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MORPHOLOGY AND DEVELOPMENT OF THE CAPE TRIBULATION FRINGING REEFS, GREAT BARRIER REEF, AUSTRALIA

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SUMMARY

The Cape Tribulation reefs are Holocene in age and began developing approximately 7800 years before present. Coral growth on the reef crest and most of the back reef ceased approximately 5400 years before present, probably in response to increasing turbidity and water quality deterioration as fine sediments accumulated offshore and became resuspended during strong winds. Significant coral growth is now restricted to the subtidal fore reef but reef progradation has been minimal over the last 5000 years.

The height of the reef crests relative to present day sea level and the absence of low magnesian calcite cements in the fringing reefs suggest that they have not been subjected to extensive subaerial exposure, with a maximum Holocene relative sea level of only 0.6 to 1.0 m above its present position being responsible for the height of the present algal covered reef crest.

The fringing reefs can be divided into four lithologic assemblages:

i) a fluvial gravel basement deposited as alluvial fans from the steeply sloping hinterland
ii) a lower framestone unit
iii) a detrital assemblage and
iv) an upper framestone-bandstone unit.

The reefs appear to be in a delicate state of balance having grown under environmental conditions more favourable than present. Further deterioration of the environment produced by anthropogenic factors such as increased sediment yield from the Cape Tribulation road have the potential to push water quality conditions beyond the point where reef growth can be maintained.

KEYWORDS: **Fringing reefs, Cape Tribulation, Great Barrier Reef, anthropogenic influences, Holocene sea levels**

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1 INTRODUCTION

The Great Barrier Reef System of northeastern Queensland, Australia encompasses an area of 230 000 km^2 and is made up of more than 2 500 reefs and numerous cays and high islands (Hopley *et al*, 1989). The reefs are distributed along a 2 000 km section of the Queensland continental shelf between 9°15' and 24°07' south latitude. The outer and middle shelf reefs are separated from the mainland by open water that attains depths of 50 m and varies from 23 to 260 km in width (Hopley, 1982; Johnson *et al*, 1986). Modern reef growth was initiated less than 10 000 years ago. In some locations Holocene reefs cover remnants of older Pleistocene and Miocene reefs (Hopley, 1982; Marshall, 1983) or clastic sedimentary deposits (Hopley *et al*, 1983; Johnson and Risk, 1987).

The Cape Tribulation fringing reefs (Fig 1) are of particular interest because they exist in turbid waters and in close proximity to a high-relief continental shoreline that is subject to high rainfall. The Cape Tribulation area shoreline is characterised by steep-gradient streams that, during episodic periods of high discharge following storms, deliver large volumes of sediment-laden fresh water to the otherwise normally saline marine waters surrounding the Cape Tribulation fringing reefs (Hoyal, 1986). Reef organisms, especially coral, are generally thought to require clear sea water and to be intolerant of fresh, hyposaline or turbid water (Wells, 1957). Despite the apparently adverse conditions in which the Cape Tribulation fringing reefs exist, the living coral zone of these reefs constitutes one of the most taxonomically diverse coral communities in the Great Barrier Reef System (Ayling and Ayling, 1985).

The fringing reefs of Cape Tribulation are also of interest because they represent a pioneer reef type that colonised the continental shelf of northeastern Australia during the latter part of the post-glacial rise in sea level (Hopley and Partain, 1987). The accessibility and relatively small size of the Cape Tribulation reefs provide a unique opportunity to study the Holocene development of mainland fringing coral reefs in the Great Barrier Reef Province.

Several investigators (Bird, 1971; Hopley, 1978; Slocombe, 1981; Hopley *et al*, 1982; Barnes, 1984; Hopley and Barnes, 1985; Johnson and Risk, 1987) have previously studied the age, evolution and structure of a number of fringing reefs in the Great Barrier Reef region. However, apart from the research contemporaneous with this study by Johnson and Carter (1987) which concentrated on the immediate offshore sedimentary environment and by Hoyal (1986) on the sedimentation patterns, there has been no previous study of the geologic history of the Cape Tribulation fringing reefs, or the coastal depositional environments and lithofacies associated with them.

The purpose of this study is to:

- Determine the age and growth rates of the reefs
- Investigate the possible influence of sea level fluctuations on the development of these reefs
- Describe the morphology and development of the reefs and the lithofacies associated with them.

The study area is located along a 10 km section of shoreline in northeastern Queensland, Australia (Fig 2). It is situated in the Cairns section of the Great Barrier Reef Marine Park. Adjacent to the study area is a portion of the Daintree tropical rainforest. The nearest major rivers that empty into the sea near the study area are the Bloomfield River, 21 km to the north, and the Daintree River, 24 km to the south. The study area ranges from latitudes 16°02'00"S to 16°08'00"S and longitudes 145°27'30"E to 145°28'30"E.

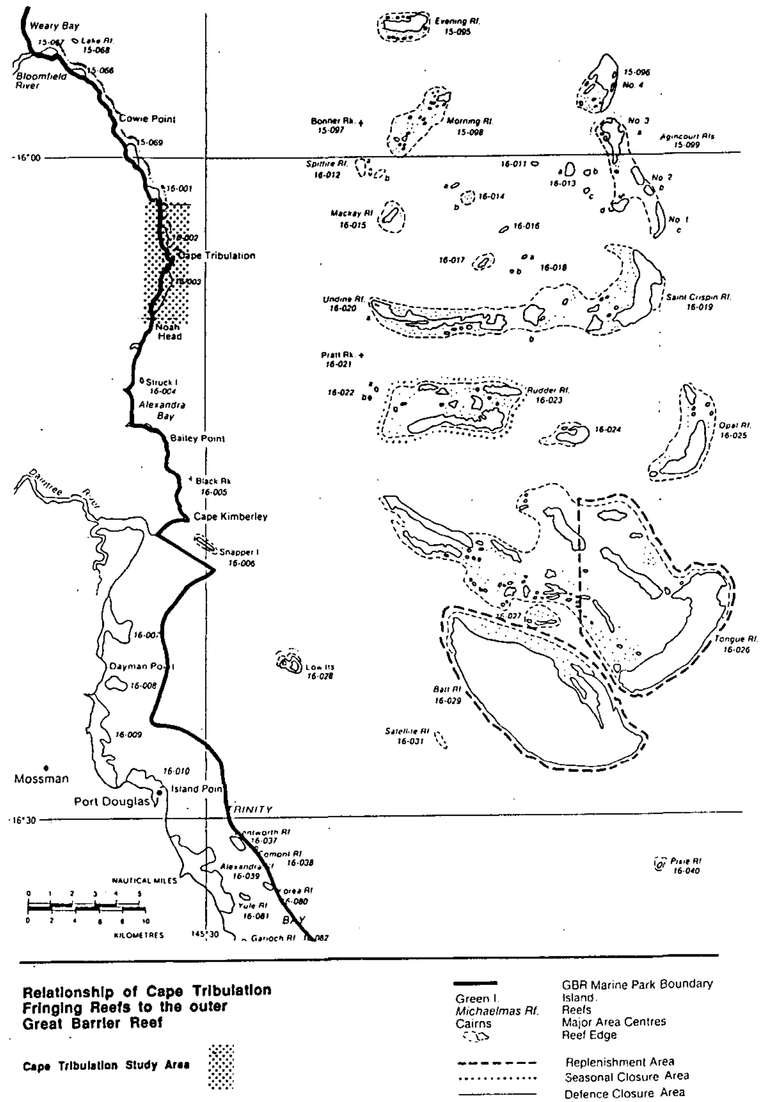

Figure 1. General location of the Cape Tribulation area.

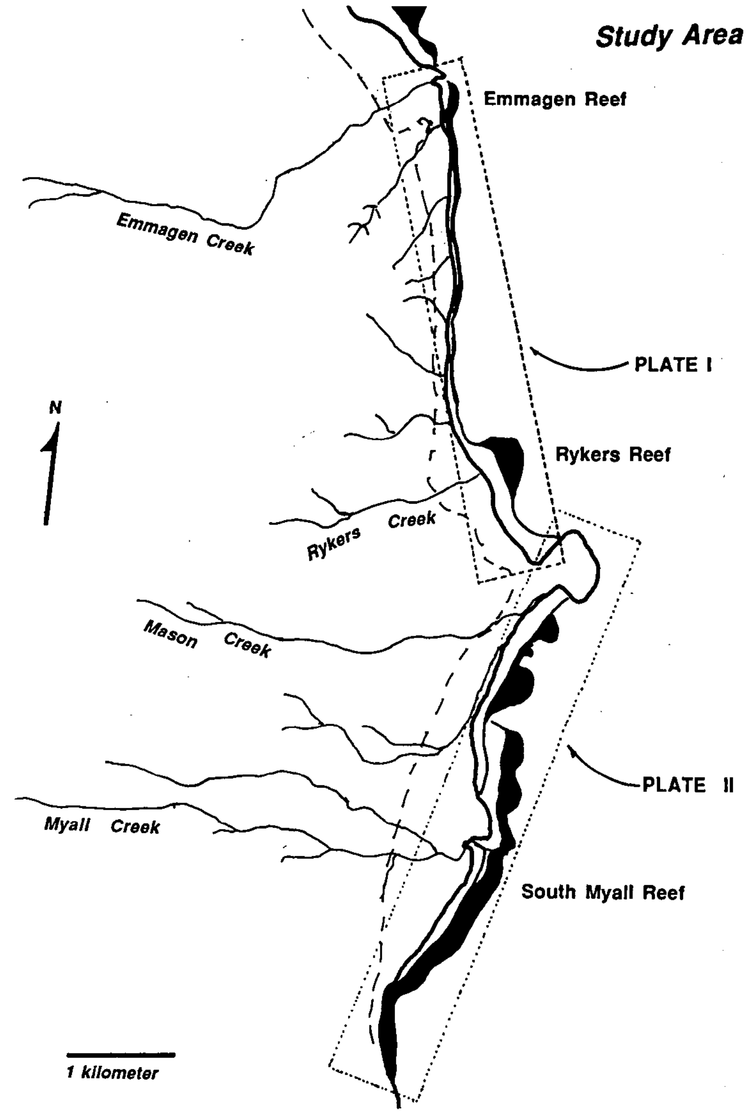

Figure 2. Location of Emmagen, Rykers and South Myall Reefs.

2 PREVIOUS INVESTIGATIONS

Studies of the Cape Tribulation Area

Ewart (1985) briefly described the geology of a small portion of the Cape Tribulation area. His research centred on the Thornton batholith, a Permian igneous intrusion that outcrops 3 km east of Cape Tribulation, and the Hodgkinson Formation, a Devonian metasedimentary complex that outcrops along the coast in the study area.

Cribb (1985) listed many species of marine algae that live in the backreef area of Rykers Reef. He also studied algae from along the rocky shore near Cape Tribulation and in the mangrove swamp south of Cape Tribulation.

Ayling and Ayling (1985) described some of the coral and fish species of the subtidal areas of several Cape Tribulation reefs. They concluded that living coral colonies on the Cape Tribulation fringing reefs constitute one of the most taxonomically diverse coral communities in the Great Barrier Reef system.

Veron (1987) listed 141 scleractinian coral species belonging to more than 50 genera found in the Cape Tribulation reefs, including three species not previously recorded on the Great Barrier Reef.

Hoyal (1986) discussed recent sedimentation trends in the Cape Tribulation area. He used sediment traps to measure suspended sediments in the water column of the intertidal and subtidal zone. Although rates of sediment settlement and levels of suspended sediment in the water column were high, Hoyal concluded that much of the sediment in the waters surrounding the reefs is continuously resuspended by normal wave action as well as by occasional storms. He also concluded that sediments from stream runoff were not the major cause of sea water turbidity.

Previous Investigations of the Age and Structure of Great Barrier Reef Fringing Reefs

Other investigators have studied fringing reefs located along and near the northeastern Australian coast. Closest to the study area, Bird (1971) described a continental fringing reef at Yule Point, located adjacent to the coastline approximately 60 km south of Cape Tribulation. He did not core this reef or determine C^{14} dates for the coral colonies in the reef, but he did obtain a C^{14} date of 4130±130 years BP (Before Present) for surface coralline algae. However, Bird acknowledged that coralline algae may yield questionable C^{14} dates.

Comparatively little work has been carried out on the age and structure of fringing reefs in the Great Barrier Reef province. Hopley *et al* (1978) examined cores obtained for engineering purposes on Hayman Island fringing reef which was shown to consist of a Holocene biohermal cover overlying a Pleistocene reefal base, the diagenetic features of which suggested prolonged subaerial exposure. The reef commenced to grow prior to 8300 yrs BP and, growing upwards at a rate of 4 to 5 mm/yr , reached modern sea level around 4500 yrs BP. The unconformity occurs approximately 20 m below MLWS beneath the present reef crest and appears to rise towards Hayman Island to about 15 m below MLWS (see also Hopley, 1982, Ch 12; and Hopley *et al*, 1983).

Slocombe (1981) as published in Hopley *et al* (1983) drilled the fringing reef adjacent to the Orpheus Island Research Station, Pioneer Bay, Palm Islands. This reef became established on the rocky shores of the island about 7000 yrs BP. It prograded over its own sand and shingle forereef talus as a relatively thin 3 to 4 m framework veneer. These reefal units have been established over an early?? Holocene transgressive unit, which in turn overlies a weathered Pleistocene clay base. Mean vertical accretion rates decline from 6.78 mm/yr for the inner reef flat to 2.2 mm/yr for the outer reef.

Hopley *et al* (1983) also reported on the drilling of a single hole on Rattlesnake Island. Again, beneath the reef at 11.5 m depth was a heavy oxidised presumably Pleistocene basement. Reef framework was very limited, forming only a thin <1.0 m veneer over a rubble base in which corals were rare but which had a mean accretion rate of 6.7 mm/yr. Information on other fringing reef structures came from engineering reports. Interpretation by Hopley *et al* (1983) suggested that reefs on Great Palm, Dunk and Magnetic Islands were all relatively thin with limited framework forming thin veneers over sand, mud or gravel lower sections.

A more exposed windward fringing reef was examined by Barnes (1984, published in Hopley and Barnes, 1985) at Iris Point on Orpheus Island. The Holocene reef was established over a Pleistocene boulder beach which currently outcrops behind the reef. Reef growth commenced prior to 7300 yrs BP and the reef was at or close to modern sea level by 6250 yrs BP. Mean vertical growth rates varied from 1.3 mm/yr to 4.7 mm/yr.

Another reef in the Palm Group, that on Fantome Island, was investigated by Johnson and Risk (1987). The reef is almost identical to the similarly situated Pioneer Bay reef on Orpheus Island, with reef flat established prior to 5500 yrs BP and a mean vertical accretion rate of 6.7 mm/yr. Terrigenous sediments also form a major part of the basal unit of the reef.

A further research programme is currently underway in the Cumberland and Northumberland Islands on the structure and growth of fringing reefs close to their southern growth limits under the supervision of one of the authors (David Hopley). To date, cores have been recovered from reefs on Cockermouth, Penrith and Scawfell Islands. Although analysis is only just commencing it is notable that extensive and shallow Pleistocene reef has been established on Cockermouth Island. Coring has also taken place on Lindquist Island in the Barnard Group though no results are yet available (T Graham, *pers comm*).

Contemporaneous with the commencement of this study was a parallel investigation on the Cape Tribulation area (Johnson and Carter, 1987) which included some auger drilling of the reef just north of Myall Creek. Radiocarbon dating of samples from the inner part of the fringing reef showed that the reef top unit commenced accumulating at least 6000 yrs BP. Encasement of the reef framework by a subsequent sediment matrix was also suggested.

3 METHODS

Field Survey

Fieldwork was conducted between February and July 1986. Initial work involved mapping the Cape Tribulation fringing reefs and associated lithofacies. Surveys were made using a transit level and a 3 m staff to:

- Outline shore and reef profiles
- Accurately locate drilling sites on the reefs
- Precisely determine the heights of the reefs relative to mean sea level and to the extremes of tidal fluctuations.

Twenty-one transects of at least four stations each were surveyed along the foreshore and across the reefs in the study area. Cross-sections of the reefs were constructed using this survey data and borehole information. All references to sea level or sea level variation were made relative to Cairns Port Datum. This predicted tidal datum, or zero point, has been calculated (Hampson, 1985) for tides at Cairns, that is 100 km south of the study area. The Cairns Port tidal charts were compared with those of Cooktown, located 72 km to the north of the study area, to determine values for Mean High Water Springs and other tidal planes in the study area.

Aerial Photography and Mapping

Aerial photography flown by both the Queensland Beach Protection Agency (QP3706: nos 87, 89, 91; QP4238: nos 22, 23, 24, 25, 26) and specially for this project in both colour and near infra-red was used in association with the surface surveys to accurately locate specific sample collecting sites. The aerial photographs were also used to construct planimetric outline base maps of the Cape Tribulation coastal area. The base maps were corrected to scale by use of a binocular plan variograph. Surface lithofacies maps (Fig 3) were made by plotting on the base maps field observations, sediment sample locations, and other measurements.

Coring

A portable rotary drilling rig (Fig 6) was used to obtain cores from nine boreholes in three of the Cape Tribulation fringing reefs. Four boreholes were cored in Rykers Reef, three in South Myall Reef, and two in Emmagen Reef. Drilling was halted when basal non-reef deposits were reached. Borehole depths ranged from 4.5 to 8.3 m. A coring bit and core catcher in the drill pipe allowed solid 45 mm diameter samples to be recovered. Sea water was continuously circulated through the drill pipe during drilling to remove cuttings and to prevent the drill string from binding in the hole. Because of the circulating water, unconsolidated sediments could not be collected in core samples. Only massive corals, cemented reef rubble and large detrital pieces were collected in the cores. Branching corals, such as acroporids, were usually obtained as broken pieces. Because of their size and shape, the pieces often jammed the core barrel.

Drilling logs were made during coring operations and amended after laboratory examination of the cores. Detailed microscopic examinations of the cores were carried out to determine lithologies and to identify fossils.

Corals were identified to genus and species if possible in the field or during subsequent laboratory study. The taxonomic names assigned to all coral specimens conform to those of Veron and Pichon (1976, 1979, 1982) and Veron and others (1977) for northeastern Australia. Coral identifications were verified by Dr Michel Pichon (*pers comm*, September 23 and 24, 1986). Identification to the species level often required an undamaged surface corallite, that was seldom obtained in core samples. Many of the borehole samples are therefore identified only as acroporids or *Porites* sp. Lithologic descriptions follow Dunham (1962) and Embry and Klovan (1971).

Core Analysis

More than one hundred individual rock samples, varying in length from less than 1 cm to 59 cm, were recovered from the cores. The core barrel was designed to collect samples up to 150 cm long. In practice, continuous cores over 60 cm long always broke during drilling.

Twenty-two 100-300 g surface samples, consisting of loose and cemented sediment, were collected along transects across each of the reefs and associated beach areas. Splits of these samples were sieved and the various grain-size fractions were determined according to methods of Folk and Ward (1957). A computer program for standard sedimentology computations, including grain-size distributions, was used to expedite data analysis. The program was written by the members of the Geology Department of the University of Waikato, New Zealand (Dr David Johnson, *pers comm*, August 12, 1986). Splits of sediment samples from each reef were placed in 10 percent HCl to determine the weight percentage of acid-soluble material in each sample. These sample splits were first dried and weighed, then placed in the acid. The residues were dried and weighed. All samples were also examined with a microscope at 10 to 100 diameters of magnification to help identify mineralogic and biologic components. Seven samples of unconsolidated sediment were also collected

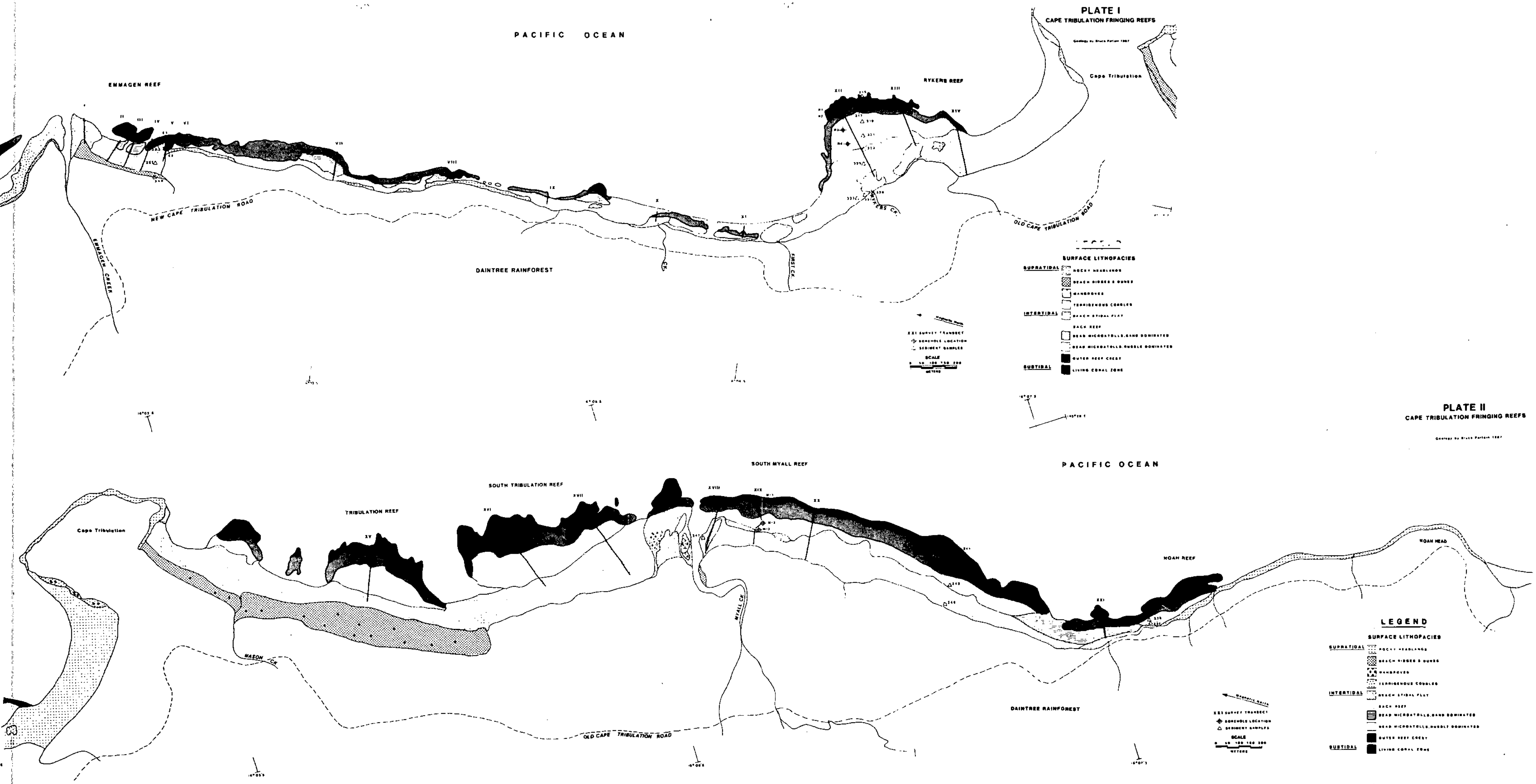

Figure 3. Surface lithofacies, Cape Tribulation reefs.

during drilling as the sediment circulated to the top of the borehole. These samples, three from Rykers Reef, three from South Myall Reef, and one from Emmagen Reef, were also analysed by sieving, acid digestion, and microscope study.

All core sections solid enough and long enough to be sawed were cut lengthwise. A 7 mm wide centre slice was taken from those core segments containing *Porites* sp. These slices were x-rayed to reveal coral growth-band patterns. Radiographs were made under the supervision of Keith Barry of Waterhouse Radiology, Townsville, Australia, using a Circlex condenser-discharge unit. Exposures ranged from 47-50 kilovolts at 15-20 milliamp-seconds with a tube-to-film distance of 90 cm. Fuji orthochromatic, green-sensitive radiographic film was used. Seventy-five thin sections were made from solid core and indurated surface sediment-samples. Because of the friable and porous nature of the samples, each thin-section sample block was vacuum-impregnated with "815" brand epoxy before being cut. The sample blocks were then mounted on frosted glass slides and cut and lapped to a thickness of 30 microns. To determine mineralogy and the extent of diagenesis in each sample, thin sections were studied at various magnifications with petrographic, scanning electron, or transmission electron microscopy. Solid sample chips were also studied with the electron microscope.

Selected thin sections were stained with Feigl's solution, Clayton Yellow, potassium ferrocyanate, and a mixture of Alizarin Red-S and NaOH (Feigl, 1958; Friedman, 1959).

High-magnesian calcite stains red while low-magnesian calcite remains colourless when stained with Clayton Yellow stain. High-magnesian calcite also stains with Alizarin Red-S in solution with 30 percent HaOH. Low-magnesian calcite remains colourless while magnesian calcite becomes purple. Feigl's solution (Feigl, 1958) is used to differentiate aragonite from calcite. Aragonite stains black while calcite and dolomite remain unstained. Control tests, using an echinoid spicule (high-magnesian calcite), a coral fragment (aragonite), and a pure (low-magnesian) calcite crystal, were performed to verify the staining procedures.

Thin sections were placed in a small beaker filled to a level where one-third of the section was stained. After one stain had dried, the section could be stained on the opposite end with a second stain. A small area in the centre of each slide was left unstained. Staining time was ten minutes for Feigl's solution, seven minutes for Clayton Yellow, and ten minutes for the Alizarin Red-NaOH solution.

The bulk of the laboratory work was done in Townsville, at James Cook University of North Queensland.

Radiocarbon Dating

Fourteen borehole samples and one surface sample, ranging from 21-103 g, were selected for C14 radiometric age dating. One surface sample and seven core samples were used from Rykers Reef, four core samples from South Myall Reef, and three core samples from Emmagen reef. Samples were selected on the basis of being relatively "clean", that is, free of bioturbation and visible precipitated cement. Generally, samples containing *Porites* sp and coalesced acroporid corals were chosen. All traces of boring or cementing organisms were removed with a Dremel Mototool hand drill. Samples were then dipped in 5 percent HCl, washed in distilled water and dried at 70°C. C14 dating was done by Sydney University's MacIntosh Centre for Quaternary Dating. Absolute ages were obtained for each sample by determining the C^{14} to C^{12} ratio and comparing this ratio to a known radioactivity-time scale (Urey, 1947; Gillespie, 1982).

4 REEF MORPHOLOGY AND LITHOFACIES

Survey transect locations are shown on Plates I and II. Transverse profiles of the reefs and adjacent shorelines (Figs 4 and 5) are numbered I through XXI, beginning with the most northerly transect. One survey, VI, is not shown in profile. This survey was made specifically to tie together two surveying stations.

Surveyed elevations of reef crests varied from 1.47 m above Cairns Port Datum (CPD) at Noah Reef to 0.70 m above CPD at South Myall Reef. The lowest backreef elevation, 0.15 m below CPD, was at South Myall Reef.

Surface Lithofacies

Eight separate surface lithofacies were mapped in the study area (Fig 3). These lithofacies are grouped according to their position relative to three tidal zones. These tidal zones are:

- Supratidal, a zone normally above sea level except during violent storms or strong onshore winds
- Intertidal, a zone alternately inundated and above water, depending on semi-diurnal tides
- Subtidal, a zone always below water.

Supratidal Zone

Rocky headlands facies

Devonian sedimentary and metasedimentary rocks of the Hodgkinson Formation and Permian-age granitic rocks of the Thornton Batholith (Amos and De Keyser, 1964; Henderson and Stephenson, 1980; Ewart, 1985) form steep headlands in the Cape Tribulation area. Many stream beds and nearshore deposits in the study area are characterised by large (1-10 m diameter) boulders derived from these formations.

Beach ridges and dune facies

Fine-grained, predominantly quartz sand forms beach ridges in deeply embayed areas associated with stream estuaries in the Cape Tribulation area. These ridges often fill the bays and are oriented parallel to the coast.

Old beach ridges are often overgrown with rainforest vegetation and mangroves. Rainforest trees colonising beach ridges in the study area include *Casuarina equisetifolia* var *incana*, *Hibiscus tiliaceus*, *Calophyllum inophyllum*, and *Aleurites moluccana* (Jessup and Guymer, 1985). Among the common mangroves in the Cape Tribulation area are *Rhizophora stylosa*, *Avicennia eucalyptifolia*, *Bruguiera gymnorhiza*, and *Heritiera littoralis* (Jessup and Guymer, 1985). The best-developed beach-ridge system is landward of South Tribulation beach, where there is an extensive mangrove thicket.

Intertidal Zone

Terrigenous cobbles facies

Cobble-size clasts (Friedman and Sanders, 1978) are most commonly found in the vicinity of stream mouths. These deposits consist of well-sorted 20-40 cm diameter igneous and metamorphic cobbles. The cobbles form irregular deposits near the streams and grade laterally into other longshore beach features (Fig 7). Individual cobble deposits adjacent to and in front of stream mouths are sometimes fan-shaped.

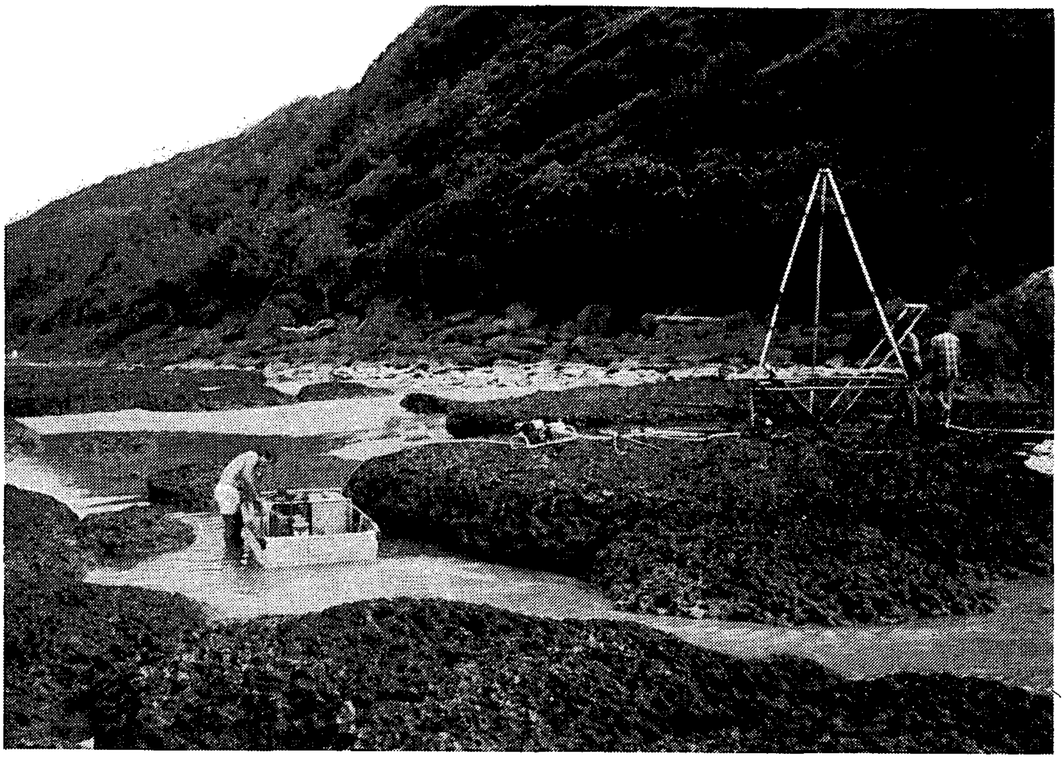

Figure 6. Portable drilling rig on Rykers Reef.

Figure 7. Terrigenous cobbles, Rykers Reef. Mangrove is about 1.5 m tall.

Beach and tidal-flat facies

Sufficient wave action occurs along the coastline in the study area to create beaches. At high tide, the reefs are underwater and waves may reach up to the margin of the treeline.

The beach and tidal flat facies in the study area is composed predominantly of fine-grained, well-sorted, (3.0-3.5ϕ) quartz- and calcium carbonate sand. Biogenic components include sponge spicules, foraminifera, coral fragments, and shell fragments. The calcium carbonate component of the beach sediment increases with proximity to the reef.

At the upper margin of the intertidal zone, swash deposits composed largely of marine shells and of pumice are sometimes present. The pumice is believed to have originated from volcanically active areas in the south-west Pacific Ocean.

Back-reef facies

A back-reef facies is found behind all the larger fringing reefs in the Cape Tribulation area. The back-reef area is largest behind Rykers Reef and South Tribulation Reef. On the narrow, elongate reefs, such as Emmagen Reef, a distinct back-reef facies is absent.

The surfaces in the back-reef areas of all the fringing reefs of the Cape Tribulation area have elevations ranging from 0.15 m below to 0.5 m above Cairns Port Datum. Live corals are sparse to nonexistent behind Emmagen, Rykers, and South Myall reefs.

The most characteristic feature of a typical Cape Tribulation back-reef area is dead microatolls which are very similar to present living microatolls. Living microatolls are flat, disk-shaped coral colonies consisting of an outer ring of living corals with near-vertical outer sides growing to the maximum elevation possible, often that of a reef flat pool isolated at low tide (see for example, Hopley, 1982, Chapter 4). Dead microatolls and the dead centres of living microatolls are often covered by crustose coralline algae. Towards the beach in the study area, microatolls are buried in moderately well-sorted siliceous and calcareous tidal-flat sands. Seaward dead microatolls at Cape Tribulation are typically overgrown with encrusting algae, such as *Porolithon* sp.

In deeper back-reef pools, loose coral rubble accumulates and brown algae, such as *Sargassum* sp, proliferates (Fig 8). Also present are the green algae *Caulerpa cupressoides*, *Chlorodesmis fastigata*, *Enteromorpha clathrata* and the brown alga *Laurencia* sp (Cribb, 1985). Very small (5-10 cm diameter) living favid and *Porites*-type corals are occasionally found. The more landward side of the back-reef facies is often covered by terrigenous sand and the more seaward side of the back reef by calcareous rubble. Therefore, the back-reef facies was mapped (Fig 3) as two distinct subfacies, one consisting primarily of terrigenous sand, the other consisting primarily of calcareous rubble.

Reef-crest facies

Rimming the seaward (eastern) perimeter of each of the Cape Tribulation reefs is the reef crest. The outer reef crest forms a ridge elevated approximately 0.5 m above the adjacent back reef and ranges from 0.7-1.4 m above the Cairns Port Datum.

On the extreme seaward margin of this rampartlike outer reef crest, algae such as *Laurencia* sp and *Gelidiella acerosa* are found (Fig 9). Encrusting algae such as *Porolithon* sp (Cribb, 1985) are also present (Fig 10). In many places, the front of the reef crest is dissected by a rudimentary spur and groove system. Within the grooves, that are typically 1-10 m in width, 2-20 m in length, and 1-2 m in depth, small colonies (0.1-1.0 m diameter) of living coral are often found.

Subtidal Zone

Living coral facies

A steep drop-off in front of each reef extends to a depth of about 2 m below Cairns Port Datum. Below the steep drop-off, a more gentle seaward slope begins. Sonar transects and diving observations indicate a dip of about 1-2 degrees for this slope. The slope reaches a maximum depth of 10-15 m at a distance 1 km beyond the reef front. Bathymetric charts show water depths of 20 m at a distance of 2-3 km seaward of the reefs (see also Johnson and Carter, 1987).

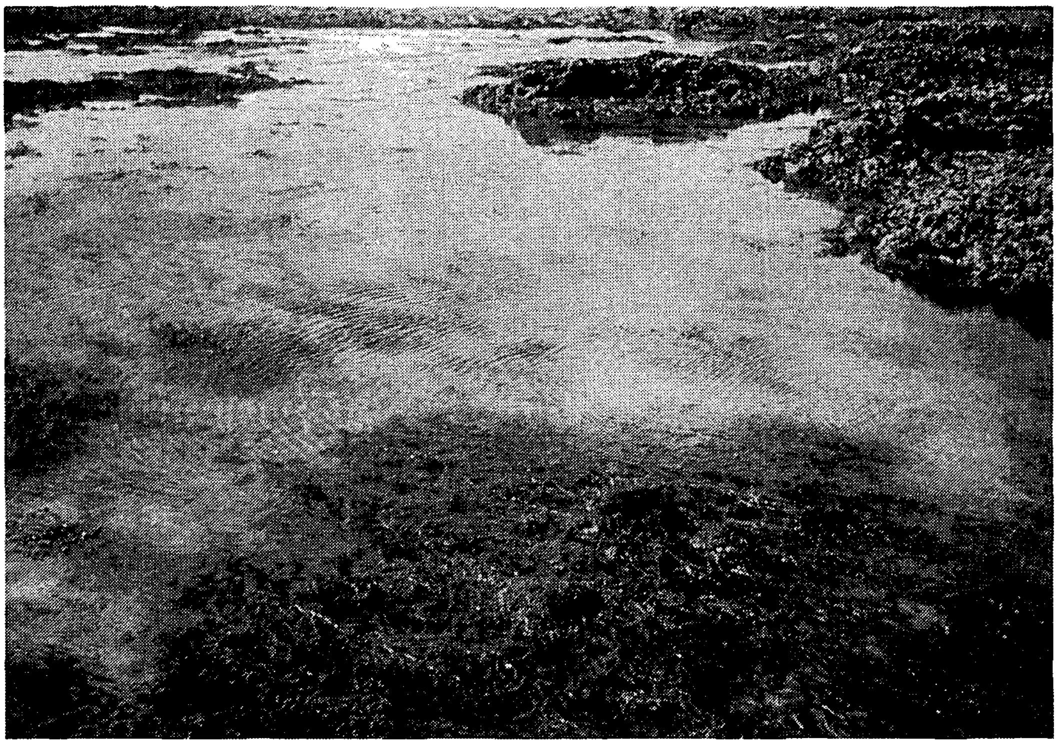

Figure 8. Back reef pool, Rykers Reef. Low elevation areas of the back reef are often characterised by the presence of *Sargassum* sp.

Figure 9. High energy conditions on the outer reef crest restrict growth to durable turf algae, South Cape Tribulation Reef

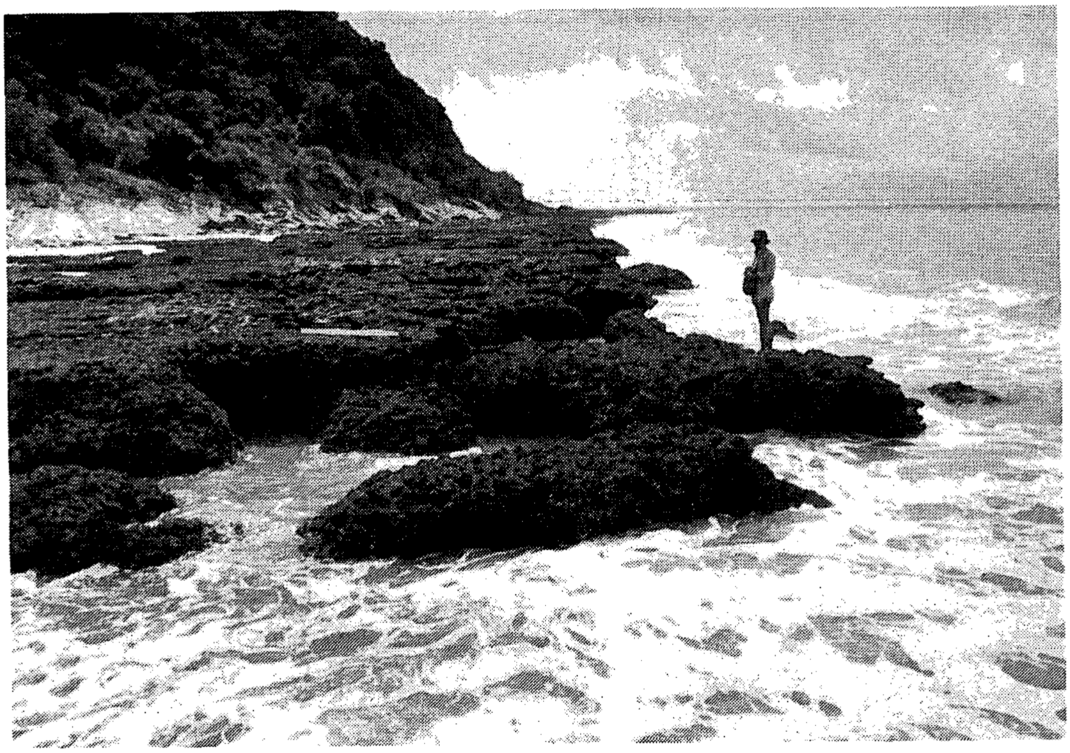

Figure 10. Reef crest of the narrow fringing reef crest south of Emmagen Creek, pictured during extremely low Spring tides.

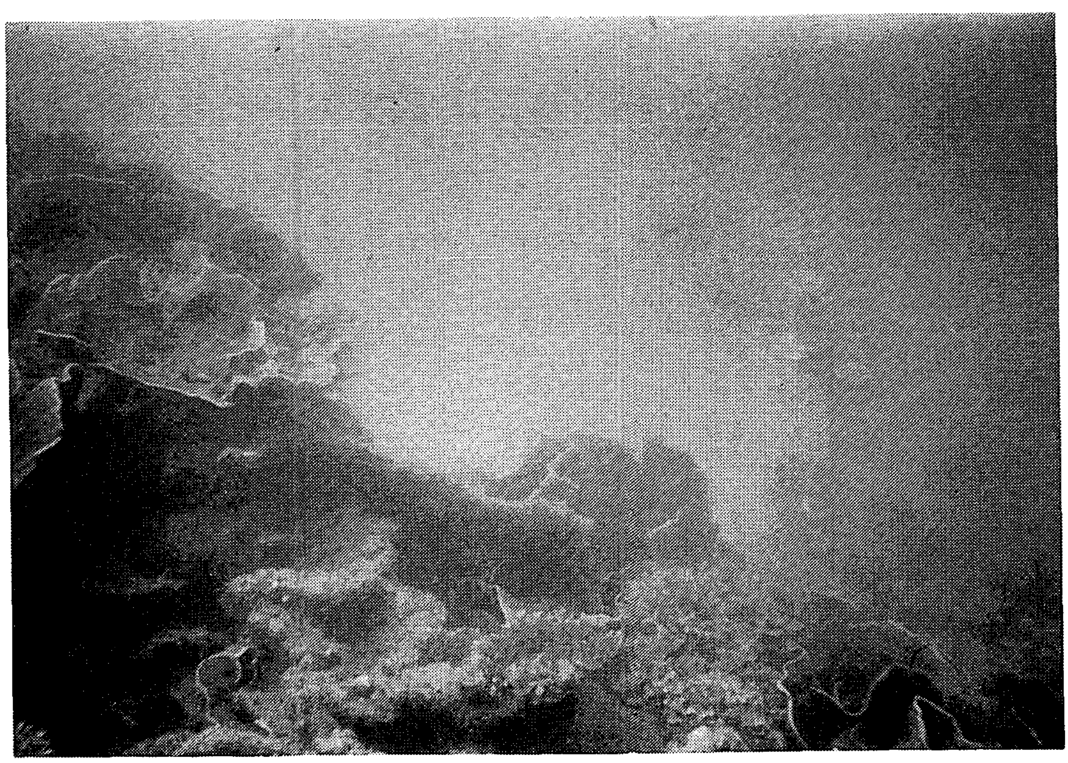

Figure 11. Subtidal branching and foliose living coral, approximately 2 m below water surface at Rykers Reef. Sediment traps used in a parallel study can be seen atthe reef base.

Living-coral communities flourish in a 30-100 m wide strip parallel to the reef, just below the fore-reef drop-off (Fig 11). Large *Porites* sp and favid colonies, exceeding 4 m in diameter, as well as acroporid communities are found here.

Sea-floor sediments on the gentle slope directly in front of the fringing reefs consist predominantly of poorly sorted (3.5 to -2.5ϕ), coarse calcareous sand and reef rubble.

5 REEF PETROLOGY

Reef rock and unconsolidated sediments obtained in cores from the Cape Tribulation fringing reefs can be classified into six lithologic or textural groups. These groups generally occur from base to top in the reefs in the following order:

- Alluvial cobbles
- *In situ* coral
- Sand
- Loose rubble
- Algal-cemented rubble
- Coralline algal boundstone

Group One: Alluvial Cobbles

These rocks are smooth, subrounded igneous and metamorphic cobbles. The only reef substrate sample obtained was in a core from Rykers Reef. It is composed of quartz greywacke similar to cobbles found on the surface in and around creeks in the study area.

Group Two: *In situ* Coral

Coral samples from the Cape Tribulation cores were identified to species level when possible (Table 1). Samples labelled "*Porites* sp" are one of four species: *Porites lutea*, *P sorita*, *P lobata*, or *P australiensis*. These specimens could not be identified to species because outer surface corallites were not obtained in the cores.

Group Three: Sand

The sand group includes sand and pebble-sized calcareous and siliceous particles that range from -2.5ϕ to +4.0ϕ in diameter. Quartz grains tend to be smaller (3.5ϕ and less) than carbonate clasts (+2.0ϕ to -2.0ϕ). Bioclastic allochems found in the sand samples include coral fragments, gastropod shells, foraminifera, soft coral spicules, and echinoid spines. Foraminifera identified in the samples include *Nummulites ammonoides*, *Calcarina* sp, *Amphistegina lessoni*, *Marginopera vertebralis*, *Peneropolis pertusus*, *Alveolinelli quoyi*, *Cellanthus craticulatus*, and *Elphidium* sp.

TABLE 1. Coral species identified from borehole samples.

TYPE	SAMPLE	DEPTH rel to CPD* (m)
	***In situ* Framework Coral**	
Porites sp#	M2-1A	+0.89
Porites sp	M3-1F	+0.15
Porites sp	M2-2D	-1.62
Porites sp	M3-2J	-1.91
Porites sp	R2-5C	-4.60
Porites sp	R4-3E	-4.80
Porites sp	R1-6B	-5.30
Porites sp	M1-4E	-5.92
Porites lutea	E2-1F	+0.18
Porites lutea	M2-1E	+0.08
Porites lutea	R2-3C	-0.60
Porites lutea	E2-2B	-0.72
Porites lutea	R4-3C	-3.90
Acropora sp	E2-4B	-3.42
Pavona sp	R2-5B	-4.30
	Cemented Rubble	
Acropora sp	R1-1E	+0.55
Stylophora sp	R2-2B	0.00
Hydnophora exesa	R2-2D	-0.10
Montipora sp	R1-4A	-1.85

* Cairns Port Datum (tidal plane of predictions)
\# one of four species: *Porites lutea*, *P sorita*, *P lobata* or *P australiensis*

Terrigenous clasts larger than 2.0ϕ in diameter in the sand group consist mostly of subrounded pebbles of igneous and metamorphic rocks. Fine (+2.5ϕ) terrigenous sand particles consist predominantly of angular quartz, subangular quartz and subrounded quartz grains and rock fragments. In all of the sand samples recovered, terrigenous particles ranging from -1.5ϕ to 1.5ϕ were nearly always absent.

Group Four: Loose Rubble

Sediments in this group are mostly acroporid coral and coralline algae interclasts. The sediments range in width from 1.0-2.0 cm and in length from 1.0-4.0 cm.

Group Five: Algal-cemented Reef Rubble

Although coralline algae is present as a binder in this group, the largest percentage of material is coral fragments, mainly acroporid.

Group Six: Coralline Algal Boundstone

Laminated calcareous algal boundstones (Dunham, 1962) predominate in this group. Some reef detritus is incorporated into the algal boundstone. Bioclasts in the boundstone include coralline algae, bryozoans, mollusc shells, agglutinated foraminifera and coral fragments. Terrigenous components are predominantly detrital quartz and clay particles. The detrital quartz particles vary in diameter from 50-100 microns (3-4o).

Serpulid worm tubes and worm borings, pelecypod (*Lithophaga obesa* and *kuehnelti*) borings and clionid sponge borings are abundant in the algal boundstone.

Core Descriptions

Borehole locations are indicated on Figure 3.

Group One alluvial cobbles were encountered at the base of all boreholes.

Rykers Reef, borehole R-1 (Fig 12)

This borehole is located on the outer reef crest. It was drilled to a depth of 6.95 m. Above the base of the borehole is 0.5 m of *Porites* sp coral, group two, in growth position. Overlying this coral framestone is approximately 4 m of loose acroporid and montiporid reef rubble, group four. The upper 2.5 m of the borehole is mainly algal-cemented rubble, group five, interspersed with coral colonies, group two, and algal boundstone, group six.

Rykers Reef, borehole R-2 (Fig 12)

This borehole is located at the boundary between the reef crest and the back reef. It was drilled to a depth of 6.2 m. Drilling began on a dead microatoll. Above the base of the borehole is a 1 m cavity, partially filled with coral rubble, group four, including a *Goniastrea retiformis* fragment. Overlying the cavity is 0.6 m of *Porites* sp coral, group two. Above this are approximately 3 m of loose rubble and sand, groups three and four. The upper 2 m of the core consists mainly of algal-cemented rubble, group five, small sections of *in situ* coral, group two, and algal boundstone, group six.

Rykers Reef, borehole R-3 (Fig 12)

This borehole was drilled in the middle back reef to a depth of 6.04 m. Drilling began on a dead microatoll. Above the base of the borehole is 0.2 m of acroporid and *Stylophora pistillata* rubble, group four. Overlying the rubble is about 0.5 m of *Acropora* sp, *Montipora* sp, and *Cyphastrea* sp coral colonies, group two. Overlying this are about 3 m of sand, group three, and rubble, group four. The upper 1.5 m of the core is mostly loose rubble, group four, interspersed with cemented rubble, group five, and algal boundstone, group six.

Rykers Reef, borehole R-4 (Fig 12)

This borehole was drilled at the most landward portion of the back reef. It was drilled to a depth of 6.17 m. Above the base of the borehole is approximately 0.2 m of acroporid and *Pocillopora damicornis* rubble, group four. Overlying this rubble are two 0.1 m *Porites* sp coral colonies, group two, separated by about 1.5 m of group three sand. Above this are 4.5 m of sand, group three, and loose rubble, group four. The upper 0.1 m of the borehole is coralline algal boundstone, group six. No group five sediments were recovered from this borehole.

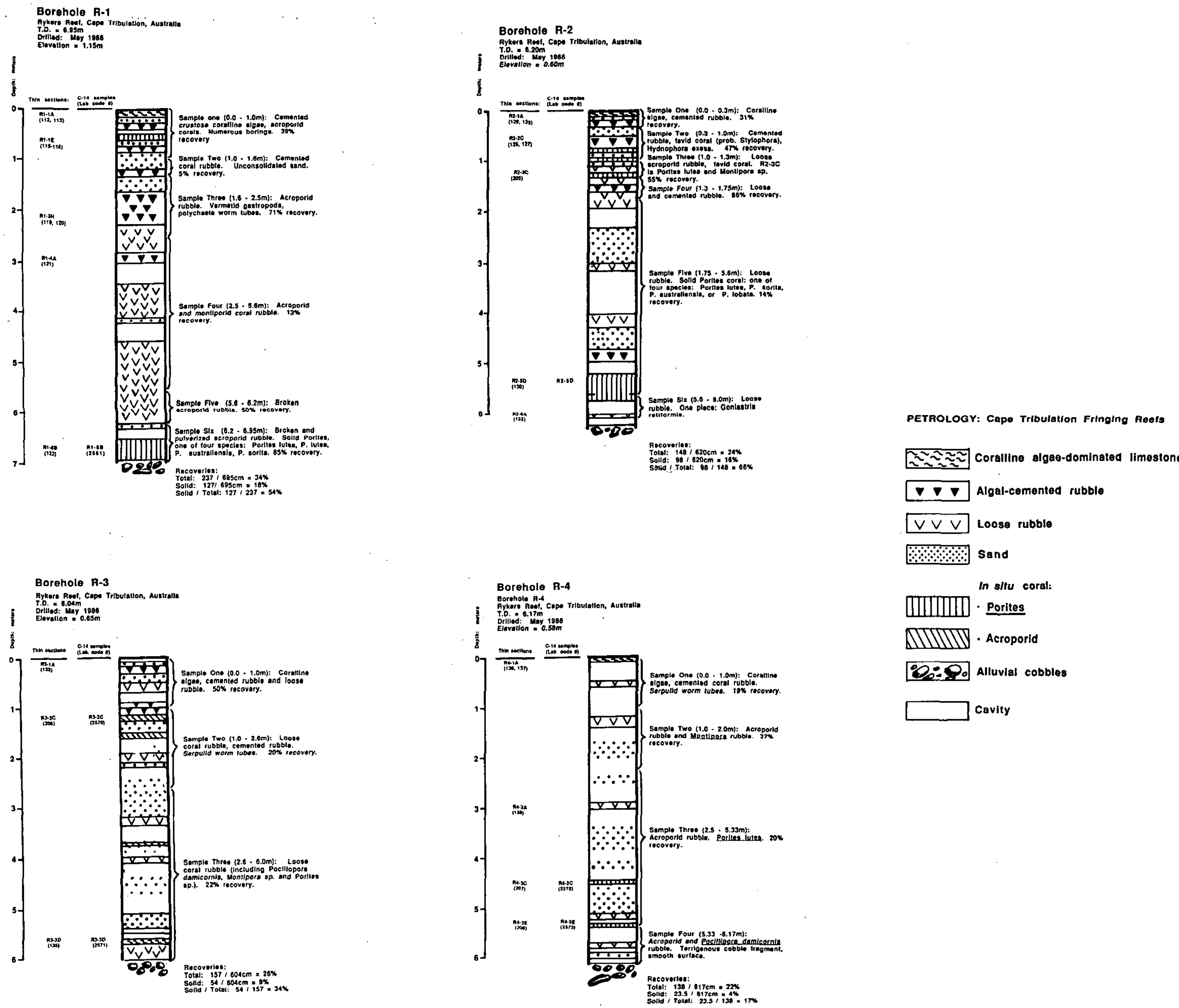

Figure 12. Borehole logs R1, R2, R3 and R4, Rykers Reef.

South Myall Reef, borehole M-1 (Fig 13)

This borehole was drilled in the outer reef crest. It was drilled to a depth of 8.3 m, and is the deepest of the nine boreholes. Above the base of the borehole is a 0.5 m thick *in situ Porites* sp coral colony, group two. Above this are about 0.5 m of loose rubble, group four, and cavity. Overlying this are 1.4 m of *Porites* sp coral, group two. This sample was the second thickest single coral colony recovered from any of the boreholes. Overlying the coral are approximately 5 m of loose acroporid rubble, group four, and sand, group three. The upper 1.5 m of the borehole samples consists of cemented rubble, group five, capped by about 0.3 m of coralline algal boundstone, group six.

South Myall Reef, borehole M-2 (Fig 13)

This borehole was drilled in the far back reef along the strand line. It was drilled to a depth of 8.2 m. Coring was begun on top of a dead microatoll, which was not covered by coralline algae. Above the base of the borehole are approximately 5 m of sand, group three, and acroporid rubble, group four. Above this is a 0.6 m *in situ Porites* sp colony, group two. Overlying this is 0.5 m of sand, group three. Above this sand are approximately 1 m of rubble, group four, and cavity. The upper 1.0 m of the core is composed mostly of *in situ Porites* sp, group two.

South Myall Reef, borehole M-3 (Fig 13)

This borehole was drilled in the middle back reef. It was drilled to a depth of 7.9 m. The borehole was started on top of a dead microatoll. Above the base of the borehole are approximately 5 m of sand, group three, with small amounts of loose rubble, group four. Above this is about 2.5 m of *in situ Porites* sp colonies, group two. Overlying this is approximately 1 m of acroporid rubble, group four. The upper 0.2 m of the borehole is coralline algal boundstone, group six.

Emmagen reef, borehole E-1 (Fig 14)

This borehole was drilled on the outer reef crest. It was drilled to a depth of 5.83 m. Above the borehole base is a 0.4 m *Porites* sp colony, group two. Overlying this are approximately 4 m of sand, group three and rubble, group four, interspersed with 0.1 m or thinner *in situ* coral colonies, group two. About 1.5 m from the top of the core is cemented rubble, group five, interspersed with cavities and rubble, group four. The upper 0.2 m of the core is coralline algal boundstone, group six. Alluvial cobbles, group one, are cemented into the upper 0.5 m of Emmagen reef. One such reef-top cobble was drilled into in the initial attempt to drill the reef crest.

Emmagen Reef, borehole E-2 (Fig 14)

This borehole was drilled in the back reef, approximately 20 m from a rocky headland. The borehole was begun in the centre of a dead microatoll. It was drilled to a depth of 4.05 m.

Several attempts at starting a borehole here had to be abandoned when surface alluvial cobbles were encountered. A 0.5 m depression in the reef top was found that was clear of these surface cobbles. The borehole was drilled successfully in this depression.

At the base of the borehole, either alluvial cobbles, group one, or bedrock were encountered. Above the base are approximately 2.5 m of sand, group three, and acroporid rubble, group four. The overlying 1.5 m includes three *in situ* coral colonies, group two, measuring approximately 0.2 m each. The top 0.2 m is coralline algal boundstone, group six.

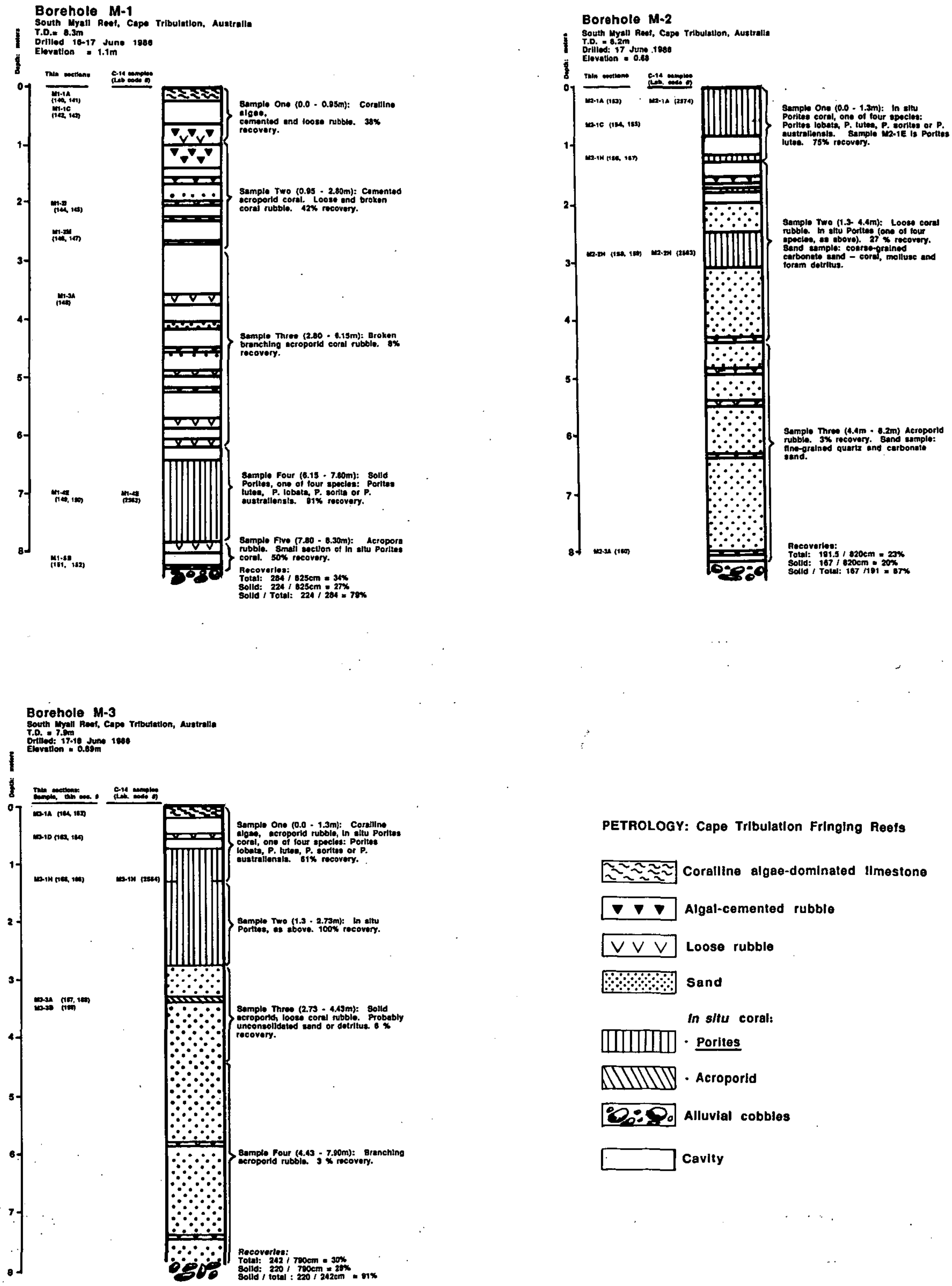

Figure 13. Borehole logs M1, M2 and M3, South Myall Reef.

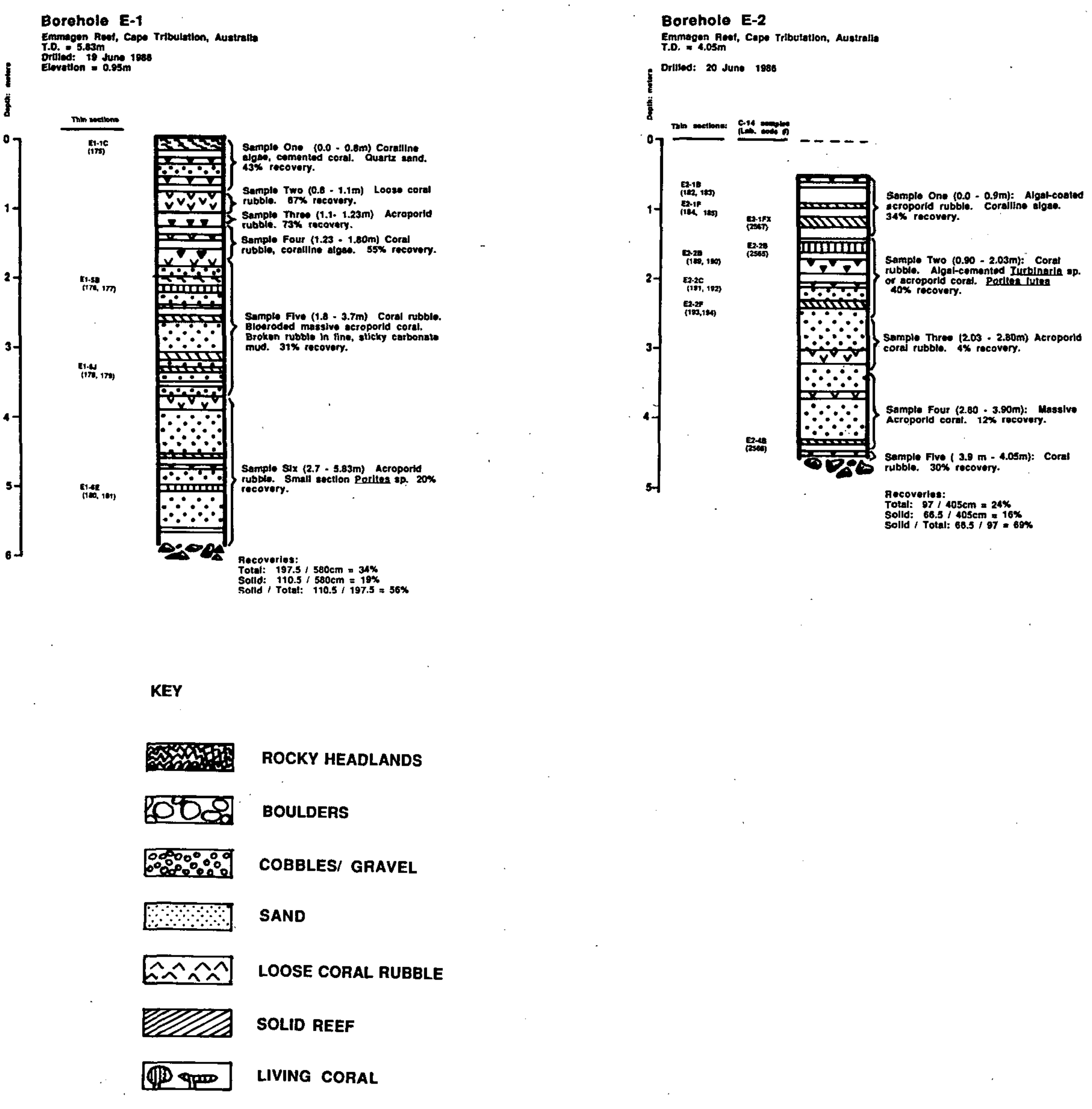

Figure 14. Borehole logs, E1 and E2, Emmagen Reef.

6 REEF LITHOLOGIC ASSEMBLAGES

Four lithologic assemblages occur in the Cape Tribulation fringing reefs (Fig 15). The assemblages encompass the six lithologic groups previously described. These assemblages were generally encountered from base to top in the following sequence in each borehole:

- Gravel assemblage
- Lower framestone assemblage
- Detrital assemblage
- Framestone-boundstone assemblage

Some assemblages are not present in some cores but the other assemblages typically remain in the sequence. These assemblages are not necessarily distinct units within the reef. Instead they are composed of a variety of coral colonies and other sediments. However, each assemblage is characterised by a predominant sediment type that suggests the environmental conditions under which these sediments were deposited.

Gravel Assemblage

The gravel assemblage consists of rounded cobbles. This unit was encountered at the base of each reef. The thickness of this assemblage is not known. This unit is present beneath the entire reef. Gravel assemblage sample R4-4B was recovered from the base of Rykers Reef. It is a dark-green, fine-grained metamorphosed greywacke with quartz-filled fractures. It is similar in appearance to the surface boulders and cobbles derived from the Hodgkinson Formation and is considered to represent the deltaic fan gravels laid down by the streams along the coastline at a lower than present sea level.

Lower Framestone Assemblage

The lower or basal framestone assemblage consists only of *in situ* coral colonies, representing the initial colonisation of the gravel base by corals during the latter part of the Holocene transgression.

This unit varies in horizontal distribution, but was always found immediately above the gravel assemblage. The lower framestone unit is typically composed of *Porites* coral colonies and varies from 0.05 m in Emmagen reef to 1.5 m in thickness in South Myall Reef.

Detrital Assemblage

The detrital assemblage consists of unconsolidated terrigenous and calcium carbonate clastics and scattered patches of *in situ* coral.

This assemblage usually overlies the lower framestone assemblage. The lower framestone unit was not encountered in boreholes M2 and M3. In these boreholes the detrital assemblage directly overlies the gravel assemblage. The detrital assemblage has a wide horizontal distribution, cropping out in the intertidal back reef and in the subtidal forereef in all reefs. This assemblage is the thickest of the four assemblages. It ranges from 1 m thick in Emmagen Reef to over 3 m in South Myall Reef.

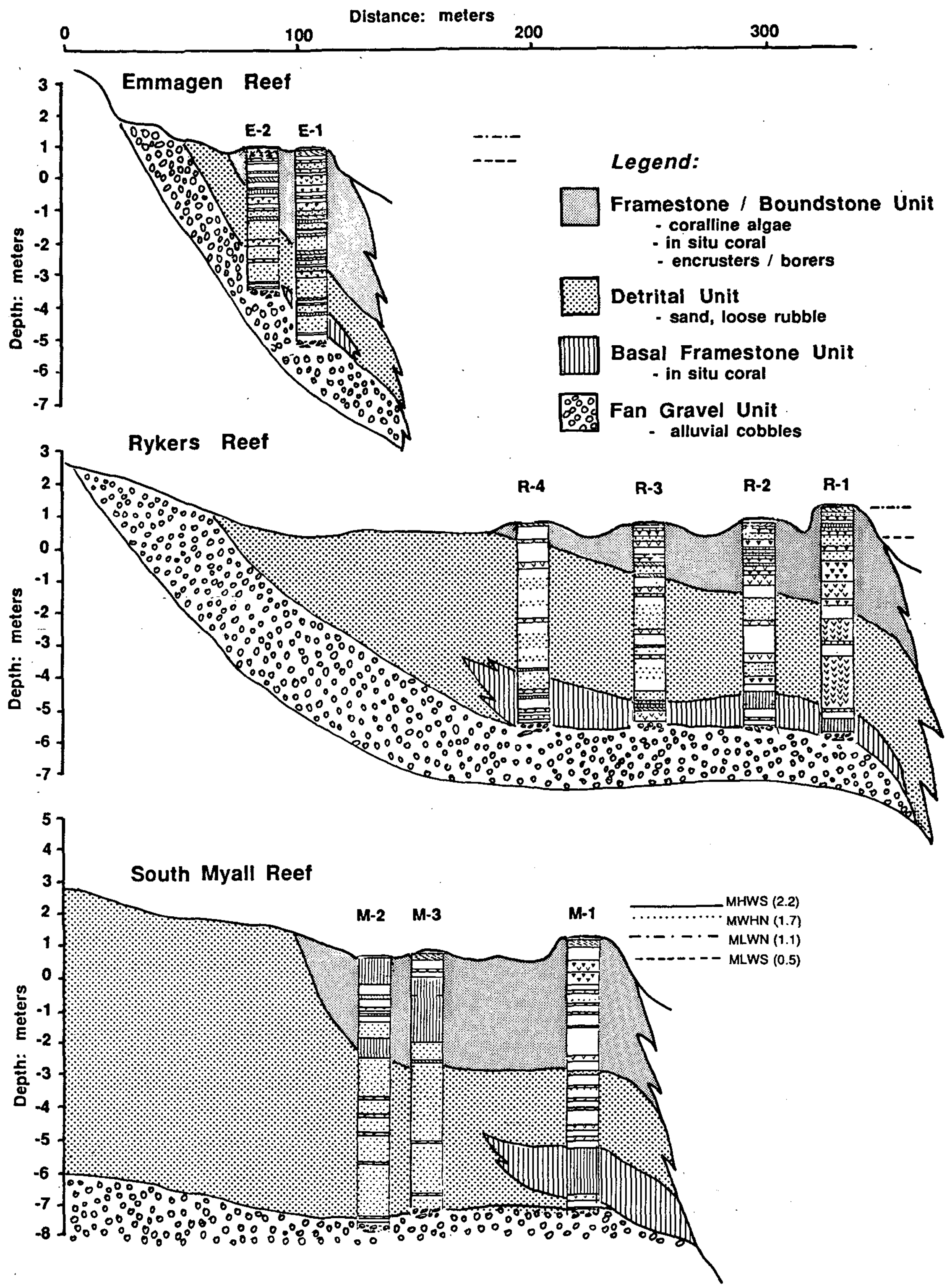

Figure 15. Cross sections of Emmagen, Rykers and South Myall Reef.

The assemblage represents the detrital deposits laid down during a rising sea level when the developing reef was within the zone of wave action, particularly during storms with carbonate clasts laid down as fore reef talus and back reef depression fills to which have been added fluvially derived cobbles.

Framestone-boundstone Assemblage

The framestone-boundstone assemblage is consolidated reef material consisting of varying combinations of coralline algae and both branching and massive colonies of coral. Branching corals include both acroporid and montiporid colonies. Massive colonies include *Porites* and favid sp.

The framestone-boundstone assemblage was found in the back-reef to fore-reef zones and usually thickens seaward. This assemblage is less than 1 m thick in the back reef and is up to 3 m thick in the outer reef-crest area in both Emmagen and Rykers Reefs. In South Myall Reef this assemblage is about 3 m thick even in the back reef.

This unit was not found at depths greater than 3 m below the reef surface, and is essentially a reef flat assemblage built at a stable sea level with the zone of wave action.

Comparison of Reefs

Although the sequence of lithologic assemblages in the Cape Tribulation fringing reefs is typically consistent, there are variations from reef to reef.

South Myall Reef is unique because of the absence of a basal framestone in the backreef, while having the thickest basal framestone unit in the forereef. South Myall Reef also has a thick coral section in the backreef portion of framestone-boundstone unit. Neither Rykers Reef nor Emmagen Reef has as thick a coral component in the framestone-boundstone unit as found in South Myall Reef.

7 CEMENTATION

Pore-lining and pore-filling acicular calcium carbonate cement is present from the top to the base of all three of the Cape Tribulation reefs that were cored. Both aragonite and high-magnesian calcite cement are present. Neither low-magnesian calcite cement nor sparry calcite cement of any kind was found.

Both high-magnesian calcite cement and aragonitic cement occur in the shallow (less than 2 m depth) samples. In deeper samples (greater than 3 m depth) the cement is almost exclusively aragonite (Fig 16).

Figure 16. Acicular aragonite cement lining the pores of *Porites* sp sample M1-5B from a depth of 8.3 m below reef surface (7.2 m below Cairns Port Datum).

Shallow-depth Cementation

The most heavily-cemented reef components are the algal boundstones at and near the tops of each reef. This type of extensive shallow-depth cementation is common in the Great Barrier Reef (Marshall, 1983) and in Caribbean reefs (MacIntyre, 1977). The algal boundstone in the Cape Tribulation fringing reef tops is subaerially exposed twice a day as a result of tidal fluctuations. This heavily-cemented zone ranges from approximately 1 m above to 2 m below Cairns Port Datum. Initial diagenetic cement in this part of the reef includes neomorphic microspar that is replacing lime mud. Uncemented lime mud (micrite) is commonly found filling void spaces in the algal boundstones. Shallow-depth samples often have a high-magnesian micrite rim surrounding these voids. This rim has the appearance of a dense coating and is described as a micrite envelope (Bathurst, 1971). A similar envelope is found around reef rubble clasts such as broken acroporid branching corals. Bathurst indicates that this "envelope" is not merely an encrustation but is evidence of recrystallisation. The envelope forms largely as a result of precipitation of microcrystalline calcium carbonate in discarded algal bores.

Estimates of primary porosity in the algal boundstones range from 10 to 40 per cent. Typically 10 to 30 percent of the primary porosity is filled with either uncemented micrite or high-magnesian calcite cement. Cement is rarely found in pores that do not contain some micrite. Some pores in the boundstone and reef ruble in the upper part of the reefs are filled only with micrite or they are empty.

Deep-depth Cementation

Deep core samples usually lack micrite. Pore-lining cement is sparse. When present, cement in deep samples is usually in the form of a thin rim of cement or, in some samples, thicker rims of acicular aragonite cement.

Porosity is highest in the deep samples, in zones composed primarily of *in situ* coral colonies. The most commonly recovered reef material at depths below 4 m is massive *Porites* sp coral colonies. The porosity in these colonies results mostly from the open structure of the individual corallites, which are about 1 mm long by 0.25 mm in diameter. The corallites contain little to no internal sediments or cements. In contrast, pores in algal boundstones are rarely larger than 0.1 mm in diameter. Visually estimated porosity in uncemented *Porites* sp colonies is approximately 50 per cent.

8 CORAL GROWTH AND REEF ACCRETION RATES

Growth is the "morphologic development of exoskeletons of coral colonies" (Buddemeier *et al*, 1974). Growth rates for individual coral colonies were determined by measuring the distance between annual growth couplets as revealed in radiographs of selected *Porites* sp samples. A dark, thin layer and a light-coloured, thicker layer together represent one annual growth couplet. The light areas on the positive radiographs (Fig 17), represent the season least favourable for growth.

Accretion is the net positive process that results in an overall accumulation of reef material. The rate at which accretion occurs is the result of both constructional processes, such as skeletal growth and deposition of allocthonous and autochthonous sediments, and destructional processes, such as bioerosion (Davies and Hopley, 1983). Average yearly accretion rates of the Cape Tribulation reefs were measured by C^{14} age dating of selected coral samples obtained from known borehole depths.

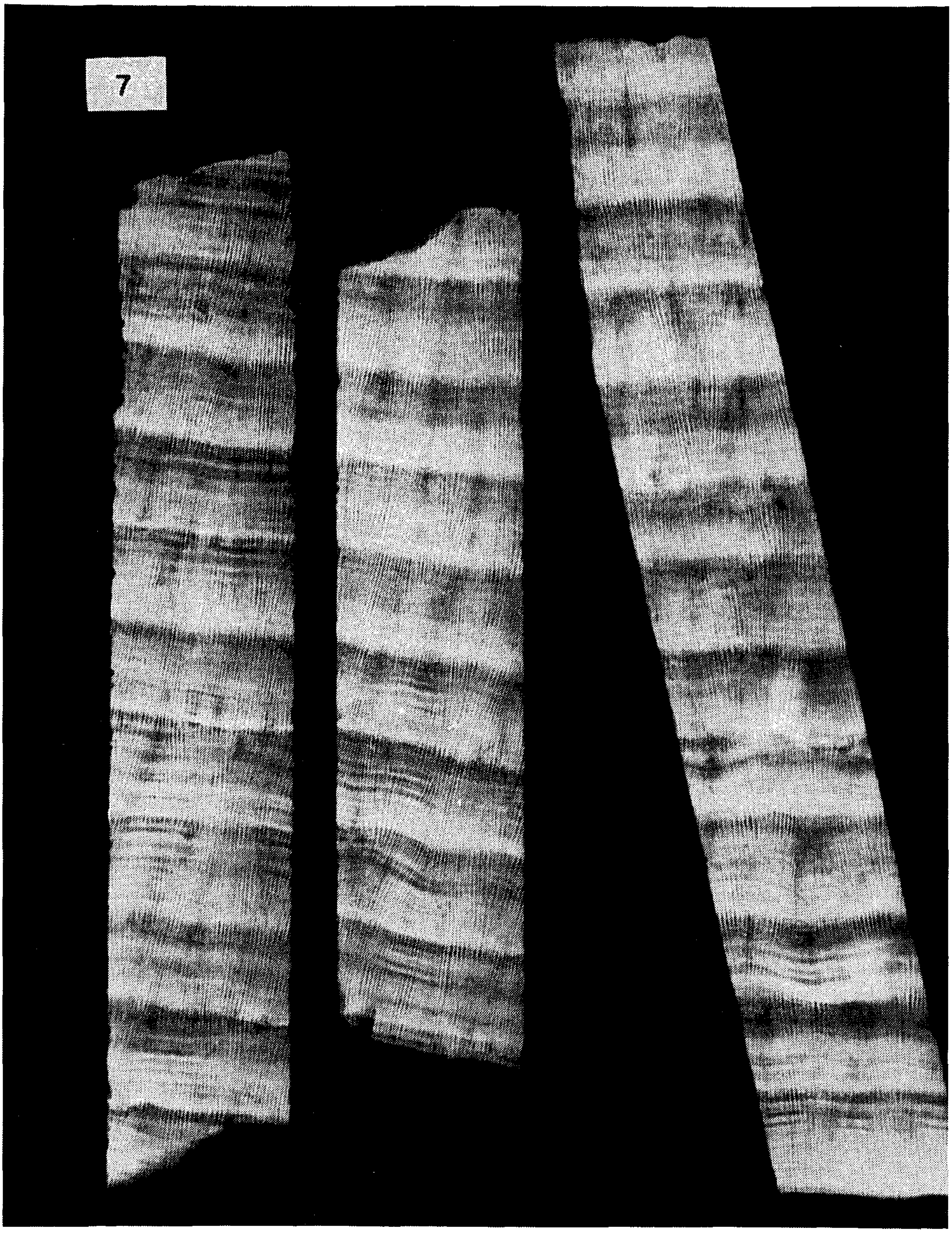

Figure 17. Positive image radiograph showing growth bands of coral core samples M3-2A, M3-2B and M3-3C, South Myall Reef. Samples were obtained from a depth of 1.3-2.0 m below the surface (0.4-1.6 m below Cairns Port Datum). Core width is 4.5 c.

Coral Growth

The Cape Tribulation reefs are composed of a variety of coral species. Massive skeletons of certain genera, such as *Porites*, are more likely to be preserved than branching corals, such as acroporids. Because of their dense structure, *Porites* sp samples provided the most legible radiographic banding patterns. This resulted in a sample bias toward *Porites*. Calculated growth rates are at best an average for this genus and are an indication only of Cape Tribulation fringing reef coral growth rates. Eight radiographs of 41 specific core sections were made to determine coral growth patterns and rates. Thirty-seven of the core sections were composed predominantly of *Porites* sp and four core sections were composed predominantly of acroporid corals. Twenty-six of the *Porites* sp core sections showed a definite banding pattern. Eleven of the *Porites* sp core sections and all four acroporid core sections showed indistinct banding patterns. Growth rates were calculated only from the samples with distinct banding patterns (Tables 2 and 3).

TABLE 2. Cape Tribulation fringing reefs - coral growth rates determined by measuring radiographs of reef cores (samples are listed in order of increasing depth).

SAMPLE NUMBER	DEPTH rel to CPD (m)	GROWTH RATE (mm/yr)	C^{14} LAB CODE SUA	C^{14} AGE (yrs BP)
M3-1F	+0.15	9.3		
M3-1G	0.00	9.3		
E2-1FX	-0.32	5.0	2567	5390± 60
M3-2A	-0.40	20.0		
M3-1H	-0.41	16.4	2564	6830± 70
M3-2B	-0.70	22.8		
M3-2C	-0.90	22.8		
M3-2D	-1.40	25.0		
M3-2e,f	-1.60	29.0		
M2-2E	-1.87	5.6		
M2-2G	-2.12	10.0		
M2-2H	-2.35	10.0	2563	6670± 60
R4-3C	-4.50	10.0	2572	
R2-5C,D	-4.70	7.1	2569	7080± 50
R2-5E	-5.00	6.7		
R1-6B,C	-5.25	5.7	2561	7220± 50
M1-4B	-5.30	8.7		
R1-6D	-5.55	5.0		
M1-4C	-5.60	7.1		
M1-4D	-5.80	10.0		
M1-4E	-5.95	10.0	2562	7330± 60
M1-4F	-6.10	10.0		
M1-4G	-6.30	15.0		

TABLE 3. Cape Tribulation mean coral growth rates determined by measuring radiographs of reef cores.

BY REEF		BY ENVIRONMENT		BY DEPTH	
Reef	Mean Growth Rate (mm/yr)	Environment	Mean Growth Rate (mm/yr)	Depth	Mean Growth Rate (mm/yr)
Rykers	6.8	Fore reef (R1, R2, M1)	7.8	>4 m	7.8
South Myall	14.1	Back reef (R4, M2, M3)	16.4	<4 m	16.4

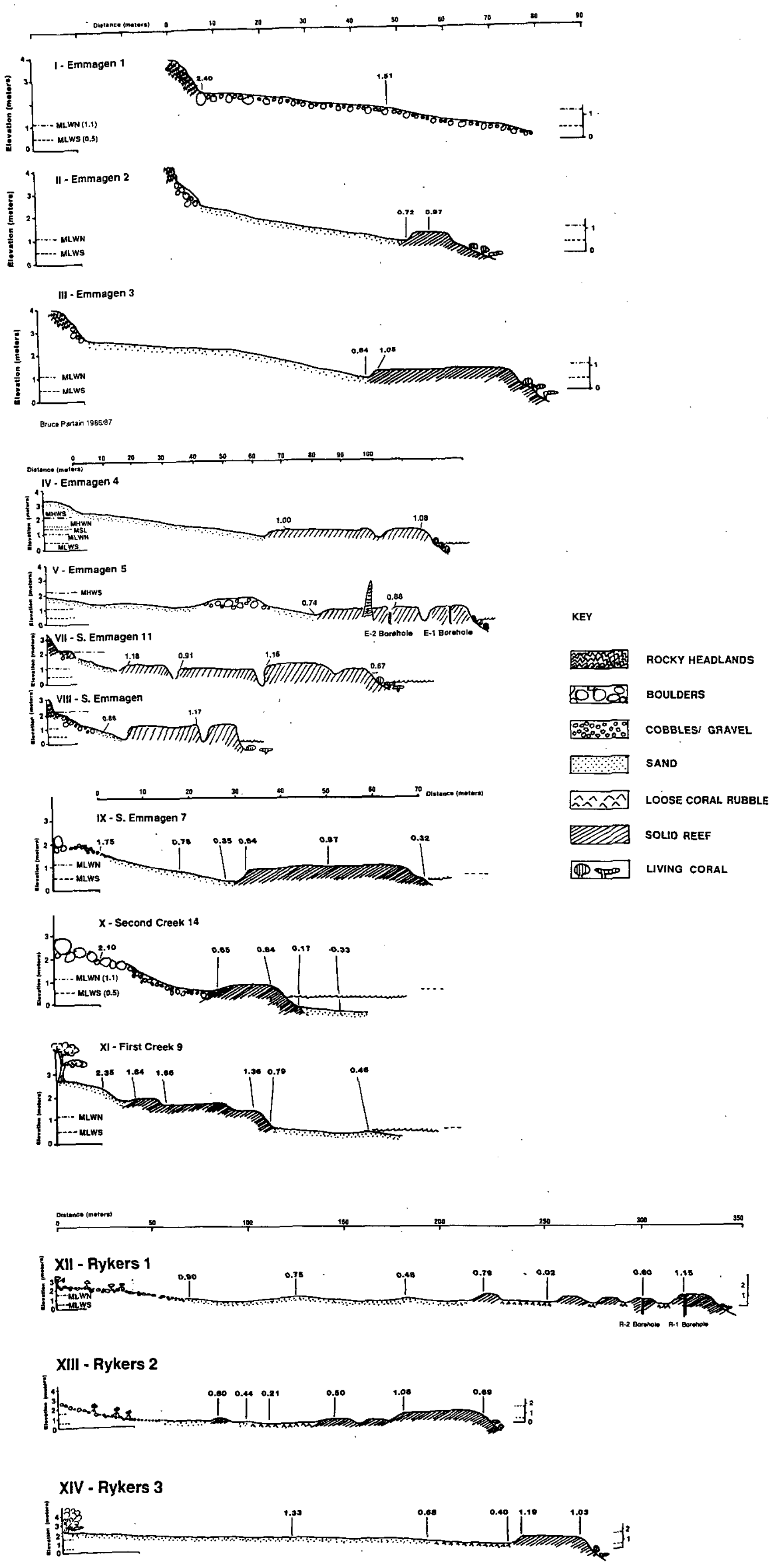

Figure 4. Surveyed reef surfaces, Emmagen to Rykers.

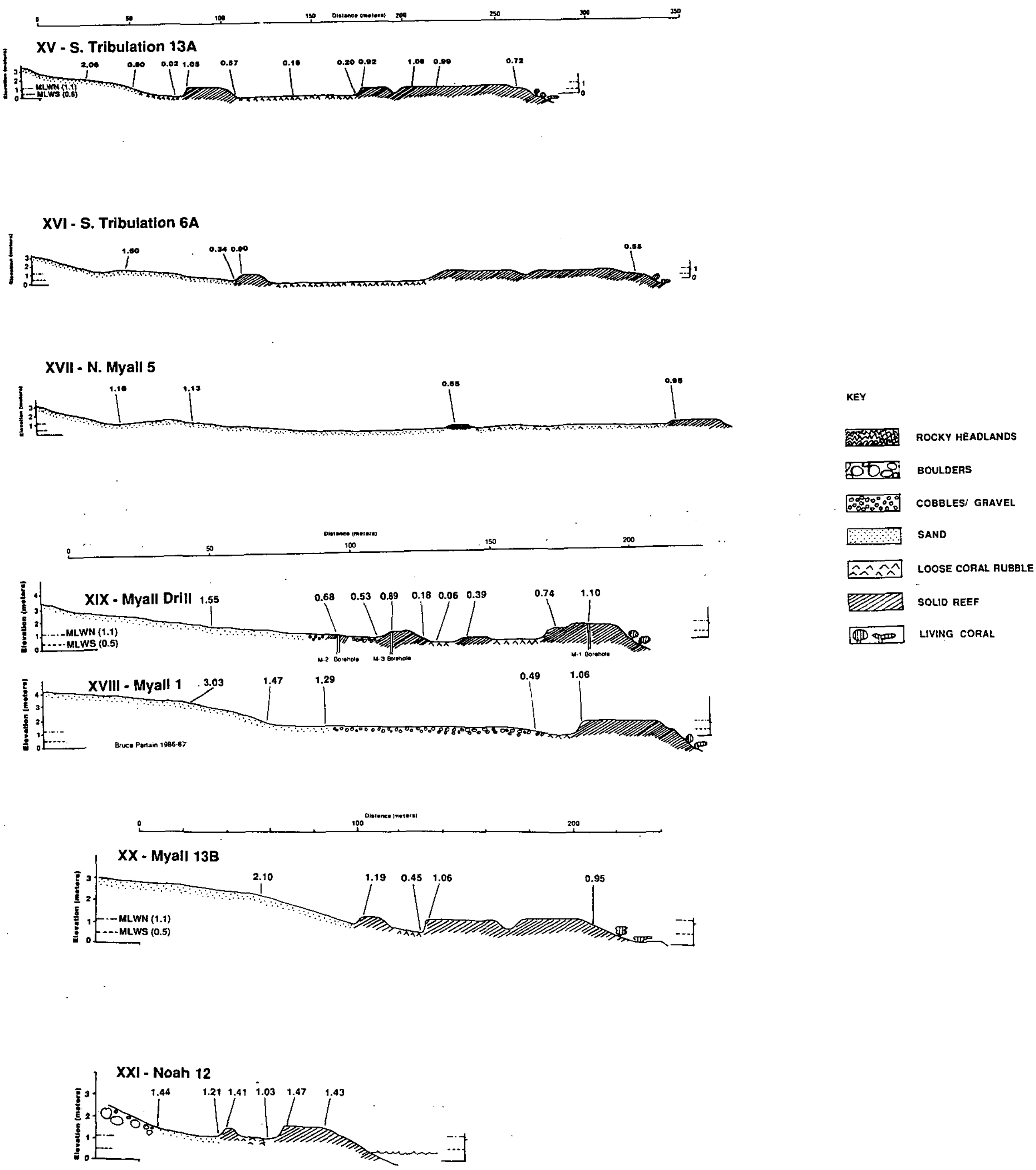

Figure 5. Surveyed reef surfaces, South Tribulation to Noah's Reef.

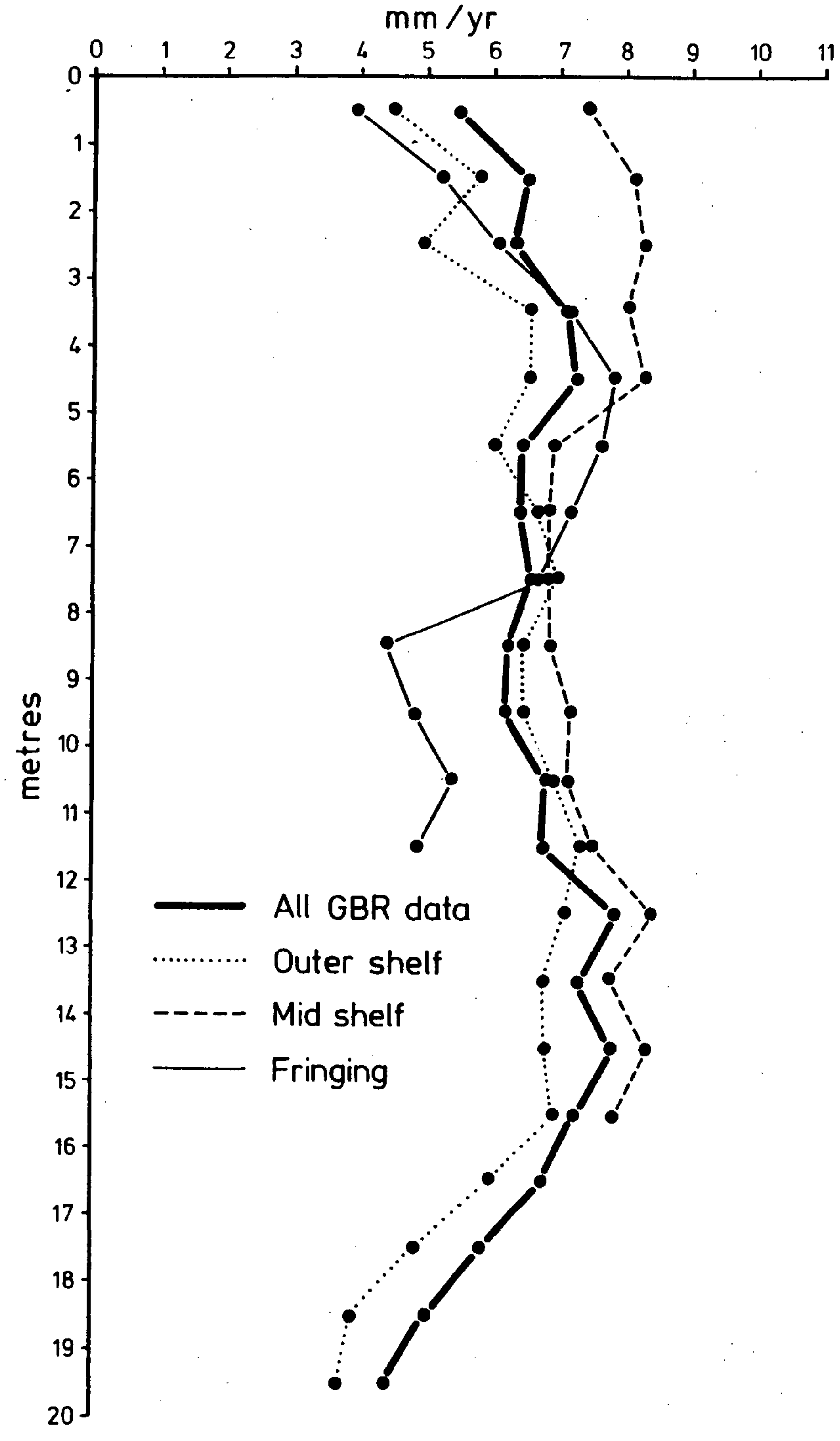

Figure 18. Vertical accretion rates (mm/yr) plotted against depth of water at time of growth (m) for fringing, mid-shelf and outer shelf reefs of the Great Barrier Reef (from dated cores of PJ Davies *et al*, BMR and D Hopley *et al*, JCU)

Field observations of the Cape Tribulation fringing reefs suggest that the back reefs and outer reef crests could have grown higher than is now possible for Great Barrier Reef corals to grow. Among the factors contributing to this hypothesis is the low number of living coral in the back reefs and on the reef crests of all the Cape Tribulation fringing reefs. The presence of erosional benches on the outer margin of several reef crests could also indicate a past higher sea level. The linear reefs between Emmagen and Rykers Reefs show this bench-cut feature.

An elevated reef could result from a past higher sea level, tectonic uplift, or moating (Hopley, 1986). However, the Cape Tribulation area is believed to have been tectonically stable since the Pleistocene (Henderson and Stephenson, 1980). Moating can occur when reef rubble ramparts trap pools of water in the lagoon behind the reef crest. Coral colonies in these moated pools are shielded from the effects of low tide and grow to higher than normal levels (Hopley, 1986; Chappell *et al*, 1983). Evidence of moating, such as a wall-like encircling rampart, was not found in any of the Cape Tribulation fringing reefs.

In the Cape Tribulation study, evidence for changes in sea level is derived from measurement of the height of the reefs compared with present sea level. Reef heights above the present maximum level for open water coral growth, Mean Low Water Springs (MLWS), would indicate an emerged reef and a higher past sea level (Hopley, 1986). The nearest tidal station to Cape Tribulation based on Cairns Datum is at Cooktown, 72 km to the north where MLWS is at 0.4 m. The majority of the reef crests surveyed were 1.0 to 1.1 m above Cairns Port Datum. The highest surveyed reef crest was 1.47 m above Datum. This was at Noah Reef, in the southern part of the study area. This suggests a relative higher Holocene sea level of 0.6 to 1.0 m above present in the Cape Tribulation area. The radiocarbon ages obtained suggest that this would have been achieved ca 5000 yrs BP. The only surface sample dated (Ryker-7) from an elevation of 0.0 m (Table 4) produced an age of 5410 ± 70 yrs BP whilst an age of 6150 ± 70 yrs BP from a depth of only 0.1 m below tidal datum at South Myall Reef (M2-1A) suggests that modern sea level had been achieved by or prior to this date.

A fall in sea level would also increase the chances of extended subaerial exposure of the reefs. This could change the types of calcium-carbonate cement found in the reefs. Low-magnesian calcite is the normal calcium-carbonate cement precipitated in subaerially exposed reefs. Reefs exhibiting this type of vadose-zone cement are found in Barbados, in the eastern Caribbean (Matthews, 1974). Cape Tribulation fringing reefs lack this type of cement but this is not surprising as a fall in sea level of only 1 m still results in immersion on each tide. Petrological analysis to differentiate between phreatic and vadose environments as outlined by Montaggioni and Pirazzoli (1984) was not carried out but could provide a more accurate determination of the sea level fall.

Reef Chronology

The C^{14} dates from the Cape Tribulation reefs agree with similarly obtained dates from other Great Barrier Reef coring projects. From 1978 to 1983, 65 boreholes were cored through 24 reefs in the Great Barrier Reef, and nearly 250 radiocarbon dates obtained from these cores (Davies and Hopley, 1983). By 1989, more than 35 reefs had been cored and ca 500 radiocarbon dates obtained, though not all the data have been published. The majority of Great Barrier Reef research coring has been carried out on reefs of the middle and outer shelf. Only six Great Barrier Reef fringing reefs had been cored and dated before the Cape Tribulation Study:

- Hayman Island in the Whitsunday Group, 600 km south of Cape Tribulation
- Rattlesnake Island, in Halifax Bay, 350 km south of Cape Tribulation
- Fantome Island, Pioneer Bay, Orpheus Island and Iris Point, Orpheus Island in the Palm Group, 300 km south of Cape Tribulation
- Lindquist Island in the Barnard Group, 250 km south of Cape Tribulation (Table 6).

All of these sites are within 20 km of the mainland. More recently, three reefs on Cockermouth, Penrith and Scawfell Islands in the southern Whitsunday Group and more distant from the mainland (>50 km) have been drilled. Preliminary radiocarbon dates suggest initial colonisation was a little later than elsewhere and on Cockermouth Reef at least was over a very extensive Pleistocene reefal sequence (J Kleypas, *pers comm*).

Overall growth rates of the banded samples varied from 5 mm/year, sample E2-1FX, to 29 mm/year, samples M3-2E and M3-2F. Growth rates for corals encountered at a depth of 0-2.3 m below Cairns Port Datum varied from 5-15 mm/year. Growth rates for corals at a depth of 4.5-6.5 m below Cairns Port Datum varied from 5-29 mm/year. These rates and the wide variation shown conform to those recorded by Isdale (1981) for *Porites* from fringing reefs in Townsville region (mean annual growth rate 10.8 mm/year, coefficient of variation 4.56 mm), growth rates which were higher than those recorded from mid- and outer-shelf reefs.

A distinctive feature of the coral growth rates as distributed through the reef structures was that in the older back reef areas of the reefs growth rates were more than twice as high as in younger fore reef areas. Similarly, growth rates tended to be higher lower down individual bore holes ie in older samples (see in particular Myall 1). Mean growth rates from less than 4 m depth were 7.8 mm/year compared to 16.4 mm/yr for samples from depths greater than 4 m. Decline in conditions suitable for coral growth are discussed in Section 9, as the pattern is the reverse of that recorded on Fantome Island by Johnson and Risk (1987) who found slower growth rates at greater depth and attributed this to greater light attenuation caused by turbid water.

Reef Accretion

One surface sample and fourteen subsurface core samples were selected for C^{14} age dating (Fig 19). Absolute ages of deposition for these specimens varied from 7780±260 years BP, sample R3-3D, to 5350±50 years BP, sample E2-4B (Table 4).

TABLE 4. Radiocarbon dates from Rykers Reef, South Myall Reef and Emmagen Reef

SAMPLE NUMBER	C^{14} LAB CODE (SUA)	DEPTH FROM REEF SURFACE (m)	DEPTH REL TO CPD* (m)	CONVENTIONAL C^{14} AGE (yrs BP)
		Rykers Reef		
Ryker-7	(2575)	0.00	+1.00	5410±70
R3-2C	(2570)	-1.20	-0.55	6860±60
R2-3C	(2568)	-1.30	-0.70	6800±110
R4-3C	(2572)	-4.50	-3.92	7280±70
R2-5D	(2569)	-5.30	-4.70	7080±50
R4-3E	(2573)	-5.30	-4.72	7160±90
R3-3D	(2571)	-5.40	-4.75	7780±260
R1-6B	(2561)	-6.40	-5.25	7220±50
		South Myall Reef		
M2-1A	(2564)	-0.10	+0.58	6150±70
M3-1H	(2574)	-1.30	-0.41	6830±70
M2-2H	(2563)	-3.03	-2.35	6670±60
M1-4e	(2562)	-7.05	-5.95	7330±60
		Emmagen Reef		
E2-1fx	(2567)	-1.20	-0.32	5390±60
E2-2B	(2565)	-1.60	-0.72	5350±50
E2-4B	(2566)	-4.30	-3.42	6280±80

*Cairns Port Datum, the tidal datum of predictions

Rykers and South Myall Reefs showed similar base-to-top age ranges of approximately 7000 to 6000 years BP, while Emmagen Reef's base-to-top range was approximately 6000 to 5000 years BP (Table 5).

TABLE 5. Reef vertical accretion rates, Cape Tribulation Reefs, determined by C^{14} age-dating

REEF BORE(S)	AGE RANGE (YEARS BP)	YEARS	DEPTH RANGE rel to CPD* (m)	ACCRETION RATE (mm/yr)
South Myall M1, M2	7330-6150	1180	-5.95 to -0.41	4.7
Rykers R3	7780-6860	920	-4.75 to -0.55	4.6
Rykers R2	7080-6300	780	-4.70 to -0.70	5.1
Emmagen E2	6280-5390	890	-3.42 to -0.32	3.5

* Cairns Port Datum

Reef vertical accretion over the approximately 1000 years of active growth of each reef ranged from 3.5 mm/year on Emmagen Reef to 5.1 mm/yr on Rykers Reef (Table 5). These rates are less than the modal rates of 7 to 8 mm/yr obtained from extensive reef drilling and dating by Davies and Hopley (1983). However, further work by these authors (largely unpublished) has allowed for the comparison of rates from different reefal environments (Fig 18). Fringing reefs appear to achieve a maximum accretion rate at depths of ca 5 m. However, in depths of less than 2 m they have accreted more slowly than elsewhere on the Great Barrier Reef. As the Cape Tribulation reefs appear to have accreted with the rise in sea level at the end of the postglacial transgression (see below) and are less than 7 m thick, most of their growth has taken place in very shallow water, and this is reflected in their low recorded accretion rates.

9 DISCUSSION

Relative Sea Level History

The relative sea level history for the eastern Australian coastline including that of Queensland over the last 18 000 years, shows a rapid rise from a lowest level of ca -135 m in response to glacial melting and first reaching its present position shortly after 6500 years BP (Hopley, ed, 1983; Thom and Roy, 1983). In some areas sea level may have reached a maximum of ca +1.0 m about 5000 years BP before falling to its present level. Regional variations exist, however, in the evidence for this higher level due mainly to hydroisostatic factors (Chappell *et al*, 1983; Hopley, 1982, 1983) and some subsidence may have occurred on the outer edge of the Great Barrier Reef shelf.

Evidence of a 1.0 to 1.5 m higher sea level has been found in North Queensland largely in the form of emerged coral reefs on fringing reefs of high islands (eg Chappell *et al*, 1983). The hindcast model of the 5500 years BP shoreline of Chappell *et al* (1982) and the reconstruction of the 5000 years BP shoreline of Hopley (1983) both suggest about 1.0 m of emergence along the mainland coastline in the Cape Tribulation area whilst the more recent modelling of Nakada and Lambeck (1989) produces a level of ca 2 m with modern sea level first achieved not long after 6500 years BP.

TABLE 6. Coring investigations of fringing reefs in the Great Barrier Reef system.

REEF	MAX DEPTH (m)	NUMBER OF HOLES	OLDEST C^{14} DATE (yrs BP)
Fantome Island (Johnson and Risk, 1987)	10.0	3	5520±100
Pioneer Bay, Orpheus Island (Slocombe, 1981)	17.25	3	6610±250
Rattlesnake Island (Hopley *et al*, 1983)	10.0	1	7010±180
Iris Point, Orpheus Island (Barnes, 1984)	8.0	7	7320±125
Cape Tribulation (this study)	8.3	9	7780±260
Hayman Island (Hopley, 1978)	47.0	6	8245±285

As Davies *et al* (1985) have noted, initiation of Holocene growth on the Great Barrier Reef was within a relatively narrow time envelope between approximately 8320 yrs and 7500 yrs BP, regardless of position on the continental shelf or depth of the pre-Holocene foundations. This meant that a considerable depth of water existed over the deeper foundations of outer reefs particularly those of the central Great Barrier Reef. The shallower foundations of the fringing reefs had been drowned by the time of this colonisation period. Reef growth appears to have commenced almost immediately suitable foundations of high continental islands were inundated. Reasons for the delay in colonisation of outer reef foundations postulated by Davies *et al* (1985) included:

- Lack of suitable substrate until well into the Holocene transgression
- Proximity of terrestrial influences to outer reefs at lower sea levels
- Unsuitable gross climatic or oceanographic factors
- Absence of immediate larval replenishment centres.

Whatever reasons the result has been that fringing reefs were established contemporaneously with outer reefs and in many instances grew upwards with the rise in sea level and established reef flat prior to 6000 years BP. Typically mid and outer shelf reefs commenced reef flat development between 5000 and 4000 years BP (see also Hopley, 1982, table 9.2 for data from shallow coring).

Comparison of Cape Tribulation reef radiocarbon dates and those from other reefs shows that the Cape Tribulation reefs are among the oldest Holocene fringing reefs in the Great Barrier Reef system, and commenced to grow not significantly long after their counterparts on the middle and outer shelf.

The Cape Tribulation reefs apparently developed in non-synchronous stages along the mainland coast. Both Rykers and South Myall Reefs began growing about 7500 years BP and all significant coral reef growth, except on the subtidal fore reef and reef slope, had stopped by about 6200 years BP. Data from the study suggest that Emmagen reef began growing about 6300 years BP and that back reef growth terminated about 5400 years BP.

Localised variance in reef foundation and coastal profile may have played a part in determining the timing of reef initiation and growth. Rykers Reef, the broadest of the three reefs cored, is built on a large apron of alluvial cobbles and is protected from the predominant southeasterly trade winds by Cape Tribulation. South Myall Reef is narrower than Rykers Reef and also has an alluvial cobble foundation. The coastline immediately behind South Myall Reef is a system of beach ridges and mangrove swamps that fill a broad valley.

Emmagen Reef is the thinnest, most ribbonlike of the three reefs cored. A massive rocky headland dominates the coastline landward of Emmagen Reef. Conditions were apparently less favourable for initiation of coral growth at the site of Emmagen Reef and reef development lagged behind the more protected sites where Rykers Reef and South Myall Reef are located. By the time the other reefs had reached maximum height, coral growth at Emmagen Reef had apparently just started and subsequent vertical accretion took place at a slower rate than that of both Rykers and South Myall (Tables 4and 5).

Vertical Accretion Rates and the Environments of Reef Evolution

Results from Davies and Hopley's (1983) comparison study of all Great Barrier Reef coring projects indicate vertical accretion rates range from 1-16 mm/yr. Modal values were about 8 mm/yr from all reef environments. Fringing reefs, such as those at Hayman Island, had the slowest accretion rate. Mean vertical accretion rates on these reefs range from 1-4 mm/yr. However, great variation in rates has been recorded. Slocombe (1981)and Hopley *et al* (1983) found vertical accretion rates at Pioneer Bay, Orpheus Island to average 7.8 mm/yr with maximum rates of 16.7 mm/yr. The Iris Point, Orpheus Island vertical accretion rates range from 1.3-7.8 mm/yr (Barnes, 1984; Hopley and Barnes, 1985). Johnson and Risk (1987) reported average reef accretion rates of 6.7 mm/yr for the fringing reef at Fantome Island.

These data are put into context in Figure 19. This shows vertical accretion rates from all available Great Barrier Reef data related to the depth below sea level at time of growth and comparing outer, mid shelf and fringing reef situations. An understandably greater variation with depth is shown for fringing reefs. These reefs have slower shallow water growth rates than other environments probably related to freshwater runoff from adjacent land masses and more rapid attenuation of growth rates below a depth of about 5 m related to a parallel attenuation of light in turbid nearshore waters.

Accretion curves for the Cape Tribulation reefs can be correlated with the changing sea levels of the Holocene transgression (Fig 20). The sea level envelope (Thom and Roy, 1983) consists of two lines that indicate the 95 per cent confidence limits of the sea levels and when these levels existed. Thom and Roy (1983) indicate that 8000 years ago sea level was 6 m lower than it is now. Core data and C^{14} dates from the Cape Tribulation fringing reef study indicate that South Myall and Rykers Reefs began growing within 500 years of inundation of the foundation sites. Accretion of these reefs generally kept pace with the Holocene transgression. The 1000-year lag of coral growth on Emmagen Reef is shown by the gap between the reef-accretion curve and the sea level envelope. This reef had most of its accretion after the Holocene still-stand.

Accretion rates for South Myall and Rykers Reefs of 4.6 to 5.1 mm/yr are very typical for fringing reefs and reflect growth in close to optimum depth conditions (2-4 m) through most of their upwardly accreting phase. The rate for Emmagen Reef of 3.5 mm/yr is significantly lower. However, as this reef commenced growth after the stabilisation of modern sea level and grew from shallow foundations, its accretion was also in optimal depths (<4 m) for most of its growth and other explanations are needed to explain the lower rate.

This rate discrepancy may be an artefact of a single dated borehole on this reef. However, prior to 6500 years BP colonisation of suitable foundations appears to have been rapid and reef growth sufficiently high to allow the reef to at least keep pace with the rise in sea level. Individual coral growth rates as determined by x-radiography also appear to have been higher (see section 8). After this date, not only was initiation of growth slower, resulting in greater depth of inundation of a site before colonisation, but also accretion rates as indicated by Emmagen Reef were lower. Reefs which had already reached sea level and had reef flats have accreted horizontally an insignificant amount. Cape Tribulation reefs have remained narrow and fragmented whilst reefs of the high continental islands to the south have seen considerable reef flat widening during the same period. The leeward Pioneer Bay Reef on Orpheus Island for example, has widened by between 5 and 10 cm/yr since about 5300 years BP (Hopley *et al* 1983) and the southern section of the windward Iris Point Reef on the same island at about 50 cm/yr since 3700 years BP (Hopley and Barnes, 1985).

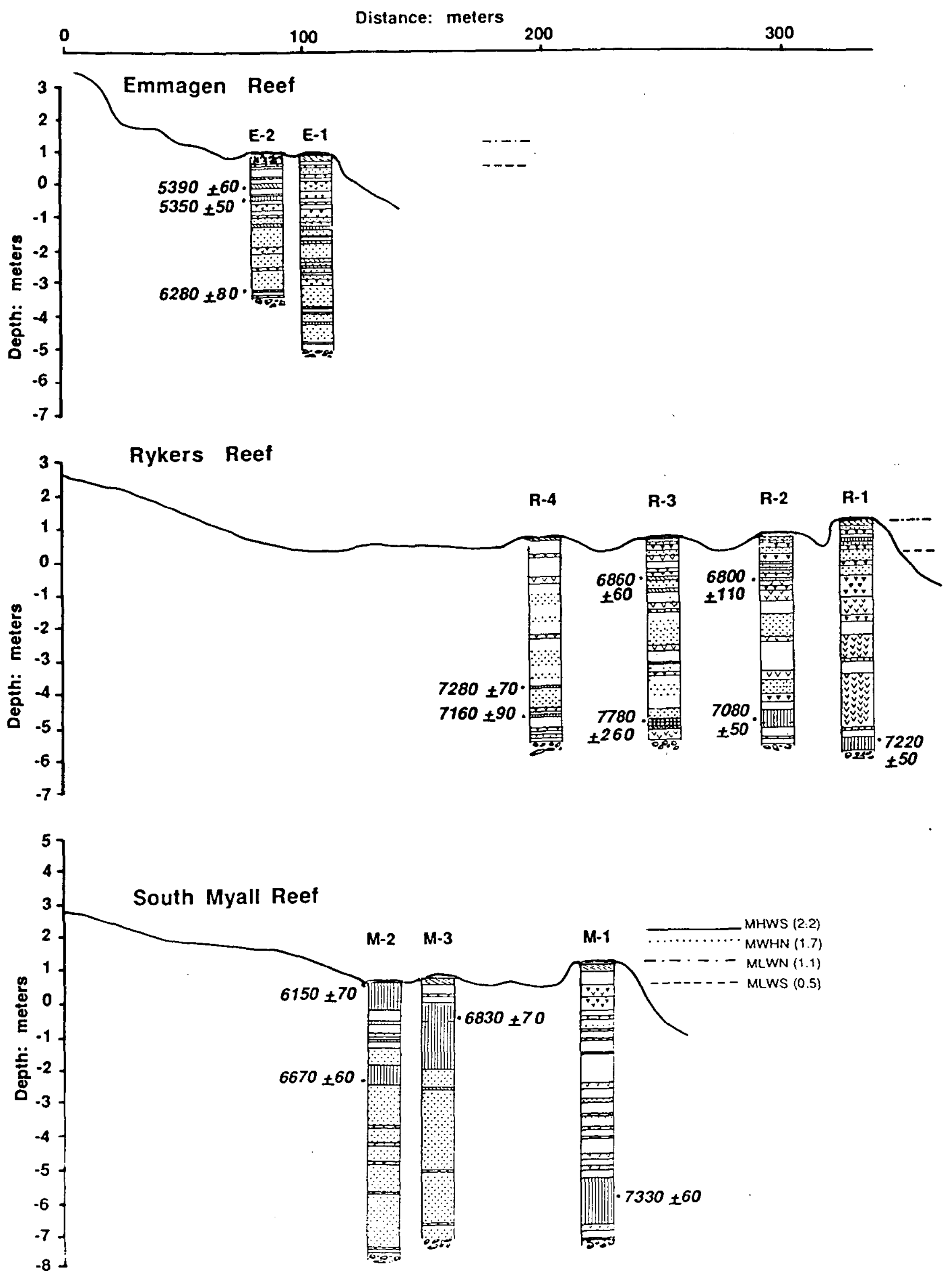

FIGURE 19. Radiocarbon ages from reef cores. Ages are in C^{14} years before present.

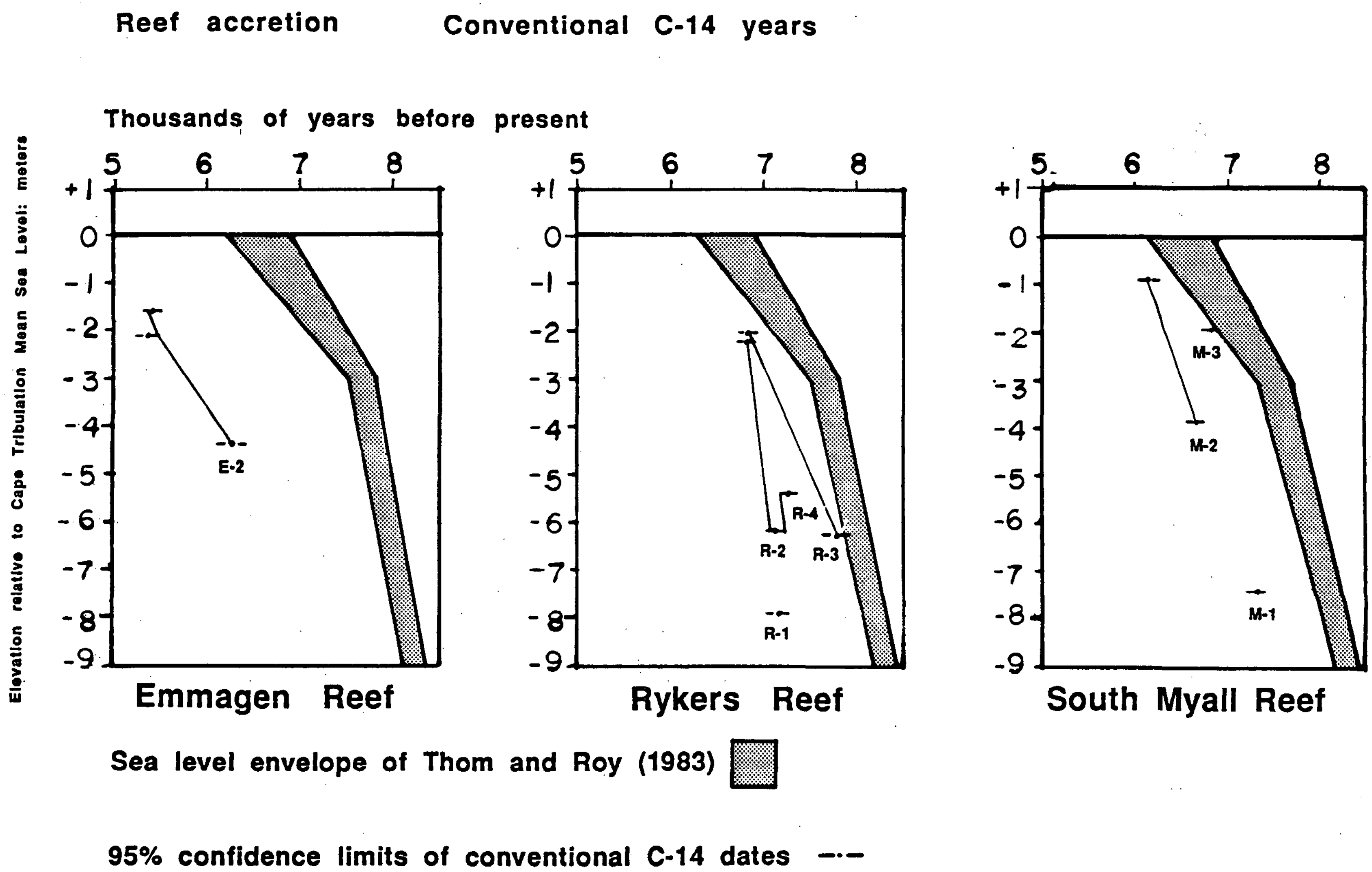

FIGURE 20. Reef accretion in relation to sea level rise, Emmagen, Rykers and South Myall Reefs.

In the Cape Tribulation area, the plume from the major river of the region, the Daintree, appears to move northwards from its mouth well away from the coast leaving only the local streams to deliver freshwater and sediment to the nearshore zone, the amount of which depends on:

- Rainfall totals and intensities
- Catchment relief
- Ground cover (vegetation type and density)
- Local geology and soil characteristics.

The second and fourth points above are independent and will not change over time scales of up to 10^6 years. The first and third points are interrelated and may alter through climatic change, and with regard to vegetation, through anthropogenic influences.

At the present time, the small coastal catchments draining the Cape Tribulation area have annual rainfall totals in excess of 3000 mm, much of it concentrated as storm rains during the summer wet season. Catchments have a naturally dense rainforest cover and are composed of mainly metamorphic rocks, which produce a relatively high yield of sediment even at low flow stages (see Douglas, 1973, 1985; and Pringle, 1986, for discussion). From Douglas's work sediment yield from these catchments under natural rainforest may be in the order of 20 $m^3 km^2 yr^{-1}$. Streams are naturally turbid with sediment concentrations over 5 mg/l even at low flows. Over the period of sea level stability of the last 6500 years, these have built up a significant inner shelf mud wedge which now has a maximum thickness of 10 m (Johnson and Carter, 1987). This large body of fine sediment, 52-87% mud, is resuspended during even moderate wave activity producing highly turbid nearshore waters adjacent to and over the fringing reefs, even without a fluvial input (Hoyal, 1986).

These conditions may have been different during the period when greatest and most rapid reef construction took place (7800-6500 years BP). Kershaw's palynological work (1970, 1971, 1975, 1976, 1980) on the Atherton Tableland, only 100 km south of Cape Tribulation identified a trend of increasing rainfall and temperature in the early Holocene resulting in a change from sclerophyll woodland to rainforest between 7800 and 6500 years BP with rainfall totals rising from <1800 mm to >2500 mm in that period. Rainfall maxima reached ca 3500 mm between 6500 and 3000 years BP with a change from Simple Notophyll Vine Forest to Complex Mesophyll Vine Forest taking place. After 3000 years BP rainfall totals declined to their present (about 2500 mm at the sites investigated) with vegetation reverting to Complex Notophyll Vine Forest.

Presuming that climatic changes of similar magnitude and direction took place in the Cape Tribulation area, then the major growth phase took place during a period of increasing rainfall when totals may have been less than present (Table 7). As rainfall totals here are higher than at the sites on the Atherton Tableland investigated by Kershaw then rainforest may still have prevailed during the whole of this period (or returned earlier). This is important for sediment yield as the protection given by vegetation would have been no different than today but throughput of water would have been less. Maung Maung Aye (1970) demonstrated that basin parameters related to erosion in north Queensland catchments indicated minimal denudation with mean annual rainfall totals of 2500-3000 mm. The increase to totals above those of present (>3000 mm) would automatically have resulted in delivery of greater sediment loads and freshwater runoff by the small coastal catchments, drastically decreasing water quality and stressing reef growth.

Resuspension processes prior to 6500 years BP would have been negligible as no mud wedge existed and pre-existing Pleistocene sediments which formed the sea floor were coarser and more cohesive. However, by the time rainfall decreased towards its present amount after 3000 years BP, the mud unit was already deposited and although runoff and sediment yield from the mainland reduced, water quality remained low due to regular resuspension of sea floor sediments. Reef growth remained stressed and retarded.

TABLE 7. Holocene vegetation and climate change on the Atherton Tableland (from Kershaw) related to stages in reef development, Cape Tribulation.

	VEGETATION	RAINFALL	SEA LEVEL	TURBIDITY	REEF STAGE
Present - 3000 yrs BP	Complex Notophyll Vine Forest	2500 mm	0	High	Negligible growth
3000 - 6500 yrs BP	Complex Mesophyll Vine Forest	3500 mm	+0.8 m	Increasing	Retarded growth
6500 - 7800 yrs BP	Simple Notophyll Vine Forest	<2500 mm	Rising from -8 m	Low	Major growth phase
Pre 7800 yrs BP	Sclerophyll	<1800 mm	Rising from glacial low	Nil	Pre-inundation

Classification of the Cape Tribulation Fringing Reefs

Hopley and Partain (1987) identified three classes of Great Barrier Reef fringing reefs (Fig 21). Recognition of these classes is based on characteristics of reef foundations, growth patterns and internal structure. "Foundation" refers to the substrate on which the reef begins growing.

The reef classes and their identifying characteristics are:

Class I

Simple reefs formed on the lowest portion of a rocky foreshore during the Holocene transgression. These reefs developed while sea level was still rising. Their structure is a basal framework unit immediately over rock, then a small biogenic detrital frontal unit capped by a reef flat veneer. Examples include the narrow fringing reefs on the windward side of the Palm and Whitsunday Islands.

Class II Reefs

Reefs developed over pre-existing positive sedimentary structures. These structures may be in the form of terrigenous mud/sand banks or barriers, lee side sand spits attached to islands, boulder beaches, deltaic bar gravels and low angle Pleistocene alluvial fans. During the transgressive phase, no reef development was possible because of the inhospitable nature of the substrate. However, once the rocky shores of the adjacent island or mainland was inundated, reef colonisation took place rapidly on these shores at shallow depth. Progradation of the reef was then rapid over the pre-existing structure with hard substrate being provided over the sedimentary base by the forereef talus from the prograding reef front.

The structure of such reefs is thus one of a basal terrigenous sedimentary unit, an inner framework with a prograding carbonate detrital unit extending over the terrigenous base, and an upper reef flat framework veneer, generally less than 4 m in thickness.

Examples include Pioneer Bay (Slocombe, 1981; Hopley *et al*, 1983), and Fantome Island (Johnson and Risk, 1987), where terrigenous sand/mud wedges provide the sedimentary foundation and were probably brought inshore by wave action during the Holocene transgression.

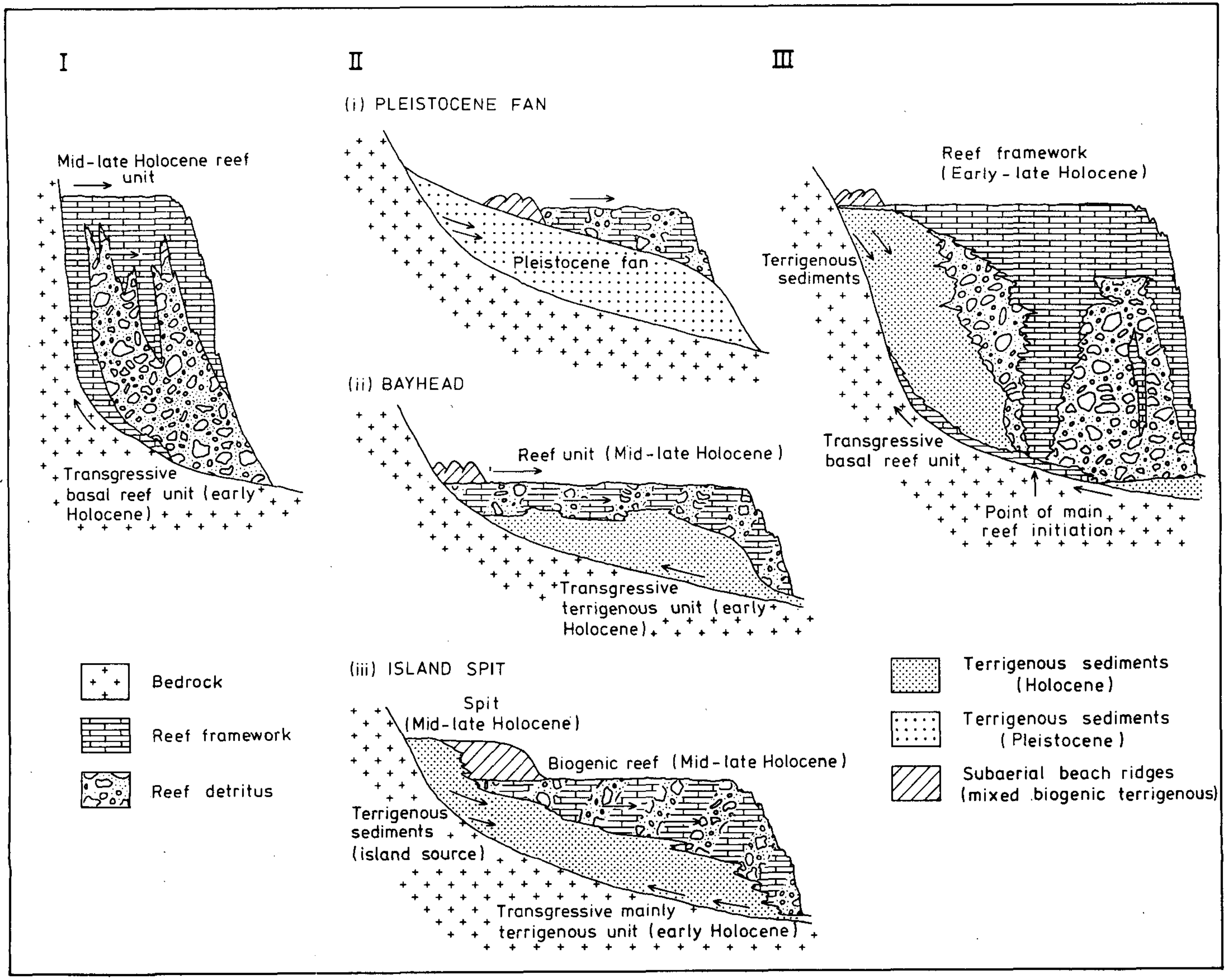

FIGURE 21. Classification of fringing reef development based on Great Barrier Reef examples.

Class III Reefs

Reefs developed over more gently sloping substrate, particularly where older foundations of Pleistocene reefs may be present. Reef growth was initiated offshore from the present coastline. As sea level rose, this initial reef was isolated and continued to grow upwards as an offshore barrier. Possibly because of poor water circulation or terrigenous input, growth behind this barrier was slow.

After still-stand, the reef grew to sea level. Eventually the outer reef became attached to the island by lagoonal infilling. This infill came from both the land as a terrigenous unit and from the outer part of the reef as biogenic carbonate detritus. Following the still-stand, some small outward growth may have occurred.

The reef structure is therefore one of a framework unit offshore from the present shoreline and an interdigitated terrigenous and biogenic detrital fill behind the framework. A reef flat framework veneer may be present over the entire reef and a small, reef-front biogenic talus may also be present. The best example of this type of reef is Hayman Island, which is developed over an older Pleistocene reef.

According to this classification, Emmagen Reef fits between Class I and Class II. Rykers and South Myall Reefs are Class II reefs. The foundations at South Myall and Rykers Reefs are believed to be deltaic fan gravels consisting of alluvial cobbles. Landward or adjacent to each reef is a creek, the source of the cobbles. Rykers Creek flows directly behind and on to Rykers Reef. Myall Creek separates South Myall Reef from South Tribulation Reef. Emmagen Reef is located immediately south of the mouth of Emmagen Creek. Cobbles from Emmagen Creek and the talus from the rocky headland behind Emmagen Reef could be sources for a gravel foundation for this reef.

Abandoned stream channels and associated lobes of beach gravels indicate that Rykers Creek has shifted its location several times. High rainfall and episodic flooding enable streams such as Rykers Creek to periodically transport large bedloads of gravel, cut new channels, and deposit gravel fans at their mouths. Under the right conditions, such gravel fans are excellent foundations for reef colonisation.

Management Implications

The apparently anomalous juxta-position of reef and rainforest as occurs at Cape Tribulation has been highlighted by numerous commentators on the issue of the Cape Tribulation road (eg Anon, 1985). The problem is one of understanding how corals can survive adjacent to an area of high rainfall and naturally high runoff and sediment yield.

However, as discussed above, net accumulation, accretion or growth of the Cape Tribulation reefs appears to have been negligible during the last 5000 years and greatly retarded during the period 6500 to 5000 years BP compared to the major growth period 7800 to 6500 years BP. This has been shown to be due to naturally deteriorating water quality conditions related initially to climatic change but subsequently to increasingly important resuspension of sediments during even moderate weather conditions from the nearshore wedge. As discussed by Buddemeier and Hopley (1989) reefs may continue to survive in an environment in which their initiation could not take place. The potential for reef development can be turned off even though significant populations of corals and coralline algae may continue to exist, eg when calcification and/or sediment retention rates are inadequate to balance erosion. Bioeroders are very prominent in the Cape Tribulation reefs and in the recovered cores. This is in part responsible for the poor recovery in the cores which ranged from 22%-35%. However, framework within the cores was only 4% to 28%.

The Cape Tribulation reefs appear to have already passed beyond the threshold which allows for active reef growth, due to a natural deterioration of water quality over the last 6 500 years. Their present mode is one of maintenance rather than growth in spite of the diversity of corals, which places them in a highly vulnerable position. Further deterioration, however small, has the potential to pass the system beyond the threshold where the reef can be maintained, ie producing an irreversible turn-off as defined by Buddemeier and Hopley (1989). As the adjacent rainforest system is one of high energy maintained within a re-cycling system and expended on vegetative growth (see Douglas, 1969 for discussion), any disturbance to this system has the potential to cause a rapid and irreversible turn-off through increased sediment yield, release of nutrients and more intensive runoff response.

10 CONCLUSIONS

This investigation is the first to describe the morphology and the geologic history of the Cape Tribulation fringing reefs. The following conclusions resulted from this research:

- The reefs are Holocene in age and began developing approximately 7 800 years BP. They are among the oldest known Holocene fringing reefs in the Great Barrier Reef Province.

- The Cape Tribulation fringing reefs developed as follows: Alluvial fan gravel deposits provided a hard substrate favourable for coral growth. As sea level began rising, deeper water forms of reef organisms such as *Porites* sp coral grew. Detrital material from both reef and alluvial sources accumulated and was incorporated within the reef structure. When sea level stabilised, shallow-water reef organisms such as coralline algae began dominating the high-energy surf zone along the outer reef crest. Living coral growth was eventually restricted to deep backreef pools and subtidal zones of the fore reef and fore reef slope.

- Four lithologic assemblages are recognisable in the reefs. From reef base to top these are: 1) gravel assemblage; 2) lower framestone assemblage; e) detrital assemblage; and 4) framestone-boundstone assemblage.

- Coral growth on the reef crest and most of the back reef ceased approximately 5 400 years ago. This coincided with the documented sea level maximum in north Queensland (Chappell *et al*, 1983; Thom and Roy, 1983). However, the evidence from the Cape Tribulation reefs suggests a maximum Holocene sea level only 0.6 to 1.0 m above its present position.

- Major environmental changes appear to have taken place after 6 500 years BP resulting in significant reductions in rates of coral growth and reef accretion. Initially this may have resulted from higher rainfall totals producing greater runoff but subsequently from the deposition of the inner shelf mud wedge from which fine sediments are resuspended windy weather conditions.

- There are management implications from this study. The close juxta position of reef and rainforest at Cape Tribulation possibly did not exist when the reef was first initiated 7 800 years ago nor during much of the reefs' early rapid growth. Deterioration of environmental conditions since that time appear to have put the reefs into a potentially stressed condition as evidenced by their insignificant growth since mid-Holocene times. Further deterioration of the environment produced by anthropogenic factors such as increased sediment yield from the Cape Tribulation road therefore requires careful monitoring to ensure that widespread mortality does not occur as conditions may already have passed beyond the point where reef growth can be reinitiated.

11 REFERENCES

Amos BJ and De Keyser F (compilers) 1964 Geological sheet SE/55-1, Mossman, Queensland: Australian Bureau of Mineral Resources, Geology and Geophysics: scale 1:250 000, 1 sheet.

Anon 1985 Mud: a danger to the Reef. *Search 16*:245.

Ayling AM and Ayling AL 1985 A preliminary survey of coastal reefs in the Cape Tribulation region. Unpublished Report to the Great Barrier Reef Marine Park Authority, 12 pp.

Bathurst RGC 1971 *Carbonate Sediments and Their Diagenesis*, Amsterdam, Elsevier, 620 pp.

Barnes RD 1984 Morphogenesis of a nearshore windward fringing reef, Orpheus Island. Department of Geography, James Cook University of North Queensland, Australia, Unpublished Honours Thesis, 65 pp.

Bird ECF 1971 The fringing reefs near Yule Point, north Queensland. *Australian Geographical Studies 9*:107-115.

Buddemeier RW and Hopley D 1989 Turn-ons and turn-offs: causes and mechanisms of the initiation and termination of coral reef growth. *Proceedings of the Sixth International Coral Reef Symposium, Townsville, 1988.*

Buddemeier RW, Maragos JE and Knutson DW 1974 Radiographic studies of reef coral exoskeletons: rates and patterns of coral growth. *Journal of Experimental Marine Biology and Ecology 14*:179-200.

Chappell J, Rhodes EG, Thom BG and Wallensky E 1982 Hydroisostasy and the sea level isobase of 5 500 years BP in north Queensland. *Marine Geology 49*:81-90.

Chappell J, Chivas A, Wallensky E, Polach HA and Aharon P 1983 Holocene paleo-environmental changes, central to north Great Barrier Reef inner zone. *BMR Journal of Australian Geology & Geophysics 8*:253-266.

Cribb AB 1985 Marine algae of the Cape Tribulation area. *The Queensland Naturalist 26*:26-29.

Curray JR 1964 Transgressions and regressions. *In* Miller RC (ed) *Papers in Marine Geology, Shepard Commemorative Volume*, New York, Macmillan, 175-203.

Davies PJ and Hopley D 1983 Growth facies and growth rates of Holocene reefs in the Great Barrier Reef. *BMR Journal of Australian Geology & Geophysics 8*:237-252.

Davies PJ, Marshall JF and Hopley D 1985 Relationships between reef growth and sea level change in the Great Barrier Reef. *Proceedings of the Fifth International Coral Reef Symposium, Tahiti, 1985 3*:95-103.

Douglas I 1969 The efficiency of humid tropical denudation systems. *Transactions of the Institute of British Geographers 46*:1-16.

Douglas I 1973 Rates of denudation in selected small catchments in eastern Australia. *University of Hull, Occasional Paper in Geography 21*:127 pp.

Douglas I 1985 Geomorphic processes during the Quaternary. *In* Henderson RA and Stephenson PJ (eds) *The Geology and Geophysics of Northeastern Australia*, Geological Society of Australia, 393-395.

Dunham RJ 1962 Classification of carbonate rocks according to depositional texture. *In* Ham WE (ed) *Classification of Carbonate Rocks: American Association of Petroleum Geologists Memoir 1*:108-121.

Embry DF and Klovan JE 1971 A late Devonian reef tract on northeastern Banks Island, Northwest Territories. *Bulletin of the Canadian Petroleum Geologists Association* *19*:730-781.

Ewart A 1985 Altitudinal transect studies at Cape Tribulation, north Queensland; Geological notes. *The Queensland Naturalist* *26*:49-52.

Feigl F 1958 Spot tests in inorganic analyses, Elsevier, Amsterdam, 469-470.

Folk RL and Ward WC 1957 Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* *27*:3-26.

Friedman GM 1959 Identification of carbonate minerals by staining methods. *Journal of Sedimentary Petrology* *29*:813.

Friedman GM and Sanders JB 1978 *Principles of Sedimentology*, Wiley, New York, 58-81.

Gillespie R 1982 Radiocarbon Users Handbook, Sydney. *Macquarie University Quaternary Research Unit, Occasional Publication* *1*:27 pp.

Glynn PW and MacIntyre IG 1976 Evolution of modern Caribbean fringing reefs, Galeta Point, Panama. *American Association of Petroleum Geologists Bulletin* *60*:1054-1072.

Glynn PW and MacIntyre IG 1977 Growth rate and age of coral reefs on the Pacific coast of Panama. *Proceedings, Third International Coral Reef Symposium, Miami, Florida* 2:251-259.

Hampson SR 1985 Official tide tables, coast of Queensland: Brisbane, Queensland Department of Harbours and Marine, 7 pp.

Henderson RA and Stephenson PJ (eds) 1980 *The Geology and Geophysics of Northeastern Australia*, Geological Society of Australia, 468 pp.

Hopley D 1968 Morphology of Curacoa Island spit, north Queensland. *Australian Journal of Science* *31*:122-123.

Hopley D 1982 *The Geomorphology of the Great Barrier Reef*, Wiley Interscience, New York, 453 pp.

Hopley D (ed) 1983 Australian sea levels in the last 15 000 years: a review. *Department of Geography, James Cook University Monograph Series, Occasional Paper* *3*:104 pp.

Hopley D 1983 Deformation of the north Queensland continental shelf in the late Quaternary. *In* Smith DE and Dawson AG (eds) *Shorelines and Isostasy*, Institute of British Geographers Special Publication, *16*:347-366.

Hopley D 1986 corals and coral reefs as indicators of palaeo-sea levels with special reference to the Great Barrier Reef. *In* Van de Plassche O (ed), *Sea Level Research: A Manual for the Collection and Evaluation of Data*, UNESCO, 195-228.

Hopley D and Barnes RD 1985 Structure and development of a windward fringing reef, Orpheus Island, Palm Group, Great Barrier Reef. *Proceedings of the Fifth International Coral Reef Symposium, Tahiti, 1985* *3*:141-146.

Hopley D, McLean RF, Marshall J and Smith AS 1978 Holocene-Pleistocene boundary in a fringing reef: Hayman Island, north Queensland. *Search* *9*:323-325.

Hopley D, Parnell KE and Isdale PJ 1989 The Great Barrier Reef Marine Park: dimensions and regional patterns. *Australian Geographical Studies* *27*:??.

Hopley D and Partain BR 1987 The structure and development of fringing reefs of the Great Barrier Reef province. *In* Baldwin CL (ed), *Proceedings of the Great Barrier Reef Marine Park Authority Fringing Reef Workshop, Townsville, Australia, October 23-25, 1986*, 13-33.

Hopley D, Slocombe AM, Muir FJ and Grant CR 1983 Nearshore fringing reefs in north Queensland. *Coral Reefs 1*:151-160.

Hoyal DCJD 1986 The effect of disturbed rainforest catchments on sedimentation in an area of nearshore fringing reefs, Cape Tribulation, north Queensland. Department of Geography, James Cook University of North Queensland, Australia, Unpublished Honours Thesis, 149 pp.

Isdale PJ 1981 Geographical variation on the growth rates of hermatypic coral *Porites* in the Great Barrier Reef Province, Unpublished PhD Thesis, James Cook University, 141 pp.

Jessup LW and Guymer GP 1985 Vascular plants from the Cape Tribulation area. *The Queensland Naturalist 26*:2-19.

Johnson DP 1985 Age structure of Fantome Island fringing reef. *Great Barrier Reef Marine Park Authority Technical Memorandum TM 6*:25 pp.

Johnson DP, Belperio AP and Hopley D 1986 A field guide to mixed terrigenous-carbonate sedimentation in the central Great Barrier Reef Province, Australia. *Geological Society of Australia, Australasian Sedimentologists Group Field Guide 3*:173 pp.

Johnson DP and Carter RM 1987 Sedimentary framework of mainland fringing reef development, Cape Tribulation area. *Great Barrier Reef Marine Park Authority Technical Memorandum TM 14*:37 pp.

Johnson DP and Risk MJ 1987 Fringing reef growth on a terrigenous mud foundation, Fantome Island, central Great Barrier Reef, Australia. *Sedimentology 34(2)*:275-287.

Kennett JP 1982 *Marine Geology*, Prentice-Hall, Englewood Cliffs, NJ, 752 pp.

Kershaw AP 1970 A pollen diagram for Lake Euramoo, northeast Queensland, Australia. *New Phytologist 69*:785-805.

Kershaw AP 1971 A pollen diagram from Quinean Crater, northeast Queensland, Australia. *New Phytologist 70*:669-681.

Kershaw AP 1975 Stratigraphy and pollen analysis of Bromfield Swamp, northeastern Queensland, Australia. *New Phytologist 75*:173-191.

Kershaw AP 1976 A late Pleistocene and Holocene pollen diagram from Lynch's Crater, northeastern Queensland, Australia. *New Phytologist 77*:469-498.

Kershaw AP 1980 Evidence for vegetation and climatic change in the Quaternary. *In* Henderson RA and Stephenson PJ (eds), *The Geology and Geophysics of Northeastern Australia*, Geological Society of Australia, 398-402.

Knutson DW, Buddemeier RW and Smith SV 1972 Coral chronometers: seasonal growth bands in coral reefs. *Science 177*:270-272.

MacIntyre IG 1977 Distribution of submarine cements in a modern Caribbean fringing reef, Galeta Point, Panama. *Journal of Sedimentary Petrology 47*:503-516.

MacIntyre IG, Burke RB and Stuckenrath R 1983 Core holes in the outer fore reef off Carrie Bow Cay, Belize: a key to the Holocene history of the Belizean Barrier Reef complex. *Proceedings of the Fourth International Coral Reef Symposium, Manilla, 1983 1*:567-574.

Marshall JF 1983 Lithology and diagenesis of the carbonate foundations of modern reefs in the southern Great Barrier Reef. *BMR Journal of Australian Geology & Geophsyics 8*:253-266.

Matthews RK 1974 A process approach to diagenesis of reefs and reef associated limestones. *In* Laporte LF (ed), *Reefs in Time and Space: Society of Economic Paleontologists and Mineralogists, Special Publication 18*:234-256.

Maung Maung Aye 1976 Variation in Drainage Basin Morphometry in Northeast Queensland, Unpublished MA Thesis, Department of Geography, James Cook University, 282 pp.

Milliman JD and Emery KO 1968 Sea levels during the past 35 000 years. *Science* *162*:1121-23.

Montaggioni LF and Pirazzoli PA 1984 The significance of exposed coral conglomerates from French Polynesia (Pacific Ocean) as indicators of recent relative sea level changes. *Coral Reefs* *3*:29-42.

Nakada M and Lambeck K 1989 Late Pleistocene and Holocene sea level change in the Australian region and mantle rheology. *Geophysical Journal* *96*:497-517.

Pringle AW 1986 Causes and effects of changes in fluvial sediment field to the northeast Queensland coast, Australia. *Department of Geography, James Cook University, Monograph Series Occasional Paper* *4*:180 pp.

Slocombe AM 1981 The Structure and Development of the Fringing Reef in Pioneer Bay, Orpheus Island. Unpublished Honours Thesis, Department of Geography, James Cook University, 98 pp.

Thom BG and Roy PS 1983 Sea level changes in New South Wales over the past 15 000 years. *In* Hopley D (ed), Australian sea levels of the past 15 000 years, *Department of Geography, James Cook University, Monograph Series Occasional Paper* *3*:64-84.

Urey HC 1947 The thermodynamic properties of isotopic substances. *Chemical Society Journal* 562-581.

Veron JEN 1987 Checklist of corals from the Daintree Reefs. *In* Baldwin C (ed), *Proceedings of the Great Barrier Reef Marine Park Authority Fringing Reef Workshop, Townsville, Australia, October 23-25, 1986* 99-103.

Veron JEN and Pichon M 1976 Scleractinia of eastern Australia, Part I. *Australian Institute of Marine Science, Monograph Series* *1*:86 pp.

Veron JEN and Pichon M 1979 Scleractinia of Eastern Australia, Part III. *Australian Institute of Marine Science, Monograph Series* *4*:422 pp.

Veron JEN and Pichon M 1982 Scleractinia of Eastern Australia, Part IV. *Australian Institute of Marine Science, Monograph Series* *5*:159 pp.

Veron JEN, Pichon M and Wijsman-Best M 1977 Scleractinia of Eastern Australia, Part II. *Australian Institute of Marine Science, Monograph Series* *3*:233 pp.

Wells JW 1957 Coral reefs. *In* Hedgpeth JW (ed), Treatise on marine ecology and paleoecology, *Geological Society of America, Memoir 67* *1*:609-631.