THE USE OF PALYNOLOGY IN SEQUENCE STRATIGRAPHY ANALYSIS A CASE STUDY: THE EOCENE NANGGULAN FORMATION

by

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ABSTRACT

This paper is a part of palynological investigation on the Eocene Nanggulan Formation, Yogyakarta, Central Java. The Nanggulan Formation containing rich palynomorph assemblage provides excellent data to support sequence stratigraphy analysis. The palynomorph assemblage changes (especially between mangrove and freshwater palynomorphs) may reflect sea level changes which can be used to interpret system tracts, which are the internal building blocks of sequences. In addition to mangrove pollen maxima, evidence for warm and/or wet climates provides support for high sea level scenarios (highstand systems tract), whereas cool/dry climate evidence suggests a low sea level setting (lowstand systems tract).

On the basis of lithology, the Nanggulan Formation can be divided into nine lithological sequences. However, these sequences do not necessarily correspond to the globally correlated sequences proposed by Haq et al. (1987) because they are informal units which probably represent shorter term events such as reflecting parasequences. By using palynology, it can be inferred the true sequences which may be comparable to the cycles (third order) from TA 3. 4 to TA 4. 1 or from 43. 0 Ma to 36.0 Ma.

I. LOCATION AND FIELD STUDY

The Nanggulan Formation outcrops near the small village of Nanggulan which is situated 20 kilometres west of Yogyakarta, Central Java (Figure 1). The formation has been interpreted as a transgressive sequence which is clearly justified by the lithostratigraphy and fossil content (Hartono, 1969 and Okada, 1981). Non-marine deposits at the base of the formation gradually change upward into shallow marine lithologies in the middle of the formation and these are topped by a deep marine succession with turbidites. This type of sequence has the potential to yield good palynomorph recovery, especially in the lower and middle part of the Formation.

Based on the local geological map three river sections were selected to span the Eocene Nanggulan Formation. The river sections are Kali Songgo, Kali Watupuru and K. Kunir (Figures 2). Each section provides a distinct lithological sequence (Figures 2) which only covers part of the formation. Although a complete section of the Nanggulan Formation is not represented at any location, the whole Nanggulan Formation can be obtained by combining those sections. The detailed measurement of the outcrops including strike and dip as well as sedimentary characteristics demonstrate that the Kali Watupuru and Kali Songgo sections are in fact overlapping (Figure 2), and form two flanks of the Nanggulan anticline. This result then revises the previous work by Purnamaningsih and Harsono (1981) which interpreted these two river sections as two separate successions.

II. Palynology in sequence stratigraphy

Sedimentary successions can be divided into unconformity-bound units (sequences) which form during a single cycle of sea-level change (Doyle and Bennett, 1998). The boundaries are indicated by an erosional surface and may be reflected by an influx of coarse-grained clastics above finer-grained sediments (e.g. Reading and Levell 1996). The erosional surface reflects an unconformity surface in the stratigraphic record which is caused by sea level fall (Nichols, 1999). A sequence boundary normally consists of an unconformity and its correlative conformity, the equivalent surface in the distal part of a basin where there was no erosion (Van Wagoner et al., 1988 in Nichols, 1999).

The sequence boundaries are here interpreted based on lithological changes, and hence are termed lithological sequences. Palynomorph assemblages and foraminifera occurrences are also used to support the interpretations

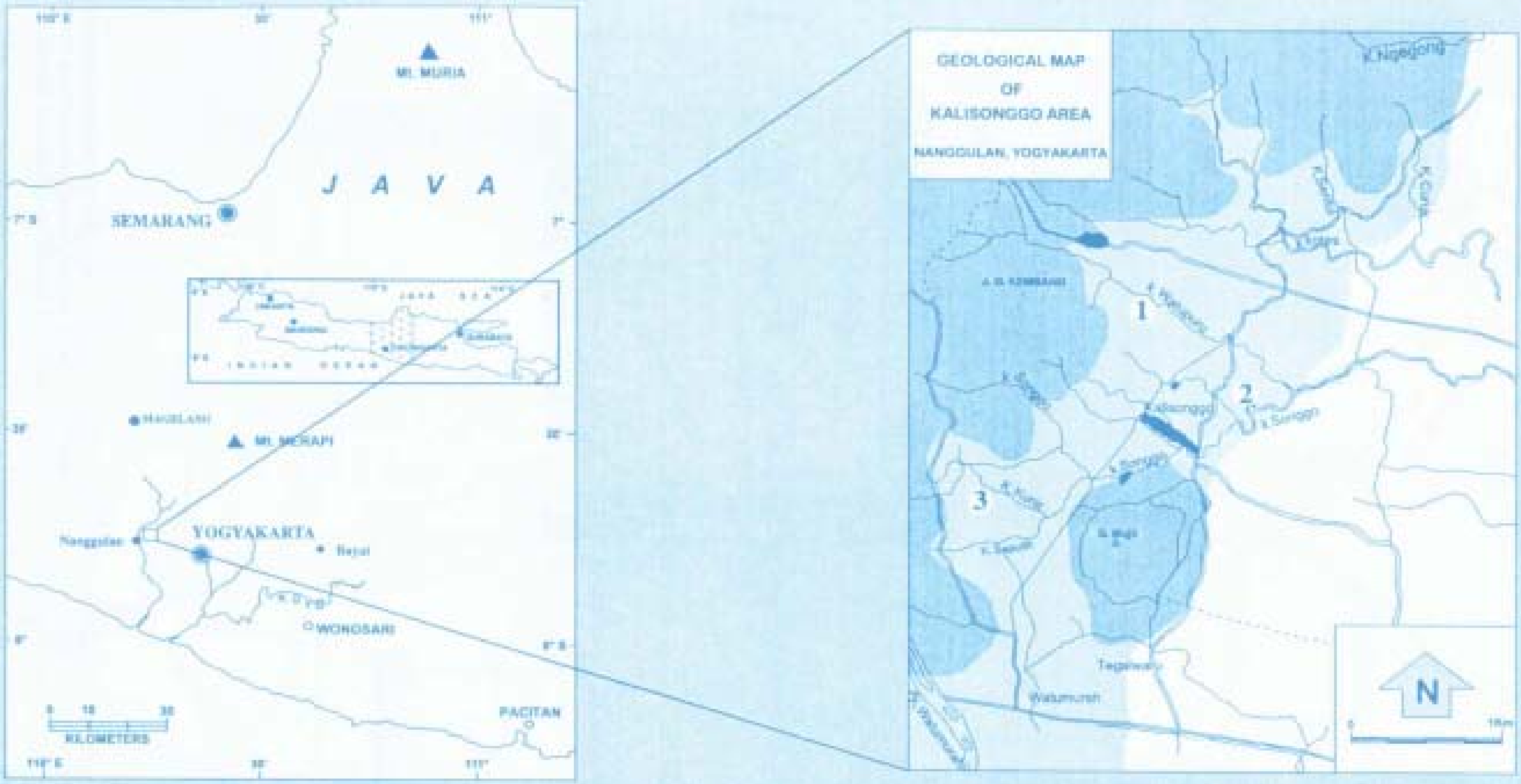

Figure 1

Location of the study area and its geological map

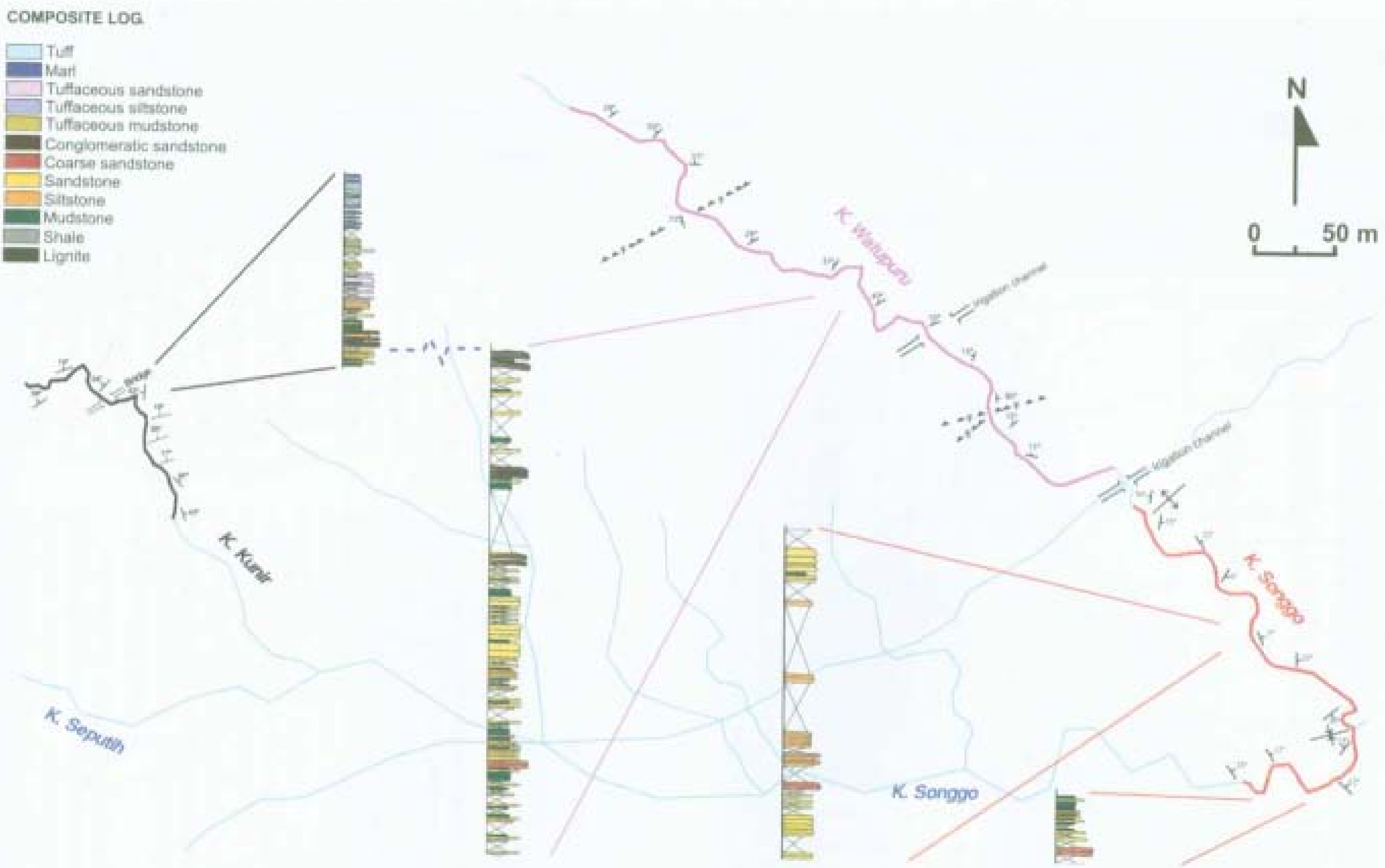

Figure 2
Field situation and various lithological columns obtained from the studied sections.

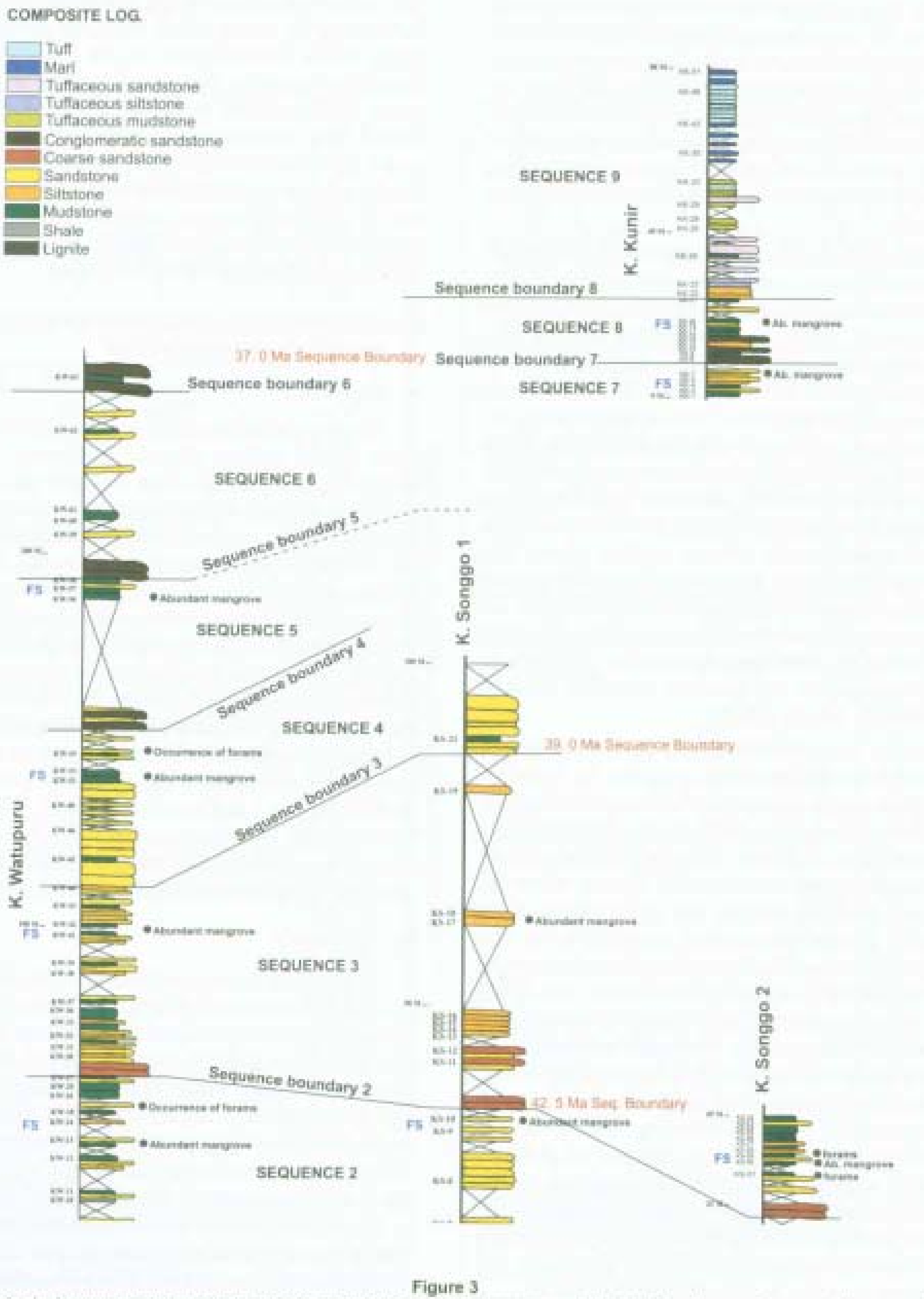

Figure 3

Lithological sequence interpretation based on lithological occurrences combined with palynomorph assemblages and foraminifer occurrences. Sequence boundary is indicated by fine-grain sediments overlain by course-grain sediments. FS is marine flooding surface based on the abundance of mangrove pollen and the occurrence of foraminifers

(Figure 3). Here, palynomorph assemblages are especially focused on the proportions of mangrove versus freshwater palynomorphs where sea level changes are interpreted. High mangrove palynomorph abundances (with the occurrences of foraminifera in some cases) are used as possible indications of the portions of the sections characterised by rising sea levels, and possibly representing flooding surfaces (FS on Figure 3) terminating intervals of relative sea level rise.

The lithological sequences interpreted here are informal units, and may not necessarily correspond to the globally correlated sequences proposed by Haq et al. (1987 in Hardenbol et al., 1998). To determine the possible relationship of the lithological sequences to the sea level curve and to globally correlatable sequences, the succession is also examined from the point of view of palynomorph assemblage change, which may reflect systems tracts, which are the internal building blocks of sequences. In addition to mangrove pollen maxima, evidence for warm and/or wet climates provides support for high sea level scenarios (highstand systems tract), whereas cool/dry climate evidence suggests a low sea level setting (lowstand systems tract). These trends are suggested for high and low sea level settings in the low latitude Quaternary (Flenley, 1979; Morley, 2000) and have been shown to be applicable to sequence stratigraphic interpretation across the low latitude Tertiary by Morley (1995).

Sequence interpretation based on climate-related palynomorph assemblage trends suggests far fewer sequences than simply considering the character of upward fining lithological packages and their associated mangrove pollen maxima on their own. It is possible that climate-driven trends are less evident in the Eocene, when climates were generally warmer, and sequestration of sea ice on polar ice caps was minimal, compared to the later Tertiary, and consequently, the number of actual sequences (in the sense of Haq et al., 1987 in Hardenbol et al., 1998) may be underrepresented. Two contrasting scenarios are presented, correlating: a) the lithological sequences, and b) possible sequences supported by palynological evidence for palaeoclimatic change, with the global sea level curve. The two scenarios provide contrasting "minimum" and "maximum" scenarios of the number of globally correlatable sequences present in the Nanggulan Formation. This comparison also allows suggestions to be made as to the overall age of the Nanggulan Formation, and also as to whether it represents the whole of the Middle and Late Eocene, or only a fraction of this time interval.

In interpreting sea level change, consideration also needs to be given to regional subsidence, which occurs across the southern margin of the Sunda platform during the later Eocene (e. g. Bransden and Matthews, 1992). The marked subsidence during this period is responsible for creating the setting which led to the development of debris flows and turbidites in the upper part of the Nanggulan Formation. Elsewhere in Central Java, this time period is characterised by the occurrence of Middle/Late Eocene deep marine sediments with large clasts of transported shallow water lithologies, for example, at Karang Sambung to the west (Paltrinieri et al.,1976) and the Bayat area to the east (Sumarso and Ismoyowati, 1975) This phase of regional subsidence possibly masks evidence for global sea level change during this period.

II. SEQUENCE STRATIGRAPHY IN THE EOCENE NANGGULAN FORMATION

A. *Sequence 1*

The lower boundary of this sequence is not recognised in the studied sections (Figure 3). However, the occurrence of lignites (marker L1) in the lower part, supported by high abundance of freshwater palynomorphs such as *Palmaepollenites* spp. and *Dicolpopollis malesianus*, but low abundance of mangrove palynomorphs, is taken to indicate relatively low sea level. Subsequently, mangrove palynomorphs increase considerably and palynomorph diversity increases indicating relative sea level rise (Figures 4 to 6). The base of the overlying sequence (sequence boundary 1) is marked by relatively low sea level which is characterised by the occurrence of lignite (KW-5) and a decrease in mangrove palynomorphs but an increase in freshwater palynomorphs. The boundary is uncertain in the Kali Songgo 1 and 2 sections because of the absence of lignite. This sequence boundary is poorly supported as it is only recognised at Kali Watupuru and the lithological change is comparable to others within the sequence.

B. *Sequence 2*

There is relative sea level rise above sequence boundary 1 as shown in the Kali Watupuru section by a fining-upward succession dominated by mudstones in the upper part (KW-24 to KW-27). High abundance of mangrove palynomorphs (Kali Watupuru and Kali Songgo 1 sections) and the occurrence of foraminifers (Kali Watupuru) also support this interpretation (Figure 3). Unfortunately, this evidence is not found in the Kali Songgo 1 and 2 sections due to the absence of outcrops. Sequence 2 is terminated by the occurrence of an inferred erosional surface at the base of coarse-grained sandstones (marker L2) deposited during relatively low sea level. This is recorded in all three sections. Low palynomorph diversity in samples KW 24 and KW 27, below the boundary but above the mangrove abundance, may also indicate relatively low sea level, i.e. the commencement of relative sea level fall.

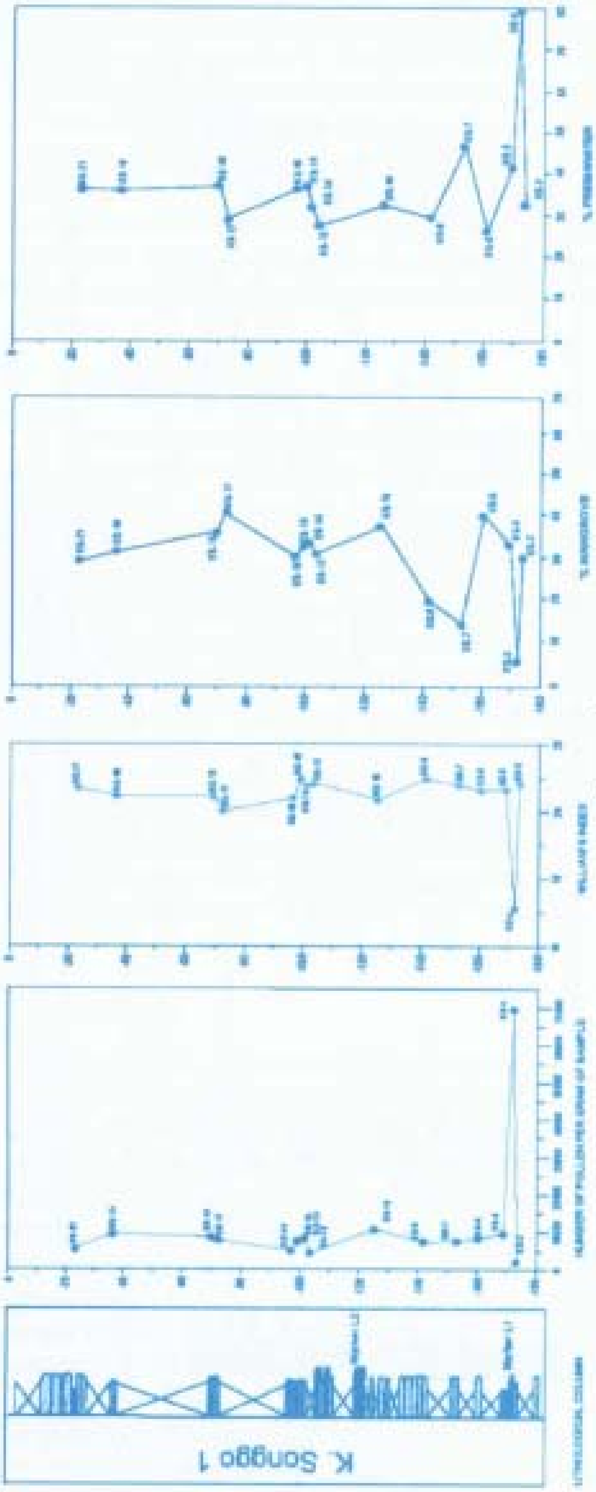

Figure 4
Palynomorph abundance and diversity, lithology and the percentages of mangrove and freshwater palynomorphs which occur in the Kali Songgo 1 section

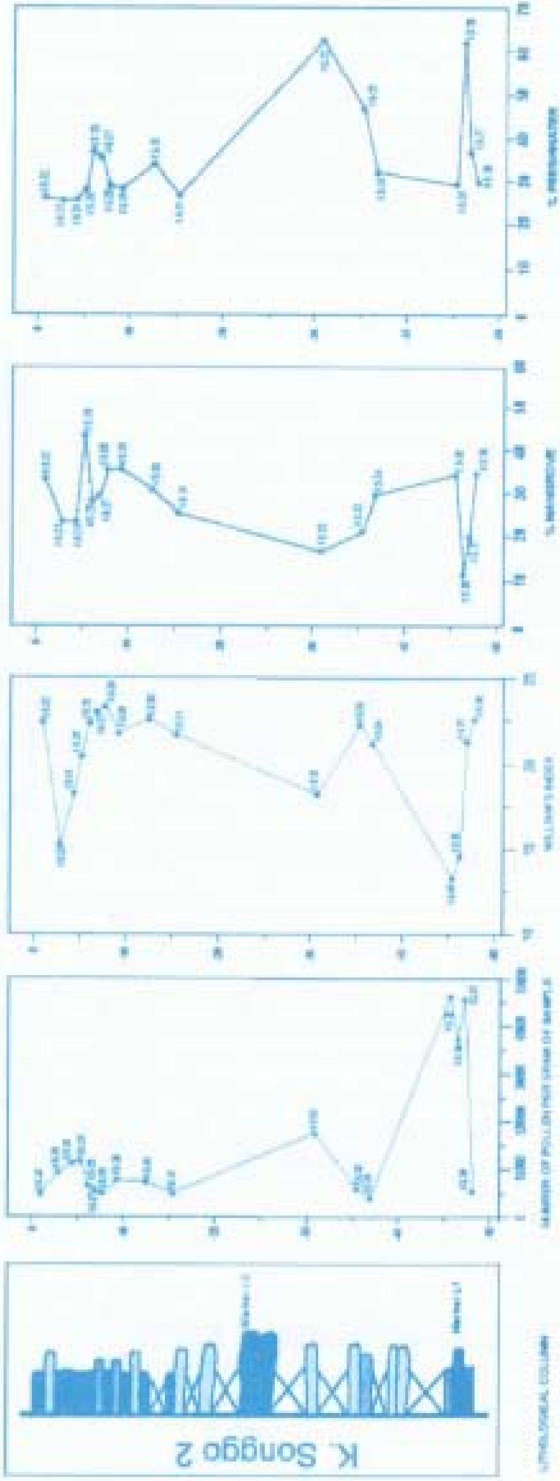

Figure 5
Palynomorph abundance and diversity, lithology and the precentages of mangrove and freshwater palynomorphs which occur in the Kali Songgo 2 section

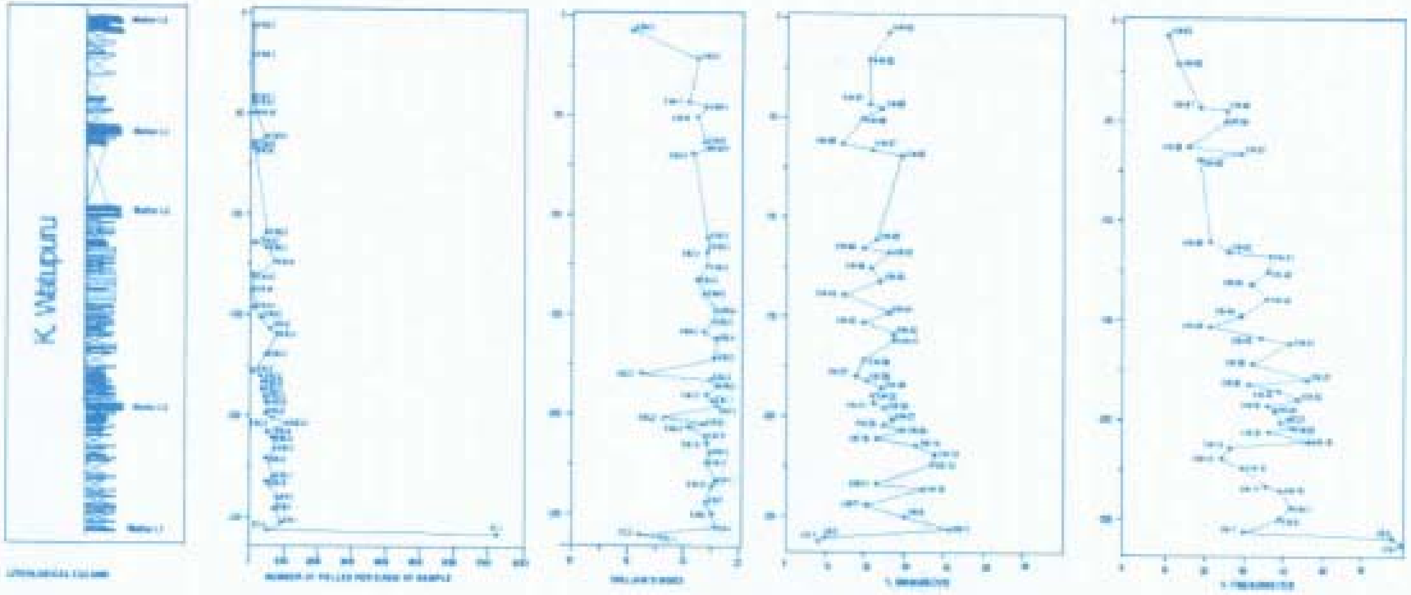

Figure 6

Palynomorph abundance and diversity, lithology and the precentages of mangrove and freshwater palynomorphs which occur in the Kali Sanggo 2 section

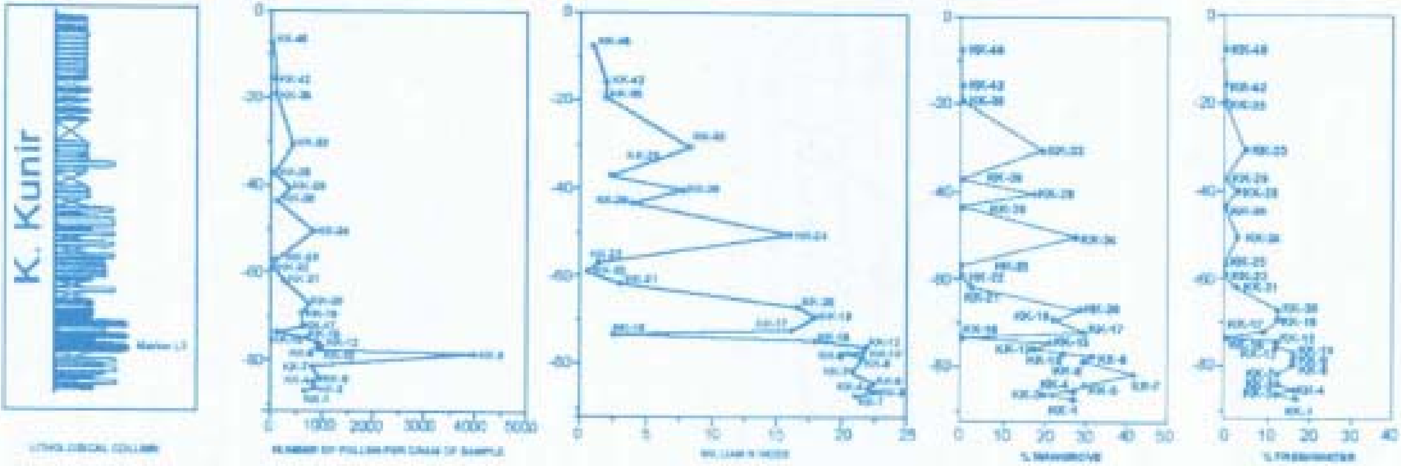

Figure 7

Palynomorph abundance and diversity, lithology and the precentages of mangrove and freshwater palynomorphs which occur in the Kali Kunir section

C. *Sequence 3*

The occurrence of coarse-grained sandstones in the lower part of sequence 3 reflects relatively low sea level. Generally, the interval shows a fining-upward succession indicating relative sea level rise (Figure 3). The increase of mangrove palynomorphs in samples KW-42, KS-18 and KS-30 together with the occurrence of foraminifers in KS-31 and KS-29 (Kali Songgo 2 section) support the interpretation of sea level rise (Figure 3). Sequence 3 is terminated by the occurrence of an inferred erosional surface at the base of massive sandstone deposited during relatively low sea level (sequence boundary 3). Sequence boundary 3 (or higher) is not represented in the Kali Songgo 2 section.

D. *Sequence 4*

The occurrence of massive sandstones in the lower part of sequence 4 suggests relatively low sea level. This is supported by the decrease in mangrove palynomorph abundance but increase in freshwater palynomorph abundance as shown in samples KW-45 and KS-21 (Figure 4 and 6). The succession fines upward into mudstones (Figure 3). Mangrove palynomorphs become abundant in the upper part of sequence 4 (sample KW-53). Foraminifers occur in the sandstone above sample KW-55 (Figure 3). Lithological and fossil evidence therefore indicate relative sea level rise. Sequence 4 is terminated by the occurrence of an inferred erosional surface beneath conglomeratic sandstone deposited during relatively low sea level. Sequence boundary 4 (or higher) is not represented in the Kali Songgo 1 section.

E. *Sequence 5*

This sequence only occurs in the Kali Watupuru section. The huge sample gap within this sequence causes a problem with sequence recognition. The occurrence of conglomeratic sandstone in the lower part of the sequence reflects relatively low sea level. The upper part of the sequence is dominated by mudstones suggesting that a fining-upwards succession may be represented in the missing outcrop. Mangrove palynomorphs are abundant in sample KW-56 in the upper part of the sequence. These features indicate relative sea level rise. Sequence 5 is terminated by an inferred erosional surface at the base of conglomeratic sandstone deposited during relatively low sea level. Low mangrove abundance, low palynomorph diversity but high palynomorph concentration immediately below the boundary (sample KW-58) may also indicate relatively low sea level, i.e. the commencement of relative sea level fall.

F. *Sequence 6*

This sequence only occurs in the Kali Watupuru section. The occurrence of conglomeratic sandstone in the lower part of sequence indicates relatively low sea level above which there is a finer-grained succession although with many sample gaps. There is also a trend that mangrove palynomorphs become more abundant (not as abundant as in lower sequences) higher in the succession, whilst the freshwater palynomorphs decline (Figure 6). These features indicate relative sea level rise. Sequence 6 is terminated by an inferred erosional surface at the base of conglomeratic sandstone deposited during relatively low sea level.

G. *Sequence 7*

The base of sequence 7 is represented by the occurrence of conglomeratic sandstone and is only found in the Kali Watupuru section. This lithology indicates relatively low sea level. On the other hand, the upper part of the sequence is marked by the occurrence of finer-grained sediments such as mudstones, sandstones and siltstones. In addition, mangrove palynomorphs are abundant in the upper part of the sequence (KK-7). The upper part of the sequence is only found in the Kali Kunir section. Correlation here is based on palynological zonations. It can be inferred that the sequence shows relative sea level rise. Sequence 7 is terminated by the occurrence of an inferred erosional surface at the base of conglomeratic sandstone deposited during relatively low sea level.

H. *Sequence 8*

This sequence only occurs in the Kali Kunir section. The occurrence of conglomeratic sandstone in the lower part of sequence 8 indicates relatively low sea level. This is supported by the decrease in mangrove palynomorph abundance but increase in freshwater palynomorph abundance (Figure 7). The conglomeratic sandstone is characterised by high palynomorph concentration which in a deep water setting may indicate low sea level phase (KK-8). The upper part of this sequence is characterised by the occurrence of mudstones with sandstone intercalation (Figure 3) and by an increase in mangrove palynomorph abundance but decrease in freshwater palynomorph abundance (Figure 7). This evidence suggests relative sea level rise. Sequence 8 is terminated by the occurrence of an inferred erosional surface at the base of siltstone.

I. *Sequence 9*

This sequence only occurs in the Kali Kunir section. Lithologically, this sequence shows fining-upward sediments in which the coarser-grained sediments in the lower part (siltstones, tuffaceous siltstones and tuffaceous sandstones) change into finer-grained sediments (tuffaceous mudstone, marl and tuff). Unfortunately, there is little evidence from the palynomorph record. This sequence was deposited in the deep marine environment. The poor palynomorph recovery might be due to long transportation, less clastic input and high carbonate content. The upper boundary of this sequence is apparently not represented in the section studied.

III. COMPARISON OF SEQUENCE STRATIGRAPHY WITH THE GLOBAL SEA LEVEL CURVE.

Comparison of the lithological sequences is made with the global sea level curve, firstly assuming that each correlates with the globally correlatable sequences of Haq et al. (1987 in Hardenbol, et al., 1998), and secondly, assuming that the lithological sequences may in fact be shorter term events (possibly reflecting parasequences). The number of true sequences is proposed by attempting to recognize systems tracts based on evidence for climate change following Morley (1995).

A direct correlation of the lithological sequences with the global sea level curve of Haq et al. (1987 in Hardenbol et al., 1998), is presented in List 1. The tie point for this correlation is positioned on the basis of the sudden appearance of regular *Podocarpidites* spp within lithological sequence 8, which reflects a sudden climate cooling, which is correlated with the only pronounced sea level fall within the Middle/Late Eocene, at the beginning of TA 4.1. This correlation would place the lower part of the Seputih Member within the Late Eocene, which fits well with other geological data. However, the correlation would require that the base of the formation is latest Early Eocene in age (Sequence TA 2.9) and this is considered unlikely, since typical Early Eocene palynomorphs, such as *Spinizonocolpites baculatus* and *Retitriporites variabilis*, are missing from the section. This correlation is thought to overestimate the age of the section present, and is thought to be erroneous.

The second approach is to identify systems tracts on the basis of a combination of lithologies, and palynological evidence for climate change. The lithological sequences can be divided palynologically into two main groups, Se-

List 1

Correlation of lithological sequences assuming that all relate to the globally correlatable sequences of Haq et al. (1987 in Hardenbol et al., 1998; See Figure 8)

Lithological sequence/ sequence boundary in Nanggulan Formation	Possible correlation with sequence/sequence boundaries of Haq et al (1987, modified according to Gradstein et al 1994 in Hardenbol et al., 1998)
Sequence 9	Sequence TA 4.2
Sequence boundary 8	36.0 Ma sequence boundary
Sequence 8	Sequence TA 4.1
Sequence boundary 7	37.0 Ma sequence boundary
Sequence 7	Sequence TA 3.6
Sequence boundary 6	39.0 Ma sequence boundary
Sequence 6	Sequence TA 3.5
Sequence boundary 5	42.5 Ma sequence boundary
Sequence 5	Sequence TA 3.4
Sequence boundary 4	43.9 Ma sequence boundary
Sequence 4	Sequence TA 3.3
Sequence boundary 3	46.0 Ma sequence boundary
Sequence 3	Sequence TA 3.2
Sequence boundary 2	48.3 Ma sequence boundary
Sequence 2	Sequence TA 3.1
Sequence boundary 1	49.5 Ma sequence boundary
Sequence 1	Sequence TA 2.9

quences 1-3 are characterised by lithologies and palynomorph assemblages characteristic of a coastal plain setting, with diverse palynomorph assemblages suggesting a warm, wet climate and consistently high palynomorph concentrations. These lithological sequences are best interpreted in terms of transgressive or highstand systems tracts. Sequences 4-9 are characterised by increased frequencies of fern spores, lithologies often include evidence for gravity flow deposits, such as debris flows and bouma cycles, with the younger sequences including deep marine marls. Palynomorph diversities fluctuate, as do palynomorph concentrations, which are sometimes very low. Terrestrially derived palynomorph concentrations probably reflect down slope transportation as a result of gravity flow processes. Cool climate indicators, such as *Podocarpidites* spp. are regularly present in the upper lithological sequences (6-8). These features are more suggestive of lowstand deposition (perhaps with intercalated condensed sections, but the latter without a palynological response).

As with the first scenario, the increase in abundance of *Podocarpidites* spp., coupled with reduced palynomorph diversities in lithological sequence 8 is the best candidate for correlation with the most pronounced sea level fall of the Middle to Late Eocene, at the beginning of sequence TA 4.1 (after 36.0 Ma). Lithological sequence 8 would therefore be correlated with Sequence 4.1 of Haq et al., (1987 in Hardenbol et al., 1998).

Litlological sequences 4-7, which contain evidence for gravity flow deposits, cannot be further divided into systems tracts, since palynomorph diversities are moderately high to high throughout, and palynomorph assemblages show few major changes. It is considered likely that these lithological sequences relate to a single lowstand systems tract in the sense of Haq (1987 in Hardenbol et al., 1998), with the four lithological sequences reflecting four phases of influx of gravity flow deposits into the region, possibly at the scale of parasequences. It is noteworthy that evidence for dry climates (normally associated with low latitude lowstands) is minimal, and that palynomorph assemblages with the moderately high to high palynomorph diversities, would fit well with the TA 3.6 lowstand during which time global sea levels did not fall to the same degree as subsequent lowstands, and equatorial climates were more likely to have remained relatively warm and wet, although the incoming of rare *Podocarpidites* spp. within lithological sequence 6 may reflect the onset of cooler climates. It would have been during the TA 3. 6 sequence that the

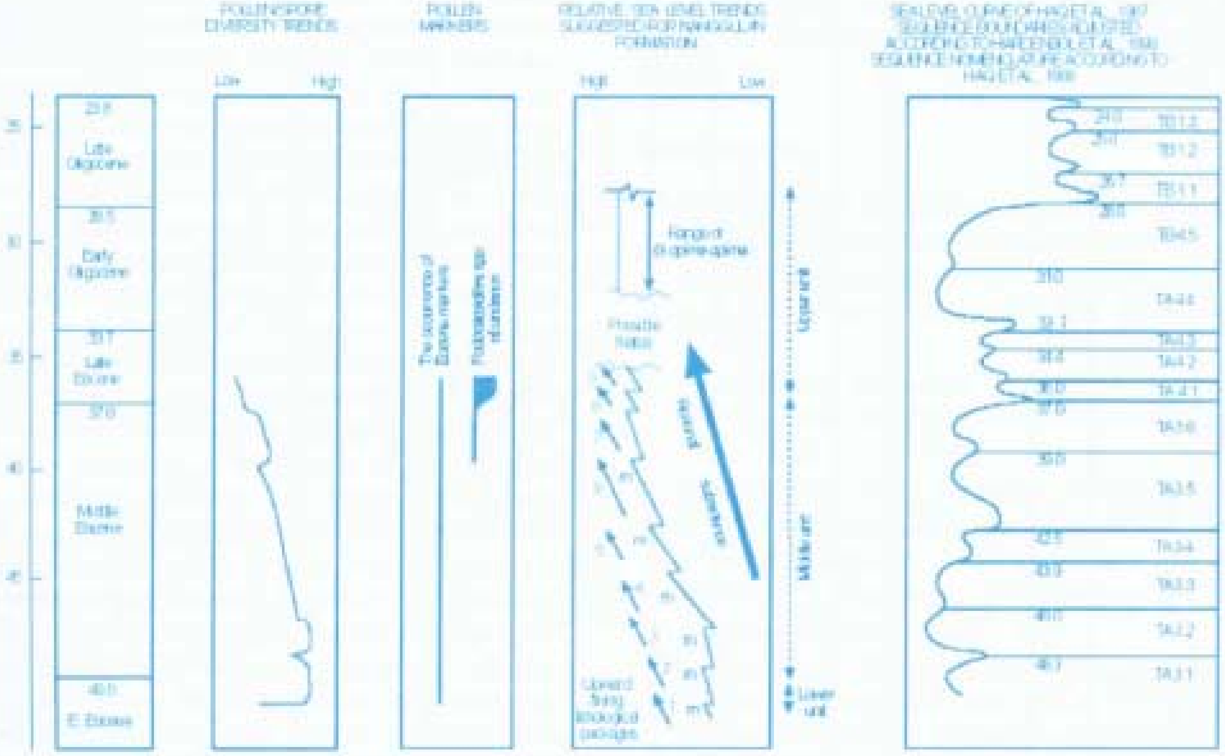

Figure 8

Correlation of lithological sequences assuming that all relate to the globally correlatable sequences of Haq et al. (1987 in Hardenbol et al., 1998). m: mangrove pollen maxima, red numbers: lithological sequences as shown in Figure 3

main phase of regional subsidence took place to account for the sudden transition from predominantly highstand deposits (see below) to lowstand deposition.

Lithological sequences 1-3 are all characterised by coastal plain and shelf lithologies, moderate to high palynomorph concentrations, very high palynomorph diversities, and the dominance of pollen types indicating very warm and wet conditions. These lithological sequences are best interpreted in terms of deposition within transgressive or highstand systems tracts. The interval represented by lithological sequences 1-3 can tentatively be divided into two units, lithological sequences 1 and 2 representing the lower unit, which is characterised by regular *Florschuetzia* spp., and *Leiotriletes* spp., and lithological sequence 2 comprising the upper unit, which is characterised by common *Palmaepollenites* spp., and with common *Spinizonocolpites echinatus* and *Proxapertites operculatus*, especially at the base. This subdivision may tentatively reflect separate transgressive/highstand systems tracts, with the increased representation of *Spinizonocolpites echinatus* and *Proxapertites cursus* (which are more reliable brackish indicators than *Florschuetzia* spp. and the *Leiotriletes* group in the pre-Miocene (Morley, pers. com.) reflecting a phase of transgression at the base of the upper transgressive/highstand package. These two systems tract packages could relate to the TA 3. 4 and 3. 5 sequences of Haq et al. (1987 in Hardenbol et al., 1998). Another possibility is that lithological sequences 1-3 may only relate to TA 3. 5 transgressive/ highstand package. Based on systems tract characterization, the correlation with the global sea level curve would be as indicated in List 2.

This scenario is considered more realistic than the earlier scenario, which assumes that all the lithological sequences present relate to the globally correlatable sequences of Haq et al. (1987 in Hardenbol et al., 1998). This sequence model suggests that the Nanggulan Formation, excluding the mid Oligocene upper part of the Seputih Member, represents the later part of the Middle Eocene, and earliest Late Eocene, from about 43-36 Ma.

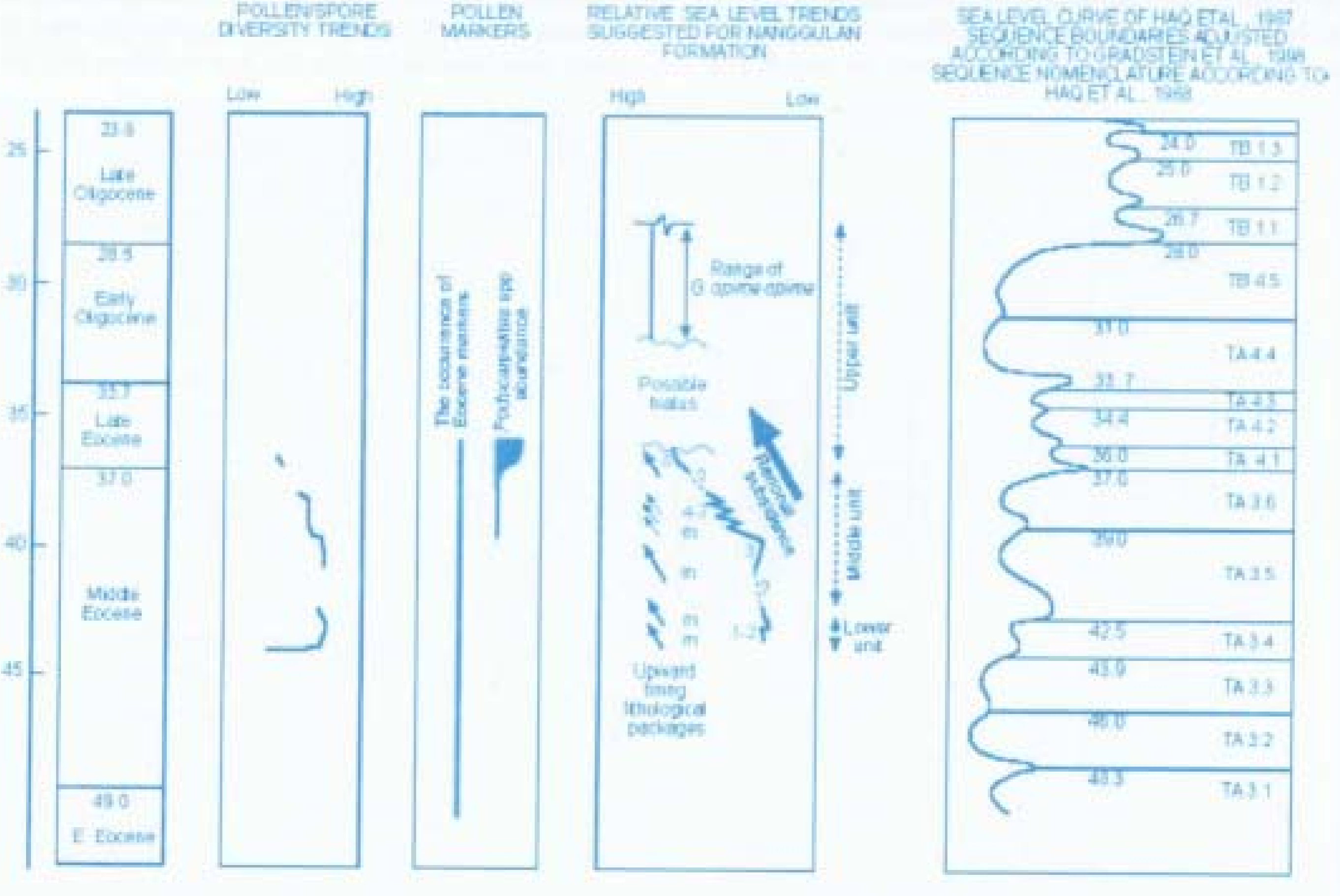

Figure 9

Realistic correlation of lithological sequences with the globally correlatable sequences of Haq et al. (1987 in Hardenbol et al., 1998). m: mangrove pollen maxima, red numbers: lithological sequences as

List 2
Realistic correlation of lithological sequences with the globally corralatable sequences of Haq et al. (1987 in Hardenbol et al., 1998; See Figure 9)

Lithological sequence/ Sequence boundary in Nanggulan Formation	Possible correlation with sequence/sequence boundaries of Haq et al (1987, modified according to Gradstein et al 1994 in Hardenbol et al., 1998)
Sequence 9	Unassigned
Sequence boundary 8	Unassigned
Sequence 8	TA 4.1 lowstand systems tract
Sequence boundary 7	37.0 Ma sequence boundary
Sequence 4-7	TA 3.6 lowstand systems tract
Sequence boundary 3	39.0 Ma sequence boundary
Sequence 3	TA 3.5 transgressive and highstand systems tracts
Sequence boundary 2	42.5 Ma sequence boundary
Sequence 1-2	TA 3.4 transgressive and highstand systems tract

IV. CONCLUSION

Lithological evidence (fining-upward trends) enables subdivision of the Nanggulan succession into nine lithological sequences (namely sequence 1 to sequence 9) and 8 sequence boundaries (namely sequence boundaries 1 to 8). This interpretation is also supported by fossil evidence (palynomorphs and foraminifers). However, these lithological sequences may not necessarily correspond to the global sea level curve and globally correlated sequences proposed by Haq et al., (1987 in Hardenbol et al., 1998) because they are informal units which probably represent shorter term events (e. g. reflecting parasequences). Palynological evidence, including mangrove palynomorph maxima and palynomorph diversity representing palaeoclimatic trend, enables more reliable comparison with the global sea level curve. The palynological evidence is used to interpret system tracts which are the internal building blocks of sequences. In addition to mangrove pollen maxima, evidence for warm and/ or wet climates provides support for high sea level scenarios (highstand systems tract), whereas cool/dry climate evidence suggests a low sea level setting (lowstand systems tract). Based on the identification of system tracts, the lithological sequences in the Nanggulan Formation can be correlated with the global sea level curve. The most realistic correlation suggests that lithological sequences 1 and 2 are correspond with TA 3. 4 transgressive and highstand system tract; lithological sequence 3 with TA 3. 5 transgressive and highstand system tract; lithological sequences 4 to 7 with TA 3. 6 lowstand system tract and lithological sequence 8 with TA 4. 1 lowstand system tract. The youngest lithological sequence (sequence 9) is unassigned. Based on correlation of the global sea level curve to the timescale (Hardenbol et al 1998) this sequence model suggests that the Nanggulan Formation, excluding the Oligocene upper part of the Seputih Member, represents the later part of the Middle Eocene and earliest Late Eocene, from about 43 to 36 Ma.

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