A DIVERSE PATCH REEF FROM TURBID HABITATS IN THE MIDDLE MIOCENE (EAST KALIMANTAN, INDONESIA)

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RRH: MIOCENE TURBID PATCH REEF IN INDONESIA
LRH: SANTODOMINGO ET AL.
Keywords: corals, biodiversity, paleoenvironmental reconstruction, mesophotic, Coral Triangle

ABSTRACT

The Kutai Basin (East Kalimantan, Indonesia) contains a rich and well-preserved Miocene fossil record of small patch reefs that developed under the influence of high siliciclastic input associated with the progradation of the Mahakam Delta. In this study, we reconstruct the biodiversity and paleoenvironments on one of these delta-front mixed carbonate-siliciclastic systems that developed at the Serravallian-Tortonian boundary near the city of Samarinda. In two newly exposed sections, we analyzed the sedimentology and distribution of main fossil biota including corals, foraminifers, coralline algae, and bryozoans. Seven facies were defined including two dominated by platy corals and two by larger benthic foraminifera. Facies distributions were driven by changes in depth and variation of terrigenous input within a range of delta-

front habitats. Despite the turbid conditions, fossil assemblages are highly diverse, including 69 coral species and 28 bryozoan species that occur in coral-dominated facies. Crustose coralline algae were mainly associated with the coral-dominated facies. Larger benthic foraminifera showed broader ecological tolerance within the range represented in the studied sections so were common in most facies. These diverse patch reef ecosystems were able to cope with high siliciclastic input during the early development of the present-day coral reef biota in the Miocene. Further studies of ancient and modern coral communities living in marginal habitats characterized by low light, high turbidity, extreme temperatures, or high nutrients are critical to understand how coral reefs could respond to the ongoing global environmental change.

INTRODUCTION

Coral reefs are declining worldwide as a result of human activities (Hughes et al., 2003; Hoegh-Guldberg, 2011). Anthropogenic stressors include local activities such as overfishing and water pollution from urban areas, and at broader scale, global warming and declining pH (Bellwood et al., 2004; Hughes et al., 2007). Global warming has changed rainfall patterns (Xie et al., 2010), that in combination with coastal expansion and deforestation around river basins have led to increased discharges of sediments into the oceans and, as a consequence, many of the coral reefs have undergone phase shifts into sediment-tolerant dominated systems (Hughes et al., 2007; Hoegh-Guldberg et al., 2007).

Understanding the dynamics of coral reefs living under terrigenous input would contribute to a better understanding of the ecological processes that support reef resilience. Terrigenous influx is a key control on the development of coral reefs, because (1) it leads to increased water turbidity, reducing light available for light-dependent organisms; and (2) smothering of biota due to high sedimentation regimes (Rogers, 1990; Nugues and Roberts, 2003; Fabricius, 2005). Numerous studies show that prolonged exposure to sediment discharges from rivers has a negative impact on corals and other reef biota leading to decreased coral reef health (Rogers, 1990; Katwijk et al., 1993; Stafford-Smith, 1993; Fabricius and De'ath, 2001; Fabricius, 2005). There is also a generally accepted view that coral diversity tends to be low in reefs substantially influenced by siliciclastic input (Van Woesik et al., 1999; DeVantier et al., 2006; De'ath and Fabricius, 2010). In contrast, other studies challenge the idea of a negative effect of high rates of sedimentation on reef development (Kleypas et al., 1999; Larcombe et al., 2001; Perry et al., 2012; Browne et al., 2012). Indeed, Perry et al. (2012) found that periods of most rapid accretion over the past ~700 years coincide with phases of reef development dominated by fine-grained terrigenous sediment accumulation.

Paleoecological studies are key to understand the dynamics of the environmental parameters that drive coral reef development and diversity at broader temporal and spatial scales (Perry et al., 2009; Roff et al., 2013). In the geological record there are numerous examples of coral assemblages developing in turbid-water environments since at least the Late Triassic (Rosen et al., 2002) in the Mediterranean (Hayward, 1982; Braga et al., 1990; Morsilli et al., 2011; Pomar et al., 2012) and the Caribbean (Mcneill et al., 2000; Klaus et al., 2008). In fact, the fossil record of Southeast Asia, the region that hosts today the most diverse marine ecosystems on Earth also known as the Coral Triangle (Bellwood et al., 2005; Hoeksema, 2007), is rich in well-preserved coral assemblages that mainly developed under high sediment influx (Gerth, 1923; Umbgrove, 1929; Wilson, 2005; Novak et al., 2013).

Sedimentology and carbonate dynamics of Miocene reefs in the Coral Triangle have been studied in a regional context (Wilson and Lokier, 2002; Wilson, 2005), revealing the potential high diversity of patch reefs that formed in mixed carbonate-siliciclastic deposits (Wilson, 2005). However, little is still known about the species composition, development, and detailed paleoecology of those Miocene turbid environments. Due to urban development in the area, numerous new outcrops are exposed regularly increasing the number of sections through patch reefs beyond those available for study by Wilson (2005). In the current study, we characterize a new example of coral-rich facies that occur within mixed carbonate-siliciclastic systems in the region referred to as the Stadion coral carbonates (Stadion CC) as they are exposed on the highway leading to *Stadion Utama Kaltim*, which opened in 2008. The main goals of this study are: (1) to describe the assemblages of corals, benthic foraminifera, coralline algae, bryozoans, and mollusks occurring in the Stadion CC sections; (2) to perform a paleoenvironmental reconstruction based on the analyses of the sedimentology and biota; (3) to describe the developmental stages of the Stadion CC sections; and (4) to discuss the importance of terrigenous input as a controlling factor for modern coral reefs. This manuscript is part of a series of papers produced by the Throughflow Project, in a collaborative effort to provide detailed information about biodiversity during the Miocene of East Kalimantan (Johnson et al., this issue).

GEOLOGICAL SETTING

The study area is located within the Kutai Basin in East Kalimantan (Fig. 1), a depositional basin that originated during the middle Eocene when the Makassar Straits and Philippines Sea opened (Cloke et al., 1999; Wilson and Moss, 1999). Throughout the Miocene, large amounts of clastic sediments formed rapidly prograding deltas (Hall and Nichols, 2002). In particular, during the Middle Miocene more than 4 km of shelf to fluvial sediments were deposited as the Mahakam Delta system prograded to its current position (Wilson and Moss, 1999; Hall and Nichols, 2002; Marshall et al., this issue). The modern Mahakam Delta is located in a low wave-energy coast and its dynamics are tide-dominated so that the deltaic sediments are characterized by high silt and clay contents as little sand is sorted by longshore currents (Allen and Chambers, 1998; Storms et al., 2005).

The Miocene Mahakam Delta sequence (Fig. 2A) begins with shale-dominated shelf deposits and includes several carbonate intervals that are exposed as prominent ridges such as the Batu Putih patch reefs (Moss and Chambers, 1999; Wilson, 2005; Lokier et al., 2009; Marshall et al., this issue). Stratigraphically above the Batu Putih patch reefs deltaic sedimentation takes place and sandstones become progressively the dominant lithology often directly above coal beds. Based on magnetostratigraphic analyses that correlate the Samarinda polarity pattern and the geomagnetic polarity timescale an average sedimentation rate of ~ 75 cm/kyr has been estimated throughout the Samarinda sequence (see Fig. 11 in Marshall et al., this issue). The Stadion CC are a second set of fossiliferous carbonates (Fig. 2). Within 20 m above the Stadion CC, fluvial sedimentation resumes as thick sandstones and fossil barren shales (Marshall et al., this issue).

The age of the Stadion locality has been placed close to the Serravallian-Tortonian boundary (11.6 Ma) using integrated magnetostratigraphy and biostratigraphy

(Marshall et al., this issue). Thus, the Stadion CC are younger than other Samarinda carbonate sections previously studied by Wilson (2005).

Terminology

Facies descriptions in this work follow the nomenclature and characterizations developed by Insalaco (1998). These terms are an extension of the boundstone category applied by Dunham (1962) to facies that are dominated by *in situ* bioconstructors (corals, sponges, bryozoans, etc.) in growth position that may or may not form a true framework. From this approach, the term 'growth fabric' is used to describe the structure of coral facies. The term 'framework', *sensu stricto*, can be applied when a degree of rigidity, wave resistance, and intergrowth could be inferred for the growth fabric (Insalaco, 1998). The Insalaco nomenclature is based on the growth form of scleractinian corals as the primary descriptor, therefore a facies dominated (>60%) by branching corals is named a pillarstone, by platy to tabular corals (width to height ratio ≤30 to ~3:1) is a platestone, by thin-platy to sheet-like corals (width to height ratio >30:1) is a sheetstone, by domal massive corals are domestones, and those facies dominated by a variety of coral growth morphologies are mixstones. Regarding the geometry of the bioconstructions, the term 'biostrome' is applied to facies that are distinctly bedded and do not thicken into lenses so that their upper and lower surfaces are flat and parallel. In contrast, 'bioherm' is used to define rigid structures that caused modification of seabed topography and therefore are likely to have distinct ecological zonation (Cummings, 1932).

Although extensively used in paleoenvironmental interpretations, the terms ‘reefs’ and ‘patch reefs’ have countless, contradictory, and ambiguous definitions (see review in Fagerstrom, 1987; Rosen, 1990). Therefore, we constrained our direct comparisons to previous studies in the region (Moss and Chambers, 1999; Wilson and Lokier, 2002; Wilson, 2005, 2008; Lokier et al., 2009; Novak et al., 2013). In East Kalimantan, the term ‘patch reef’ has been applied to modern coral communities characterized as small isolated assemblages, which develop in shallow waters on the delta-front eight kilometers from the mouth of the Berau River (Tomascik et al., 1997). A similar approach was used for the interpretation of Miocene fossil coral assemblages located in the delta-front of the Mahakam delta, in which the term ‘patch reef’ has been applied to carbonate structures that “developed in shallow waters, form low-relief coral buildups, lack rigid frameworks, and had gently sloping margins of a few degrees” (Wilson, 2005). It is important to note that Wilson’s definition implies the use of the term ‘reef’ in a broad sense due to the ‘lack of rigid framework’ of the carbonate structures; likewise, in the present study the term ‘patch reef’ is used according to Wilson (2005), to describe coral carbonates regardless the lack/presence of rigid frameworks (Moss and Chambers, 1999; Wilson and Lokier, 2002; Wilson, 2008; Lokier et al., 2009; Novak et al., 2013).

From our descriptive approach, we suggest to treat ‘biostrome’ independently from the term ‘coral carpets’ proposed by Riegl and Piller (2000b, 2002), because the use of coral carpets implies an environmental interpretation by analogy with modern coral settings. While coral carpets can be preserved as biostromes, not all biostromes have been interpreted as being deposited by coral carpets (e.g. algal biostromes, Bosence, 1983; Benisek et al., 2009; bryozoan biostromes, Taylor and Zaborski, 2002). These concepts provide the background for further interpretations of the different facies within the Stadion CC.

METHODS

The Stadion CC are exposed in two outcrops, Stadion CC-1 located at 0.585 S, 117.120 E (Fig. 1C) and Stadion CC-2 at 0.586 S, 117.120 E (Fig. 1D) that are 150 m apart, at the crossroad of the stadium highway and a coal mine road. The outcrops Stadion CC-1 and Stadion CC-2 correspond to the Throughflow project localities TF57 and TF51, respectively. The two studied sections are 8-10 m thick, with an eastward dip of 55°, and were laterally exposed for a few tens of meters but partially covered by vegetation. Both sections were logged and sampled to identify lithological units, sedimentary structures, relative abundance of carbonaceous content, sediments and fossil components, and main taphonomic features. Photomosaics were taken to describe morphology and lateral variation (Figs. 1C-D), and the units were correlated and summarized in two logs (Fig. 2B) and a schematic sketch of the facies architecture (Fig. 3). Lithological samples were collected in each unit for further microfacies analysis of 21 thin sections (28x48 mm). Lithology and facies descriptions follow Folk (1980) for siliciclastics, and Dunham (1962) and Insalaco (1998) for carbonates. Carbonate contents of the sediment matrix were determined using Total Inorganic Carbon (TIC) analysis; for this assessment 50 mg of each sample was ground and then analyzed with the front-end acid digestion instrument CM 5240, which converts inorganic carbonate species into CO_2. The generated CO_2 is transported into a CM 5014 Coulometer that measures the TIC percentage from which the $CaCO_3$ percentage was calculated. Standard used for the carbon calibration is 12% carbon.

Fossil Content

The Stadion CC sections have mainly corals, foraminifers, coralline algae, bryozoans, and mollusks. In addition, some echinoid spines, serpulid tubes, small brachiopods, and crustacean chelae were found within the sediments or cemented to coral surfaces. In this study, only the former five main groups were considered based on their abundance and the taxonomic expertise of the research team. The primary datasets used to describe the distributions of these five main taxa within the units include field observations, hand specimens and bulk samples collected from the fossiliferous units, and thin sections. Bulk samples consisted of approximately 5 to 7 kg mix of sediment and fossil material that were dug out from each unit in the outcrops; once in the laboratory the bulk samples were soaked in water, washed, and sieved through 5 mm, 2 mm, 500 µm and 125 µm sieves. Fossil specimens were identified, mostly to genus or species, according to their preservation and taxonomic framework available for each group. Some taxa were left in open nomenclature pending detailed taxonomic description that is beyond the scope of this study. Representative specimens of corals, bryozoans and mollusks are deposited at the Natural History Museum (London), larger benthic foraminifera at the Naturalis Biodiversity Center (Leiden), and coralline algae at the Departamento de Estratigrafía y Paleontología of the University of Granada.

Corals were studied from 53 bulk samples as well as specimens individually collected from the outcrop surface. Bulk samples were collected randomly within each unit and also along 4-5 m long line transects. Transects were placed at each observed change of composition within each unit, thus nine transects were measured at Stadion CC-1 and equivalent seven transects at Stadion CC-2 (Fig. 3). High taxonomic richness and the lack of a rigorous regional taxonomic framework for Miocene reef corals restricted our ability to identify taxa in the field, so transects were used to estimate percentages of the different types of coral growth forms, including massive, branching (ramose and phaceloid), solitary, and platy, the later one sub-classified as thin-platy and platy tabular (Insalaco, 1998; Rosen et al., 2002). The relative abundance of sediment and corals in each unit was estimated along each transect. Specimens recovered from bulk samples were counted and weighed, and relative abundances were estimated as a percentage of each taxon per unit (Appendix A). External morphological characters of corals observed with a Leica microscope MZ16, such as colony forms and calice features were used for taxonomic identifications in the laboratory and taxa names were assigned following the recent revision on Indo-Pacific fossil corals by Johnson et al. (this issue). *Acropora* specimens were identified into ‘species groups’ (Wallace, 1999). Well-preserved corals weathered out at the base of the outcrops were also collected to enhance taxonomic lists and identifications.

Larger benthic foraminifera were examined in 11 thin sections (28x48 mm) and as specimens picked from 14 bulk samples (500 µm to 2 mm fractions; ~300 foraminifera per sample). Taxon abundances were estimated relative to the total number of foraminifera identified in each sample or thin section (Appendix B). A semi-quantitative approach was applied to evaluate benthic foraminiferal assemblages within the 125-500 µm fraction from each sample. In each sample, ~100 specimens were sorted, identified, and scored as abundant if they represented more than 40%, common between 15 and 40%, frequent from 5 to 15%, and rare if less than 5%. The percentage of planktonic/benthic foraminifera was also calculated (Appendix C).

Coralline algae were selectively collected in the field and subsequently studied in a total of 32 ultra-thin sections (10-15 µm thick). Relative abundances of taxa of coralline algae were estimated by measuring the proportional cross-sectional area occupied by each taxon in relation to the total coverage of coralline algae (Perrin et al., 1995). Structures built by coralline algae such as crusts, rhodoliths, and foralgaliths that are compact nodules with foraminifers (Prager and Ginsburg, 1989), were recognized in hand specimens and in thin sections. Growth forms were described using the terms of Woelkerling et al. (1993).

Bryozoans were found encrusting the bases of platy corals and coral branches, and as colony fragments picked from sediment fractions larger than 500 µm from ten bulk samples. Bryozoan specimens were identified using a stereomicroscope or SEM to genus or family. Relative abundances of taxa were estimated by counting the number of encrusting colonies on the corals and fragments of erect species scattered in the sediments. The proportion of corals encrusted by bryozoans was also estimated by comparing the number of coral specimens and/or fragments encrusted by bryozoans and the total number of coral specimens and/or fragments contained in the bulk samples. Colony growth-forms of bryozoans included two main categories, encrusting and erect, and their respective proportions were calculated in terms of both species richness and specimen abundance.

Statistical Analysis

To assess changes in the community composition among facies and between the two sections, non-metric multidimensional scaling (NMDS) ordinations were produced for corals and larger benthic foraminifera. Coral abundances were estimated as weight percentages standardized using the “Wisconsin double standardization” where species are first standardized by maxima and then site by site totals (Oksanen et al., 2013). NMDS plots based on transformed data from percentages of the number of fragments and/or colonies showed a similar pattern of clustering to that obtained from their respective weight percentages; hence the former plots are not included here. Analyses of similarity (ANOSIM) were used to test for intergroup differences, and similarity of percentages analysis (SIMPER) was used to identify species that were most responsible for the discrimination between facies and outcrops. Statistical analyses were performed using the vegan package (Oksanen et al., 2013) within the R statistical software environment (R-Core Team, 2013)

RESULTS

Seven main lithological units were recognized and correlated across both sections (Fig. 2B). Each of the lithofacies extended laterally at least 150 m, as along-strike exposures were identified no farther than 50 m north from Stadion CC-1 and 300 m south from Stadion CC-2. Therefore, the horizontal size of the structure could be interpreted as larger than 150 m and less than 300 m.

Facies Types

A combined analysis of the sedimentary composition and main fossil contents of the seven lithological units showed that each unit corresponds to a distinctive facies type (Figs. 2B, 3-4). Table 1 shows a summary of the most relevant characteristics of the facies and their respective fossil contents.

Laminated Siltstone Facies.—This facies is characterized by a laminated siltstone with thin mudstone layers (3-10 mm) and occasional ripple marks (Fig. 4A). The laminated siltstone facies can be recognized in lithological Unit 1. The lower part of the unit is intensely bioturbated. Towards the top, the siltstone alternates with fine-grained sandstones and thin carbonaceous shale layers (< 1 cm). Invertebrate fossils are absent. The exposed facies is about 1 m thick in both sections, with its base covered.

Carbonaceous Shale Facies.—This facies is characterized by dominance of carbonaceous shale with occasional thin clay and silt layers (Fig. 4B). The carbonaceous shale of Unit 2 is 20 cm thick in Stadion CC-1 and 40 cm thick in Stadion CC-2. This unit has a sharp contact with the laminated siltstone facies at the base and a gradual change into the mixed siliciclastic-carbonate facies towards the top. Carbonaceous content decreases upwards as clay and silt content increases. Small pieces of amber were observed in the lower part of this unit.

Bioclastic Sandstone Facies.—This facies is characterized by larger benthic foraminifera and mollusk bioclasts in a predominantly moderate to well-sorted fine sand matrix, composed of a mix of subangular to subrounded fine-grained quartz. This facies occurs in Unit 3, which it is a 20-cm thick transitional bed of mixed siliciclastic and bioclastic carbonate components (Fig. 4C). Contacts at the base and the top are gradual. Compared to the underlying facies, the carbonaceous content is lower (<10 %) while the average carbonate content is higher (36 %). Larger benthic foraminifers comprise about 15% of the sediment (Fig. 4D). A few planktonic foraminifers were observed in the finer fractions (2%).

Coral Platestone Facies.—This mixed carbonate and siliciclastic facies is characterized by a coral framework with thick-platy corals that develop a platestone growth fabric (*sensu* Insalaco, 1998). This facies can be recognized in Unit 4, where corals and other bioclasts occur in a gray matrix with an average of 45% $CaCO_3$ (Figs. 4E-F). The thickness of this unit is 1.1 m at the Stadion CC-1 and 3 m at the Stadion CC-2. The transition from the underlying bioclastic sandstone facies is gradual from sand to a silt-rich sediment matrix with abundant fossils. Corals constitute the main carbonate-forming component of this unit (60-70%, Fig. 5). Most corals are densely packed in growth position, with their calicular surfaces facing upwards and bioclastic sediment in the interstices (Fig 4E). Relative abundances of the different coral growth forms change from the base to the top of the unit (Fig. 5). Corals first appear in transect 2 (Fig. 5), mainly as thin-platy forms (1 to 7 mm thick) and delicate ramose corals (1 to 6 mm in diameter). More robust forms became abundant in the middle of this unit, including ramose corals (up to 16 mm in diameter), platy-tabular (4 to 7 cm thick), and small massive forms (10 to 15 cm high). At the upper part of the unit, the growth fabric is composed by relatively similar proportions of small massive (21.2%), phaceloid (17%), and platy-tabular corals (16.4%) (Fig. 5). Larger benthic foraminifers appear as a subordinate component (10%) within the siliciclastic matrix. Coralline algae occur in low abundances (5%), mainly as encrusting plants. The majority of mollusks recovered from the Stadion CC belong to this unit. Some echinoid spines were also observed within the sediments.

Foraminiferal Packstone Facies.—This facies is characterized by packstone dominated by larger benthic foraminifers (Figs. 4G-H). It occurs in Unit 5 with relatively uniform thickness of 1 m at Stadion CC-1 and 1.2 m at Stadion CC-2. It has the highest carbonate content (72%). The contacts with the units below and above are sharp. Corals were observed as a subordinate component (15%), preserved in growth position, and evenly distributed among thin-platy, massive, tabular, and ramose forms. From the base to the top, no changes in the fossil assemblages were observed. Coralline algae, *Halimeda* fragments, echinoid spines, and entirely recrystallized gastropods occur as minor components.

Coral Sheetstone Facies.—This facies is characterized by dominant thin-platy corals forming a sheetstone fabric (*sensu* Insalaco, 1998). It occurs in Unit 6 where corals are the main component (40-60%) of this mixed carbonate-siliciclastic bed (Fig. 4I). The thickness is 1.6 m at Stadion CC-1 and 1.8 m at Stadion CC-2. Carbonate content within the sediment matrix is on average 30%, decreasing from 40% to 11 % up section. The upper part of the unit is characterized by a decline in coral abundance. Among the corals, thin-platy forms dominate (65-95%). These thin-platy corals are mostly 1-5 mm thick, and densely packed in growth position. Platy-tabular corals (30%) up to 3 cm thick were also observed, mainly towards the top of the bed, and some clusters of branching corals were sparsely distributed along the transects. The siliciclastic sediment matrix is yellow and clay-rich with abundant larger benthic foraminifers (20-30%). Crustose coralline algae occur in low proportions (5%), mainly encrusting corals together with foraminifers (Fig. 4J). Bryozoans are commonly found encrusting the under surfaces of thin-platy corals, colonizing 27% of the corals. Sparse cidaroid echinoid spines, gastropods and fragments of bivalves also occur.

Clay-shale Facies.— This facies is characterized by dominant clay sediments and the absence of fossils. This facies is formed in the uppermost Unit 7 exposed at the Stadion CC sections. Although the top of the outcrop is covered by vegetation with no other deposits exposed, several hundred meters of thick deltaic sandstones are visible further up the section (Cibaj, 2009).

Fossil Assemblages

Rich fossiliferous biofacies are characteristic in the four middle facies of the Stadion sections, including the coral-dominated facies (coral platestone and sheetstone) and foraminifer-dominated facies (bioclastic sandstone and foraminiferal packstone). The other facies are barren in fossils. Percentages of abundance for the five main fossil groups studied in the Stadion sections are illustrated in Fig. 5 and principal taxa are summarized in Table 1. Most fossil taxa recovered from the Stadion CC sections have complete or partial calcitic skeletons with higher potential of preservation, such as coralline algae (Bosence, 1991), foraminifera (Lowenstam and Weiner, 1983), octocoral sclerites (Bayer and Macintyre, 2001), echinoderm spines (Su et al., 2000), and polychaete tubes (Vinn et al., 2009), among others. Even though scleractinian corals deposit aragonitic skeletons, those were recrystallized and transformed from original aragonite into secondary calcite as it is commonly found in corals older than Pleistocene age (Constantz, 1986; Mcgregor and Gagan, 2003; Reuter et al., 2005).

Corals.— A high richness of coral species was recorded from the studied sections (Table 1; Fig. 6). A total of 69 species belonging to 41 genera were identified from the 4686 studied specimens. They include 66 species from 38 genera of scleractinians. Other taxa were the hydrozoan *Millepora* sp., and the octocorals *Heliopora* sp. (Fig. 6G) and *Isis* sp. (Appendix A). A few octocoral sclerites (3-5 mm long) were also recovered. A small percentage of the specimens (<1%) could not be identified. The 157 specimens collected from the outcrop surface only yielded two additional taxa, *Leptoseris* aff. *mycetoserioides* and *Lobophyllia* sp. The latter two taxa could not be assigned to any specific facies so were left out of the statistical analyses.

Statistical ordinations showed that the coral assemblages were significantly different between the coral sheetstone and coral platestone facies (Fig. 7; ANOSIM R= 0.278, p-value=0.022) but not between the Stadion CC-1 and Stadion CC-2 sections (R= 0.078, p-value= 0.206). External morphological features of corals were well preserved in the coral platestone facies allowing taxonomic identifications. Internal microstructures of coral skeletons were highly recrystallized and some specimens have a friable consistency. The reconstruction of the coral succession shows that the first corals appeared at the base of the coral platestone facies in transect 2, about 20 cm above the carbonaceous shale, including *Porites* sp. 1 (Fig. 6A), *Leptoseris* sp. 7, and *Heliopora* sp. Coral abundances and richness increased to 22 in transects 3 and 5, reaching its maximum number of 31 species in transect 4. Within this facies, platy tabular forms of *Progyrosmilia* sp. 2 (Fig. 6C) and *Astreopora* spp. were dominant in the Stadion CC-2, while small massive colonies of *Porites* sp. 3 (Fig. 6E) were typical in the Stadion CC-1. At the top of the coral platestone facies, the phaceloid taxa *Galaxea* spp. (Fig. 6F) and ramose *Porites* sp. 2

and *Dictyaraea* sp. were more abundant. In total for the coral platestone facies, 48 species from 30 genera were identified, with 24 species common to both sections.

Corals were poorly preserved in the foraminiferal packstone facies and highly cemented into the matrix. No new taxa were found in this facies, and 43 coral species that were present in the previous coral platestone facies did not occur in this facies. Only five species were identified from samples collected in transect 6, from which massive *Porites* sp. 3 (44%), ramose *Porites* sp. 2 (30.5%), and platy *Porites* sp. 1 (9.8%) were the most abundant corals.

With a total of 56 species, the highest coral richness and the best-preserved specimens were observed in the coral sheetstone facies, mainly dominated by thin-platy forms of *Porites* sp. 1, the agariciids *Leptoseris* spp. (e.g. Fig. 6J) and *Pavona* spp. (e.g. Fig. 6L), the merulinid *Cyphastrea* spp. (e.g. Fig. 6M), and the siderastreid *Psammocora* sp. (e.g. Fig. 6N). Twenty-three coral species were present in the upper part of coral sheetstone facies, including *Porites* sp. 1, *Cyphastrea* cf. *imbricata*, and other agariciids. Thirty-seven species were shared with the previous coral platestone facies, and except for the small massive *Porites* sp. 3, all species from the underlying foraminiferal packstone facies were present in the coral sheetstone facies.

Foraminifera.—In the coarser fractions (0.5-2 mm and >2 mm), assemblages of larger benthic foraminifera varied among the lithofacies (Table 1, Fig. 5, Appendix B). Ordination analyses showed two distinctive groups (Fig. 7B), a first one preserved in the bioclastic sandstone, coral platestone, and foraminiferal packstone facies and a second group found in the coral sheetstone facies (ANOSIM R= 0.706, p-value= 0.001). No significant differences were found between the two Stadion CC sections (ANOSIM R= 0.461, p-value <0.001). Small and robust forms of *Amphistegina* and *Nephrolepidina* (Fig. 8A) dominated in the bioclastic sandstone facies, with rare occurrences of thin and flatter *Lepidosemicyclina*. In the coral platestone facies richness increased slightly, with *Amphistegina* and *Nephrolepidina* still dominant, albeit with increased abundance of *Lepidosemicyclina*, and subordinate *Operculina*. Although very abundant, they were less rich in the foraminiferal packstone facies than in the coral platestone facies, and again contained abundant *Amphistegina*, with subordinate *Nephrolepidina* and *Lepidosemicyclina.* In the uppermost fossiliferous unit, the coral sheetstone facies, there was an abrupt change in larger benthic foraminifers composition as *Lepidosemicyclina bifida* (Fig. 8C) became the most abundant taxon with subordinate *Nephrolepidina* (e.g. Fig. 8A), *Amphistegina* and *Operculina*, and rare occurrences of flat discoidal *Cycloclypeus annulatus* (Fig. 8B).

Among the 125 μm fractions recovered from the bulk samples, benthic foraminifera were present in the bioclastic sandstone, coral platestone, and coral sheetstone facies, but absent from the clay-shale facies (Appendix C). In general, foraminiferal tests were poorly preserved and taxonomic identifications were only possible at the genus level. Six taxa were identified, from which *Amphistegina* spp. (Fig. 8D) were the most abundant, followed by *Operculina* spp. (Fig. 8E), *Elphidium* spp. (Fig. 8G) and *Cibicidoides* spp. (Fig. 8H). Small differences could be noticed among the facies types: abundances of *Cibicidoides* and *Elphidium* increased from frequent at bioclastic sandstone and coral platestone facies, to common in coral sheetstone facies. Similarly, miliolids (Fig. 8F) were rare in the bioclastic sandstone and coral platestone facies but common in coral sheetstone facies. Samples from the coral sheetstone facies were moderately well preserved and contained the highest benthic foraminiferal richness.

Coralline Algae.—Abundances, growth forms, and groups commonly associated with coralline algae assemblages in the successive carbonate units are shown in Table 1 and detailed data per taxon in the Appendix D. Coralline algae were present as a subordinate component in the coral platestone, foraminiferal packstone, and coral sheetstone facies. Abundances were higher in coral platestone and coral sheetstone facies, mainly encrusting corals, forming foralgaliths, and also as fragments within the matrix (Fig. 5). Assemblages and growth forms of coralline algae did not vary significantly between the coral-dominated facies, but both were characterized by abundant mastophoroids (Fig. 9), mainly *Neogoniolithon* spp. (Figs. 9A-B). In the foraminiferal packstone facies, coralline algae were less abundant and very recrystallized limiting taxonomic identification.

Bryozoans.—Although bryozoans were restricted to the coral sheetstone facies (Table 1, Fig. 5), they included 28 species, with 3 cyclostomes, 25 cheilostomes (9 anascan-grade and 16 ascophoran-grade species), and rare ctenostome borings visible on the undersurfaces of corals (Appendix D). Species richness and specimen abundance was very similar in the two sections: 25 species (450 specimens) at the Stadion CC-1 and 24 species (475 specimens) at the Stadion CC-2. Twenty-one of the species that occur in both sections were the most abundant taxa. In contrast, the four species found exclusively in Stadion CC-1 and the three species unique to Stadion CC-2 were represented by a few or even a single colony. The dominant taxa among erect colonies were the articulated anascan *Vincularia berningi* (11%) and the fenestrate ascophoran *Triphyllozoon* sp. (7%), both found as scattered fragments and as specimens cemented to coral surfaces and a few colony bases. Among encrusters the anascans *Steginoporella* sp. (27%; Fig. 10B), ?*Crassimarginatella* sp. (3%), *Cranosina rubeni* (Fig. 10A), *Antropora* cf. *subvespertilio* (Fig. 10D), the cribrimorph *Puellina* spp., and the ascophorans *Reptadeonella* sp. nov. (Fig. 10C) and *Hippopodina* cf. *feegeensis* (5%) usually developed large colonies on coral undersides; only a few specimens were observed encrusting the surfaces of ramose corals. Unidentifiable cheilostome species accounted for 33% at Stadion CC-1 and 17% at Stadion CC-2, mainly represented by fenestrate phidoloporid fragments.

Most taxa were encrusters (78%), mostly with two-dimensional colonies of low relief; 21% of the species were erect, mostly flexible because of jointing and anchored to a substrate by rootlets, or rigid fenestrate with a cemented base; a single ctenostome species occurs as borings in the corals. Almost the same proportions of growth-forms occurred in terms of specimen abundance: 81.6% of specimens were encrusters, 18.3% were fragments of erect species, and only one specimen (0.1%) was boring a coral substrate (Fig. 5).

Mollusks.—Eighty-six poorly preserved specimens were recovered, including representatives of three bivalve families and at least eleven gastropod families (Appendix F). Aragonitic mollusks are rare and mainly represented by very small, incomplete, and highly recrystallized shells. Gastropods with an outer calcitic shell layer and/or relatively thick shells (e.g., Trochidae and Turbinidae; Gainey and Wise, 1980; Beesley et al., 1998) are comparatively common in the Stadion CC sections. The majority of bivalves present at the studied sections are epifaunal taxa that aggregate calcitic foliated, and therefore relatively hard and chemically resistant shells (Kennedy et al., 1969; Taylor and Layman, 1972).

Most mollusks were recovered from coral platestone facies, in which 92% of the total number of specimens was collected. Bivalves were predominately preserved as fragments and include oysters (e.g. *Lopha* s.l.), pectinids, and one specimen of the

Lucinidae ?*Anodontia* (*Pegophysema*). The most common gastropod families were Turritellidae (n = 13), Trochidae (?*Euchelus* sp., n = 12) and Turbinidae (*Astraea* sp., n = 6; opercula of two species). Other identifiable families were Cerithiidae, Scaliolidae, Rissoidae, Iravadiidae, Triphoridae, and Pyramidellidae, each with very low abundances (n < 4). Gastropods were represented by herbivores, suspension feeders, and parasites (Fig. 5). Predatory taxa are entirely lacking, although they are dominant in modern reef-associated gastropod faunas (Taylor, 1977) due to the preservation constrain.

DISCUSSION

Most of the fossils found in the Stadion sections are light-dependent benthic organisms, including zooxanthellate corals, larger benthic foraminifera and coralline algae, that lived as distinct communities during deposition of bioclastic sandstone, coral platestone, foraminiferal packstone, and coral sheetstone facies (units 3 to 6), indicating that in those settings light reached the benthic environment. The varying composition of the communities in these facies suggest a variation in light levels, most likely related to changes in depth and/or alterations in terrestrial input (Perrin et al., 1995; Wilson, 2005, 2012; Bassi and Nebelsick, 2010; Novak et al., 2013). Terrestrial input can drive the response of light-dependent biota based on: (1) the amount of siliciclastic input that can vary from low to high; (2) frequency of input that can be constant or episodic; (3) grain-size; and (4) associated nutrient input (Sanders and Baron-Szabo, 2005; Wilson, 2005; Lokier et al., 2009). Disentangling the role of each factor involved with terrestrial input effects is not a straightforward task, especially because they interact with other factors such as depth and hydrodynamic regimes to produce similar effects on the amount of light available to the benthic community. For example, similar low-light levels could result from at least three different scenarios: constant fine-grained sediment input in shallow waters, low siliciclastic input but high resuspension of sediments in shallow waters, or no terrigenous input at all in deeper waters. In this sense, paleoenvironmental interpretations based on the studied communities of light-dependent organisms are relative rather than absolute, and only possible if independent evidence obtained per fossil group is taken into account to subsequently capture further elements with the analysis of the assemblages as a whole. In this study, the growth forms and taxonomic composition of fossil assemblages were analyzed because these two aspects are key to interpret paleoenvironments as it has been shown in previous studies for scleractinian corals (Perrin et al., 1995; Pandolfi, 1996; Perrin, 2000; Klaus et al., 2008; Johnson et al., 2009), larger benthic foraminifera (Hallock and Glenn, 1986; Hottinger, 1997; Hohenegger et al., 1999; Renema and Troelstra, 2001), and coralline algae (Bosence, 1983; Perrin et al., 1995; Braga et al., 2009).

Facies Interpretation and Paleoenvironmental Evolution

The Stadion CC were deposited during a brief interval of time within the 3 km thick Samarinda section that includes a succession of alternating shallow marine, deltaic, and fluvial intervals and a depositional time framework between 16 and 11 Ma (Marshall et al., this issue). The development of the Stadion CC is part of a transgressive interval characterized by an important change in relative water depth and sedimentation rates that created marginal marine environments with deltaic sand and lagoonal coal cycles (Marshall et al., this issue). The Stadion CC signals a furthering of this trend by introducing reef taxa that require fully marine environments and relatively lower turbidity (Cibaj, 2009; Marshall et al., this issue). The observed geometry and lateral continuity of the deposits that extend at least 150 m between the two studied sections suggests that the Stadion CC could have developed as a low-relief patch reef (Moss and Chambers, 1999; Wilson, 2005). The main factors controlling this patch reef were most likely depth and episodic variations in sedimentation rates and grain size of terrigenous input (Fig. 11).

At the base of the Stadion CC sections, the lack of marine fossils in the laminated and occasionally rippled siltstones and fine-grained sandstones facies suggests a low-energy depositional environment within the delta plain (Allen and Chambers, 1998). Increase in marine influence leading to the development of coastal swamps or estuarine mangrove environments can be inferred from the appearance of thin carbonaceous layers, first occasionally at the top of the laminated siltstone facies and becoming more abundant until they form the distinctive carbonaceous shale facies (Figs 11A-B). Although a definitive interpretation of mangrove facies would require to satisfy the criteria proposed by Plaziat (1995), recent research has shown that coal-bearing sequences of Miocene age in the Kutai Basin evolved from lower delta plain deposits of *Nipa* palm in swamp environments and brackish water-fed mangroves (Widodo et al., 2010; Gastaldo, 2010).

Following on from these low-energy swamp conditions, the first occurrence of larger benthic foraminifera marks the transition into a fully marine environment during deposition of bioclastic sandstones (Fig 11C). The foraminiferal assemblage in the bioclastic sandstone facies, dominated by smaller and robust specimens of *Amphistegina* and *Nephrolepidina* with subordinate miogypsinids and *Operculina*, supports the interpretation of shallow-water conditions and the increase of energy levels in the environment (Hallock and Glenn, 1986). Similar communities of foraminifers remain in the subsequent coral platestone facies, even though up section smaller and more robust forms decreased in favor of the appearance of slightly thinner and elongated forms.

In the coral platestone facies corals are preserved in growth position indicating autochthonous deposition and fully marine conditions. The platy morphology of corals has been recognized as an adaptation to low-light environments (Rosen et al., 2002; Sanders and Baron-Szabo, 2005) that could have resulted as a response to terrigenous input indicated by the silty siliciclastic matrix of the facies. However, at these initial stages relatively low silty siliciclastic input can be interpreted because corals could develop certain degree of robustness as platy-tabular and small massive colonies (Figs. 6C-E, 11D); in addition, relatively constant sedimentation rates can be proposed because corals do not present signs of partial mortality during development. The subsequent appearance of phaceloid and ramose morphologies towards the top of the coral platestone facies can be indicative of an environment with relatively higher sedimentation rates of silt-size siliciclastics (Perrin et al., 1995; Sanders and Baron-Szabo, 2005). The initial stage of the coral platestone facies was characterized by low coral abundances (<10%) and dominance of thin-platy forms (Fig. 5), suggesting plausible constratal framework (Insalaco, 1998) with corals barely exceeding the rates of siliciclastic deposition. Once this pioneer coral community was established, the framework might have become partially suprastratal as suggested by higher abundances of corals arranged with more colony intergrowth and the appearance of small massive and branching growth forms (Insalaco, 1998). However, any growth above sea floor was limited to a few decimeters resulting in the relatively flat parallel geometry of the bed after compaction. Gastropods from the coral platestone facies such as Turbinidae, Trochidae, Cerithiidae, and Turritellidae are typical inhabitants of reefs and other shallow marine habitats (Taylor, 1968; Héros et al., 2007). The presence of sponges in the community is inferred by the occurrence of the gastropod family Triphoridae that are recognized sponge parasites (Marshall, 1983). The absence of encrusting bryozoans in the coral platestone facies, despite the abundant offer of coral substrates for their colonization, can be explained as a preservation issue due to the cementation of sediments on coral surfaces, as it has been suggested by Taylor and Di Martino (in press).

Coralline algae assemblages provide the most reliable signal for an interpretation of paleodepth for the coral platestone facies. Mastophoroids are well-known components of the algae communities that live on shallow parts of modern coral reefs, mainly in the first 30 m depth (Adey, 1986; Minnery, 1990; Verheij and Erftemeijer, 1993; Iryu et al., 1995). Relatively high abundance of thick crusts of members of the subfamily Mastophoroideae (such as *Neogoniolithon* and *Spongites*) has also been well constrained to shallow-water environments in tropical Miocene reefs (Perrin et al., 1995; Braga et al., 2009, 2010). While the paleodepth interpretation of coralline algae with affinity for low light is ambiguous, as they could mean deep/clear or shallow/turbid waters, the photophilic (high-light affinity) property of thick mastophoroid species constitutes an unequivocal indication of a shallow paleodepth for the coral platestone facies. Large discharges of sediments have characterized the Kutai Basin since its early formation (van de Weerd and Armin, 1992; Allen and Chambers, 1998). In the modern Mahakam delta-front system water transparency is very low, with Secchi disc estimation at maximum of 13 m depth (Budhiman et al., 2012), due to high quantities of suspended sediments (Storms et al., 2005). Therefore, by analogy to modern conditions around the Mahakam delta, the co-occurrence of mastophoroids and platy coral communities within a terrigenous-rich matrix suggest that coral development took place at a few meters depth, most likely less than 10 m depth and probably even shallower. Intolerable sediment input for most coral species could have promoted a partial interruption of coral development at the end of the coral platestone facies allowing the abrupt dominance of foraminifers at the foraminiferal packstone facies (Fig. 11E).

In the foraminiferal packstone facies, the dominance of flatter forms of *Nephrolepidina* combined with the presence of *Cycloclypeus* suggest a decrease of light-levels, indicating the deposition in the darkest and lowest-energy habitat of the studied sections, most likely due to a depth increase (Hallock, 1981; Hallock et al., 1986; Renema, 2006). Even though nutrients can also indirectly affect the shape of larger foraminifera by reducing the light reaching the benthic environment (Hallock, 1987), in the current study the nutrients effect can be disregarded because the highest $CaCO_3$ content of the foraminiferal packstone facies suggests the lowest terrigenous input responsible for the transport of nutrients into the marine environment. Corals are the secondary component within this facies, providing additional evidence for a reduction in light-levels. The presence of unidentifiable crustose corallines and fragments of geniculate corallines merely confirm that the foraminiferal packstone facies was deposited in the photic zone but cannot provide a more refined interpretation.

Subsequently, the recolonization of thin-platy corals in the coral sheetstone facies could be a response to a stabilized environment by larger benthic foraminifers and a change of the grain-size composition from silt to clay (Fig. 11F), as it has been found that thin-platy corals are successful in turbid environments if the input contains finer fractions of sediments (Lokier et al., 2009). Flat forms are more common in the foraminiferal assemblage that is dominated by *Lepidosemicyclina bifida* and includes abundant *Amphistegina* and *Nephrolepidina*. Increased surface area to volume ratios has been proposed as a morphological response of foraminifers to provide more surface for symbionts to capture light in low-light environments (Hallock et al., 1986), as was characteristic of the coral sheetstone facies. On the other hand, corals from this facies were mostly thinner than 5 mm suggesting that light availability was much lower under clay-sized than under the silty sediment input in the coral platestone facies, as corals growing at their tolerance limits can develop helical spiraling colony forms to maximize both light capture and ability to shed sediment (Rosen et al., 2002; Sanders and Baron-Szabo, 2005). Ragged margins were observed in some thin-platy colonies (Figs. 6A,K), suggesting that episodic higher discharges of clay sediments produced partial mortality followed by regrowth during moments of less sediment stress (Sanders and Baron-Szabo, 2005). Agariciids are among the most common corals of the coral sheetstone facies and provide more evidence for a turbid habitat. Agariciid corals are the principal inhabitants of many modern mesophotic reefs (Kahng et al., 2010), mainly associated with deep and clear waters in the Indo-Pacific (Maragos and Jokiel, 1986), Red Sea (Fricke et al., 1987), and Caribbean (Reed, 1985). In fact, *Leptoseris* species are the deepest known zooxanthellate corals that live today at depths of 150 m (Kahng and Maragos, 2006), suggesting that not only growth forms but also the taxonomic composition of coral communities in low-light environments could be analogous between turbid shallow waters, such as the Stadion CC habitats, and clear deep waters as in the modern examples. Although coping with episodic terrestrial input, the coral community did not acquire ecological differentiation at this stage, but remained as thin veneers following the sea-floor morphology, similar to those described as coral carpets (Riegl and Piller, 2000a,b).

The rich community of bryozoan epibionts preserved on the underside of agariciids and other taxa, indicates that corals may have grown suprastratally, even though the sheetstone facies was built almost entirely of thin-platy corals. Abundant larger benthic foraminifera and crustose coralline algae were observed partially overgrowing the calicular surfaces of thin-platy corals, suggesting significant partial mortality of the corals before burial. For some taxa, coral growth can be enhanced in turbid habitats (Edinger et al., 2000), and rapid growth would allow colonies to survive high levels of partial mortality, promoting rapid accretion of coral carbonates in turbid environments (Perry et al., 2012). Higher nutrient input associated with episodic terrigenous influx can also be inferred at this stage, based on the proliferation of large encrusting colonies of filter-feeding organisms such as bryozoans (Moissette et al., 2007).

The abundance of mastophoroid corallines indicates relatively high light levels in this shallow habitat influenced by siliciclastics. Thus, thin-platy agariciid corals, elongated foraminifera, the occurrence of mastophoroid coralline algae, and a clay-rich matrix all suggest a habitat characterized by episodic high terrigenous input at a paleodepth of about 10 m depth but in relatively calm waters. The absence of fossils and any carbonate contents in the overlying clay-shale facies record the return to fluvial-deltaic environments with higher levels of siliciclastic input, most likely accompanied by drastic decrease of salinity and increase of nutrient input, producing altogether intolerable conditions for coral growth (Fig. 11G).

In summary, the laminated siltstone and carbonaceous shale were deposited within the lower delta plain, most likely on the flood plain in peat swamp or mangrove estuarine environments. In contrast, the bioclastic sandstone, coral platestone, foraminiferal packstone and coral sheetstone developed on the delta front, probably at depths < 10 m, and fully marine environmental conditions. The clay shales record the termination of marine-dominated habitats suitable for reef biota.

Diversity of Fossil Assemblages

Species richness varied among the studied fossil assemblages, in which corals were both the main carbonate-forming group and the most diverse taxon. The substrate provided by corals is likely to have enhanced overall diversity in the Stadion settings by hosting bryozoans, mollusks, and coralline algae. The bryozoan community had a medium diversity in comparison to other studied localities of Miocene age in East Kalimantan (Di Martino et al., this issue), yet did not contribute significantly to carbonate accretion. The record of mollusks in the Stadion section is highly biased due to a lack of aragonite preservation as it appears to be typical of reef associated mollusk faunas in the Miocene of East Kalimantan (own observations, 2010-2011) and it has been observed in other modern habitats and several fossil localities (Wright et al., 2003, and references therein); hence this preservational bias impedes the reconstruction of the molluscan faunal diversity or ecology. Larger benthic foraminifera were present in the greater number of fossil facies due to their higher ability to tolerate terrigenous input with respect to corals (Lokier et al., 2009) and because they are efficient colonizers of soft substrates (Hohenegger et al., 1999; Renema, 2008). Richness of larger benthic foraminifera of the Stadion CC is comparable to modern low-light marine environments of Indonesia, but it is lower than in clear waters (Renema and Troelstra, 2001; Renema, 2008). Higher richness in clear waters is probably due to increased habitat partitioning along an extended photic gradient (Hallock, 1987; Renema and Troelstra, 2001; Novak and Renema, this issue).

In this study, the analysis of larger benthic foraminifera was used mainly as a paleoenvironmental proxy rather than as a diversity indicator. Even though coralline algae are important paleodepth indicators, in the Stadion patch reef their abundance and diversity was relatively low and restricted to a few mastophoroids species and *Sporolithon* (Rösler et al., this issue). Therefore, discussion about diversity in the Stadion CC sections is focused on the richest taxa found represented by corals and bryozoans.

Corals.—The 69 coral taxa identified from these sections indicate that high coral richness could develop under turbid conditions in the Stadion CC. Of course corals will be smothered and die at high levels of terrigenous input (Van Woesik et al., 1999; Fabricius, 2005), but these findings clearly show that below this lethal threshold, turbid environments can support rich coral communities over ecologically significant time scales. Likewise, the Stadion coral assemblages were not building large-scale high relief reef structures, supporting the idea that high coral species diversity can be independent of reef development (Johnson et al., 2008). Thus, high siliciclastic input is a major control on the functioning of reef-coral communities even though a high diversity of coral species would be able to thrive under turbid conditions (Klaus et al., 2011).

The Stadion coral assemblages are the richest known for a Miocene setting in the Indopacific. Previous records in the area (Wilson, 2005; Lokier et al., 2009) include at least ten coral genera, one quarter the richness discovered in this study. In terms of species richness, the maximum number of species per locality recorded so far is at 34 species in a Middle Miocene site in Fiji (Bromfield and Pandolfi, 2012), and 36 species for a Burdigalian patch reef located about 80 km to the north of the Stadion CC (Novak et al., 2013). Coral assemblages of Late Oligocene age in similar mixed carbonate-siliciclastic settings in Sabah, Malaysian Borneo are also less rich, with a maximum of 37 genera per site (McMonagle et al., 2011, unpublished data).

Comparisons of the Stadion patch reef assemblages with modern assemblages may be limited by time-averaging processes in the fossil community (Pandolfi and Greenstein, 1997; Pandolfi, 2002). Even though the high richness of the studied fossil assemblage could be due to a time-averaged effect, it is notable that the Stadion patch reef contains a similar number of species as communities living today in clear waters on the nearshore Great Barrier Reef, estimated to be around 60 species per site (Van Woesik et al., 1999). The Stadion patch reef is almost three times as diverse as coral assemblages currently growing under high river and tidal influence, in which average coral richness per site could vary from 20 to 24 species per site (Van Woesik et al., 1999). In comparison to a larger study performed along the nearshore of the Great Barrier Reef that included 135 reefs with average coral richness of 39.5 taxa per site (DeVantier et al., 2006), the Stadion patch reef contained almost as twice as the number of taxa.

There are significant differences in taxonomic composition of coral assemblages between the coral platestone and coral sheetstone facies (Fig. 7A) in terms of the abundances of the dominant *Porites* species. Studies on *Porites* species at the Great Barrier Reef have shown that colonies of this genus are able to tolerate long-term input of sediments, low-light levels, in relatively calm waters for large periods of time (Stafford-Smith and Ormond, 1992; Stafford-Smith, 1993; Anthony, 1999; Perry et al., 2009); thus, *Porites* was able to dominate in the coral sheetstone facies that contained higher levels of terrigenous clay.

The coral platestone and sheetstone facies also differed in the presence of acroporids and agariciids, so that acroporids are characteristic of the platestone facies, while agariciids are more common and diverse in the sheetstone facies (Table 2). Although acroporids are mainly known to prefer clear and shallow water habitats on modern reefs, some *Astreopora* and the *A. elegans*-group (Fig. 6H) species that are typical of the coral platestone facies are also known from low-light environments such as shallow turbid reefs and reef slopes (Wallace, 1999; Veron, 2000). A higher abundance and diversity of agariciids in the coral sheetstone facies, including *Pachyseris*, *Leptoseris* and *Pavona* species, could be explained by their ability to grow and colonize disturbed habitats as observed in modern Indo-Pacific (Tomascik et al., 1997) and Caribbean reefs (Jackson and Hughes, 1985). In the Leitha Limestone (Austria), Middle Miocene coral assemblages dominated by a platy *Leptoseris* species developed as coral carpets with a rich associated bryozoan community that are comparable to the Stadion CC (Reuter et al., 2012). Even though both coral carpet communities have been interpreted to occur under similar high siliciclastic environments, species richness of the Stadion in the Indo-Pacific is much higher than the one of the impoverished carpets of the Leitha Limestone in the Paratethys.

Bryozoans.—Twenty-eight bryozoan species occurred within the Stadion coral environments and these new records increase our knowledge of this poorly studied group in fossil communities of the Indo-Pacific (Di Martino and Taylor, 2012). The undersides of platy corals supported a relatively rich encrusting bryozoan community. These surfaces represented potentially long-lived, cryptic habitats for the settlement of bryozoan larvae, offering a large surface area for the growth of encrusting bryozoans and adequate vertical space for erect colony growth. Despite their richness, the abundance of bryozoans is essentially due to a few common encrusting species, particularly *Steginoporella* sp. and *Reptadeonella* sp. nov. In the studied units, these two cheilostomes covered more substrate space than any other species. Furthermore, *Steginoporella* sp. often overgrows older colonies of the same species by frontal budding. Congeneric species encrusting the undersurfaces of foliaceous reef corals in Jamaica at the present-day show a similar tendency to monopolize the substrate (Jackson and Winston, 1982; Jackson, 1984). According to Jackson and Hughes (1985), Jamaican species of *Steginoporella* are usually extremely mobile, growing laterally at rates up to 11 cm per year. This growth rate is faster than in any other encrusting bryozoan. They form asymmetrical lobes or fans that sweep across the coral undersurface, and colonies survive an average of only about 120 days. In contrast, Jamaican species of *Reptadeonella* are relatively stationary, growing only 3-4 cm per year. They form fairly symmetrical colonies that are highly persistent, surviving for an average of about 500 days. These differences reflect the distribution of the two species on the undersides of platy corals, with *Steginoporella* more common than *Reptadeonella* in more disturbed microhabitats such as the edges of coral colonies. Although in the Stadion material it is impossible to distinguish with certainty between coral edges and inner zones due to the levels of colony fragmentation, the occurrences of *Steginoporella* sp. and *Reptadeonella* sp. nov. on different coral colony fragments may reflect the same pattern showed by congeneric Jamaican species (Jackson and Hughes, 1985).

Comparison with Coeval Regional Patch Reefs

Wilson (2005) described seven other Miocene delta-front patch reefs located in the Kutai Basin. She proposed that all seven patch reefs most likely developed under constant high siliciclastic input in turbid shallow waters with low-light penetration at about or less than 10 m depth during periods of lowstand to transgressive intervals that favored the transient confinement of terrestrial influx. Within this context, the local-scale paleoenvironmental reconstruction and fossil assemblages presented here have similar sequence development to other reefs described in the region, but also add new elements that help to better understand the dynamics of turbid-water coral communities during the Miocene. Here we limit comparisons between the Stadion and the Batu Putih and Dibelakan Parliament patch reefs described by Wilson (2005) and the Bontang patch reef described in Novak et al. (2013). The Batu Putih carbonates occur about 2.3 km below the Stadion CC in the Samarinda sequence, and the Dibelakan Parliament has been considered as a lateral extension of the youngest carbonates of Batu Putih patch reef (Marshall et al., this issue). The Bontang patch reef (Novak et al., 2013) is about 83 km to the north and Late Burdigalian in age.

As for most Miocene patch reefs in the region, it is inferred that coral development in the Stadion patch reef occurred during a transgressive interval, based on the transition from carbonaceous shale to coral-rich facies in the lower part of the section that clearly indicates a change from fluvial-deltaic into fully marine environments. Although disseminated carbon and some leaves (2-4%) were also observed at the base of the succession in Batu Putih and Dibelakan Parliament patch reefs (see Fig. 8 and Table 2 in Wilson, 2005), the development of the patch reef on top of a carbonaceous shale makes the Stadion coral assemblages unique from all previously described patch reefs of the region. Coral assemblages occurring immediately after carbonaceous deposition shows that a relatively minor change in depth could trigger coral development in the ancient Kutai Basin.

In terms of biota composition, mastophoroid coralline algae are dominant in the Stadion CC in contrast to the dim-light Melobesioidae assemblage observed in patch reefs described by Wilson (2005) and Novak et al. (2013). Coral assemblages follow a relatively similar succession, that in the case of the Batu Putih patch reef has been described as ‘ideal’ because it shows a change from sheet-platestones to mixstones and pillarstones (Wilson, 2005; Lokier et al., 2009). This succession is, however, partially developed in the Bontang patch reef that has a change of facies from sheetstone into platestone (Novak et al., 2013). In the coral platestone facies of the Stadion patch reef this succession of thin-platy to tabular, small massive and branching coral growth forms occurs as a ‘condensed succession’ within a very small thickness but without a sharp differentiation into distinct facies.

Common coral genera mentioned by Wilson (2005) are also present in the Bontang patch reef (Novak et al., 2013) and the Stadion patch reef, yet direct taxa comparisons can only be performed between the latter two. Although poritids (*Porites* and *Goniopora*) are abundant in the four settings, the Bontang patch reef hosts more common merulinid taxa (former Faviidae), while in the Stadion CC, acroporids (*Astreopora* spp.) and agariciids are more abundant.

Thus, a spectrum of three different types of biota assemblages within these turbid environments can be recognized: first, the Stadion patch reef with characteristic photophilic coralline algae and ‘condensed succession’ of coral development; second, Batu Putih and Dibelakan Parliament patch reefs with coralline algae tolerant of a broader range of turbid low-light habitats and an ‘ideal’ succession of reef development (Wilson, 2005); and third, the Bontang patch reef (Novak et al., 2013) also with coralline algae that can thrive in turbid low-light but an incomplete succession of corals restricted to sheet and platestones. Such differences in the composition of coralline algae and corals could be interpreted as a response of the biota to slightly different levels of light within the low-light levels range of these shallow turbid habitats, in which the Stadion patch reef developed in the upper limits of such low-light levels, the Batu Putih and Dibelakan Parliament patch reefs (Wilson, 2005) within the whole range of low-light levels allowing more habitat partitioning, and the Bontang patch reef (Novak et al., 2013) developed at the lower boundaries of low-light levels. According to Wilson (2005), turbid conditions on the delta-front would limit coral development to habitats less than 10 m deep, within or above the fair-weather wave base. The lithology and fossil assemblages found in the Stadion patch reef suggest that the Stadion patch reef also occupied this kind of habitat. In the case of the Bontang reef, mesophotic conditions resulted from both high terrigenous input and relatively deeper waters below the fair-weather wave base (Novak et al. 2013).

An alternative scenario that could explain the differences found among the three fossil assemblages in question could be associated to the relative position of the patch reefs within the delta system. In deltaic environments, turbidity and light penetration are largely controlled by the relative position of a site within the deltaic complex. In the modern Mahakam delta system, the maximum concentration of suspended particles is found in the mouth of the main delta lobes, while the minimum concentration is observed in the offshore region (Budhiman et al., 2012). Similarly, sands decrease in grain size in an offshore direction (see Fig. 8 in Storms et al., 2005). Superimposed on these onshore-offshore trends there is a north-south variation caused by the southward flow of the Indonesian Throughflow current that generally persists throughout the year (Murray and Arief, 1988) and favors a higher concentration of carbonates on the northern part of the shelf (Roberts and Sydow, 2003). Therefore, the Stadion patch reef might have developed north of an active delta lobe, whilst the Bontang (Novak et al., 2013) and the Batu Putih and Dibelakan Parliament patch reefs

(Wilson, 2005), could have been located closer to different active delta lobes. However, this hypothesis cannot be tested here, as larger temporal and spatial scale studies, including detailed multi-taxa and sedimentological analyses are required to untangle the effect of depth and sediment input on the light-levels and how are the biota responses in the past history of coral development of the Kutai basin.

Shallow Turbid Reefs and Coral Diversity

The reef-coral fauna recovered from the Stadion patch reef is one of the richest Miocene assemblages yet discovered and is a useful record of the transition from foraminifera- to coral-dominated carbonates that occurred during the Early Miocene in this region (Wilson and Rosen, 1998) and it is likely related to the initiation of the modern-day Indo-West Pacific biodiversity hotspot as recorded by diverse coral assemblages from the Late Oligocene in Malaysian Borneo (McMonagle et al., 2011). These Oligocene faunas, and the various patch-reefs that have been described from the Kutai basin all developed in turbid habitats yet contain significant diversity. This suggests that such habitats might have played a role in either increasing diversification during the Miocene or might have acted as refuges allowing taxa to escape extinction during intervals of accelerated regional or global environmental change in the Miocene. The potential role of turbid environments as sites of both accelerated speciation and as potential refugia demands further study, as turbid settings might act in similar ways as clear-water reefs are increasingly damaged by present-day anthropogenic environmental change (Hoegh-Guldberg, 2011; Rogers, 2013).

In the search for candidate refugia habitats, investigations have been focused on resilient marginal ecosystems, such as deep mesophotic habitats (Kahng et al., 2010; Bongaerts et al., 2010). Recent studies have shown that mesophotic habitats located in clear deep-waters could potentially escape from current impacts (pollution, storms, etc.), yet they only host about 25% of the species that are also present in shallow waters and thus could only provide recolonization for species with broad depth tolerances (Bongaerts et al., 2010). Shallow turbid habitats might be more promising candidates, despite receiving more direct anthropogenic impacts. For example, corals growing in turbid waters in Palau bleached less during the 2010 event than those in clearer, offshore waters, even though they experienced the highest temperatures (Van Woesik et al., 2012). In this context, our findings show that shallow-water turbid habitats hosted a high diversity in the past that could cope with ancient environmental changes. These fossil patch reefs that developed in turbid waters might be providing a glimpse into the future of reef systems as “typical” clear-water reefs continue to decline in most regions.

CONCLUSIONS

The carbonate bodies of the Stadion CC sections can be interpreted as a shallow-water patch reef, in which the main controls for coral development were depth and varying levels of water turbidity related to the amount, frequency and grain size of siliciclastic input. Evidence gathered in this study support a paleodepth interpretation for the Stadion patch reef within turbid waters at a maximum of 10 m depth. Different facies were most likely deposited following a proposed deepening sequence:

laminated siltstone ≤ carbonaceous shales < bioclastic packstones < coral platestone < foraminiferal packstone ≤ coral sheetstone ≤ clay shales.

Larger benthic foraminifera were present in all fossiliferous facies supporting their role as the most siliciclastic-tolerant group. Although the environmental conditions for coral development within the Samarinda sequence were ephemeral, the Stadion patch reef had a rich coral assemblage that could cope with changing terrigenous input. Yet their demise was due to increased siliciclastic input exceeding the tolerance of any coral species. Corals enhanced the overall diversity in these turbid settings by hosting bryozoans, coralline algae, mollusks, echinoderms and probably sponges.

Comparisons to coeval patch reefs in East Kalimantan show that platy corals are dominant in these environments with some taxa found in most sites but other taxa more unevenly distributed among habitats. Communities of larger benthic foraminifera tend to be similar among all patch reefs, but calcareous coralline algal assemblages vary significantly according to light availability with characteristic assemblages in lower and higher light habitats within the Samarinda turbid settings during the Miocene. Bryozoans are diverse and its presence in the studied fossil record is usually associated with thin platy coral assemblages. Mollusks are poorly preserved in platy-coral dominated settings. Large ecologically-sampled collections and multi-taxa analysis of fossil assemblages are important to the better understanding of paleoenvironmental conditions.

The high diversity of coral species highlights the importance of marginal turbid habitats as a reservoir of diversity during the origins of the Coral Triangle hotspot and might provide useful analogues to understand the future of reef systems as they become restricted to former "marginal" habitats.

ACKNOWLEDGMENTS

This research is part of the Throughflow Initial Training Network, funded by the Marie Curie Actions Plan, Seventh Framework Programme of the European Union (grant no. 237922). Fieldwork was possible thanks to the collaboration of J. Todd, L. Stevens, J. Young, A. Kusworo, U. Margono, A. S. Erawatna, and safety access to the road-cut outcrops provided by staff of the KTC Group. B. Rosen is greatly acknowledged for his help on coral identifications and fruitful discussions regarding ancient coral environments and interpretations. P. D. Taylor, F. Wesselingh, and A. Holborn assisted with the taxonomic identification of bryozoans, mollusks, and foraminifera, respectively. A. F. Budd and C. Wallace are thanked for their advice on coral identifications of Merulinidae and *Acropora*, respectively. J. Darrell and L. Douglas assisted with the curation of specimens at the NHM, and we gratefully acknowledge the enthusiastic support of A. Thomas and the NHM "V-Factor" volunteers for exhaustive sample processing. This study was conducted under research license 0266/SIP/FRP/XI/2010 issued by RISTEK (Kementerian Riset Dan Teknologi Republik Indonesia) with special thanks '*terima kasih*' to Professor F. Hasibuan of the Indonesian Geological Agency - Center for Geology Survey, for his support to this work. C. Perrin and one anonymous reviewer are acknowledged for their constructive suggestions that helped in improving this manuscript.

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FIGURES CAPTIONS

FIGURE 1—Location of the Stadion patch reef in A) East Kalimantan, Indonesia, nearby B) Samarinda city. The Stadion coral carbonates (Stadion CC) were studied in two sections C) Stadion CC-1 and D) Stadion CC- 2.

FIGURE 2—A) The Samarinda sequence exposes the Miocene progradation of the Mahakam Delta System. B) Log correlation of measured sections from the Stadion coral carbonates.

FIGURE 3—Interpretation of the Stadion coral carbonates sections, including lithological units (U1 to U7) and facies, laminated siltstone = LZ, carbonaceous shales = CaS, bioclastic sandstone = BSa, coral platestone = CPl, foraminiferal packstone = FPa, coral sheetstone = CSh, clay shales = ClS. Red contours indicate line transects (T1 to T9).

FIGURE 4—Facies: A) Laminated siltstone. B) Carbonaceous shale. C-D) Bioclastic sandstone and D) micrograph of thin section showing well sorted fine-sand and larger benthic foraminifera. E-F) Coral platestone, E) large tabular colony of *Progyrosmilia* sp. and F) micrograph of thin section showing *Nephrolepidina ferreroi*. G-H) Foraminiferal packstone H) micrograph of thin section showing *Nephrolepidina* and *Amphistegina*. I-J) Coral sheetstone showing multiple stacks of thin platy coral colonies and J) detail of larger benthic foraminifera encrusting on coral surface of a *Pavona* sp. Common larger benthic foraminifera include *Nephrolepidina* = Ne,*Amphistegina* = Am, and *Lepidosemicyclina bifida*= Lb

FIGURE 5—Facies of the Stadion patch reef, including percentages of the main substrate components and fossil groups. Biotic distribution and abundance of corals, foraminifers, coralline algae, bryozoans, and mollusks are illustrated, including the

main growth forms, taxa or feeding strategy, accordingly. Asterisks (*) indicate the occurrence of the fossil group but preservation issues hampered the estimation of its abundance within the facies. Percentages of calcium carbonate ($CaCO_3$) in the marine facies are shown in the last column.

FIGURE 6—Representative corals from the Stadion patch reef. A-B) *Porites* sp.1 NHMUK AZ6718 from the coral sheetstone facies. A) Fragment of a platy colony of *Porites* sp. 1 and B) Detail of corallites. C-H) some corals from the coral platestone facies: C) *Progyrosmilia* sp. NHMUK AZ6575. D) *Symphyllia recta*, NHMUK AZ7214. E) *Porites* sp. 3, NHMUK AZ7238. F) *Galaxea* sp. NHMUK AZ6477. G) *Heliopora* sp. NHMUK AZ7230. H) *Acropora* sp. *elegans* group, NHMUK AZ7302. I-O) some corals from the coral sheetstone facies: I) *Goniopora planulata*, NHMUK AZ6606. J) *Leptoseris* sp. AZ7329. K) *Pachyseris* sp. 4, NHMUK AZ6722. L) *Pavona* cf. *varians*, NHMUK AZ7351. M) *Cyphastrea* sp., NHMUK AZ6979. N) *Psammocora* sp., NHMUK AZ7159. O) *Coscinaraea* sp. NHMUK AZ6833.

FIGURE 7—Non-metric multidimensional scaling analysis of A) Coral assemblages. B) Larger benthic foraminiferal assemblages. Open symbols correspond to Stadion CC-1 and filled symbols to Stadion CC-2.

FIGURE 8—Representative foraminifera from the Stadion patch reef. Common foraminifers from the coarse fraction (>0.5 mm) include A) *Nephrolepidina martini*, B) *Cycloclypeus annulatus*, and C) *Lepidosemicyclina bifida*. Foraminifers from the fine fraction (>125 um-0.5 mm) include D) *Amphistegina* sp., E) *Operculina* sp., F) miliolid, G) *Elphidium* sp., and H) *Cibicidoides* sp.

FIGURE 9—Representative crustose coralline algae of the Stadion patch reef. A) *Neogoniolithon* sp. AR274-3. B) *Neogoniolithon fosliei*, AR262-1. C) *Spongites* sp., AR267-1. D) *Lithoporella* sp. AR263D-1.

FIGURE 10—Representative bryozoans from the Stadion patch reef. A) *Cranosina rubeni*. B) *Steginoporella* sp. C) *Reptadeonella* sp. nov. D) *Antropora* cf. *subvespertilio*.

FIGURE 11—Interpretation of depositional environments of the Stadion patch reef.

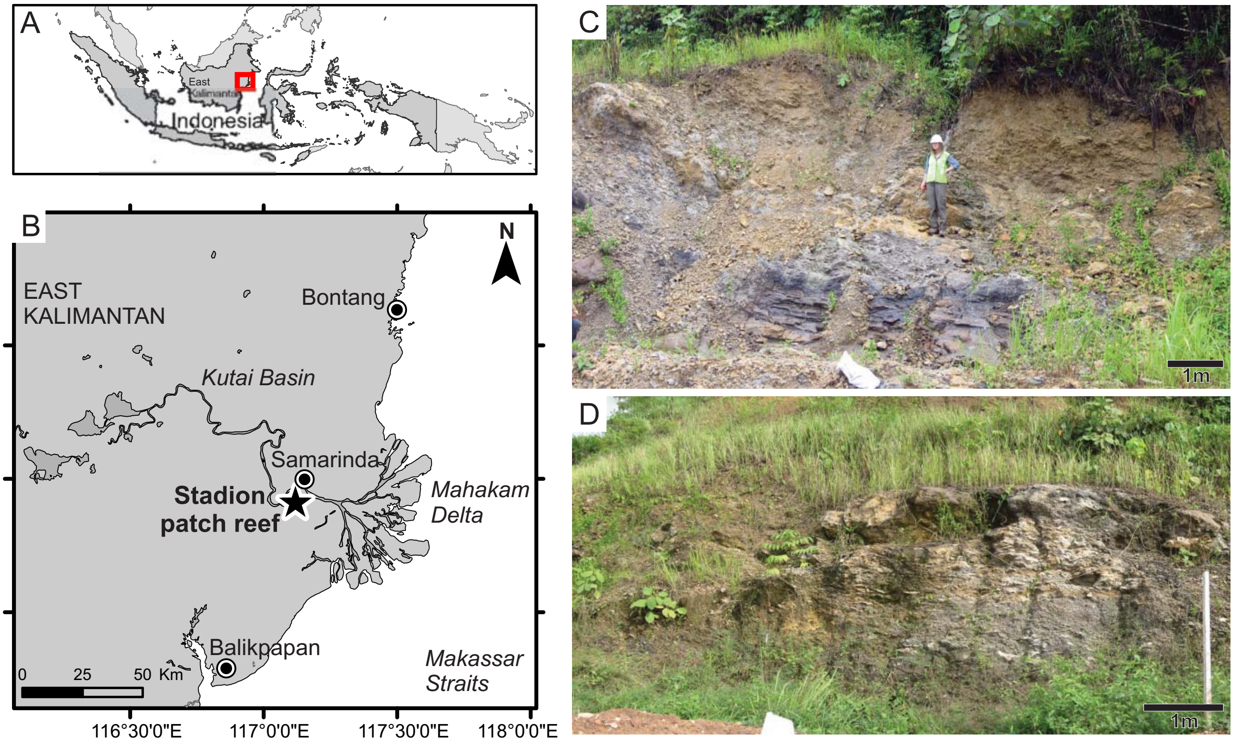
TABLES CAPTIONS

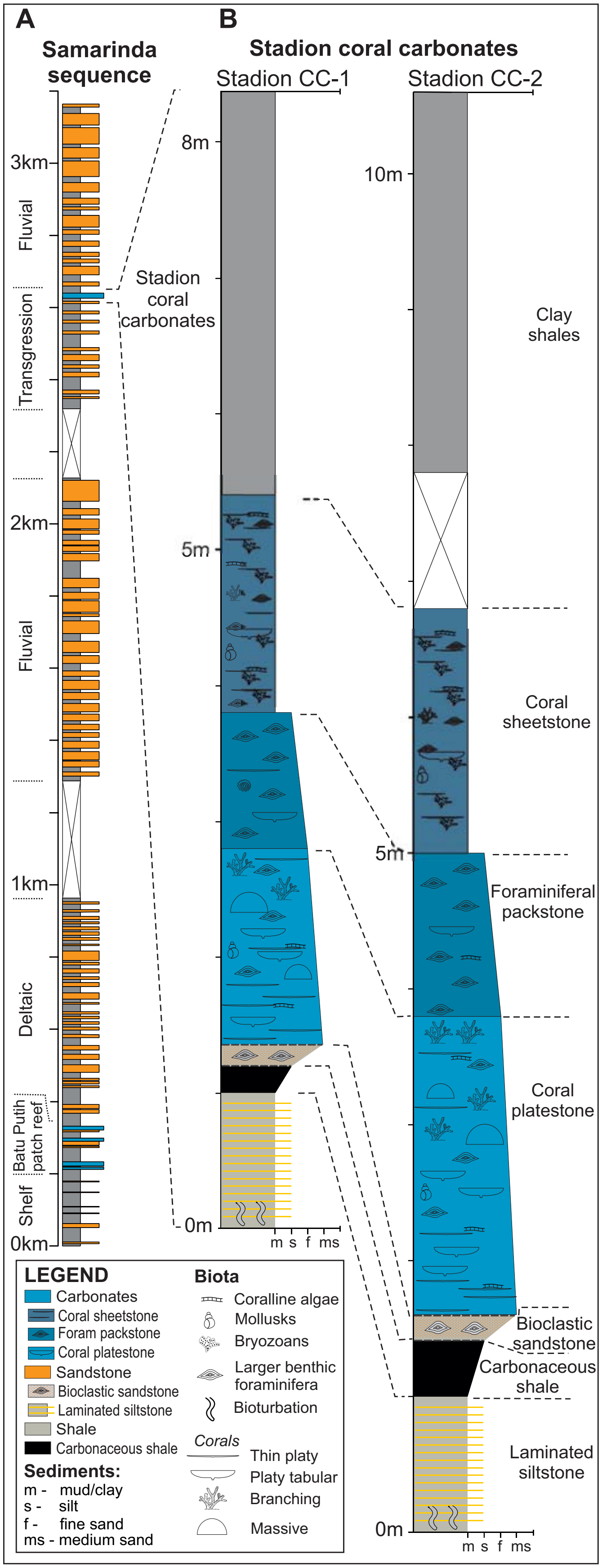
TABLE 1—Principal characteristics of the Stadion coral carbonates, including facies types, lithologies and main fossil groups.

TABLE 2—Percentage contribution by the top 24 coral species to the Bray-Curtis similarity (SIMPER analysis) in species biomass (weight in grams) at the coral platestone = CPl and coral sheetstone = CSh facies in the Stadion patch reef.

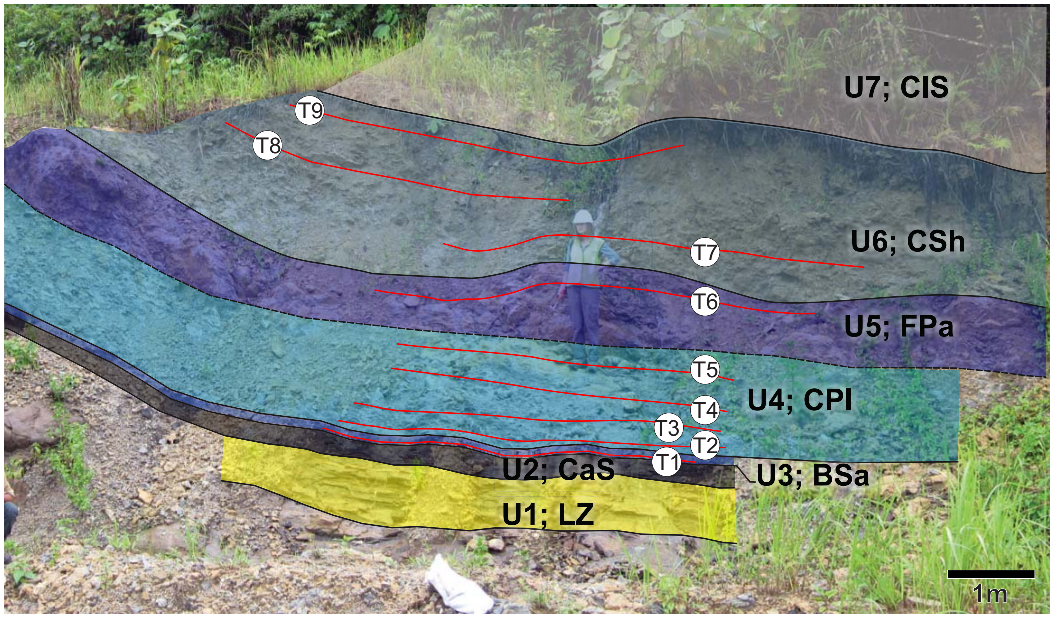
ELECTRONIC SUPPLEMENTARY MATERIAL

APPENDICES—List of taxa and percentages of abundance of each fossil group: A) Corals. B) Larger benthic foraminifera in the fraction > 500 μm. C) Foraminifera from the fraction >125 – 500 μm. D) Crustose coralline algae. E) Bryozoans. F) Mollusks.

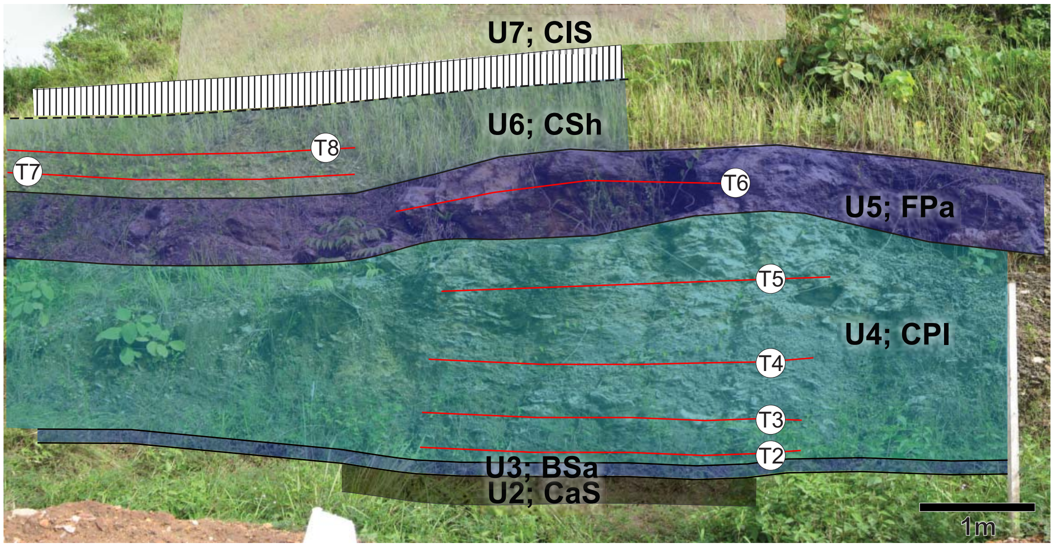

A
East
Kalimantan
Indonesia
B
N
EAST
KALIMANTAN
Bontang
Kutai Basin
Samarinda
Stadion
patch reef
Mahakam
Delta
Balikpapan
Makassar
Straits
0 25 50 Km
0°0'0"
0°30'0"S
1°0'0"S
116°30'0"E
117°0'0"E
117°30'0"E
118°0'0"E
C
1m
D
1m

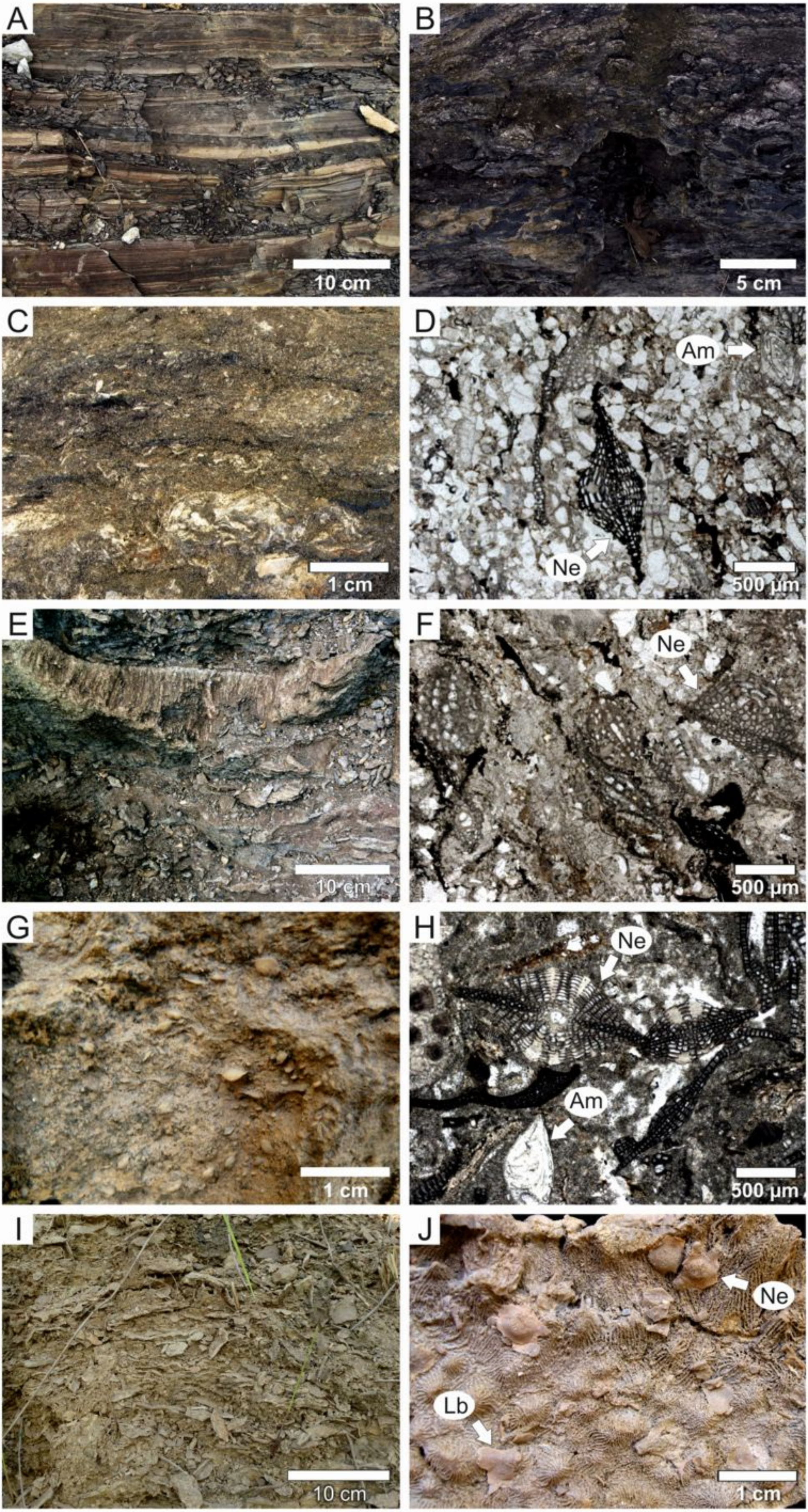

A
Samarinda sequence
3km
2km
1km
0km
Fluvial
Transgression
Fluvial
Deltaic
Batu Putih patch reef
Shelf
Stadion coral carbonates
B
Stadion coral carbonates
Stadion CC-1
Stadion CC-2
8m
5m
0m
m s f ms
10m
5m
0m
m s f ms
Clay shales
Coral sheetstone
Foraminiferal packstone
Coral platestone
Bioclastic sandstone
Carbonaceous shale
Laminated siltstone
LEGEND
Carbonates
Coral sheetstone
Foram packstone
Coral platestone
Sandstone
Bioclastic sandstone
Laminated siltstone
Shale
Carbonaceous shale
Sediments:
m - mud/clay
s - silt
f - fine sand
ms - medium sand
Biota
Coralline algae
Mollusks
Bryozoans
Larger benthic foraminifera
Bioturbation
Corals
Thin platy
Platy tabular
Branching
Massive

A Stadion coral carbonates 1



B Stadion coral carbonates 2




A
10 cm
B
5 cm
C
1 cm
D
Am
Ne
500 µm
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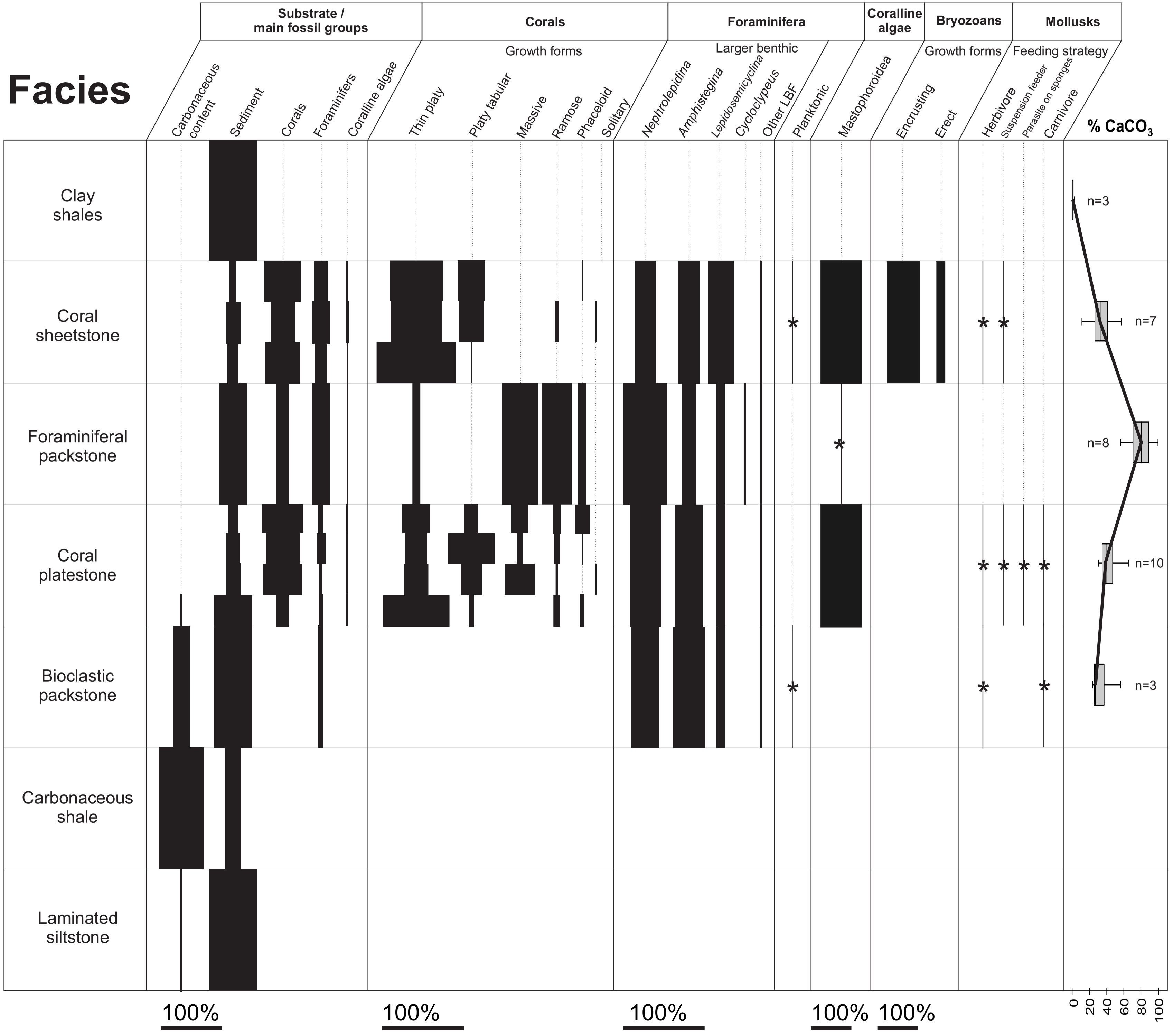
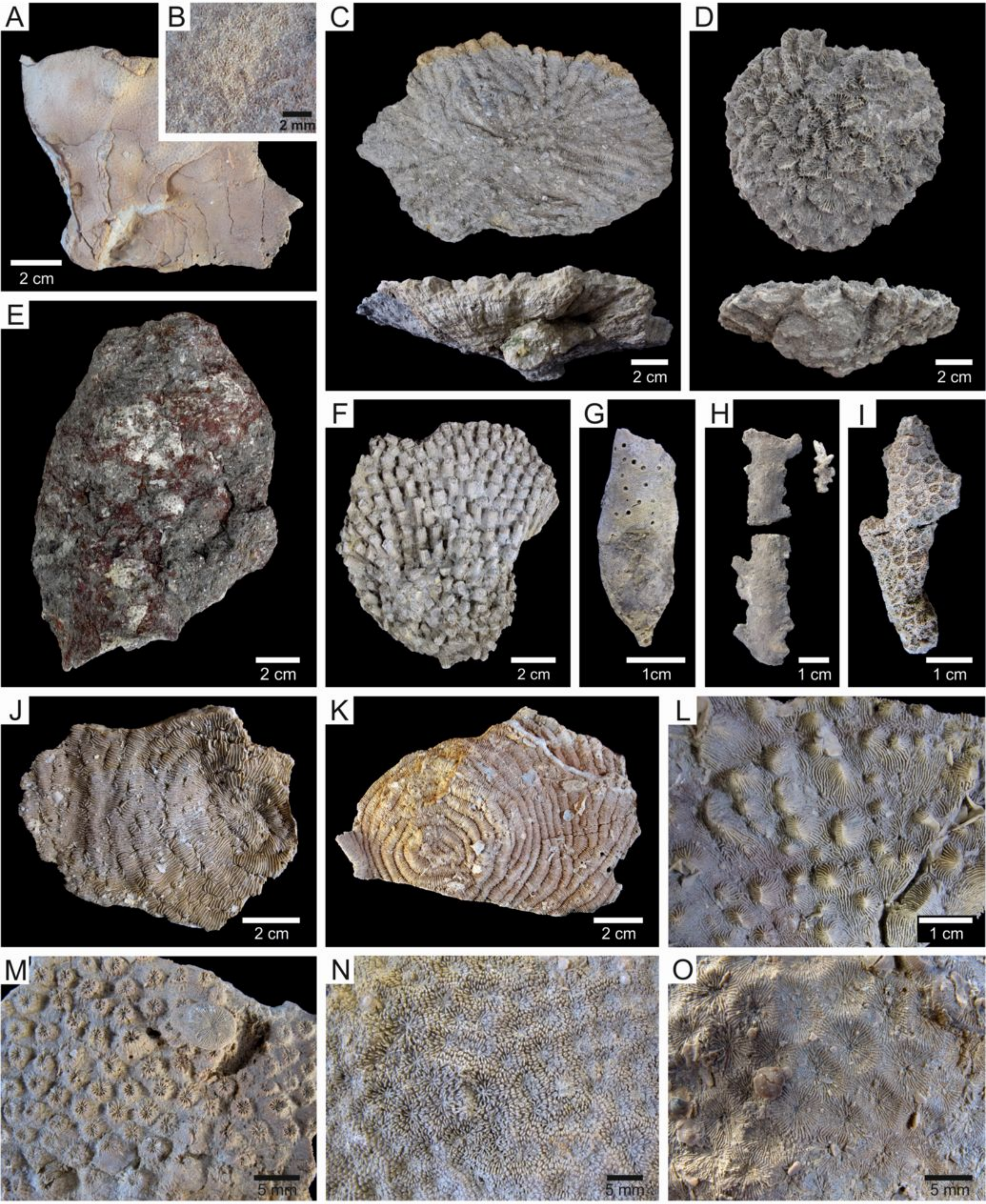
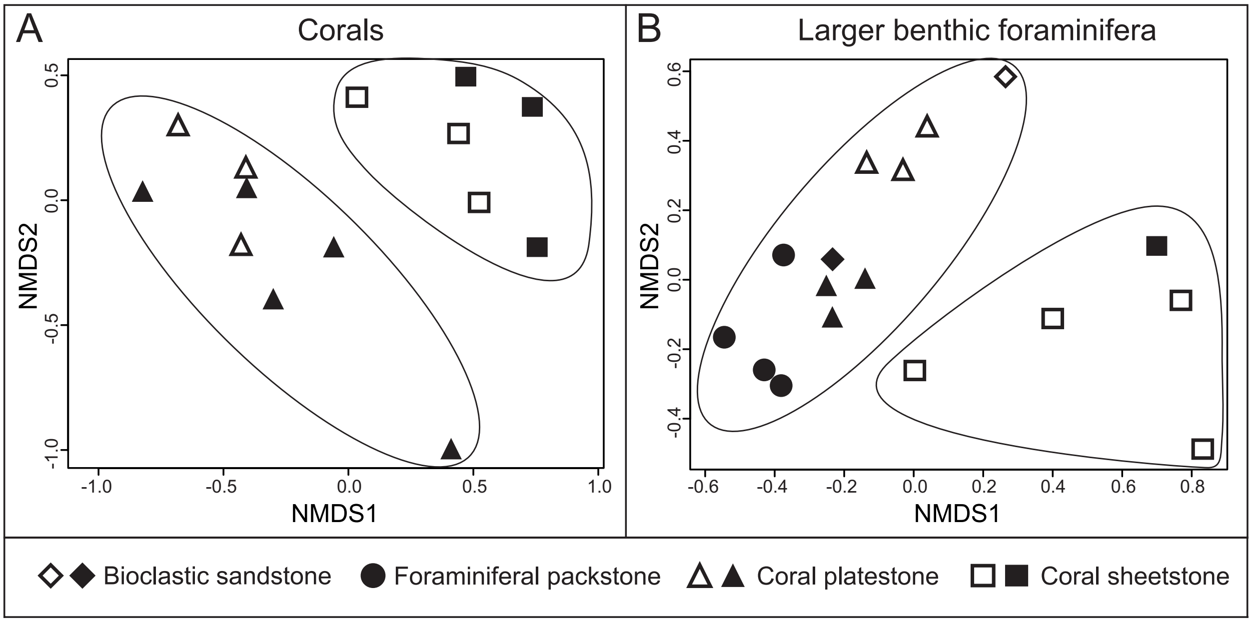
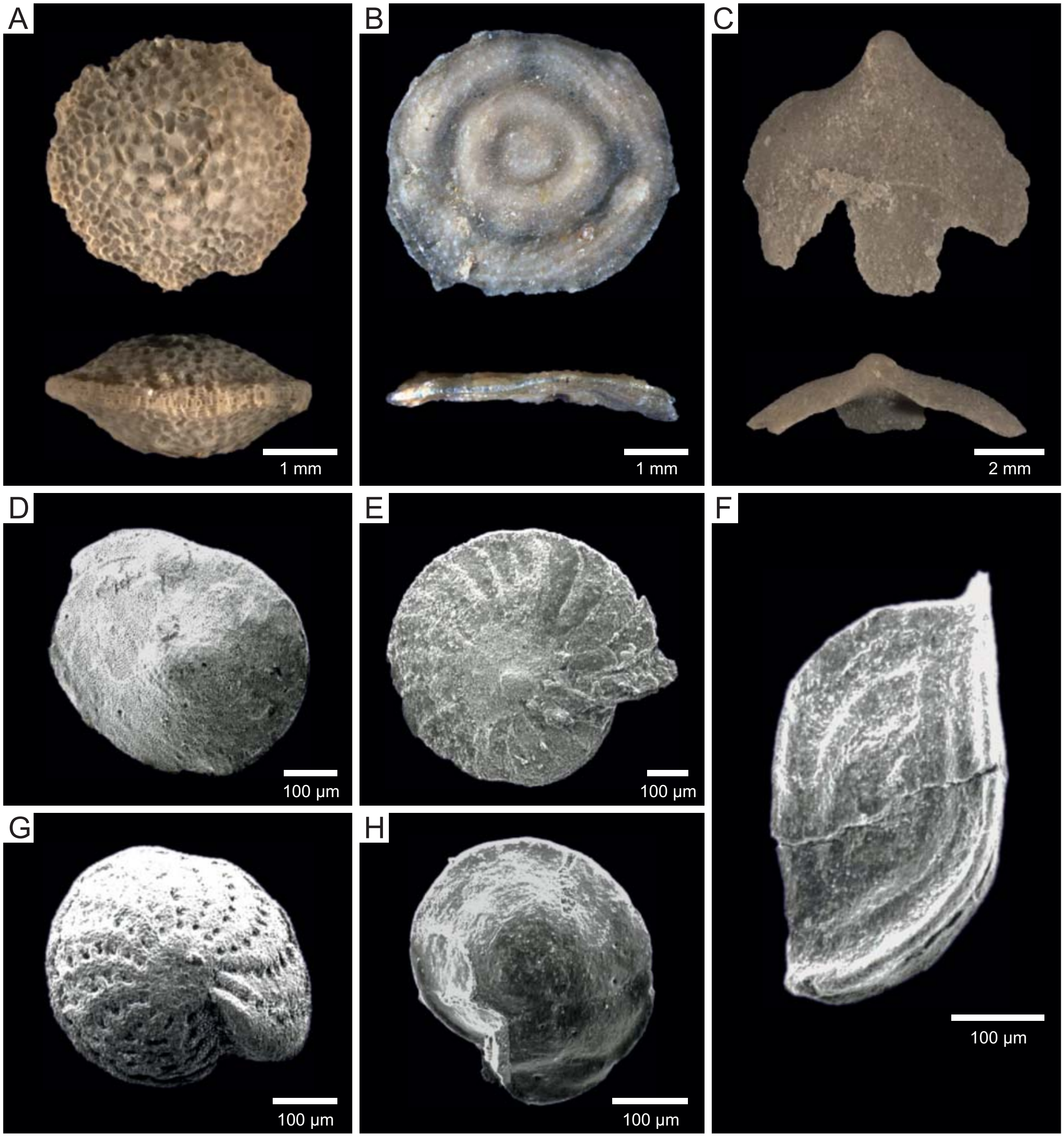
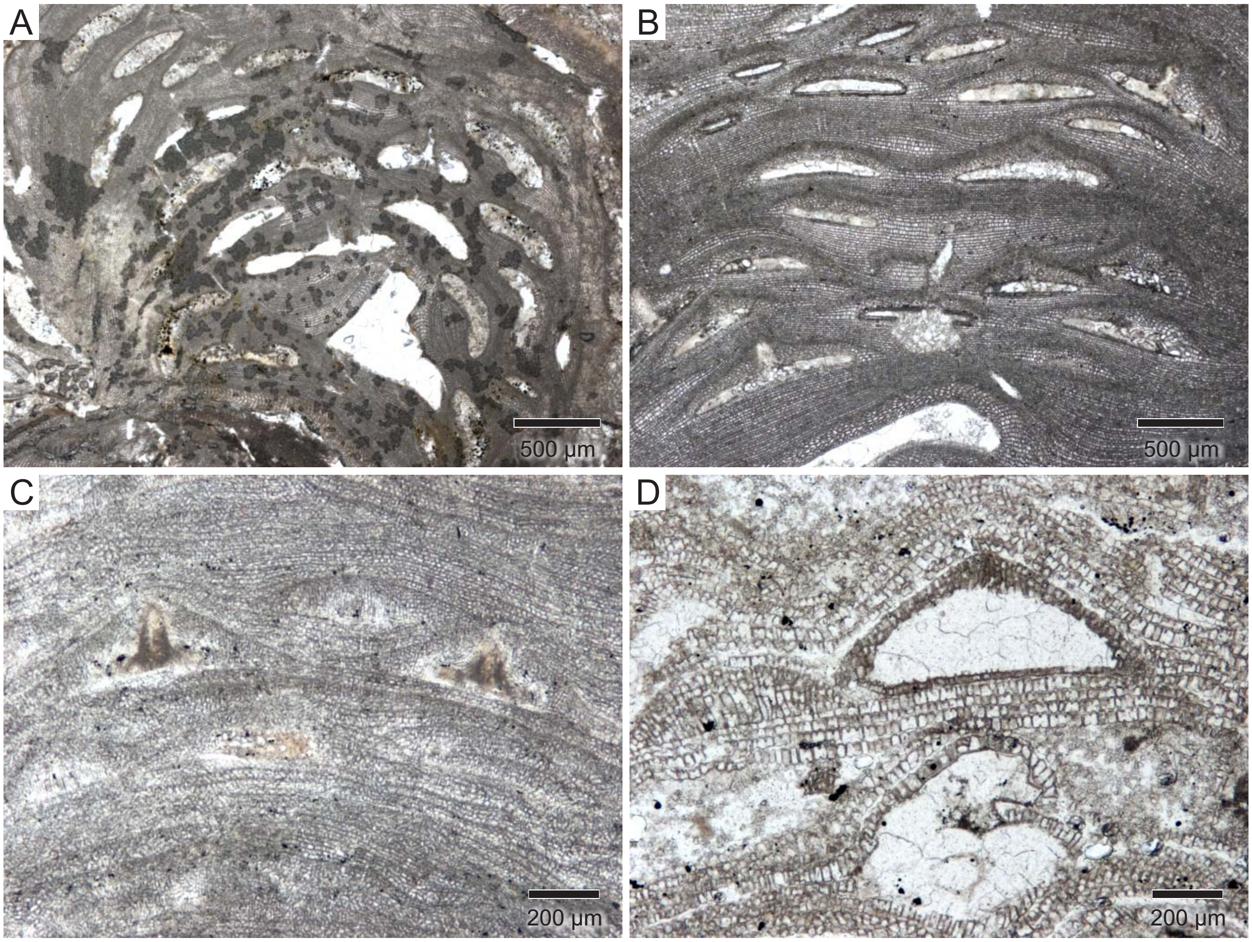
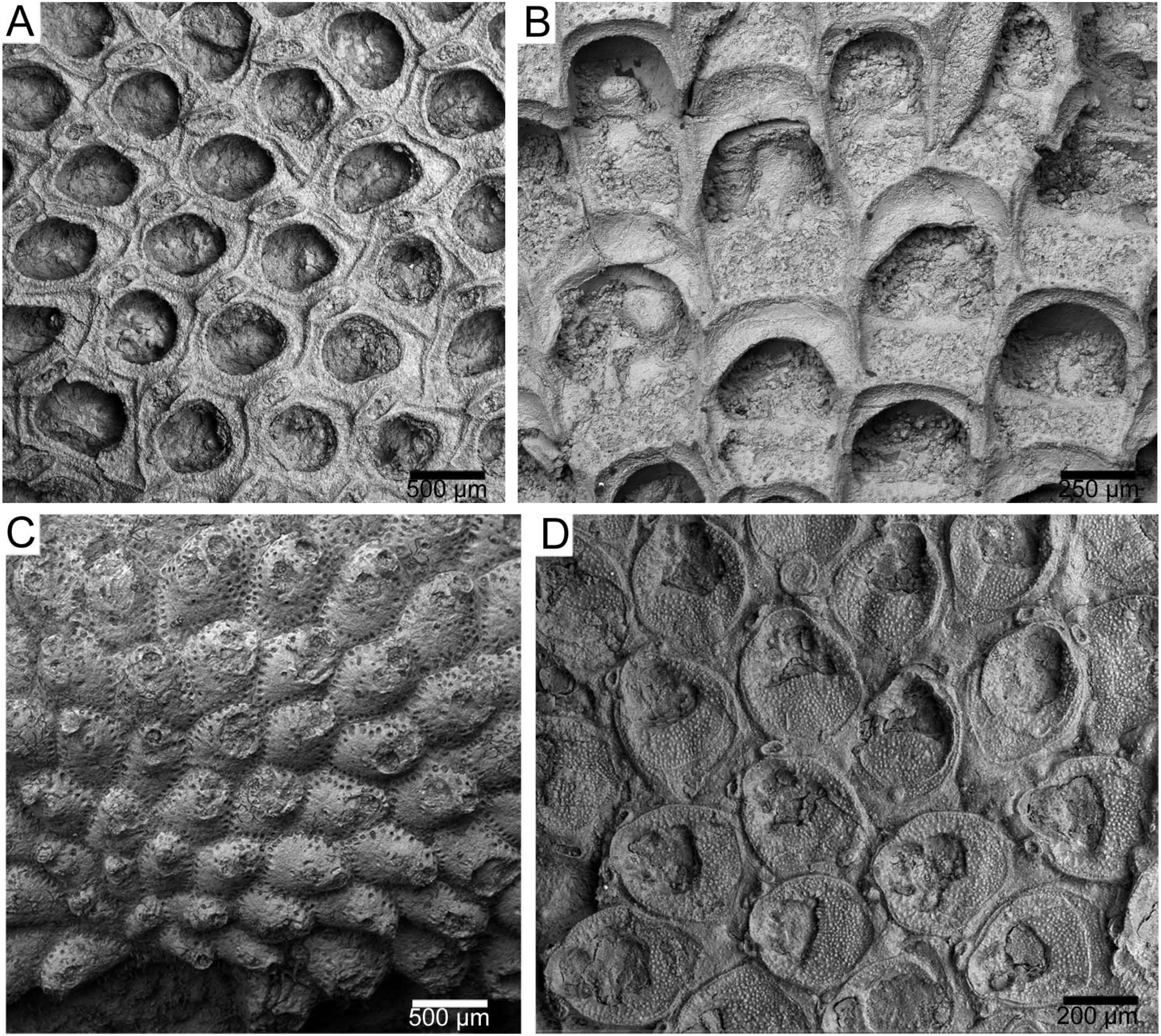

Facies
Substrate / main fossil groups
Corals
Foraminifera
Coralline algae
Bryozoans
Mollusks
Growth forms
Larger benthic
Growth forms
Feeding strategy
Carbonaceous content
Sediment
Corals
Foraminifers
Coralline algae
Thin platy
Platy tabular
Massive
Ramose
Phaceloid
Solitary
Nephrolepidina
Amphistegina
Lepidosemicyclina
Cycloclypeus
Other LBF
Planktonic
Mastophoroidea
Encrusting
Erect
Herbivore
Suspension feeder
Parasite on sponges
Carnivore
% CaCO$_3$
Clay shales
Coral sheetstone
Foraminiferal packstone
Coral platestone
Bioclastic packstone
Carbonaceous shale
Laminated siltstone
n=3
n=7
n=8
n=10
n=3
100%
100%
100%
100%
100%
0
20
40
60
80
100


A
B
2 mm
2 cm
C
2 cm
D
2 cm
E
2 cm
F
2 cm
G
1cm
H
1 cm
I
1 cm
J
2 cm
K
2 cm
L
1 cm
M
5 mm
N
5 mm
O
5 mm


A
Corals
B
Larger benthic foraminifera
NMDS1
NMDS2
-1.0
-0.5
0.0
0.5
1.0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
◇◆ Bioclastic sandstone
● Foraminiferal packstone
△▲ Coral platestone
□■ Coral sheetstone


A
1 mm
B
1 mm
C
2 mm
D
100 µm
E
100 µm
F
100 µm
G
100 µm
H
100 µm


A
500 µm
B
500 µm
C
200 µm
D
200 µm


A
500 µm
B
250 µm
C
500 µm
D
200 µm

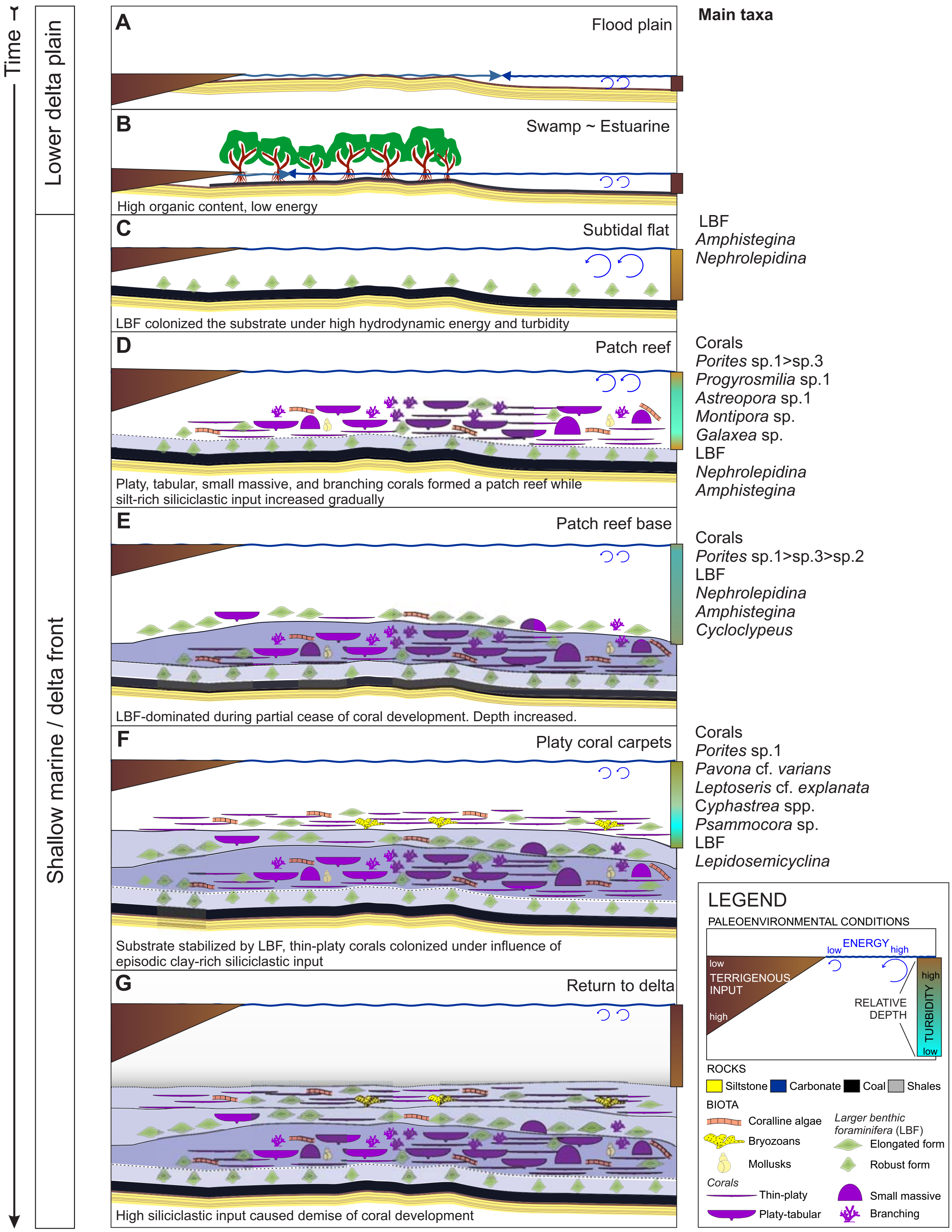

Time
Lower delta plain
Shallow marine / delta front
A
Flood plain
B
Swamp ~ Estuarine
High organic content, low energy
C
Subtidal flat
LBF colonized the substrate under high hydrodynamic energy and turbidity
D
Patch reef
Platy, tabular, small massive, and branching corals formed a patch reef while silt-rich siliciclastic input increased gradually
E
Patch reef base
LBF-dominated during partial cease of coral development. Depth increased.
F
Platy coral carpets
Substrate stabilized by LBF, thin-platy corals colonized under influence of episodic clay-rich siliciclastic input
G
Return to delta
High siliciclastic input caused demise of coral development
Main taxa
LBF
Amphistegina
Nephrolepidina
Corals
Porites sp.1>sp.3
Progyrosmilia sp.1
Astreopora sp.1
Montipora sp.
Galaxea sp.
LBF
Nephrolepidina
Amphistegina
Corals
Porites sp.1>sp.3>sp.2
LBF
Nephrolepidina
Amphistegina
Cycloclypeus
Corals
Porites sp.1
Pavona cf. varians
Leptoseris cf. explanata
Cyphastrea spp.
Psammocora sp.
LBF
Lepidosemicyclina
LEGEND
PALEOENVIRONMENTAL CONDITIONS
low ENERGY high
low
TERRIGENOUS INPUT
high
RELATIVE DEPTH
high
TURBIDITY
low
ROCKS
Siltstone
Carbonate
Coal
Shales
BIOTA
Coralline algae
Bryozoans
Mollusks
Corals
Thin-platy
Platy-tabular
Larger benthic foraminifera (LBF)
Elongated form
Robust form
Small massive
Branching

TABLE 1—Principal characteristics of the Stadion coral carbonates, including facies types, lithologies and main fossil groups.

Unit	Facies type	Lithology	Foraminifers	Corals	Coralline algae	Bryozoans	Mollusks
7	ClS	Fossil barren clay-shales	Absent	Absent	Absent	Absent	Absent
6	CSh	Coral sheetstone within a clay-rich matrix	Dominance of elongated forms of *Lepidosemicyclina bifida* (37%), followed by *Amphistegina* (30%) and *Nephrolepidina* (29%). *Operculina*, *Cibicidoides*, and *Elphidium* common in finer fraction; Planktonic foraminifera increase from base to top (<1 to 11%)	Main carbonate-forming group. Highly diverse, 56 species, and well-preserved specimens. Mainly thin-platy corals of *Porites* sp. 1 (41%), and the agariciids *Leptoseris* spp. (17%). Most colonies are 1 to 5 mm thick; n=3042	Very abundant crusts, mainly *Neogoniolithon* spp. (80%) and other mastophoroids, encrusting corals, some protuberant, and some forming foralgaliths; n=25	Fifty-five species. Mostly encrusting (78%) the under surfaces of platy corals as large colonies, up to 10 cm width; *Steginoporella* sp.1 (21%) is the most common species. Among the erect forms (21%), with *Vincularia* spp. (8%) as the most common species; n=925	Two fragments of oysters and one gastropod *Angaria* sp. Poorly preserved specimens; n=3
5	FPa	Foraminifera packstone	Main carbonate-forming group. *Nephrolepidina* (63%) dominate. Subordinate *Amphistegina* (19%) and *Lepidosemicyclina* (12%). *Cycloclypeus* present, but in low abundances (3.5%); Planktonic foraminifera absent	Low abundance, very recrystallized, and low species richness, mainly represented by the genus *Porites* in massive (44%), ramose (30.5%) and platy (10%) forms; n=16	Low abundance, very recrystallized, hard to identify, some *Lithophyllum pseudoamphiroa*; n=4	Absent	Absent
4	CPl	Coral platestone	High diversity. Dominance of *Nephrolepidina* (45%) and *Amphistegina* (39%). Some *Lepidosemicyclina* (13%); No planktonic foraminifera	Main carbonate-forming group. Forty-eight species in 43 genera. Thin-platy forms decreased from the base (82%) to the top (27%); in the middle part, platy-tabular *Porites* sp.1 (24%) and *Progyrosmilia* sp. 2 (23%), and small massive *Porites* sp. 3 (33%) dominate. At the top, phaceloid *Galaxea* spp. (15%) and ramose *Porites* sp. 2 (10%) become more abundant; n= 1471	*Neogoniolithon sp.*, *Hydrolithon sp.* and thick crusts of *Spongites* encrusting corals, partly with forams; n=6	Absent	Eighteen taxa, including 14 genera. Mostly herbivore gastropods (52%), followed by suspension feeders (28%). Poorly preserved specimens, yet identifiable; n=79
3	BSa	Bioclastic packstone	Low diversity. Smaller and robust forms of *Amphistegina* (47%) and *Nephrolepidina* (39%) dominate. A few *Lepidosemicyclina* (12%); Planktonic foraminifera present (2%)	Absent	Absent	Absent	Gastropods, including ?*Calliostoma* sp. Poorly preserved; n=4
2	CaS	Carbonaceous shale	Absent	Absent	Absent	Absent	Absent
1	LZ	Laminated siltstone interbedded with mudstone	Absent	Absent	Absent	Absent	Absent

TABLE 2— Percentage contribution by the top 24 coral species to the Bray-Curtis similarity (SIMPER analysis) in species biomass (weight in grams) at the coral platestone = CPl and coral sheetstone = CSh facies in the Stadion patch reef.

	Coral species	Contrib	SD	Ratio	av. F4, CPl	av. F6, CSh	Cumulative
1	*Porites* sp.1	0.183	0.132	1.390	728.9	2679.9	0.214
2	*Progyrosmilia* sp.2	0.066	0.103	0.639	448.9	247.8	0.291
3	*Leptoseris* cf. *explanata*	0.063	0.101	0.621	6.6	649.7	0.364
4	*Porites* sp.3	0.056	0.099	0.569	545.5	-	0.431
5	*Cyphastrea* cf. *divaricata*	0.046	0.057	0.805	-	442.6	0.485
6	*Pavona* cf. *varians*	0.042	0.053	0.797	-	743.9	0.534
7	*Leptoseris* sp.7	0.035	0.049	0.710	328.3	-	0.575
8	*Psammocora* sp.1	0.033	0.046	0.714	-	366.4	0.614
9	*Pachyseris* sp.4	0.030	0.031	0.973	33.3	429.1	0.649
10	*Astreopora* sp.1	0.021	0.060	0.355	340.3	-	0.674
11	*Astreopora* sp.2	0.021	0.021	0.994	245.2	155.9	0.698
12	*Goniopora planulata*	0.021	0.035	0.596	1.1	288.2	0.723
13	*Montipora* cf. *venosa*	0.021	0.032	0.655	252.1	12.4	0.748
14	*Galaxea* sp.1	0.020	0.035	0.555	215.2	3.9	0.770
15	*Merulina* sp.1	0.018	0.042	0.437	-	304.8	0.792
16	*Progyrosmilia vacua*	0.017	0.030	0.547	-	303.3	0.811
17	*Fungophyllia* sp.1	0.013	0.021	0.629	37.1	88.4	0.827
18	*Cyphastrea* cf. *imbricata*	0.013	0.031	0.430	-	143.7	0.843
19	*Symphyllia* sp.1	0.010	0.014	0.717	103.2	33.7	0.855
20	*Porites* sp.2	0.010	0.012	0.825	61.6	111.6	0.866
21	*Coscinaraea* sp.1	0.009	0.020	0.473	4.4	185.6	0.877
22	*Alveopora* sp.1	0.009	0.013	0.694	100.2	1.1	0.887
23	*Stylophora* sp.1	0.009	0.017	0.502	59.6	53.7	0.897
24	*Goniopora* sp.2	0.008	0.019	0.402	64.2	26.2	0.906