From the Solo to the Madura Strait: Quaternary geology, vertebrate palaeontology and hominin chronology of eastern Java and submerged Sundaland

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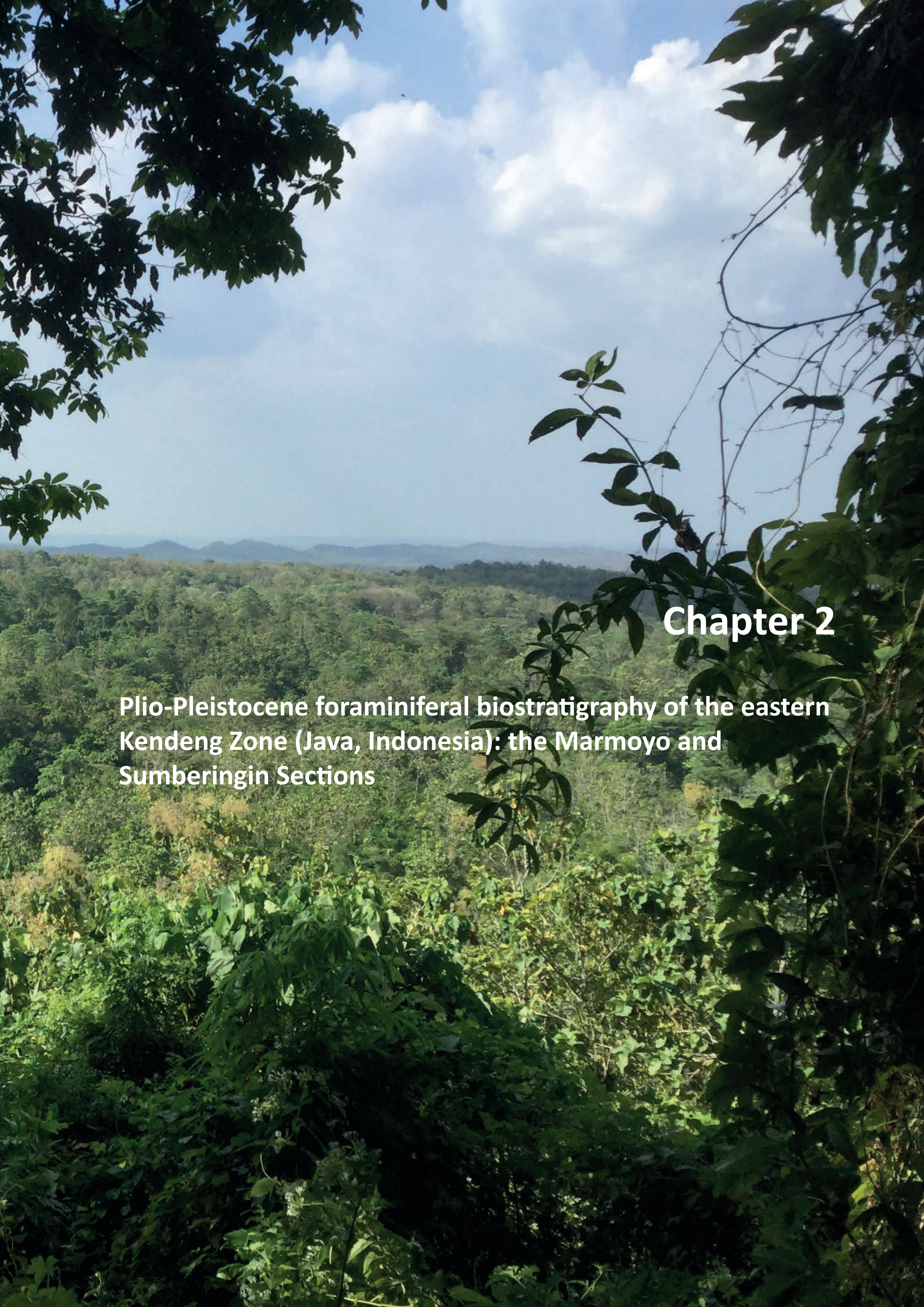
View from Gunung Marmoyo, looking to the northwest. The Marmoyo River is beneath the canopy.



Chapter 2

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Plio-Pleistocene foraminiferal biostratigraphy of the eastern Kendeng Zone (Java, Indonesia): the Marmoyo and Sumberingin Sections

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ABSTRACT

The Plio-Pleistocene of the eastern Kendeng Hills (Java, Indonesia) consists of a more than 1,250 m thick series, passing upwards from diatomaceous laminated mudstones to blue clays and deltaic sandstones. The fine-grained marine beds have received little attention from researchers. Age assumptions are based on correlations with better-studied sections in the western Kendeng Hills. In contrast, the deltaic sandstones at the top of the series have received ample attention. These beds are renowned for their fossil vertebrate fauna, including *Homo erectus*. Lately, doubts have arisen concerning the age and stratigraphic position of the fossiliferous sandstones. The aim of this study is to establish a detailed biostratigraphy of the fine-grained marine beds, which may also provide new age indications for the overlying fossil-bearing sandstones.

We selected the Marmoyo and Sumberingin Sections as suitable representatives for the local marine stratigraphy. Both sections were logged and sampled, and the samples were analysed for their foraminifera content. The sections provide sufficient biostratigraphic markers to allow for a reasonable age control. We found that the diatomaceous facies is older than previously thought: it dates from the Early Pliocene and corresponds in age with bathyal, foraminifera-rich mudstones of the western Kendeng Zone. It implies the existence of two bio-geographic zones in the Early Pliocene basin, with eutrophic, oxygen-depleted conditions in the east and normal oxygen conditions in the west. The diatomaceous mudstones change upwards into foraminifera-rich mudstones, marking a return to normal oxygen conditions later in the Early Pliocene, and eventually into blue clays, representing a shift from bathyal to outer shelf conditions in the Late Pliocene. Higher up in the blue clays, changes in the planktonic foraminifera assemblage indicate cooler water conditions, which we relate to the beginning of the Pleistocene.

Although generally regarded as a continuous regressive series, our work revealed the existence of an unconformity within the blue clays. The blue clays above this unconformity represent a shallow marine, deltaic setting. It is this second blue clay series that passes conformably into the overlying deltaic sandstones. The presence of reworked planktonic foraminifera in the upper clay-series hampers adequate biostratigraphic dating, but the stratigraphic break within the clays suggests that this second sequence is younger than previously assumed.

1. Introduction

The Kendeng is an east-west trending fold zone in East-Java (**Fig. 1**). Nowadays it is an undulating hill-range, reaching heights of around 300 m ASL, but during the Miocene it formed the deepest part of a narrow, marine retro-arc basin located north of an east-west trending volcanic arc (Lunt, 2013). In the Late Miocene, local volcano-tectonic conditions changed. Volcanic activity decreased and the basin, which had previously been subsiding, became subject to compressive conditions, marking a transition to large-scale uplift (Genevraye and Samuel, 1972; Hamilton et al., 1979; Smyth et al., 2008). This uplift is recorded in the foraminiferal fauna of the thick Pliocene mudstone series, which bears evidence of a gradual regression from bathyal to shelfal conditions. The mudstones pass upwards into coastal beds and subsequently into breccias and sandstones, marking emergence and resumption of active volcanism in the Pleistocene. On-going compression of the basin deposits caused folding and thrusting, characteristic of the present-day Kendeng Hills.

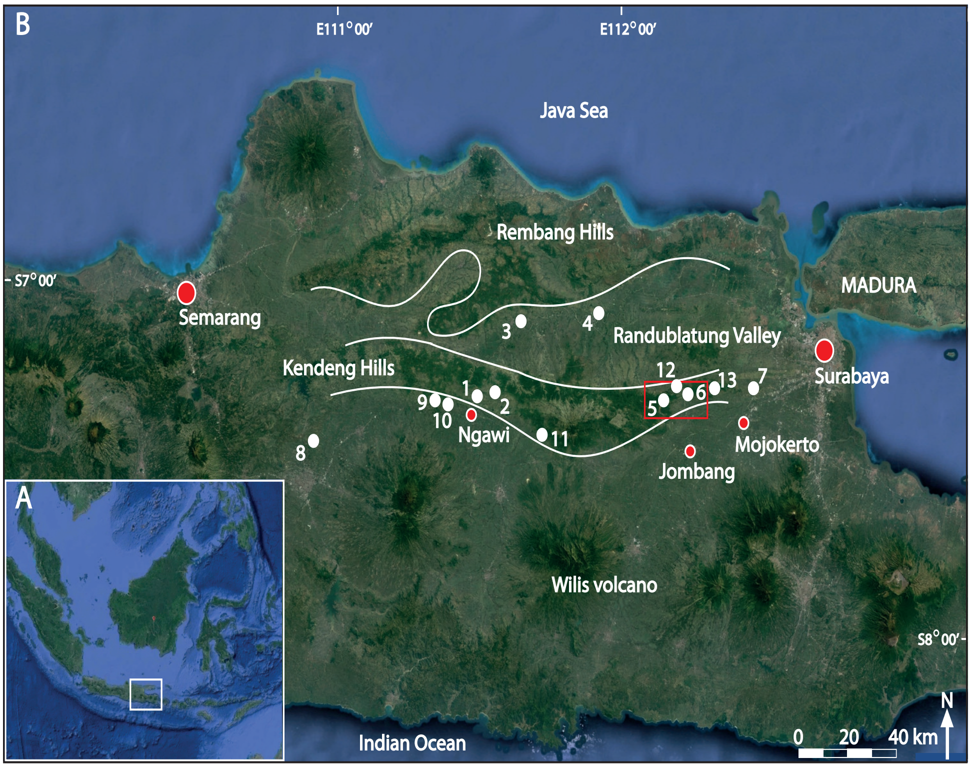


Fig. 1. A: The Indonesian archipelago with the study area on the eastern part of the island of Java. **B:** East-Java, physiographic zones, locations of the biostratigraphic sections and sites mentioned in the text. 1: Solo River Section. 2: Ngepung Section. 3: Tobo-Cepu wells. 4: Bojonegoro-1 well. 5: Marmoyo Section. 6: Sumberingin Section. 7: Perning. 8: Sangiran. 9: Sonde. 10: Trinil. 11: Kedung Brubus. 12: Kali Beng. 13: Gn. Pucangan. Red box: area shown in Figure 3. Map data: Google, DigitalGlobe.

The Plio-Pleistocene regression of the Kendeng Zone is primarily known from detailed foraminiferal biostratigraphic studies of the southwestern Kendeng Hills (Saint-Marc and Suminta, 1979; Van Gorsel and Troelstra, 1981). The local stratigraphy consists of a thick regressive series of marine mudstones, overlain by coastal beds with corals and molluscs, and capped by terrestrial breccias and sandstones. The Plio-Pleistocene series of the eastern Kendeng Hills has a different character. It consists of massive marine mudstones, overlain by several hundred metres of laminated diatomaceous mudstones, which change upwards into blue clays, which in turn change into deltaic sandstones. Except for the sandstones at the top, this series has received little attention from researchers. Based on historic mapping work by Duyfjes, the diatomaceous beds were correlated with the coastal beds of the southwestern Kendeng. The overlying blue clays were correlated with the terrestrial breccias of the southwestern Kendeng Zone.

A foraminiferal biostatigraphy of the marine series of the eastern Kendeng Zone is, so far, not available. Our study aims to establish this. It will fill an important gap in the local biostratigraphy and will allow us to test the validity of the currently used stratigraphic correlations.

The study also aims to provide a better insight into the age of the deltaic sandstones, conformably overlying the fine-grained marine series. These beds are renowned for their fossil vertebrate fauna (Cosijn, 1932, 1931; Von Koenigswald, 1935, 1934). Ever since the discovery of a *Homo erectus* skullcap in 1936, the age and stratigraphic position of the deltaic sandstones has been a source of debate (e.g. Huffman et al., 2005; Huffman, 2001a). A detailed biostratigraphy of the underlying marine series may provide a new insight into the (maximum) age of these sandstones.

2. Background

2.1 Stratigraphy, ages and correlations

2.1.1 Stratigraphy by Duyfjes

The stratigraphy of the Kendeng Zone (**Fig. 2**) was set up by Duyfjes (1936, 1938a). This author based his Plio-Pleistocene units on reference sections in the eastern Kendeng Zone. Duyfjes defined two Pliocene units, the Lower and Upper Kalibeng Formations, named after the Kali (River) Beng. The Lower Kalibeng Formation consists of massive calcareous mudstones rich in foraminifera, reaching a thickness of around 800 m. The Upper Kalibeng Formation conformably overlies this unit. It consists of several tens of metres of marine sandstones, which pass upwards into thinly laminated diatomaceous mudstones, reaching a thickness of 400 to 700 m. Duyfjes traced his Pliocene units westwards over the Kendeng Zone. The Lower Kalibeng Formation retains its facies of a massive calcareous mudstone and is well traceable in the field. In the western Kendeng Zone, this monotonous series can be seen to overly bedded sandstones and argillaceous mudstones, a transition that Duyfjes marked as the lower boundary of the unit. Mapping the Upper Kalibeng Formation from its reference area in the eastern Kendeng Zone toward the western Kendeng Zone, Duyfjes found its facies changing to slightly sandy calcareous-argillaceous mudstones and finally to the well-known reefal limestones and calcareous mudstones with marine molluscs and coral fragments, as exposed along the southwestern flanks of the Kendeng Zone. These reefal strata generally have a thickness of 100 to 200 m.

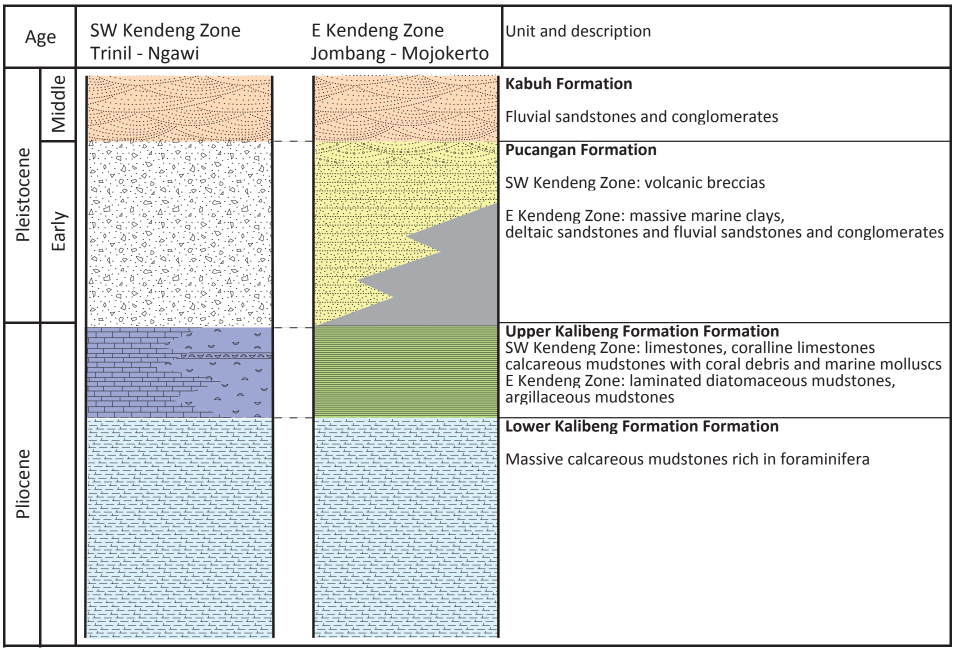


Fig. 2. Plio-Pleistocene Kendeng Zone stratigraphy. Adapted from Duyfjes (1936, 1938).

Duyfjes also defined two relevant Pleistocene units: The Pucangan and Kabuh Formations. He used the Sumberingin Section as his reference section; the names of the units refer to a nearby hill (Pucangan) and village (Kabuh). The base of the Pucangan Formation consists of marine blue clays, which Duyfjes found conformably overlying the diatomaceous mudstones of the Upper Kalibeng Formation. The clays change upward into deltaic and fluvial sandstones, which he referred to as the Volcanic Facies of the Pucangan Formation. For Duyfjes, the Pucangan Formation represented a prograding delta over a shallow muddy sea. In the Sumberingin Section, the clays reach a thickness of ca. 300 m, whereas the overlying sandstones are almost 500 m thick. Toward the northeast, the thickness of the clays increases and the sandstones eventually wedge out. The upper part of the Sumberingin Section consists of cross-bedded, fluvial sandstones and conglomerates, which Duyfjes regarded as a separate unit: the Kabuh Formation.

Tracking his Pleistocene units westward over the Kendeng Zone, Duyfjes found that the Clay Facies of the Pucangan Formation gradually disappears. Around Ngawi and Trinil, volcanic breccias directly overlie the Upper Kalibeng Formation, which in this area consists of reefal beds. Duyfjes regarded the breccias as the Volcanic Facies of the Pucangan Formation. These breccias are overlain by cross-bedded fluvial sandstones, which Duyfjes correlated with the cross-bedded sandstones in the eastern Kendeng Zone and consequently regarded as the Kabuh Formation.

2.1.2 Von Koenigswald’s vertebrate biostratigraphy

Von Koenigswald (1935, 1934) developed a vertebrate biostratigraphy for the terrestrial strata of Java. Duyfjes (1936, 1938a) referred to this biostratigraphy, stating that the Pucangan Formation contains the Early Pleistocene Jetis Fauna and that the Kabuh Formation contains the Middle Pleistocene Trinil Fauna. The timing of the publications suggests that Duyfjes drew the boundary between his two Pleistocene units based on Von Koenigswald's faunal units. However, Huffman (2005) suggested that Duyfjes defined his units earlier, based on lithological characteristics.

2.1.3 The *Homo erectus* of Perning and its age

Ever since the finding of a *Homo erectus* skullcap in Perning (Mojokerto) in 1936, the age of the deltaic sandstones of the eastern Kendeng Zone has been subject of debate (Huffman et al., 2005). The fossil was found in a conglomerate bed, which Duyfjes indicated as the Pucangan Formation (Duyfjes, 1936). Based on his stratigraphic correlations, it is older than the *Homo erectus* fossils of Trinil (Dubois, 1894a), which come from beds that Duyfjes indicated as the Kabuh Formation. Using Von Koenigswald's biostratigraphy, the Trinil fossils are of Middle Pleistocene age and the Perning skullcap is of Early Pleistocene age. Many years later, a similar debate came up after de Vos (1982) and Sondaar (1984) rejected Von Koenigswald's vertebrate biostratigraphy, indicating that it was based on fossils from mixed localities and a poorly known stratigraphic provenance. They presented a new vertebrate biostratigraphy, consisting of an Early Pleistocene Trinil HK Fauna and a Middle Pleistocene Kedung Brubus Fauna. They assigned the fossils of the sandstones near Perning to the Middle Pleistocene Kedung Brubus Fauna and the main fossil-bearing bed of Trinil to the Early Pleistocene Trinil HK Fauna. Their revision suggests that the deltaic sandstones of the eastern Kendeng Zone date from the Middle Pleistocene. Moreover, it implicates that Duyfjes' stratigraphic correlations of the Pleistocene units over the Kendeng Zone are invalid, again leading to debate (Bartstra, 1983; Hooijer, 1983; Hooijer and Kurtén, 1984). A decade later, Swisher et al. (1994) carried out ^{40}Ar/^{39}Ar on volcanic pumice of the Perning site, arriving at an age of 1.81 ± 0.04 Ma. This again pushed back the age of the Perning *Homo erectus* and the surrounding deltaic beds to the Early Pleistocene, however, it was rejected by others, claiming that the pumice is reworked (Langbroek and Roebroeks, 2000; Vos et al., 1994). Reworked or not, Morwood et al. (2003) conducted fission track dating on pumice at the Perning site and found an age of 1.49 ± 0.13 Ma.

2.1.4 Revisions by Pringgoprawiro and local stratigraphic practice

Pringgoprawiro (1983) renamed the Lower Kalibeng Formation as the Kalibeng Formation and the Upper Kalibeng Formation as the Sonde Formation, using a type section near the village of Sonde in the southwestern Kendeng Zone. Holding on to Duyfjes correlations, he also renamed the laminated diatomaceous mudstones of the eastern Kendeng Zone to Sonde Formation. Moreover, he separated the blue clays from the Pucangan Formation and assigned them to the Lidah Formation, which is an older name for similar clays found in the Randublatung Zone, the lowland north of the Kendeng Hills. Although international researchers generally hold on to Duyfjes' units, Indonesian researchers often follow Pringgoprawiro's revisions (Noya e.a., 1992; Sukardi, 1992).

2.2 Foraminiferal biostratigraphy

Foraminiferal biostratigraphic studies have greatly contributed to our understanding of the Kendeng Zone stratigraphy. Calibration using the magnetostratigraphy acquired by regional deep-sea drilling has provided detailed ages for first occurrences (F.O.) and last occurrences (L.O.) of planktonic foraminifera species (Berggren et al., 1995, 1985; Wade et al., 2011). Unless specified, biostratigraphic ages mentioned in this paper are based on Wade (2011). Below we summarize and briefly discuss several relevant biostratigraphic studies from different localities.

The Bojonegoro-1 well (Bolli, 1966) is located in the Randublatung Zone, north of the Kendeng Hills. During the Mio-Pliocene, this area formed the slope north of the deeper Kendeng Basin. The base of the well reaches calcareous mudstones with a Miocene planktonic foraminifera fauna. These are overlain by argillaceous-calcareous mudstones containing Late Pliocene biostratigraphic markers, implying a latest Late Miocene – Early Pliocene hiatus. The Late Pliocene mudstones above the hiatus represent upper bathyal to outer shelf conditions (Boomgaart, 1949; Lunt, 2013).

The Ngepung Section (Saint-Marc and Suminta, 1979) is a river section located in the southwestern Kendeng Zone, covering 650 m of massive calcareous mudstones representing Duyfjes' Lower Kalibeng Formation. The mudstones provide a continuous depositional record, starting in the Late Miocene and covering the entire Pliocene, without the hiatus of the Bojonegoro-1 well. The mudstones are overlain by reefal limestones (Upper Kalibeng Formation), which the authors date as Early Pleistocene.

The Solo River Section (Van Gorsel and Troelstra, 1981), re-evaluated by Lunt (2013), offers the most detailed foraminiferal biostratigraphy of the western Kendeng Zone. It covers approx. 800 m of massive calcareous mudstones, rich in well-preserved foraminifera and contains a fine array of relevant biomarkers. The mudstones form an uninterrupted series, starting in the Late Miocene age and covering the entire Pliocene. The regressive nature of the upper part of this series is reflected by its benthic fauna and a decreasing ratio between planktonic and benthic foraminifera (P/B-ratio). The reefal limestones overlying the mudstones contain several datum levels suggesting an Early Pleistocene age: the F.O. of *Globorotalia* cf. *truncatulinoides* (1.93 Ma), the last occurrences of *Globigerinoides extremus*

(1.99 Ma) and *Globigerinoides fistulosus* (1.88 Ma), as well as a dextral to sinistral coiling change in *Globorotalia menardii*.

Biostratigraphic data are also available for several wells near Tobo - Cepu, in the western Randublatung Zone. Although not very detailed and relatively far from the eastern Kendeng Zone, the sections are relevant because they cover the blue clays that Pringgoprawiro (1983) correlated with the blue clays of the eastern Kendeng Zone (as the Lidah Formation). In this area, the clays occur from the surface down to depth of approx. 350 m. The clays overlie a coarse lag of sandstones with marine molluscs, locally known as the Selorejo Formation. The base of this coarse interval is an unconformity above the Pliocene calcareous mudstones. Several researchers report the first arrival *G. truncatulinoides* (F.O. 1.93 Ma) in the base of the clays, directly above the Selorejo Formation (Pringgoprawiro and Baharuddin, 1979; Sanyoto, 2009).

3. Methods

3.1 The sections

After an elaborate inspection of local river sections, we concluded that a continuous section, running through the entire marine series, from the diatomaceous mudstones to the blue clays and the overlying sandstones, is not available. This is mainly due to a poor exposure of the blue clays. We selected two river sections, which together provide the best possible coverage of the local stratigraphy: The Marmoyo Section and the Sumberingin Section (**Fig. 3**). Both sections were described by Duyfjes (1938a) and form key sections in his original stratigraphy.

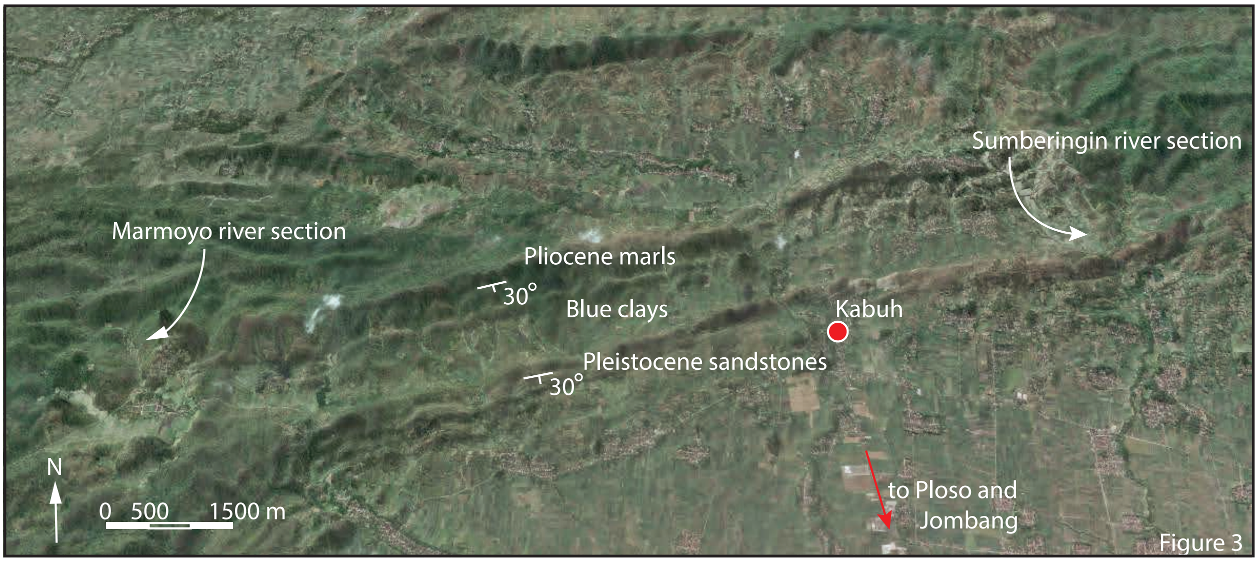


Fig. 3. Location of the Marmoyo and Sumberingin Sections and local geological structure. For location see **Figure 1**. Map data: Google, DigitalGlobe.

The studied river sections cut through the southern flank of a large anticline. North of Marmoyo, this flank of the anticline is thrusted northwards over younger strata. The Marmoyo Section exposes a marine series of ca. 600 m. The series is undisturbed by the thrustzone, which is located just north of the section, and the beds have a constant dip of approx. 30 degrees to the south. The base of the section consists of bedded marine sandstones, regarded by Duyfjes as the base of the Upper Kalibeng Formation in its eastern facies. Moving southwards, the sandstones pass into the overlying laminated diatomaceous mudstones, which dominate this section. The laminated mudstones pass into massive calcareous-argillaceous mudstones rich in foraminifera, which in turn change into massive blue clays, regarded by Duyfjes as the Clay Facies of the Pucangan Formation. The clays form the top of the section and are exposed in the creek just before it enters a wider, east-west trending valley. The blue clays make up the subsoil under this valley, although poorly exposed.

Moving approx. 10 km to the east, parallel to the axis of the anticline and following this wide valley, we find the Sumberingin creek cutting a gully through the fields and exposing the local blue clays. The creek continues to the south where it cuts through another ridge, representing the sandstones overlying the blue clays. The gradual transition from clays to deltaic sandstones is well exposed. The sandstone section was first described by Van Es (1931) and later by Duyfjes (1938a). Duyfjes used it as the standard section for his Pleistocene units, the Pucangan and Kabuh Formations. Both authors mentioned the underlying clays, but did not include them in their detailed descriptions, merely describing the clays as ‘homogenous’. We found the exposed clays in the base of this section to have a thickness of almost 300 m. Unfortunately, the creek does not expose the lower boundary of the clays. The blue clays, as exposed in the creek, generally dip southward by ca. 30 degrees, following the dip of the flank of the anticline. But the dip of the strata also reveals the existence of a gentle superimposed fold, forming a small local anticline. The core of this gentle fold represents the lowest stratigraphic level of the clays exposed in the creek. In the fields, near the core of this small anticline, there is an isolated hill consisting of lighter coloured calcareous mudstones, indicating that we are very close to the lower boundary of the clays.

The Sumberingin Section stratigraphically overlies the Marmoyo Section. Together, the sections form a marine record with a thickness of ca. 1,400 m. Our biostratigraphic study includes the combined stratigraphic section, up to the base of the deltaic sandstones, covering more than 800 m. The sandstones were left out of the biostratigraphic study, as they are largely made up of transported erosion products.

We attempted to ensure a stratigraphic overlap between the two sections, in order to provide a good stratigraphic fit. However, appearances of new species in the base of the Sumberingin Section indicate that there is a minor gap between the two sections **(Section 5.3.1)**. For detailed charts of the sections and field pictures reference is made to supplemental figures S1 to S4.

3.2 Field and laboratory procedures

We measured, described and photographed the sections in detail and sampled with an interval of 10 – 20 m. Sample preparation was carried out in the Laboratory for Sediment Analysis of the Vrije Universiteit, Amsterdam. To retrieve the foraminifera, the samples were emerged in petroleum ether for two days, after which the fluid was decanted. Subsequently, boiling water was poured over the samples, disaggregating the material. This method provided reasonable residues which, after sieving through a >63 µm mesh and drying on a hotplate, were studied under a binocular microscope.

We studied a total of 43 samples for their foraminiferal content. We listed the total occurrences per sample of planktonic and benthic foraminifera and diatoms as poor, moderately rich or rich. Diatom occurrences mentioned in this paper only include the >63 µm specimens. Diatoms were not included in further identification work. Preservation of the foraminifera is generally reasonable, allowing for proper identification. Planktonic species strongly dominate the assemblages. Benthic species are scarce and often occur as single specimens. The faunal analysis was carried out semi-quantitatively, with occurrences per species listed as scattered, common or abundant. P/B-ratios were determined based on actual counts, however note that there are large differences in total foraminifera occurrences per sample, affecting the significance of the P/B-ratios. A sample may for example be rich in planktonic foraminifera and poor in benthic foraminifera and have a P/B-ratio of 95%, whereas another sample may be poor in planktonic foraminifera and extremely poor in benthic foraminifera, and yet also have a P/B ratio of 95%.

3.3 Nomenclature for fine-grained rocks

The studied sections are dominated by clay to silt sized marine sediments. In previous publications on the Kendeng Zone, similar sediments where either named marls (Duyfjes, 1938a, 1936) or mudstones (Lunt, 2013), the latter referring to a carbonate-classification system such as proposed by Dunham (1962). The studied sediments have a varying composition, which makes the description ‘mudstones’ insufficient. We follow Lazar et al. (2015) and refer to all indurated sediments with more than 50% of the grains being clay or silt-sized (< 63 µm) as mudstones. The mudstones have been given an attribute for their dominant composition (calcareous, argillaceous or diatomaceous). In cases of mixed composition, sediments were given two attributes (e.g. calcareous-argillaceous). Composition of the sediments was determined by field observation and laboratory analysis. Carbonate content was estimated with hydrochloric acid (10%). Not indurated, clay-dominated, plastic sediments have been referred to as clays.

4. Results: facies and fauna

We divided the combined biostratigraphic section into 11 zones, each with a characteristic facies and microfauna (**Fig. 4**). Zones I – V represent the Marmoyo Section; Zones VI – XI the Sumberingin Section.

4.1 Zone I (917 – 940 m)

Lower boundary: not exposed. Facies: Brownish-yellow, bedded, fine to medium grained sandstones and interbedded calcareous-argillaceous mudstones. Sand grains are mainly of terrigenous origin, with admixture of foraminifera and sporadic fine shell debris. Sandstone beds range in thickness between 10 and 40 cm and are massive or vaguely planar laminated. Interbedded mudstones are massive and have an average thickness of 10 cm. Rich in foraminifera, P/B-ratio: 99%.

Planktonic foraminifera: Rich. Abundant occurrences of *Globorotalia tumida*, *Globorotalia menardii* (dextral), *Globigerinoides trilobus* and *Globigerinoides ruber.* Common occurrences of *Globigerina bulloides*, *Dentogloboquadrina altispira* and *Sphaeroidinella dehiscens.* Scattered occurrences of *Neogloboquadrina* cf. *pachyderma* and *Pulleniatina obliquiloculata.*

Benthic foraminifera: Poor. Scattered occurrences of *Cibicidoides wuellerstorfi, Uvigerina peregrina, Pullenia bulloides*, *Gyroidina* sp., *Bulimina marginata*, *Eponides* sp. and *Lenticulina* sp.

4.2 Zone II (793 – 917 m)

Lower boundary: Gradational. Facies: Greyish-white, planar laminated diatomaceous mudstones. Rich in diatoms in the > 63 µm fraction. Slightly calcareous. Poor to moderately rich in foraminifera, P/B-ratio: 99%.

Planktonic foraminifera: Poor to moderately rich. Common occurrences of *G. tumida* and *Globigerinoides trilobus*. Scattered occurrences of *G. menardii* (dex.)*, Globigerinoides ruber, G. bulloides* and *P. obliquiloculata.*

Benthic foraminifera: Poor. Scattered occurrences of *Gyroidina* sp., *Osangularia bengalensis* and *Oridorsalis tener.*

4.3 Zone III (635 – 793 m)

Lower boundary: Gradational. Facies: White, planar laminated (platy) diatomaceous mudstones. Very rich in diatoms. Slightly calcareous. Poor in foraminifera, P/B-ratio: >99%.

Planktonic foraminifera: Poor. Scattered occurrences of *G. tumida*, *G. trilobus, G. ruber* and *S. dehiscens.*

Benthic foraminifera: Extremely poor to absent. Scattered occurrences of *Hyalinea balthica.*

Zone III contains two interbedded sandstone beds (at 725 and 792 m), with a thickness of ca. 0.5 m. Facies: Brownish-yellow, fine to medium grained sandstones. Sand grains are mainly of terrigenous origin, with admixture of foraminifera and sporadic fine shell debris. Beds are internally unstructured. The sand bed at 725 m was analysed for foraminifera. The material is moderately rich in foraminifera. Many of the foraminifera are broken. P/B-ratio: 90%.

Planktonic foraminifera: Moderately rich. Abundant occurrences of *G. menardii* (dex.) and *P. obliquiloculata.* Scattered occurrences of *G. tumida, G. trilobus* and *Neogloboquadrina pseudopima.*

Benthic foraminifera: Moderately rich. Common occurrences of *Hyalinea balthica.*

Scattered occurrences of *Bulimina marginata, Lenticulina* sp., *Ammonia supera* and *Melonis barlaeanus.*

4.4 Zone IV (475 – 635 m)

Lower boundary: Conformable, but sharp. Facies: Light grey, massive calcareous-argillaceous mudstones. Upward, detrital clay content increases and colour changes from white to light grey. Rich in foraminifera, P/B-ratio: 99%.

Planktonic foraminifera: Rich. Abundant occurrences of *G. menardii* (dex.), *N. pseudopima, G. trilobus* and *G. bulloides*. Common occurrences of *G. tumida, G. tumida flexuosa* (abundant in the lower part of this zone)*, P. obliquiloculata, G. ruber, Pulleniatina primalis, Orbulina universa, S. dehiscens, S. subdehiscens* and *Neogloboquadrina acostaensis*. Scattered occurrences of *Globorotalia miocenica, Globorotalia multicamerata*, *Neogloboquadrina humerosa* and the *Globorotalia crassaformis–tosaensis* group.

Benthic foraminifera: Poor. Scattered occurrences of *Cibicidoides wuellerstorfii, Pullenia bulloides*, *Gyroidina* sp., *Bulimina marginata*, *Bolivina robusta*, *Globocassidulina subglobosa* and *Sigmoilopsis schlumbergeri*.

Zone IV contains a well arranged series of first (F.O.) and last occurrences (L.O.) of index species: L.O. of *Globorotalia margaritae* (3.84 Ma), F.O of *G. miocenica* (3.76 Ma), L.O. of *Globorotalia plesiotumida* (3.76 Ma), L.O. of *Sphaeroidinellopsis seminula* (3.67 Ma), L.O. of *P. primalis* (3.65 Ms), L.O. of *S. subdehiscens* (3.57 Ma), L.O. of *D. altispira* (3.46 Ma), F.O. of *Globigerinoides fistulosus* (3.33 Ma) and the F.O. of *Globorotalia pertenuis* (3.1 Ma).

4.5 Zone V (393 – 475 m)

Lower boundary: gradational. Facies: Bluish-grey, massive clays. Very low admixture of silt, plastic, slightly calcareous. Poor to moderately rich in foraminifera, P/B-ratio: 95%.

Planktonic foraminifera: Base is poor in planktonics. Upwards the fauna recovers to moderately rich. Common occurrences of *G. tumida, G. trilobus, G. ruber, G. bulloides* and *N. acostaensis.* Scattered occurrences of *G. menardii* (dex.)*, N. pseudopima* and the *G. crassaformis-tosaensis group*.

Benthic foraminifera: Poor. Scattered occurrences of *Lenticulina* sp*., Bulimina marginata, Ammonia* sp*., Hoeglundia elegans, Hyalinea balthica, Brizalina* sp., *Bolivina quadrilatera* and *Pseudorotalia gaimardii.*

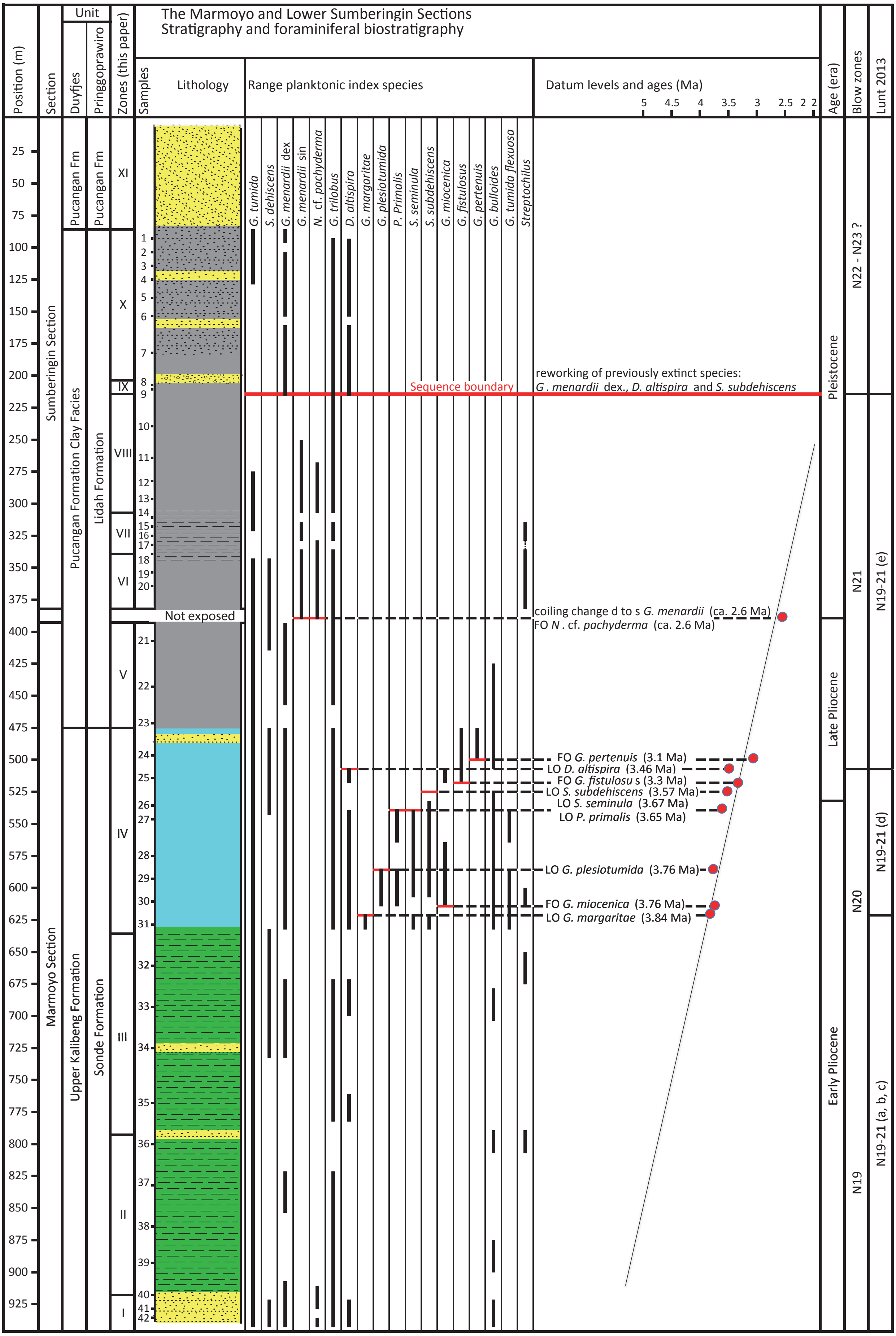


Fig. 4. Planktonic foraminifera biostratigraphy of the combined Marmoyo-Sumberingin Section. Note: only a selection of planktonic index species is shown. See text for full assemblage descriptions. Lithology legend: see **Fig. 5**.

4.6 Unexposed interval: (383 – 393)

Zone V forms the top of the Marmoyo Sections and Zone VI forms the base of the Sumberingin Section. Differences in the foraminiferal fauna indicate that there is an unexposed interval between the sections. We provisionally assumed a thickness of 10 m for this unexposed interval (see section 5.3.1).

4.7 Zone VI (340 – 383 m)

Lower boundary: Not exposed. Facies: Bluish-grey, massive clays. Very low admixture of silt, plastic, moderately calcareous. Contains carbonate concretions. Rich in foraminifera, P/B-ratio: 95%.

Planktonic foraminifera: Rich. Abundant occurrences of *G. menardii* (sin.), *N. pseudopima, N. humerosa, G. trilobus, G. ruber* and *Streptochilus* sp. Common occurrences of *P. obliquiloculata* and *N.* cf. *pachyderma.* Scattered occurrences of *G. tumida, O. universa* and *S. dehiscens.*

Benthic foraminifera: Poor. Scattered occurrences of *Ammonia* sp., *Sphaeroidina bulloides, Gyroidina* sp.*, Brizalina* spp.*, Hyalinea balthica, Bulimina marginata, Uvigerina* sp*.* and *Hoeglundia elegans.*

4.8 Zone VII (306 – 340 m)

Lower boundary: Conformable, but sharp. Facies: Light grey, laminated argillaceous-diatomaceous mudstones. Rich in diatoms and radiolaria. Poor to moderately rich in foraminifera, P/B-ratio: 99%.

Planktonic foraminifera: Poor to moderately rich. Scattered occurrences of *N. pseudopima*, *N. humerosa*, *G. trilobus*, *G. ruber*, *Streptochilus* sp.*, G. menardii* (sin.) and *N.* cf. *pachyderma.*

Benthic foraminifera: Poor. Common occurrences of *Brizalina* spp. Scattered occurrences of *Bulimina marginata* and *Bulimina aculeata.*

4.9 Zone VIII (215 – 306 m)

Lower boundary: Conformable, but sharp. Facies: Bluish-grey, massive clays. Very low admixture of silt, plastic, rich in organic matter, moderately calcareous. Rich in foraminifera, P/B-ratio: 95%.

Planktonic foraminifera: Rich. Abundant occurrences of *G. menardii* (sin.), *N. pseudopima* and *N. humerosa.* Commom occurrences of *P. obliquiloculata*, *G. ruber, G. trilobus* and *N.* cf. *pachyderma.* Scattered occurrences of *G. tumida* and *G. crassaformis ronda.*

Benthic foraminifera: Poor. Scattered occurrences of *Ammonia* sp.*, Sphaeroidina bulloides, Gyroidina* sp.*, Brizalina* sp., *Hyalinea balthica, Bulimina marginata, B. aculeata, Uvigerina* sp.*, Hoeglundia elegans, Nodosaria* sp.*, Lenticulina* sp.*, Eponides* sp. and *Baggina indica*.

4.10 Zone IX (210 – 215 m)

Lower boundary: Erosive. Facies: Mottled greyish-red, conglomerate. Matrix of coarse sand (moderately rounded), sand grains mainly of terrigenous origin, but with abundant shell fragments, highly calcareous. Gravel pebbles up to 3 cm, moderately rounded, polymict composition (mainly andesitic). Vaguely bedded, channel-fill structures. Moderately rich in foraminifera, P/B-ratio: 50%.

Planktonic foraminifera: Moderately rich. Common occurrences of *G. trilobus* and *P. obliquilocuta.* Scattered occurrences of *G. menardii* (dex)*, G. ruber, G. obliquus, D. altispira* and *S. subdehiscens.*

Benthic foraminifera: Moderately rich. Abundant occurrences of *Brizalina* sp., *Pseudorotalia conoides* and *Asterorotalia trispinosa.* Scattered occurrences of *Elphidium* sp. and the larger foraminiferal species *Amphistegina lessonii* and *Gypsina* sp*.*

4.11 Zone X (85 – 210 m)

Lower boundary: Gradational. Facies: Bluish-grey, massive clays, low admixture of silt and fine sand, plastic, rich in organic matter, highly calcareous. Upward, the sand content increases, with lenses and laminae of fine sand and fine shell debris. In the upper part of this zone, sandbeds of several cm thickness occur, locally showing small scale loading structures. The upper part of this zone also contains two hard, calcareous sandstone beds with abundant marine molluscs (single valves). Moderately rich in foraminifera, P/B-ratio: 75%.

Planktonic foraminifera: Moderately rich. Abundant occurrences of *G. trilobus* and *D. altispira*. Common occurrences of *G. menardii* (dex.) and *P. obliquiloculata.* Scattered occurrences: *S. subdehiscens*, *G. tumida, N. pseudopima* and *G. obliquus*.

Benthic foraminifera: Moderately rich. Common occurrences of *Ammonia* sp., *Pseudorotalia conoides* and *Asterorotalia trispinosa.* Scattered occurrences of *Elphidium* sp. and the larger foraminiferal species *Amphistegina lessonii* and *Gypsina* sp.

4.12 Zone XI (0 – 85 m)

Lower boundary: Gradational. Facies: Fine-grained, bedded sandstones. Sand grains are mainly of terrigenous origin. Most beds are internally massive and have a thickness of 20 to 40 cm. The beds are separated by mud drapes and show frequent dewatering and loading structures. The fine-grained sandstones change upward into bedded medium-grained sandstones, with beds that are finely laminated and normal graded. Locally the beds show a hummocky or wavy cross-stratification. Note that the marine sandstones have a total thickness of app. 400 m. Only the base of the sandstones has been included in our descriptions. No foraminiferal analysis was carried out on samples from this zone.

In general the sandstone series shows a coarsening upward trend, with upward thickening beds. The sandstones pass into fluvial conglomerates and cross-bedded sandstones. For detailed accounts of the overlying sandstones, see Van Es (1931) and Duyfjes (1938a).

5. Discussion

5.1 Dating

Zone I does not provide clear biodatums, but the presence of *G. tumida* (F.O. 5.51 Ma), and *S. dehiscens* (F.O. 5.48 Ma) indicates that the sediments are not older than Pliocene. The dextral coiling direction of *G. menardii* forms another indication of a Pliocene age of this zone, as this species changes its coiling direction from sinistral to dextral near the Miocene-Pliocene boundary and remains dextral throughout the Pliocene (Blow, 1969; Bolli et al., 1989). Zones II and III are low in planktonic foraminifera and contain no distinct marker horizons. Zone IV is rich in planktonic foraminifera and contains a good succession of first and last occurrences of index species (**Fig. 4**). A plotted timeline provides a uniform deposition rate of 18 cm/ka for the calcareous-argillaceous mudstones of Zone IV, which is relatively high, but agrees nicely with the rate of 17 cm/ka found by Van Gorsel and Troelstra (1981) for the mudstones of the Solo River Section of corresponding age. The timeline provides a good age estimate of 4 Ma for the base and 3 Ma for the top of zone IV.

The ages found for the calcareous-argillaceous mudstones of Zone IV show that the underlying diatomaceous mudstones are older than 4 Ma. Assuming a uniform deposition rate of 18 cm/ka throughout this series, we come to an age of approx. 5 Ma for the base of the diatomaceous mudstones (base of Zone II). As commonly the deposition rate of diatom ooze is lower than the deposition rate of calcareous ooze and detrital clays (Hüneke and Henrich, 2011), the base of the diatomaceous mudstones may be even older. However, the Pliocene planktonic content of the sandstones at the base of the section confines the entire section to the Pliocene. With an approximate age range of 5 to 4 Ma, the laminated diatomaceous series dates from the Early Pliocene, which makes it older than previously assumed based on Duyfjes' extrapolations. It is interesting to note that an Early Pliocene age of these beds was already postulated by Reinhold (1937) based on diatom analyses.

With an estimated age of 3 Ma, the base of the blue clays, represented by Zone V, is of Late Pliocene age. This zone, which forms the top of the Marmoyo Section, does not contain age diagnostic markers. But the dominant coiling direction of *G. menardii* remains dextral throughout this zone, indicating that it pre-dates the Plio-Pleistocene boundary. In the overlying blue clays of Zone VI, forming the base of the Sumberingin Section, the coiling direction of *G. menardii* is reversed to sinistral. This coiling change, regarded as an indicator for a change to cooler water conditions, is used regionally to mark the base of the Pleistocene (Blow, 1969; Bolli et al., 1989). Zone VI also shows the appearance of a new species: the cool-water immigrant *N.* cf. *pachyderma*. The arrival of this species in the equatorial waters of the Kendeng Zone points to changing ocean currents and influx of cooler water from high latitude regions, which can also be linked to the beginning of the Pleistocene.

The overlying blue clays of Zones VI, VII and VIII are of Early Pleistocene age. The age of the blue clays of Zone VIII is of special interest as it underlies an unconformity and represents the end of a long depositional sequence. Zones VI, VII and VIII do not contain clear age-diagnostic horizons. However, these zones do contain scattered occurrences of *Globigerinoides obliquus extremus* (L.O. 1.99 Ma) and *G. fistulosus* (L.O. 1.88 Ma). Although these occurrences are not very consistent over these zones, they provide an indication that Zone VIII predates the last occurrences of these species. It agrees with the projected timeline as plotted in **Fig. 4**, assuming a deposition rate of 18 cm/ka. It gives a rough age estimate of 2 Ma for the top of Zone VIII, directly below the unconformity.

The conglomerates and blue clays overlying the unconformity (Zones IX and X) contain a mixed planktonic fauna which includes Pliocene species such as *D. altispira*, *S. subdehiscens* and dextrally coiled *G. menardii*, species for which we found extinctions much lower in the stratigraphy. The re-appearance of these species indicates reworking of older planktonics, which implies nearby exposure and erosion of older strata. The presence of reworked planktonics impedes dating with planktonic bio-horizons.

5.2 Blow's zonation

Biostratigraphic studies in Indonesia generally use Blow's zonation (1969). The base of the Marmoyo-Sumberingin Section is not older than N18, because of the occurrence of *G. tumida* at the base of the section. The occurrence of *S. dehiscens* in the base of the section suggests an N19 age. The boundary between zones N19 and N20 is determined by the evolutionary transition from *N. dutertrei* to *N. pseudopima*. This transition is hard to identify in many Indo-Pacific sections, as was already noted by Lourens et al (2004). We referred to all members of this lineage as *N. pseudopima.* Hence, the boundary between zones N19 and N20 cannot be identified. For the boundaries between Zones 20, 21 and 22, Blow's system relies on the *G. crassaformis-tosaensis-truncatulinoides* lineage. Again, the evolutionary forms of this lineage are hard to identify in the Pliocene – Pleistocene of the Indo-Pacific. Moreover, the members of this lineage are scarce in local sections. Both features were noted by Lourens et al. (2004) and Lunt (2013). It makes the lineage not very useful for biostratigraphic purposes in this region. It also raises questions about the significance of ages or correlations based on species of this lineage in previous studies in the vicinity. In **Fig. 4**, the boundary between N20 and N21 was provisionally drawn at the last occurrence of *D. altispira.* The boundary between N21 and N22 was drawn at the last occurrence of *G. fistulosus* and *G. extremus*, which coincides with the unconformity within the blue clays.

Lunt (2013), recognizing the difficulties to indicate the boundaries between Blow's Mio-Pliocene Zones, proposed a revised subdivision of Blow's Zones N19-21 for the Indo-Pacific region (N19-21 a to e). In the same publication, he used this zonation for a discussion of the Solo River Section. We added his zonation, as far as applicable, to our stratigraphic column of **Fig 4.**

5.3 The unexposed interval and the unconformity within the marine clays

5.3.1 The unexposed interval

The faunal changes in the base of Zone VI show that there is no overlap between the top of the Marmoyo Section (Zone V) and the base of the Sumberingin section. There probably is a stratigraphic gap between the sections. The thickness of this missing interval is unknown, but there are reasons to assume that it is a minor interval only. In the first place, the total thickness of the blue clays investigated in the two sections is 390 m (Zones V – X). This is very near to the total thickness of the blue clays as can be deduced from the width of the east-west trending valley between the two ridges (**Fig. 3**). This valley has a width of ca. 675 to 700 m. Based on a constant dip of 30 degrees measured in this flank of the anticline, the valley roughly represents a clayey interval of 395 m. In the second place, calcareous mudstone outcrops right beside the Sumberingin creek (see **Fig. S2**) indicate that the basal clays as exposed in the creek have a stratigraphic position very close to the unit boundary. We provisionally estimate an unexposed interval of 10 m between Zones V and VI.

5.3.2 The unconformity

As noted in section 5.1, the base of the conglomerate bed of Zone IX forms an unconformity. It has a sharp, erosive lower boundary over the massive marine clays of underlying Zone VIII. The unconformity is also marked by a sudden change in foraminifera fauna. The clays below this level contain a marine fauna, with benthics representing upper bathyal to outer shelf conditions. The conglomerate and overlying clays of Zone X are characterized by near-coastal benthic species and the occurrence of previously extinct planktonic species, indicating reworking. The time hiatus represented by the unconformity is unknown; the overlying deposits may be of Early or Middle Pleistocene age.

5.4 Correlations with other biostratigraphic sections

Fig. 5 shows the correlation of marker horizons between the Marmoyo-Sumberingin Sections, the Solo River Section and the Bojonegoro-1 well. The laminated diatomaceous mudstones of the Marmoyo Section correspond to the middle part of the massive mudstones of the Solo River Section, both dating from the Early Pliocene. The overlying calcareous-argillaceous mudstones have a number of biomarkers that can be directly correlated to the Solo River Section, i.e. the L.O. of *G. margaritae* (3.84 Ma), the L.O. of *Sphaeroidinellopsis* spp. (3.57 Ma) and the F.O. of *G. fistulosus* (3.33 Ma), indicating that these strata correspond to the higher parts of the massive mudstone series of the Solo River Section and date from the latest Early Pliocene and Late Pliocene.

Remarkable is the upward continuation of *D. altispira* in the Solo River Section, up to the overlying limestones. In the Marmoyo Section, as well as in the Bojonegoro well, the L.O. of this species (3.46 Ma) is recorded close to the F.O. of *G. fistulosus* (3.33 Ma), but in the Solo River Section, it continues upwards until well above the first appearances of this species and the first appearance of *G. tosaensis* (3.35 Ma). This occurrence of *D. altispira* high in the stratigraphy of the Solo River Section, also noted by Lunt (2013), is not consistent with the other biomarkers. We regard the occurrences of *D. altispira* in the limestones of the Upper Kalibeng Formation as reworked. Note in this respect that the same species is found as reworked specimens in the top of the Sumberingin Section. Here, its reworked origin is easily recognizable, as the extinction of the species was recorded lower in the stratigraphy.

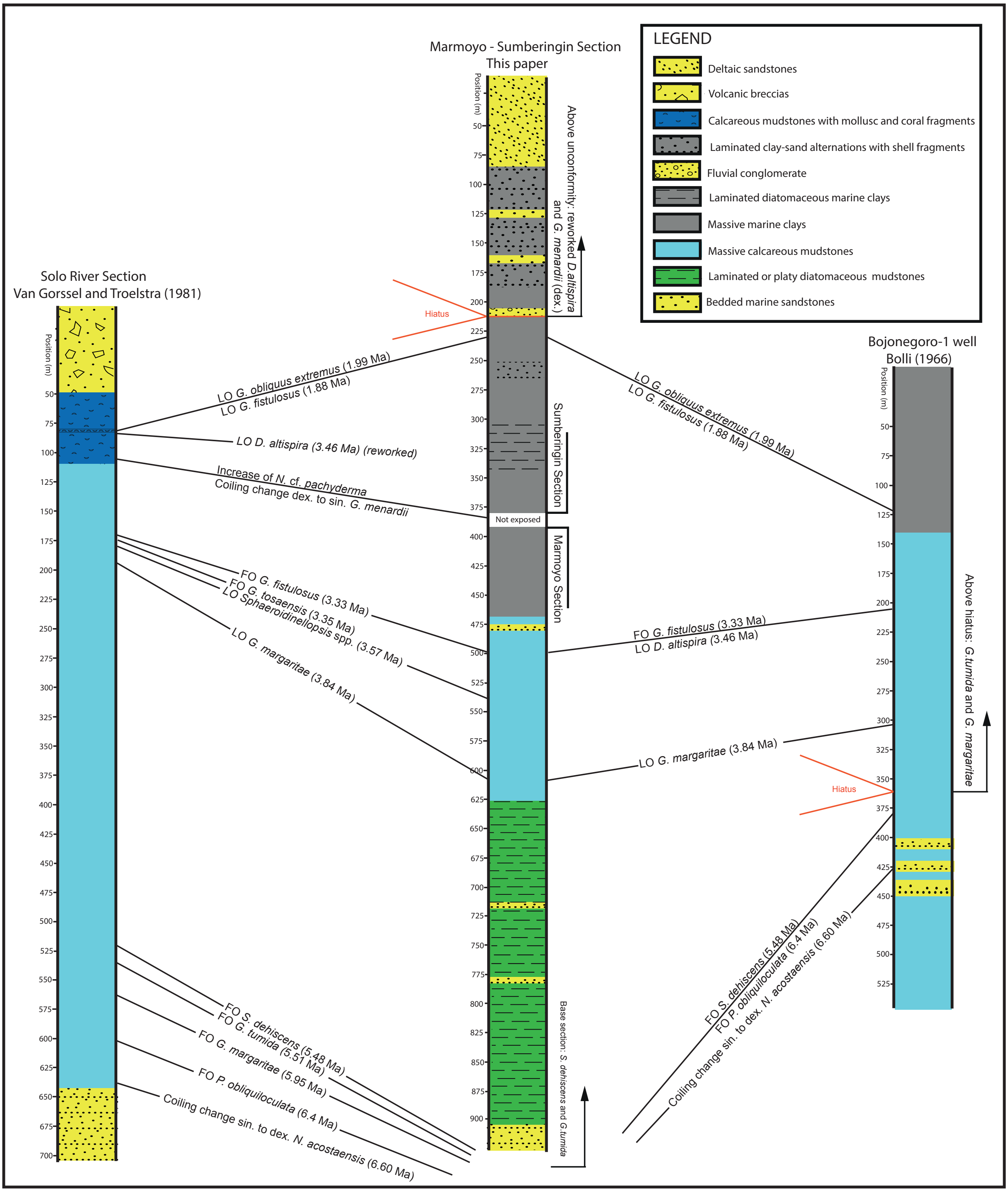


Fig. 5. Biostratigraphic correlations between the Solo River Section, the Marmoyo-Sumberingin Section and the Bojonegoro-1 well.

We conclude that all mudstones of the eastern Kendeng Zone form the lateral equivalent of the Lower Kalibeng Formation of the western Kendeng Zone. Duyfjes' correlation with the coastal strata of the western Kendeng Zone (Upper Kalibeng Formation) was incorrect. Looking at the Bojonegoro-1 well, we find that the laminated diatomaceous mudstones of the Marmoyo Section largely correspond to the depositional hiatus in the Bojonegoro-1 well. The overlying calcareous-argillaceous mudstones of the Marmoyo Section correspond to the mudstones above the hiatus in the Bojonegoro-1 well.

The Late Pliocene base of the blue clays, as exposed at the top of the Marmoyo Section, still forms the lateral equivalent of the top of the Lower Kalibeng Formation of the Solo River Section. The overlying clays of Early Pleistocene age, as exposed in the base of the Sumberingin Section, correspond in age with the reefal limestones of the Solo River Section, both containing the characteristic sinistrally coiled *G. menardii* and the increased occurrences of *N.* cf. *pachyderma*.

Correlations between the blue clays of the Bojonegoro-1 well and the blue clays of the Sumberingin Section are more complicated, due to the sparsity of biostratigraphic markers within the blue clays and the low sample density in the blue clays of the Bojonegoro-1 well. However, we found scattered occurrences of *G. fistulosus* and *G. obliquus extremus* in the blue clays of the Sumberingin Section below the unconformity, whereas these species were found extinct at the base of the blue clays in the Bojonegoro-1 well. This is an indication that the clays of the Bojonegoro-1 well are younger than the basal clays of the eastern Kendeng Zone. Possibly, this accounts for the blue clays of the entire Randublatung Zone. The clays of the Randublatung Zone may correspond to the second clay sequence of the Sumberingin Section, above the unconformity. This would be in agreement with the stratigraphic position of the blue clays in the western Randublatung Zone, overlying a similar unconformity and coarse coastal bed (Selorejo Formation).

Duyfjes (1938a) did not recognize the unconformity in the clays of the Sumberingin Section and correlated the entire clay series with the breccias of the western Kendeng Zone. Our biostratigraphic study indicates that this is incorrect: the blue clays below the unconformity are older. The clay above the unconformity and the overlying deltaic sandstones may correlate in age with the breccias of the Solo River Section, which would be more or less in line with Duyfjes' correlations. However, the unconformity within the clays may also represent a larger hiatus, which would make the overlying clays and deltaic sandstones younger.

5.5 Depositional conditions

5.5.1 Zone I

The stratigraphic position of this thin sandstone interval, interbedded between deep marine mudstones, points to a turbiditic origin. Unambiguous sedimentological features of turbidity currents have not been found. The sandstone beds are vaguely parallel laminated and alternate with thinner beds of calcareous-argillaceous mudstones. The beds are provisionally interpreted as layers D and E of the Bouma sequence, possibly representing a distal turbiditic setting. The benthic assemblage dominated by *Gyroidina* sp., *Uvigerina peregrina, Pullenia bulloides, Bulimina marginata* and *Cibicidoides wuellerstorfii* indicates bathyal conditions, which is confirmed by a P/B-ratio of 99%.

The sandstones can be correlated with thinner sandstone beds intercalated in the Solo River and Ngepung Sections at the same level. Previous authors linked these sandstone intercalations to uplift and volcanic activity of the volcanic arc during the Late Miocene and Early Pliocene (Genevraye and Samuel, 1972; Saint-Marc and Suminta, 1979) or to climatic influences (Van Gorsel and Troelstra, 1981) (see also section 5.6).

5.5.2 Zones II and III

The P/B-ratio of over 99% indicates bathyal conditions, consistent with the depositional depth of the corresponding part of the Solo River and Ngepung Sections.

The laminated mudstones are poor in foraminifera and rich in diatoms, indicating eutrophic conditions, blooming phytoplankton and reduced oxygen conditions. The extremely low benthic species diversity also indicates reduced oxygen conditions at the seabed. Zone III represents similar conditions as Zone II, but more extreme. The sediment consists primarily of diatoms; benthic foraminifera are extremely scarce or even absent. This zone represents the peak of the algal productivity.

The two interbedded sandstone layers of zone III are interpreted as turbidites. They have a similar, relatively rich foraminifera content as Zone I, with a mixed benthic assemblage of shelfal and bathyal species. The frequent occurrence of broken foraminifera indicates transport, which is in line with a turbiditic origin.

Eutrophication of marine waters is generally related to an increased supply of siliceous nutrients. It is commonly associated with volcanic activity, influx of erosion products or upwelling. The sediment of Zones II and III is very low in clastic components, which makes the first two factors unlikely. Upwelling is the most likely explanation for the increased nutrient-supply, which is supported by the occurrence of specific, upwelling-related planktonic species (see section 5.6).

5.5.3 Zone IV

The rich planktonic foraminifera fauna of this zone, and the sharp reduction in diatoms, mark a return to normal oxygen conditions. The more homogenous nature of this material indicates increased benthic activity. Nevertheless, benthic foraminifera are still relatively scarce and the P/B-ratio remains around 99%, pointing to deep-water conditions. The benthic assemblage contains similar bathyal species as were found in the underlying zones, but also some new species occur: *Bolivina robusta*, *Globocassidulina subglobosa* and *Sigmoilopsis schlumbergeri*. The higher species diversity points to a better oxygenation of the bottom waters. The introduction of *Bolivina robusta* may indicate slightly shallower conditions, which we postulate as upper bathyal.

5.5.4 Zone V

The plastic, argillaceous nature of this material indicates an increased supply of fine detrital clay, a trend that was already visible in the calcareous-argillaceous mudstones of Zone IV. The planktonic assemblage is similar to the underlying zone IV, but with reduced abundances. The P/B-ratio of 95% indicates a minor further shallowing. This is supported by the benthic assemblage, consisting of a mixture of upper bathyal species and shelfal, muddy-substrate species such as *Ammonia supera* and *Pseudorotalia gaimardii.* We postulate an outer shelf environment for this zone, which is consistent with the corresponding part of the Ngepung and Solo Sections.

5.5.5 Zone VI

The benthic assemblage of this zone is dominated by bathyal species, although we still find sparse occurrences of the shelfal *Ammonia* sp. The P/B-ratio of 95% indicates similar depth conditions as the underlying Zone V. However, the re-appearance of *Uvigerina* sp.*,* *Laticarinina pauperata* and *Gyroidina* sp. indicates a return to somewhat deeper water conditions, which we tentatively describe as upper bathyal to outer shelf.

The abundant occurrence of planktonic species is striking. The assemblage indicates cooler conditions as well as upwelling (see section 5.6).

5.5.6 Zone VII

The laminated argillaceous mudstones of Zone VII are poor in foraminifera and rich in diatoms, indicating eutrophic conditions, blooming phytoplankton and reduced oxygen conditions. The common occurrence of the benthic species *Brizalina* spp. also indicates low oxygen conditions at the seabed. The P/B-ratio of 99% conditions and the dominance of bathyal benthic species as *Bulimina marginata* suggest further deepening, however the extreme sparsity of benthic species is also related to the reduced oxygen conditions at the bed. We tentatively regard the depth conditions as upper bathyal to outer shelf, similar to Zone VI.

The eutrophication represented by this zone is likely related to upwelling (see section 5.6). Note that the occurrence of a diatomaceous zone within the blue clays was never reported before.

5.5.7 Zone VIII

The rich planktonic foraminifera fauna of this zone, and the sharp reduction of diatoms, mark a return to normal oxygen conditions. The facies of the clays, as well as their planktonic content, strongly resemble the clays of Zone VI, underlying the diatom zone. The benthic assemblage still contains deep-water species such as *Hoeglundia elegans, Bulimina marginata, Gyroidina* sp. and *Uvigerina* sp., but it is dominated by shelf species as *Ammonia* sp., *Lenticula* sp.*,* and *Eponides* sp*.* Also the P/B-ratio of 95% indicates slightly shallower conditions than the underlying zone, which we tentatively interpret as upper bathyal to outer shelf.

5.5.8 Zone IX

The erosive base of this zone represents the first Pleistocene emergence of this part of the Kendeng Zone. It also represents a significant and abrupt change in the foraminifera fauna.

The conglomerates with shell fragments, overlying the unconformity, represent coastal conditions. The material is rich in planktonic foraminifera, with an assemblage that is characterized by the return of the Pliocene species *D. altispira* and *S. subdehiscens*, and the return of dextrally coiled *G. menardii.* The return of these species indicates erosion and reworking of older marine deposits, which is in line with the coastal depositional setting.

The benthic foraminifera assemblage consists of a new group of species, characteristic for deltaic, near coastal environments: *Pseudorotalia conoides*, *Asterorotalia trispinosa, Elphidium* sp., *Amphistegina lessonii* and *Gypsina* sp.

5.5.9 Zone X

The facies of these clays, with fine sand laminae and laminae of fine shell debris, indicates (inner) shelf conditions, dominated by settling of mud and regular influx of fine sand, either by small-scale turbidites or by settling of high suspension-loads, initiated by storms or events of high river discharge. The planktonic assemblage is similar to the underlying conglomerates of Zone IX and contains reworked Pliocene species, indicating an influx of erosion products and hence a near-coastal setting. The benthic assemblage also resembles the conglomerates of zone IX. It is dominated by typical deltaic species such as *Pseudorotalia coinoides, Asterorotalia trispinosa, Elphidium* and the larger foraminiferal species *Amphistegina lessonii* and *Gypsina* sp. We postulate an inner shelf environment in a near-coastal, pro-delta setting. This is in line with the gradual transition to the overlying deltaic sandstones of Zone XI.

5.5.10 Zone XI

The fine-grained, normal-graded sandstone beds with mud drapes represent a proximal deltafront environment. The dewatering structures indicate rapid sedimentation rates. The coarsening and thickening upward trend within the thick sandstone series indicates deltaic progradation.

5.6 Water temperature and upwelling

The planktonic assemblage of the Marmoyo Section is dominated by tropical species such as *G. trilobus*, dextrally coiled *G. menardii*, *G. tumida*, and *D. altispira.* The warm, tropical conditions are consistent with the regional climate-record for the Pliocene. Occurrences of *N.* cf. *pachyderma* in the sandstones of Zone I suggest that base of the Marmoyo Section represents cooler water conditions. The species was also found in the corresponding segment of the Solo River Section. Van Gorsel and Troelstra (1981) interpreted the occurrence of this species as a sign of temporary global cooling around the Miocene-Pliocene boundary, which they associated with a less dense vegetation cover of nearby landmasses and an increased supply of coarse clastics to the basin.

Zone VI, at the base of the Sumberingin Section, bears evidence of cooler water conditions: i.e. the abundant appearance of *N.* cf. *pachyderma,* a strong decline of *G. tumida* and the change in coiling direction from dextral to sinistral in *G. menardii.* The dispersal of the cooler-water species *N.* cf. *pachyderma* to low-latitude waters is regionally linked to changing ocean currents related to global cooling at the beginning of the Pleistocene. Also the coiling change in *G. menardii,* is linked to cooling water conditions marking the Plio-Pleistocene boundary (Bandy, 1972; Ericson et al., 1955; Jenkins, 1967; Kucera, 2007). A decrease in tropical planktonic species and the appearance of *N.* cf. *pachyderma* and sinistrally coiled *G. menardii* was also found in the Solo River Section (Van Gorsel and Troelstra, 1981), at the base of the limestones overlying the massive mudstones.

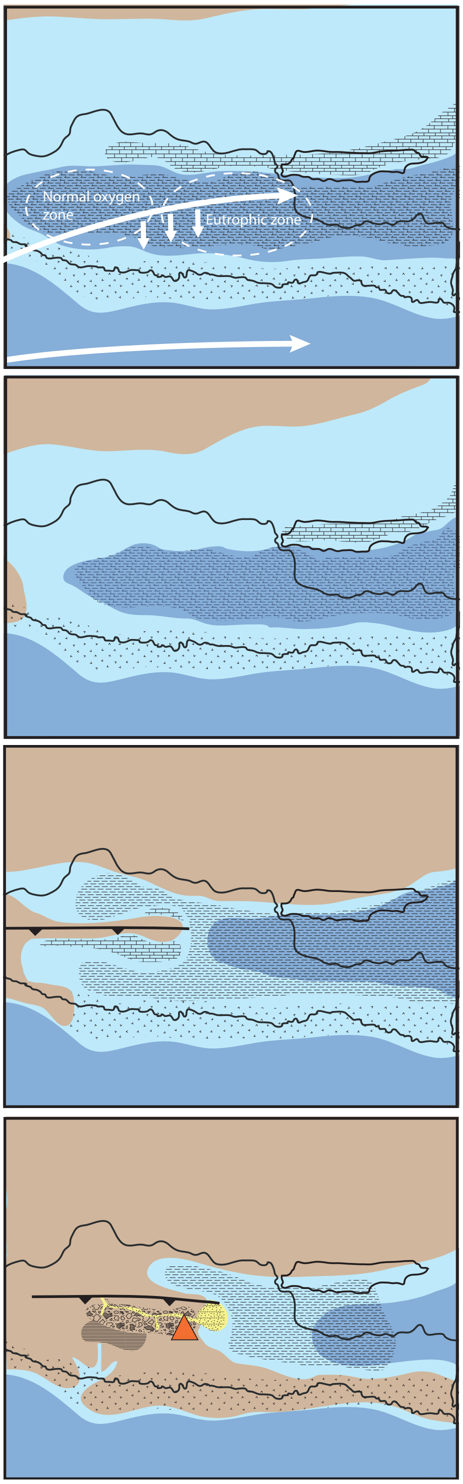
Another temperature-indicative species found in the Marmoyo Section is *G. bulloides.* It is a cool-water species, but also a species known to thrive under high-productivity conditions, which makes it a good indicator for upwelling conditions (Schiebel and Hemleben, 2005; Thiede, 1975). The species is consistently found throughout the entire Marmoyo Section. Another indication of upwelling conditions is the scattered occurrence of the biserial planktonic species *Streptochilus* sp. in the diatomaceous zones (Zones II, III and Zone VII). *Streptochilus* sp. is associated with near-coastal upwelling (Pardo and Keller, 2008; Smart and Thomas, 2006). It makes upwelling the most likely explanation for the increased nutrient-supply and algae-production as recorded in the diatomaceous strata. Another interesting feature is the common occurrence of *G. tumida flexuosa* in Zone IV. The species is an indicator for changing, suboptimal oceanographic conditions (Lamb and Beard, 1972), which can once again be associated with upwelling.

The occurrence of upwelling-conditions in the Pliocene Kendeng Zone may be explained by its oceanic setting. For much of the Pliocene, there was probably no active volcanic arc to the south and the Kendeng basin was situated along the southern margin of the large exposed landmass of Sundaland (Hall, 2013; Hall and Spakman, 2015; Morley et al., 2017). This makes the setting more or less comparable to the Indian Ocean area south of present-day Java. This area is subject to semi-annually reversing currents. During the northwest monsoon, an eastward current results in coastal downwelling and a redistribution of warm Indian Ocean water in the coastal seas. However, during the southeast monsoon, steady easterly winds drive the current westward, resulting in Ekman-induced upwelling and a drop in surface-water-temperatures (Sprintall et al., 1999; Wyrtki, 1961). Assuming a similar oceanic setting, upwelling may have been a seasonal phenomenon in the Pliocene and Early Pleistocene Kendeng Zone.

5.7 Paleogeography (Fig. 6)

5.7.1 Early Pliocene

The diatomaceous mudstones of the eastern Kendeng Zone correlate in age with the Early Pliocene massive mudstones of the western Kendeng Zone. Both series were deposited under bathyal conditions, but show a striking differ ence in facies. The mudstones of the western Kendeng Zone have a rich and well-preserved foraminiferal fauna and are thoroughly bioturbated. The corresponding strata of the eastern Kendeng Zone consist primarily of diatoms, are laminated and have a highly reduced foraminiferal fauna. This gives an image of an Early Pliocene Kendeng Zone in which phytoplankton-blooms and resulting low-oxygen conditions were a local phenomenon, occurring primarily in the eastern part of the basin. We found coastal upwelling as the most likely cause for this eutrophication. However, there is evidence that upwelling occurred over the entire Pliocene Kendeng Zone. The admixture of *G. bulloides* was also found throughout the mudstones of the Solo River Section (Van Gorsel and Troelstra, 1981). Also, Burckle (1982) found *Thallasionema nitzschiodes,* a species indicative for upwelling conditions, in the Early Pliocene diatom assemblage of the Ngepung Section. If upwelling occurred over the entire Kendeng Zone, then additional factors must have



Early Pliocene
Bathyal depth conditions prevail in the entire Kendeng Zone. The volcanic arc has become inactive and is largely submerged, creating an open connection to the Indian Ocean in the south. In the north, the basin is bordered by the shallow Sunda Shelf and coral reefs on the uplifted Rembang - Madura high. Upwelling conditions occur, linked to seasonal eastward marine currents and off-shore directed Ekman currents. It causes the development of an eutrophic zone with high diatom productions. In the western part of the basin, normal oxygen conditions prevail and sedimentation is dominated by calcareous muds rich in foraminifera.

Late Pliocene
Compression and uplift of the Kendeng Zone result in gradual shallowing. Upper bathyal conditions prevail in most of the basin. Normal oxygen conditions return to the entire Kendeng Zone.The supply of detrital clays increases, which is marked by a transition in the depositional record to calcareous-argillaceous mudstones rich in foraminifera and finally to marine bluish clays. In the eastern Kendeng Zone, the base of the marine clays dates from ca. 3.0 Ma.

Early Pleistocene (ca. 2.6 - 2.0 Ma)
Continuing compression of the Kendeng Zone results in folding and northward thrusting of the axial part of the Kendeng Zone. In the east, the thrust belt emerges. Coral reefs develop along this emerged axial part of the Kendeng Zone. The surrounding area develops as a shallow embayment, with shelfal depth conditions in the west and upper bathyal conditions in the east. The supply of detrital clay to these shallow waters is high, marked by the deposition of bluish marine clays.

Early Pleistocene (after 2.0 Ma)
Continuing uplift of the Kendeng Zone results in further regression. In the remaining embayment, shallow marine conditions prevail. The supply of detrital clay is high and sedimentation is dominated by marine clays. Around 1.9 Ma, volcanic activity returns to the area, starting in the Wilis volcanic complex. The area south of the Kendeng thrust belt is covered with volcanic breccias. A large delta develops, prograding over the shallow marine embayment.The exact timing of this deltaic development remains unclear.

Fig. 6. Plio-Pleistocene paleogeography of the Kendeng Zone. Charts based on Hall (2013) and Lunt (2013) with addition of new data from the present study.

been involved in the development of a eutrophic biogeographic zone in the eastern Kendeng Zone. This may have been an interaction between oceanic currents and paleogeography. Possibly, the Early Pliocene eastern Kendeng Zone had a relatively sheltered position, leading to more extreme eutrophication.

5.7.2 Late Pliocene

In the Late Pliocene, normal oxygen conditions and a rich foraminifera fauna returned to the entire Kendeng Zone. Gradual uplift brought upper bathyal to outer shelf conditions to the basin. Deposition changed from predominantly calcareous to more argillaceous, indicating a higher supply of detrital clay from surrounding land surfaces. Eventually, deposition changed to blue marine clays, the base of which has been dated at 3 Ma in the eastern Kendeng Zone.

5.7.3 earliest Early Pleistocene (2.6 – 2.0 Ma)

The Plio-Pleistocene boundary (2.6 Ma) is roughly placed at the appearance of *N.* cf. *pachyderma* and the coiling change from dextral to sinistral in *G. menardii*. In the eastern Kendeng Zone, this transition lies within the marine blue clays. In this area, upper bathyal to outer shelf conditions and clay deposition continued well into the Early Pleistocene. In the southwestern Kendeng Zone, this microfaunal transition is found at the base of the reefal limestones. It shows that the limestones date from the earliest Early Pleistocene and correlate laterally with marine blue clays in the east. The limestones of the southwestern Kendeng Zone were formed as reefs fringing the axial part of the Kendeng Zone, which had been subject to folding and thrusting and emerged in this period.

5.7.4 Early Pleistocene after 2.0 Ma

This period is characterized by the return of active volcanism to this part of East Java, with the Wilis volcanic complex as the first eruption centre. Large-scale eruptions started around 1.9 Ma (Hartono, 1994), supplying volcanic breccias to a vast area south of the axial Kendeng ridge, nowadays the area around Kedung Brubus, Ngawi, Trinil and Sangiran. Continuing uplift, possibly in combination with periods of temporary sea-level drop, resulted in more widespread exposure of the Kendeng Zone.

Around Sangiran, a lagoonal or lacustrine environment developed after the first phase of highly active volcanism, followed by a phase of fluvial deposition. Fluvial deposition is also widespread in the Trinil area, where fluvial sands overlie the volcanic breccias. The breccias are regarded as the Early Pleistocene Pucangan Formation and the fluvial sands as the Middle Pleistocene Kabuh Formation (Duyfjes, 1936, 1938a).

In the eastern Kendeng Zone, we found evidence for a period of exposure, followed by a new transgression and a return to shallow marine conditions. It corresponds to what Huffman (2001b) calls the Pleistocene Randublatung Embayment. It is characterized by a nearby coastline and a large, prograding sandy delta. The northeast directed deltaic progradation over shallow marine clays can nowadays be traced in the depositional record of the eastern Kendeng Zone between Jombang and Mojokerto. This shallow marine, deltaic phase cannot be accurately dated by foraminifera biostratigraphy, due to strong admixture of reworked foraminifera. The exact timing of this deltaic phase in relation to the deposition of volcanic breccias and fluvial sandstones in the SW Kendeng Zone around Trinil and Ngawi remains unknown.

6. Conclusions

This study fills the last great gap in the local biostratigraphy. It shows that some of the previously assumed correlations (Duyfjes, 1936, 1938a) between strata of the western and eastern Kendeng Zone are incorrect. The laminated, diatomaceous mudstones of the eastern Kendeng Zone are older than previously assumed and date from the Early Pliocene. The blue clays of the eastern Kendeng Zone represent two different sequences. The lower sequence forms the continuation of the Pliocene regressive series. With an age of ca. 3 Ma, its base is older than assumed by Duyfjes, who regarded the base of the blue clays as Pleistocene. It dates from the Late Pliocene and continues into the Early Pleistocene. The second blue clay sequence postdates a period of exposure and represents shallow marine conditions and prograding sandy deltas. Its content of reworked planktonic foraminifera impedes accurate dating. It may be of Early or Middle Pleistocene age.

Although the finding of an unconformity within the blue clays puts the deltaic sandstones in a new stratigraphic context, our study does not provide a final conclusion about the age and stratigraphic position of the vertebrate fossil bearing sandstones.