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# AGES OF MIOCENE FOSSIL LOCALITIES IN THE NORTHERN KUTAI BASIN (EAST KALIMANTAN, INDONESIA)

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ABSTRACT: **We discuss the ages of twelve (clusters of) localities along the northeastern margin of the Kutai Basin (East Kalimantan, Indonesia). These localities form the basis for a large-scale study to improve our documentation of the fossil record of shallow marine environments in the center of maximum biodiversity. We integrated the results of investigations of occurrences of calcareous nannoplankton, (rare) planktonic foraminifera, larger benthic foraminifera, strontium isotope stratigraphy, and magnetostratigraphy. In addition to previously well-documented middle Miocene carbonates, new surface outcrops of early Tortonian- and Messinian-age carbonates are reported.**

## INTRODUCTION

The central part of the Indo-West Pacific (IWP) harbors the highest modern marine biodiversity on earth (Hoeksema 2007 and references therein), but few data are available on the fossil record of this biodiversity hotspot (Wilson and Rosen 1998; Renema et al. 2008). To address this data deficiency the EU Throughflow Initial Training Network was established providing a three-year field- and laboratory-based study by an international team. To improve our documentation of the fossil record of key intervals, larger collections, and improved age constraints on key localities are needed. Based on available collections, especially in Naturalis Biodiversity Center, the northeastern part of the Kutai Basin was identified as having several Miocene fossil localities (e.g., Rutten 1913; Staub 1915; Gerth 1923; Beets 1983, 1986) with abundant well-preserved fossils, especially mollusks and corals (Johnson et al. 2015). Most of these sites were visited for prospecting purposes in the early 1900s and later publications were reinvestigations of these collections (Johnson et al. 2015). Moreover, sampling methods and insights into stratigraphy have changed since these samples were collected. Without additional field research, it was not possible to improve our understanding of the regional stratigraphy, and thus the timing of changes in biodiversity and the regional environment.

In this paper, we discuss the ages of the most important fossil localities in the northern part of the Kutai Basin and the consequences these new ages have for regional biostratigraphy. Although the Kutai Basin has long been of geologic interest for hydrocarbon and paleontological studies, a precise age framework has proven problematic. Here we present new data on biostratigraphy and Strontium isotope stratigraphy on key localities sampled during two fieldwork campaigns by the Throughflow project. These data form the geochronological framework in which paleoenvironment and diversity can be discussed.

### *Geological Setting*

The Kutai Basin is one of the largest sedimentary basins on the island of Borneo. It is flanked by the Mangkalihat platform to the north, the Kalimantan High to the west, and the Pater Noster platform and Barito Basin to the south (Moss and Chambers 1999). The deep Makassar Straits Basin on the eastern side represents the offshore deep-water continuation of the Kutai Basin. Cenozoic sedimentation was initiated during a period of widespread Paleogene extension and subsidence, which may have begun in the middle Eocene (Moss and Wilson 1998). Following initiation, the tectonic history of the Kutai Basin includes a phase of late Eocene to Oligocene subsidence and renewed tectonic activity in the late Oligocene–early Miocene (Moss and Chambers 1999). During the Miocene, an important change in the sedimentary regime occurred as substantial volumes of sediment were deposited (Moss and Chambers 1999; Hall and Nichols 2002). Basin inversion, starting as early as the late early Miocene, resulted in reworking of earlier sediments and the increased deposition of deltaic packages. Continued uplift in the western part of the basin resulted in the accelerated eastward progradation of deltaic deposition in the middle Miocene (Moss and Chambers 1999; Marshall et al. 2015). During the late Miocene–Pliocene, a second phase of compression resulted in the development of a series of southwest-northeast–trending anticlines.

This paper deals only with sediments deposited during the Miocene inversion phase. The research area (Fig. 1) is located in the eastern part of the Kutai Basin, close to the present-day coast and shelf margin. Sediments in this area are dominated by clay and organic carbon-rich silt- to sandstone, with fossil-bearing carbonates only present in relatively small-sized outcrops. We focused on shallow marine fossil-bearing deposits, which developed as delta-front reefs (Wilson et al. 2005; Santodomingo et al. 2015), shelf-edge reefs (Marshall et al. 2015; Novak et al. 2013, Novak and Renema 2015), and small carbonate platforms (Wilson et al. 2012).

## METHODS

### *Biostratigraphy*

In the field, both bulk and/or consolidated rocks (usually carbonate) were sampled from exposed intervals in each outcrop/section. In all areas,

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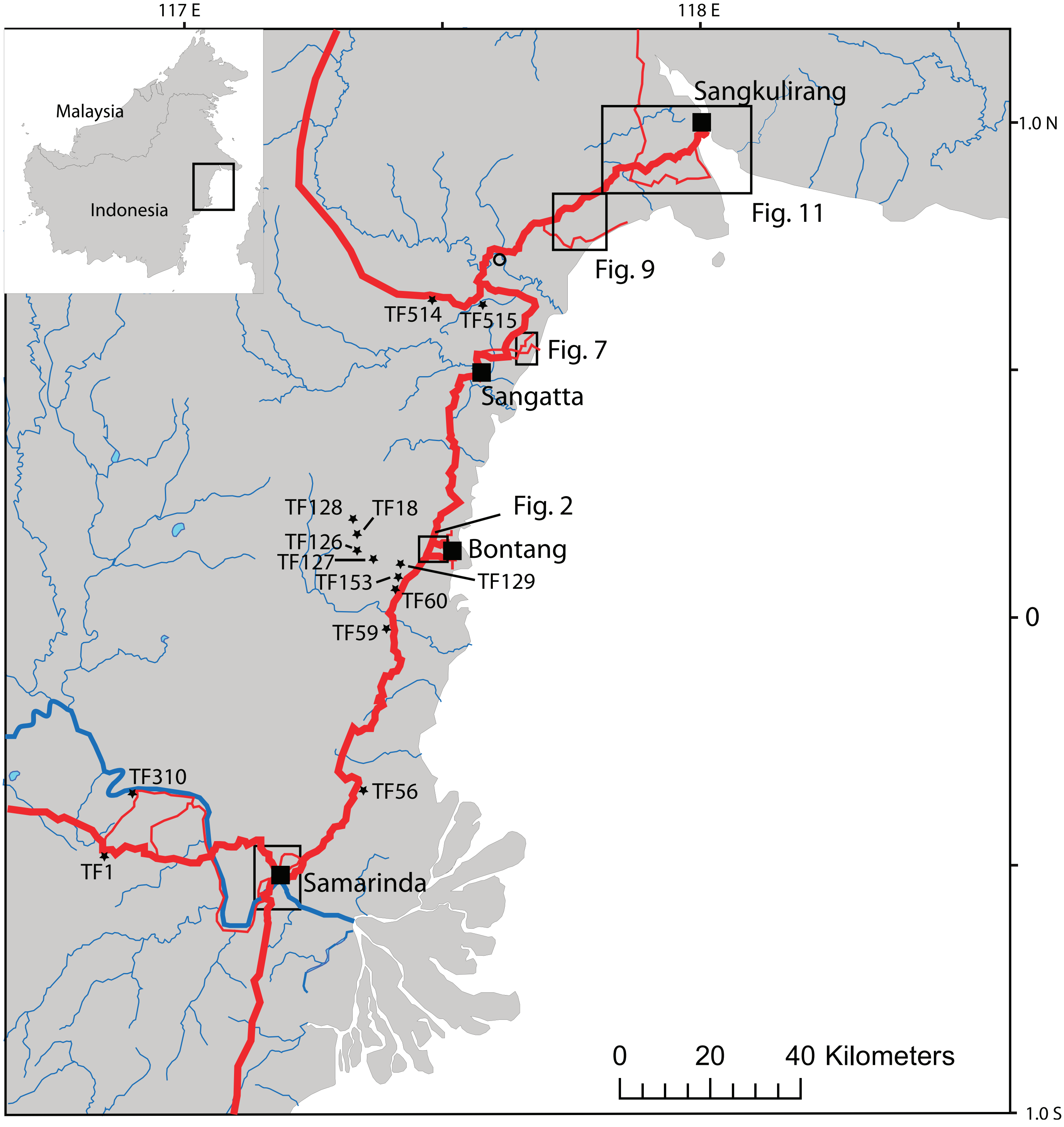

FIG. 1.—Map of the research area. Boxes indicate the location of the detailed maps in Figures 2, 7, 9, and 11.

samples were collected from multiple horizons. Consolidated rocks were thin sectioned. Bulk samples were sieved and a subsample was studied for nannoplankton. The least representatively sampled areas include Senoni and Badak. From Senoni we looked at ~10 thin sections from 3 horizons. In Badak we had access to more thin sections, but many of those were recrystallized and only allowed identification at the generic level or above. In all other localities, samples with isolated specimens as well as bulk samples were studied (see Supplementary Data for coordinates of fossil localities).

**Larger Benthic Foraminifera.**—Larger benthic foraminifera (LBF) are the most frequently used stratigraphical markers in shallow marine Cenozoic deposits in Southeast Asia (e.g., Adams 1970, Lunt and Allan 2004; Renema 2007). The ranges have been used as the basis for the "Letter Classification" in the then–Netherlands East Indies since the 1920s (van der Vlerk and Umbgrove 1927; Leupold and van der Vlerk 1931). Since then, frequent updates have been published (e.g., Adams 1970; BouDagher-Fadel and Banner 1999; Lunt and Allan 2004; Renema

2007). These studies dealt to a large extent with defining recognizable stratigraphical units, but in later publications, correlation to the geologic time scale became an increasingly important topic (e.g., van der Vlerk 1955; Glaessner 1959; Adams 1970). Most of these studies focused on the middle Miocene and older sections, the most important strata for oil and gas exploration. For the present study, the Tf–Th zones are the most important, of which only Tf is defined on the occurrence of LBF (Lunt and Allan 2004). The base of Tf is defined as last occurrence of *Spiroclypeus* and *Eulepidina* (van der Vlerk and Umbgrove 1927, and subsequent revisions by, e.g., Lunt and Allan 2004; Renema 2007). Originally, the upper boundary of Tf was defined as the middle Miocene mass extinction (van der Vlerk and Umbgrove 1927; Lunt and Allan 2004). At this event most lepidocyclinids, miogypsinids, and some other groups simultaneously went extinct. Adams et al. (1984) found lepidocyclinids (*Nephrolepidocyclina rutteni*) in younger sediments, and argued that Tf should be stretched to include the late Miocene. In this way, he treated the Tf zones as a range-defined zonation, whereas originally it was intended as a chronostratigraphical zonation with the units recognized by LBF turnover events, since these were easy to recognize in the field while prospecting (Lunt and Allan 2004).

In most works, Tf is divided in three or more zones, but the definition of these zones varies, probably due to regional variations in stratigraphic values of some of the indicator taxa or facies-dependent occurrences. For western Indonesia, Renema (2007) used the last occurrence (LO) of *Austrotrillina* for the upper boundary of Tf1, the LO of *Flosculinella* for the upper boundary of Tf2, and the LO of *Nephrolepidina rutteni* for the upper boundary of Tf3. Lunt and Allan (2004) only recognize the division of lower (Tf1–2) and upper Tf (Tf3), the boundary of these two defined by the LO of a number of very characteristic groups, such as *Cycloclypeus annulatus*, *Nephrolepidina ferreroi,* and *Lepidosemicyclina.* The lower–upper Tf (Tf2–3) transition is one of the most typical stratigraphic events in Southeast Asia, and is associated with a marked decrease in the abundance of LBF, and an increase in corals and green algae (especially *Halimeda*).

Ranges of LBF in Tf3 and younger sediments have been poorly documented. The discussion on whether the extinction of *Nephrolepidina rutteni* is at the same time as the LO of the other *Nephrolepidina* taxa or not (Adams et al. 1984) indicates that this taxon is rare in Tf3 strata. This time interval includes the rise of the modern LBF fauna, and is characterized mostly by first occurrences (FO) rather than LOs.

A number of studies propose divisions for this interval. Billman and Kartaadiputra (1974) proposed five zones based on smaller benthic shallow marine foraminifera, i.e., the *Ammonia yabei* zone in lower Tf3, the *Pseudorotalia catilliformis* zone in the upper Tf3, the *Asanoina* zone roughly corresponding to the Pliocene, the *Ammonia ikebei* zone in the early Pleistocene, and finally, the *Calcarina* zone roughly equivalent to the Quaternary. Whittaker and Hodgkinson (1979) evaluated this zonation and re-identified several of the taxa mentioned by Billman and Kartaadiputra (1974). They found an overlap between the *P. catilliformis* and *Asanoia* zones in both their own and Billman and Kartaadiputra's material. They concluded that at least part of the extinctions observed by Billman and Kartaadiputra (1974) were facies determined, with the possible exception of *Ammonia yabei.* However, the latter species was originally described from the Pliocene, and is also abundant in, e.g., the Pliocene of Java (Kadar 1985), where its occurrence is strongly facies dependent.

### *Nannoplankton Biostratigraphy*

Other groups often used in biozonations have been studied at as well. Samples were collected for calcareous nannoplankton from all study localities containing macrofossils and from intervening non-fossiliferous sequences. More than 200 samples were collected, from all of which smear slides were prepared and examined by polarized light microscopy using standard methods (Bown and Young 1998). Recovery of nannofossils was not good, with most samples proving barren and the relatively few non-barren samples having sparse, low-diversity, and moderately preserved assemblages. The principal causes of the rarity of nannofossils are likely to have been ecological exclusion and dilution by clastic sediments, both reflecting the deposition in shallow shelf environments with high deposition rates. In the reef facies, nannofossils were sometimes found in the clayey facies, but were excluded from the limestones, almost certainly due to diagenetic loss. Nannofossil assemblages were assessed semi-quantitatively and referred to the Martini (1971) NN zonation, as reviewed by Young (1998). No obviously reworked nannofossils were seen, and numerous samples with suitable lithologies were entirely barren. This suggests that the sediment source for the region did not include nannofossil-rich sediments.

A range of samples were also processed for planktonic foraminifera and other calcareous microfossils. As with nannofossils, assemblages were sparse, again probably due to a combination of ecological exclusion and sediment dilution. Plankton foraminiferal faunas in most of the outcrops were rare and of very limited (if any) stratigraphic use due to low abundance, and impoverished assemblages. No biostratigraphically useful planktonic foraminiferal assemblage data were collected.

### *Strontium Isotope Stratigraphy (SIS)*

The ability to date and correlate marine sediments using Sr isotopes relies on the variation in $^{87}Sr/^{86}Sr$ over time. With the technique of Strontium isotope stratigraphy (SIS) becoming more familiar and the potential sources of error better understood (e.g., van Buchem et al. 2010), this method is increasingly being applied to sites with well-preserved marine fossils (e.g., Lunt and Allan 2004; Bromfield and Renema 2011). The strontium isotope ratio of seawater is considered globally uniform and stable at any given time (within the present-day analytical precision), because the Sr residence time is much longer ($10^6$ years) than the ocean's mixing time ($10^3$ years) (e.g.,Veizer 1989). Variation in $^{87}Sr/^{86}Sr$ of seawater is primarily a function of high $^{87}Sr/^{86}Sr$ terrigenous versus low $^{87}Sr/^{86}Sr$ oceanic crustal input into the oceans (Oslick et al. 1994). Wet geochemistry procedures for strontium purification included sample dissolution (using concentrated $HNO_3$), acidic redigestion (using 4 M $HNO_3$), and strontium purification achieved by conventional cation exchange chromatography using Eichrom® Sr-spec resin (30 mg). For calcitic samples (LBF and echinoid spines), additional steps preceded sample dissolution, to avoid analysis of diagenetically altered material. These samples were preleached in sufficiently diluted acetic acid in order to dissolve a third of the mass, then the procedure was repeated to dissolve a second third, with just the last third of the mass analyzed. Separated strontium was loaded onto degassed single rhenium filaments using $H_3PO_4$ and tantalum fluoride emitter ($TaF_5$). Strontium isotope ratio analysis was performed on a VG354 multicollector thermal ion mass spectrometer (TIMS) in multi-dynamic mode (Thirlwall 1999) at Royal Holloway University of London. Control over mass fractionation for all measured ratios was guaranteed by normalization to the $^{86}Sr/^{88}Sr$ ratio of 0.1194. The long-term mean (2011–2012; n = 97) of measured $^{87}Sr/^{86}Sr$ of the international standard NIST SRM 987 was 0.710256 ± 0.000020 (2SD). All data were corrected against the internationally accepted NIST SRM 987 $^{87}Sr/^{86}Sr$ ratio of 0.710248. Analytical age minima and maxima were calculated by combining the statistical uncertainty of the SRM 987 long-term reproducibility (2SD) with the upper and lower confidence limit reported with each Sr isotope ratio in the SIS Look-Up Table, Version 4: 08/04 (McArthur et al. 2001; McArthur and Howarth 2004).

Potential sources of error include uncertainty in the seawater $^{87}Sr/^{86}Sr$ curve, analytical error, and any isotopic heterogeneity in the material analyzed, e.g., due to diagenesis, and /or contamination from a non-marine Sr source (van Buchem et al. 2010). SIS is especially useful in those intervals experiencing relatively rapid changes in the $^{87}Sr/^{86}Sr$ of seawater. Analytical error is typically $\pm 1\text{–}2 * 10^{-5}$, in the studied interval equivalent to ±~0.4 Ma in the middle Miocene and ~1 Ma in the late Miocene–Pliocene (McArthur and Howarth 2004).

## RESULTS

### *Senoni*

This is the westernmost outcrop in this study, west of Samarinda (Fig. 1). The outcrop is where a limestone ridge is intersected by the Mahakam River. This ridge connects the outcrops Senoni (TF310) and Kota Bangun (TF1) discussed by Wilson (2005).

The LBF assemblage consists of two miogypsinids, one without cubiculae, i.e., belonging to the genus *Miogypsinoides*, and one with cubiculae, i.e., belonging to the genus *Miogypsina*, as well as rare *Nephrolepidina ferreroi,* and a flat species of *Nephrolepidina*. These taxa co-occur in Tf1 (Burdigalian). *Miogypsina* and *Miogypsinoides* overlap in stratigraphical range in the early part of Tf, but *Miogypsinoides* rapidly becomes rare (Lunt and Allan 2004). This is supported by the absence of *Lepidosemicyclina*, a taxon abundant in most other upper Burdigalian-Serravallian localities in the Kutai basin of similar facies. Based on these data, we infer an age in the early part of Tf1/ Burdigalian. This is compatible with Wilson (2005), who inferred an early Miocene age for these localities.

### *Samarinda*

Location and stratigraphy of the Samarinda outcrops are discussed in detail and placed in a magneto- and biostratigraphical context in Marshall et al. (2015). Several of the invertebrate fossil-bearing sites have been included into this section. TF52 and TF76 (Air Putih in Wilson 2005) include three Langhian carbonate intervals (the Batu Putih interval), which becomes a thick ridge-forming unit toward the South that forms the limestone hogback to the west of Samarinda. TF77 and TF130 are located on this ridge and can be directly correlated to TF52 and TF76. Two other localities (TF311 and TF79; Permasip in Wilson 2005) and TF101 (DPR in Wilson 2005) occur along strike of TF76 and TF52 and represent the lower part of the sequence in this outcrop. Marshall et al. (2015) correlated the TF52 and TF76 carbonates to magneto chron C5Br or C5Bn, or between 14.8–15.3 Ma. Wilson (2005) placed these outcrops in the early to predominantly middle Miocene, so our age interpretations are slightly younger and more precise. Numerous localities in this area yielded low-diversity nannofossil assemblages with the marker species *Sphenolithus heteromorphus*, suggesting zones NN4–5, which is compatible with the other data.

Apart from these Langhian carbonates, a second interval with carbonate sedimentation was observed along the road to the new sports stadium on the southern side of the Mahakam River, stratigraphically about 2.2 km higher in the section (Marshall et al. 2015). The sedimentology and fossil assemblages of these sites (TF51 and TF57) are discussed in Santodomingo et al. (2015). This carbonate interval contains the larger benthic foraminifera *Nephrolepidina ferreroi, Cycloclypeus annulatus,* and *Lepidosemicyclina bifida,* suggesting a late Tf2 age. The *L. bifida* are large (up to 1.5 cm) and have a highly irregular outline with 3–5 lobes branching from the central area. Magnetostratigraphically, this interval was correlated to a brief normal interval in magneto chron C5r, or ~11.6 Ma (discussed in detail in Marshall et al. 2015). This occurrence pinpoints the Tf2–Tf3 boundary close to the Serravallian-Tortonian boundary (Marshall et al. 2015). Samples from this carbonate horizon contained nannofossil assemblages similar to those from the lower limestones, including particularly the presence of *Sphenolithus heteromorphus*. This suggests an earlier age than the other evidence, but it was concluded that the nannofossils were likely to have been reworked (Marshall et al. 2015).

### *Badak-Bontang*

North of Samarinda, limestone outcrops are concentrated along a number of ridges of a similar NNE strike to the Samarinda hogback (Fig. 1). Coal mining and quarrying for aggregate have made them accessible for study. These include TF56 and TF58 (Badak in Wilson 2005), the Southern Hemisphere (TF59; Bontang in Wilson 2005), and several outcrops further North in the Bontang area.

The LBF in TF58 were poorly preserved, and did not allow more precise age indication than Tf1–early Tf2, or late Burdigalian–Langhian. SIS resulted in an age of 14.6 (13.5–14.9) Ma, compatible with the LBF biostratigraphy. Wilson (2005) inferred a middle Miocene age for her Badak site, and interpreted it as younger than the Batu Putih interval in the Samarinda area. Our findings for Badak are very imprecise , and can be congruent with Wilson's (2005) interpretation. Although poorly preserved, the LBF appear more similar to the two following sites, however, suggesting an age older than the Batu Putih, in the late Burdigalian.

Most of the other outcrops are isolated occurrences in relatively shallow marine settings. They are made up of 1–3 stacked reefs separated by LBF packstones and sometimes shales (Novak et al. 2015; Rösler et al. 2015). The sedimentology and fossil assemblages of one of these sites is described in detail by Novak et al. (2013). Calcareous nannoplankton in each of these sites resulted in a placement in zones NN4–5, based on the presence of the marker species *Sphenolithus heteromorphus,* together with a low-diversity assemblage compatible with this age.

The LBF in each of the sections are also very similar, with small *Lepidosemicyclina*, abundant *Nephrolepidina* sp., *Nephrolepidina ferreroi* (not in TF153 and TF59), and *Miogypsina*. *Flosculinella bontangensis* was found in TF126 and TF153. *Lepidosemicyclina* at all sites were small and did not show the large, irregular test shapes as in, for example, the Stadion carbonates in Samarinda (TF51 and TF57; Santodomingo et al. 2015) or the more lobed specimens in the Batu Putih carbonates (Marshall et al. 2015). In the absence of more independently dated occurrences of this group, it is not certain that the size and irregularity of the test is of any stratigraphical value. However, this, in combination with the relatively short *Flosculinella* specimens and the presence of *Miogypsina* cf. *globulina* indicates that these localities all have a comparable age, late Tf1/early Tf2, or close to the Burdigalian-Langhian boundary. This is supported by SIS data indicating an age of 15.7–15.8 (15.6–16.0) Ma for TF59 (Table 1). However, the SIS results from TF153 and TF126 are ambiguous. In TF153, ages from two samples were not overlapping: 16.1 (15.9–16.3) Ma and 18.8 (18.6–18.9) Ma for TF153, and 18.9 (18.8–19.1) Ma and 21.1 (20.9–21.3) Ma for TF126; and the older ages do not match with the biostratigraphical results. All the analyzed samples were either echinoid spines or *Nephrolepidina* and screened in the same way for preservation.

Thus, TF58 and TF59 show internally consistent SIS ages overlapping with expected ages from biostratigraphy, whereas SIS results in TF126 and TF153 are internally inconsistent, and only one out of four overlap with LBF and calcareous nannoplankton age indications. However, as long as we do not understand the reasons for these differences in SIS results, we have to remain cautious using them for all sites with SIS ages on calcite of *Nephrolepidina* tests or echinoid spines in the shallow, muddy reefs in the Kutai basin.

### *Bontang Garden*

Along the road from Samarinda to Sangatta, west of the city of Bontang a narrow stretch of carbonates crop out in an area otherwise

TABLE 1.—*$^{87}$Sr/$^{86}$Sr isotope ratios found in this study. Reported age estimates are derived from correlation with best fit data from SIS Look-Up Table V4: 08/04 (McArthur et al. 2001; McArthur and Howarth 2004). Errors result from the statistical uncertainty of the SRM 987 external reproducibility (±0.000020) combined with the upper and lower confidence limits of the respective "best fit" data, and the mineral and source the measurements were obtained from.*

| Sample | Site | Area | Mineral | Source | Cor. Sr$^{86/87}$ | Error (*$10^{-6}$) | Age (My) | Min age (My) | Max age (My) |
|---|---|---|---|---|---|---|---|---|---|
| WR2-1 | TF511 | Bengalon | Ca | echinoid | 0.708961 | 9 | 6.76 | 6.48 | 7.1 |
| WR2-2 | TF511 | Bengalon | Ca | foram | 0.708969 | 13 | 6.51 | 6.19 | 6.95 |
| WR5 | TF512 | Bengalon | Ca | echinoid | 0.708966 | 10 | 6.59 | 6.33 | 6.95 |
| SR01-3 | TF533 | Bengalon | Arag | mollusk | 0.708957 | 9 | 6.91 | 6.59 | 7.25 |
| SR01-1 | TF533 | Bengalon | Arag | mollusk | 0.70898 | 9 | 6.24 | 6.07 | 6.45 |
| SR01-2 | TF534 | Bengalon | Arag | mollusk | 0.708958 | 14 | 6.87 | 7.4 | 6.3 |
| VN02-1 | TF153 | Bontang | Ca | foram | 0.70853 | 9 | 18.76 | 18.64 | 18.87 |
| VN02-2 | TF153 | Bontang | Ca | echinoid | 0.708713 | 10 | 16.10 | 15.94 | 16.28 |
| VN11-1 | TF59 | Bontang | Ca | foram | 0.708731 | 9 | 15.82 | 15.68 | 15.96 |
| VN11-2 | TF59 | Bontang | Ca | echinoid | 0.708737 | 10 | 15.73 | 15.57 | 15.88 |
| BW_1 | TF102 | Bontang Garden | Arag | coral | 0.708931 | 10 | 8.24 | 7.53 | 8.95 |
| BW_2 | TF102 | Bontang Garden | Arag | coral | 0.708903 | 11 | 9.52 | 9.14 | 9.9 |
| BW_7 | TF154 | Bontang Garden | Arag | coral | 0.708895 | 12 | 9.75 | 9.38 | 10.12 |
| NS_7.1 | TF502 | Bontang Garden | Arag | coral | 0.708897 | 12 | 9.70 | 9.33 | 10.07 |
| BW4 | TF108 | Bontang Garden | Arag | mollusk | 0.708903 | 11 | 9.75 | 9.38 | 10.12 |
| LGS1 | TF109 | Bontang Garden | Arag | mollusk | 0.708921 | 11 | 9.16 | 8.69 | 9.81 |
| BW6 | TF108 | Bontang Garden | Arag | mollusk | 0.708921 | 11 | 9.16 | 8.69 | 9.81 |
| WM | TF109 | Bontang Garden | Arag | mollusk | 0.708910 | 9 | 9.55 | 10.03 | 9.17 |
| BW3 | TF110 | Bontang Garden | Arag | mollusk | 0.708930 | 10 | 8.75 | 8.18 | 9.75 |
| BW10 | TF108 | Bontang Garden | Arag | mollusk | 0.708910 | 12 | 9.55 | 10.03 | 9.17 |
| BW | TF108 | Bontang Garden | Arag | mollusk | 0.708897 | 10 | 9.92 | 9.54 | 10.30 |
| NS_10a | TF516 | Sangatta | Arag | coral | 0.708921 | 10 | 8.80 | 8.24 | 9.78 |
| NS3.14 | TF516 | Sangatta | Arag | coral | 0.708906 | 19 | 9.43 | 9.04 | 9.98 |
| NS_10b | TF516 | Sangatta | Arag | coral | 0.708930 | 9 | 8.30 | 7.6 | 9.24 |
| FW3_1 | TF517 | Sangatta | Arag | mollusk | 0.708907 | 11 | 9.39 | 8.94 | 9.73 |
| FW3_2 | TF517 | Sangatta | Arag | mollusk | 0.708918 | 11 | 8.94 | 8.36 | 9.39 |
| FW3_3 | TF517 | Sangatta | Arag | mollusk | 0.708921 | 11 | 8.8 | 8.14 | 9.29 |
| FW3_4 | TF517 | Sangatta | Arag | mollusk | 0.708925 | 9 | 8.89 | 8.32 | 9.12 |
| SR02 | TF517 | Sangatta | Arag | mollusk | 0.708911 | 15 | 9.25 | 9.89 | 8.82 |
| NS1_9B | TF529 | Sangkulirang | Arag | coral | 0.708996 | 17 | 5.96 | 5.65 | 6.27 |

dominated by deposits of clay, sand, and coal (Fig. 2). The base of these carbonates forms an escarpment in the landscape due to its resistance to erosion. These outcrops stratigraphically overlie the Burdigalian–Langhian limestones mentioned above by an estimated 1100–1500 m (1200 m and 1400 m by, respectively, Rutten 1913; and Felix 1921).

The carbonates and marls are well exposed in a series of building sites, hillside clearings (probably for development), roadside exposures, and small quarries over a distance of about 7 km (Fig. 2). Although dip direction was very consistent, beds were dipping steeper in the western than in the eastern part of the series of outcrops. We measured seven sections perpendicular to the strike (Fig. 3). In the longest section, parallel to the northern road to Bontang, the surface between outcrops was flat and vegetated, so that the exact thickness could only be estimated by using distance and dip slope measurements. In ~180–250 m stratigraphical thickness we observed at least five levels containing fossiliferous marine sediments separated by barren sands, clays, and coals (Fig. 3). The poor exposures between the sections and the lateral variability observed within outcrops made bed-to-bed correlation between sections difficult to impossible. Tracing the outcrops in the field allowed correlation between the base of sections TF501 to TF151 and TF151 to TF106 (Figs. 2, 3). Continuing along strike, the outcrop almost reached TF107 but was obstructed by a steeply eroded valley and building area (Figs. 2, 3). Similarly, TF61 and TF154 could be correlated by tracking the strike of the beds.

In the northernmost 5 km of the outcrop, the base is formed by an indurated micritic bioclastic float to packstone rich in *Halimeda*, containing the larger benthic foraminifera *Operculina* sp., *Cycloclypeus carpenteri,* and (rare) *Nephrolepidina rutteni*, as well as platy and branching corals. This facies is best developed in TF504, in which also locally small head-coral–dominated patch reefs developed (max 5 m high, 30–40 m long).

In the northern part of the outcrop, the overlying sediments are dominated by non-indurated coral rudstones in a carbonate sand/silt wackestone to packstone matrix. In TF504, this facies is dominated by platy corals, elsewhere mostly by *Stylophora/Seriatopora* branching corals. From TF151 and further north, branching coral- and mollusk-rich clays with a high organic carbon content are alternating with this facies. It is not the purpose of this paper to describe the depositional environment in detail; the relative positions of the localities in Bontang Garden can be seen in Figure 3.

In only two samples, very similar nannofossils assemblages were observed. The assemblages are well preserved but very low in abundance. They are dominated by *Reticulofenestra minuta* and *Sphenolithus moriformis* with rare *Reticulofenestra pseudoumbilicus, Pontosphaera* sp., *Umbilicosphaera rotula, U. jafari,* and *H. orientalis*. Discoasters are very rare but include *D. bollii, D.* cf. *hamatus* (no unambiguous specimens observed), *D. calcaris* (1 good specimen), and *Catinaster coalitus* (3 good specimens observed). The occurrence of *C. coalitus* is indicative of zones NN8 or NN9, and the possible specimens of *D. Hamatus* would indicate zone NN9. The rest of the assemblage is consistent with this, although given the low abundance the possibility that the assemblage is reworked cannot be excluded. In the bioclastic packstones, abundant, long-ranging taxa were observed (*Operculina* sp., mature-evolute *Heterostegina* cf. *depressa*, and rare *Cycloclypeus carpenteri* and *Nephrolepidina rutteni,* an assemblage indicating a Tf3/late Miocene age (Lunt and Allan 2004; Renema 2007)). In the muddy facies there are abundant benthic

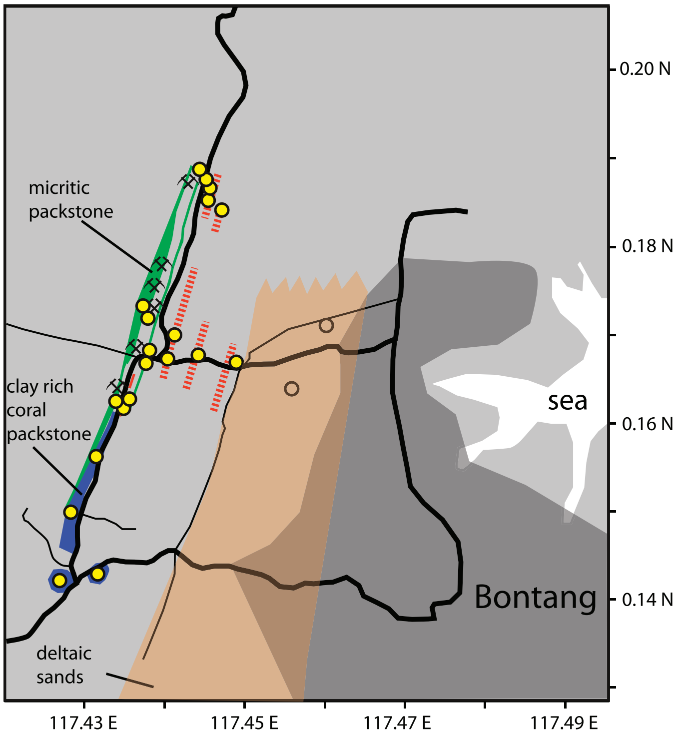

FIG. 2.—Detailed map of the Bontang Garden area. The dashed red lines indicate lateral continuation of the strikes of fossiliferous horizons traced in the field.

foraminifera, especially *Celanthus* spp., *Asterorotalia yabei, Peneroplis* cf. *planatus, Parasorites* sp. (Fig. 4A), and both *Alveolinella quoyi* (Fig. 5B), another *Alveolinella* species (Fig. 5A), and very rare *Nephrolepidina rutteni*. All in all this is a distinct Tf3 assemblage, with the occurrence of *A. yabei* suggesting the early part of this biozone (Billman and Kartaaputra 1974) in the Kutai Basin. However, the occurrence of *A. yabei* could be facies induced.

Fourteen SIS ages indicate a range from 8.2–9.9 Ma (Fig. 6; Table 1), including measurements on aragonite in *Tridacna* shells and aragonitic coral skeletons. With the exception of a single sample, all error margins overlap in the 9.6–9.8 Ma interval. The weighted average (following Edinger et al. 2007) resulted in a comparable 9.6 ± 0.23 Ma.

Given the length of the section and the facies alterations, it is likely that a considerable amount of time (possibly 0.2–0.3 Ma) was involved in the sedimentation of the entire section. However, with the currently available data, it was not possible to determine differences in age between each of the fossiliferous intervals. Most if not all of the SIS ages are from the second or third fossiliferous interval in the section, and none are from the base. The single outlying sample is from TF110, which cannot be placed in the sections due to the lack of the MP facies in the south. The other TF110 sample, however, falls within the range of the other samples. So, an early Tf3/early Tortonian age for the Bontang localities is inferred.

Rutten (1913) and Felix (1921) inferred a younger age for this locality based on the very modern appearance of the benthic foraminifera assemblage (around the Mio-Pliocene boundary) and the absence of *Nephrolepidina* in the samples they studied.

### *Sangatta*

At the base of a hillside to the East of Sangatta a series of quarries, targeting limestone for road fill, were encountered. The lithology in these quarries includes coral packstone with mollusks and locally branching coral and mollusk-rich clays and even coal rich in gypsum. Quarrying overhauled the local stratigraphy, so determining exact lithologic relationships was difficult. We sampled three localities within this region (TF534, TF516, and TF517; Fig. 7).

Samples TF354NS1, TF516NS10, and TF516WR1 include a diverse LBF fauna. In the TF516 samples, a small species of *Marginopora* sp. (Fig. 4D), a simple form of *Amphisorus* (with a double row of apertures; Fig. 4B), and *Parasorites* sp. (Fig. 4A) make up a diverse soritid assemblage. *Alveolinella* is represented by a species with only three rows of small apertures (Fig. 5; compared to ≥4 large apertures and one row of small apertures in *A. quoyii*). All soritid and alveolinid specimens are fragmented. Other taxa include abundant *Cellanthus* spp. and *Elphidium* spp., *Operculina* sp. (in TF516NS1 only), *Amphistegina* spp., and *Asterorotalia yabei*.

Eight SIS ages on aragonitic mollusk shells and coral skeletons indicate a range from 7.6 to 10.0 Ma, all error margins overlap in the 9.0–9.3 Ma interval (Fig. 8; Table 1). If the youngest SIS age is regarded as an outlier, this would widen up the range of overlapping error margins to 9.0–9.4 Ma. The weighted average is 9.0 ± 0.12 Ma, or 9.2 ± 0.10 Ma when the outlier is not incorporated.

A further indication that the Sangatta outcrops are younger than those in Bontang Garden is provided by species in the mollusk genus *Gourmya. Gourmya* cf. *parungpontengensis,* a taxon with well-developed ribs and shoulders, is found in Sangatta, whereas in Bontang the more gentle and smooth *G.* cf. *nyalingdungense* was found. Given their overall morphology, this is likely an ancestor-descendant relationship, with the ancestral species occurring in Bontang (F.P. Wesselingh, personal communication 2013). All in all, a slightly younger, but still early Tortonian, age compared to Bontang Garden is inferred for these outcrops.

### *Bengalon*

Near Bengalon, along the hauling road of the PIK coal mine and along the road to Sangkuliran, we found additional outcrops (Fig. 9). These outcrops flank the west slope of a karstic platform, which is locally more than 450 m high, with mostly lower–middle Miocene limestones that.

The southernmost outcrops (TF175, TF269, especially TF510 and TF511) are consolidated limestones containing poorly preserved, often recrystallized corals. At TF510 and TF511, the hauling road cuts through an about-40-m-high structure that is interpreted as a reef, with mostly (transported) coral fragments in the lower part (TF510), and at the top (TF511), locally head, tabular, and platy corals in growth position with wedges of *Operculina* packstone were present.

TF512 and TF533 have been collected 400 m to the west along the same hauling road (Fig. 9) and are interpreted as the back-reef environment of TF510 and TF511. These are organic-rich siltstones with abundant mollusk and coral fossils. The contact between the siltstone and massive limestones is not exposed. This facies is very similar to the coral and mollusk-rich clay facies in Bontang Garden and Sangatta.

LBF in TF511 include *Operculina* sp., large *Amphisorus* with multiple rows of apertures, i.e., a differentiation between marginal and median apertures (Fig. 4C), mature-evolute *Heterostegina* sp., *Amphistegina* sp., and rare *Calcarina* sp. In TF512 and TF533 a similar fauna as in Bontang Garden and Sangatta is observed, with *Alveolinella quoyi*, *Alveolinella fennemai, Celanthus* spp., *Asterorotalia yabei*, and the soritids *Marginopora* sp., *Parasorites* sp., *Sorites* sp., and *Amphisorus* spp. (both with a ”simple” apertural face and with complex marginal and median apertures), but also *Calcarina* sp.

Six SIS ages from aragonitic mollusk shells and calcitic echinoid spines (Fig. 10; Table 1) indicate a range from 6.1 to 7.2 Ma; all error margins overlap in the 6.4–6.6 Ma interval. If the youngest SIS age is regarded as an outlier, this would widen up the range of overlapping error margins to 6.4–7.0 Ma.

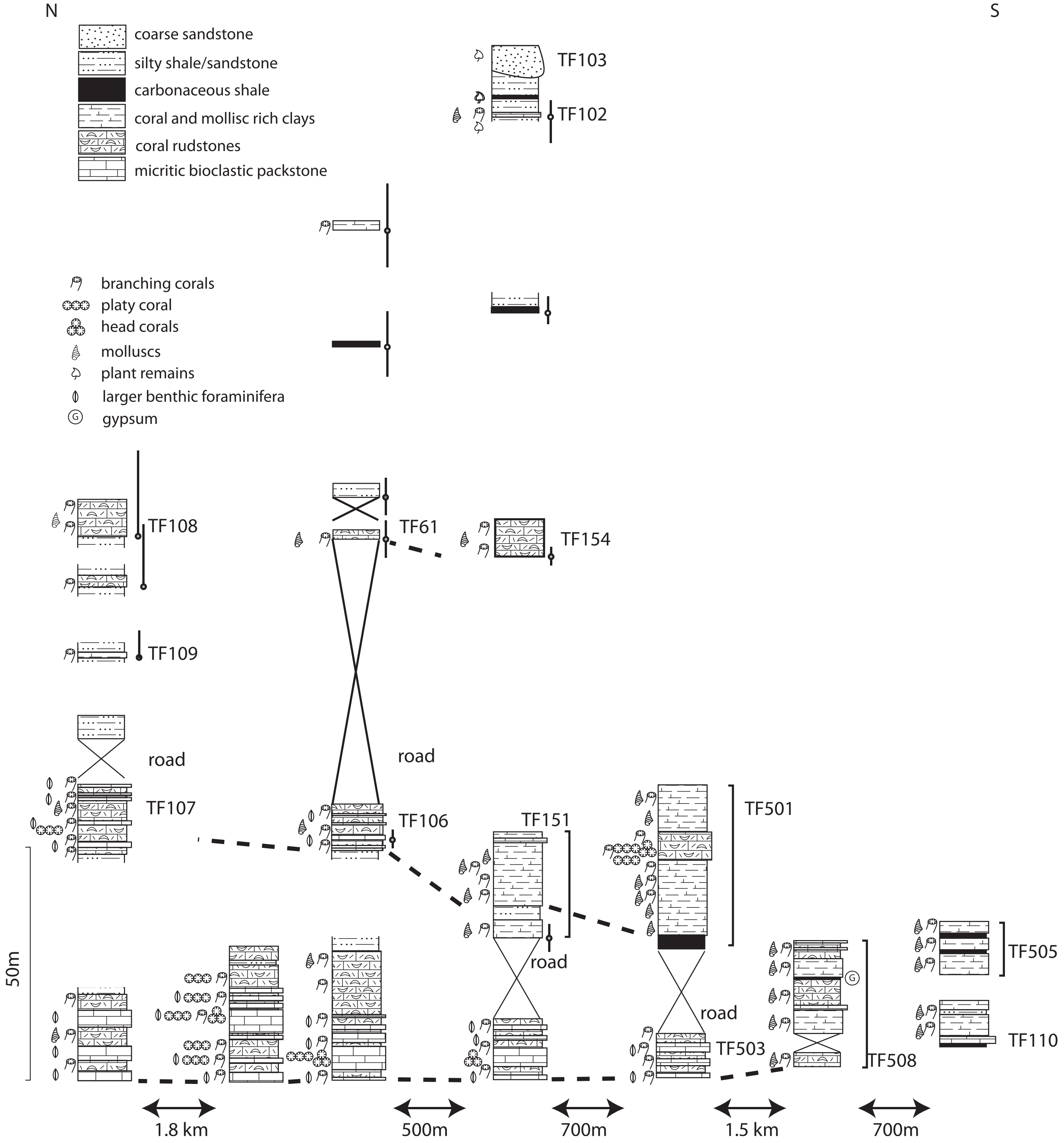

FIG. 3.—Lithology and relative position of the Bontang Garden localities.

Further north is a section outcropping along the Sg Narut, parallel to the road between Bengalon and Sangkulirang (included as TF171 here; Fig. 9). There is a section exposed in the river, made up mostly of siltstone high in organic carbon, locally with mollusks. In the top of the section, branching coral packstones are found in beds of up to 1 m thickness. On top of these coral packstones, several levels with indurated micritic coral and foraminifera packstones are found. In this part of the section, a number of faults with small amounts of displacement were observed, so the overall succession should be treated with caution. The foraminiferal fauna in most of the samples is highly impoverished and indicative of marine to brackish water environments. Several freshwater mollusks were observed in the lower part of the section as well.

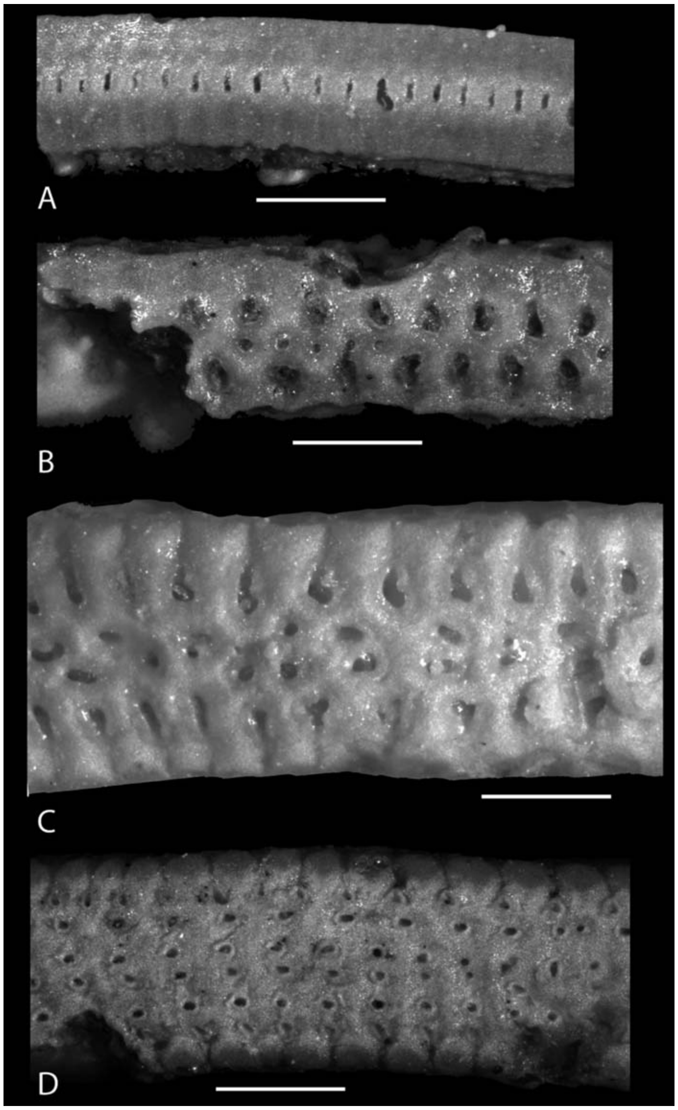

FIG. 4.—Apertural faces of four soritid morphological units recognized in this study. A) *Parasorites* sp. with a single row of vertically elongated apertures at the suture between two chamberlets (RGM791549; Bontang Garden area, early late Miocene); B) *Amphisorus* sp. with a double row of alternating apertures (RGM791548; Bontang Garden area, early late Miocene); C) *Amphisorus* sp. with a double row of lateral apertures separated by a double row of median apertures (RGM791550; Bengalon area, late late Miocene); D) *Marginopora* sp., with a double row of lateral apertures and multiple rows of median apertures. All apertures similar sized, almost round and rimmed (RGM791547; Bontang Garden area, early late Miocene). All scale bars represent 0.2 mm.

In the branching coral packstones, LBF were not abundant, but *Heterostegina* sp., *Operculina* sp., *Amphistegina* spp., and *Calcarina* sp. were present. This is an assemblage very similar to that found in modern coastal reefs in the region (e.g., Renema 2006). Within the micritic LBF packstone, abundant *Operculina* and rare *Nephrolepidina rutteni* were present. Further along the road to Sangkulirang there are a number of small quarries which are all targeting a micritic LBF packstone with similar LBF as in TF171. Based on the LBF fauna composition with abundant *Operculina*, rare (but frequently present) *Calcarina* and complex *Amphisorus*, all localities are inferred to be of similar age. The SIS age of 6.4–7.0 Ma for the hauling road carbonates is compatible with the LBF assemblages in the Sg Narut section and indicates a late Tf3/Messinian age (Renema 2007).

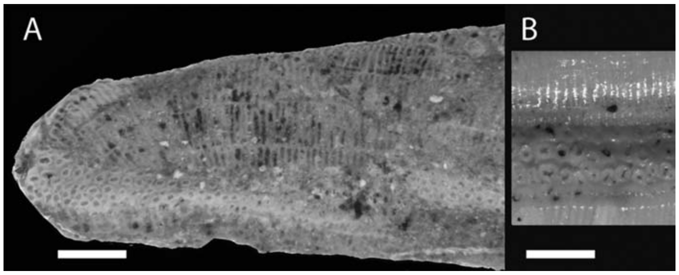

FIG. 5.—Apertural face of two species of *Alveolinella*. A) *Alveolinella* sp. with three rows of small, rimmed apertures (RGM791555; Sangatta, early late Miocene), B) modern *Alveolinella quoyi* with multiple rows (in this case four) of large-rimmed apertures and a single row of small nonrimmed apertures. All scale bars represent 0.2 mm.

### *Kari Orang*

Further northwest along the road from Sangatta to Sangkulirang, another mining road was being built, and numerous fresh outcrops were present (Fig. 11). To the north of the road, most outcrops consisted of barren, clay and organic carbon-rich silt- to sandstone. However, we found some more carbonate-rich layers containing (decalcified) mollusks, corals, bryozoans, and benthic foraminifera at the tops of three successive hills (TF520, TF522 and TF275, and TF523). LBF occurred in low abundance. The sample with most specimens (TF522WR01) included an assemblage with *Nephrolepidina ferreroi, Cycloclypeus carpenteri,* C. *annulatus, Lepidosemicyclina polymorpha*, and *Miogypsina* sp. The co-occurence of *C. carpenteri* and *C. annulatus* indicates a late Serravallian age (Renema 2015). This is supported by the large size and complex shape of *Lepidosemicyclina*.

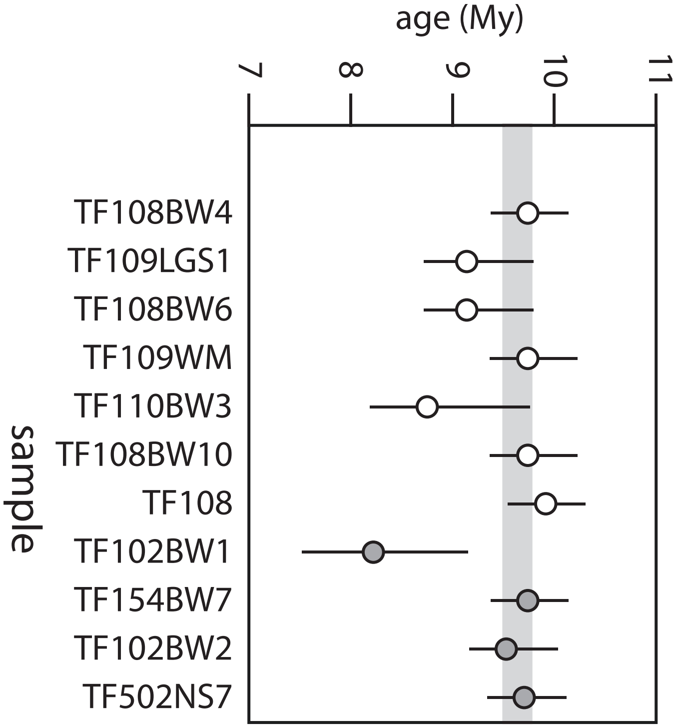

FIG. 6.—SIS ages of 11 samples in the Bontang Garden area. Open symbols = aragonitic mollusk shells, gray = coral skeletons. Details of the measurements are in Table 1. The gray bar represents the age interval which is congruent with all measurements.

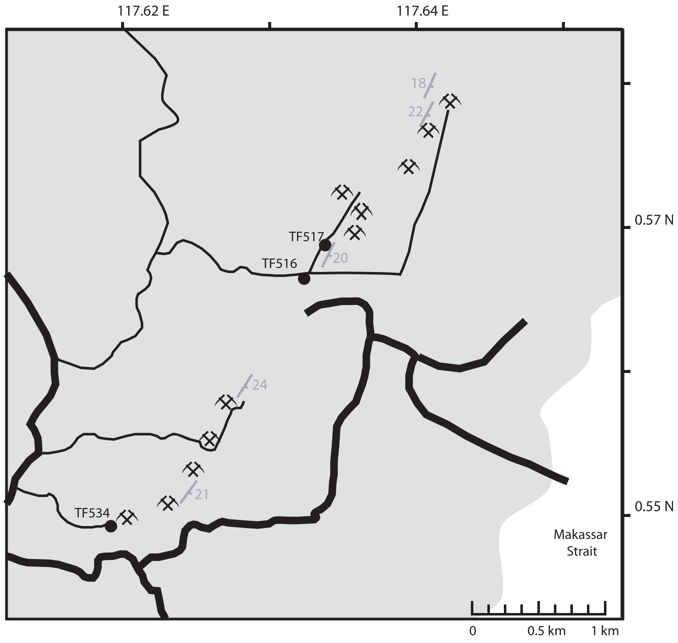

FIG. 7.—Detailed map of the Sangatta area.

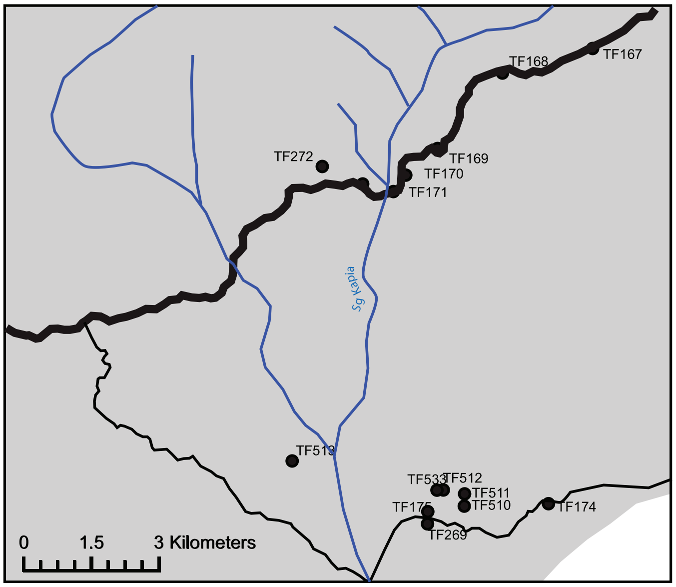

FIG. 9.—Detailed map of the Bengalon area.

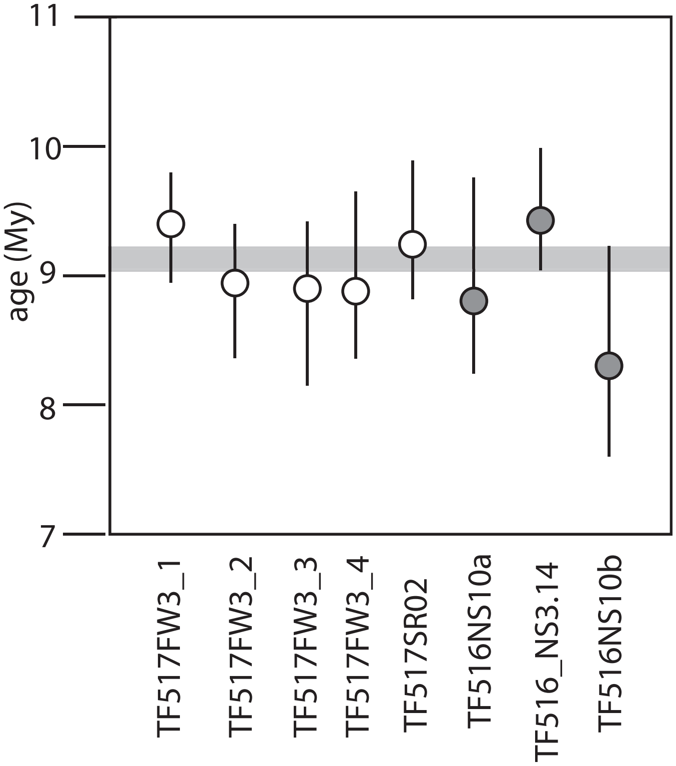

FIG. 8.—SIS ages of eight samples in the Sangatta area. Open symbols = aragonitic shells, gray = coral skeletons. The gray bar represents the age interval which is congruent with all measurements. Details of the measurements are in Table 1.

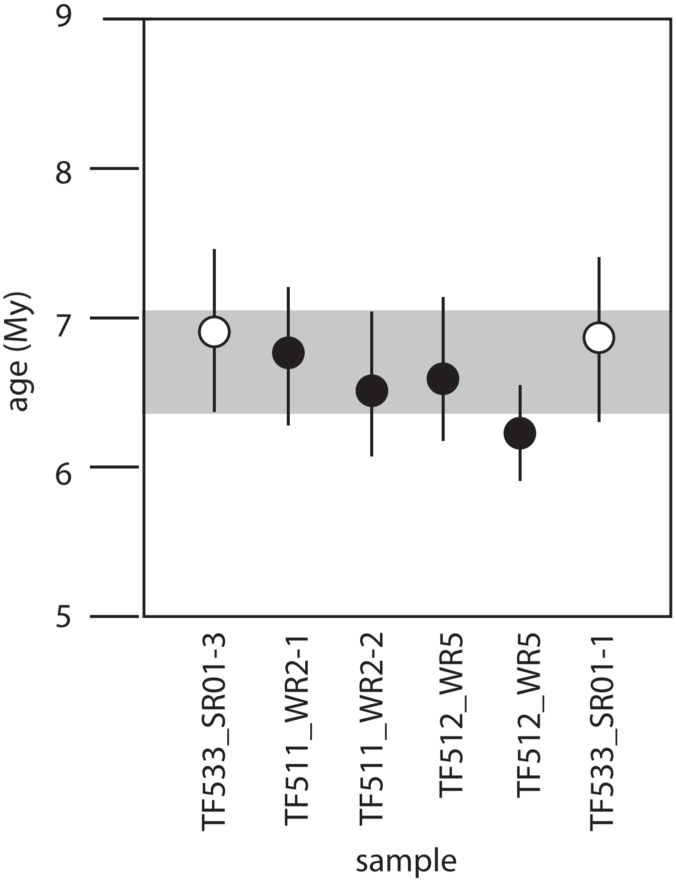

FIG. 10.—SIS ages of eight samples in the Bengalon area. Open symbols = aragonitic shells; black = calcitic echinoid spines. The gray bar represents the age interval which is congruent with all measurements. Details of the measurements are provided in Table 1.

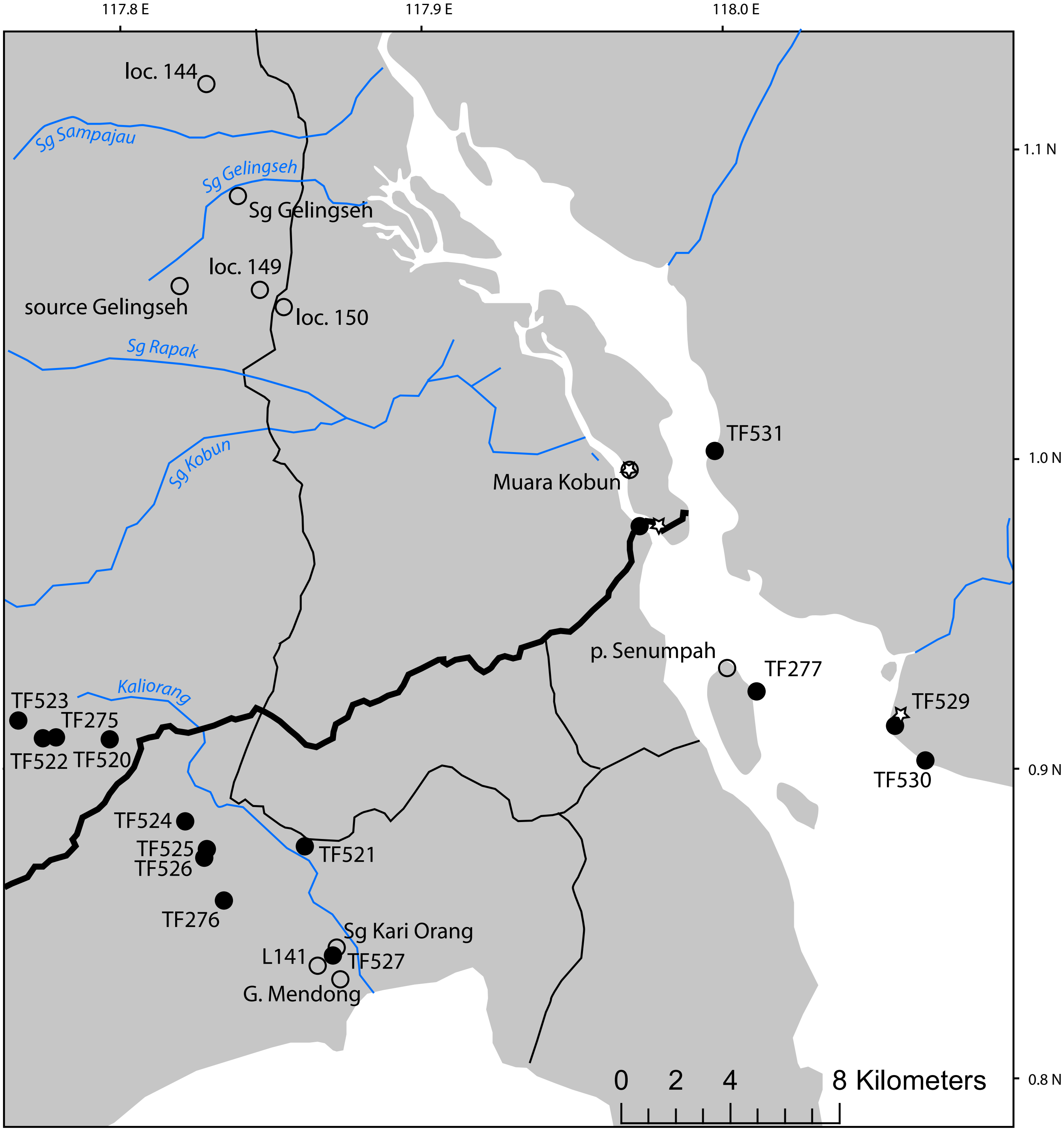

FIG. 11.—Detailed map of the Kari Orang area.

To the south, the hauling road first passes east of the karstic plateau, then bends over a flat area, finally running along another low hill to a jetty. In the first part, bulldozing has obscured the visibility of stratigraphical relationships between localities. The poorly bedded lithology, which are mostly planktonic foraminifera-rich clays, locally interbedded with presumably transported corals (rare), mollusks, and LBF-bearing sediments further impair correlation of the outcropsTF524, TF525, and TF526 represent such localities. In TF524 *Eulepidina* sp., *Nephrolepidina* spp., *Amphistegina* sp., and *Operculina* sp. were observed, indicating a $Te_5$/Aquitanian age. The planktonic foram assemblage (including *Orbulina* sp., *Globorotalia praemenardi,* and *Sphaeroidellinopsis* sp.), though impoverished, indicated a late middle Miocene or younger age (Wade et al. 2011). Similarly, in TF525 the LBF indicate Tf1/Burdigalian age (*Austrotrillina, Nephrolepidina, Cycloclypeus annulatus*) and a late Miocene or younger age was inferred for the planktonic foraminifera-rich (including *Orbulina* sp., *Sphaeroidellinopsis* sp., and *Neogloboquadrina* sp.) clays.

TABLE 2.—*Summary table providing the ages and the definition of upper and lower limit of the age estimates, and literature source when this is discussed in more detail elsewhere.*

| Area | Exposure kind | Locality | | Age | Based on | Source |
|---|---|---|---|---|---|---|
| Badak-Bontang | group of quarries closely together | TF6; TF7; TF8; TF53; TF54; TF56 | old age | 17.9 My | lower boundary NN4 | |
| Badak-Bontang | | | young age | 14.8 My | not younger than TF76 | |
| Badak-Bontang | quarry | TF17; TF18;TF60, TF111, TF127, TF128 | | | similar to Tf126; Tf153 based on LBF assemblage | |
| Badak-Bontang | | TF111 | | | similar to Tf126; Tf153 based on LBF assemblage | |
| Badak-Bontang | first quarry | TF153 | old age | 17.9 My (16.0 My) | lower boundary NN4; 16.0 My based on SIS (table 1) | |
| Badak-Bontang | road cut | TF153 | young age | 15.3 My (15.6 My) | LBF; older than Batu Putih; 15.6 M based on SIS (table1) | |
| Badak-Bontang | road section | TF23; Tf129 | old age | 17.9 My | older than TF126 by lithological correlation | |
| Badak-Bontang | road section | TF23; Tf129 | young age | 15.3 My | older than TF126 by lithological correlation | |
| Badak-Bontang | road cut | TF22; TF128 | old age | 17.9 My | | |
| Badak-Bontang | road section | TF22; TF128 | young age | 15.3 My | younger than TF126 by lithological correlation | |
| Badak-Bontang | road cut | TF21; TF126 | old age | 17.9 My | lower boundary NN4 | Novak et al. (2013) |
| Badak-Bontang | road cut | TF21; TF126 | young age | 15.3 My | LBF; older than Batu Putih | Novak et al. (2013) |
| Badak-Bontang | quarry | TF13; TF14; TF59 | old age | 17.9 My | lower boundary NN4 | |
| Badak-Bontang | quarry | TF13; TF14; TF59 | young age | 15.3 My | LBF; older than Batu Putih | |
| Bengalon | road cut | TF175, TF269 | | | probably similar to TF510-512, TF533 based on proximity and bedding | |
| Bengalon | road cut | TF510, TF511 | old age | 7 My | SIS | |
| Bengalon | quarry | TF174 | | | probably similar to TF510-512, TF533 based on proximity and bedding | |
| Bengalon | quarry | TF510, TF511 | young age | 6.4 My | SIS (table 1) | |
| Bengalon | road cut | TF173, TF271 | | | probably similar to TF510-512, TF533 based on proximity and bedding | |
| Bengalon | road cut | TF512, TF533 | old age | 7 My | SIS (table 1) | |
| Bengalon | road cut | TF512, TF533 | young age | 6.4 My | SIS (table 1) | |
| Bengalon | road cut | TF270 | | | probably similar to TF510-512, TF533 based on proximity and bedding | |
| Bengalon | mine | TF272 | | | probably similar to TF510-512, TF533 based on proximity and bedding | |
| Bengalon | river section | TF170; TF171; TF278; TF518 | old age | ~8 My | based on the LNF assemblage, second half of late Miocene | |
| Bengalon | river section | TF170; TF171; TF278; TF518 | young age | ~5 My | LO of *Nephrolepidina rutteni* | |
| Bengalon | quarry | TF169 | old age | ~8 My | in section, between TF170 and TF168 | |
| Bengalon | quarry | TF169 | young age | ~5 My | | |
| Bengalon | quarry | TF168 | old age | ~8 My | younger than TF170 based | |
| Bengalon | quarry | TF168 | young age | ~5 My | LO of *Nephrolepidina rutteni* | |
| Bengalon | quarry | TF167 | old age | ~8 My | younger than TF170 based | |
| Bengalon | quarry | TF167 | young age | ~5 My | LO of *Nephrolepidina rutteni* | |
| Bontang Garden | construction site | TF15-16; TF19; TF61; TF102-110; TF152; TF154; TF166; TF TF500-TF509 | old age | 9.8 My | SIS (table 1) | |
| Bontang Garden | construction site | TF15-16; TF19; TF61; TF102-110; TF112-113; TF131; TF152; TF154; TF166; TF TF500-TF509 | young age | 9.4 My | SIS (table 1) | |
| Kari Orang | road cut | TF526, TF276 | old age | ~18 My | Based on late Tf1/early Tf2 LBF. Slumped into late Miocene or younger planktonic foraminifera marl | |
| Kari Orang | road cut | TF526, TF276 | young age | ~13 My | Based on late Tf1/early Tf2 LBF. Slumped into late Miocene or younger planktonic foraminifera marl | |
| Kari Orang | road cut | TF525, TF275 | old age | ~18 My | Based on early Tf1 LBF. Slumped into late Miocene planktonic foraminifera marl | |
| Kari Orang | road cut | TF525, TF275 | young age | ~20 My | Based on early Tf1 LBF. Slumped into late Miocene planktonic foraminifera marl | |
| Kari Orang | road cut | TF524 | old age | ~20 My | Based on Te5 LBF. Slumped into middle-late Miocene planktonic foraminifera marl | |
| Kari Orang | road cut | TF524 | young age | ~24 My | Based on Te5 LBF. Slumped into middle-late Miocene planktonic foraminifera marl | |

TABLE 2.—*Continued.*

| Area | Exposure kind | Locality | | Age | Based on | Source |
|---|---|---|---|---|---|---|
| Kari Orang | road cut | TF520 | | | same as TF522 | |
| Kari Orang | road cut | TF522, TF273 | old age | ~13 My | FO of *Cycloclypeus carpenteri* | |
| Kari Orang | road cut | TF522, TF273 | young age | 11.6 My | LO of *Cycloclypeus annulatus* | |
| Kari Orang | road cut | TF523 | | | same as TF522 | |
| Samarinda | other | TF52; TF77; TF79; TF130; TF311 | | as TF76 | correlation to TF76 | Marshall et al. 2015 |
| Samarinda | quarry | TF76 | old age | 15.3 My | | Marshall et al. 2015 |
| Samarinda | | TF76 | young age | 14.8 My | | Marshall et al. 2015 |
| Samarinda | building site | TF358 | | | stratigraphically below TF76 | Marshall et al. 2015 |
| Samarinda | building site | TF357 | | | stratigraphically below TF76 | Marshall et al. 2015 |
| Samarinda | building site | TF356 | | | stratigraphically below TF76 | Marshall et al. 2015 |
| Samarinda | road cut | TF4; TF51; TF51; Tf201 | | 11.6 My | | Marshall et al. 2015 |
| Samarinda | road cut | TF5; TF57 | | 11.6 My | | Marshall et al. 2015 |
| Sangatta | quarry | TF516; TF517; TF534 | old age | 8.9 My | SIS (table 1) | |
| Sangatta | quarry | TF516; TF517; TF534 | young age | 9.3 My | SIS (table 1) | |
| Sangatta | quarry | TF515 | old age | 16 My | Tf2 LBF assemblages | |
| Sangatta | quarry | TF515 | young age | 11.6 My | Tf2 LBF assemblages | |
| Sangatta | quarry | TF514 | old age | 16 My | Tf2 LBF assemblages | |
| Sangatta | quarry | TF514 | young age | 11.6 My | Tf2 LBF assemblages | |
| Senoni | first quarry | TF1 | | | correlation to TF10, 11, 310 | |
| Senoni | first quarry | TF10; TF11; TF310 | old age | 20 My | LBF | |
| Senoni | first quarry | TF10; TF11; TF310 | young age | 18 My | LBF | |

In TF526 the LBF indicate Tf1$_{-2}$ (*Nephrolepidina, Lepidosemicyclina, Cycloclypeus annulatus*), and the planktonic foraminifera also indicate a late Miocene or younger age (including *Orbulina* sp., *Sphaeroidellinopsis* sp., and *Neogloboquadrina* sp.). An explanation for these mixed faunas could be that during or following uplift of the nearby karstic platform, erosional products were transported into a nearby deep-marine basin. This would suggest that basin inversion in this area started in the latest middle Miocene or later.

## DISCUSSION

Within the northeastern part of the Kutai basin, we have observed and dated numerous fossil-bearing localities (Table 2). The use of an integrated approach, including benthic and planktonic foraminifera, calcareous nannoplankton, and SIS, improved our understanding of several previously published sites, and has revealed a general south-to-north decrease in age of the studied sites. An exception to this trend is formed by the karst platform between Bengalon and Sangkulirang.

In the middle Miocene and younger outcrops no pristine aragonite was found, and SIS in several outcrops (Stadion, Batu Putih, TF126, and TF153) produced internally inconsistent SIS ages, most of them also not consistent with biostratigraphy. SIS on pristine aragonitic shells produced much more consistent results in the late Miocene and younger, although even here an outlier with nonoverlapping error margins was observed. To avoid these errors it is recommended to use multiple specimens from each sample. This will not only show inconsistencies within the data, but also improve the precision of the dating. Different methods to deal with multiple measurements from a single outcrop have been evaluated, but most of them result in very similar ages.

With the calibration of the Tf2-Tf3 boundary close to the Serravallian–Tortonian boundary (Marshall et al. 2015), Tf1–2 now incorporates the Burdigalian to Serravallian, a period of more than 8 myr. Even though this is a period in which many changes in the LBF fauna occur, and in which the ancestors to the modern LBF fauna evolved (Adams et al. 1984; Lunt and Allan 2004; Renema 2007), no consensus on the biozonation exists. Our LBF data suggest that there might be regional differences that obscure zonation schemes, and can be either biogeographically or environmentally induced. In the siliciclastics-dominated Kutai Basin, LBF occur in muddy environments, and porcellaneous taxa, such as *Austrotrillina, Pseudotaberina*, and *Flosculinella* are rare. For example, *Austrotrillina* has not been observed in Tf1 sediments, whereas it occurs at least into early Burdigalian in Java (Renema 2008), and into the Langhian in Papua, New Guinea (Wonders and Adams 1991). Renema (2007) used this taxon to define the Tf1-Tf2 boundary. *Pseudotaberina* and especially *Flosculinella* are less rare, and have been found in middle Langhian deposits. *Pseudotaberina* is a good indicator for the Burdigalian (Renema 2008; Lunt and Allan 2004), but here we present evidence that it ranges into the middle part of the Langhian. Within the Kutai Basin the occurrence of hyaline taxa that are more tolerant to muddy and low light conditions are more useful for subdividing Tf1–2. Our data suggest that from the late Burdigalian (or even close to the Burdigalian-Langhian boundary) to Serravallian different morphotypes in *Lepidosemicyclina* can be observed, from generally small, lobed specimens, to large and very irregular specimens. Since most of the outcrops are isolated patches of carbonate, and (non LBF) stratigraphical resolution is poor, it needs to be clarified whether this is a gradual trend, or whether these are different, but morphologically stable, species as suggested by van Vessem (1977).

The late Miocene has received very limited attention by earlier LBF workers. Even though it was already suggested by van der Vlerk and Umbgrove (1927) that the LO of *Nephrolepidina* is younger than that of the miogypsinids, this was only generally accepted since Adams et al. (1984) discussed this in detail using occurrences from Fiji and the Kutai Basin. This extended Tf3 to the latest Miocene, and it incorporates a time in which the modern LBF fauna gets established (Renema et al. 2008). Our new data suggests that there are possible bioevents that could subdivide this zone. The first occurrence of large and complex *Amphisorus* seems to be a good candidate for a subdivision into an early and later part. This is supported by data from the nearby Mangkalihat Peninsula (Renema and Novak, unpublished data), and Cebu (W. Renema, 2013).

## CONCLUSION

Our data confirm the presence of short-lived reefal environments in an environment otherwise dominated by clastic sedimentation. Contrary to the nearby thick carbonate deposits in large carbonate platforms, these usually incorporate only 1–3 reef cycles at a time (Wilson 2005; Novak et

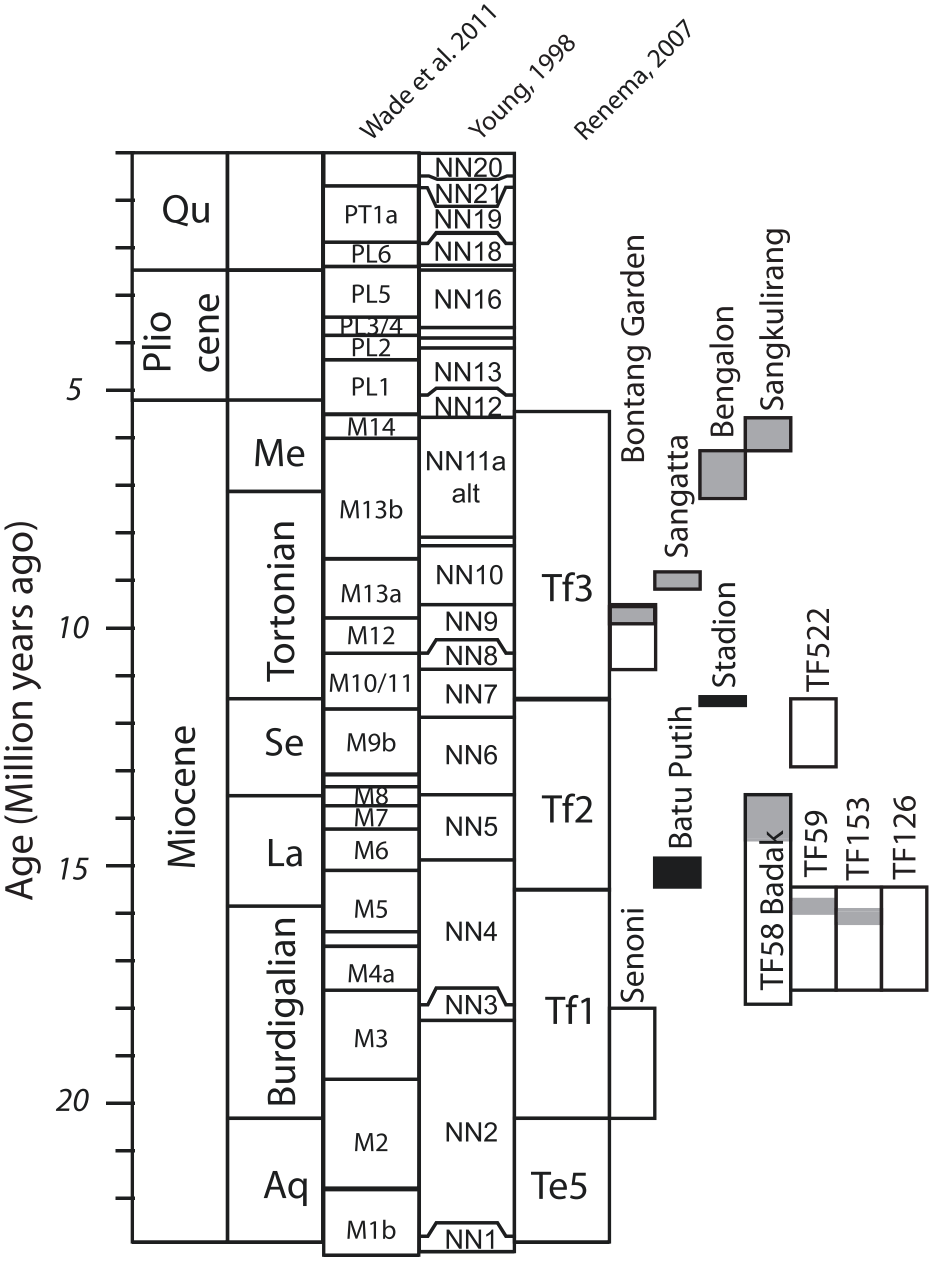

FIG. 12.—Summary diagram of the ages of the twelve (clusters of) localities discussed in this paper. White = defined on biostratigraphy; gray = defined on Strontium isotope stratigraphy; black = defined on magnetostratigraphy.

al. 2013; Rösler et al. 2015; Santodomingo et al. 2015), and represent various deltaic environments (Novak and Renema 2015). Ages of these reefal deposits vary from early Burdigalian to Messinian in age (Fig. 12). In addition to providing more precise ages for previously documented middle Miocene carbonates, new surface outcrops of early Tortonian and Messinian age are reported.

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## SUPPLEMENTAL MATERIAL

Data is available from the PALAIOS Data Archive: http://www.sepm.org/pages.aspx?pageid5332.

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