These results indicate that the sequence of Ngimbang -1 well is correlated as follows (Fig. 6). The sequence from top to 460m is correlated to NN9 of late Miocene. The unconformity between the middle Miocene and late Miocene is found in 460m/480m based on the presence of datum 9, 10, 11, 12. This evidence means that the interval from NN6 to NN8 is missing in this well. The sediment from 480m to 1520m is correlated to NN4 to NN5 of the latest to middle Miocene. Datum 8, which defines the NN4/NN5 boundary, is situated in 1240m/1260m. The section 1600m-3260m is correlated to NP23 to NP25 of the Oligocene. This result shows that the unconformity between Oligocene and Miocene is present in this well based on the presence of datum 4 and 7 in-depth. The Oligocene datum 1, 2, 3 are respectively found in 2920m/2940m, 2800m/2820m, 2200m/2220m.

B. Correlation

Based on the results of nannofossil biostratigraphy, we correlated these wells and Dander-1 well [7] based on nannofossil datum (Fig. 7). The lower to upper Pliocene sequence, which is included datum 17 and 18, is distributed in Lasem-1, Kalijati-1, and Kedungtuban-1 wells. Although the lower Pliocene sequence above datum 17 also found in Dander-1, the thickness is not as large as the thickness of Kedungtuban-1, Kalijati-1, and Lasem-1 located on the western side of the study area. No Pliocene and younger formations are found in Ngimbang-1 well. The big unconformity from the middle Miocene to early Pliocene is situated on the western side of the area. This unconformity is defined from datum 9 to 17 detected in the Lasem-1 and from datum 8 to 16 in Kalijati-1. The unconformity of the latest Miocene to early Pliocene is also traceable between Kedungtuban-1 and Dander-1 wells.

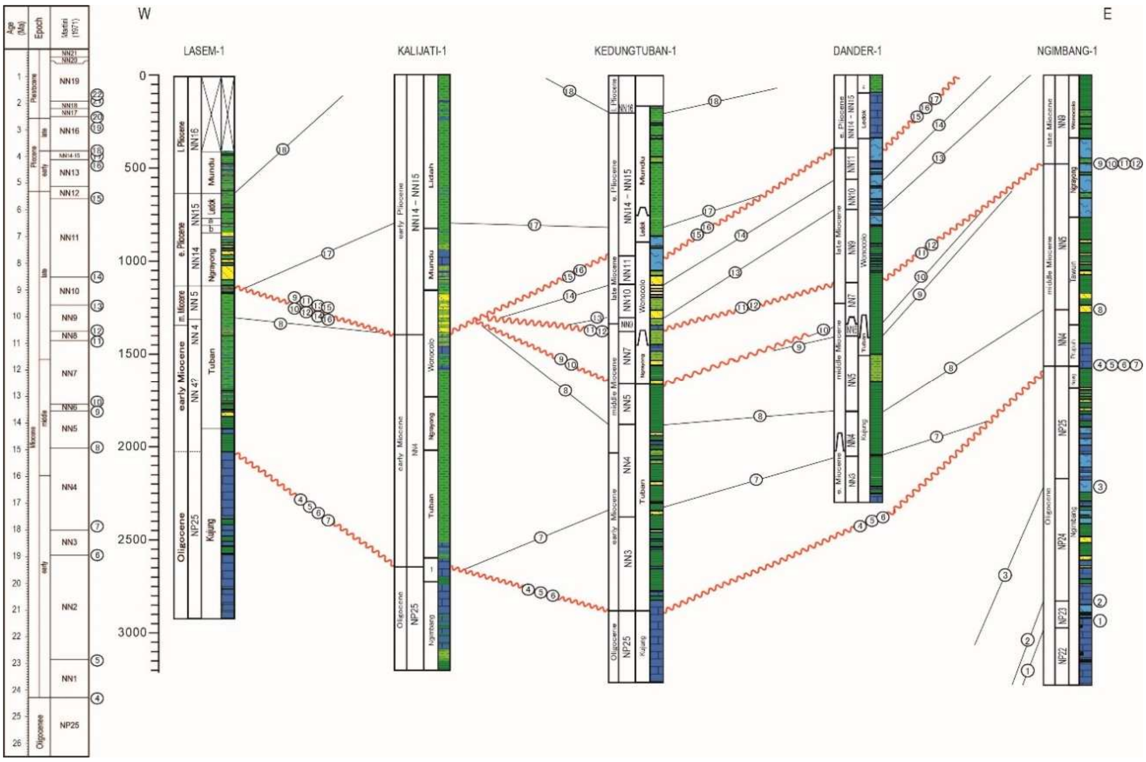

Fig. 7 Correlation of five wells based on nannofossil biostratigraphy. Refer Fig. 2 for Encircled number. The red wavy line indicates the unconformity

The upper Miocene sediments between datum 12 and 15, is found in Kedungtuban-1 and Dander-1 wells. The sequence is also present in Ngimbang-1 well. However, two datum of 13 and 14 of the upper Miocene is not found in the section. The sediments between datum 7 and 11 are distributed in Kedungtuban-1 and Dander-1wells. However, the sequence between 9 and 10 of the middle Miocene, is missing in Kedungtuban-1 well. The sequence below the lower Pliocene in Lasem-1, Kalijati-1, is composed of NN4 or NN4 to NN5 sediments. The sequence below upper Miocene in Ngimbang-1 well is also correlated to NN4 to NN5 of early-middle Miocene. The big unconformity between Oligocene and Miocene is traceable in the study area. The missing interval of the lower Miocene is found in the sequence wells, indicated by the co-occurrence of datum 4 to 6 and 7 (Fig. 7).

As a result, a total of four unconformities are traceable in the study area. Although the distribution of the sediments in the lower to upper Miocene is mainly on the eastern side (such as Kedungtuban-1, Dander-1, and Ngimbang-1 wells), the thick sediments of lower to upper Pliocene are present in the western side (such as Lasem-1, Kalijati-1, and Kedungtuban-1 wells).

Based on our results, our correlation is not corresponding with the previous report of the lithostratigraphy "Formation" unit reported by PERTAMINA. As mentioned first in this paper, the lithostratigraphic unit, especially "Formation" and "Member", has been confusing between several papers. Our results also show such a background of problems of the lithostratigraphy. The discussion on correlations of the lithostratigraphy of the wells is excluding in our study.

C. Unconformities Detected in this Study

Many research papers on geology and stratigraphy of the East Java area have been published until now. Lunt [1], [2] and Sharaf et al. [6] clarified the stratigraphic evolution of the area based on summarizing geology of the Java Island. In this context, research on the biostratigraphy of the Cenozoic sediments in Indonesia has also been studied. Although the research is mainly focusing on benthic, planktic, and larger foraminifera, detailed biostratigraphic data of each area was not discussed in the papers [6], [10], [11]. Research on nannofossil biostratigraphy is also published recently; however, the studied interval and area are limited [12]–[14]. As this result, detailed timing and scale of unconformities indicated in many papers, are still not clear until now.

Our research on nannofossil biostratigraphy of the Cepu area indicates that a total of four unconformities are present in the studied area, and two of four unconformities are traceable in the whole studied area, and these are as follow (Figs. 7):

Unconformity 1: This unconformity is situated in Oligocene/early Miocene boundary. Datum 4, 5, and 6 are situated in the unconformity of Kedungtuban-1. In Lasem-1, Kalijati-1, and Ngimbang-1 wells, along with mentioned datum, datum 4, 7 are also present in this unconformity.

Unconformity 2: Datum 9 and 10 are present in the same depth in Kedungtuban-1 well. This evidence indicates that middle Miocene NN6 sediments are missing in this well.

Unconformity 3: NN8 interval between datum 11 and 12 are missing. This unconformity is traceable to Kedungtuban-1, Dander-1, and Ngimbang-1 wells. In Ngimbang-1, well, the sediments from datum 9 to 12 are missing.

Unconformity 4: This unconformity is situated in the lower Pliocene base. In this area, the lower Pliocene Series above datum 16 or 17 is distributed. The time gap of the unconformity is the biggest in Lasem-1 and Kalijati-1 located in the western area. Datum 9 to 17 of middle Miocene to lowest Pliocene is missing in Lasem-1 well, and datum 8 to 16 is not distributed in Kalijati-1 well.

Based on the correlation of the well, the generalized geologic column of the studied area is illustrated in Fig. 8. The figure shows the stratigraphic distributions of the sediments in the east-west section (Ngimbang-1 to Kalijati-1 wells). The Oligocene NP25 sediments are widely distributed in the area. The upper-lower Miocene to lower-middle Miocene NN4 sequence is also traceable to all areas. The distributions of upper-middle Miocene NN7 and Upper Miocene NN9, 10, 11sediments are limited in the central area of the basin, Kalijati-1, and Dander-1 wells. Although the lower Pliocene series is not present in Ngimbang-1 well, it is distributed in the wells located in central to the western part of the basin, Dander-1, Kedungtuban-1, and Kalijati-1 wells.

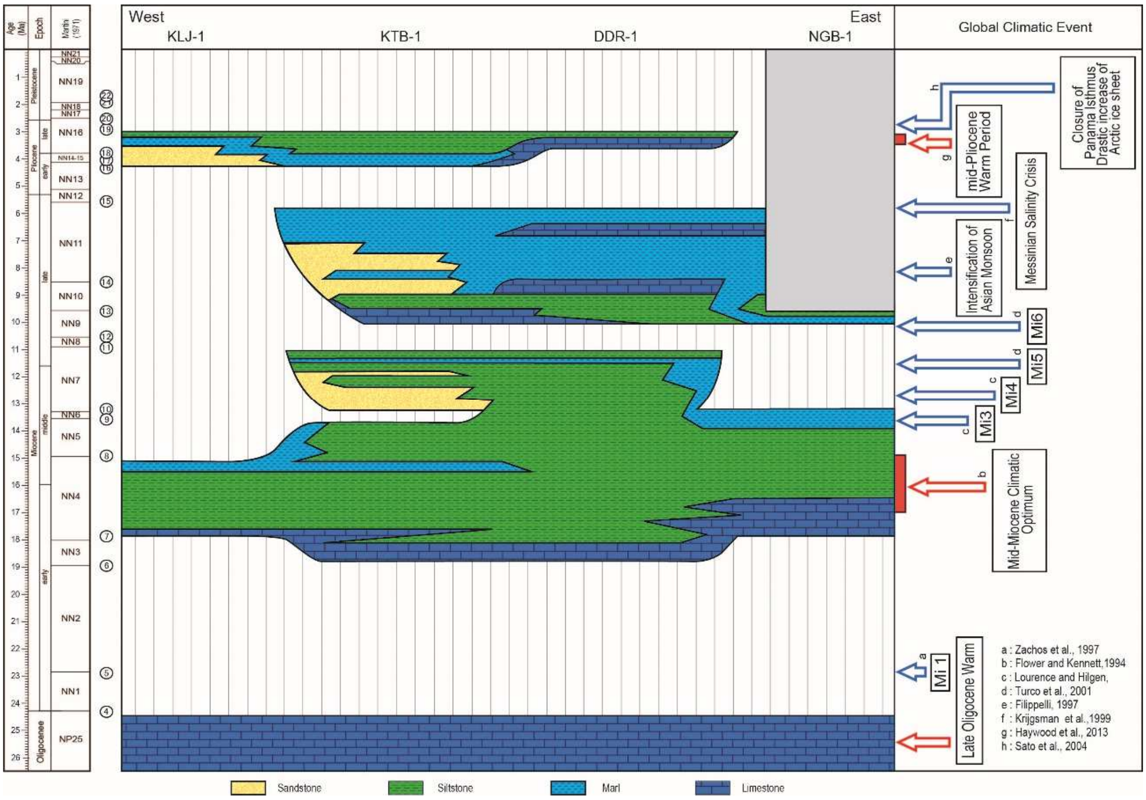

Fig. 8 The generalized geologic column of the studied area. Global climatic events are indicated: a [20], b [21], c [22], d [17], e [23], f [24], g [19], h [25].

Of particular interest in the stratigraphy of the study area is three big unconformities. The unconformity which is present between the late Oligocene and early Miocene (Unconformity 1 mentioned above), is 5 million years gap. Unconformity 3 of early late Miocene NN8, which is about one million years gap, is traceable in the whole area. Unconformity 4 between Miocene/Pliocene boundary is also distinct in this area. Among them, the lower Pliocene series directly overlay the NN4 lower Miocene series. Furthermore, no outcrop of the Pliocene series is distributed in the eastern part of the area.

This fact means that the sedimentary basin shifted to the western area in the early Pliocene.

We correlate the unconformities detected in this area to the Global climatic events (Fig. 8). The Oligocene Series, which is widely distributed in the study area, is correlated to the late Oligocene warm event. The Miocene Series unconformably overlie the Oligocene Series. The formation of this unconformity is correlated to the cooling event of Mi 1 [15]. The lower Miocene series above this unconformity is assigned to the Mid-Miocene climatic optimum event, which is traceable to worldwide. This evidence indicates that the sea level rise by warming event "Mid-Miocene Climatic Optimum" is strongly influenced by the distribution of marine lower Miocene series in this area. Unconformity 2 may be correlated to the cooling events Mi3 or Mi4 just after the Mid-Miocene Climatic Optimum. The NN7 sequence "Ngrayong Formation" of Kedungtuban-1 well between unconformities 2 and 3 is considered a single Transgressive- Regressive cycle. This opinion is supported by the result of the facies analysis of Ngrayong sandstone by Khaing *et al*. [16]. Based on nannofossil biostratigraphy, unconformity 3 is correlated to the cooling event of Mi5 [17]. Turco *et al*. [17] interpreted the Mi5 event that the event is correlated to a eustatic sea-level drop of 3.1Mya [18]. Unconformity 4 between late Miocene and early Pliocene is correlated to the well-known global event, "Messinian Salinity Crisis". The upper-lower Pliocene series above the unconformity is correlated to the mid-Pliocene Warm Period [19]. These facts indicate that the formation of the unconformities detected in the study area is strongly influenced by eustacy sea-level changes (Fig. 8).

D. Change of the Location of LST

Our result indicates that the transgression and regression were occurred many times in the Cepu area during the late Paleogene to recent. Based on the result, we clarify the change of the position of Low Stand Systems Tract (LST) in the study area for reconstructing the basin history.

Fig. 9 shows the LST sediments above the unconformities, which were detected in this study. Each LST above the unconformity is respectively correlated to the lower Miocene NN3, upper-middle Miocene NN7, lower upper Miocene NN9, and lower Pliocene NN13-NN15. The important point that needs to be noticed, first, LSTs of NN3 and NN7, is in the center of the studied area (Kedungtuban-1 and Dander-1 wells). Then, the LST of NN9 slightly shifted east toward the outside of the sedimentary basin (Ngimbang-1 well). In contrast with the LST of Miocene, the LST of NN13-NN15 move to the area in the western part (Lasem-1 well; Fig. 9).

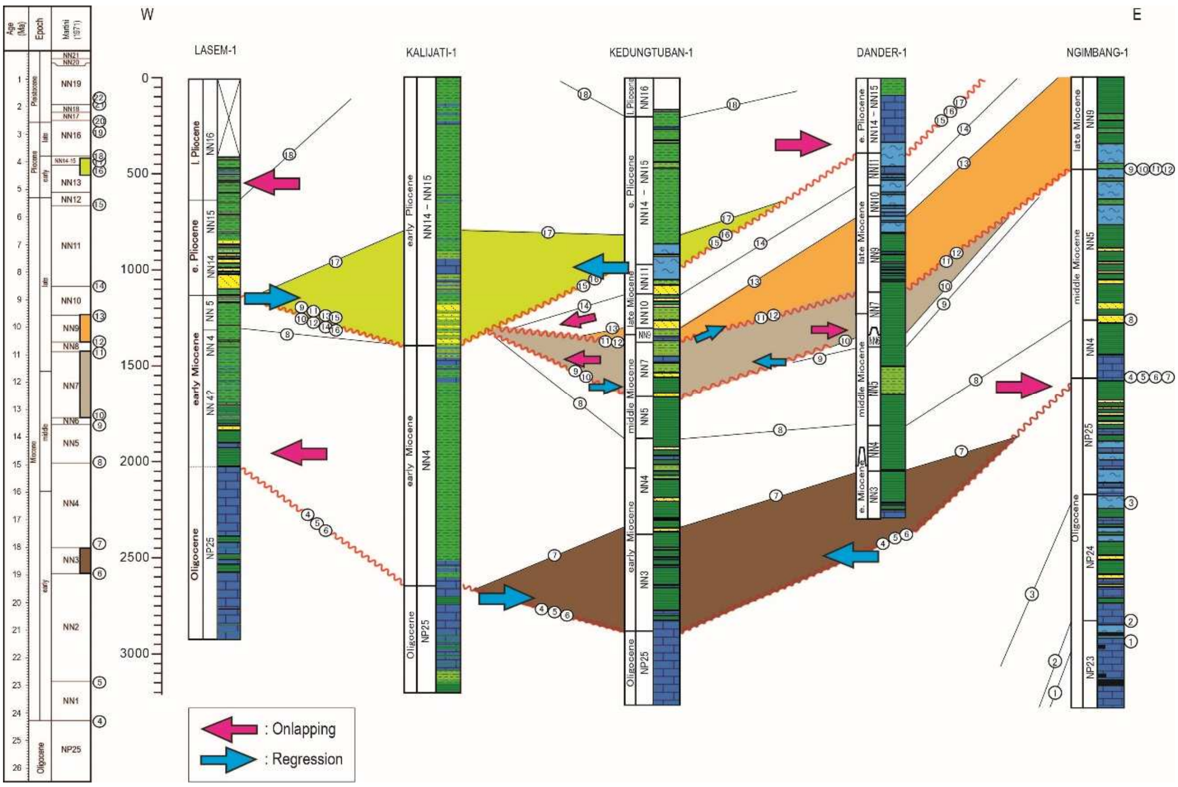

Fig. 9 Positions of Low Stand Systems Tract during the Oligocene to Pliocene.

These results show that the depocenter of the sedimentary basin in the Cepu area was changed as follows (Fig. 9). The late Oligocene limestone was widely deposited in the area. After the early Miocene unconformity 1, the sedimentary basin was developed around the center of the studied area (Kedungtuban-1 and Dander-1 wells). After unconformity 2 of the middle Miocene, the development of the basin is similar to the early Miocene. However, following the late Miocene unconformity 3, the basin depocenter moved east to the edge of the sedimentary basin (Ngimbang-1). The time gap of the early Pliocene unconformity 3 is about 11 million years in maximum (in Lasem-1 and Kalijati-1 wells). The depocenter of early Pliocene after unconformity 4 is drastically changed to the western part of the basin (Kalijati-1 well).

Based on the result, the depocenter of the sedimentary basin has changed from the central area (early to middle Miocene), eastern area (late Miocene), and to the western area (early Pliocene). In the middle to late Miocene, Lasem-1 and

Kalijati-1 wells were on the edge of the sedimentary basin. This condition is due to tectonics occurred in the latest Miocene when the Pliocene depocenter was moved from the central area to Lasem-1 and Kalijati-1 wells location.

E. The Relationship between Lithology and Unconformity-Focusing to the Distribution of Sandstone

As described above, the lithostratigraphic unit, especially "Formation" and "Member", has been confusing between several papers in the study area. For this reason, we correlate the lithology based on nannofossil datum. Fig. 10 shows the correlation of sandstone, limestone, and marl between the wells based on nannofossil datum. The Oligocene Series widely distributed in the area is composed of limestone. The lower Pliocene Series above the big unconformity between early Miocene and early Pliocene found in Lasem-1, and the distribution of thick sandstone layers characterizes Kalijati-1 wells. As these sandstones are characterized by the onlapping to the unconformity (Fig.9), sandstones were deposited as transgressive system tracts. The sandstones above the unconformities 2 and 3 in Kedungtuban-1 well are also interpreted as the sediments of the transgressive system tract.

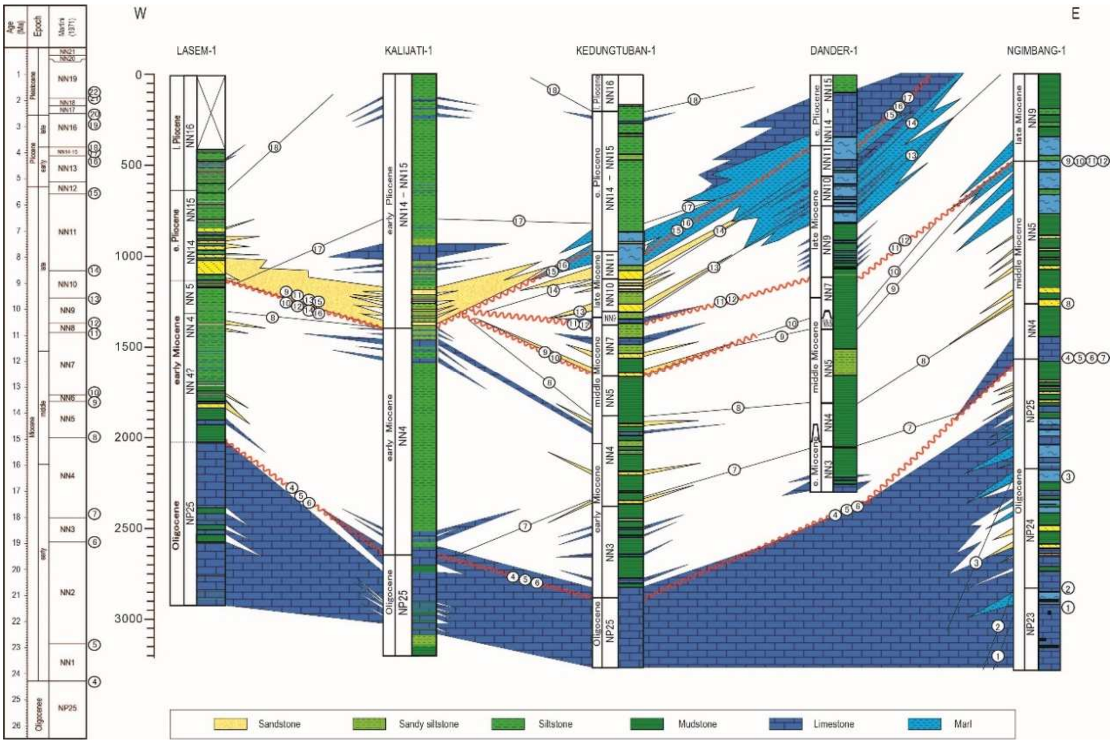

Fig. 10 Correlation of the sandstones, limestone, and marl between the wells based on nannofossil datum

The lower Pliocene sandstone, which is correlated to the Wonocolo Formation in Kalijati-1 well by PERTAMINA, is characterized by the petroleum reservoir in Dander-1 well [7]. However, the Wonocolo Formation is generally correlated to the late Miocene [1]–[3]. Furthermore, the Ngrayong Formation, which is characterized by thick sandstone layers, is interpreted as the middle Miocene below the Wonocolo Formation [1]. In this way, the assignment of the lithology of each well to the "Formation" unit used in the Cepu area is confusing. This problem occurs because of the unclear definitions of each Formation Unit and their exact age.

Although we do not discuss the age of each "Formation" of the wells as this reason mentioned above, we interpret the distributions of each sandstone layer based on the well's correlation. The thickest sandstone, which is distributed in the western area, is correlated to the early Pliocene Transgressive Systems Tract above the unconformity 4. Some sandstone layers also found above the unconformities 2 and 3 in the central area; however, the volume of these layers is not significant compared with lower Pliocene sandstone. The lower Pliocene sandstone is already interpreted as remarkable petroleum reservoir rocks in this area [7]. We clearly describe the characteristic of this sandstone, which is early Pliocene LST and Transgressive Systems Tract above the unconformity 4.

IV. Conclusions

We describe the detailed nannofossil biostratigraphy of four wells in the Cepu area. As many confusions on lithostratigraphy of the wells are found in the previous studies, we study and reconstruct the basin history based on lithology and nannofossil biostratigraphy. A total of four unconformities are detected in the studied area, and two of four unconformities are traceable in the whole studied area. Unconformity 1: This unconformity is situated in Oligocene/early Miocene boundary. The earliest Miocene nannofossil zone NN1 to NN2 is missing in Kedungtuban-1, and NN1 to NN3 is not present in Lasem-1, Kalijati-1, and Ngimbang-1 wells. Unconformity 2: Nannofossil zone NN6 is not present in Kedungtuban-1 well. Unconformity 3: Nannofossil zone NN8 is missing in Kedungtuban-1, Dander-1, and Ngimbang-1 wells. In Ngimbang-1, well, the sediments from NN6 to NN8 is not present. Unconformity 4: This unconformity is situated in the lower Pliocene base. In this area, the lower Pliocene NN14 sediment is distributed. The time gap of the unconformity is the biggest in Lasem-1 and

Kalijati-1 located in the western area. NN6 to NN13 of middle Miocene to lowest Pliocene is missing in Lasem-1 well, and NN5 to NN13 (part) is not distributed in Kalijati-1 well.

These results indicate that the LSTs (Low Stand Systems Tract) above the unconformities 1 and 2 are situated in the centre of the studied area (Kedungtuban-1 and Dander-1 wells), and LST above unconformity 3 is found in the eastern area located in out of the sedimentary basin (Ngimbang-1 well). In contrast with LSTs of Miocene, the LST above unconformity 4 moves to the area in the western part. Furthermore, the thickest sandstone, which is distributed in the western area, is correlated to the early Pliocene LST and Transgressive Systems Tract above the unconformity 4.

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