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# Environmental reconstruction of a late Burdigalian (Miocene) patch reef in deltaic deposits (East Kalimantan, Indonesia)

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## ABSTRACT

Most studies of Cenozoic shallow-water, mixed carbonate–siliciclastic depositional systems have focused on their sedimentology. To date, however, comprehensive analyses of biotas and biofacies of Indo-West Pacific reefs that developed in mixed carbonate–siliciclastic systems are lacking. This study describes the palaeoenvironment and biodiversity of a late Burdigalian patch reef that developed in a mixed carbonate–siliciclastic depositional system. The studied exposure is located at the northeast margin of the Kutai Basin near Bontang (Indonesia), and is approximately 80 m wide and 25 m thick. Multi-taxon analysis of the most abundant fossil groups, including larger benthic foraminifera, corals, coralline algae, and bryozoans, aims to provide a model for environmental interpretation that will allow comparison with similar deposits of Indo-West Pacific region. Based on fossil content and lithology, five different facies types have been distinguished: foraminiferal packstone (FP), bioclastic packstone with foralgal communities (BP), thin-platy coral sheetstone (CS), platy-tabular coral platestone (CP), and shales (S). Among larger benthic foraminifera, smaller and more robust forms dominate in the FP and BP facies, while larger and flatter forms are the most abundant in the CS and CP facies. Thin-platy corals are dominant in the CS facies and gradually change into thicker platy-tabular forms in the CP facies. Assemblages and growth forms of coralline algae show no major differences between the facies types and are dominated by melobesioids and *Sporolithon*. The majority of bryozoan species are encrusting and were found only in the CS facies. Light-dependent organisms occurring in the reef indicate low light conditions typical for mesophotic reefs. The relatively small size of this reef complex and quite distinct vertical changes in the facies types, combined with the high siliciclastic content in most of the units, points to strong terrigenous input affecting water transparency as the main factor controlling the reef growth.

## 1. Introduction

The Miocene was an important interval for the origin of exceptional shallow marine diversity in Southeast Asia (Williams and Reid, 2004; Williams, 2007; Renema et al., 2008). Miocene reef development was globally widespread, characterised by a notable increase in coral reefs during the early Miocene that reached an acme in the Middle Miocene (Perrin, 2002). This trend is largely based on the records from Europe, while Caribbean reef development was low and restricted during the Miocene (Johnson et al., 2008). Southeast Asian reef development, however, is less well-documented, even though it is likely to have been the most diverse region for corals from the Neogene to the Recent (Wilson and Rosen, 1998). Documenting palaeoenvironments of Southeast Asian reefs during the Miocene could help to understand the observed differences in the history of reefs and other shallow marine ecosystems between European and Indo-West Pacific regions.

Mixed carbonate–siliciclastic depositional systems are no longer thought to be an exceptional phenomenon in shallow-water habitats and many coral reefs in Southeast Asia during the Miocene thrived in such turbid environments (Wilson and Lokier, 2002; Sanders and Baron-Szabo, 2005; Wilson, 2005; Lokier et al., 2009; Wilson, 2012). The development of isolated patch reefs within siliciclastic sediments epitomises the Miocene carbonate deposits of East Kalimantan (Indonesia) where shallow-water reefal carbonates were deposited in turbid waters. These reefs developed in mesophotic conditions (Kahng et al., 2010; Morsilli et al., 2011) and contain a diverse marine biota, including corals, larger benthic foraminifera, calcareous algae, echinoderms, and bryozoans (Wilson, 2005; Lokier et al., 2009). Depositional mechanisms and the influence of terrigenous sediments on the organisms living in these environments have been described in previous sedimentological studies (Allen and Chambers, 1998;

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Wilson and Lokier, 2002; Lokier et al., 2009; Morsilli et al., 2011; Wilson, 2012). However, palaeoecological information can also be extracted from the biotic assemblages preserved in such a mesophotic reefs. To date a comprehensive analyses of the biota and biofacies of mixed carbonate–siliciclastic system reefs in Indo-West Pacific region are lacking.

This study describes the palaeoenvironment and biodiversity of a late Burdigalian shallow-water carbonate patch reef that developed in a mixed carbonate–siliciclastic depositional system, based on a multi-taxon analysis of the most abundant fossil groups, including larger benthic foraminifera, corals, coralline algae, and bryozoans. Larger benthic foraminifera and coralline algae are known to be excellent palaeoenvironmental indicators (Hallock and Glenn, 1986; Hottinger, 1997; Braga and Aguirre, 2001; Renema and Troelstra, 2001; Braga and Aguirre, 2004; Renema, 2006a,b; Bassi and Nebelsick, 2010; Braga et al., 2010). The distribution of both groups is primarily controlled by light and substrate conditions, but nutrient input and sedimentation rate may also play important roles. In addition, larger benthic foraminiferal biostratigraphy can establish a timeframe for reef formation, allowing further comparisons with the better-known coeval reefs of other regions (i.e., Jackson and Johnson, 2000; Schuster, 2002; Johnson et al., 2008; Brandano et al., 2010; Morsilli et al., 2011). Corals are the main frame builders in these reefs, determining their three-dimensional structures and their distribution is controlled by light intensity and wave exposure (Rosen, 1975; Geister, 1977; Chapell, 1980). Bryozoans have been poorly documented from both fossil and extant Indo-West Pacific reefs, but they are likely to add information about palaeobathymetry and Miocene reef biodiversity.

The aims of this study are (1) to assess the depositional environment within the prodeltaic setting in a late Burdigalian Indo-West Pacific reef, (2) to describe the biotic assemblages (larger benthic foraminifera, corals, coralline algae, and bryozoans) of the patch reef, and (3) to place these data in the context of modern coral reefs growing under the influence of terrestrial input.

## 2. Geological setting

The research area is situated in the Kutai Basin, the largest siliciclastic dominated sedimentary basin in Borneo. Rifting of the Makassar Straits during the Middle Eocene initiated basin development (Wilson and Moss, 1999). This was followed by high rates of Neogene uplift and erosion of the Borneo landmass, resulting in progradation of the Proto-Mahakam delta and filling of the Kutai Basin (Hall and Nichols, 2002). In East Kalimantan, Cenozoic carbonates were deposited in three environmental settings: large-scale platforms, mixed carbonate–siliciclastic systems, and localized carbonate build-ups (Wilson et al., 1999). Carbonate outcrops of Miocene age are shelf sediments formed between deltaic and deep-water marine deposits (Allen and Chambers, 1998). They are considered to be low-relief patch reefs that developed in turbid, shallow waters influenced by high siliciclastic input (Wilson, 2005). Reef carbonate formation in East Kalimantan is usually within muddy sediments at the bases and tops of depositional sequences with the thickness of the siliciclastic sediments (hundreds of metres) far exceeding the amount of reef carbonates (tens of metres), reflecting the dominance of terrigenous input in the Kutai Basin (Wilson, 2005).

## 3. Methods

The studied outcrop is located in East Kalimantan (Indonesia), in the Indominco Mine area near Bontang (Fig. 1B), within Miocene sediments at the northeast margin of the Kutai Basin. The exposure is approximately 80 m wide and 25 m thick, with beds dipping WSW at an angle of about 25°. The relatively complete section through a reefal structure offers the opportunity to study the bedding geometry, facies architecture, and biotic composition in detail.

Fieldwork was undertaken in two steps: (1) characterisation of lithology and geometry of the reef deposits, and (2) sampling for fossil assemblages. Lithological units were identified following a detailed logging of eight sections along the outcrop in order to describe reef morphology and lateral changes (Fig. 1A). Samples for petrographical analysis were collected from each unit. Microfacies analyses of thin sections included carbonate lithofacies classification and skeletal component logging, from which relative abundances of larger benthic foraminifera, corals, and coralline algae were estimated for each sample. For the facies classification we adopted the textural schemes of Dunham (1962) and Insalaco (1998).

Larger benthic foraminifera and coralline algae were primarily examined using petrographic thin sections (48 × 28 mm). For foraminiferal assemblage analysis 31 samples were processed, including 26 thin sections and washed isolated specimens (500 μm mesh) from five bulk samples. Additionally, 10 oriented thin sections were polished from isolated larger foraminifera specimens. Foraminifera were identified to the lowest taxonomic level (typically species or genus) and their abundance was calculated by counting the foraminifera specimens that were identified in each sample. Coralline algae were studied in a total of 57 ultra-thin sections (48 × 28 mm; 10–15 μm thick) with the nongeniculate coralline algae identified to the most precise level possible (typically species or genus). Relative abundances of coralline algae were estimated in ultra-thin sections by measuring the proportional cross-sectional area occupied by each taxon relative to all coralline algae.

Corals and bryozoans were examined in nine bulk samples that were soaked in water overnight, then washed, sieved through 5 mm, 2 mm, and 500 μm meshes and air-dried. Corals were identified to species level in most cases and taxon abundances were calculated as the percentage of the total volume from the bulk samples. Abundances of typical coral colony forms, including free-living solitary, branching, encrusting, and platy (defined by Rosen et al., 2002), were also estimated. Bryozoans were identified using a stereomicroscope to genus or family level and their relative abundances were estimated by counting the number of encrusting colonies observed on the corals and the fragments of erect species scattered in the sediments. Following Cheetham et al. (1999) bryozoan species were assigned to three major colony growth-form categories: encrusting (runners, unilaminar sheets, multilaminar massive), erect (articulated, rigid), and free-living. Scanning electron microscope (SEM) images were used to confirm identifications and generate images of bryozoan specimens.

## 4. Results

### 4.1. Age

Stratigraphically important larger benthic foraminifera (Fig. 3) include the common occurrence of *Nephrolepidina ferreroi* (Burdigalian to late Serravallian; Lunt and Allan, 2004), *Miogypsina* cf. *globulina* (Burdigalian; Lunt and Allan, 2004), *Lepidosemicyclina polymorpha* (late Burdigalian to late Serravallian; Lunt and Allan, 2004), and *Flosculinella bontangensis* (late Burdigalian to Langhian; Lunt and Allan, 2004). An NN4–5 age can be assigned to this locality based on the presence of the coccolith *Sphenolithus heteromorphus* (Jeremy Young, personal communication). These occurrences allow a late Tf1 stage in the East Indian Letter Classification to be inferred, that equates to a late Burdigalian age (Renema, 2007).

### 4.2. Fossil groups

The taxonomic composition, growth form, and facies of the nine units are shown in Table 1 and Fig. 7. Two assemblages of larger benthic foraminifera can be distinguished. Smaller robust forms dominate in

**Fig. 1.** Late Burdigalian (early Miocene) patch reef complex, Indominco Mine, Bontang (Indonesia). A. Photomosaic of the logged section with log positions; B. Location of the studied outcrop (GPS: 0.1513 N, 117.3044 E).

Units 1 and 2 (*Amphistegina*, *Lepidosemicyclina*, *Quinqueloculina*, smaller rotaliids), while larger and flatter forms (*Cycloclypeus*, *Nephrolepidina*, *Amphistegina*, *Miogypsina*) are the most abundant in Units 3 to 7 (Table 1, Figs. 3, 7).

Scleractinian corals are very abundant in Units 4, 5 and 7, rare in Units 3 and 6, and absent at the base (Units 1 and 2) and top of the outcrop (Units 8 and 9; Table 1, Fig. 7). Octocorals were observed in Units 4 and 5, represented by branches of *Isis* sp. and large sclerites of indeterminate affinity (~5 mm). Corals were examined from cleaned individual specimens recovered from bulk samples. *Porites* spp. specimens were also studied in four thin sections made for lithological analysis. In total, the coral assemblage included 36 coral species from 29 genera and 14 families (Appendix A). Species richness is higher in Unit 4 (29 spp.) and Unit 7 (21 spp.), than in Unit 5 (14 spp.), and *Porites* is the only genus present throughout the coral-bearing part of the succession (Units 3–7).

The taxonomic composition and growth form of coralline algae assemblages in the successive units are shown in Table 1. There are no major differences in the coralline algal assemblage and growth forms between the units of the studied reef. Assemblages are dominated by melobesioids (mainly *Mesophyllum*) and *Sporolithon* (Table 1, Fig. 7). Foralgaliths (defined as nodules containing an abundance of both encrusting foraminifera and coralline algae; Prager and Ginsburg, 1989) and crusts of coralline algae and encrusting foraminifera on coral surfaces were common, especially in Units 4 and 5 (Fig. 5).

Bryozoans were found only in Units 4 and 7. The bryozoan assemblage in total consists of 62 species, with 7 cyclostomes and 54 cheilostomes (Appendix A). Richness in Unit 4 is 27 species (107 specimens), and in Unit 7 richness is 54 species (1651 specimens). The difference in species richness and specimen abundance between these units is probably due to the better quality of preservation observed Unit 7. The majority of species are encrusting (73%) with mostly two-dimensional colonies, 25% of species are erect, and only one species is free-living.

### *4.3. Facies types*

By combining the data from the eight logged sections, nine sedimentary units (Units 1–9; Fig. 2) were distinguished in the studied reef and associated deposits, including both siliciclastic- and carbonate-dominated rocks. They were grouped into five different facies types, based on rock textures, components and geometrical relationships (Figs. 2, 7; Table 1).

#### *4.3.1. Foraminiferal packstone (FP)*

The FP facies is characterised by slightly altered bioclastic packstone with a moderate larger benthic foraminiferal content (~20%; Fig. 8), fragmented bioclasts, and a medium- to fine-grained siliciclastic component. Based on the low fossil diversity, restricted to larger benthic foraminifera floating in the sediment without any

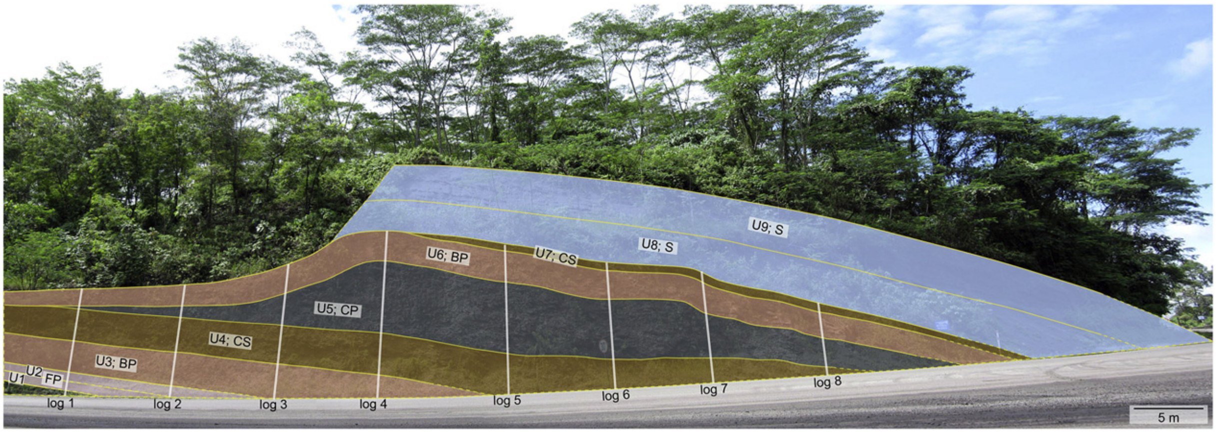

**Fig. 2.** Interpretation of the studied section at the Indominco Mine (Indonesia), with lithological units (Units 1–9), log positions (log1–8) and facies types (FP, BP, CS, CP, S).

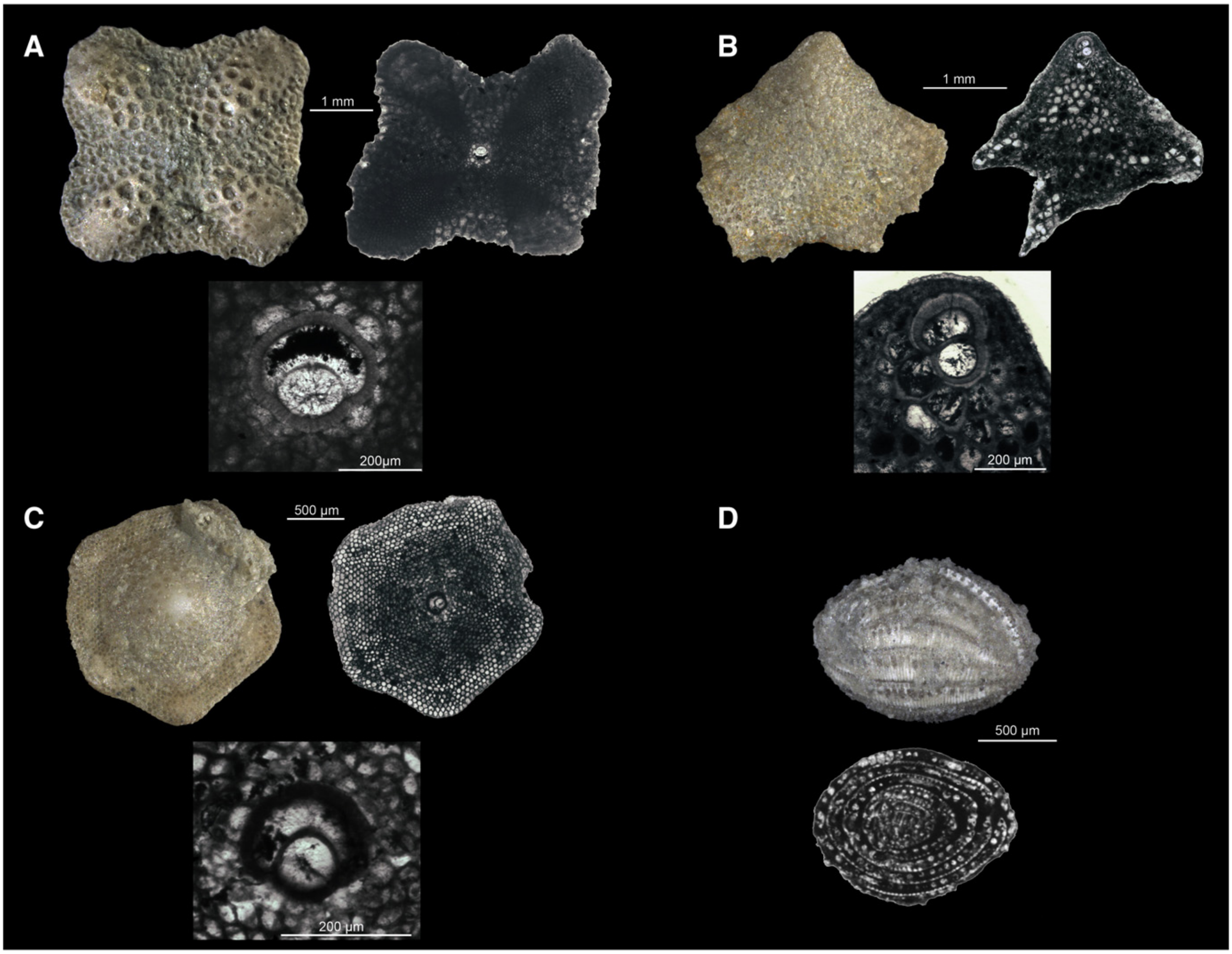

**Fig. 3.** Stratigraphically important larger benthic foraminifera from the studied reef. A. *Nephrolepidina ferreroi*, B. *Miogypsina* cf. *globulina*, C. *Nephrolepidina martini*, D. *Flosculinella bontangensis*.

sedimentary structures, this facies can be recognized in Units 1 and 2 of the studied outcrop. The foraminiferal assemblage shows a dominance of robust *Amphistegina* and *Lepidosemicyclina*, with subordinate *Operculina* and *Quinqueloculina*, and rare *Palaeonummulites*.

### 4.3.2. Bioclastic packstone with foralgal communities (BP)

The foralgal bioclastic packstone facies includes slightly recrystallised bioclastic packstone with fine-grained matrix and a reduced siliciclastic component compared to the FP facies. Co-occurrence of larger benthic foraminifera and small amounts of corals and coralline algae (Figs. 7, 8), and absence of bryozoans mark the BP facies, represented in Units 3 and 6. Among larger benthic foraminifera the highest abundance of flat and elongated foraminifera (*Cycloclypeus* and *Nephrolepidina martini*), and a decrease in the abundance of robust forms (*Amphistegina*, *Lepidosemicyclina* and *Operculina*) characterise BP facies. A single occurrence of soritid foraminifera was detected. Melobesioid coralline algae are the most dominant algal group in BP facies.

### 4.3.3. Thin-platy coral sheetstone (CS)

The thin-platy coral sheetstone facies (Insalaco, 1998; growth fabric dominated by sheet like and lamellar colonies) comprises dominant platy growth forms and occasional branching coral fragments, with isolated larger foraminiferal tests occurring in a muddy matrix. This facies occurs in Units 4 and 7. Compared to BP facies, the larger benthic foraminiferal assemblage shows an increase in diversity (Appendix A) and dominance of more robust forms, mostly *Amphistegina* and *N. ferreroi*. The coral assemblage shows a similar composition in Units 4 and 7, with 12 species in common (out of 29 spp. in Unit 4, and 21 spp. in Unit 7). The thin-platy colonies are mainly represented by *Echinopora* sp., *Porites* sp. 1, *Psammocora* sp. and *Cyphastrea*, with thicknesses ranging from 0.3 to 1.5 cm. The best preservation was observed in Unit 7, where a large number of thin platy corals conserve most of the calicular and coenosteum features on their surfaces (Fig. 4). Corals in Unit 4 are likewise frequently well preserved. Bryozoa were found only in this facies. The dominant bryozoan taxa are the flexible branching *Margaretta* sp. 2, and the encrusting *Oncousoecia* sp. 1, Lichenoporidae spp., and *Puellina* spp. (Fig. 6).

### 4.3.4. Platy-tabular coral platestone (CP)

This facies is characterised by thick-platy corals (up to 10 cm) and tabular corals that developed a platestone growth fabric (*sensu* Insalaco, 1998). A rigid coral framework marks this facies type in Unit 5, and gaps within the coral framework are filled with foraminiferal and algal packstone. The larger benthic foraminiferal assemblage is similar to FP and CS facies, with *Nephrolepidina* being the most abundant taxon. Platy-tabular colonies in CP facies include *Porites* sp. 1, *Oxypora* sp. and *Progyrosmilia* sp. (maximum thicknesses of 10.5 cm). In Unit 5 platy-tabular coral skeletons are in growth position, poorly preserved,

**Table 1**
Overview of stratigraphical units, facies types, lithologies and fossil groups from the studied reef.

| Unit | Facies type | Lithology | Larger benthic foraminifera | Corals | Coralline algae | Bryozoa |
|---|---|---|---|---|---|---|
| 9 | S | Shales and sandstone interbeds | Absent | Absent | Absent | Absent |
| 8 | S | Homogeneous shales | Absent | Absent | Absent | Absent |
| 7 | CS | Thin-platy coral floatstone with a muddy matrix | Dominance of *Amphistegina* (47%), *Nephrolepidina* (34%); n = 497 | Well-preserved thin platy coral colonies, dominated by *Cyphastrea* spp. (40%) and *Podabacia* sp. (12%). Free-living solitary *Cycloseris* cf. *sinensis* (6%) and branching *Porites* sp. 2 (9%) | Encrusting with foraminifers, unidentified thin laminar (35%), *Sporolithon* (30%), *Lithophyllum pustulatum* (20%) and Melobesioideae (15%); n = 6 | Bryozoans encrusting the bases of corals and as fragments scattered in the sediment. 54 species: 56% erect and 44% encrusting; n = 1651 |
| 6 | BP | Algal floatstone with micritic matrix | Rare smaller benthic foraminifera, no LBF assemblage; n = 25 | Recrystallised unit; rare debris of *Porites*. | Foralgaliths and fragments in sediment; Melobesioideae (57%), *Lithoporella* (15%), *Sporolithon* (13%), unidentified thin laminar (2%), undefined Mastophoroideae (13%); n = 8 | Absent |
| 5 | CP | Platy-tabular coral framestone | Elongated to robust forms: *Nephrolepidina* (31%), *Lepidosemicyclina* (21%), *Amphistegina* (17%), *Cycloclypeus* (13%); n = 402 | Dominate by platy-tabular *Porites* (28%), *Oxypora* (12%) and *Cyphastrea* spp. (10%). Branching *Porites* sp. 2 (13%) embedded in matrix. | Encrusting or nodules with foraminifers or as fragments in sediment; Melobesioideae (35%), *Sporolithon* (19%), thin laminar (18%), *Lithoporella* (10%), foliose fragments (10%), unidentified Mastophoroideae (6%), *Halimeda* (2%); n = 21 | Absent |
| 4 | CS | Thin-platy coral floatstone with a muddy matrix | Dominance of *Amphistegina* (53%) and *Nephrolepidina* (37%); n = 1331 | Dominate by thin platy corals *Echinopora* sp. (23%), *Cyphastrea* sp. (7%), and *Porites* (22%). Branching corals (8%) represented by *Porites*, *Seriatopora*, and *Dyctiaraea* cf. *micrantha*. | Encrusting with foraminifers; unidentified Melobesioideae (32%), *Sporolithon* (30%), *Lithoporella* (14%), unidentified thin laminar (17%), foliose fragments (6%), green algae and *Peysonnelliaceae* (1%); n = 15 | Bryozoans encrusting the bases of corals and as fragments scattered in the sediment. 27 species: 59% encrusting, 39% erect, 2% free living; n = 107 |
| 3 | BP | Slightly recrystallised bioclastic packstone | Elongated forms dominate: *Nephrolepidina* (37%), *Cycloclypeus* (20%), *Lepidosemicyclina* (13%), *Amphistegina* (13%); n = 380 | Very rare corals with poor preservation. Few thin platy and branching *Porites* observed. | Foralgaliths and fragments in sediment; Melobesioideae (65%), mainly cores and few fine protuberances of *Mesophyllum*, *Sporolithon* (12%), *Lithoporella* (5%), geniculate fragments (3%), thin laminar (15%); n = 7 | Absent |
| 2 | FP | Fine-grained packstone | Robust forms dominate: *Amphistegina* (39%), *Lepidosemicyclina* (25%), *Heterostegina* (14%); n = 51 | Absent | Absent | Absent |
| 1 | FP | Bioclastic packstone | Robust forms dominate: *Amphistegina* (34%), *Lepidosemicyclina* (27%), *Operculina* (17%); n = 121 | Absent | Absent | Absent |

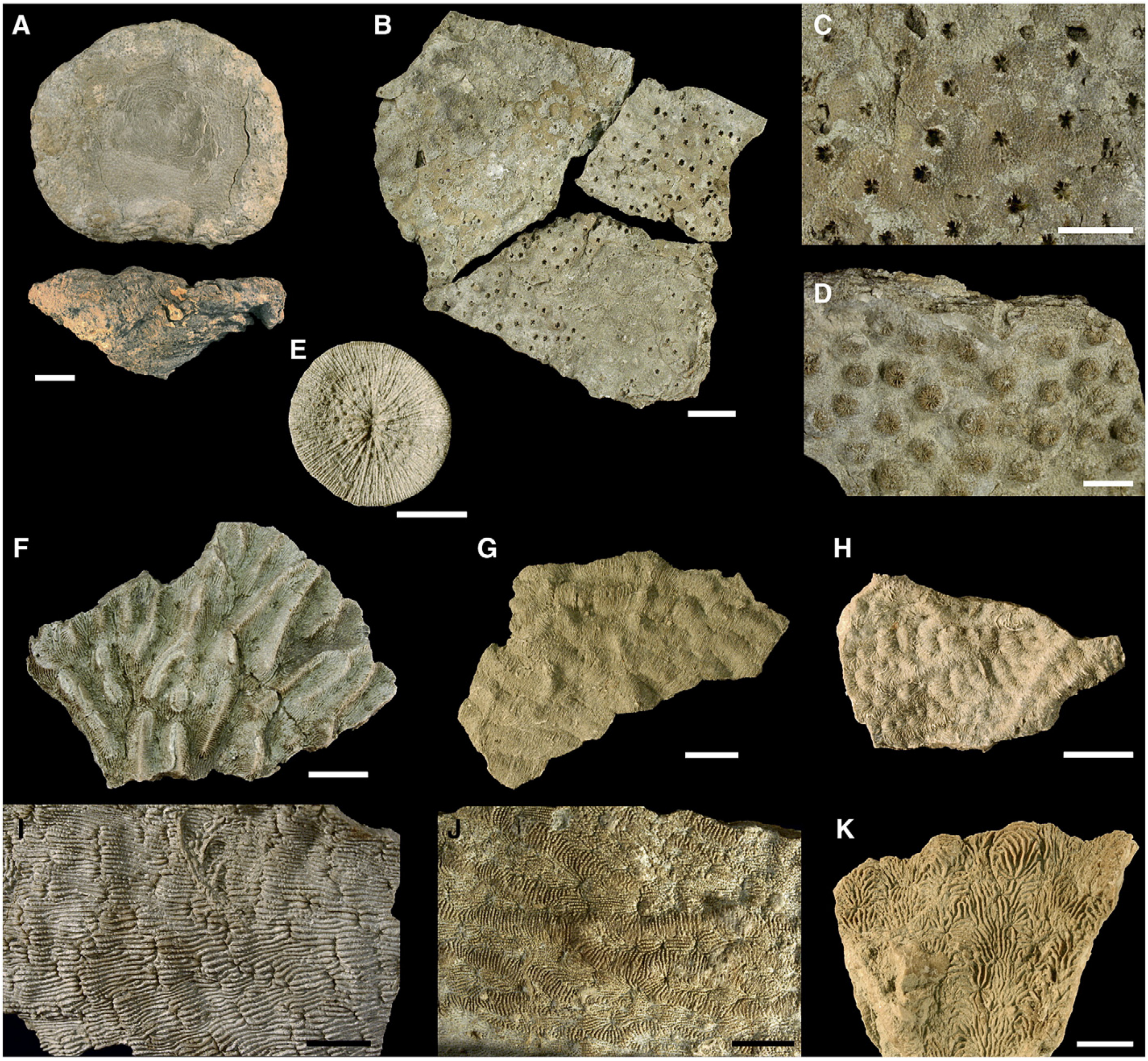

**Fig. 4.** Representative scleractinian corals from the studied reef. A. Colony of *Porites* sp. 1. showing a plate-patellate shape (scale bar = 2 cm); B–C. *Cyphastrea* sp. 1, B. three fragments of a thin-platy colony (scale bar = 2 cm), C. detail of calices (scale bar = 1 cm); D. calices of *Echinopora* sp., (scale bar = 1 cm); E. free-living solitary coral *Cycloseris* cf. *sinensis*, (scale bar = 1 cm). F–K. Scleractinian corals from different species and families, showing convergence on skeletal features: platy forms, serial corallites, and/or septal arrangements: F. *Hydnophora* sp., Family Merulinidae, (scale bar = 1 cm); G. *Pachyseris* sp., Family Agariciidae, (scale bar = 1 cm); H. *Pavona* sp., Family Agariciidae, (scale bar = 1 cm); I. *Podabacia* sp., Family Fungiidae, (scale bar = 1 cm); J. *Coscinarea* sp. Family Siderastreidae, (scale bar = 1 cm); K. *Cyathoseris* cf. *lophiophora*, Family Agariciidae, (scale bar = 1 cm).

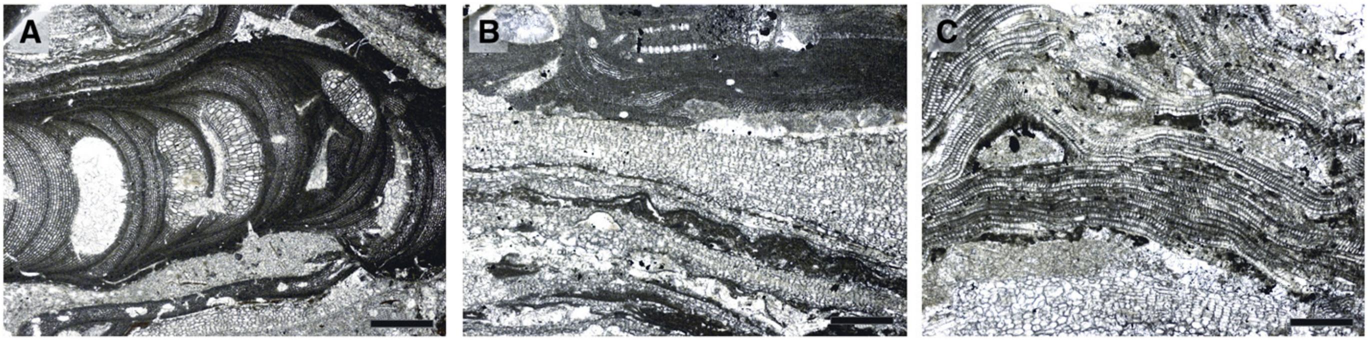

**Fig. 5.** Coralline algae from the studied reef. A. *Mesophyllum* sp. (protuberant morphology); B. Foralgalith: thin laminar coralline alga (middle) and *Sporolithon* sp. (top) with encrusting foraminifera; C. *Lithoporella* sp.

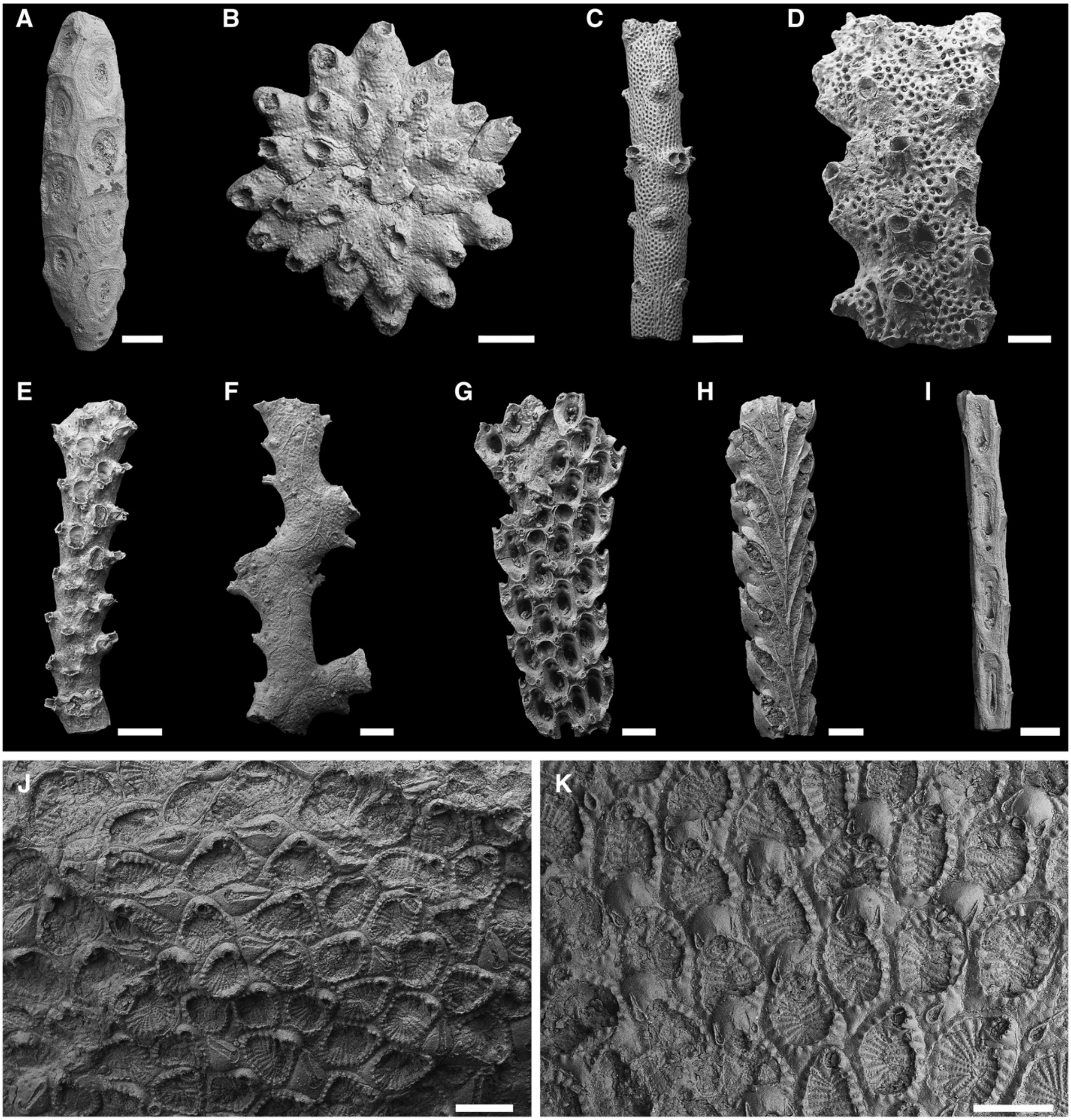

**Fig. 6.** Representative bryozoans from the studied reef. A. *Skylonia* sp.1 (scale bar = 200 μm); B. *Actisecos* sp.1 (scale bar = 200 μm); C. *Margaretta* sp.1 (scale bar = 500 μm); D. *Porina* sp.1 (scale bar = 200 μm); E. *Reteporella* sp.1, front (scale bar = 200 μm); F. *Reteporella* sp.1, back (scale bar = 200 μm); G. *Caberea* sp.1, front (scale bar = 100 μm); H. *Caberea* sp.1, back (scale bar = 100 μm); I. *Vincularia* sp.1 (scale bar = 200 μm); J. *Puellina* aff. *voigti* (scale bar = 200 μm); K. *Puellina* aff. *vulgaris* (scale bar = 200 μm).

characterised by a friable texture and mostly embedded in a compact sediment matrix.

#### 4.3.5. Shales (S)

Homogeneous, organic-rich, dark shales and fine-grained interbedded sandstones that are barren in fossils belonging to the studied groups constitute the final S facies which occurs in Units 8 and 9.

### 4.4. Lithological geometry

Units 1 and 2 (FP facies) form two beds of relatively constant thickness (0.75 and 1 m, respectively) underlying the entire reefal structure. The sharp contact between these units (Fig. 2) is caused by a change in the grain size. Unit 3 forms a package of 3.2 m in thickness composed of BP facies. The contact with the underlying beds is sharp and no sedimentary structures were detected. Towards the top of the Unit 3, the

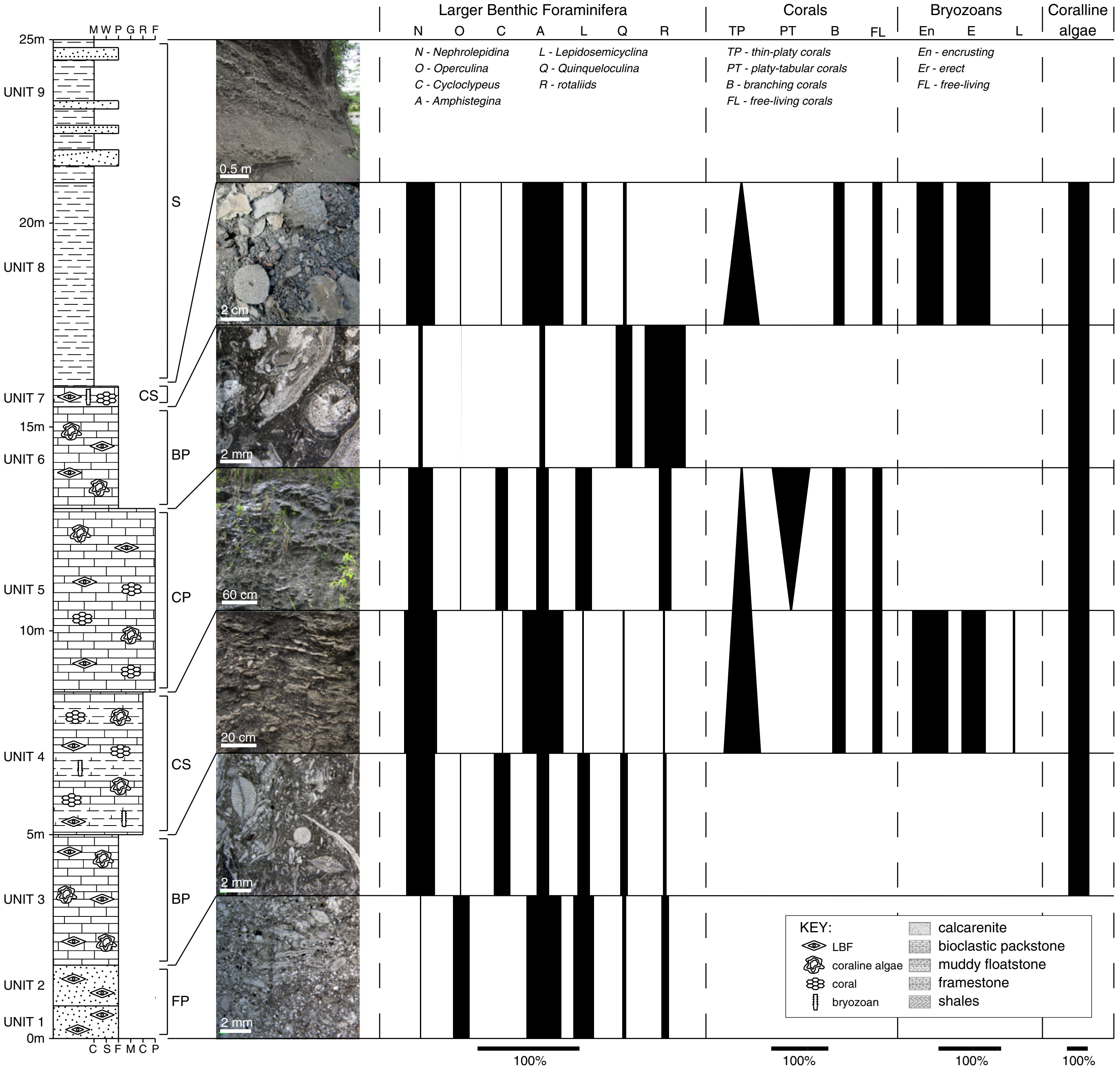

**Fig. 7.** Lithological log of the section of the studied reef, with biotic zonation and abundance within studied fossil groups.

muddy component increases and gradually transits into Unit 4 with CS facies. The thickness of Unit 4 (2.5–3.2 m) is more variable than the previous units, with the thickest part occurring at the centre of the outcrop and fossil size (coral thickness) increasing towards the top of the bed. This is the only unit present in all eight logged sections. The boundary between Units 4 and 5 is gradual and is defined based on the width to height ratio of the corals in the bed, with ratio being >30:1 in Unit 4, and <30:1 in Unit 5 (*sensu* Insalaco, 1998). The coral platestone of Unit 5 contains CP facies and is the most laterally variable bed in the studied outcrop, with a lens-like geometry and thickness ranging from 0 to 3.5 m. A less variable thickness of 1.2–1.5 m characterises Unit 6 which consists of BP facies and shows a sharp contact with both the underlying and overlying beds. Unit 7 is a thin layer of coral sheetstone (0.5 m) composed of CS facies without any sedimentary structures. The gradual disappearance of platy corals defines the transition to thick shales in the final part of the outcrop (S facies). The top of the outcrop was covered by vegetation so the full thickness of the shales is unknown.

In general, excluding the fossil barren siliciclastic S facies, larger benthic foraminifera occur in all four remaining facies (FP, BP, CS, CP), followed by coralline algae present in three (BP, CS, CP), corals in two (CS, CP), and bryozoans only in CS facies (Table 1). Coralline algae always co-occur with larger benthic foraminifera, mainly in packstone lithofacies, while bryozoans are coupled with corals in the muddy matrix, growing on their undersides.

## 5. Discussion

Based on observed geometry and vertical facies changes, the studied outcrop was characterised as a patch reef (i.e. small isolated reef

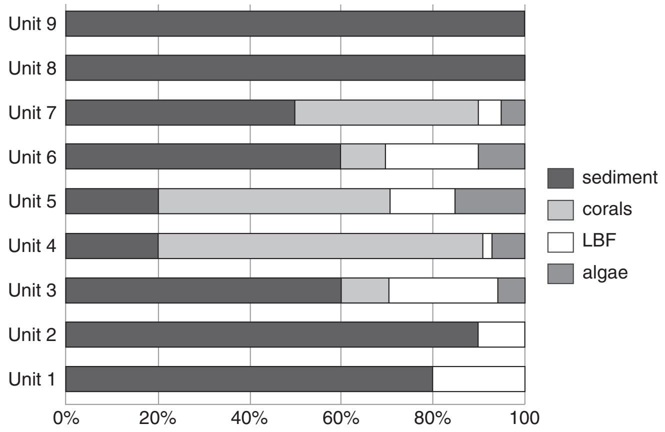

**Fig. 8.** Percentage of sediment matrix, corals, larger benthic foraminifera, and calcareous coralline algae estimated for each lithological unit of the studied reef. LBF — larger benthic foraminifera; CCA — calcareous coralline algae.

outcrop). The absence of lateral variation observed throughout logs along the outcrop, and relatively flat geometry of the initial reef unit, could suggest that the structure corresponds to a coral carpet (Reiss and Hottinger, 1984). In the studied reef, however, the coral framework in the CP facies changed the seabed topography as it developed a bioherm morphology that shows a three-dimensional structure. In contrast, a coral carpet habitat should result in the development of a relatively uniform biostromal coral framework facies (Riegl and Piller, 2000). In addition, the size of the main reef body in the studied outcrop is relatively small in contrast to proposed high areal extension of coral carpets (Riegl and Piller, 1999).

The fossil communities of light-dependent reef building organisms indicate variations in light levels (Wilson and Lokier, 2002; Wilson, 2005; Lokier et al, 2009; Brandano et al., 2010; Morsilli et al., 2011). Changes in light regime can result from sea-level fluctuations (deepening/shallowing) or alterations in terrestrial influx, including sediment and nutrient input. In environments influenced by terrestrial input, transparency changes depending on depth and distance from the sediment source (Renema and Troelstra, 2001; Bassi and Nebelsick, 2010). For example, the same amount of light would irradiate corals growing closer to a delta in shallower depths, as corals growing further from the sediment source, but in deeper environment. Taking into consideration the relatively high siliciclastic component in the sediment, the studied reef grew in a turbid mesophotic environment. Paleoenvironmental interpretation based on light dependant organisms in such a mixed depositional setting can therefore only be completed by comparison between different fossil assemblages, which would provide relative rather than absolute depth interpretations.

### 5.1. Larger benthic foraminifera

As larger benthic foraminifera host photosymbionts (Leutenegger, 1984; Reiss and Hottinger, 1984), they require light which limits their occurrence to the photic zone. Changes in foraminiferal assemblages can indicate fluctuations in light level, providing information valuable for interpretation of palaeoenvironments (Hallock and Glenn, 1986; Hottinger, 1997; Hohenegger et al., 1999; Renema and Troelstra, 2001; Hohenegger, 2006; Renema, 2006a,b).

Even though several of the taxa found in the Miocene reef complex are now extinct, it is possible to interpret the palaeoenvironment of the fossil assemblages from the studied reef in a modern environmental context. Assemblage of larger benthic foraminifera in the FP facies (Units 1 and 2) is dominated by *Amphistegina* and *Lepidosemicyclina*, that are characteristic of an inter-reef environment. In the present day, such conditions occur distal to the prodelta, for example on the Berau shelf in Indonesia (Renema, 2006b). The unusual shape of the foraminifera belonging to the *L. polymorpha* group may reflect an adaptation to the muddy environment by increasing the surface vs. volume ratio, preventing the foraminifera from being buried in sediment. The environmental affinities of the assemblage identified in BP facies (Unit 3), with the highest abundance of *Nephrolepidina* and *Cycloclypeus*, indicate lower light conditions than underlying FP facies. Although there is no modern analogue of *Nephrolepidina*, the flat shape of *N. martini* (Fig. 3C) observed in this unit, and the co-oocurrence with *Cycloclypeus*, a genus that is typical for one of the deepest facies of the recent Berau shelf (Renema, 2006b), indicates a position in the lower part of the photic zone. The CS facies (Unit 4) is characterised by representatives of *Nephrolepidina* and *Amphistegina* which are found in shallower waters. Compared to the previous facies, more robust morphology of these taxa resulted either from a need to shelter the symbionts from irradiation overexposure, or from living in higher hydrodynamic conditions. The high abundance of *N. ferreroi* (Fig. 3A) in combination with the absence of *Cycloclypeus* points to a shallower depositional environment than one of the underlying BP facies (Renema, 2006b). The foraminiferal assemblage composition of the CP facies (Unit 5), with relatively high abundances of *Nephrolepidina* and *Lepidosemicyclina* along with *Cycloclypeus*, is very similar to BP (Unit 3), again suggesting light conditions typical of the lower part of the photic zone. Samples of these facies (CS and CP) were collected from sediments accumulated within the gaps of coral framework. In modern Indonesian platy-coral reefs rich larger benthic foraminiferal assemblages have been observed living on corals covered by sand (Renema, 2006b). Moving up-sequence, the BP facies re-occurs in Unit 6, but the low abundance and diversity of benthic foraminifera indicates less favourable conditions, most likely caused by a rapid change in the light regime. In contrast, the CS facies in the overlying Unit 7 contains the highest species richness of larger benthic foraminifera in the studied reef, with the abundant *Amphistegina* and *Nephrolepidina* indicating stabilisation of environmental conditions, in the form of decrease of terrigenous input. Although some changes in the light regime can be inferred based on the larger benthic foraminiferal communities, the assemblages present in the studied reef show a generally similar composition throughout the succession, indicating low light conditions typical for the mesophotic reefs.

### 5.2. Corals

Turbid-water coral communities are common in the geological record (Rosen et al., 2002, and references therein; Sanders and Baron-Szabo, 2005). The studied reef is a typical representative of a turbid reef that developed under conditions of considerable terrigenous input. Study of modern examples of turbid-water coral communities (Johnson and Risk, 1987; Perry et al., 2009; Palmer et al., 2010) indicates their importance as alternative states of reef development, as compared to the warm and clear-water coral reefs currently distributed across the tropical belt (Kleypas et al., 1999; Perry and Larcombe, 2003). The complex interplay of factors that influence coral communities living under high sediment input is still not well-understood even in these modern examples (McClanahan and Obura, 1997; Perry and Smithers, 2010). Furthermore, the studied modern examples all represent coastal reefs and not delta front or prodelta reefs.

The influence of sediment stress on fossil coral assemblages can be interpreted on the basis of the colony forms present. Most of the corals found in CS facies (Units 4 and 7) exhibit thin-platy growth forms. Three interrelated factors can favour platy colony forms in corals: low-light conditions, substrate and turbidity. The adoption of platy forms by corals has been widely interpreted as a strategy to optimise light capture in low-light settings, due to deeper and/or more turbid environments (Rosen et al., 2002). We infer that most of the corals in the Miocene patch reef were zooxanthellate because all of their extant representatives are zooxanthellate forms including *Porites*, *Cyphastrea*, *Echinopora*, and *Oxypora*. The flattening strategy has been observed in modern corals with high morphological plasticity, e.g. *Stylophora pistillata* which photoacclimatizes to deeper water (down to 40 m) by changing from its regular branching form to a more plate-like morphology allowing increased light capture (Mass et al., 2007). It has also been observed that substrate type can drive the most successful forms found on soft sediments towards thin-platy shapes (Hoeksema and Moka, 1989). Thin-plate corals have a relatively high surface area to mass ratios that reduces the risk of sinking down into muddy sediment. The development of small polyps arranged in cerioid and plocoid forms seems to be a common characteristic of Cenozoic turbid-water communities (Sanders and Baron-Szabo, 2005). Small-caliced forms are dominant in this patch reef, including *Porites* (cerioid with a calicular diameter of 1–1.5 mm) and *Cyphastrea* species (plocoid with a calicular diameter of up to 3 mm). In addition, it has been suggested that among mushroom corals, flat forms and convex surfaces can facilitate sediment rejection in silty environments (Schuhmacher, 1979). These characteristics were common not only in the mushroom corals recovered from the studied reef (*Podabacia* sp., *Lithophylon* sp. and *Cycloseris* cf. *sinensis*; Fig. 4E), but also in some agariciids (*Cyathoseris*, *Pavona*, *Pachyseris* and *Leptoseris*), pectiniids (*Oxypora*, *Echinophyllia* and *Fungophyllia*), siderastreids (*Coscinarea* and *Pironastrea*), and the eusmiliid *Progyrosmilia*.

Thin-platy corals of CS facies (Unit 4) gradually change into thicker platy-tabular forms in CP facies (Unit 5), indicating more optimal environmental conditions of better illuminated, shallower and/or less turbid water due to a change in delta input, as suggested by Rosen et al. (2002) for “abandoned delta lobe environments” in the palaeoenvironmental interpretation of different platy coral communities. The low abundance of branching corals in the studied reef reinforces the interpretation as a setting with relatively constant low energy, as ramose coral morphologies are inferred to require more water movement for sediment clearance and feeding (Sheppard, 1982; Huston, 1985; Morsilli et al., 2011).

Coral species richness (36 species) is high compared to other coral assemblages known from Indonesia during the Neogene (8 to 22 species), and is comparable with the Tokelau Limestone of Fiji (late Burdigalian) with 34 species (Bromfield and Pandolfi, 2012).

### *5.3. Coralline algae*

In coralline algal assemblages on present-day coral reefs, the relative abundance of members of the subfamily Melobesioideae (such as *Mesophyllum* and *Lithothamnion*) increases with depth (Adey et al., 1982; Adey, 1986; Iryu et al., 1995). Melobesioids together with *Sporolithon* are the dominant coralline algae in deeper settings, from 15–20 m to 100–120 m (Adey et al., 1982; Minnery, 1990; Verheij and Erftemeijer, 1993; Iryu et al., 1995; Lund et al., 2000). A similar pattern in the proportions of melobesioids can be observed in Miocene reefs in which palaeodepth gradients are well constrained (Perrin et al., 1995; Braga et al., 2009, 2010). As with other algal groups, light is the primary factor controlling the distribution of coralline algal species, and light intensity and wavelength strongly depend on depth. Water turbulence generally decreases with depth as well. Therefore, the dominance of melobesioids in deeper reef settings probably reflects the preference of members of this subfamily for low light intensity and quiet habitats. The melobesioid-dominated coralline algal assemblages in the studied reef can be interpreted as indicative of a deep-water environment, or a shallower setting with lower light conditions due to high sediment load. However, the absence of shallow water assemblages in the units with lowest sediment influx (Unit 4 and 5) suggests a relatively deep environment.

In addition, coralline algal thalli become thinner with decreasing light conditions. Deep rhodoliths, crusts and the algal parts of foralgaliths are composed of thin laminar and foliose coralline algae (Montaggioni, 1979; Adey et al., 1982; Lund et al., 2000; Webster et al., 2009). The four main growth forms of coralline algae in the studied reef are foralgaliths with thin encrusting corallines, relatively thin crusts on corals or superimposed on other corallines, fine protuberant, and foliose thalli. No coralline algae show thick crusts. The recorded growth forms support the interpretation of an environment with low light levels.

The most plausible reason for the absence of coralline algae in Units 1, 2 and 8 is the high siliciclastic influx. As observed in the Great Barrier Reef, coralline algal abundance decreases with an increase of siliciclastic influx (Fabricius and De'ath, 2001; Fabricius, 2005).

### *5.4. Bryozoans*

Platy corals provided the main substrates for bryozoan settlement. The present bryozoan species exhibit a wide range of colony morphologies including encrusting runners (3%), encrusting unilaminar sheets (67%), encrusting multilaminar (massive) (3%), erect rigid fenestrate (reteporiform) (5%), erect rigid branching (7%), erect articulated branching (13%), and free-living (2%). Encrusting colonies and the cemented base of erect species usually grew on the undersides of corals, but a few specimens of *Puellina* were observed encrusting the upper surface of corals. It is likely that coral undersides represented exposed sites for settlement of bryozoan larvae while the corals were living. These larvae were unable to settle directly on the muddy sea-floor whereas the corals offered a large surface area for the development of both encrusting and small erect colonies. Therefore, the studied reef could be interpreted as a framework that maintained a three-dimensional structure above the sea-bottom. While unilaminar encrusting bryozoans do not require significant vertical space, massive nodular and erect species demand more vertical space for their growth, although some reteporiform colonies are able to grow horizontally in a plane roughly parallel to the surface of the substrate at a rather constant distance of 2–5 mm (Cuffey and McKinney, 1982). In contrast to encrusting and erect, the rare free-living cheilostome *Actisecos* is directly associated with soft unstable sea-bottoms. The application of uniformitarianism allows the presence of this genus to give a tentative estimate of palaeobathymetry based on the depth ranges of extant congeneric species. Only two species belonging to this genus are known so far, *Actisecos pulcher* and *Actisecos regularis*, and their depth range extends from 59 down to 104 m (Canu and Bassler, 1929; Harmer, 1957). All the other bryozoan genera co-occurring with *Actisecos* in the studied reef belong to genera with large depth ranges that cannot provide any useful palaeobathymetrical information. However, the extinct genus *Skylonia*, reported from tropical and subtropical regions in the Middle Eocene to the Pliocene, according to Keij (1973) is found in faunal assemblages that suggest a depth not much greater than 50 m. Based on their relatively good preservation, it is unlikely that these specimens were re-sedimented.

The presence of 62 species of bryozoans and as many as 54 in a single unit, is noteworthy. This figure is double the number (31 species) of fossil bryozoans reported previously from the Cenozoic of the entire Indonesian Archipelago (e.g. Lagaaij, 1968; Lagaaij and Cook, 1973). Despite the great diversity of bryozoans at this locality, they do not contribute significantly to carbonate production in this coral reef complex as the number of specimens is low and most species are represented by small-sized colonies. The high species richness, low number of colonies and small body sizes are characteristic of oligotrophic tropical environments, where bryozoans are diverse but subordinate in biomass with respect to other faunal components (Scholz and Hillmer, 1995).

### *5.5. Facies interpretation*

Light dependent organisms occurring in the studied reef suggest a mesophotic environment. The dominance of flat shaped larger benthic foraminifera combined with melobesioid coralline algal assemblage indicates low light intensity and quiet habitats. In addition, the morphology of the platy corals is indicative of muddy substrate type. These conditions characterised by low energy and mesophotic illumination could, in general, be developed in relatively deep clear-water settings, or in shallow-water turbid conditions. The observed vertical changes in fossil assemblages and reef facies can be explained either by sea level variations or/and changes in terrestrial influx, possibly accompanied by changes in nutrient input. Lithological analysis revealed minimal lateral variation between eight sections along the outcrop, and no sedimentary structures indicative of water turbulence were detected in any of the units. Based on the data gathered from the facies analysis and fossil components, deposition in a low energy environment below the fair-weather wave base is proposed for the studied reef. The relatively small size of this reef and the distinct vertical changes within a reduced thickness, combined with the high siliciclastic content in most of the units, point to changes in the delta morphology, and its consequent terrigenous influx affecting transparency, as the driving factor of reef facies variations.

The studied sequence was initiated with the deposition of a bioclastic packstone (FP facies; Fig. 9A) with a high siliciclastic content. The fine- to medium-grain size of the bioclastic and siliciclastic constituents suggests that the FP facies developed closer to the delta front than the overlying facies. The low diversity of fossil groups, with only larger foraminifera observed in these samples, suggests that high siliciclastic influx inhibited reef growth (Lokier et al., 2009). Reduced terrestrial influx increased illumination resulting in conditions favourable for scarce platy corals and coralline algae to appear and colonise the soft sediment, joining the existing larger benthic foraminiferal communities (BP facies; Fig. 9B). This highlights the role of foraminifera and, in a lesser extent, of coralline algae in stabilising the substrate allowing the initiation of reef growth, particularly in mixed carbonate–siliciclastic systems. With further decrease in terrestrial influx, platy corals dominated the environment and in turn provided habitat for colonisation of bryozoans (CS facies; Fig. 9C). In the overlying CP facies, the reduced input of siliciclastic material, and increased transparency in the water column, enhanced carbonate production of the thick-tabular coral framework (Fig. 9D). This framework contrasts with previously studied outcrops in the region that were described as low-relief buildups lacking rigid frameworks (Wilson, 2005). The development of reef framework was inhibited by high sediment input (Macdonald and Perry, 2003), reflected by the higher proportion of siliciclastic matrix and lower fossil abundance in the following BP facies (Fig. 9E). Only a few corals, coralline algae, and rare larger foraminifera were able to survive in this rapidly changing environment. When conditions and substrate were stabilised again, platy corals reappeared for a brief period within a muddy matrix (CS facies; Fig. 9F). The top of this unit marks the end of local reef development and is followed by deposition of fine-grained siliciclastics (S facies; Fig. 9G), coinciding with the local disappearance of all studied fossil groups. This last step of sedimentary evolution was probably driven by a relative sea level rise, promoting the deposition of prodelta shales in the area.

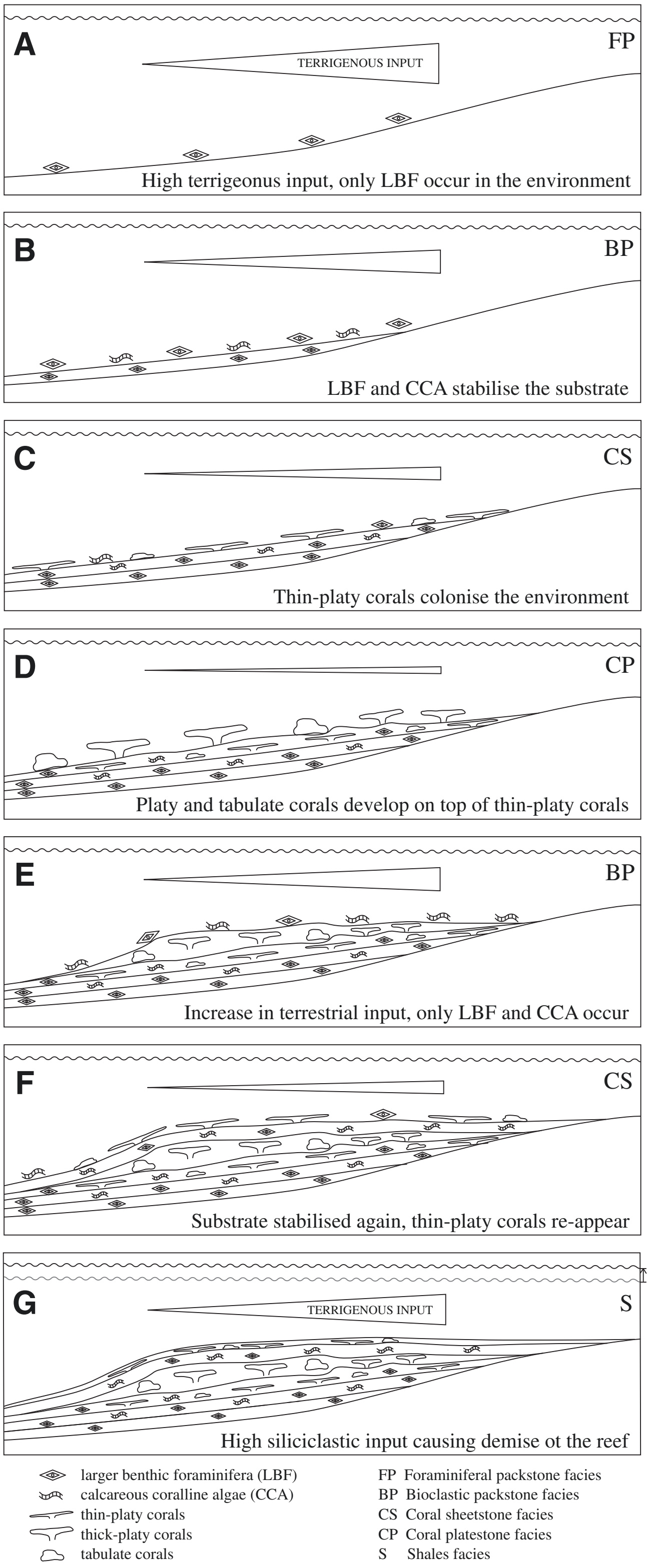

**Fig. 9.** Interpretation of depositional environment of the studied reef, showing facies changes driven by fluctuations in terrigenous input.

The morphology of the studied reef can be compared with that of a Recent reef from the central Great Barrier Reef in Australia that developed at sea level in a turbid zone influenced by fluvial sediments (Palmer et al., 2010). Although the external morphologies of the two reefs show some similarities, there are also significant differences, for example in the size of the reefs, the lack of framestone in the modern reef, and the coral types building the reefs. This contrast can be explained by differences in depth, energy of the environment, and the amount of terrigenous input. However, some morphological similarities are present suggesting the potential for identifying different depositional environments based on the facies (Palmer et al., 2010). Recurrent patterns of coral community development since the onset of reef sedimentation led Perry et al. (2011) to suggest that reefs can be re-established successfully and that re-growth may be nearly identical by reef-building communities with identical depositional structures. In the reef described in this study, autocyclicity can be observed in the repetitive pattern of the CS facies developed after deposition of BP facies. Although incomplete, this repetitive pattern occurs with thin-platy corals following the deposition of foralgal packstones. This supports the findings proposed by Perry et al. (2011) of the ability of the reefs to re-establish when environmental conditions improve or new (stabilised) substrate becomes available.

## 6. Conclusion

Based on facies analysis and fossil components, the depositional setting of the studied reef was interpreted as a low energy mesophotic environment within a prodelta. Coral reefs in such settings are very rare in the present day Indo-West Pacific area, and when found contain low biodiversity. Taking into consideration the thickness of the reefal deposits, distinct vertical changes in facies types, and the absence of sedimentary structures, the main factor controlling the reef growth is proposed to be fluctuations in light level caused by terrigenous influx affecting water transparency, most likely brought into the depositional basin by a large river. Of the reef-building taxa considered here, larger benthic foraminifera show the highest tolerance to siliciclastic input in the fossil reef and played an important role in stabilising the substrate, allowing the initiation of reef growth. Corals and coralline algae were most affected by terrigenous input and entered the environment only when conditions and the substrate were stabilised. The appearance of platy corals in turn provided suitable substrates for bryozoans which colonised cryptic undersides. Combined data from the studied fossil groups, based on morphology and environmental affinities (primarily light conditions), provided important information for palaeoenvironmental reconstruction.

The multi-taxon fossil assemblage analysis employed here proved to be effective for the understanding and interpretation of the dynamic deltaic palaeoenvironment represented by the studied reef complex, and can serve as a model for further studies on Indo-West Pacific patch reefs developed in mixed carbonate–siliciclastic depositional systems.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.palaeo.2013.01.009. These data include Google maps of the locality described in this article.

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