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DATING BORNEO'S DELTAIC DELUGE: MIDDLE MIOCENE PROGRADATION OF THE MAHAKAM DELTA

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ABSTRACT: **Borneo's geologic and paleontological history remains poorly understood because of the lack of outcrops and difficulties with dating. Urban development around the city of Samarinda has produced over four kilometers of well-exposed stratigraphy depicting the progradation of the ancient Mahakam river delta across the Samarinda area, which includes slope, shelf, and deltaic deposits (clastic and carbonate). Previous studies have preliminarily dated the succession as middle Miocene, but reworking and the scarcity of diagnostic fossils make dating difficult. In this paper, an integrated stratigraphic age model has been constructed for the middle Miocene of the Samarinda region with a combination of magnetostratigraphy, sequence stratigraphy, and biostratigraphy (nannofossil, planktonic foraminifera, and larger benthic foraminifera). This age model provides improved temporal constraints for part of the Mahakam Delta succession. It also helps to place the pattern of biodiversity changes seen in Indonesian reef communities into a better time perspective, and permits more accurate sedimentation rates to be determined. It may also serve as a reference point to compare other Neogene sections in Southeast Asia. The two reef complexes at Samarinda, the Batu Putih and the Stadion section, are magnetostratigraphically dated at ~ 15 Ma and 11.6 Ma, respectively. The new chronology for the Samarinda succession shows that the Mahakam Delta went through a major phase of buildout and progradation during the middle and earliest late Miocene, during which time progradation across the former shelf break took place in the Samarinda area.**

INTRODUCTION

Borneo is home to record-breaking biodiversity levels and flourishing natural-resource industries. Located in the middle of the Indo-Pacific biodiversity hotspot, the seas around Borneo contain the most biodiverse coral reef communities in the world (Myers et al. 2000; Hughes et al. 2002; Renema et al. 2008). Centered in this hotspot is the hydrocarbon-rich Kutai Basin (Chambers and Daley 1997; Cloke et al. 1999; Cibaj et al. 2007). Strong deltaic sedimentation within the basin initiated within the early Miocene and continues presently (Moss and Chamber 1999; Wilson and Moss 1999; Hall and Nichols 2002). New data suggest that this was concurrent with the global marine biodiversity hotspot in Borneo (Renema et al. 2008). Contrary to its importance as a living laboratory and hydrocarbon producing region today, Borneo's paleontological history remains poorly documented. In Borneo, as with much of Southeast Asia, the lack of natural outcrops and difficulties with dating have resulted in few detailed studies of ancient geologic settings being described. Urban development around the city of Samarinda has produced many large exposures of Miocene sediments. Over four kilometers of relatively well-exposed stratigraphy record an offshore to deltaic progradational succession. The quality and length of the composite section provide a significant opportunity to understand Miocene sedimentation processes within this rapidly filled basin. Moreover, the presence of two reef complexes separated by a thick siliciclastic succession provides important insight into the rate of evolutionary development of biodiversity in the area. Previous studies have preliminarily dated the section as middle Miocene (Wilson 2005; Cibaj 2009), but reworking and the scarcity of age-diagnostic fossils make dating inaccurate. The extent of new exposure makes possible magnetostratigraphic dating, which can be a very accurate dating technique with detailed sampling (Langereis et al. 2010). With a combination of magnetostratigraphy, sequence stratigraphy, and biostratigraphy (nannofossils, planktonic foraminifera, and larger benthic foraminifera (LBF)), an integrated stratigraphic, depositional, and age model for the middle and lowermost upper Miocene of the Samarinda region is presented herein. Additionally, magnetostratigraphy, when combined with other dating techniques, provides a means within which the likelihood of reworked index fossils can be assessed. A precise age model allows better quantification of sedimentation rates and precise dates for the two reef systems. The detailed time framework can also serve as a reference point to compare other Neogene sections in Southeast Asia and can be used to better understand the timing and rate of uplift, sedimentation, and biodiversity change in the Miocene. Furthermore, a detailed age study adds constraints to the LBF zonations. Larger benthic

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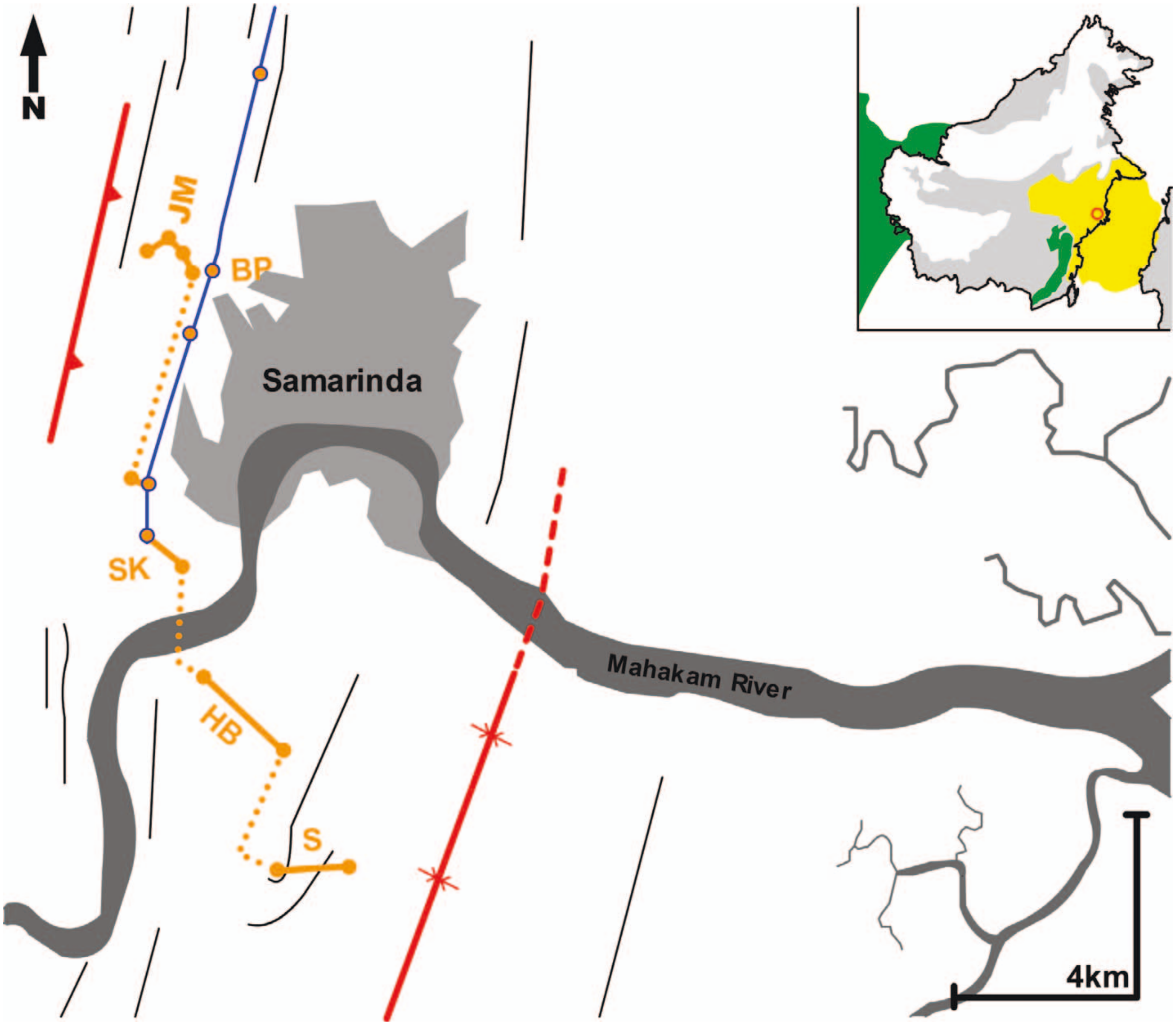


FIG. 1.—Outline map of Borneo with the Kutai Basin highlighted in yellow and non-Cenozoic bedrock in green. Red circle indicates the location of this study. The large schematic map of the Samarinda area shows the sampling locations in orange. Blue lines show the correlation of the Batu Putih reef spatially. Black thin lines highlight strike directions and the approximate location of structures. The Separi Anticline runs along in the northwest corner of the map and is oversteepened, forming a thrust fault. Note that the sample location paths run roughly perpendicular to strike, with the oldest rocks to the NW. Locations are indicated by their Throughflow site numbers but are given subsection names in this paper: JM = Jalan Mangkunegara (a = Bukit Pinang, b = Garage, c = Hutunan Village, d = Rapak). BP = Batu Putih. SK = Sungai Kunjang. HB = Harapan Baru. S = Stadion. Outline map modified from Hall and Nichols (2002).

foraminifera are an important group of index fossils in the region, but their middle Miocene chronostratigraphy is still not fully understood.

DESCRIPTION OF THE MIOCENE SAMARINDA SUCCESSION

The thick Neogene section in the Kutai Basin (up to 14 km) was entirely derived from the island of Borneo as result of inland uplift (Chambers and Daley 1997; Cloke et al. 1999; Hall and Nichols 2002). During the middle Miocene the depocenter for this basin shifted to the Samarinda area. Uplift in the interior of the island also shifted eastward and old rift faults were reactivated during the Miocene (Moss and Chambers 1999). Miocene sediments were initially sourced from uplifted Paleogene or older sediments and later reworked from inverted Neogene bedrock (Moss and Chambers 1999). The lower and basal middle Miocene section was folded and faulted within the Samarinda Anticlinorium (Fig. 1). Seismic studies have demonstrated that the NNE-SSW–trending ridges that dominate the region are expressions of tight linear anticlines and broader synclines (Chambers and Daley 1997; Cloke et al. 1999). Beds typically strike at 24°–40° with an eastward dip of 50°–70°.

The section studied begins in the core of the Separi Anticline, through the eastern flank of the anticline, and into the adjacent syncline (Fig. 1). Over four kilometers of stratigraphy are exposed in the area. The succession has been divided into five distinctive sections based on changes in depositional setting (Figs. 2–6) outlined below.

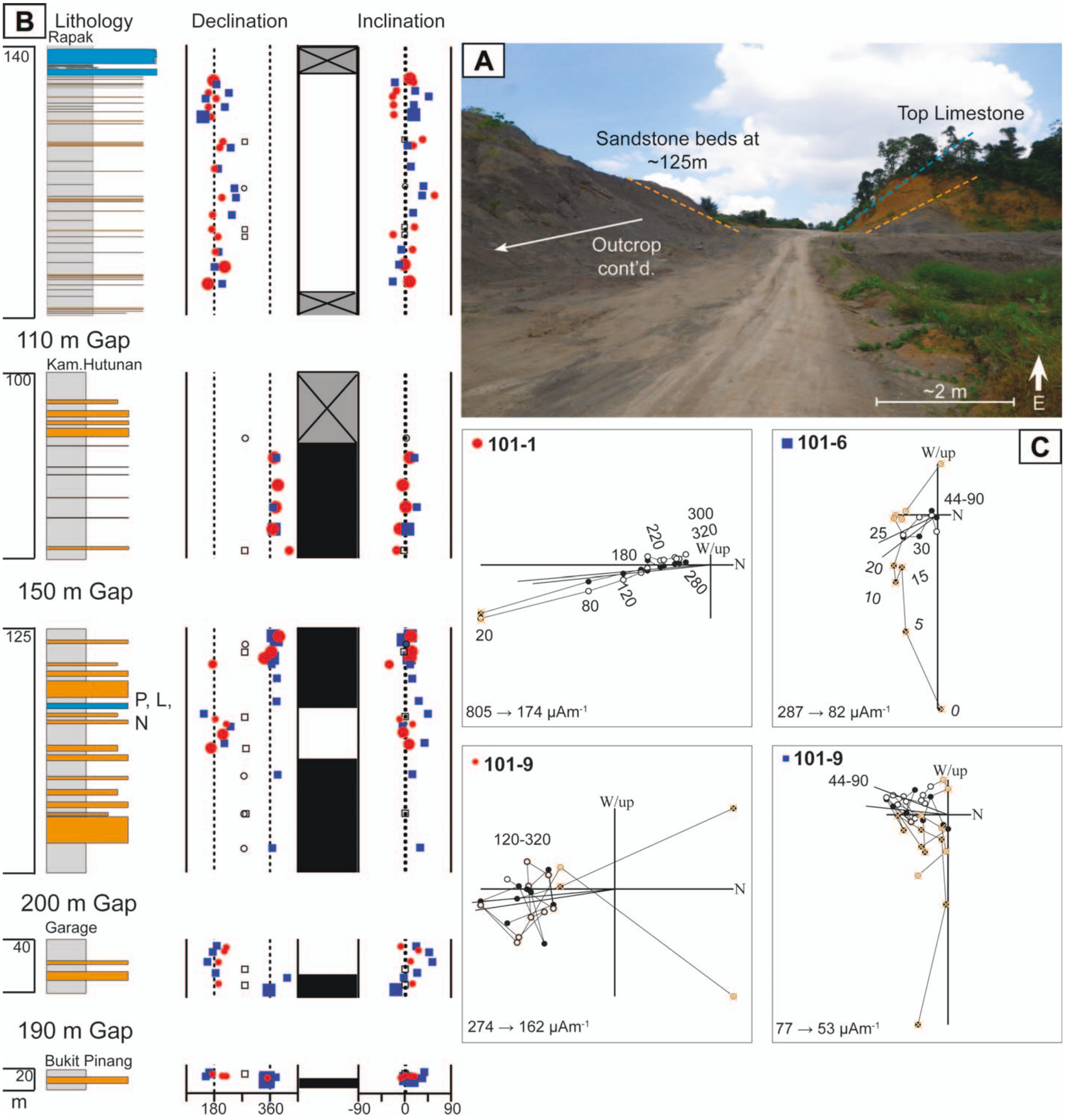


FIG. 2.—Jalan Mangkunegara: Paleomagnetic interpretation vs. stratigraphy. **A**) Photo of the capping Batu Putih reef with construction site exposing shale-dominated sequence below. **B**) Detailed lithographic log with magnetic declination, inclination, and resulting polarity. Orange indicates resistant sandstone beds, blue indicates carbonate lithologies (containing macrofauna), black beds are coal or highly carbon-rich shale, and gray indicates recessed shale or silty-shale. Red circles = TH, blue squares = AF, large and small shapes are for class A and class B samples respectively. Class C results are indicated by open shapes centered arbitrarily around 270° for declination and 0° for inclination. Regions of gray on the polarity plot indicate stratigraphy that was either not sampled (hatched with an X) or where samples gave ambiguous results. Letters next to log indicate positions of biostratigraphically important fossils: L = larger benthic forams, N = nannofossils, P = planktonic forams. **C**) Examples of Zijderveld diagrams showing both AF and TH results for class A and B samples. Orange X's indicate data that was deemed overprint and excluded from polarity analysis. Respective temperature/magnetic steps (°C/mT) are given next to the data points. Numbers in lower corner indicate the starting and ending intensity of the data points used. These labeling and color schemes are used in figures 3–6 as well.

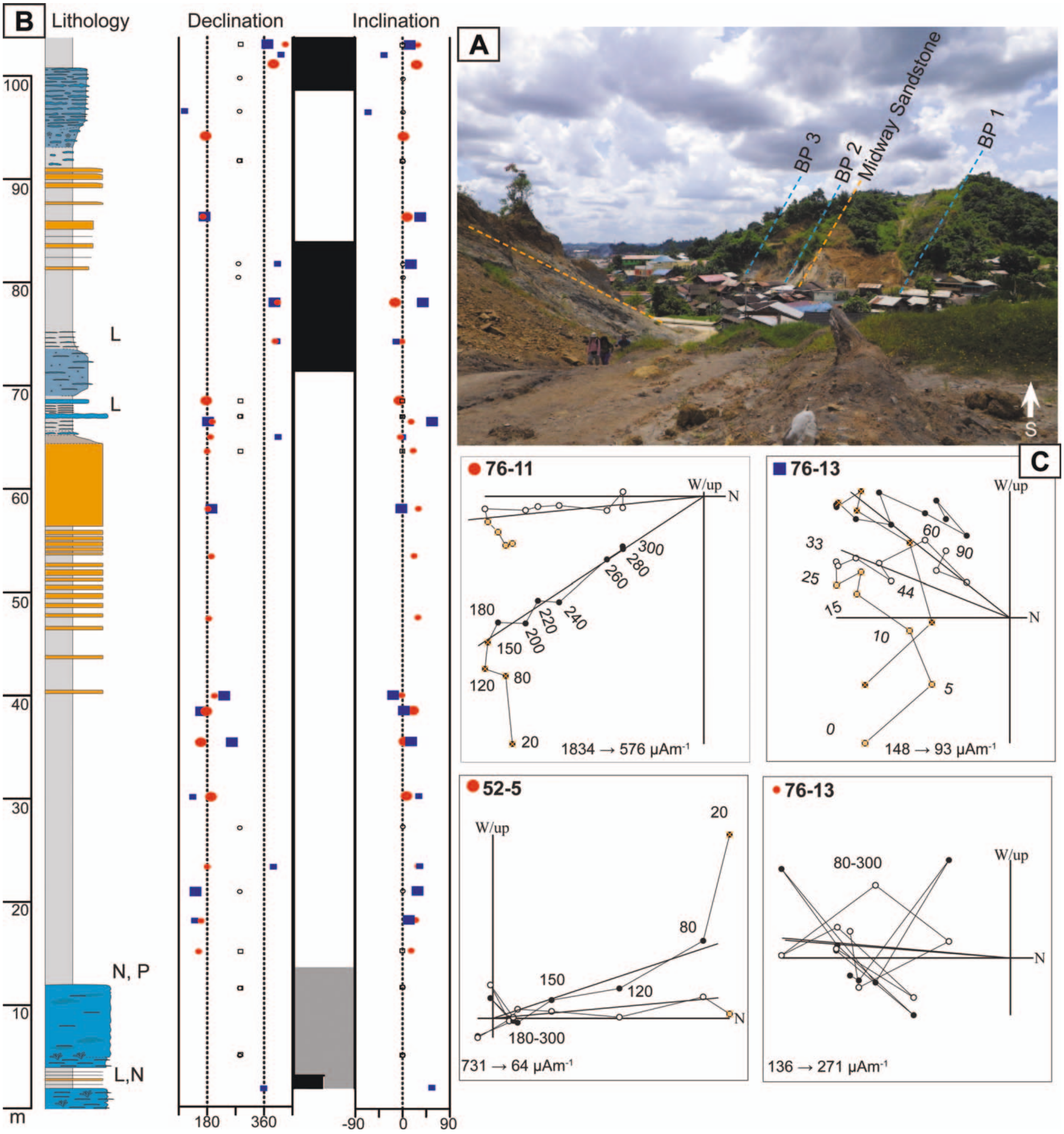


FIG. 3 Batu Putih: paleomagnetic interpretation vs.—stratigraphy. **A**) Photo taken standing on the Batu Putih reef (BP 1), looking up section. Dashed colored lines indicate bedding contacts continued across an inhabited area, in two quarries. **B**) Detailed lithographic log with magnetic declination, inclination, and resulting polarity. Artistic texturing added to the limey beds is meant to emphasize their visual appearance in the outcrop. These include hard-blocky limestone beds containing many macrofossils, undulating interbedded shale and platy coals, and grainy, LBF-dominated limey shale. See figure 1 caption for explanation of colors and notations.

Jalan Mangkunegara

The oldest section contains five outcrop sections which range from 20 to 130 m in thickness, separated by gaps of between 100 and 200 m (Fig. 2). The lower section contains thick (~ 10 m) beds of sandstone that contain terrestrial plant fossil fragments including well-preserved angiosperm leaves. Notably, in the lower exposure is a fossiliferous debris flow, composed almost entirely of LBF. The upper part of the Kampong Hutunan section contains more shale and thinner sandstone beds. The topmost part of this subsection terminates below the first

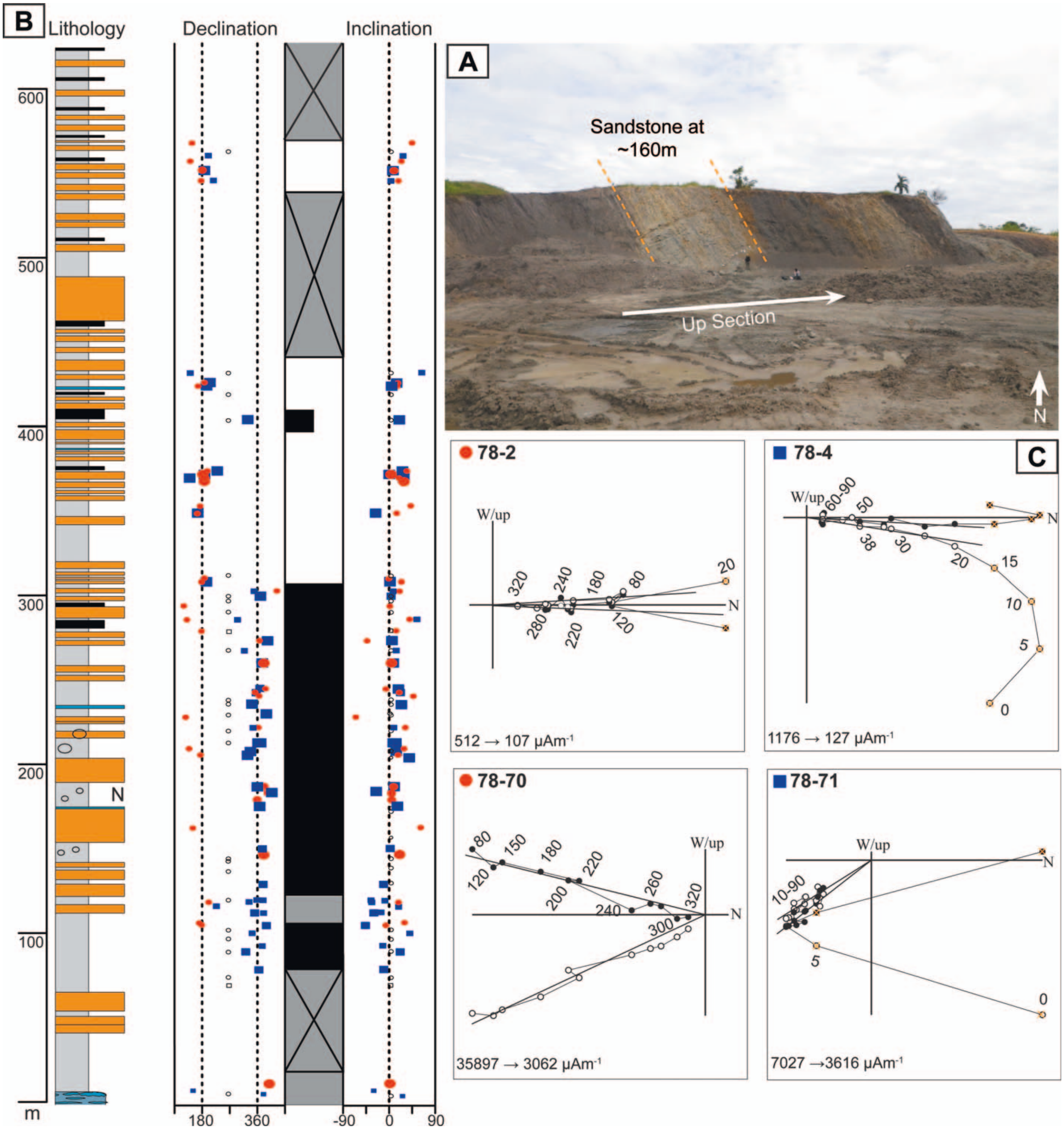


FIG. 4.—Sungai Kunjang: paleomagnetic interpretation vs. stratigraphy. **A**) Photo showing the sandstone beds surrounded by shale containing bivalve, crab, and echinoid fossils and concretions. **B**) Detailed lithographic log with magnetic declination, inclination, and resulting polarity. Circles indicate locations of concretions. Red circles = TH, blue squares = AF, large and small shapes are for class A and class B samples respectively. Class C results are indicated by open shapes centered arbitrarily around 270° for declination and 0° for inclination. Regions of gray on the polarity plot indicate stratigraphy that was either not sampled (hatched with an X) or where samples gave ambiguous results. Letters next to log indicate positions of biostratigraphically important fossils: L = larger benthic forams, N = nannofossils, P = planktonic forams. **C**) Examples of Zijderveld diagrams showing both AF and TH results for class A and B samples. Orange X's indicate data that was deemed overprint and excluded from polarity analysis. Respective temperature/magnetic steps (°C/mT) are given next to the data points. Numbers in lower corner indicate the starting and ending intensity of the data points used.

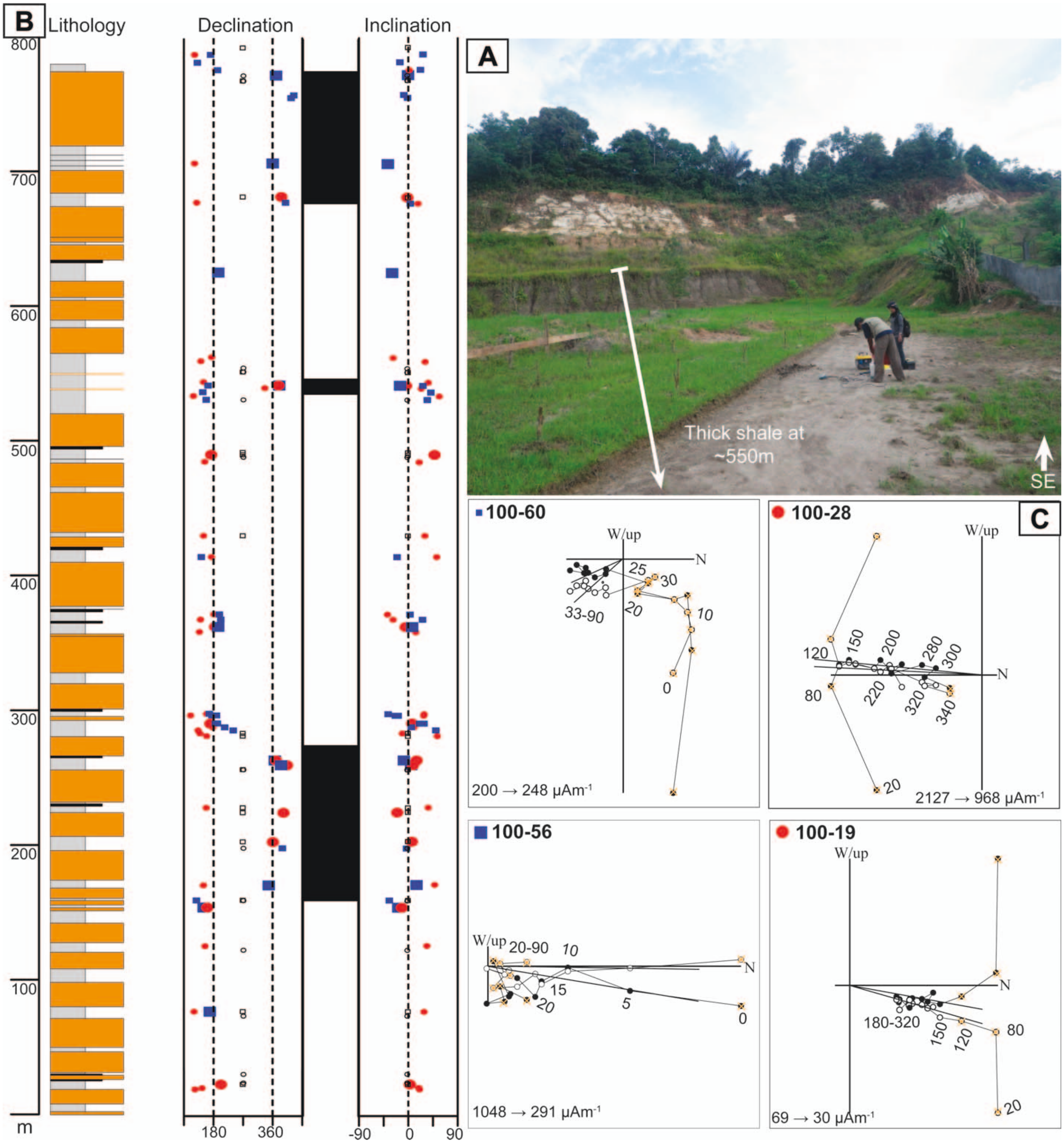


FIG. 5.—Harapan Baru: paleomagnetic interpretation vs. stratigraphy. **A**) Photo of thick shale in otherwise sandstone-dominated sequence. White arrow indicates top of the thick shale interval and points to the bottom, exposed in the open field. **B**) Detailed lithographic log with magnetic declination, inclination, and resulting polarity. Circles indicate locations of concretions. Red circles = TH, blue squares = AF, large and small shapes are for class A and class B samples respectively. Class C results are indicated by open shapes centered arbitrarily around 270° for declination and 0° for inclination. Regions of gray on the polarity plot indicate stratigraphy that was either not sampled (hatched with an X) or where samples gave ambiguous results. Letters next to log indicate positions of biostratigraphically important fossils: L = larger benthic forams, N = nannofossils, P = planktonic forams. **C**) Examples of Zijderveld diagrams showing both AF and TH results for class A and B samples. Orange X's indicate data that was deemed overprint and excluded from polarity analysis. Respective temperature/magnetic steps (°C/mT) are given next to the data points. Numbers in lower corner indicate the starting and ending intensity of the data points used.

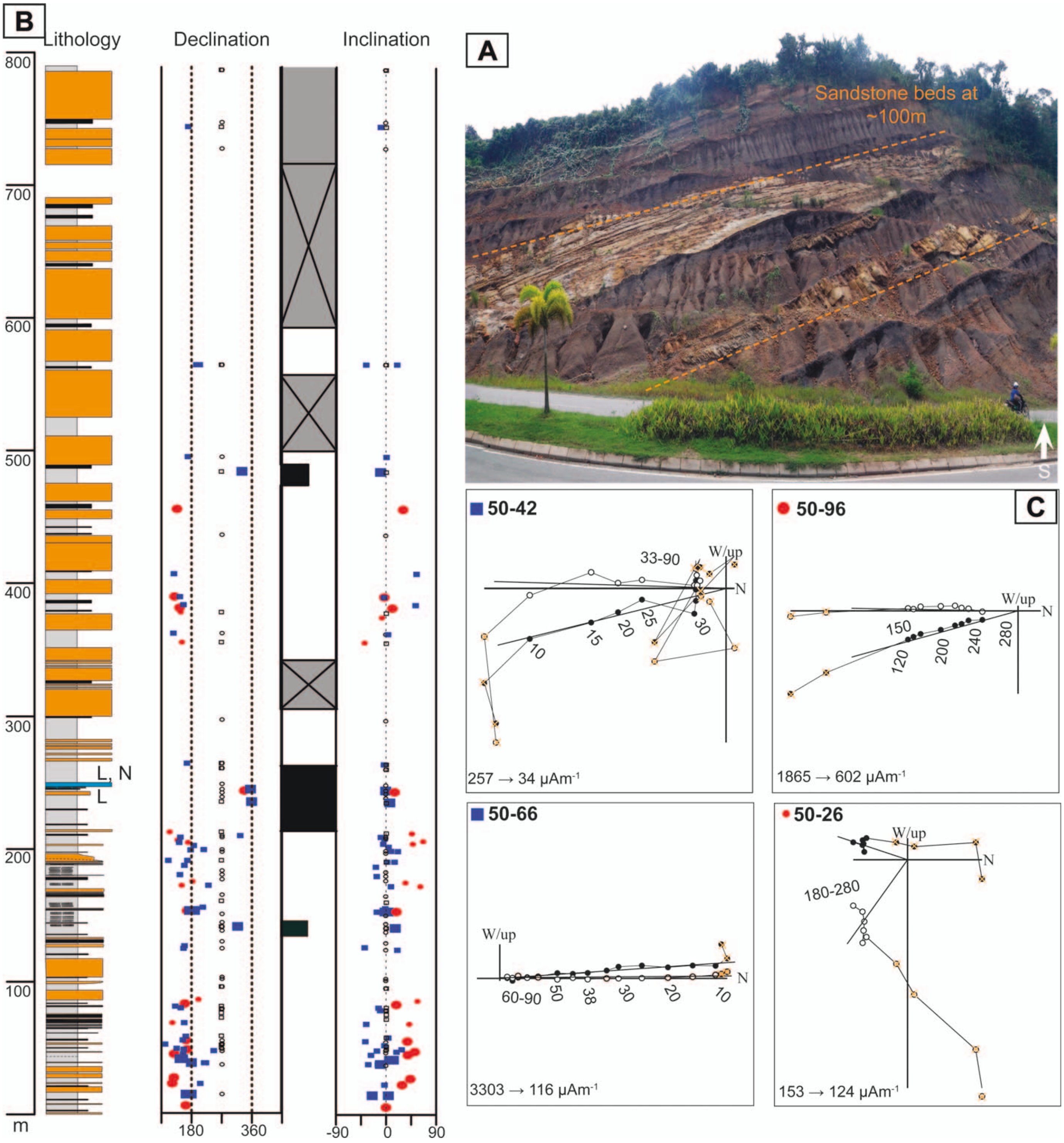


FIG. 6.—Stadion: paleomagnetic interpretation vs. stratigraphy. **A**) Photo of sandstone beds, coal, and shale from the lower part of the section. **B**) Detailed lithographic log with magnetic declination, inclination, and resulting polarity. Circles indicate locations of concretions. Red circles = TH, blue squares = AF, large and small shapes are for class A and class B samples respectively. Class C results are indicated by open shapes centered arbitrarily around 270° for declination and 0° for inclination. Regions of gray on the polarity plot indicate stratigraphy that was either not sampled (hatched with an X) or where samples gave ambiguous results. Letters next to log indicate positions of biostratigraphically important fossils: L = larger benthic forams, N = nannofossils, P = planktonic forams. **C**) Examples of Zijderveld diagrams showing both AF and TH results for class A and B samples. Orange X's indicate data that was deemed overprint and excluded from polarity analysis. Respective temperature/magnetic steps (°C/mT) are given next to the data points. Numbers in lower corner indicate the starting and ending intensity of the data points used.

carbonate interval of the Batu Putih reef complex described subsequently. Below the limestone is predominantly shale with thin (3–5 cm) sandstone beds. The bedding is disturbed and is slightly folded on a small scale (submeter) compared to the overall strike/dip of the region. Throughout Jalan Mangkunegara, the shale beds are typically dark, rich in vegetal organic matter and barren of marine macrofossils. Cibaj (2011) described the sedimentary details of this interval and noted that the thicker sandstone beds were laterally extensive and included Bouma sequences. Thus, Jalan Mangkunegara is interpreted as a slope depositional environment with event deposits of mostly sand but in some cases, as observed in Kampong Hutunan, carbonate material.

Batu Putih

Capping the Jalan Mangkunegara section is a 16 m interval of white muddy limestone overlain by two intervals of shale, coarsening upward to sandstone and then fossiliferous marl. There are three carbonate intervals; referred to as BP 1, 2, and 3 (Fig. 3). The upper two carbonate units are weakly lithified limestone beds interbedded with fossiliferous shale, marl, and thin (~ 3–20 cm) limestone beds. This succession has been previously studied by Wilson (2005) who interpreted the interval as consisting of reefs which were initiated by the buildup of LBF banks with platy corals forming a substrate for a diverse reef of corals, algae, bryozoa, mollusks, and echinoids. The reef-forming organisms are in life position and appear to have been buried rapidly. The limestone beds are ridge forming and were traced in the field for over 10 km although individual beds vary in thickness. The Batu Putih section is interpreted as a patch reef that formed on the shelf edge in front of the rapidly prograding paleo-Mahakam delta. The change from the more carbonate-rich BP 1 to the more clastic-rich intervals of BP2 and 3 shows the increasing clastic input up section, which is consistent with a prograding delta setting.

Sungai Kunjang

Directly above the Batu Putih is about 650 m of shale punctuated by thick sandstone beds and eventually coal beds in the upper part (Fig. 4). While the shale/sandstone ratio stays about the same throughout (around 40% shale), the first ~ 250 m of this section contains thicker continuous shale intervals as opposed to the more punctuated overlying sediments. Only the lower shale beds contain macrofossils. Some of the lower sandstone beds contain prevalent echinoids, palm root structures, fossil leaves, and woody material. Trace fossils are common in the upper parts of the sandstone beds. Mollusks and concretions, some containing crab fossils, also occur within the lower shale intervals. Above 250 m, the sandstone beds become generally thinner and more frequently spaced in addition to thin coal beds forming cycles of sandstone, shale, and coal. Cibaj (2009) interpreted the lower 250 m of the section, before the first coaly beds, as a very shallow marine environment with the sandstone beds representing prograding shelf lobes in a prodelta environment. Above 250 m, the section has fewer fossils, more sandstone beds, and thin (< 1 m) coal/organic shale beds, indicating a delta-plain environment (Cibaj 2009). Stratigraphic exposure above this section is interrupted by the Mahakam River.

Harapan Baru

South of the Mahakam River, over 800 m of shale, coal, and sandstone cycles are exposed (Fig. 5). This section is about 200–350 m stratigraphically above the Sungai Kunjang section. The thick (10–30 m) sandstone beds often have sharp bases and several contain sedimentary structures that suggest complex channeling. The sandstone beds are poorly cemented and are composed mostly of coarse-grained immature quartz grains but also coarse lithic clasts including pebbles of sandstone, coal shards, and chert that visually emphasize sedimentary features. Sedimentation is therefore thought to be mainly terrestrial for the coals, but part of the shale succession may reflect marginal marine flooding events.

Stadion

Poor exposure of up to 200 m separates this ~ 800 m section to Harapan Baru (Fig. 6). While the whole Stadion section contains shale-coal-sandstone cycles, there is a marked difference in the lower 300 m and the section above. The first 300 m of this section contains thin and infrequent sandstone beds, and includes at least two shale intervals with poorly preserved oysters and gastropods. Around 250 m above the base of the Stadion section, the succession is punctuated by a 10-m-thick interval of fossiliferous shale and coralline limestone. This limey succession shows a progression from platy corals in the lower part to larger head corals above, with associated LBF, bryozoan, and coralline algae. After a relatively thin (1–2 m) transition to shale with platy corals and LBF, thicker (10–40 m) sandstone beds with thicker and better developed coal beds dominate the remaining ~ 500 m of the section. The first 300 m has a notably marine influence based on the marginal marine oysters and higher sulfur content, culminating in the Stadion patch reef (Sykes and Cibaj 2010). This transition, starting with the Harapan Baru section, indicates that a transgression is manifested in the lower 300 m of the Stadion section, culminating with the turbid front-delta reef, followed by fluvial sedimentation.

Overall Environmental Progression

It is beyond the scope of this paper to provide a proper facies analysis, which has been discussed by other authors (e.g., Wilson 2005; Cibaj et al. 2007; Cibaj 2009, 2011; Novak and Renema 2015; Santodomingo et al. 2015). The study area shows a paleoenvironmental progression from a slope setting (Jalan Mangkunegara) shallowing to a midshelf setting suitable for reef formation (Batu Putih) and then shallowing further into a prodelta, delta-front (Sungai Kunjang), and eventually delta-plain setting (Harapan Baru) (Fig. 7). Sediment supply was very high and active subsidence kept pace with base-level fall, providing sufficient accommodation space to bury and preserve the large amount of sediment input. The reef in the Stadion section is sandwiched between kilometers of deltaic sediments, although the underlying few hundred meters is markedly less sandstone rich and contains marginal marine macrofossils. The Stadion reef is interpreted as environmentally similar to the upper limey parts of the Batu Putih section, showing a very high level of turbidity (Santodomingo et al. 2015).

MAGNETOSTRATIGRAPHY

Methods

Samples for magnetostratigraphy were preferentially drilled in the shale, because fine-grained sediments are generally considered more suitable for magnetostratigraphic dating (e.g., Langereis et al. 2010). Over 400 samples were taken from the entire succession with an average sample spacing of about 8 m, depending on the exposure and the presence of suitable lithologies. The samples were collected with an electrical drill powered by a gasoline generator. At least two drill cores were taken for each stratigraphic sample level.

To determine the magnetic carrier(s) in the samples, thermomagnetic measurements of 25 samples, from throughout the stratigraphy, were performed with a modified horizontal translation-type Curie balance in air (Mullender et al. 1993; noise level 5×10^{-9} Am^2). 70–90 mg of powdered sample was heated from room temperature to 700 °C with periodic cooling loops of about 100 °C to test for chemical alteration,

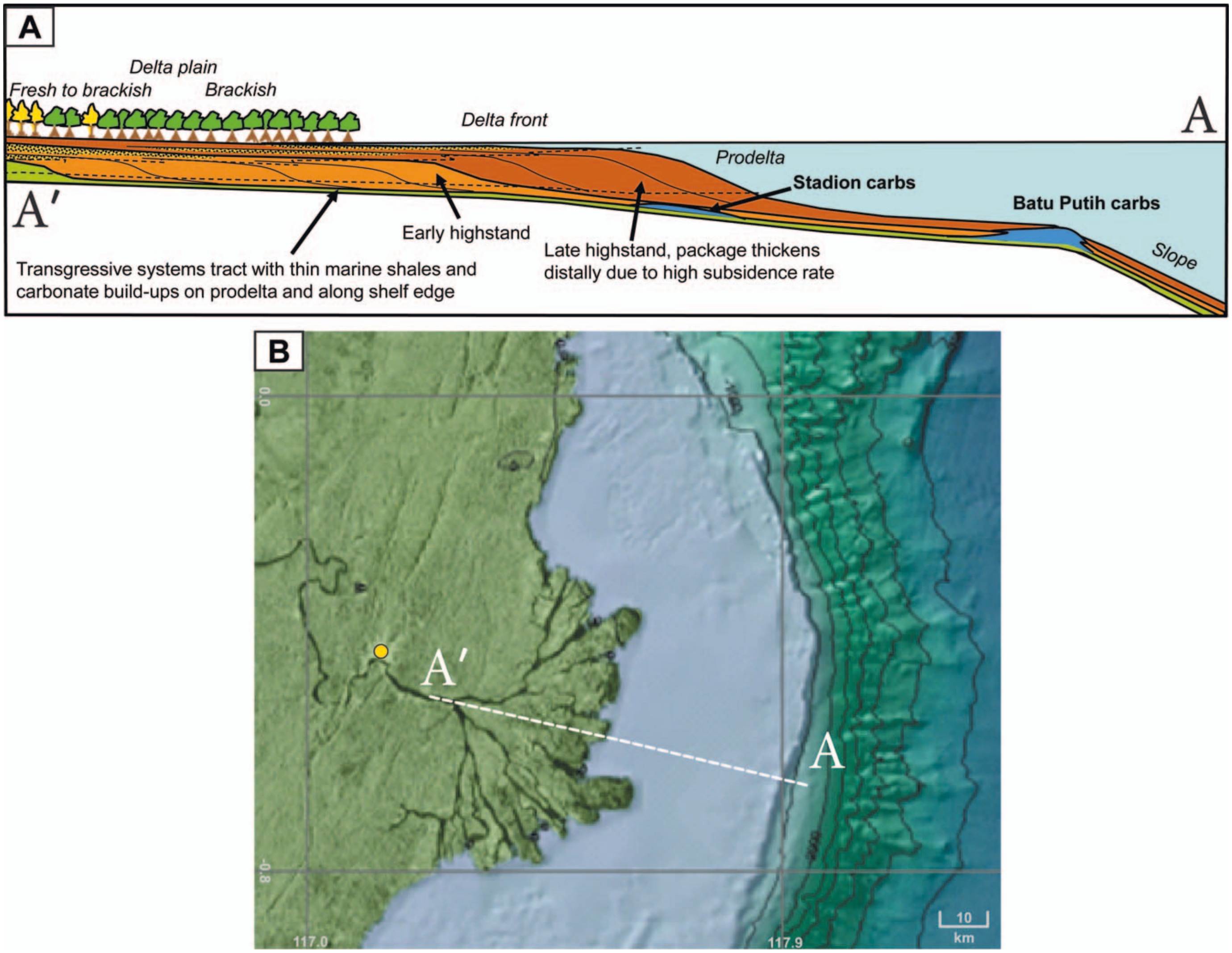


FIG. 7.—**A**) Schematic cross section of the depositional environments and sequence stratigraphic model for the Miocene Mahakam Delta and middle Miocene of Samarinda. **B**) Map view of the modern delta showing the approximate position of the paleoenvironments in the cross section on the modern Mahakam Delta; yellow dot indicates the city of Samarinda. The studied interval shows a general progression of depositional environments from A to A′, with a relative transgression during the lower Stadion subsection which shows a temporary return to a prodelta environment. The cross section represents one transgressive-regressive cycle, of which the whole Samarinda succession is composed. Many of these transgressive-regressive cycles aggregated as the basin subsided and the delta slowly prograded (see Fig. 12 for further discussion).

which makes the change in magnetization nonreversible. The path of the magnetic moment across the temperature range is helpful in determining magnetic mineral content, as different minerals have different Curie temperatures and behave differently with changing temperatures. In addition, isothermal remanent magnetization (IRM) acquisition curves were determined from 0 to 700 mT (in 60 steps) on 40 samples from throughout the stratigraphy. Prior to IRM acquisition, samples were demagnetized with alternating fields (AF) at 300 mT with the final AF demagnetization axis parallel to the IRM acquisition axis. When pretreated in this manner, the IRM acquisition curve mostly conforms to a cumulative log-normal distribution (cf. Heslop et al. 2004; Egli 2004). Magnetic moment was measured on a horizontal 2G Enterprises DC SQUID magnetometer (noise level 3×10^{-12} Am^2).

Analysis of the data uses the methodology and software of Kruiver et al. (2001). The distribution of magnetic field strength in log-field space gives constraints to the number of magnetic carriers and their origin. Magnetic components plot as symmetric distributions and one or more are manually added until a calculated cumulative curve of those components fits the analytical curve. The shapes of the component curves are usually not indicative of specific minerals, but of their origin (i.e., biogenic or detrital). The two controlling parameters are the width of the distribution, called the dispersion parameter (DP) and the midpoint of the distribution, at the field strength at which half of the saturation IRM is reached ($B_{1/2}$). A narrower DP is indicative of biogenic minerals. Detrital minerals have a relatively wide DP, indicating a wider range of grain sizes. For natural remanent magnetization (NRM) analysis, both thermal demagnetization (TH) and alternating field demagnetization (AF) were performed. Demagnetization was performed on at least one and often two samples per stratigraphic sampling level to determine the paleomagnetic polarity. TH was performed at room temperature, through to 340 °C with increments of 60–20 °C in a shielded furnace. The NRM was measured after every temperature step on a magnetometer. AF demagnetization was carried out with small increments up to a maximum of 100 mT on an in-house–built robotized sample handler attached to a magnetometer. An initial heating of 150 °C, in an attempt to lower the stress gradient in minerals and boost signal strength, did not affect the signal quality of AF measurements, so it was not continued past a pilot run. All samples were measured by a horizontal 2G Enterprises DC SQUID cryogenic magnetometer.

Magnetic Mineralogy

Curie balance results demonstrate that pyrite is often present, characterized by a strongly increasing magnetic intensity starting around 380–420 °C when pyrite is converted to magnetite (e.g., Passier et al. 2001). Some samples, especially after magnetic separation (using setup described in Dekkers 1988), show a magnetic signal from room temperature that decreases in magnetization to 280–340 °C, when the magnetic signal is lost, until pyrite is converted to magnetite (Fig. 8). Samples with stronger magnetic moments mostly have a strong signal at the beginning that diminishes at around 300 °C, seen best in 78_72, which is perhaps indicating titanomagnetite. Compare 50_2 and 50_57, which both had weak signals, but after mineral separation on 50_57, the pyrite peak is reduced and the other signal is stronger. A mineral that shows such behavior is detrital titanomagnetite from volcanic rocks. There was an increase in volcanic activity in Kalimantan from late Oligocene to middle Miocene (Moss et al. 1998; Hall and Nicholas 2002), which makes this mineral a plausible candidate. IRM component analysis indicated that almost all the samples contain 80%–90% detrital magnetic minerals, as indicated by a relatively wide DP value (0.3–0.4), well above the typical biogenic threshold of 0.2 (Kruiver 2001; Egli 2004). Little ($< 5\%$) to no biogenic magnetic minerals are present as a minor component, seen in gradient acquisition plot (GAP) diagrams in Figure 8. 76_10 shows a representative pattern for most samples throughout the entire sections and 78_72 shows the wider curve seen in samples in Sunjai Kunjang and Harapan Baru. The dominant component does change stratigraphically. In Harapan Baru and Sungai Kunjang the midpoint is typically between 31.6 and 44.7 mT and has a DP of 0.4. Samples from other sections have midpoints at or above 16.5 and a DP closer to 0.3. In summary, IRM analysis indicates that the vast majority of the magnetic grains are from a detrital source and samples contain few biogenic minerals. NRM analysis did produce many overprinted results, indicating that diagenesis certainly is a problem, although the main culprit seems to be the rapid modern weathering of outcrops and the detrital grains within. Curie balance results point to the presence of titanomagnetite (*sensu lato*), which is supported by middle Miocene volcanism in the region.

Magnetostratigraphy

Up to 280–340 °C, TH samples had fairly weak magnetic moments, with most samples only having strengths in the hundreds of $\mu\mathrm{Am}^{-1}$. After ~ 320 °C most samples became too weak and gave highly erratic data. AF samples were mostly depleted at 100 mT and showed agreeing results to TH results, and at times gave a clearer signal. Declination (solid points) and inclination (open points) are plotted against magnetic strength collapsed onto a two-dimensional x-y plane known as Zijderveld diagrams. The y-axis denotes west/east and up/down for declination and inclination respectively. Declination directions used to construct magnetic polarity patterns were determined using at least four data points (most of the time > 6) on tectonically corrected demagnetization paths, forced through the origin. Since many samples displayed an overprint up to around 200 °C for TH and 30 mT for AF, those temperature steps were commonly removed in samples with a noisy demagnetization path. This was unless they obviously passed a tectonic correction test; otherwise, the data is assumed to be an overprint.

Zijderveld diagrams resulting from both TH and AF demagnetization were ranked into three quality categories (class A, B, and C) based on the clearness of the demagnetization path, discernibility of overprint, and reasonability of the inclination compared to the latitude/longitude of Samarinda (−0.50°, 117.140°) with a declination of 0.88° and inclination of −0.55°. Class A samples have a discrete record of the depositional remanent magnetization, with a reliable polarity and stable direction. These samples have an orderly demagnetization path that passes the tectonic correction test, in having only reasonable latitudes after tectonic correction is added. Often, doglegged or scattered paths occurred because an overprint signal was also present in the lower temperature/magnetic field steps that failed the tectonic correction test. Overprint signals normally occur from room temperatures to 150–220 °C. For AF, overprint is typically seen in the first several steps below 30 mT. Class B samples are often very weak, disordered with a mixing of viscous and original remanent magnetization with only the polarity discernible, while the direction is highly inaccurate. These samples do not have a clear demagnetization path, often appearing as clouds of points or a wild demagnetization path, but fall consistently on the north or south portion of the Zijderveld diagram. Applying a tectonic correction test often produces more reasonable results than without. Class C samples are either a totally modern overprint or a noisy pattern of viscous remanent magnetization with no original magnetic information apparent. Totally overprinted samples are determined by a tectonic correction test, where adding a tectonic correction results in an unreasonable latitude and vice versa. Both TH and AF techniques produced samples that fit into these criteria, but in different proportions. Class A and B showed dual polarities and are used to define the magnetostratigraphy of the subsections. The two lowermost exposures of the Jalan Mangkunegara subsection (Fig. 2) are short (only 20 m and 40 m) but each shows a transition from normal to reversed polarity, although based on mostly class B samples. The Kampong Hutunan exposure is longer and contains more class A samples. They show a predominantly normal signal with a small reversed interval. The Rapak section has few class A samples, but shows a consistently reversed polarity signal. Moreover, in the class B samples an overprint signature can be identified and removed, and although only a cloud of points remains, an original polarity signature is likely being displayed.

The Batu Putih Limestone section (Fig. 3) has many class A samples with generally congruent class B samples. The polarity remains reversed until above 70 m, where a 10 m normal zone is seen in five samples. This is followed by approximately 15 more meters of reverse polarity, before the very top of the section has a well-constrained normal interval. The Sungai Kunjang section (Fig. 4) was unfortunately not well exposed for the first 50+ meters. While TH samples were typically poor and showed dual polarity, class A samples and all AF samples show that most of the lower half of the section is likely normal polarity. Above around 300 m, although having large inaccessible sections, almost all remaining samples show a reversed polarity.

The Harapan Baru section (Fig. 5) remains mostly reversed with the exception of two 100 m intervals of normal polarity at around 250 m and 750 m. There is also a very small normal polarity interval at around 550 m, but it is only represented by two sample levels. The Stadion section (Fig. 6) is mostly of reversed polarity with the exception of a ~ 40-m-thick interval around the Stadion reef at about 250 m from the base of the section. Above the reef the reversed signal seems to continue, although there was drastic diminution of resolution of samples because of the high percentage of coarse-grained sandstone beds and poorer-quality exposures. Therefore, the upper third of the section is largely of undetermined polarity.

BIOSTRATIGRAPHY

Moss and Chambers (1999) concluded that deltaic sedimentation in the Samarinda area was not established until planktonic foraminiferal zone N8, during the earliest middle Miocene. Later studies found the

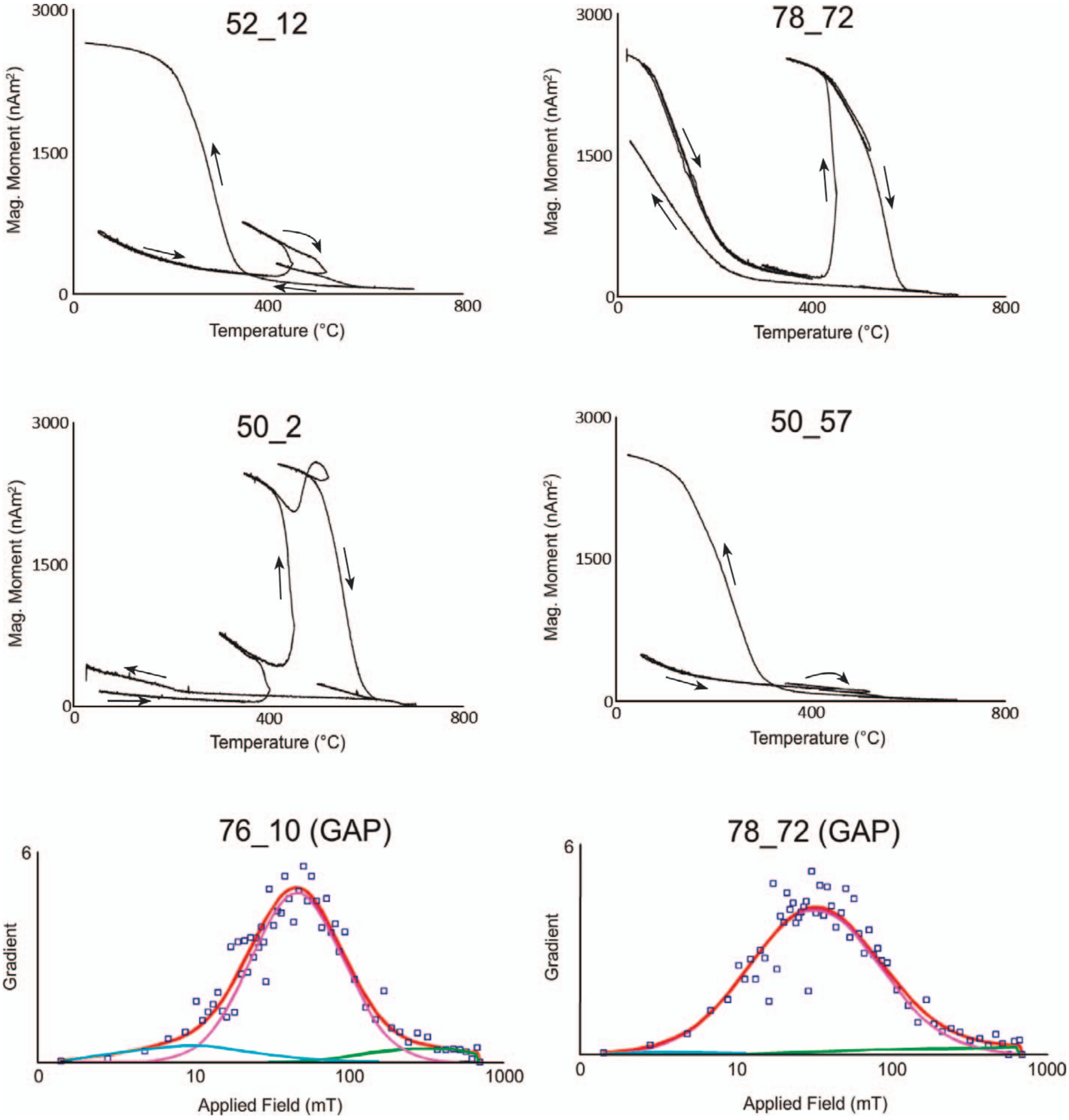
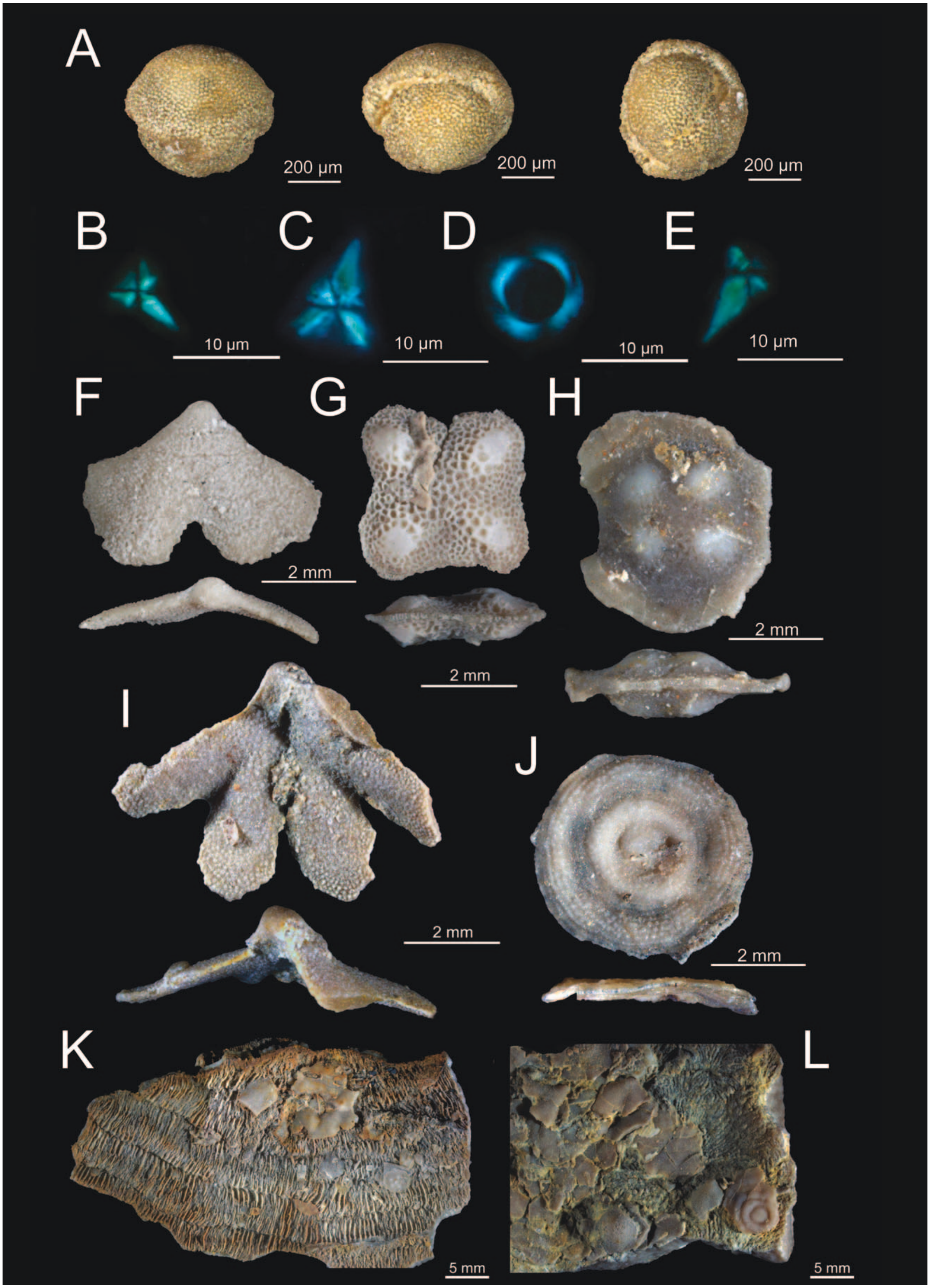


FIG. 8.—Example results from magnetic-mineralogical analysis. The top four graphs show temperature (x-axis) vs. signal strength (y-axis) for typical Curie balance results from throughout the stratigraphy with a field strength of 150–300 mT. The lower two plots show gradient of acquisition plots (GAP) (Kruiver et al. 2001). These plots show the log of the applied field (x-axis) vs. IRM (y-axis). The red line is fitted to the data points by addition of multiple components (purple, green, and blue lines). The purple line represents the largest constituent (80%–90%). See text for more explanation.

chronostratigraphically equivalent nannofossil zones NN4–NN5 for the same interval (Wilson 2005; Cibaj 2009). The lower part of the Stadion section was also reported to contain NN4–NN5 nannofossils (Cibaj 2009). These findings place the succession entirely within the middle Miocene. Most workers in the region have noted the difficulties in getting more precise age constraints in the Kutai Basin. A biostratigraphic overview study for the offshore region by Morley et al. (2006) has shown that ''common reworking'' and ''thick barren shales'' resulting from dissolution of calcareous microfossils have hindered age correlation across the basin. For this study, selected samples from horizons thought


A
200 µm
200 µm
200 µm
B
C
D
E
10 µm
10 µm
10 µm
10 µm
F
G
H
2 mm
2 mm
2 mm
I
J
2 mm
2 mm
K
L
5 mm
5 mm

to reflect the most open marine deposition were analyzed for planktonic foraminifera and nannofossils, whereas detailed sampling of carbonate horizons was undertaken for LBF.

Planktonic Foraminifera

For planktonic foraminiferal analysis, samples were collected from the Kampong Pinang section and the LBF flow deposit from Jalan Mangkunegara, shale above and below the Batu Putih limestone units 1 and 2, lower Sungai Kunjang, and the Stadion reef. These sections were thought to reflect the deepest marine environments within the entire stratigraphy. To process the samples, approximately 300 to 500 g of bulk sample was briefly soaked in a weak hydrogen peroxide solution. This was buffered with calcium carbonate, to disaggregate clay particles before washing and sieving. The 125- to 500-µm-size fractions were then picked for planktonic foraminifera. Ten samples collected from Sungai Kunjang were barren of planktonic foraminifera, emphasizing the marginal marine depositional setting. Three samples from the upper part of the Stadion patch reef also proved to be barren of planktonic foraminifera. However, samples from the Batu Putih and Jalan Mangkunegara sections contain age-diagnostic species. Two of six samples taken four meters above BP 1 contained just over 130 tests, including *Globoquadrina altispira* and *Globigerinoides subquadratus*. The former has a last occurrence at 3.46 Ma in the Pacific (Wade et al. 2011) and has an uncertain first occurrence in the early Miocene. The latter has its last occurrence at 11.46 Ma (Wade et al. 2011) or 11.55 Ma (Turco et al. 2002) and a stratigraphic base in planktonic M3/N5 (Burdigalian). One of four samples from above BP 2 contained ~ 80 tests but none were of biostratigraphic importance. Samples from Jalan Mangkunegara were taken from the Bukit Pinang locality (8), Rapak (12), and Kampong Hutunan (3). Although interpreted as the deepest marine section, all samples were barren of planktonic foraminifera, except for the LBF flow deposit. This suggests that the absence of planktonics from the shale is due to carbonate dissolution, which is widespread in Kutai Basin sediments, since planktonics are preserved in rapidly deposited debris flows but not in hemipelagic shale (Morley et al. 2006). Samples from the LBF flow deposit from Kampong Hutunan yielded several variously preserved specimens of *Praeorbulina* sp., which has a first appearance at the base of planktonic zone M5/N8 at 16.38 Ma (Wade et al. 2011) (Fig. 9A). *Praeorbulina* spp. were also found from petroleum exploration wells from the Samarinda area containing Batu Putih equivalent limestone beds (R. Morley 2013 unpublished). The presence of *Globigerinoides subquadratus* thus indicates a Burdigalian to Serravalian age range. The *Praeorbulina* specimens from Kampong Hutunan further constrain the age of the Batu Putih patch reef to younger than 16.83 Ma (very late Burdigalian). Given that the location where *Praeorbulina* was found is stratigraphically more than 500 m below the Batu Putih reef, it is reasonable to assume that earliest the reef would have occurred was in the middle to upper part of the M5/N8 zone. These findings are in agreement with Moss and Chambers (1999), suggesting a Langhian age or younger for the Batu Putih section.

Nannofossils

Initially samples were directly analyzed during fieldwork. Six of 30 samples from the Batu Putih and upper Jalan Mangkunegara sections produced age-diagnostic fossils. Most notable was *Sphenolithus heteromorphus*, indicative of zones NN4–NN5 (Burdigalian/Langhian) (Fig. 9B). Seven of 16 samples from the Stadion section and reef also gave a similar assemblage with *S. heteromorphus* (similar to Fig. 9D). While the concentration of nannofossils is low, the preservation of *S. heteromorphus* is very good. However, the Stadion nannofossil markers are thought to be reworked (see below). Fifty samples were then taken from magnetostratigraphic drill cores for nannofossil analysis; six produced nannofossils and only two samples, from the Sungai Kunjang section, gave age-diagnostic markers: once again, *Sphenolithus heteromorphus* (NN4–NN5) (Fig. 9C). Additionally, a single specimen of *Coronocyclus nitescens* was also found in the lower part of Sungai Kunjang, which ranges from NN4 to lower NN6 (Fig. 9D). The large number of barren samples for nannofossil analysis is also thought to be due to carbonate dissolution, as noticed also in offshore wells (Morley et al. 2006).

Larger Benthic Foraminifera

LBF are a major constituent among the fossil assemblages in the Samarinda reefal depositional environment. Bulk samples and thin sections were processed for LBF identification. Bulk samples were sieved with a 500 micron sieve and all LBF were collected with over 1000 specimens counted. Taxon point counts were then collected from 25 thin sections. Additionally, 50 oriented thin sections were produced from isolated LBF specimens. After identification, the assemblage was interpreted by reference to the East Indian letter classification biozones (Lunt and Alan 2004; Renema 2007) and correlated with the global stratigraphic scheme (Hilgen et al. 2012). At the Batu Putih reef, LBF samples were taken from the limestone and shale beds surrounding BP 1, and from the top and bottom of BP 2. In the Batu Putih samples, significant LBF include *Lepidosemicyclina polymorpha* (Fig. 9F) (late Burdigalian–Serravallian) and *Nephrolepidina ferreroi* (Fig. 9G) (Burdigalian–Serravallian). Based on their co-occurrence and the absence of *Austrotrillina* (last occurrence in Burdigalian), an early Tf2 age (Langhian–early Serravallian) can be suggested for the Batu Putih carbonates. Samples from the Stadion reef were collected and analyzed in a similar manner to Batu Putih, within and just above the carbonate buildup. Identified LBF assemblages show similar composition, with dominance of *Nephrolepidina*, *Lepidosemicyclina*, and *Amphistegina*. Important, however, is the presence of *Cycloclypeus annulatus* (Burdigalian–Serravallian) (Fig. 9J) and *Lepidosemicyclina bifida* (late Burdigalian–Serravallian) (Fig. 9I). Occasionally, LBF were observed growing directly on *in situ* corals in the Stadion reef (Fig. 9K, L). The advanced morphology of *C. annulatus* with well-developed annulae, co-occurring with *L. bifida*, suggests a late Tf2 age (late Serravallian) for the Stadion reef. Additional characteristics to note are the difference between the embryont morphology of the *Nephrolepidina* specimens at the different localities (Fig. 9G versus 9H). In the Stadion reef they show an increase in degree of enclosure of the protoconch by the deuteroconch, and an increase in average number of adauxiliary chambers, indicating evolutionarily more developed forms (Lunt and Allan 2004; BouDagher-Fadel and Price 2010) compared to the specimens from the Batu Putih carbonates.

←

FIG. 9.—Examples of stratigraphically important fossil taxa. **A**) Planktonic foraminifera *Praeorbulina*; two side views and a ventral view. B–E) Representative nannofossils from Samarinda area. **B**) *Sphenolithus heteromorphus* from the Batu Putih subsection. **C**) *S. heteromorphus* from the Sungai Kunjang subsection. **D**) *Corornocylcus nitescens* from the Sungai Kunjang subsection. **E**) *S. heteromorphus* from the Stadion area. **F–J**) Representative larger benthic foraminifera in dorsal and side view from Samarinda area. **F**) *Lepidosemicyclina polymorpha* from the Batu Putih subsection. **G**) *Nephrolepidina ferreroi* from the Batu Putih subsection. **H**) *N. ferreroi* from the Stadion reef (note the morphological difference compared to the Batu Putih specimen). **I**) *Lepidosemicyclina bifida* from the Stadion reef. **J**) *Cycloclypeus annulatus* from the Stadion reef. **K, L**) Examples of larger benthic foraminifera (*C. annulatus*, *L. bifida*) growing on *in situ* corals from the Stadion reef.

AN INTEGRATED STRATIGRAPHIC TIME FRAME FOR THE SAMARINDA SUCCESSION

Of the more than 4 km of stratigraphic exposure in Samarinda, the magnetic signal, coupled with age control gained from the biostratigraphic findings, provides refinement of the middle Miocene age defined in the previous biostratigraphic studies of Moss and Chambers (1999), Wilson (2005), and Cibaj (2009) by correlation to the global magnetostratigraphic time scale (Fig. 10). The composite polarity pattern for Samarinda contains five small normal intervals that account for only about a third of the total polarity pattern. Only between 18–15 Ma and 14–11 Ma, on the Geomagnetic Polarity Timescale (GPTS), is there enough reversed polarity to allow for a match. While age estimates from nannofossils and LBF range back to the late Burdigalian, the presence of the planktonic foraminiferal genus *Praeorbulina* in the Kampong Hutanan LBF flow deposit indicates the oldest possible age for the Batu Putih reef is M5/N8 and probably early Langhian. An age of less than ~ 16 Ma for the Batu Putih necessitates that most of the Samarinda polarity pattern occurs within the 14–11 Ma interval, and not the period from 18–15 Ma on the GPTS.

The ~ M5/N8 lower boundary for the Batu Putih reef is thus in the upper half of the nannofossil zone NN4 and LBF zone Tf1. The nannofossil marker *Sphenolithus heteromorphus,* found in the stratigraphically younger Stadion reef—nearly 2.5 km higher in the stratigraphic section—indicates extremely rapid deposition and also conflicts with magnetostratigraphic data, since nannofossil zones NN 4–5 are mainly characterized by normal polarity, whereas the Stadion section is mainly reversed. The likelihood is that the specimens of the robust species *S. heteromorphus* are reworked at the Stadion section into a succession otherwise barren of nannofossils. Previous studies on successions within the Kutai Basin have noted that reworking is a major problem (Morley et al. 2006). Unpublished data from several wells in the nearby Bontang area show a reworking event within nannofossil zone NN7, which represents the same age suggested by magnetostratigraphy (from the predominance of reversed polarities). The continuation of basin inversion that started in the early Miocene is a plausible mechanism for reworking (Moss and Chambers 1999). LBF, on the other hand, are clearly *in situ*, or penecontemporaneously deposited, as in the case of the Hutanan LBF flow. The LBF flow and Batu Putih assemblages tie in well with the proposed magnetostratigraphic correlation, with the Hutanan LBF flow and Batu Putih corresponding to lower Tf2, and the Stadion reef with upper Tf2. The portion of the GPTS between the C5n Chron (upper limit) and M5/N8 planktonic foraminiferal zone (lower limit for the Batu Putih) contains three thicker reversed-polarity–dominated intervals (C5Br–C5AD, C5Ar, and C5r) which are possible points of correlation to the Samarinda polarity pattern. The normal-dominated interval of C5AD–C5AA does not match well with any part of the polarity pattern. But, if C5Br is taken to equate to the long reversed interval below the Batu Putih section and the normal above can be correlated to C5AD, then the normals of C5AD, C5AC, and C5AB are missed within the unexposed portions of the succession around the Mahakam River.

The two normals from Harapan Baru can correlate to C5AA and C5An with the C5Ar matching the long reversed interval in that section. The Stadion section contains mostly reversed intervals with one smaller normal, which fits within C5r and correlates the Stadion patch reef with the C5r.2n normal at around 11.6 Ma. The placement of the Batu Putih patch reefs falls somewhere around 15 Ma, somewhere between the lower part of C5AD and the upper part of C5Br, depending on whether the two small normals around the upper Batu Putih limestones correlate to C5Bn or are considered as part of the larger normal of C5AD. The polarity pattern rapidly degrades below the Batu Putih section because of gaps and weaker signals, making it possible that normals were missed in the Jalan Mangkunegara section. Two correlations are therefore possible (Fig. 11), one with the Batu Putih patch reefs at about 14.8 Ma (Fig. 11A), and the other at 15.3 Ma (Fig. 11B). Reasons for selecting the more likely of these based on sedimentation rates are discussed below.

DISCUSSION

Sedimentation Rates

Graphic correlation of the Samarinda polarity pattern and the GPTS, assuming that no major breaks in sedimentation occurred in the covered intervals above the Batu Putih section, indicates an average sedimentation rate of around 74.6 cm/kyr (Fig. 11). Estimates for the Kutai Basin since the Miocene to present are around 30 cm/kyr, but this also includes the late Miocene and Plio–Pleistocene succession, which was characterized by much slower sedimentation rates (Morley and Morley 2011). Preliminary observation of well data from the middle Miocene in the Kutai Basin suggests similar rates. For the Batu Putih section and below, two correlation options are possible, as noted above. Both options for the Batu Putih section suggest a marked reduction in sedimentation rate, which seems plausible given the interpretation of a more distal depositional setting. However, the two options differ in a number of ways. By reference to Figure 11A, the resulting sedimentation rate in the option where the C5Bn normals are missing is 26.5 cm/kyr. This rate continues until an increase due to deltaic progradation. Alternatively, if the two small normals seen in the upper Batu Putih are correlated to C5Bn, sedimentation rate is substantially reduced to about ~ 18 cm/kyr for the upper two limestones of Batu Putih (Fig. 11B). This second option indicates that the Batu Putih occurs during a sea-level rise on the isotope curves of Zachos et al. (2008) and Holbourn and Khunt (2010), making it a more favorable option because it fits the slowing sediment influx during reef formation. In both cases, the sudden fall in sea level at 13.8 Ma (Zachos et al. 2008; Holbourn and Khunt 2010; De Boer et al. 2012) correlates to the unsampled interval between the Sungei Kunjang and Harapan sections. Option B shows a larger change is sedimentation rate, which also gives it more credibility based on the expectation that reef formation is likely to occur at a major reduction in sedimentation rate. Although the sedimentation rate model shown in Figure 11B is given preference, the first model should not be cast out because the interval around Batu Putih is not definitive paleomagnetically. The proposed timing of progradation of the Mahakam Delta across the Samarinda area is based on the integration of magnetostratigraphic results with biostratigraphic data, and the correlation presented in Figure 11B for the Batu Putih section. Consequently, the succession can be accurately dated as follows in Table 1.

The early-middle Miocene boundary at 15.97 Ma therefore lies midway through the Jalan Mangkunegara section, whereas the middle-late Miocene boundary at 11.61 Ma occurs within the basal interval of the Stadion section. Also, deposition occurred on the upper slope until 15.3 Ma; the shelf formed in the Samarinda area after this time, with delta-front deposition occurring after 15.1 Ma, and delta-plain sedimentation after about 13.9 Ma.

Samarinda Succession within a Sequence Stratigraphic Model

The combination of repeated sand/shale packages, absence of erosional sequence boundaries with thin marine horizons, and carbonate buildups though the entire succession, coupled with sedimentation rate data, allows a detailed model of depositional sequences to be proposed.

The interpretation of depositional sequences in the Kutai Basin has been discussed by Saller et al. (2004) for the Pleistocene Mahakam Delta (Fig. 12). They proposed a sequence model using the transgressive surface rather than the sequence boundary for sequence classification, which they indicated could also be applied to the middle Miocene to Pliocene of the offshore Kutai Basin. Their model proposed an initial short-lived

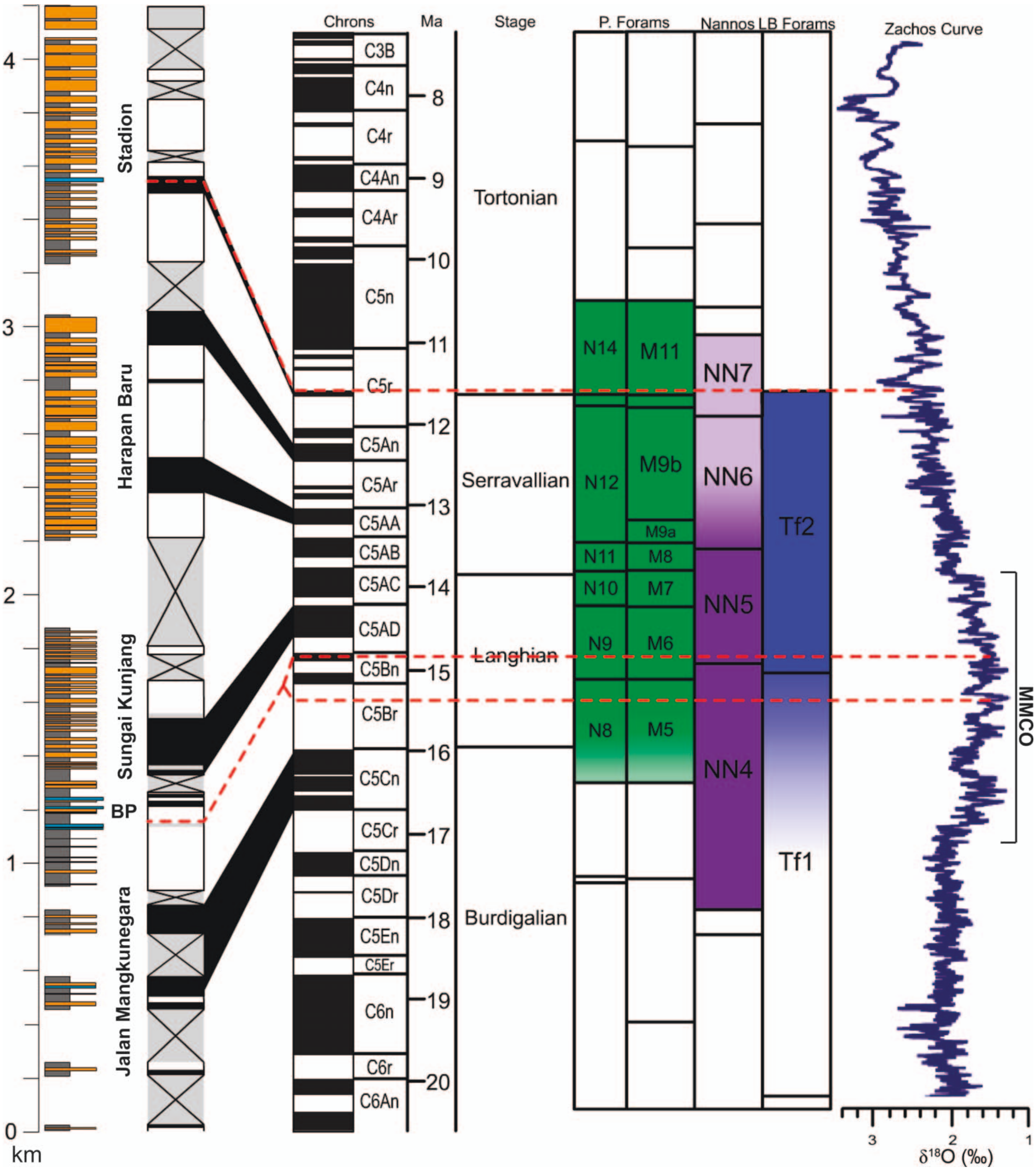


FIG. 10.—Stratigraphic column for entire studied succession with composite magnetic polarity pattern correlated with most preferred match to the GPTS given the biostratigraphic constraints (P. Forams = planktonic forams; Nannos = nannofossils; LB Forams = larger benthic forams) within their respective zonations; N (for Neogene) represents the older planktonic foram zonations, and M (for Miocene) is the newer zonations scheme (as seen in Wade et al. 2011), NN = Neogene nannofossil zones; Tf (Tertiary zone f) for LBF from the East Indian letter classification biozones (Lunt and Alan 2004; Renema 2007). Red dashed lines highlight the locations of the lower Batu Putih reef (two possibilities) and the upper Stadion reef. For comparison to global climate the smoothed benthic $\delta^{18}O$ "Zachos Curve" is plotted to the right (Zachos et al. 2008)). Note that this correlation places the Batu Putih in the middle of the middle Miocene Climatic Optimum (MMCO), the change to a fluvial setting during the 13.8 Ma sea-level fall and the Stadion reef during a small warming (higher $\delta^{18}O$ values) event. Resulting sedimentation rates for correlation to the GPTS is shown to the left in cm/kyr.

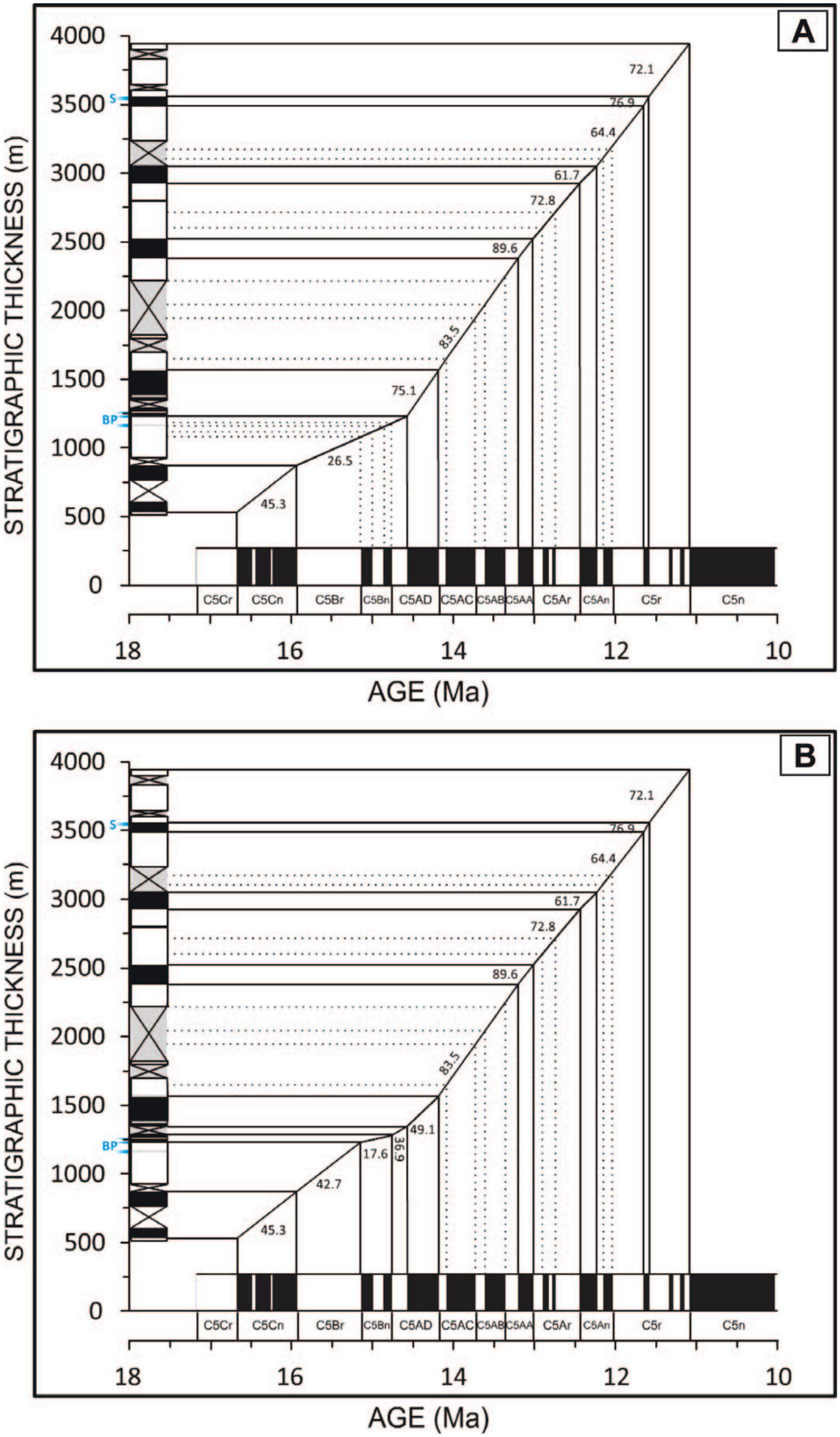

A
STRATIGRAPHIC THICKNESS (m)
4000
3500
3000
2500
2000
1500
1000
500
0
S
BP
72.1
76.9
64.4
61.7
72.8
89.6
83.5
75.1
26.5
45.3
C5Cr
C5Cn
C5Br
C5Bn
C5AD
C5AC
C5AB
C5AA
C5Ar
C5An
C5r
C5n
18
16
14
12
10
AGE (Ma)
B
STRATIGRAPHIC THICKNESS (m)
4000
3500
3000
2500
2000
1500
1000
500
0
S
BP
72.1
76.9
64.4
61.7
72.8
89.6
83.5
49.1
36.9
17.6
42.7
45.3
C5Cr
C5Cn
C5Br
C5Bn
C5AD
C5AC
C5AB
C5AA
C5Ar
C5An
C5r
C5n
18
16
14
12
10
AGE (Ma)

TABLE 1.—*List of stratigraphic sections and their corresponding GPS start and end points and determined age range from this study.*

Section	Start		End	Age (Ma)
Jalan Mangkunegara	S0.4632°, E117.1112°		S0.5071°, E117.1003°	<18–15.3
Bukit Pinang		S0.4632°, E117.1112°		
Garage		S0.4627°, E117.1156°		
Kampong Hutunan	S0.4680°, E117.1174°		S0.4691, E117.1184°	
Rapak	S0.5071°, E117.1003°		S0.5073, E117.1011°	
Batu Putih	S0.4678°, E117.1217°		S0.4689, E117.1213°	15.3–15.1
Sungai Kunjang	S0.5172°, E117.1000°		S0.5228, E117.1044°	15.1–13.8
Harapan Baru	S0.5448°, E117.1061°		S0.5650, E117.1200°	13.5–12.2
Stadion	S0.5858°, E117.1109°		S0.58600, E117.1252°	11.8–11.05

transgression, reflecting a period of rapid sea-level rise coinciding with a glacial termination, at which time deposition of marine muds took place across the shelf with carbonates bordering the shelf edge. With subsequent stabilization and eventual fall of sea levels, the delta prograded across the shelf as a series of clinoforms, with regional subsidence ensuring sufficient accommodation space for this depositional regime. On reaching the shelf edge, the prograded clinoforms built onto the upper slope as a lowstand delta, with no definable sequence boundary between the highstand and lowstand. Plint and Nummendal (2000 and references therein) proposed the combined highstand and lowstand as the falling stage systems tract. The above model works admirably for the Samarinda succession, with its thin transgressive shale/carbonate and obscured differentiation between highstand and lowstand deposition. It also explains the growth and drowning of the Batu Putih carbonates, which formed at a time of very high regional subsidence. This is also reflected in the repeated aggrading sediment packages of similar depositional facies. The Batu Putih carbonates show evidence of drowning just before the transition to clastic deposition. The high rate of subsidence resulted in reef formation during the transgressive systems tract, but was successively drowned as relative sea levels rose. During highstand and regression, the delta progrades. Sediment becomes thick and coarser grained, weighing down the shelf edge, furthering subsidence, and causing an apparent drowning and burial of the transgressive carbonate. A simplified model of the stacked succession of depositional sequences in the Samarinda area is shown in Figure 12.

Correlation to Global Climate Change

Much of the Samarinda stratigraphy is deltaic, and delta-lobe shifting can cause sudden changes in sedimentary environment that might be misinterpreted as coming from external forces. With this caveat in mind, the succession is remarkable due to the very high sedimentation rates, and broad aggradational rather than progradational sequence stacking pattern. This infers that subsidence was very high, since most of the accommodation space was created by subsidence alone. The rate of subsidence exceeded known rates of sea-level fall, and because of this, both eustatic and tectonic events should be reflected in the depositional succession, since whereas eustatic change operates at a millennial scale, tectonic changes typically take place at rates that are an order of magnitude slower (Miller et al. 2005). For this reason, complete lowstand-highstand successions should be present as predicted by Saller et al. (2004)—without stratigraphic gaps and lacking classic type 1 sequence boundaries. The Samarinda succession is therefore an ideal area to examine the interaction between high-resolution eustatic change and sedimentation patterns within a deltaic setting.

From a paleoclimate perspective, the Samarinda stratigraphy begins during the latest early Miocene, already within the middle Miocene Climatic Optimum (MMCO) (Zachos et al. 2008; De Boer et al. 2012). The progradation of the delta, in the Sungai Kunjang subsection, occurred during the ebbing of global sea level, with the major sea-level fall at ~ 13.8 Ma occurring close to the top of that section. Estimates for the end-MMCO sea-level fall from De Boer et al. (2012) are substantial (40–60 meters), and would have driven, or at least aided in, the initiation of a strong progradational succession. The change from a more marine-influenced, delta-front to brackish to fluvial setting for the Harapan section ties in well with this. The suggested timing of the two Samarinda reefs between 15.3 and 15.1 compared to the high resolution Pacific benthic δ^{18}O curve for this period indicates that they may correlate to periods of rapid sea-level rise, with the strongest sea-level rise of the middle Miocene at 15.3 Ma and a second at 15.15 Ma (Holbourn et al. 2007). The Stadion reef development occurs at 11.6 Ma but occurs at a less definitive eustatic interval compared to the Batu Putih reef. At around 11.6 Ma, a rise in global sea level is reported to have occurred (Zachos et al. 2008) which likely aided in the formation of the reef specifically. This short shift cannot, on its own, explain the overall relative transgression that occurs in the lower Stadion section. This suggests the transgression was caused by eustatic change, but it is difficult to discount a local shift in basin dynamics with only one example studied. River shifting could well account for sudden changes in sedimentary environment, leaving correlation to sea-level changes as coincidental. The relationship between eustasy, sedimentation, and tectonics therefore warrants further, detailed investigation involving cyclostratigraphic methods coupled with high-resolution biostratigraphic studies.

Refining the LBF Tf2-Tf3 Boundary

The larger benthic foraminiferal Tf letter stage (Burdigalian–Messinian) in the East Indian letter classification has been subject to frequent reinterpretation (e.g., Renema 2007). Most authors agree that the Tf2-Tf3 boundary is defined by the extinction of *Cycloclypeus annulatus*, *Nephrolepidina ferreroi* (and other large *Nephrolepidina* species with the exception of *Trybliolepidina*), and miogypsinids (Adams 1970; Boudagher-Fadel and Banner 1999; Lunt and Allen 2004; Renema 2007), but the timing of these extinctions remains controversial. Boudagher-Fadel and Banner (1999) and Sharaf et al. (2005) place the entire Tf stage in the early–middle Miocene, although Sharaf et al. (2005) extends the range of *Trypliolepidina rutteni* into the late Miocene (following Adams 1984). Lunt and Allan (2004) place the Tf2-Tf3 (their lower Tf-upper Tf) boundary in the base of the Serravallian, implicitly assuming an association with the middle Miocene sea-level drop. The most important

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FIG. 11.—Graphical correlation of the Samarinda polarity pattern in thickness vs. the age of the GPTS. Blue tick marks on the y-axis highlight the location of the Batu Putih (BP) and Stadion (S) reefs. Resulting sedimentation rates in cm/kyr are shown for each matched segment. **A**) and **B**) show the two options of correlation of the section below the C5AD chron.

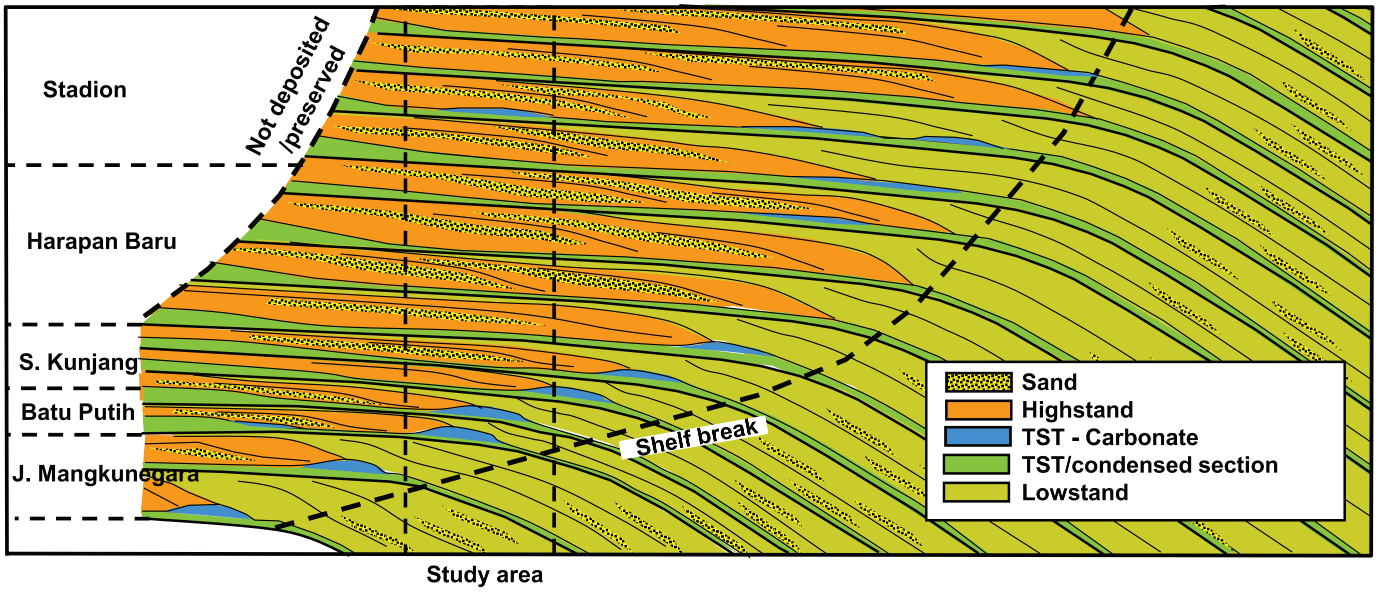

FIG. 12.—Schematic basin cross section for the study area and nearby settings on the shelf and slope, building upon the sequence stratigraphic model presented in Figure 7. While the architecture for the study area is well attested to in outcrop, the regions outside of that are extrapolated based on the sedimentary packages seen in seismic studies from both the Miocene and Pleistocene. The regularly repeating sandstone/shale bundles are taken to be transgressive/regressive cycles as seen in modern studies. In practice no differentiation of highstand and lowstand can be made in the Mahakam Delta system. Both highstand and lowstand are amalgamated as a Falling Stage Systems Tract (*sensu* Nummendal). For the slope, the condensed section consists of the combined TST and highstand. Transgressive limestone units most likely form at the shelf edge but also around the prodelta or elsewhere on the slope. Therefore patch reefs are shown forming sporadically in these environments, especially during times of slower delta progradation (i.e., Sungai Kunjang and below) or larger-scale transgression (i.e., Stadion).

Tf1–Tf2 marker is the very characteristically shaped *Nephrolepidina ferreroi* (Fig. 9G, H). This species is especially abundant in late Tf1 and Tf2 carbonates all over the Indo-West Pacific, and is prevalent within the Samarinda succession. The youngest reported occurrences of *N. ferreroi* are within NN6 (Lunt and Allan 2004) and 12.98 Ma (Sharaf et al. 2005 (strontium isotope stratigraphic median age)). Sharaf et al. (2005) suggest that the extinction of *N. ferreroi* was before ~ 11.8 Ma. The last distinctive species characterizing Tf1–Tf2 is *Cycloclypeus annulatus*. The youngest occurrence of this taxon in Indonesia was from the Bulu Limestone formation in East Java at 12.98 Ma (strontium isotope stratigraphic (SIS) median age; Sharaf et al. 2005; Donovan et al. 2010). However, the youngest occurrence of this taxon in Fiji was reported as within the planktonic zones M10–11, between ~ 10.4 Ma and ~11.8 Ma (Adams 1984). The specimens in this young sample from Fiji have a very large proloculus (0.5–0.8 mm), compared to much smaller sizes in Indonesia (0.2–0.4 mm), and were interpreted as a relictual population (Adams and Frame 1979). As a result of the integrated stratigraphic model presented here, the Tf2-Tf3 boundary older limit of uncertainty must be younger. *Lepidosemicylina* sp., *Nephrolepidina ferreroi*, and *Cycloclypeus annulatus* have been found in the Stadion reef, thus extending their range and the Tf2-Tf3 boundary to at least 11.6 Ma. Based on these data there is an indication that their extinction was within the same time range.

CONCLUSIONS

In the Samarinda area, a 4-km-thick sedimentary succession is largely exposed and shows a general progradation from offshore slope deposits to deltaic and fluvial sediments between the latest early Miocene at < 18 Ma at the base of the Jalan Mangkunegara section to the earliest late Miocene (at 11.05 Ma) at the top of the Stadion section, with the majority of deposition taking place during the middle Miocene. This succession reflects progradation of the Mahakam delta shelf-slope break and subsequent delta facies across the Samarinda area with two reef-forming successions, one in the earliest middle Miocene (Batu Putih) and the other in the earliest late Miocene (Stadion Reef). An integrated stratigraphic framework has been developed for the Miocene Samarinda succession by combining magnetostratigraphic and biostratigraphic data. Rock magnetic analyses on shale samples indicate that volcanogenic titanomagnetite is a likely carrier of the paleomagnetic signal. The dual polarity of this component suggests that it is of primary origin; i.e., from the time of sediment deposition, and can thus be used for magnetostratigraphic dating. Thermal and AF demagnetization diagrams of the various subsections are generally of mixed quality but contain enough reliable (class A and B) samples to determine the polarity pattern. Based on the result that 2/3 of the pattern is reversed and only five small normal intervals have been detected, correlation to the time interval between 16 and 11 Ma of the standard geological time scale is considered the most likely option. This has been corroborated from biostratigraphic observations. There is ambiguity in the record within the lower part of the succession, and two possible models have been evaluated based on sedimentation criteria, with the older of the two possible correlations being selected, placing the base of the Batu Putih carbonates at about 15.3 Ma. The Stadion Reef is dated at 11.6 Ma.

The very high sedimentation rate recorded, and the mostly aggradational stacking pattern of depositional sequences, indicates that accommodation space was created primarily by subsidence with subsidence rates exceeding typical rates of eustatic sea-level fall. Because of this, a virtually complete depositional succession is preserved without classic type 1 sequence boundaries. The succession therefore provides an ideal locality for studying the interaction between sedimentation patterns, eustacy, and local tectonics. The two reef systems are thus ~3.8 Ma apart, which provides important constraints on rates of Miocene biodiversity change in the Mahakam Delta ecosystems. Correlation to high resolution isotope data of Zachos et al. (2008) and Holbourn and Khunt (2010) suggests that the Batu Putih reef formed between 15.3 and 15.1 Ma, and probably formed following periods of rapid sea-level rise, whereas the Stadion reef at 11.6 Ma also coincides with a period of high sea levels. The accurate dating obtained from magnetostratigraphic evaluation allows the Tf2-Tf3 letter stage boundary to be adjusted to approximately 11.6 Ma.

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