10. DISCUSSION

Enhanced Sedimentation Rates in the Cape Tribulation Area

In spite of the numerous difficulties encountered, we believe that the information collected for the Cape Tribulation area, forms the largest data set for sedimentation rates on any fringing reef in the world and confirms the concerns expressed at the time that the New Road was being constructed.

Above the New Road, streams in the area appeared to behave in exactly the same way as other small rainforest catchments (see Pringle, 1986, for review). Under low intensity rainfall conditions sediment concentrations are frequently below 10 mg/l. High intensity showers can increase this towards 200 mg/l. Even very intense falls such as occur once every two or three years increase these figures to about 250 mg/l. Under natural conditions figures higher than this may be expected only after a major event such as a cyclone when the combined effects of intense rainfall and high winds with consequent damage to the protective rainforest canopy are combined. Enhanced sediment yield has been clearly demonstrated below the the disturbed areas along the road. Nonetheless, concentrations exceed 200 mg/l only after heavy rainfall events, ie are within the limits normally found in undisturbed catchments. However, figures obtained in March 1985 shortly after the completion of roadworks show that exceptionally high sedimentation rates are possible. Although there is an indication in the results that sediment yield is declining with time as revegetation of disturbed bare soil areas takes place as suggested by O'Loughlin (1985) (Figure 1), the lack of a rainfall event equalling that of 1985 during subsequent sampling periods makes such a conclusions tentative.

Results of studies of the sediment settlement on the fringing reefs show regional and zonal patterns which are statistically distinct. The Northern Control area may be regarded as having sedimentation rates close to natural conditions. In comparison, the Old Road section (Area 1) has a sedimentation rate more than three times that of the control, whilst the New Road section has a sedimentation rate approaching six times as great. Concerns that suspended sediment from the New Road section may be transported northwards by longshore currents do not appear to be justified. Accumulation of mud in this northern area is less than in the two areas to the south. However, mud makes up only a small part of the total sediment settling on the reefs, and does not show the same areal or zonal distinctions as the sand fraction and total sediment accumulated. Disturbance does not seem to have increased the sedimentation rate of fines. Indeed, the highest figures are found in the southern-most area corresponding to the largest and widest nearshore mud wedge just north of the Daintree River as indicated by Johnson and Carter (1987). Lack of significant correlation between the mud sedimentation rates and any rainfall factors appears to confirm that most of the mud is originating from resuspended material picked up from the nearshore zone by waves of even modest size.

Nonetheless, there is a clear indication that the New Road section has significantly higher total sedimentation rates whilst the Old Road section in the south has levels which are intermediate. These intermediate levels may represent conditions in disturbed but more stable conditions several years after major disruption. They may indicate the expected sedimentation rates along the New Road section in ten years time.

As the high sedimentation rates in the New Road section are the result almost entirely of high sand accumulation rates (even though the sand is extremely fine), there is the suggestion that the mud component of the fluvial sediment yield passes straight over the reef as the streams enter the sea and contribute only a small amount to the total of resuspended sediment in the nearshore zone. In contrast, the fine sand fraction also carried in suspension by the streams is being dumped almost immediately on the reefs. Where the reefs are wide much of this sediment is being deposited in the backreef zone. However, considerable proportions are also being carried into the

living coral zone of the reef front. Lowest settlement rates associated with the reef crest are probably the result of two factors. First, the reef crest is in part an emerged mid-Holocene high sea level feature and is the highest part of the reef, and is therefore out of water for the longest period. Second, this outer crest feature at high water is also the location of wave breaking and severe agitation which may also limit the amount of settlement taking place.

There is an apparent contradiction in the fact that whilst highest sedimentation rates are associated with the New Road section, there are few correlations with rainfall factors but several significant correlations with wind factors. It is suggested that major sediment input from the local streams was not taking place during the measurement period and that the sediment, particularly the sand fraction, may have already been present on the reef flat having been brought down from the disturbances along the New Road during the period of construction, particularly when this coincided with a major rainfall event. Such a massive sediment input during early 1985 has already been indicated by the stream sampling programme. Much of the sand is being retained in the nearshore zone and as indicated by the correlation with strong wind factors is being resuspended generally when wind speeds exceed 20 knots. Whilst larger areas of unsealed roads on steep gradients and associated ground disturbance remain, the potential for further sharp short inputs of sediment into the New Road section of the coastline remain. The fact that this sediment subsequently may be moved around in weather conditions which can occur more than 50% of the time in the Cape Tribulation area suggests that the chronic sedimentation stress which these reefs have suffered ever since sea level stabilised more than 6000 years ago (see Partain and Hopley, in press), may reach acute thresholds at some stage in the future.

Comparison with Sedimentation Rates from Other Areas of the Great Barrier Reef

The enhanced sedimentation rates established for the New Road section of the Cape Tribulation area can be evaluated in terms of their detrimental influence on coral growth by comparison with sedimentation rates from elsewhere. The contrast between the highly turbid inner shelf and the transparent waters of the outer shelf has long been recognised (Hedley, 1925; Orr, 1933; Pickard, 1977). Typically, suspended sediment concentrations on the outer shelf are in the order of 3 mg/l (Wolanski *et al*, 1981). In contrast, a wide range of readings have been determined for inner shelf waters dependant on weather conditions and proximity to stream mouths. Closer inshore, values of approximately 6 mg/l appear ubiquitous, but higher values between 35 and 115 mg/l have been recorded under strong wind or tidal current additions.

Most significantly, sediment trap data is also available from several sites in the Great Barrier Reef region. These can be evaluated with respect to distance offshore.

i) *Mid to outer shelf, John Brewer Reef, 75 km north-east of Townsville*. Hoyal (1986) carried out a pilot study in the lagoon of John Brewer Reef with sediment traps identical to those used at Cape Tribulation. The range of sedimentation rates for this mid-shelf reef is 0.17-2.87 mg cm^2 dy^{-1}. These low figures may be considered representative of mid to outer shelf locations and compare well with other data from elsewhere in the world where terrigenous influences are non-existent.

ii) *Inner shelf reef, Low Isles, 10 km north-east of Port Douglas*. A study well ahead of its time was carried out in 1929 by Marshall and Orr (1931) on the Royal Society Expedition to the Great Barrier Reef. Sediment traps 24 cm high and with an opening of 44 cm^2 were fixed to the reef flat of the Low Isles Reef. Sediments were collected at weekly intervals over a six-month period. Sedimentation rates ranged from 0.6 to 899.9 mg cm^2 dy^{-1} with an average

value of 69.7 mg cm^{-2} dy^{-1}. The composition of the sediments was a combination of sand and mud with carbonate values ranging from 35-98%. Whilst the carbonate values are higher than those found in Cape Tribulation sediments, this site lies only 35 km to the south and is affected by the plume of the Daintree River. Resuspension of muddy, terrigenous sediments occurs around this reef and the mean sedimentation rate is more than twice that recorded in the Northern Control site of Cape Tribulation. The figures are comparable with those obtained from the southern Old Road area. Although considerable clearing had taken place on the mainland by 1929 and sugarcane was established in the Cairns area, the compatibility of figures from the southern area of Cape Tribulation and at Low Isles suggests that proximity to the Daintree River and resuspension of sediments derived from the Daintree may be an important factor influencing reef sedimentation in the region.

iii) *Daydream Island within the Whitsunday Passage.* A study of sedimentation rates using traps identical to those at Cape Tribulation has been undertaken by Steven and van Woesik (*pers comm*) with respect to a dredging programme in the area. Sedimentation rates at a control site unaffected by the dredging range between 5 and 15 mg cm^2 dy^{-1}, but exceeded 40 mg cm^2 dy^{-1} at stations affected by dredging.

iv) *Magnetic Island, 10 km offshore from Townsville.* Sediment trap data using traps similar to those in the Cape Tribulation area has been collected recently for Magnetic Island (Mapstone *et al*, 1989) as part of a baseline study related to hotel and marina developments at Nelly Bay. For the four-week period during which traps were deployed (collections were made weekly), average sedimentation rates ranged from 6.6 mg cm^{-2} dy^{-1} to 114 mg cm^{-2} dy^{-1}. Like Cape Tribulation, the reef slope traps collected most sediment with concentrations ranging from 2.6 to 356 mg cm^2 dy^{-1}. Although their values in general are much lower than for the New Road section of Cape Tribulation, they are similar to values obtained for the Northern Control area and for the southern Old Road section. Morphologically, the bays of Magnetic Island are most similar to the southern road section with wide embayments and bayhead coastal plains. However, rainfall totals are considerably less (approximately 1300 mm/yr) and the geology of the eastern side of the island consists largely of granite.

Mapstone *et al* (1989) noted:

> *"Sedimentation on the reefs during January and February 1989 was greater than that measured in most coral reef environments elsewhere in the world".*

There is an indication that in general inshore fringing reefs off north-east Australia experience very high sedimentation rates, perhaps under even completely undisturbed conditions. Thus the figures for Cape Tribulation though high when compared to data compiled from elsewhere in the world are consistent with sedimentation rates for comparable sites within the Great Barrier Reef Province.

Sedimentation Rates from Sites Other than the Great Barrier Reef and Tolerance Limits of Coral Reefs

Sedimentation rates quoted from sites elsewhere in the world are frequently an order of magnitude lower than those discussed above from the Great Barrier Reef. For example, Aller and Dodge (1974) report natural sedimentation rates of only 0.45 to 1.1 mg cm^2 dy^{-1} from Jamaica. Similarly, Rogers (1979) also in the Caribbean, reported rates of 1-21 mg cm^{-2} dy^{-1} producing sub-lethal effects with mortality being produced more readily by shading than sedimentation. Marzalak (1982) described the effects of dredging in Florida where control site sedimentation rates were

19.9 g m^{-2} dy^{-1} and dredge site rates 38.2 g m^{-2} dy^{-1} with some siltation events several orders of magnitude higher. Stress symptoms in corals included loss of zooxanthellae, polyp swelling and excessive mucus secretion with the range of affected corals being between 3% and 32.4% (average 9.7%). In the long term, mass mortality of corals did not occur, though after two dredging seasons 5% of corals near the dredge showed a partial loss of zooxanthellae and after four seasons as many as 32.3%. However, the corals appeared to be tolerant to short term (few days) sediment loading.

Maragos (1972) recorded rates of 35 to 41 mg cm^{-2} dy^{-1} from Kanehoe Bay, Hawaii. However, the stress which produced most reaction here came from freshwater inflow and eutrophication. Only Cortes and Risk (1985) have reported rates from the Caribbean which compare with those from Australia. Their data came from Puerto Rico and were enhanced by land clearance. Sedimentation rates ranged from 12.8 to 1179.9 mg cm^{-2} dy^{-1}. They considered that figures >30 mg cm^{-2} dy^{-1} produced stress if maintained.

Probably the most referenced studies on sedimentation effects are those from Guam of Randall and Birkeland (1978) as discussed and used in Pastorak and Bilyard (1985). They produce graphs indicating coral species richness, percentage cover and colony size as a function of sedimentation rate. They quote figures for average sedimentation rates measured over extended periods in natural coral reef habitats as ranging from 0.3 to 37 mg cm^{-2} dy^{-1} for the Caribbean and 0.1 to 228 mg cm^{-2} dy^{-1} in the Indo-Pacific region. Pastorak and Bilyard produced a table (their Table 3) which estimated the degree of impact on coral communities by various levels of sedimentation. They suggest that sedimentation rates of 1-10 mg cm^{-2} dy^{-1} produces slight to moderate degrees of impact, 10-50 mg cm^{-2} dy^{-1} moderate to severe impact, and >50 mg cm^{-2} dy^{-1} severe to catastrophic impact. These figures have been widely quoted and suggestions have been made that they should be used as controls for assessing impact in Australian waters. However, it can be seen that even John Brewer Reef would be considered to have a slight to moderate impact from its low sedimentation rate whilst all other Australian sites examined to date would be considered to be moderately to catastrophically affected by sedimentation. Pastorak and Bilyard, however, put limitations and provisos on their data. For example (p 179):

> *"In shallow waters of both regions highest sedimentation rates which are beyond the upper ends of the quoted ranges may be found."*

And further (p 180):

> *"In general coral species inhabiting the seaward margins of a reef are less tolerant of high sediment loads than species found in nearshore areas."*

Of their own table 3 they quote (p 182):

> *"Because limited data are available in the literature, the degree of impact assigned to each level of sediment deposition should be considered tentative"*

and as a footnote to their table 3, they state:

> *"Data used to generate this table are for reef communities at moderate depth and moderate exposure. Some variation occurs among authors in the sedimentation rates associated with the degree of impact."*

Clearly, the new data obtained over the last four years for the Great Barrier Reef confirms the importance of the provisos made by Pastorak and Bilyard (1985). Why then, are the figures for sites quoted by Pastorak and Bilyard so different from those of the Great Barrier Reef? First, great emphasis was put on the figures derived from Guam. Guam is an island some 50 km long and up to 15 km wide, the northern half of which consists of an elevated limestone plateau without surface drainage (Tracey *et al*, 1964). Input of sediment to the marine environment from the land is therefore very restricted. This is confirmed by examining sedimentation rates from a similar environment in the Caribbean, ie Barbados. Tomascik and Sander (1985) report suspended

sediment values between 4 and 7 mg/l, quite clearly at the lower end of the scale of figures found in Great Barrier Reef waters and a reflection of the uplifted coral reef limestone environment of which Barbados consists.

Second important factor influencing the amount of sediment resuspended in the water column has been the relative sea level history of the Australian region compared to the northern Pacific and the Caribbean. For isostatic reasons the relative Holocene sea level history of different parts of the world varies (see for example Clark *et al*, 1978). Off the Australian mainland coast, sea level has been stable or close to its present position for approximately 6500 years during which time, fluvial sediment yield from the mainland has been able to build up a significant nearshore terrigenous sediment wedge consisting largely of fine sediments (eg Searle *et al*, 1980; Johnson and Searle, 1984; Johnson and Carter, 1987). It is this material which is resuspended by even moderate wave activity. In contrast, parts of the north Pacific and even more importantly the Caribbean have seen a continuously rising sea level throughout the Holocene period. The shoreline has not been stable in its present position, but has continued to move inland and therefore sedimentation in the nearshore zone has been spread over a much wider area. Fine sediments available for resuspension are considerably less than in the Great Barrier Reef region.

Johnson and Carter (1987) suggested that the Cape Tribulation reefs have always lived under heavy, terrigenous sedimentation influence. It would appear that the coral communities of the Cape Tribulation area and other inshore reefs of north Queensland have become acclimatised to heavy high rates of sedimentation. However, as Mapstone *et al* (1989) have pointed out, these high rates of sedimentation can be tolerated only under the conditions that are likely to be their cause, ie rough seas and great water movement. Under these conditions, it is unlikely that sediment would remain on the surface of the corals for more than a short period, and accumulation of sediment and consequent physiological stress of corals seems unlikely. Under natural conditions, high sedimentation rates do not take place when seas are calm.

11. CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Under natural conditions, sedimentation rates on north Queensland fringing reefs are high. However, sediment movement takes place mainly during high energy periods and whilst sediment may be collected in the artificial sediment traps, it does not normally remain on coral reef communities.

Cape Tribulation reefs have clearly had an additional load of sediment imposed upon them by the development of the new Cape Tribulation to Bloomfield Road. Sedimentation rates on the reef are up to six times those on reefs adjacent to undisturbed catchments in the same area. This research programme has shown that much of this additional sediment was provided during and shortly after road construction when large areas of bare soil combined with unusually intensive rainfall. Much of the sediment moving on the reefs subsequently is resuspended.

From a light attenuation viewpoint, the extra sediment may not be significant. Ayling and Ayling (1987) report that normal visibility in water adjacent to Cape Tribulation reefs is in the range of 2-6 m, and only occasionally reaches 10 m in calm weather. During strong south-easterlies, visibility is reduced to 0.5-2 m. The result is a vertically compressed biotic zonation on the reefs, and is clearly produced by turbidity levels which have occurred over a very long period of time. Large amounts of sediment are moving around and over the reefs, but this sediment can remain on the corals for a long time only during calm periods when the amount of sediment in the water column

is very much reduced. The possibility that coral formations of shapes similar to the sediment traps (vase shaped) may also collect sediments should not be dismissed. However, Ayling and Ayling (1987) concluded from their survey that there was no evidence of hard coral death due to siltation, and Fisk and Harriott (in press) could find no evidence from three years of data that the consequences of the New Road affected juvenile corals or availability and recruitment of coral larvae.

The amount of sediment moving in the nearshore zone suggests that the Cape Tribulation reefs may be approaching critical thresholds. Partain and Hopley (1989) have already indicated that there has been negligible reef accretion over the last 5000 years and that the Cape Tribulation reefs over this period have been under a chronic siltation stress. Kinsey (1989) suggested that whilst reefs seemed to be well able to tolerate chronic stresses and are able to be maintained through extended time without dramatic visible response from the reef system, it is possible that system function may be modified appreciably without concomitant obvious community changes. He further suggests that when acute stresses are then applied to such reefs, recovery may be difficult. The chronic stress of high turbidity levels is something which will not alter in the Cape Tribulation area. An acute stress could easily result from exceptionally high intensive rainfall events such as those associated with a cyclone. Even under natural conditions, destruction of the rainforest canopy could result in exceptionally high sediment loadings from the small catchments. Results from March (1985) suggest that the disturbed catchments of the area will yield what may be catastrophically high sediment amounts.

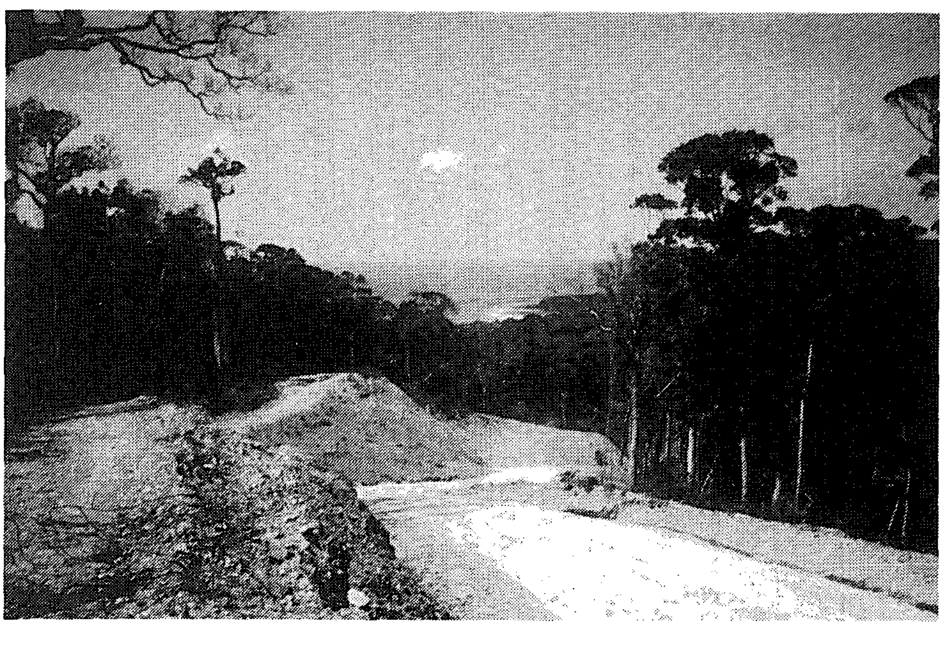

FIGURE 17. Typical road section with steep grades, unstabilised cut and fill sections

FIGURE 18. Gullying and landslips are frequent after heavy rain especially on steeper road sections. Potential remains for complete slope failure and massive sediment yield.

In their conclusions, Partain and Hopley (1989) state:

> *"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 6500 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 turnoff as defined by Buddemeier and Hopley (1989). As the adjacent rainforest system is one of high energy, maintained within a recycling 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 turnoff through increased sediment yield, release of nutrients and more intensive runoff response."*

Observations along the new section of the Cape Tribulation road, suggest that time may not be an important factor in reducing this risk of acute stress as was suggested by O'Loughlin (1985) (see figure 1). Although some revegetation and stabilisation has taken place on banks adjacent to the New Road, there are still large areas of bare ground (Figures 17 and 18) and the road remains unsealed with gradients of up to 1 in 3. Cut bank sections continually slump and maintenance work frequently consists only of bulldozing landslips off the road and downslope, thus providing material for further enhanced sedimentation. The exact time at which an irreversible mortality of corals in the Cape Tribulation area takes place cannot be predicted. However, the exceptionally high rates along the New Road section in an area in which sedimentation rates are already high would suggest that the next major cyclone in the region could produce such a result. Whilst closing the road would appear to be an unacceptable solution to the problem, it is strongly recommended that a programme of sealing and associated engineering works, such as providing more effective culverts, stabilising of steep banks and provision of adequate drainage, be undertaken.