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Coral Reefs

Fluorescent and skeletal density banding in *Porites lutea* from Papua New Guinea and Indonesia

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Abstract. Shallow water *Porites lutea* corals were collected along two transects normal to mainland shorelines, parallel to gradients in water quality: one, 7 km long, near Motupore Island in South Papua New Guinea, the other, 70 km long, from Jakarta Bay along the Pulau Seribu chain in the Java Sea. The corals were slabbed and studies were made of skeletal density bands as revealed by X-ray photography and fluorescent bands as revealed by ultraviolet light. Water quality measurements and rainfall data were assembled for the two areas and related to skeletal banding patterns. For both areas, with increasing distance from mainland there is a decrease in overall brightness of fluorescence in corals and an increase in the contrast between bright and dull fluorescent bands. Fluorescence is bright, but seasonal banding is obscure in corals within about 2 km of stream mouths at Motopure and about 5 km of the coast in Jakarta Bay; this suggests that, despite low freshwater run-off during dry seasons, there are sufficient organic compounds which cause fluorescence in coral skeletons, to swamp seasonal effects. During the wet seasons, deluges of freshwater consequent on mainland rainfall of greater than about 150 mm/month extend at least 7 km offshore in the Motupore area and perhaps tens of kilometres into Java Sea, giving distinctive bright and dull fluorescent banding in offshore corals. The fluorescent banding pattern within corals on the Motupore reefs is similar in most corals along the transect and it correlates well with the Port Moresby monthly rainfall data. This relationship suggests that the same body (or bodies) of freshwater affect all reefs of the area during the wet season. The fluorescent banding in Java Sea corals does not show a precise correlation with either mainland or island monthly rainfall data; indeed the pattern of fluorescent banding on Pulau Seribu can only be matched in corals from reefs less than about 25 km apart. This suggests that in this area discrete water bodies carrying the relevant organic acids for coral fluorescence affect the fringing reefs on the chain of islands. Comparisons of fluorescent and density banding have revealed that for these areas, in general, periods of high freshwater run-off are times of deposition of less dense skeleton in *Porites lutea* corals.

Introduction

The recent discovery in Australia of fluorescent banding in massive corals when viewed under ultraviolet light and the correlation of this banding with periods of freshwater run-off from the adjacent mainland (Isdale 1984) appeared to provide a simple but valuable new technique for both mapping the areal extent of plumes of turbid freshwater from past floods, and assessing the impact of these plumes on the corals. Here we discuss the results of X-radiography and ultraviolet (u/v) light analyses of skeletal banding in shallow water reef corals from two areas (a) the Papuan southern shelf, 25 km SE of Port Moresby (Fig. 1) and (b) the Pulau Seribu chain of reef islands north of Jakarta Bay, Indonesia (Fig. 2). Both regions have high seasonal rainfall with the main monsoonal wet season from December to April (Figs. 3 and 4). Our primary aim, in both areas, was to observe the skeletal banding patterns over recent years in corals collected along gradients normal to the mainland coasts and to compare these patterns with rainfall records. From such a study it might be possible to determine whether or not there was a line, representing the boundary between corals with fluorescent banding and those without it, which could be used as a means of mapping the limits of seaward spread of seasonal freshwater plumes, and if this line existed, could the directional course of migration of coherent bodies of freshwater be plotted for the past few years using banding chronology?

In addition, we hoped to see if there was a relationship between skeletal density and fluorescent banding; for example, whether or not high influxes of freshwater caused sufficient stress in corals to generate dense bands?

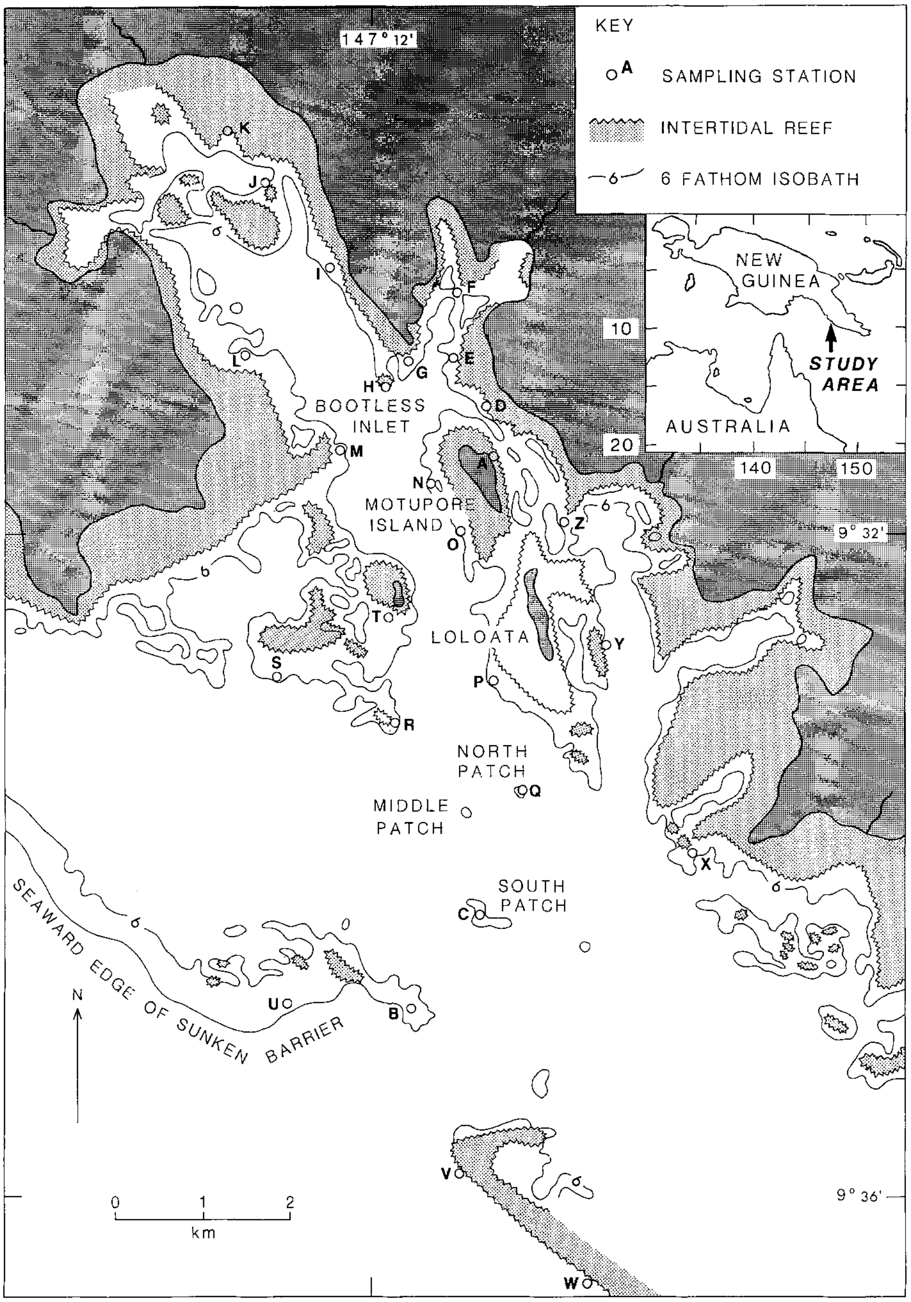

Fig. 1. Location of samples, Motupore area, Papua New Guinea

Fluorescent banding

Where corals have grown within the range of freshwater run-off, then organic compounds, such as fulvic and humic acids produced by plants in soils, may be incorporated into the coral skeleton (Isdale 1984; Boto and Isdale 1985). Certain of these compounds fluoresce under ultraviolet light (for example low-relative molecular mass fulvic acids give a yellow-green band) which causes a bright/dull banding within coral skeletons which relates to rainfall, river discharge and proximity to land. This observation potentially allows the reconstruction of past climates and changes in rainfall or run-off patterns (e.g. related to deforestation) over long periods (hundred of years for large massive corals). As well as indicating the temporal pattern of freshwater discharge, this technique, with an appropriate distribution of samples, potentially allows an assessment of the areal variation in freshwater discharge over time.

Density banding

The retrospective method of coral sclerochronology, utilising the seasonality of density bands within the skeleton as revealed by X-radiography, has been adopted for some time (Buddemeier et al. 1974; Knutson et al. 1972), though there is still considerable controversy as to the exact cause of the variations in density of the skeleton. It is generally believed (Highsmith 1979) that the low density bands are produced under optimum growth conditions

Fig. 2. Location of samples, Jakarta Bay and Pulau Seribu, Indonesia. (Jakarta is latitude 6° 08′S, 106° 45′E)

and the high density bands accrete during non-optimum growth conditions. Physical environmental factors which are known to influence coral skeletal density are: (a) light (Macintyre and Smith 1974; Stearn et al. 1971; Knutson et al. 1972; Wellington and Glynn 1983), (b) temperature (Highsmith 1979; Hudson et al. 1976), (c) levels of suspended sediment (Dodge et al. 1974; Brown 1986). Salinity and water agitation may also exert some control. Other factors which influence the metabolism of the coral which may be reflected in skeletal growth include nutrient availability and reproductive activity – the production of gametes may diminish energy available for growth and calcification (Wellington and Glynn 1983). The roles played by the symbiotic zooxanthellae in influencing calcification, and endolithic algae in modifying density patterns, are further complications. When density banding was compared with stain experiments on living corals by Wellington and Glynn (1983), they noted within the skeletons of *Pavona gigantea* and *Pavona clavus* in Panama, firstly, that a couplet of a high density band and a low density band normally represent one year's growth; secondly, low density bands represent an increase in linear extension as well as a marked increase in calcification rate relative to the high density portion; and thirdly, the low density portion appears to accrete over a shorter period than the high density portion.

Areas of study

Papua New Guinea

The area selected for study was around Motupore Island, 25 km southeast of Port Moresby on the country's south coast (Fig. 1). The collection sites (26 in total) were in water 2–5 m deep ranging from nearshore muddy embayments close to the mouths of small streams which drain into Bootless Inlet, through lagoonal water with island-fringing and patch reefs, out to the clear water of the outer barrier reef 7 km offshore (Fig. 1). Collections were made in April, 1985. Between reefs, lagoonal waters reach a maximum of 50 m depth and the barrier reef marks the edge of the shelf. Passes in this barrier reef allow regular tidally-induced exchange between lagoonal and open ocean waters.

The climate of this region is tropical with distinct wet (NW Monsoon winds dominant December–April) and dry (SE Trade winds dominant April–November) seasons. Rainfall records are from Port Moresby (Fig. 3). Annual water temperature range is approximately 26° to 30 °C, and surface (0.5 m) and bottom waters (up to 50 m) vary by less than 1 °C. During the dry season the lagoon's waters develop to a homohaline condition at approximately 35–36‰; whereas, during the wet season the salinity of the surface 2m is in the range 30‰ for nearshore embayments, to 33‰, for the outer lagoon (Moore 1982).

Java Sea, Indonesia

The Pulau Seribu chain of islands occurs on a submarine ridge trending north-south from Jakarta Bay for a distance of 70 km (Fig. 2). The depth of water between islands seldom exceeds 20 m except in the north of the chain where deep channels occur. Corals were collected from 28 reef sites along the chain (Fig. 2). All the reefs visited were fringing vegetated islands. The reef and island sizes varied within the chain but in general the islands were between 300 m and 1000 m in diameter and the reef flats between 50 and 200 m wide. The collection sites were in water 2–4 m deep towards the outer edge of reef flats on the northern sides of islands. At the time of collection (May 1985) prevailing winds were from the north and water turbidity was much greater on the southern sides of islands, due: (a) to the leeward confluence of refracted waves and (b) greater population, and therefore man-induced effluence, on the sheltered sides of islands. Water clarity was compared at each site by recording the depth of extinction of a secchi disc. These values were as low as 2.5 m on reefs near to the mainland but increased to the north along the island chain to values up to 28 m. Water temperatures and salinities were also measured at each site at 3 m depth. The waters at sites near to the mainland were characterised by relatively high temperatures (30 °C) and low salinities (29‰), and also very low percentages of living coral cover (1%–5%); the waters at sites tens of kilometres from the mainland were characterised by lower temperatures (27 °C), higher salinities (33‰) and luxuriant coral cover (40%–80%) (Brown 1986). The rainfall data presented here (Fig. 4) is from Pari Island (mid-way along the Pulau Seribu chain), and from the mainland (at sea level near Jakarta). The records are incomplete but give a good idea of the seasonal variation in precipitation.

Materials and methods

From each site (26 at Motupore, Papua New Guinea, and 28 at Pulau Seribu, Indonesia) three specimens of *Porites lutea* of 20–30 cm diameter were collected. This species was selected since it was very abundant on the reefs, was easily identified, occurred in 20 to 30 cm diameter colonies that were easily collected, and was known to show skeletal banding. The corals were air dried and cut longitudinally by hand saw into slabs be-

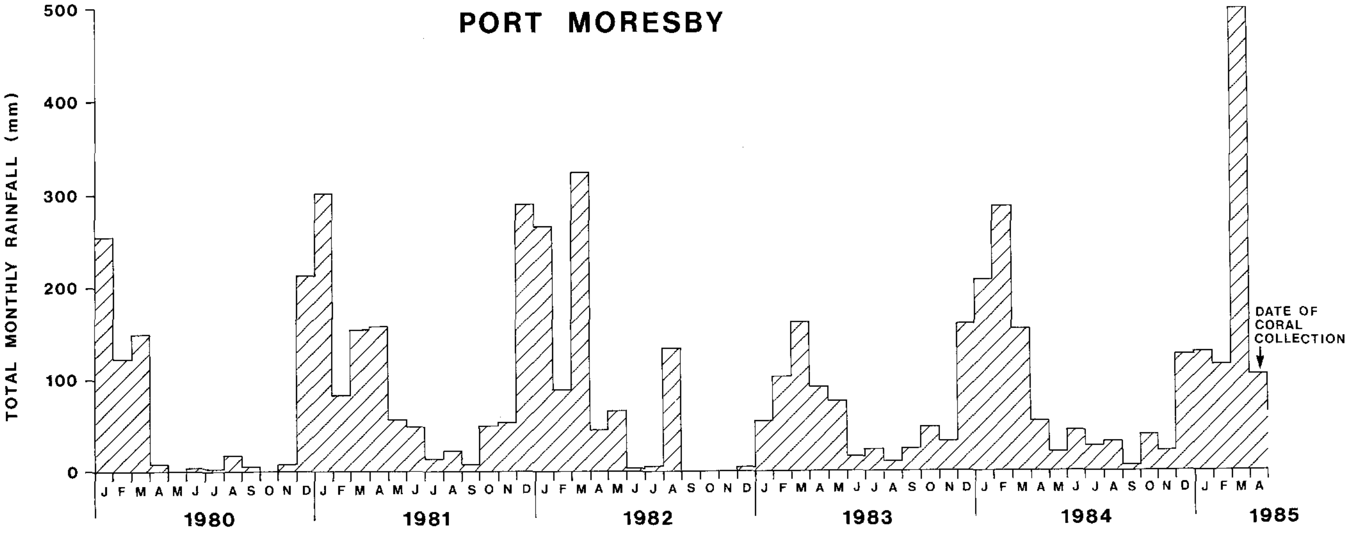

Fig. 3. Monthly rainfall record, Port Moresby, Papua New Guinea

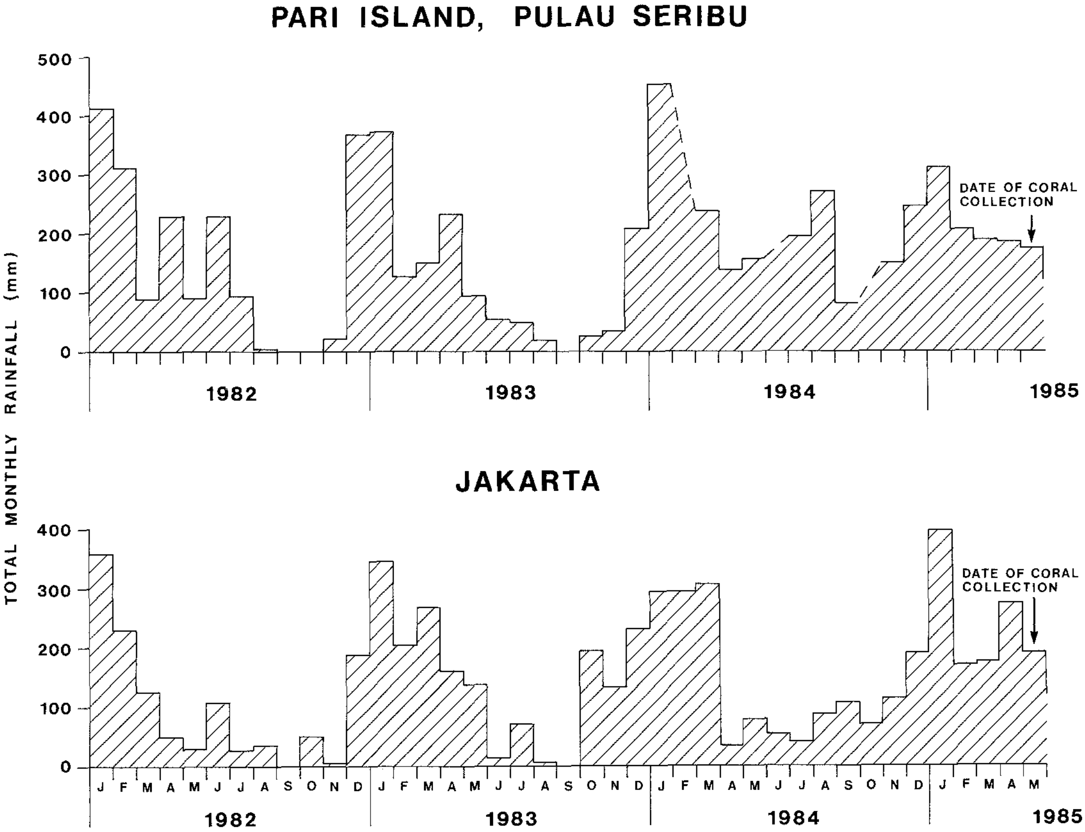

Fig. 4. Monthly rainfall record, Pari Island (Pulau Seribu) and Jakarta, Indonesia. Dashed lines indicate months for which no rainfall data are available

tween 5 and 15 mm thick parallel to the growth axes. In the laboratory the coral slabs were recut, using a mechanical rock saw, to an even thickness of about 5 mm. The slabs were then cleaned, bleached and treated in an ultrasonic resonator to remove any fine loose particles attached to the skeletons. The slabs were viewed and photographed under ultra-violet light. Long wave-length u/v light gave the brightest fluorescence and photography was aided using a u/v filter and 160 ASA, Kodak Ektachrome tungsten colour film. Exactly life-size black and white prints of the two faces of each coral slab were prepared from the colour slides. The photography of one side of each slab was reversed during printing so that the two pictures were of similar shape (and not mirror images). The prints were cut vertically through the middle and spliced so that the accuracy of the match between bands on the front and back of the slab could be assessed. Any obliquity between the cut face and growth axis was thus detected and the extent recorded. The majority of slabs showed no obliquity between cut face and growth axis. The slabs were photographed on an X-ray machine using Kodak type AX film at exposures of approximately 120 s at 70 kV and 3 mA with a source to film distance of approximately 1 m. Each X-radiograph (life-size print prepared from contact negative) was spliced against the print of identical size of the photograph of u/v banding allowing comparison of skeletal density and fluorescent banding for each coral. When attempting correlation between fluorescent and density banding any measured obliquity between cut face and growth axis was taken into account. The pattern of banding was compared between corals of each site and between corals of different sites.

We have not attempted quantification of the absolute values of intensity and spacing of banding (see Isdale 1984) since our prime objective was the comparison of *patterns* of skeletal banding. We found the visual analysis of photographs of whole coral slabs the most effective method for this purpose, since local variations in growth rate within the coral and any blemishes in banding intensity, caused, for example, by the activities of endoliths, could then be quite easily taken into account. While we believe that this essentially qualitative approach is the most effective in tackling this type of study it does unfortunately preclude a rigorous statistical testing of the results and consequently our conclusions contain an element of speculation.

Results

Motupore, Papua New Guinea

Analysis of coral slabs showed the following:

1. Under ultra-violet light all corals display fluorescent banding (Fig. 5). However the presence of endoliths (such as sponges, bivalves, worms) locally reduces the intensity of fluorescence and obscures the banding pattern (Fig. 6).

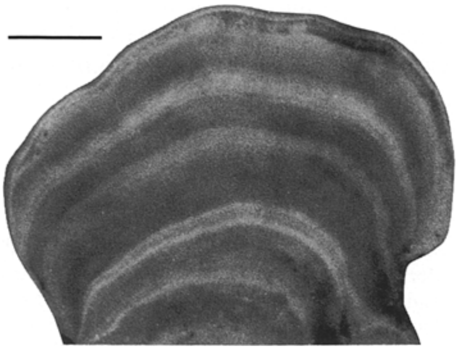

Fig. 5. Fluorescent banding on cut face of *Porites lutea* from Station C, Motupore area, Papua New Guinea. Scale bar 2 cm

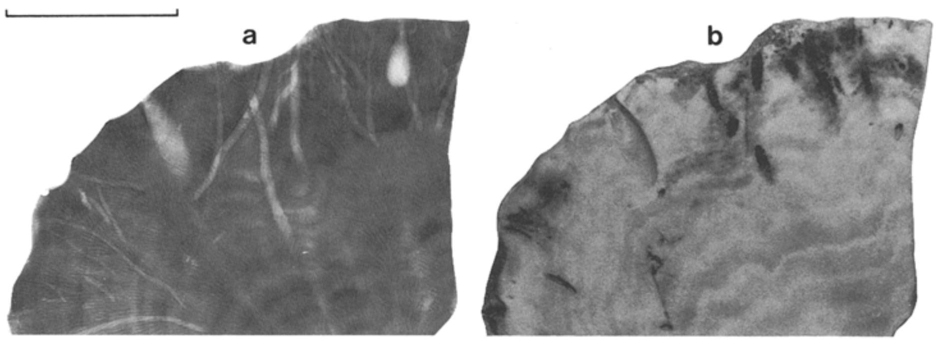

Fig. 6. Two positive prints of a slab of bored *Porites lutea* from Station A, Motupore area, photographed (**a**) using X-rays and (**b**) ultra violet light. Note how the activity of endoliths has obscured banding. Scale bar 5 cm

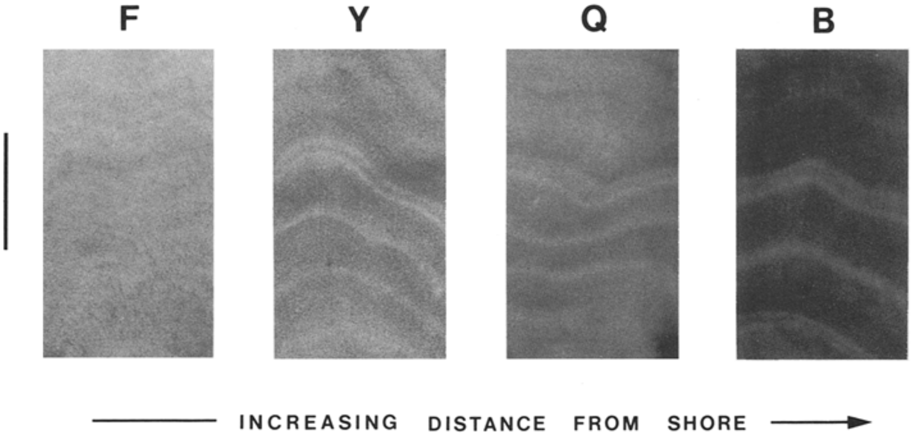

Fig. 7. Four slabbed *Porites lutea* corals, photographed under ultra violet light, collected from stations (F, Y, Q, B) representing a progressive increase in distance from stream mouths. All photographs were exposed and processed in an identical manner; note the increase in contrast in banding offshore. See Fig. 1 for locations. Scale bar 2 cm

2. The degree of overall fluorescence of coral skeletons decreases with increasing distance from the coastal inlets, presumably reflecting a decrease in terrestrial influence away from stream mouths (Fig. 7). The corals collected from less than about 2 km distance from stream mouths display strong overall fluorescence, pale yellow in colour, in which banding is diffuse and indistinct. Moving offshore, bands become more sharply defined.

3. There is a distinctive fluorescent banding pattern (characteristic spacing, thickness and intensity) in all corals collected from greater than about 2 km from the stream mouths. This banding pattern correlates closely with the Port Moresby monthly rainfall record (brightly fluorescent band = heavy rainfall) (Fig. 8). For example, the distinctive double fluorescent band (Fig. 8) matches the bimodal distribution of rainfall in the 1981–82 wet monsoon, and the low rainfall of the 1982–83 monsoon (related to the el Niño phenomenon of that year) is recorded as an unusually weak fluorescent band (Fig. 8). Clearly, the heavier the rainfall then the brighter the fluorescent band.

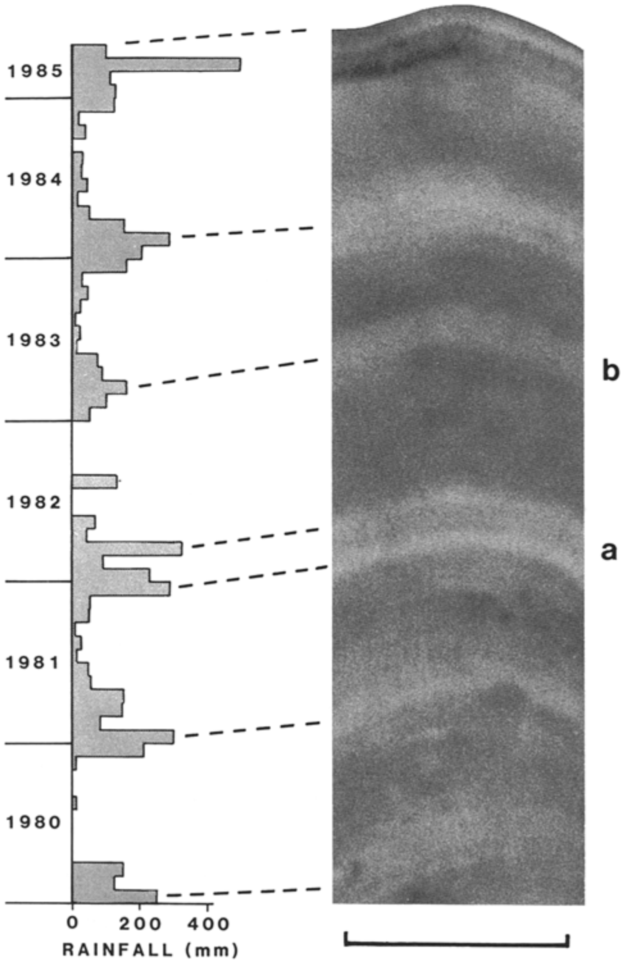

Fig. 8. Comparison of Port Moresby monthly rainfall record with characteristic fluorescent banding pattern (Station C) Motupore area. Note that the bimodal distribution of rainfall in the 1981–1982 wet monsoon is equivalent to the distinctive double fluorescent band (a), and the low rainfall of the 1982–1983 wet monsoon is reflected in an unusually weak fluorescent band (b). Scale bar 2 cm

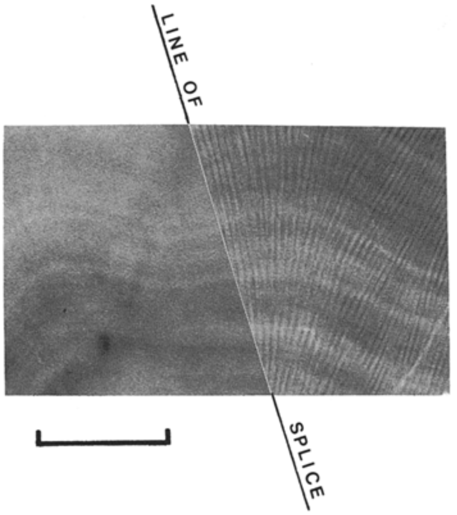

Fig. 9. Spliced positive print photographs (under u/v light, left, and X-rays, right) of slab of *Porites lutea* (Station X) Motupore area, illustrating the correlation of bright fluorescent bands with less dense (lighter tone) skeletal bands. Scale bar 2 cm

4. Comparison of the characteristic banding pattern with the rainfall record (Fig. 8) reveals that freshwater plumes (with effective quantities of terrestrially derived organic acids) reach the outer barrier only during periods when monthly rainfall exceeds about 150 mm, causing distinctive skeletal banding, whereas close to the stream mouths (<2 km) freshwater influence is perennial and masks seasonal effects.

5. Analysis of X-radiographs shows that skeletal density banding is apparent in all corals throughout the area though not all show distinctive annual dense/less dense couplets. However, where annual density couplets can be clearly discerned (70% of coral specimens) we note that there is a close correlation between fluorescent and skeletal density banding patterns in which the wet season's brightly fluorescent band is equivalent to the less dense skeletal band. Even subsidiary, within-season, bands correlate well (Fig. 9).

6. Using as a marker the distinctive double fluorescent band generated by the bimodal distribution of rainfall in the 1981–82 monsoon, the mean linear growth rate of corals over the period November 1981 to April 1985 was determined to be 10.5 mm/year (standard deviation = 0.3, $n = 56$). There is no significant variation in growth rate with increasing distance from shore in this study area.

Pulau Seribu, Indonesia

There is a gradient in water quality away from the Java mainland; water temperatures decrease, salinities increase and water turbidity decreases. The corals reflect this trend; firstly, in the marked increase in the percentage cover of living corals on reefs out to sea, secondly, in the increase in species diversity, thirdly, a decrease in fluorescence within *Porites lutea* along the gradient away from the mainland (Brown 1986).

Most *Porites* sampled fluoresce to some degree when subjected to u/v light. Corals from reefs within 5 km of the mainland coast do not show distinct contrasty banding, instead they have an overall bright, even or mottled pale yellow fluorescence. Corals of these nearshore reefs are also extensively bored by *Lithophaga*, sponges, worms and algae, and these infestations locally reduce fluorescence and obscure banding (similar to Fig. 6). *Porites lutea* sampled from reefs greater than 5 km offshore show couplets with distinctive bright (yellow) and dull (steel blue) bands. Minor variations in fluorescence make striped patterns of narrow subsidiary bright bands within major bright/dull couplets.

After visual analysis of the fluorescent banding patterns the following points emerged:

1. With only a few exceptions corals from one reef show similar correlatable fluorescent banding patterns (i.e. similar relative spacing, thickness and brightness of bands).

2. Corals from reefs within about 25 km of one another possess banding patterns which are broadly similar and correlatable, though, in detail differences may occur. Indeed the most recent band is not always of the same phase (Fig. 10). There appears to be a gradual change in banding patterns along the island chain. As a consequence, it is not generally possible to correlate with confidence the banding patterns in corals from reefs separated by more than about 25 km (Fig. 10).

3. The average thickness of major bright/dull couplets for corals showing clear banding is 9.4 mm (standard deviation = 0.3, $n = 130$) and suggests the couplets represent one year's growth.

4. Though the major bright/dull couplets appear to represent the wet and dry seasons, we cannot detect a close correlation between the monthly rainfall records (from Pari Island or Jakarta) and the detailed banding patterns.

5. As is the case with the Papuan corals, the skeletal density banding revealed by X-radiography is more complex than the fluorescent banding, with distinct dense/less dense couplets not always easy to discern.

6. Where major bright/dull couplets and dense/less dense couplets can be clearly discerned (60% of coral specimens) we note that the major bright fluorescent bands equate with less dense bands in the skeleton (Fig. 11). However we do note in a few corals that very thin, very bright, subsidiary fluorescent bands equate with very thin dense bands (Fig. 12).

7. The absence of a distinctive band in all corals from Pulau Seribu which could be keyed into a specific rainfall event meant that it was not feasible to obtain measurements of growth rates in the manner achieved for the Papuan corals, but for those corals with clear bright/dull fluorescent banding the implication is that annual linear growth is about 9.4 mm with no marked trend in variation along the chain.

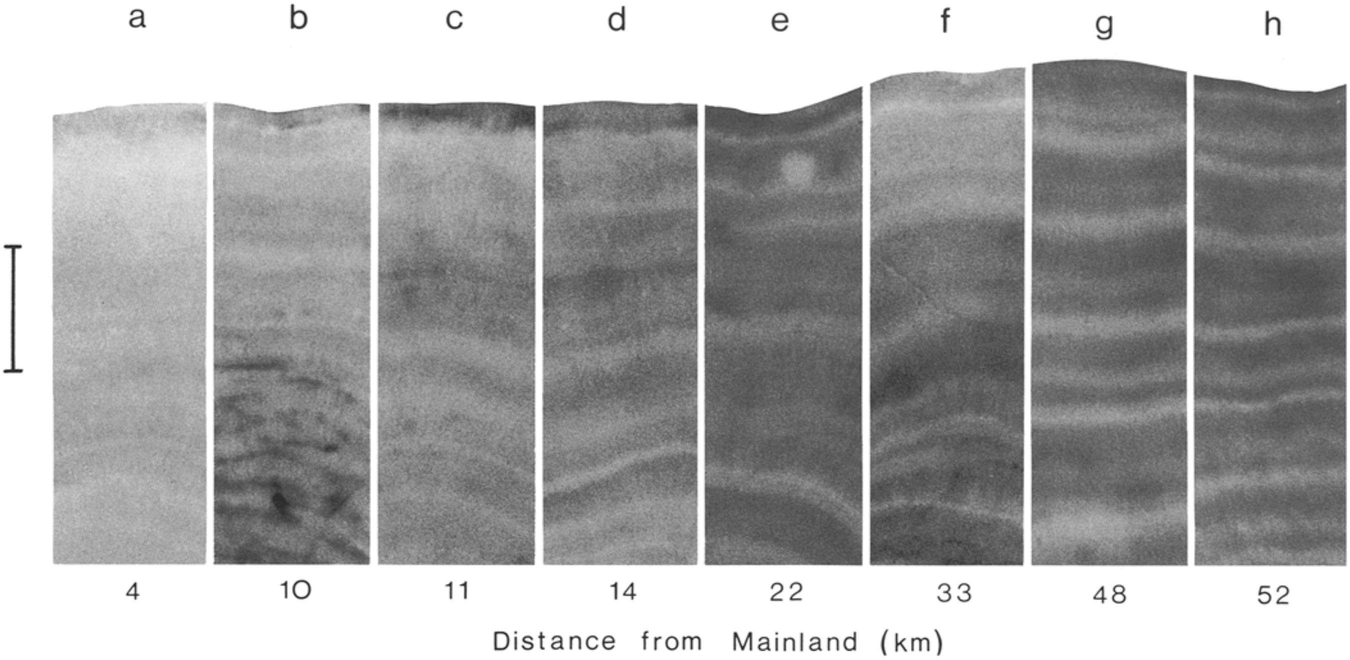

Fig. 10. Fluorescent banding, revealed by u/v light, in *Porites lutea* corals from along the Pulau Seribu chain, arranged according to distance from mainland. a = Rambut; b = Nyamuk Kecil; c = Damar Kecil; d = Damar Besar; e = Payung; f = Congkak; g = Jukung; h = Hantu Besar. See Fig. 2 for locations. All photographs were exposed and processed in an identical manner. The tops of the photographs are the tops of each coral. Note, with increasing distance from mainland there is a decrease in overall brightness and an increase in banding contrast. Also note that only reefs from similar distances from the mainland have similar banding patterns. (Coral b has suffered endolithic infestation near the base, and the top few mm of corals b, c and d are dark due to residual coral tissue not removed by bleaching.) Scale bar 2 cm

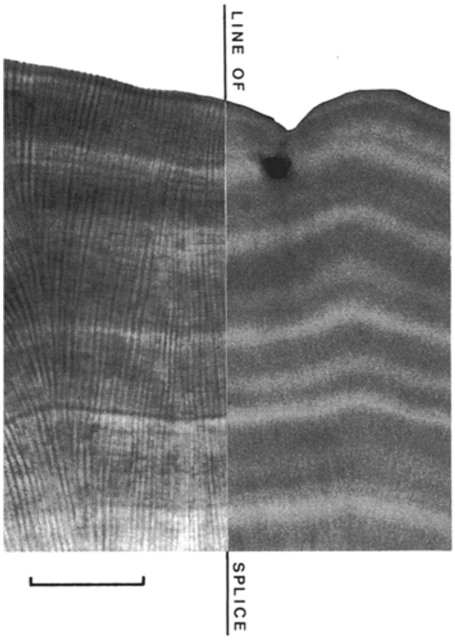

Fig. 11. Spliced positive print photographs (under u/v light right, and X-rays left) of slab of *Porites lutea* from Jukung, Pulau Seribu, illustrating the correlation of bright fluorescent bands with less dense (lighter tone) skeletal bands. The top of the photograph is the top of the coral. Scale bar 2 cm

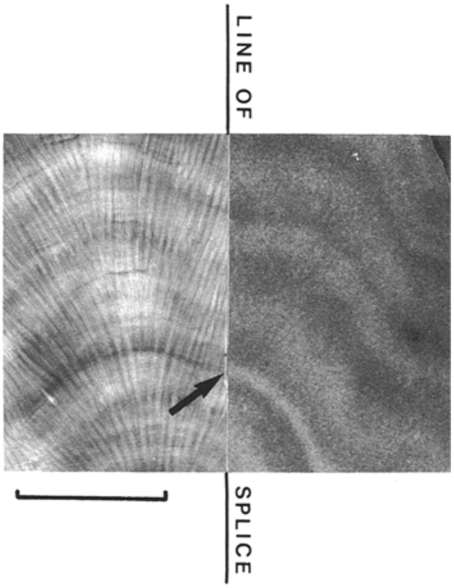

Fig. 12. Spliced positive print photographs (under u/v light right, and X-rays left) of slab of *Porites lutea* from Damar Besar, Pulau Seribu, illustrating the general correlation of bright fluorescent bands with less dense (light tone) skeletal bands, except in the position arrowed where a very thin, very bright, fluorescent band correlates with a very thin dense (darker tone) skeletal band. Scale bar 2 cm

Discussion

Supply, to reefs, of organic compounds that cause fluorescence in corals

The fulvic and humic acids causing fluorescence are terrestrial in origin and carried to the sea by freshwater streams and rivers (Boto and Isdale 1985). The likelihood of mainland freshwater impinging on reefs is controlled by the proximity of the reef to river mouths, the volume of fresh water discharge and the circulation of the coastal waters. The volume of freshwater discharge relates not only to rainfall but also to catchment area. Regrettably we have only part of these data; the nearby mainland and mid-chain rainfall records and the distances of reefs from the mainland coasts.

Porites lutea corals on the offshore reefs in the Motupore area all have a similar fluorescent banding pattern, and this distinctive pattern clearly correlates well with the Port Moresby monthly rainfall data suggesting that during the wet season the same body (or bodies) of freshwater affects all the reefs in the Motupore area. This is in agreement with Moore's (1982) oceanographic findings which indicated rapid mixing and flushing of these lagoonal waters during the wet season.

The situation appears to be more complex in the Pulau Seribu chain. Though there is an underlying trend of reduction in freshwater influence away from the mainland (salinity increase and coral fluorescence decrease) we note that there is no direct relationship between Jakarta monthly rainfall records and the pattern of fluorescent banding in *Porites lutea* corals. Also, along the island chain, variation and inconsistencies in fluorescent banding patterns imply that there is more than one source of input of these yellow-green fluorescing compounds (presumed to be of terrestrial origin) to these reefs. There are several possible explanations. Firstly, one discrete seasonal freshwater plume may be fragmented by marine currents. Secondly, there are several rivers which discharge along this stretch of north Java coast and initial studies of satellite imagery have revealed that freshwater plumes from these rivers affect different reefs. Thirdly, since all corals were collected from reef flats surrounding vegetated islands it is likely that *local* freshwater run-off from these islands will affect the fluorescent banding pattern. For example, after heavy rain we recorded low salinity (25‰) water draining across the reef flat of Sepak Island. And fourthly, it is conceivable that the fluorescing terrestrial organic compounds are deposited over wide stretches of the shallow Java Sea bed and though their introduction may be seasonal and result in a general reduction offshore, the resuspension of these compounds by turbulent waters may follow a temporal pattern unrelated to rainfall.

Relationship between fluorescent banding and skeletal density banding

For both regions it is apparent that the brightly fluorescent bands match the less dense skeletal bands revealed by X-radiography (Figs. 9 and 11). The only exceptions to this general rule are a few instances where very thin, very bright fluorescent bands equate with very thin *dense* bands. Assuming that less dense skeletal bands represent periods of optimum calcification (Wellington and Glynn 1983) and that fluorescent bands represent times of high rainfall, we are forced to conclude that, in general, fastest coral growth takes place during times of high freshwater run-off but that exceptionally high run-off events can be briefly deleterious to corals.

Thus it would seem from our observations of *Porites lutea* in Papua New Guinea and Indonesia (where in general, bright fluorescent bands equate with less dense skeletal bands) and from those of Isdale (1984) on the same species from the Australian Great Barrier Reef (where bright fluorescent bands equate with dense skeletal bands) that no simple universal model relating fluorescent and density banding can at present be constructed.

Conclusions

Both the regions studied have heavy seasonal discharge of freshwater from the mainland superimposed on a perennial (background) drainage. The low levels of discharge during dry seasons appear to be sufficient to impart bright fluorescence to corals growing within about 2 km of stream mouths in the Motupore region and about 5 km of the mainland coast in Pulau Seribu. During the wet seasons, deluges of freshwater, consequent on mainland rainfall of greater than about 150 mm/month, extend at least 7 km offshore in the Motupore area, and perhaps tens of kilometres in Pulau Seribu, resulting in distinct bright/dull fluorescent banding. Corals on the offshore Papuan reefs have a distinctive fluorescent banding pattern which correlates with the Port Moresby monthly rainfall records suggesting that during the wet season, the same body (or bodies) of fresh water affects all the reefs of the area. In the Indonesian material, although there is an underlying trend of reduction in freshwater influence further offshore, there is no close correlation between fluorescent banding patterns and Jakarta or Pari Island monthly rainfall records. This observation, combined with the variations in fluorescent banding patterns along the island chain, suggest that there is more than one source of the terrestrial organic compounds that cause coral fluorescence affecting these reefs. These could be for example, one seasonal freshwater plume fragmented by marine currents, discrete freshwater plumes from different rivers, run-off from offshore vegetated reef islands or resuspension of sea bed sediments containing previously deposited terrestrial organic compounds.

Comparisons of skeletal density banding with fluorescent banding revealed that in both the Motupore area, Papua, and Pulau Seribu, Indonesia, periods of high freshwater run-off are times of deposition of less dense skeleton in *Porites lutea* corals.

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