DEVELOPMENT OF EQUATORIAL DELTA-FRONT PATCH REEFS DURING THE NEOGENE, BORNEO

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ABSTRACT: Miocene patch reefs formed in turbid waters associated with high siliciclastic input at the seaward margin of the equatorial Mahakam Delta in eastern Borneo, SE Asia. Patch reefs were initiated on unstable substrates on localized low-relief bathymetric highs associated with delta-front channels or distributary mouthbars in the process of abandonment. Patch reefs developed only in shallow waters, formed low-relief buildups, lacked rigid frameworks, and had gently sloping margins. Although the biodiversity of the patch reefs may be comparable with that of clear-water systems, all the organisms present were adapted to turbid-water areas associated with siliciclastic, and sometimes nutrient, influx. The patch reefs were transient features, and their demise was influenced by increased siliciclastic and nutrient input, perhaps at times associated with deepening.

Carbonate production and bioherm or patch-reef development can occur in turbid-water delta-front areas as localized or more regionally extensive units during any phases of eustatic sea level. However, development and preservation of turbid-water carbonates is most likely during relative transgression or perhaps late lowstand periods. This is in contrast with common highstand carbonates from clear-water environments. The patch reefs were transient features, and their demise was influenced by increased siliciclastic and nutrient input, perhaps at times associated with deepening.

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The aims of this paper are threefold. (1) To describe the deposits, and evaluate the depositional environment, of patch reefs containing abundant admixed siliciclastics that formed in a delta-front setting. (2) To evaluate the depositional morphology and evolution of the patch reef deposits. (3) To evaluate the influences of local and regional factors on patch-reef and delta-front sequence development from turbid-water areas. This is one of the first detailed geological studies of shallow-water reefs that were influenced by siliciclastic influx throughout their history. The study has implications for siliciclastic-carbonate interactions, sequence development, and the survival of comparable modern reefs forming in siliciclastic-impacted environments.

INTRODUCTION

There is growing recognition that shallow-water carbonate production can and does occur in areas of coeval siliciclastic input (Mount 1984; Doyle and Roberts 1988; Woolfe and Larcombe 1998, 1999; Wilson and Lokier 2002). Between 5 and 25% of coral reefs at any time throughout their geological history are known to have developed in siliciclastic, coastal, or restricted settings, with the greatest abundances known from the Cretaceous and Tertiary (Kiessling 2002; Sanders and Baron-Szabo in press). However, previous detailed documented geological examples of mixed carbonate–siliciclastic systems tend to concentrate on successions in which nearly pure carbonates are interbedded with nearly pure siliciclastics (e.g., Dutton 1982; Santisteban and Taberner 1988; Braga et al. 1990). There is limited data from sections, particularly of Tertiary or Miocene age (Sanders and Baron-Szabo in press), in which coral-rich deposits contain a significant admixed siliciclastic component, i.e., the in situ mixing category of Mount (1984). In particular there is a paucity of sections where detailed lateral and vertical facies changes have been documented from siliciclastic-influenced reefs, and little quantification of deposit components and characteristics. Where data is available from siliciclastic coral deposits, such as from Jurassic successions (Insallaco 1996, 1998; Leinfelder 2001; Dupraz and Strasser 2002), the deposits are often highly localized, patchy, and of limited size (few meters). Sedimentological and morphological characteristics of turbid-water reefs are rarely described, and there is limited discussion of factors influencing their local initiation, development, and demise. There is a fine balance between siliciclastic input and in situ mixed carbonate–siliciclastic development, with the actual responses of carbonate producers dependent on a range of factors including rates and frequency of elastic influx, grain sizes, energy, and the presence of nutrients (Wilson and Lokier 2002).

On a larger scale, although there is growing discussion of mixed carbonate–siliciclastic sequence development (Rankey et al. 1999), particularly for Cenozoic successions, most descriptions are of those with limited in situ admixing of components where highstand carbonates commonly develop (e.g., Ferro et al. 1999; Cunningham et al. 2003; Yang and Kominz 2002). To date there is little discussion of influences on sequence development where in situ mixed carbonate–siliciclastic reefs developed, and little from delta-front areas with nearly constant siliciclastic input.

This study reveals that shallow-water carbonate production can occur in an apparently inhospitable environment; that of a proximal delta-front setting contemporaneous with high, constant siliciclastic input. Studies of modern patch reefs and their ancient equivalents from outcrop, core, and seismic from the Mahakam Delta, Borneo (Figs. 1, 2), allow evaluation of small-scale temporal and spatial variations in facies and biotic distribution. These properties were influenced by local water depth, siliciclastic input, and water clarity. Regional development of delta-front patch reefs was controlled by a range of factors including intrinsic changes in the activity of the delta lobes, and by extrinsic relative variations in sea level, amounts of siliciclastic input related to tectonic uplift and climate, and changes in shelf currents.

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CARBONATE DEVELOPMENT AND THE MAHAKAM DELTA

Cenozoic plate-tectonic convergence in SE Asia and weathering in a humid equatorial climate have resulted in high rates of Neogene uplift and erosion of the landmass of Borneo (Hall and Nichols 2002). Sediment derived from this eroding landmass resulted in delta progradation and significant siliciclastic input into basinal areas to the north and east of Borneo (Hamilton 1979; Hutchison 1989; Wilson and Moss 1999; Hall and Nichols 2002). The Mahakam Delta has been actively prograding eastwards and contributing towards infilling the Tertiary Kutai Basin (Fig. 1) with around 9 (Hamilton 1979; Hall and Nichols 2002) to 14 (Chambers and Daley 1995) km of sediment since at least the early Miocene (van de Weerd and Armin 1992; Allen and Chambers 1998; Moss and Chambers 1999).

The formation of the modern Mahakam Delta has been influenced by moderate tides of about 3 m, a steady, high fluvial input of between 500 and 5000 m³/s, and very low wave energy (Allen and Chambers 1998). The morphology of this fluviolacustrine and lobate delta is fan-shaped and lobate (Figs. 1, 3). A network of bifurcating fluvial distributaries radiates out from the Mahakam River and are actively forming mouthbars where they meet the sea (Allen and Chambers 1998). Separate highly sinuous tidal channels present on the lower delta plain allow drainage of tidal water from interdistributary areas (Fig. 3). Tidal channels are up to 18 m deep, whereas the distributary channels are generally between 8–13 m deep. It is inferred from outcrop and core studies that the Neogene delta developed under tide and wave conditions similar to those of the present day (Allen...
DELTA-FRONT PATCH REEF DEVELOPMENT

Fig. 1.—A) Location of Borneo in SE Asia, B) the research area in Borneo, and C) the locations of the patch reefs studied in eastern Borneo. Position of anticlinal structures from Allen and Chambers (1998) and Alam et al. (1999).

and Chambers 1998). However, the development of the Kutai Lakes in the upstream part of the Mahakam River, due to post-Miocene uplift associated with growing thrust-top anticlines (Fig. 1C), is thought to have recently damped the effects of fluvial floods (Allen and Chambers 1998). Source rivers for the Mahakam Delta drain an area of ~ 750,000 km², and annual rainfall in the drainage basin varies between 3000 and 4000 mm. The average sediment supply to the delta is $8 \times 10^6$ m³/yr (Allen et al. 1976). Deposits of the Mahakam Delta are predominantly fine-grained with clay-and silt-size particles constituting ~ 70% of the material and sand the remainder (Allen et al. 1976).

Despite high siliciclastic input to the Mahakam Delta, modern and Pleistocene carbonates are known from two settings in the delta front. These are proximal patch reefs and more distal shelfal buildups developed in water depths of < 10 m and between 30–100 m, respectively (Fig. 3; Roberts and Sydow 1996). Delta-front reefs are not just a recent phenomenon, in that outcrop (Figs. 1, 2) and subsurface (Figs. 3, 4; Alam et al. 1999; Hook and Wilson 2003) carbonates within the Neogene deltaics are analogous to modern deposits.

Miocene onshore carbonate outcrops (Figs. 1C, 2) are the subject of this study. Using the lithostratigraphic scheme of Land and Jones (1987), these are classified as the Batih Putih Limestone (equivalent to the Bebulu Carbonates; Moss and Chambers 1999). The Batu Putih Limestone was originally interpreted as being older than the deltaics and deep-water shales that entomb them (Land and Jones 1987). However, these carbonates are in fact transitional shelf deposits that accumulated contemporaneously between deep marine deposits and deltaics (Fig. 5; Allen and Chambers 1998).

The Pleistocene and Recent distal carbonates, imaged using shallow seismic, occur mainly on the northern part of the shelf, forming mounds, platforms, and buildups (Figs. 3, 4; Roberts and Sydow 1996). Bioherms of

Fig. 2.—Outcrop photograph looking north, showing deposits of the patch reef at Airputih dipping steeply towards the east. Upstanding ridge of the Permasip patch-reef outcrop is arrowed in the background.
and foraminifera in a micritic to clay matrix. Their radiocarbon dates revealed that these uppermost bioherm deposits accumulated less than 12 ka ago. Along the shelf margin, buildups with 40–120 m relief proved difficult to core. The well-sorted sediments retrieved by Roberts and Sydow (1996) contained common foraminifera, coralline algal rhodoliths, molluscs, and solitary corals. These shelf carbonates were inferred to have developed on transgressive ravinement surfaces with the thin mud layer draping the bioherms on the inner and middle shelf interpreted as late highstand to lowstand deposits (Roberts and Sydow 1996). The recent concentration of carbonates around the northern part of the delta is related to two factors. The southern delta lobe is currently more active than the northern lobe, and the Indonesian Throughflow Current flowing southwards with velocities of up to 90 cm/s both result in less-turbid waters to the north (Roberts and Sydow 1996). Neogene carbonates were also concentrated in the north, although there was variation through time. Nutrient loading has been suggested as a factor contributing to abundant Halimeda development on the inner-shelf bioherms (Roberts and Sydow 1996).

METHODOLOGY

Sedimentary outcrop logging, sample collection, and facies mapping were undertaken on seven patch-reef complexes in eastern Borneo (Fig. 1). The carbonates are interbedded with Miocene deposits of the proto–Mahakam delta, and are exposed in the limbs of NNE–SSW trending rollover anticlines associated with Miocene and younger basin inversion (Chambers and Daley 1995; Allen and Chambers 1998). Excellent two- to three-dimensional outcrops (Fig. 2), with up to 90% exposure, allowed section correlation through individual patch reefs. Dip directions are towards the ESE or WNW, and dip angles vary from ten degrees to nearly vertical. The carbonates crop out as isolated areas of upstanding modern karst, 200 m to 4 km across, and up to 200 m high (Fig. 2). Outcrops were studied in active quarries (Figs. 2, 6A), disused, often densely vegetated quarries, and on unquarried karst. Despite the low-tech ‘‘sledgehammer’’ method of quarrying, many of the sections were being rapidly removed and no longer exist.

Twenty-three sections through the seven reef complexes were logged, and of the 250 samples collected, 130 were studied petrographically. Thin sections were half stained with Alizarin Red S and potassium ferricyanide to highlight different carbonate phases. Point counting of thin sections provided additional quantitative data. Micropaleontology, larger benthic foraminifera (BouDagher-Fadel and Wilson 2000), and coral analysis of hand specimens, thin sections, and sieved samples was undertaken to obtain additional biostratigraphic and environmental data. Fifty samples were dissolved in 10% hydrochloric acid to determine the percentages of carbonate and siliciclastics present. Analysis of the mineralogical components of the clay-size fraction from 20 samples was undertaken by X-ray diffraction.

SHALLOW-WATER PATCH REEFS

Locations, Ages, and Dimensions of Patch Reefs

The locations, ages, and characteristics of the seven patch reefs studied are shown in Figures 1 and 7, and in Table 1. The western patch-reef outcrops at Senoni and Kota Bangun are older (early Miocene) than those exposed to the east at Airputih, DPR, Permasip, Badak, and Bontang (early to predominantly middle Miocene; BouDagher-Fadel and Wilson 2000) on the basis of larger benthic foraminifera and nannofossil biostratigraphy (Table 1). Individual patch-reefs are up to 2–4 km across and have post-compactional thicknesses of up to 40 m. Patch-reef thickness may vary considerably along strike, with variations from 20+ m to less than 10 m seen over lateral distances of 200–300 m at Airputih and Permasip. Carbonate and mixed carbonate–siliciclastic facies of the patch reefs, overlie, interdigitate with, and are overlain by fine-grained siliciclastic deposits of the delta (Figs. 6B, C, D). An area where a patch reef has developed may...
be the location for later patch reefs to form. This relationship is seen at Senoni and Permasip, where the older patch reefs are separated from younger patch reefs by 15–20 m and 75–100 m of deltaic siliciclastics respectively.

**Patch-Reef and Associated Deltaic Facies and Successions**

Twelve facies were identified, based on their constituent components, textural and lithologic characteristics (Table 2). These facies were subdivided into three facies associations, on the basis of weight % insoluble non-carbonate material. These are siliciclastic facies (> 95% siliciclastics), mixed carbonate-siliciclastic facies, or mixed facies (35–90% siliciclastics), and carbonate facies (6–35% siliciclastics). Throughout the reefal succession there is consistently greater than 6% by weight of insoluble siliciclastic material, most of which consists of clays and silts.

The carbonate and mixed facies are classified on the basis of the textural schemes of Dunham (1962) and Insalaco (1998). The latter is an expansion, and modification, of the Embry and Klovan system (1971), and is suited to describing coral growth fabrics with subdivisions based on dominant growth forms. The subdivisions are domestone (domal and massive colo-
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**Fig. 7.**—Simplified diagram showing ages, dimensions, and characteristics of the patch-reef deposits. The predominantly siliciclastic facies of the proto–Mahakam Delta present between the patch reefs are not shown. Lateral distances between patch reefs are not drawn to scale. The Bontang, Permasip, Airputih, and Senoni localities were characterized by multiple measured sections, whereas the Badak, Dibelakan Parliament, and Kota Bangun localities have limited lateral extent and were studied in single measured sections.

**Fig. 6.**—Representative outcrop photographs and thin-section photomicrographs of lithologies from the Miocene siliciclastic-influenced delta-front patch reefs of Borneo. 

A) Quarried outcrop of patch reef carbonates at Senoni. The piles of carbonate rocks under the shelter have been broken by hand for use mainly as roadstone. 

B) Basal deposit of the patch reef at Senoni showing bedded and laminated silts and clays passing gradationally upwards into platy coral sheetstones (p). 

C) Close-up photograph of part B showing interlaminated silts and clays at base of patch reef at Senoni (Section SB). 

D) Plane-polarized-light (PPL) photomicrograph of sandy packstone from Airputih (sample AE2). Fragmented bioclasts are mainly larger benthic foraminifera. Field of view 1 cm × 1.7 cm. 

E) Platy coral sheetstone from the base of patch reef at Airputih (Section AA) containing about 60% insoluble fine-grained siliciclastics. 

F) In situ recrystallized head coral from coral domes at Airputih. Surrounding matrix is gray and contains 10% fine-grained siliciclastics. 

G) PPL photomicrograph of branching coral float–rudstone with recrystallized corals (c) encrusted by foraminifera (f) from Airputih. Field of view 2 cm × 3.2 cm. 

H) Larger benthic-foraminifera packstones capping the patch reef at Airputih; the PPL photomicrograph shows *Miogypsinia*. Field of view 1 cm × 1.7 cm. 

I) PPL photomicrograph of *Halimeda* wackestone from top of patch reef section at Permasip. Field of view 1 cm × 1.7 cm.
or partially developed succession, or mixed facies may sharply overlie carbonaceous facies. The upper to middle parts of meter-scale units of siliciclastic facies at the margins of the patch reefs often correspond with boundaries between two stacked successions towards the reef center.

**Siliciclastic Facies**

Two siliciclastic facies were encountered: a shale–clay facies, and an interlaminated silty sand and clay facies (Table 2). These facies underlie, overlie, and are interbedded with deposits from the margins of the patch reefs, with the shale–clay facies usually adjacent to, and passing gradationally into, mixed facies (Fig. 6B). Dark gray shale–clay deposits may be massive, bioturbated, or laminated on a millimeter scale and include cross-laminated stringers of silty sand. Clays, such as kaolinite and siltite, are the main components of this facies. Most units contain a few percent of unabraded, flattened larger benthic foraminifera, and whole or disseminated plant material.

The silty to fine or medium-grained sand of the interlaminated silty sand and clay facies is quartz rich, contains abundant clay drapes and laminae, and is often cross-laminated or planar-laminated on a millimeter scale (Fig. 6C). Ripples have asymmetric to symmetric form, and facing direction of asymmetric ripples is unidirectional to more rarely bidirectional with up to a few tens of degrees variability. Bioturbation, although commonly absent, may disrupt some bedding. Load and flame structures are present. Where present, carbonate bioclasts consist of fragmental shelly material and foraminifera. Disseminated carbon and well-preserved leaves are common, particularly along laminae surfaces.

**Interpretation.**—Both facies are inferred to have accumulated under predominantly low to moderate energy conditions, on the basis of their small constituent grain sizes, and presence of parallel lamination and well-preserved plant material. Fluctuations in energy are suggested for the silty sand, because of the abundance of clay drapes and laminae. The ripple forms are indicative of deposition under low-velocity wave and/or current flow, with some evidence for both a predominant flow direction and bidirectional flows. The influence of tides would be consistent with the variations in current direction and inferred changes in velocity. Both facies are inferred to have accumulated above fair-weather wave base on the basis of the presence of wave-formed ripples. The well-preserved larger benthic foraminifera in the shale–clay facies are indicative of deposition in a marine setting within the photic zone. It is suggested that high influx of clays and/or turbid waters hindered further development of phototrophs. Water depth is not thought to have been a factor limiting carbonate producers, because these facies are interbedded with the marginal deposits of the patch reefs. Rapid sedimentation under waterlogged conditions is inferred for the silty sands, on the basis of load and flame structures. The siliciclastic grains making up these facies are inferred to have been predominantly terrestrially derived, judging by abundant reworked material from land plants. This interpretation is supported by the occurrence of kaolinite, a clay mineral most commonly formed in equatorial terrestrial settings. Because marine bioclasts were absent from some of the silty sand facies, it may be that some of these facies developed under brackish conditions. A shallow, delta-front depositional environment is inferred for these facies on the basis of the combined evidence of wave activity, high sedimentation rates, a terrestrial influx, and the suggestion of tidal activity in a marine to perhaps brackish environment.

Through comparison with cored deposits of the modern Mahakam Delta (Carbonel and Moyes 1987; Gastaldo and Huc 1992; Allen and Chambers 1998), it is possible to more accurately define likely depositional environments for the two siliciclastic facies. Medium- to fine-grained sand and silt are localized in channels and at the delta front (Allen and Chambers 1998; Gastaldo and Huc 1992). The interlaminated silty sand and clay facies most closely resembles the muddy sand facies of Allen and Chambers (1998) and the bioturbated sand–mud couplet facies of Gastaldo and Huc (1992). These modern facies are most commonly observed in the lower reaches of the distributary channels with a tidal influence, in subaqueous channels at the delta front adjacent to mouth bars, and as an infill to abandoned channels at the delta front, or sometimes in interdistributary areas. The shale–clay facies of this study is comparable with gray to black muds found in interdistributary areas, in abandoned channel fills at the delta front, and at the periphery of distributary mouth bars (Gastaldo and Huc 1992; Allen and Chambers 1998). Some of the more massive, homogeneous clays may be prodelta muds, which in the modern delta are accumulating in water depths of 5 to 70 m (Allen et al. 1976; Allen and Chambers 1998). The overall succession at the base of the patch reefs of interlaminated silty sands and muds, passing upwards into shale–clay facies is most consistent with abandonment and then colonization of: (1) a tidally influenced distributary channel, (2) a tidal channel, or (3) the margins of a distributary mouthbar adjacent to a channel (cf. Allen and Chambers 1998).

**Mixed Carbonate–Siliciclastic Facies**

The four facies in this association all contain 35–90% siliciclastics as well as common to abundant skeletal bioclasts (Table 2). Three facies (the platy coral sheetstone, the clayey wackestone, and the larger benthic foraminifera packstone) contain a dark gray, predominantly clay matrix. The matrix of the bioclastic sand is a muddy fine to medium quartz-rich sand (Fig. 6D).

The platy coral sheetstones invariably form the basal few meters of the patch reefs (Fig. 6B), and are also common towards their top and margins. The shales–clays below the patch-reef deposits pass gradationally upwards into the sheetstones containing abundant laminar and platy corals, such as *Pachyseris* and *Leptoseris* (Fig. 6E). The sheetstones contain up to 80% clayey matrix, although there is a general trend up section for platy corals to become larger and thicker associated with a decreased siliciclastic content (~40%), resulting in sheetstone–platestone textures. Other bioclasts present are pectens, solitary corals, such as *Cycloseris*, and flattened larger benthic foraminifera up to 2.5 cm across. Although uncommon, encrustation by coralline algae and larger benthic foraminifera is present on both the upper and lower surfaces of corals.

Deposits of the clayey wackestone facies are common along patch-reef margins closest to siliciclastic input, and may also be present in the upper parts of the reefs. This facies includes a comparable siliciclastic content (50–70%) and similar bioclastic components to the platy coral sheetstone facies. However, instead of platy corals, delicate branching *Tubastrea* up to a few millimeters in diameter are dominant, and are preserved bed parallel and compacted.

The larger benthic foraminifera facies predominantly forms the uppermost unit capping earlier patch-reef deposits. Characteristic of this facies is an abundance of well-preserved, curved, flattened, to robust larger benthic foraminifera (Fig. 6H), aligned parallel to bedding. *Myeypisina, Amphistegina*, and, in Serravallian *Tz2* deposits, *Katacycloclypeus* are abundant, with less common *Lepadocyclina* and *Cycloclypeus* (BouDagher-Fadel and Wilson 2000). Rhodoliths may be common, and are formed by coralline algae encrusting the larger benthic foraminifera. Other components in the clayey micritic matrix are pectens, gastropods, and echinoid spines.

Bioclastic sands are interbedded with siliciclastic facies at the margins of the patch reefs and may cap reef deposits. This facies is predominantly homogeneous, although it may be burrowed along bed surfaces. Bioclasts make up to 20% by weight and include larger benthic foraminifera, pectens, shelly fragments, and echinoid spines (Fig. 6D). Disseminated plant material is common (5%).

**Interpretation.**—Marine depositional conditions are inferred for all these facies, on the basis of the common occurrence of well-preserved stenohaline biota. There is minimal breakage and abrasion of bioclasts, particularly in facies containing the clayey matrix, and most of the bioclasts are inferred to be *in situ*, or very close to *in situ*. Because a number of the
skeletal components are photoautotrophs, production occurred in the photic zone. The abundance of clay-size particles, and good preservation of delicate bioclasts, in the platy coral sheetstones and clayey wackestone is indicative of their formation under low energy conditions. Moderate energy conditions are inferred for the larger benthic foraminifera packstones and sandy packstones on the basis of the occurrence of sand-size particles, some abrasion of bioclasts, and the robust, lenticular shapes of some of the larger benthic foraminifera present (cf. Hallock and Glenn 1986). All the facies formed under moderate to high siliclastic input. The presence of common disseminated plant material in the sandy packstone facies is indicative of a terrestrial input and nutrient influx during deposition of this facies. The common occurrence of coralline algae and disseminated carbon in the larger benthic foraminifera packstone facies is also suggestive of accumulation under high nutrient conditions.

Among photoautotrophs, thin and flattened shapes, with a high surface area to volume ratio, are an adaptation to production in environments with low incident irradiation (Hallock and Glenn 1986). Deposits containing predominantly thin platy corals form in marine environments with little light penetration, either in clear, deep-water settings towards the base of the photic zone, or in turbid waters, where suspended material hinders light penetration (Rosen et al. 2002). The platy coral sheetstones are inferred to have formed in the later turbid-water setting, because they contain abundant clay-size material. In life, at least some of the platy corals grew projecting above the sediment surface, as inferred from encrustation on their underside. Angled, tiered, or whorled growth forms of platy corals facilitate the shedding of sediment (Rosen et al. 2002). Whorled platy corals have been recorded from modern turbid environments where only the outer margins have live tissue and the central portion is covered in fine-grained siliclastics (Rieg et al. 1996; Tomascik et al. 1997).

A low-energy, turbid depositional setting is also inferred for the clayey wackestone facies. Being azooxanthellate, Tubastrea does not require sunlight and is today reported in abundance from cryptic reef habitats, underhangs, cave walls, deep reef slopes, and very turbid environments in Indonesia (Tomascik et al. 1997). It is here suggested from the presence of larger benthic foraminifera co-occurring with Tubastrea that the clayey wackestone facies developed under low light levels rather than in the dark. Tomascik et al (1997) noted that where Tubastrea is present in modern turbid waters, the environment is commonly current-swept. During accumulation of the clayey wackestone facies, currents may have been a factor in breakage of the Tubastrea and maintaining low water clarity, hindering abundant development of photoautotrophs. However, it is inferred that velocities of any currents were not high, judging by the delicate growth forms of corals and the abundance of clay-size material.

The depositional setting of the larger benthic foraminifera packstone facies is constrained from the life habits and paleoecology of the highly abundant foraminifera present (BouDagher-Fadel and Wilson 2000). Mio-gypsina has a median layer composed of many convex cubiculae, which act as lenses focusing sunlight and providing a "greenhouse environment" for the development of symbiotic diatoms. It is likely that Mio-gypsina, and Katacyclopleus (Röttinger 1971), relied on their symbionts to provide nutrients, with their pseudopodia little used for food gathering. Because these foraminifera were reliant on their symbionts for energy, they occurred only in shallow-water environments with high incident light. The irregular shape of many of the Mio-gypsina in this facies result from a sedentary life habit on a strongly curved substrate, such as seagrass. The larger benthic foraminifera deposits therefore formed in shallow seagrass beds, under low to moderate energy conditions associated with fine silicilastic input, possibly in areas of high nutrient input.

The bioclastic sand units are comparable with the modern bioclastic sand facies of Gastaldo and Huc (1992), and are inferred to have formed as delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits. Allen and Chambers (1998) note that similar deposits are forming where an inactive mouthbar at the delta-front or distributary-mouth-bar deposits.
### Table 2: Associations, descriptions, and inferred depositional environments of facies.

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<td>Base of succession: overlain by platy coral plate-sheetstones. Margins of patch reef: interbedded with platy coral sheetstones and coralline algae and coral floatstones. Top of succession: overlies platy coral plate-sheetstones or larger benthic foraminifera packstones.</td>
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<td>Planar or undulose and gradational.</td>
<td>Metres to 10s metres</td>
<td>Predominantly (&gt;95%) clays (kaolinite &amp; smectite), silt (quartz) and minor mica. Flattened larger benthic foraminifera (&lt;1%), small benthic foraminifera, barren of nannofossils. Disseminated carbon and leaves (2-4%).</td>
<td>Fissile, mm parallel lamination, homogeneous or bioturbated. Some cross-laminated silty sand stringers.</td>
<td>&gt;95%</td>
<td>Low-energy deposits, above fair-weather wave base. Locally aerobic.</td>
</tr>
<tr>
<td>Silty sand and clay facies</td>
<td>Laminated silty sand and clay</td>
<td>Base of succession: overlain by shale-clay. Top of succession: overlies shale-clay.</td>
<td>cm/dm</td>
<td>Planar and sharp or gradational.</td>
<td>Metres to 10s metres</td>
<td>Quartz-rich silty sand with often abundant clay laminae. Abundant disseminated carbon, and well-preserved leaves along laminae. Fragmented shells (3-4%).</td>
<td>mm parallel and cross-lamination. Load and flame structures. Bio-turbation. Some massive sands</td>
<td>&gt;95%</td>
<td>Low to moderate-energy above fair weather wave base. Significant siliciclastic input.</td>
</tr>
<tr>
<td><strong>Mixed carbonate-siliciclastic facies association</strong>&lt;br&gt;(35-80% siliciclastics)</td>
<td></td>
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</tr>
<tr>
<td>Platy coral sheetstone facies</td>
<td>Platy coral sheet-platestone.</td>
<td>Base of succession and margins of patch reef: overlies shale facies, interdigitates with, and overlain by bioclastic wacke-flourstones and branching coral pillastones. Top of succession: overlain by larger benthic foraminifera packstones, interdigitates with bioclastic wacke-flourstones.</td>
<td>dm/m</td>
<td>Planar or undulose and gradational.</td>
<td>Metres to 10s metres</td>
<td>Well-preserved, abundant platy corals (20-40%), up to few cm thick and 40 cm across. Fragmented unabetted platy and branching corals. Disc-shaped solitary corals (1-25%), few cm across. Flattened larger benthic foraminifera (2-3%). Pectens and gastropods (1-2%). Halimeda (&lt;10%). Coralline algae encrustation at top of section. Abundant clay, minor silt and mica matrix (20-45%).</td>
<td>Clayey wackestone facies</td>
<td>40-80%</td>
<td>Low-energy deposits in photic zone. In situ growth of platy corals in turbid waters with high influx of fine siliciclastics.</td>
</tr>
<tr>
<td>Clayey wackestone facies</td>
<td>Branching coral clayey wackestone, Branching coral and foraminifera clayey wackestone.</td>
<td>Top of succession and margins of patch reef: interbedded with wacke-flourstones and coral mud-flourstones.</td>
<td>dm/m</td>
<td>Planar or undulose and sharp or gradational.</td>
<td>Metres to 10s metres</td>
<td>Dark gray clay matrix (40-70%). Abundant flattened branching corals, few mm diameter (30-40%), flattened larger benthic foraminifera (&lt;5%), disc-shaped solitary corals (1-25%), few cm across.</td>
<td>Elongate larger benthic foraminifera mostly bed parallel.</td>
<td>50-70%</td>
<td>Low-energy, high influx of clays in photic zone. Biotic production in turbid waters.</td>
</tr>
<tr>
<td>Sandy packstone facies</td>
<td>Bioclastic sandy packstone.</td>
<td>Top of succession and margins of patch reef: overlies platy coral sheetstones, overlain by mudstones.</td>
<td>dm/m</td>
<td>Planar and sharp or gradational.</td>
<td>Metres to 10s metres</td>
<td>Quartz-rich (90%) packstone, with clayey matrix. Disseminated plant material common (5%). Flattened larger benthic foraminifera (80%), pectens (4-5%) and echinoid spines (2-3%).</td>
<td>Friable. Burrows common along bed surfaces.</td>
<td>60%</td>
<td>Moderate energy influx of fine sand and nutrients above fair-weather wave base. Some biotic production.</td>
</tr>
<tr>
<td>Larger benthic foraminifera packstone facies</td>
<td>Larger benthic foraminifera wacke-packstone, rhodolith and larger-benthic-foraminifera bioclastic packstone.</td>
<td>Top of succession: overlies platy coral sheetstones, overlain by shale-clay facies, coralline algae and coral floatstones, or coral mud-flourstones.</td>
<td>dm/m</td>
<td>Planar or undulose and sharp.</td>
<td>Metres to 100s metres</td>
<td>Abundant larger benthic foraminifera, up to 1.5 cm across, then flat and more robust forms (25-50%). Some fragmentation and encrustation by coralline algae of robust foraminifera. Rare planktonic foraminifera. Well-preserved pectens and gastropods (2-3%). Fissile clay-silt matrix.</td>
<td>Elongate larger benthic foraminifera mostly bed parallel.</td>
<td>20-50%</td>
<td>Low to moderate energy in photic zone. Unstable shifting substrate, possibly with seagrass in turbid water with considerable fine siliciclastic input.</td>
</tr>
</tbody>
</table>
Table 2.—Continued.

<table>
<thead>
<tr>
<th>Facies Association and Faces</th>
<th>Lithologies</th>
<th>Location and Occurrence</th>
<th>Bed Thickness</th>
<th>Bed Contacts</th>
<th>Lateral Continuity</th>
<th>Components</th>
<th>Sedimentary Structures</th>
<th>% Non-carbonate</th>
<th>Environmental Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching coral pillar-peloidstone facies</td>
<td>Branching coral pillar-peloidstone, branching and platy coral pillar-peloidstone</td>
<td>Lower to middle part of succession: interbedded with branching and head coral mix-domestones and platy coral sheet-platestones.</td>
<td>dm/m</td>
<td>Planar or undulose and sharp or gradational</td>
<td>Metres to 10s metres</td>
<td>Predominantly in situ branching corals (30-50%), some bored &amp; encrusted. Fragmented and unbudded branching corals (&lt;2%), head corals (&lt;15%), and platy corals (&lt;15%). Micritic or shaley wacke-packstone matrix includes echinoid spines (1-2%), pectens (1-2%). Excavation of corals by coralline algae (5-10%) and foraminifera (&lt;3%).</td>
<td>25-35%</td>
<td>Low to moderate energy in shallow part of photic zone. In situ growth of branching corals in area of moderate fine siliclastic input. Some toppling of near in situ corals.</td>
<td></td>
</tr>
<tr>
<td>Coral rud-floatstone facies</td>
<td>Branching coral rud-float-packstone, Head coral rud-float-packstone, Head and branching coral rud-floatstone</td>
<td>Towards base and top of succession: interbedded with platy coral sheet-platestone and branching coral pil- larstones. Top of succession: also interbedded with rhodolith and coral floatstones.</td>
<td>dm/m</td>
<td>Planar or undulose and sharp or gradational</td>
<td>Metres to 10s metres, may form low angle lens, few-metre across</td>
<td>Corals (30-60% fragmented, unbudded branching and head corals). Minor platy corals. Micritic or shaley wacke-packstone matrix includes echinoid spines (1-2%), pectens (1-2%). Excavation of corals by coralline algae (5-10%) and foraminifera (&lt;3%).</td>
<td>15-30%</td>
<td>Low to moderate energy in shallow part of photic zone. Toppling of in situ branching or head corals. Some fine siliclastic input.</td>
<td></td>
</tr>
<tr>
<td>Coralline algae and coral floatstone facies</td>
<td>Rhodolith and coral pack-float-mix-mudstone, Rhodolith and branching coral float-pillar-packstone, Coralline algae and coral float-mudstone</td>
<td>Towards top of succession: overlies head coral mix-domestones, interbedded with coral float-rudstones and platy coral sheetstones. Rare at base of succession: interbedded with platy coral sheetstones and coral rud-floatstones.</td>
<td>dm/m</td>
<td>Planar or undulose and gradational.</td>
<td>Metres to 10s metres</td>
<td>Branching and head corals (30-40% fragmented and in situ, bored and encrusted). Rhodoliths, up to 6 cm, branching and encrusting coralline algae (10-15%). Micritic shaley wacke-packstone matrix includes echinoid spines (2-4%), pectens (&lt;1%) and disseminated Halimeda plates (&lt;2%).</td>
<td>10-30%</td>
<td>Low to moderate energy in shallow part of photic zone. In situ growth of coralline algae and corals in area of moderate fine silicilastic and nutrient input. Some toppling of near in situ corals.</td>
<td></td>
</tr>
<tr>
<td>Bioclastic wacke-packstone facies</td>
<td>Bioclastic wacke-pack-floatstone, Coral bioclastic pack-floatstone</td>
<td>Base of succession: Interbedded with platy coral sheet-platestones.</td>
<td>dm</td>
<td>Planar or undulose and sharp or gradational</td>
<td>Metres to 10s metres</td>
<td>Well-preserved platy corals (&lt;20%), up to few cm thick and 40 cm across, some bored and fragmented. Minor branching and head corals, up to 10 cm across (&lt;10%). Larger benthic foraminifera (&lt;5%). Echinoid spines (1-2%), pectens and gastropods (1-2%). Coralline algae, branching or mm encrustation (2-3%). Clay, minor silt and micrite matrix.</td>
<td>Some alignment of elongate bioclasts</td>
<td>15-25%</td>
<td>Low energy within photic zone. Some influx of fine silicilastic material.</td>
</tr>
<tr>
<td>Halimeda and foraminifera-wackestone facies</td>
<td>Halimeda and larger benthic foraminifera-bioclastic packstone, Halimeda and platy coral sheetstones, Halimeda and branching coral pack-floatstone</td>
<td>Top of succession and margins of patch reef: overlies platy coral sheetstones, overlain by shale-clay.</td>
<td>dm</td>
<td>Planar and sharp or gradational</td>
<td>Metres to 10s metres</td>
<td>Well-preserved Halimeda plates (15-40%). Flat layered large benthic foraminifera (up to 20%). Thin platy or branching corals (up to 30%). Fragmented branching coralline algae (2-15%), echinoid spines (&lt;2%) and pectens (&lt;3%). Micritic to shaly-silty matrix (30-80%). Disseminated plant material (up to 4%).</td>
<td>Elongate bioclasts aligned bed parallel.</td>
<td>10-25%</td>
<td>Low energy, high influx of clays and possibly nutrients in photic zone. Biotic production in turbid waters.</td>
</tr>
<tr>
<td>Head coral mix-domestone facies</td>
<td>Head coral mix-dome-mudstone, Head and branching coral pillar-mudstone</td>
<td>Middle of succession: interbedded with branching coral pillastones and coral rud-floatstones.</td>
<td>m</td>
<td>Planar or undulose and sharp or gradational</td>
<td>Metres to 10s metres</td>
<td>Predominantly (50-60%) in situ head and branching corals. Head corals up to 60-100 cm across. Some boring and encrustation of corals particularly fragmented corals by coralline algae. Micritic wacke-packstone matrix includes echinoid spines (1-2%), pectens (1-2%), and Halimeda plates (&lt;2%).</td>
<td>Massive bed, in situ head and branching corals common. Fragmented corals bed parallel to random alignment.</td>
<td>&lt;10-15%</td>
<td>Low to moderate energy in shallow part of photic zone. In situ growth of branching and head corals in area of limited fine silicilastic input. Some toppling of near in situ corals.</td>
</tr>
</tbody>
</table>
floatstone and the *Halimeda* and foraminifera–coral wackestone, other bioclasts dominate.

Bioclastic wacke–pack–floatstone beds are present throughout the patch reefs, but are most commonly found interbedded with platy coral sheet–platestones. The bioclasts present (< 40%) include corals, larger benthic foraminifera, echinoid spines, pectens, and gastropods.

The platy coral sheetstones and clayey wackestone units forming the basal and marginal deposits of the patch reefs are interbedded with, and pass up-section and laterally into, branching coral pillarstones and coral rud–floatstones. Siliciclastic content within the pillarstones and float–rud–floatstones is 15–35%. These facies contain abundant branching corals, such as *Porites* and *Stylophora*, together with possible hydrozoans (*Heliopora*), which are commonly distinctive but may become more robust up-section. The pillarstones and float–rud–stones pass up-section and along strike into head coral mix–domestones (Fig. 6F), and coral float–rud–stones. The mix–domestones contain a variety of recrystallized branching and head corals, including *Favia*, *Porites*, and *Goniopora*, showing minimal evidence for fragmentation and abrasion, with colony sizes up to 1–2 m across. The micritic or shaly wackestone matrix to these facies contains echinoid spines, larger benthic foraminifera, pectens, and minor *Halimeda*. As the succession becomes richer in *in situ* branching and then head corals, there is a decrease in the siliciclastic content to around 20% and 6–10%, respectively. Although these are the general trends in corals and lithologies along beds, there is considerable local variation, particularly in the mix–domestones and float–rud–stones. Lateral changes in lithologies from sheetstones through to domestones along strike of individual beds may be accompanied by a stratigraphic difference of just a few meters, with the mix–domestones developed in slightly elevated positions.

Coralline algae and coral floatstone facies are common in the upper parts of the patch reefs. Siliciclastic content within these deposits at 10–30% is higher than in the head-coral mix–domestones, which they commonly overlie. Coralline algae is present as branching fragments and loosely laminar rhodoliths up to 6 cm in diameter. Fragmented and *in situ* branching and head corals are heavily bored and encrusted with coralline algae, commonly *Mesophyllum*, and *Acervulinid* foraminifera. Coral pillarstones and float–rud–stones are also common towards the top of the patch reefs, but in contrast to deposits lower in the section, corals are commonly bored and encrusted (Fig. 6G). Lithologies towards the top of the patch reefs tend to be rich in carbonaceous material together with echinoid plates and flattened larger benthic foraminifera.

**The Halimeda and foraminifera–coral wackestone facies was only seen capping, or forming marginal deposits to, the patch reefs.** This facies contains 15–40% unabraded, recrystallized *Halimeda* plates (Fig. 6I) and up to 4% disseminated plant material. Other bioclasts present include thin platy or branching corals, flattened larger benthic foraminifera, echinoid spines, pectens, and fragmented branching coralline algae. **Interpretation.**—As in the mixed facies, there is minimal breakage and abrasion of bioclasts and most skeletal components accumulated *in situ*, or very close to *in situ*. The occurrence of well-preserved stenohaline photosynthetic organisms throughout these facies is indicative of marine conditions within the photic zone. Formation under low to moderate energy conditions is here suggested, on the basis of the presence of clay-size particles in all facies, general absence of abrasion of bioclasts, and the delicate to robust growth forms of skeletal components. All facies contain a siliciclastic component, and only the head-coral mix–domestone with 6–15% insoluble material is inferred to have formed during periods of low siliciclastic influx.

The remaining deposits, particularly from the upper parts of patch reefs, accumulated under high nutrient conditions associated with moderate siliciclastic input.

The diversity and robust growth forms of the branching and massive corals in the pillarstones, rud–floatstones, and mix–domestones is suggestive of development in shallow waters. Despite this diversity, *Acropora*, one of the most abundant corals in modern SE Asian reefs, is rare, perhaps because of its known modern preference for moderate to high energy, generally clear-water settings (Tomascik et al. 1997). Many of the corals present in the assemblages, such as *Porites* and *Goniopora*, are known for their sediment shedding ability and have been documented in low-energy, turbid environments today (Tomascik et al. 1997). Facies containing branching corals generally contain a higher siliciclastic component than those with massive corals, perhaps related to the sediment shedding ability of the former (Scoffin 1997).

The coralline alga *Mesophyllum* is reported from low-light environments and is commonly found in clear waters at depths of 20–80+ m (Ady 1979; Minnery et al. 1985; Perrin et al. 1995). *Acervulinid* foraminifera are a common component in reefal environments where ecological conditions, most frequently related to a decrease in light intensity, lead to the reduction of competition for substrate encrustation (Perrin 1992). Increased nutrient availability may be the explanation for the positive correlation between increased organic matter, siliciclastic content and degree of bioerosion and encrustation by algae and infaunal suspension feeders (Hallock and Schlager 1986; Perrin et al. 1995; Edinger et al. 2000) in the upper parts of the patch reefs. It is here inferred that the coralline algae facies accumulated during periods of high turbidity associated with nutrient input.

In Indonesia, *Halimeda* associated with a stenohaline fauna is common on lower reef slopes or platforms in 20–40 m water depth (Tomascik et al. 1997). An environment with low light penetration is inferred for the *Halimeda* and foraminifera–coral wackestone facies on the basis of the commonly flattened growth forms of photosynthetic corals. Although *Halimeda* is tolerant of siliciclastic and nutrient input (Gussman and Smith 2002), water clarity may have been moderate during accumulation of this facies because it contains a low to moderate concentration of fine siliciclastic material (10–25%). In Borneo, some beds of this *Halimeda*-rich facies occur at the margins of the patch reef, and would have formed in slightly deeper water depths than along strike *patch reef* “core” facies (see below). On the basis of the combined evidence it is here suggested that this facies accumulated predominantly in deeper, perhaps nutrient-rich waters, similar to the *Halimeda* bioherms offshore today (Roberts et al. 1987, 1988; Phipps and Roberts 1988; Roberts and Sydow 1996).

**DEVELOPMENT OF PATCH REEFS**

**Initiation and Growth of Patch Reefs**

Patch reefs initially developed on a soft, muddy substrate either at the margins of a distributary-mouth bar or in abandoned tidal or distributary channels. Although corals are good colonizers of rubble (Hayward 1985; Braga et al. 1990) there is less documentation that corals colonize soft, fine-grained substrates. During an early coring study, deposits of a fringing reef developed in turbid waters bordering Sumatra were found to rest entirely on a muddy substrate (Sluiter 1890; Umbgrove 1947). Subsequent studies in Java, Sulawesi, Borneo, and Thailand have shown that reefal initiation on soft substrates is common in SE Asia (Umbgrove 1947; Neth-erwood and Wight 1992; Tudhope and Scoffin 1994; Tomascik et al. 1997).
Fig. 9.—Detailed log correlation of measured sections from the Airputih patch reef. Colored correlation tie lines shown are based on a combination of walking out bed surfaces in the field, biostratigraphic age dating, and changes in siliclastic content. Note that the colored correlated surfaces shown generally correspond to patch-reef “sequence boundaries” related to changes in siliclastic content. The deposits of the Airputih patch reef are interpreted as two major amalgamated patch-reef successions. Rough correlation of units is also possible through lateral and vertical tracing of the siliclastic content (white, gray, and stippled background effects). However, because there is some overlap in siliclastic content between carbonate and mixed carbonate–siliciclastic facies, some beds of carbonates facies with a > 30% siliciclastic content appear in the gray, predominantly mixed carbonate–siliciclastic facies field.
Mechanisms for coral colonization of soft substrates include settling and growth of planulae on any loose solid fragments of rocks or bioclasts (Umbgrove 1947; Tomascik et al. 1997), or through laminar growth forms spreading out over the substrate (Martin et al. 1989). It is inferred that both of these mechanisms were important during early colonization by platy corals, with larger benthic foraminifera, solitary corals, or molluscs perhaps acting as suitable initial substrates. The Agariciidae, which includes the Pachyseris and Leptoseris found in abundance in the platy-coral sheetstones, are known to be one of the early colonizers in Indo-Pacific reefs following environmental disturbance (Tomascik et al. 1997). A further mechanism for soft substrate colonization through breakage and regrowth of fragmented corals, such as Porites (Tudhope and Scoffin 1994; Tomascik et al. 1997) may have been locally important within the patch reefs or towards their margins.

Once the corals were established, rigid frameworks did not form in the patch-reef deposits. This is due to the growth forms of the biota present, the contemporaneous deposition of fine siliciclastic material surrounding bioclasts, and the common occurrence of bioerosion. The lack of rigid frameworks and limited depth range inhabitable by photosynthesis hindered development of steep margins, and the patch reefs slope gently into deeper water (Figs. 10, 11). The susceptibility of turbid-water reefs to early reworking (Tudhope and Scoffin 1994) due to the combined lack of rigid frameworks, paucity of marine cements, the high proportion of unconsolidated matrix, and the presence of structurally delicate, often bioeroded skeletons, affects their preservation potential (see below).

**Morphology and Differential Compaction of Patch Reefs**

The dimensions of the patch reefs preserved at outcrop gives some idea of their original low-relief morphology during development, albeit with a profile accentuated by differential compaction (Figs. 7, 9). Dewatering and burial of shales may result in 80–90% compaction (Tucker 1992). In the modern delta, prodelta clays in areas of mouth-bar formation have compacted by 5–7 m, resulting in greater accommodation space and thickening of delta-front deposits (Allen and Chambers 1998). In the patch reefs carbonate facies containing more abundant clays show progressively greater compaction effects. On the basis of measuring the profile of crushed bioclasts in the clayey wackestones and platy-coral sheetstones, it is inferred that these clay-rich facies underwent 60–80% compaction. Compaction of carbonate-rich lithologies has taken place through a combination of mechanical and chemical compaction, the later resulting in dissolution seams and minor sutured grain contacts. Judging by draping of units over competent uncompacted massive corals and petrographic studies of dissolution seams, compaction of 20–30% is suggested for the head-coral mix-domestone. Using these rough values all patch reefs are inferred to have had low depositional relief, on the order of a few meters, prior to compaction (Fig. 10). The patch-reef surface would have been irregular, with slope angles no higher than a few degrees.

**Demise of Patch Reefs**

All the patch reefs studied were transient and met their demise in different ways:
Major controls on carbonate development

- Climate
- Siliciclastic input
- Tectonics

Factors related to siliciclastic input
- External factors (e.g., relative sea-level change & hydrodynamic regime)

Influences on carbonate development related to siliciclastic input
- Siliciclastic, shoreline-attached, humid equatorial settings, such as a delta front

- Amount of clastic input: High
- Timing of influx: Nearly continuous
- Clast size: Predominantly clay to sand
- Marine water salinity: Normal to low
- Nutrients: High
- Turbidity & light penetration: High turbidity, low light penetration
- Substrate: Often soft (muddy or sandy)

Other local environmental factors:
- Temperature (optimum 25-35°C)
- Depositional energy

A) Local environmental conditions
- High, nearly continuous input of freshwater, rich in fine-grained terrigenous siliciclastics +/− nutrients
- Turbidity of water is highest closest to siliciclastic input or in areas of resuspension
- Salinity often < 35%
- Limit of photosynthesis: where incident light < 20-50% surface illumination
- Photic zone: often < 10 m

B) Type of biota and their morphology
- Tolerant of fine siliciclastics &/or low light
- Mobile benthos
- Colonizers or inhabitants of unstable substrates
- Tolerant or able to utilize elevated nutrients

Flattened photosynthetic organisms to tolerate low light
- Adapted to shed sediment
- Adaptation to soft sediment inhabitation
- Change due to incorporation of sediment

C) Local sequence development
- Reduction in depth range of photosynthetic organisms and change to biotic depth zonation
- Depth range & deposit texture influenced morphology of carbonate deposits
- Carbonates often on minor bathymetric highs
- Localized, patch reefs in shallow water

Vertical and lateral variations influenced by siliciclastic input, turbidity, and nutrients

D) Regional location of carbonate development (mostly autogenic controls)

Carbonates (black) most common on highs in areas of active shelf currents, abandonment of fluvial distributaries, or less active delta lobe.

E) Regional sequence development (allogenic or autogenic controls)

Late highstand to early regression - Carbonates unlikely during highstand delta progradation, but may occur if hinterland is supplying little siliciclastic material or if delta lobe or distributary abandonment occurs due to dispersion along broad delta front. Preservation of carbonates unlikely due to subsequent reworking (unless subsidence).

Late transgression to early highstand - Carbonates likely in shallow water during stillstand. Highstand deltas may prograde over and preserve carbonates, or they may be eroded during later sea level fall.

Late lowstand to early transgression - Carbonates likely following delta lobe or distributary abandonment likely after "dispersion" of siliciclastics, along broad delta front, and decreasing sediment supply from hinterland. Carbonates have good preservation potential unless eroded during high-energy transgressive flooding.

Late regression to early lowstand - Continued progradation of deltaic, carbonates unlikely, but if present highly localized. Carbonates have moderate preservation potential due to likely covering by siliciclastics.

Regression - Renewed progradation of deltaic, carbonates, if present, likely to be highly localized. Non-framework carbonates likely to be reworked during subsequent emergence.

Result: Localized carbonates can form in delta-front areas during any stage of relative sea level. However, they are most likely to form and be preserved during late lowstand to transgression, and possibly highstands.
Increase in Siliciclastic Input and/or Nutrient Input in Very Shallow Water.—Most of the patch-reef deposits have an increasing siliciclastic, and carbonaceous, component associated with shallow-water biota in their upper parts. Many successions are capped by foraminifera-rich deposits together with plant-rich clays and rippled silty sands, all of which accumulated in shallow, high-nutrient waters. It is inferred that increased siliciclastic and nutrient input due to renewed delta front progradation resulted in demise of patch-reef production through a combination of physical smothering by sediment, decreased light levels, and increased nutrient levels.

Increase in Siliciclastic Input and/or Nutrient Input in Moderate Water Depths, Perhaps Associated with Deepening.—Because all the reef sections studied are overlain by shallow-water siliciclastics, the overall mechanism for their demise is inferred to be via increased siliciclastic input as described above. However, for the larger patch reefs such as Permasip, as the areas closer to siliciclastic input were “smothered,” more distal, perhaps moderate-water-depth areas might have experienced increased nutrients. The deposits rich in Halimeda, formed at the margins and capping some of the patch-reef sections, are inferred to have formed under these conditions of high nutrient input. A relative rise in sea level, perhaps associated with increased nutrient input, might also result in Halimeda-rich deposits capping patch reefs, as may be the case for bioherms on the modern shelf.

Subaerial Exposure.—This is not thought to have resulted in the demise of any of the reefs studied, but it may have caused a temporary cessation in production at Senoni. At Senoni an irregular, possibly karstified horizon (Fig. 7) with up to 20 cm relief is overlain by a head-coral mix–domestone. If subaerial exposure occurred, carbonate production was reestablished as relative sea level rose. In turbid settings renewed photoautotroph production may be the cause for bioherms on the modern shelf.

DISCUSSION

Siliciclastic–Carbonate Interactions

The results from this study and other recent studies indicate that reefal development, although modified by siliciclastic input, is a natural, if transient, phenomenon in many turbid-water equatorial areas. Of the four categories of mixed carbonate–siliciclastic successions recognized by Mount (1984) only “in situ mixing” is applicable to the delta-front reefs of Borneo. However, Mount (1984) suggested that in situ mixing is favored in temperate settings with foramol deposits rather than warm-water equatorial settings. The apparent paucity of in situ mixing in warm-water settings was attributed to the inhibiting effects of increased turbidity, unstable substrates, and the clogging of feeding mechanisms, all factors thought to hinder development of chlorozoo–chlaralgal assemblages (Mount 1984). However, these Miocene patch reefs contain a diverse chlorozoan and chloralgal assemblage; they formed in turbid waters, on unstable substrates, with the organisms present using a variety of feeding strategies despite contemporaneous siliciclastic input. Recent results from this, and other similar Cenozoic (Netherwood and Wight 1992; Saller and Vijaya 2002; Wilson 2002) and modern (Tomasick et al. 1997; Larcombe et al. 2001) examples in Australasia reveal that if conditions are suitable, siliciclastic input and turbid waters do not always limit equatorial reef development.

Using the Miocene patch reefs of Borneo as one example, Wilson and Lokier (2002) evaluated the influences of siliciclastic and volcaniclastic input on carbonate development in different climatic or depositional settings. They recognized that in humid equatorial settings high rainfall is associated with high rates of weathering, erosion, terrestrial runoff, and onshore organic productivity. Consequently, nearshore carbonate producers in equatorial areas were subjected to high levels of terrestrial-derived fine-grained elastic input associated with freshwater and high nutrient influxes.

This study corroborates the findings of Wilson and Lokier (2002) that clastic influx has three major influences on carbonate development: (1) changes in types of biota, (2) changes in morphology of biota, and (3) influences on deposit characteristics and sequence development. Wilson and Lokier (2002) did not document the third point, and sequence development and influencing factors are discussed in more detail below and in Figure 11. To briefly summarize the findings on the first two points, a variety of carbonate-producing biota, including larger benthic foraminifera, coralline algae, echinoderms, molluscs, and platy and branching corals could tolerate nearly continuous siliciclastic influx approximately equal to their production rates. These organisms adopted various strategies for coping with clastic influx, including a degree of mobility, some heterotrophic feeding, morphologies adapted to unstable substrate inhabitation or sediment shedding, and shapes adapted to low light levels (Wilson and Lokier 2002). A commonly held view is that carbonates developed in areas of siliciclastic input would have low biotic diversity. As shown herein, although low diversities may occur in deposits such as the platy coral sheetstones, for the patch reefs as a whole diversities are considered moderate to high, with at least ten coral genera and a wide range of other biota present. This is consistent with other turbid-water reefs where coral diversity may be similar to or up to around two thirds that of clear-water reefs (McClanahan and Obura 1997; Larcombe et al. 2001; Sanders and Baron-Szabo in press).

Influences on Patch-Reef and Sequence Development

A range of commonly interlinked factors, operating on a variety of scales, influence the development of turbid-water mixed carbonate–siliciclastic successions (Fig. 11). On a local scale, changes in siliciclastic input, environmental conditions, and presence of slight basement highs were the main influences on trophic levels and light penetration, and consequently the biota and stratigraphy of individual patch reefs. Locally, accommodation space for individual patch reefs could be created through a decrease in siliciclastic supply, together with compaction, although distinguishing this from a gradual rise in relative sea level is problematic. On a regional scale carbonate development within the delta is related to autogenic changes in lobe activity or sediment supply, or rises in relative sea level due to eustasy or tectonics.

Local Siliciclastic Input.—Reduced water clarity resulting from turbidity, associated with siliciclastic input or resuspension events (Larcombe et al. 2001), is interpreted as the dominant influence on local development of patch reefs rather than fluctuations in relative water depth. Reasons for this interpretation include that the biota and sedimentary structures present throughout the deposits are indicative of shallow waters. There is no evidence, such as plankton-rich flooding surfaces or abundant subaerial exposure surfaces, that relative changes in sea level had a major affect on patch-reef development. Changes in phototrophs towards forms better adapted to low light levels, which in clear-water reefs would be interpreted as a response to deepening, are instead associated with periods of increased siliciclastic content (Fig. 8). Although morphology of biota can also be related to changes in energy, low to moderate energies are inferred for all deposits. The patch reefs developed in shallow waters over a bathymetric
range of a few meters, yet these deposits show all the common zonation of clear-water reefs normally spread over many tens of meters (Pomar 2001). On the basis of their morphology and depth zonation these patch reefs are inferred to have formed in an area where light penetration was restricted to around the upper ten meters of the water column. In turbid waters the depth at which light penetration drops below that required for hermatypic corals (2–0.5% of incident surface radiation) is typically up to, or significantly shallower than, 20 m (Acevedo et al. 1989; Titlyanov and Latypov 1991).

In initial patch-reef deposits siliciclastic content is high, and it is inferred that turbid waters resulting in low water clarity allowed colonization only by opportunistic photautotrophs in very shallow water (Figs. 10, 11). As siliciclastic content decreases, organisms adapted to lower siliciclastic input and higher light levels dominate the very shallow-water assemblages. During periods of fine-grained siliciclastic onlap onto the gently sloping margins, siliciclastic content increases in patch-reef deposits. At these times of onlap, the area of carbonate production shrinks to the central, shallowest-water area of the patch reef (Fig. 10). There is also vertical contraction of the carbonate zonation, and assemblages adapted to low light levels and high siliciclastic input moved into bathymetrically elevated positions (cf. Acevedo et al. 1989). Any subsequent decrease in siliciclastic content was associated with an increase in areal extent of carbonate production, and patch-reef, or seagrass, deposits spread out over, or downlap onto, the fine-grained siliciclastics at their margins. There is also a reexpansion of the light-dependent depth zonation of biota within the patch reef.

Other Local Environmental Influences.—In addition to turbidity other factors that influenced local patch-reef development are nutrient influx, deposition rate, and presence of slight bathymetric highs (Fig. 11). Nutrient input is often associated with increased siliciclastic input, and organisms adapted to eutrophic conditions such as algae, associated grazers, and infaunal suspension feeders become common in the upper parts of successions. Some photautotrophic organisms, such as *Leptoseris*, may be able to switch to more heterotrophic feeding mechanisms in turbid, high-nutrient waters (Insalaco 1996). Development of low-light-level assemblages, in which organisms produce thin or structurally lighter skeletons (Tomascik et al. 1997), would have been feasible only in shallow waters under the inferred predominantly low-energy conditions. In higher-energy, turbid waters, robust corals may develop, but only within the upper few meters of the water column (Larcombe et al. 2001). The depositional topography at the delta front affects the highly localized distribution of carbonates. Patch reefs were preferentially developed on slight bathymetric highs inferred to be elevated into the photic zone and bypassed or shielded from some siliciclastic influx.

Autogenic Factors, such as Deltaic Switching, or Current Activity.—On the modern shelf, high sedimentation rates of the southern delta lobe and southward-flowing shelf currents result in less turbid waters, and a concentration of carbonates, on the northern part of the shelf (Roberts and Sydow 1996). On a smaller scale, individual distributary channels and associated mouthbars may be abandoned, convert to tidal channels, and become sites of local carbonate colonization, as seen in the northern part of the delta today (Allen and Chambers 1998). In Miocene outcrops, interdigation of plant-rich siliciclastics, containing bidirectional-facing asymmetric ripples, with patch-reef marginal deposits suggests that these environments were prone to fluvial flooding and renewed influx of siliciclastics in a tidal environment. Delta lobe switching, distributary abandonment, and shelf currents are all factors that may alter local siliciclastic supply and water turbidity independently of any relative sea-level change. Fossiliferous intervals from Spanish Eocene, and Texan Carboniferous, fan deltas were also highly localized and developed during the last of the delta-prograding paleodunes and distributary-channel mouthbars (Dutton 1982; Molenaar and Martinus 1996).

Effects of Base-Level Change, Compaction and Subsidence.—Sediment supply to the Kutai Basin has been variable with time, with intervals of rapid sedimentation associated with periods of uplift and erosion of older sediments (Allen and Chambers 1998). Compaction effects are known to be considerable in many deltas, with the original “soupy,” water-rich pro-delta muds and delta-front shales of the Mahakam reducing in thickness by 50% or more (Allen and Chambers 1998). Given that individual progradational deltaic units are typically on the order of tens of meters thick, compaction of the shale sequence could generate enough accommodation space for the thickness of carbonates seen in many of the outcrops. Overall the Miocene deposits of the Mahakam Delta are several kilometers to over ten kilometers in thickness. Regionally, tectonic subsidence during the Miocene has been considerable, with suggested long-term subsidence rates of 200–300 m/Myr. On a local scale, gravitational collapse and shale diapirism may also have been important in generating accommodation space. Regional subsidence would have provided accommodation space for carbonate and siliciclastic deposition and resulted in likely burial of carbonates. Since turbid-water reefs are generally uncremented and lack rigid frameworks, subsidence and burial is considered necessary for their preservation (Tudhope and Scoffin 1994).

Relative Sea-Level Changes.—Relative changes in sea level, with or without linked variations in siliciclastic input, may have a number of potential effects on the development of individual turbid-water patch reefs. Evidence of emergence associated with sea-level fall is not commonly seen in the patch reefs studied, perhaps because of the overall regime of subsidence, and the likelihood of erosion of the unconsolidated deposits (Johnson and Risk 1987; Tudhope and Scoffin 1994). Falling sea level is commonly associated with increased siliciclastic input, causing compaction of underlying prodelta clays and likely burial of carbonates. Gradual relative rise in sea level, whether through subsidence or eustasy, appears to have been instrumental in creating accommodation space and allowing carbonates to develop (see below). However, a rapid relative sea-level rise has the potential to result in deepening-upwards successions if carbonate production is unable to keep pace (Holland 1993; Choi et al. 1999; Yang and Komiz 2002; Rankey et al. 1999). This would be particularly important if siliciclastic input is not reduced in association with any relative rise, because carbonate producers may become submerged below the depth of a shallow photic zone. The production rates of uppermost *Halimeda*-rich deposits from offshore bioturbations are inferred to have decreased rapidly because of increasing water depths (Phelps and Roberts 1988). It is suggested here that the shallow-water coral-rich reefs may convert to deep-water *Halimeda* banks if they are unable to “keep-up” with relative sea-level rise in the nutrient-rich waters of the delta front. A sea-level stillstand during the current relative highstand period has allowed renewed progradation of the Mahakam Delta. This high siliciclastic input has limited carbonate production to distal areas of the shelf, or areas of moderate to low delta-lobes activity following local reduction of siliciclastic input along a broadening delta front (Roberts and Sydow 1996; Allen and Chambers 1998).

**Sequence Development**

Many of the internal changes observed within individual patch reefs can be attributed to variations in siliciclastic input, with accommodation space resulting from decreased siliciclastic input together with subsidence and/or relative changes in sea level. Additional data on larger-scale sequence development of turbid mixed carbonates–siliciclastics is gleaned from regional and published studies, and it remains for many of the ideas discussed here and summarized in Figure 11 to be fully tested. In turbid delta-front areas, although regional development and preservation of extensive carbonates is most likely under specific conditions, if local conditions are suitable they may develop during any stage of eustatic sea level (above and Fig. 11).

Similar to the extensive Holocene and earlier shelfal or subsurface carbonates from the Mahakam Delta (Roberts and Sydow 1996), the outcapping patch reefs developed at the lower to middle Miocene boundary (DPR, Airputih, Permasip and Bontang) are also interpreted as transgressive de-
in situ localized, restricted to a reduced photic zone, and any carbonates contain the shelf. In these turbid, highstand areas, carbonate development is highly restricted to coastal areas and the carbonates are predominantly siliciclastic. Extensive highstand carbonates formed, siliciclastic deposition was confined to coastal zones. However, in areas of high siliciclastic input such as the Mahakam Delta extensive turbid-water reef development is most common. The settings of patch-reef initiation during the Miocene were delta-front channels, or distributary-mouth bars, in the process of being abandoned. Although siliciclastic input was reduced compared with active distributary mouths, siliciclastic input was still considerable.

- Carbonate producers, particularly those dependent on light, were able to develop only in shallow water depths, because of a reduced depth of the photic zone. Extensive clear-water reefs are forming today in the northern, less active regions if the local environmental conditions are suitable. This is at odds with the suggestion that in situ mixing of carbonate and siliciclastic deposits favored cooler-water settings dominated by foraminiferal assemblages (Mount 1984). These turbid reefs may have variable, but close to comparable biodiversity as clear-water reefs, although their constituent biota, deposit characteristics, and sequence development often differ considerably.

**CONCLUSIONS**

- Carbonate production and does occur in areas of high, nearly constant, fine-grained siliciclastic input, such as delta-front areas in equatorial regions.
- Turbid-water reefs may have moderate to high biodiversity, but the organisms present are adapted to the local environmental conditions. As a consequence the assemblages of turbid-water reefs can be quite different from their better studied clear-water counterparts.
- Organisms found to be tolerant of siliciclastic input in the Miocene patch reefs include some larger benthic foraminifera, coralline algae, echinoids, molluscs, together with solitary, platy, and branching corals. Characteristics that enabled these organisms to inhabit areas affected by siliciclastic input included mobility, heterotrophic feeding, and morphology changes among photoautotrophs to maximize surface area available to incident light (Wilson and Lokier 2002).
- Patch-reef development was initiated on soft substrates in shallow waters on slight bathymetric highs. The settings of patch-reef initiation during the Miocene were delta-front channels, or distributary-mouth bars, in the process of being abandoned. Although siliciclastic input was reduced compared with active distributary mouths, siliciclastic input was still considerable.

**DELTA-FRONT PATCH REEF DEVELOPMENT**

- Carbonate production and bioherm or patch-reef development may occur in turbid-water, delta-front areas as localized or more regionally extensive units during any phase of eustatic sea level. Extensive clear-water highstand carbonates may develop where siliciclastic deposition is confined to coastal zones. However, in areas of high siliciclastic input such as the Mahakam Delta extensive turbid-water reef development is most likely when terrestrially derived material is confined during transgressions, regional decreases in influx, or local lobe abandonment often following progradation (Roberts and Sydow 1996; Allen and Chambers 1998). It is the interplay between factors such as tectonics, eustasy, delta switching, shelf currents, and amount and size fraction of siliciclastic sediment supply that ultimately control carbonate development and preservation (cf. Yang and Kominz 2002; Rankey et al. 1999).

Turbid-water reefs have been a natural phenomenon since at least the Triassic (Sanders and Baron-Szabo in press), and do develop in equatorial regions if the local environmental conditions are suitable. This is at odds with the suggestion that in situ mixing of carbonate and siliciclastic deposits favored cooler-water settings dominated by foraminiferal assemblages (Mount 1984). These turbid reefs may have variable, but close to comparable biodiversity as clear-water reefs, although their constituent biota, deposit characteristics, and sequence development often differ considerably.
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