Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Long-term records of sediment yield from coral skeletons: results from ion beam analyses

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Abstract Variations in coral growth and skeletal geochemistry reflect changes in chemical and physical water properties. Long-term records of streamflow occur in fluorescent bands in massive corals. The use of massive corals to record parallel records of sediment yield and the behaviour of sediment plumes between the river mouth and the coral site was investigated. Results indicate that sediment plumes are generally forced away from areas of coral growth by prevailing winds. Bottom sediment resuspension is a significant source of noise and a sediment yield record in corals will be very sensitive to the location of corals sampled. The PIXE/PIGME technique has spatial resolution suited to high resolution analysis of coral skeleton. However, the low sediment concentrations in the coral skeleton, contamination due to endolithic borers, and the effect of changing skeletal morphology limit the usefulness of this analytical technique.

INTRODUCTION

In a recent review, Meybeck (1992, p. 94) suggested that "enhancement of erosion by man's activities is one of the major, and probably one of the earliest, influences of man on the environment". Also, "... almost any kind of activity (agriculture, urbanization, communication, mining, industry, etc.) leads to an increase in suspended matter in surface waters." It is of importance in terms of geomorphic processes and terrestrial and aquatic ecosystems management to know the mean annual sediment yield, the inter-annual variability of sediment yield and the sediment yield response to land use intensification in tropical basins. Given the paucity of data, however, techniques for reconstructing sediment yield histories are of particular importance.

Corals of the *Porites* genus with a massive growth form are useful environmental recorders by virtue of their incorporation, at the time of calcification, of various constituents of the waters in which they are growing. They are tolerant of turbid waters, grow in nearshore areas, and are widely distributed in the Indo-Pacific and Atlantic coral reef provinces. They grow to a great age, in the order of 1000 years for some colonies. They have annual growth increments of sufficient size (*c*. 9-10 mm and often > 15 mm) to allow resolution to a sub-annual time-scale. Nearshore specimens have annual bands which fluoresce under ultraviolet light. The fluorescence intensity is correlated with flow from adjacent streams, establishing the hydrological context of coral records.

If massive coral colonies contain records of the sediment yield from coastal basins over centuries at a resolution better than annual, they have the potential to provide a powerful tool for geomorphic analysis. The literature contains research findings which indicate that such an approach is feasible (e.g. Barnard *et al.*, 1974; Cortes & Risk, 1985) and others which indicate the contrary (e.g. Goreau, 1977a,b; Davies, 1992, in prep.; Budd *et al.*, 1993). Given the characteristics of the ultraviolet fluorescence record (Isdale, 1984) it is anticipated that a sediment yield record with a resolution of one month is possible.

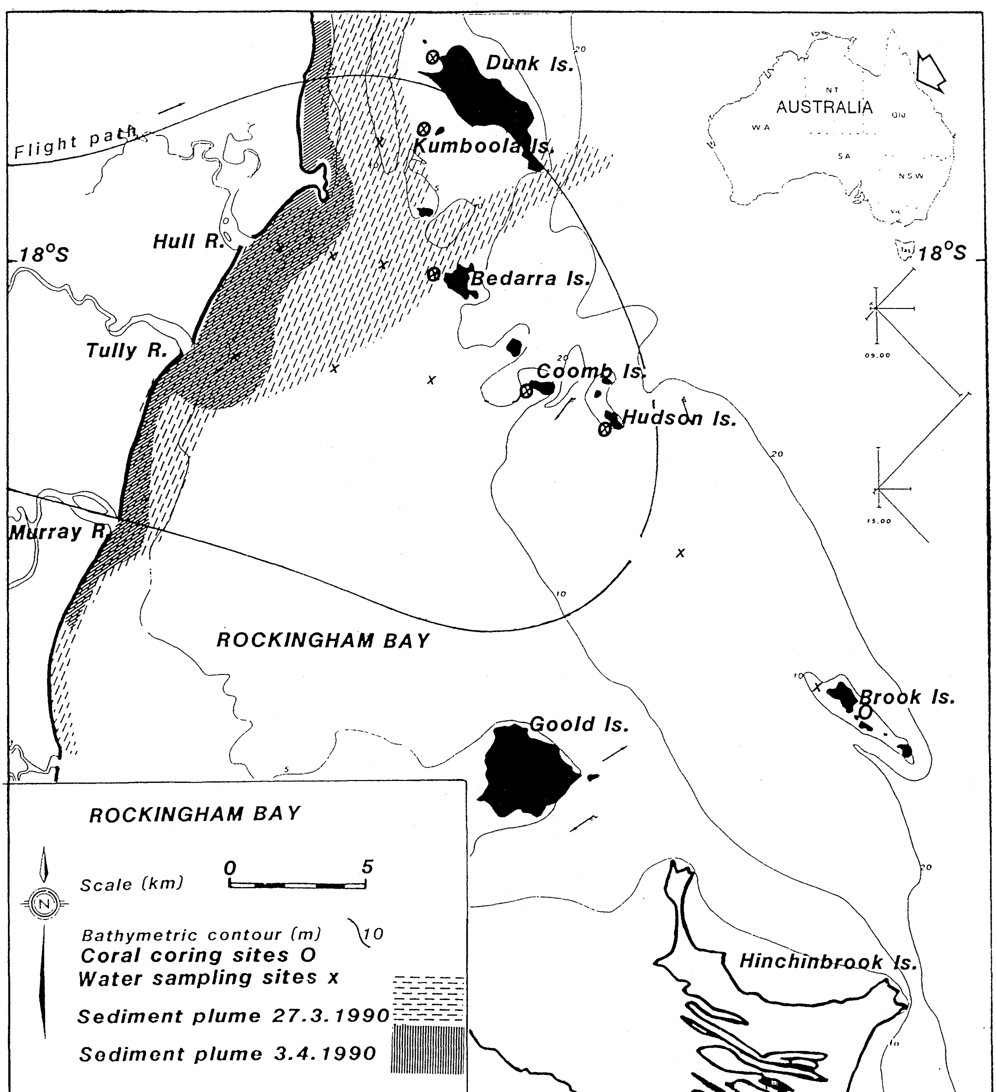

Fig. 1 Coral coring and water sampling sites, flight path and sediment plume distribution in Rockingham Bay.

The Tully River (1685 km^2), discharging to Rockingham Bay at 18°S latitude in the humid tropics of northeast Queensland, Australia, was selected as an appropriate site for the investigation of the sediment yield response to land use intensification and the potential of massive corals to record this response. The Tully basin has a high mean annual rainfall (4200 mm at Tully town), a high runoff coefficient (0.74), and low inter-annual streamflow variability. Continental islands with fringing reefs lie over a wide arc (105°) from the Tully River mouth so variations in the direction of river plume movement will not necessarily result in the plume bypassing coral colonies selected for analysis. This paper reports (a) the results of analyses of the spatial relationships between sites of coral growth and environmental variables such as sediment plume movement and bottom sediment resuspension, and (b) analyses of coral skeletal material using the proton induced X-ray emission (PIXE) and proton induced gamma emission (PIGME) techniques of ion beam analysis.

METHODS

Sediment plume movement in Rockingham Bay was monitored twice by aerial surveys during a major flood in March-April 1990 (Fig. 1). Turbidity and streamflow in the Tully River were also monitored. Boat surveys were used to sample surface water quality (10 cm depth) at sites in Rockingham Bay during the 1988 and 1990 wet seasons. Turbidity was determined using an Analite Model 155 nephelometer, calibrated ($R^2 = 0.96$ – river waters; $R^2 = 0.70$ – bay waters) by suspended sediment concentration (SSC) measured as non-filterable residue on 0.45 μm filter papers.

Coral coring was carried out during an Australian Institute of Marine Science (AIMS) research cruise. Multiple cores (93 mm diameter) were extracted from massive *Porites* colonies at six sites in Rockingham Bay (Fig. 1) using a lightweight, underwater drilling rig (Isdale & Daniel, 1989). Preprocessing, including cutting 1.7 and 7.0 mm thick slices from the cores using a milling machine, was carried out at AIMS.

Preliminary analyses of coral skeletal material from Bedarra Island (SEM/EDX; XRD; Ion microprobe; gravimetric determination of non-filterable dissolution residue) indicated that sediments, consistent with a terrigenous origin, were present in the coral skeleton. High resolution analyses are best served by scanning techniques and the facility for the PIXE and PIGME techniques of ion beam analysis at the Lucas Heights Research Laboratories is configured so as to allow continuous stepping down a >1.0 m length of core at any interval, carrying out non-destructive multi-element surface analyses at each step. Details of the accelerator and target chamber configurations for these measurements are given in Neil (1994) and overviews of the PIXE method are given by Johansson & Johansson (1976) and Cohen & Clayton (1989).

The target elements were Al, Si and Fe. Al is particularly diagnostic of fluvial inputs, given the absence of primary Al-bearing particulates in the marine environment. Si is not exclusively diagnostic of terrigenous quartz, because a broad peak in the XRD spectra is due to amorphous silica with a probable marine origin. Fe could be derived directly from soils of the Tully basin, or indirectly from resuspension, precipitated from solution, or co-precipitated with fulvic and humic acids.

RESULTS AND DISCUSSION

Spatial relationships and suspended sediments in the nearshore marine environment

Several spatial factors in the nearshore marine environment influence the feasibility of using massive corals as long-term recorders of sediment yield, including sediment plume movement, sediment sources and vertical SSC gradients, and constraints on the location of suitable coral coring sites.

The Tully River hydrograph and sedigraph for the March-April 1990 sampling period is shown in Fig. 2. During the high streamflow period between 20 and 26 March, winds were generally light and variable in direction (Fig. 3) and had little effect on the Tully River plume which reached two of the northern coral core sites (Fig. 1). A SSC of 10 mg l^{-1} was recorded at Kumboola Island on the morning of 27 March, but had fallen to only 3.1 mg l^{-1} by that afternoon. Plume movement was determined by the geostrophic current. On 3 April 1990, with Q at 350 $m^3 s^{-1}$, the plume reached <2 km offshore at 7 km north of the river mouth. Movement of the sediment plume generated by the high streamflows from 30 March onward (Fig. 2) was northward, close to the coast (Fig. 1) under the influence of consistent southeasterly winds (Fig. 3).

The pattern of Tully River plume movement in Rockingham Bay during the 1990 monitoring period is consistent with the combination of a geostrophic current (Wolanski & van Senden, 1983; Roberts & Murray, 1983) and the prevailing winds. The movement of the Tully River sediment plume is similar to that during June 1961, mapped from aerial photographs (Neil, 1994). It differs from the direction of movement following the February 1986 flood (cyclone Winifred) when the plume passed to the south of Coombe Island (Hopley, 1987, personal communication). Plume movement at that time was probably influenced by the strong winds from the northern and western quadrants which followed the passage of cyclone Winifred (Walker & Reardon, 1986).

Wind directions at the times of 10 Tully River floods during the period 1987-1991 were analysed. In all but two of these events winds were almost entirely from the southeast quadrant. These results suggest that, for most flood events in the Tully River,

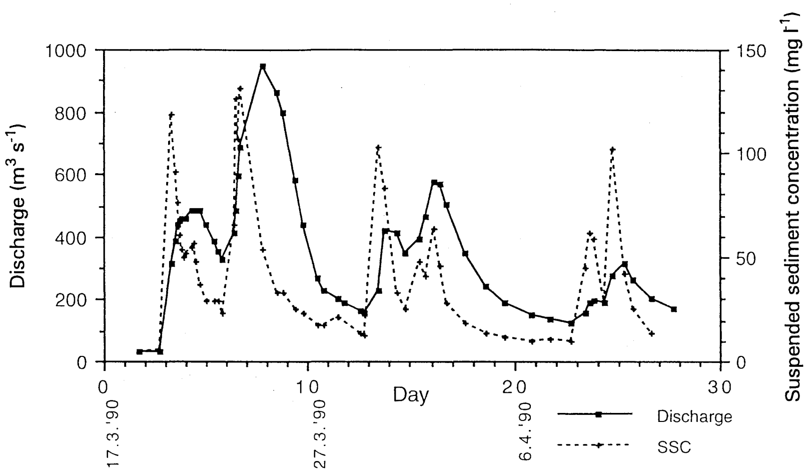

Fig. 2 Streamflow and SSC in the Tully River, March-April 1990.

winds from the southeast are the dominant influence on sediment plume movement throughout the event, such that sediment plumes will generally be confined close inshore, similar to the pattern on 3 April 1990 (Fig. 1). As a result, fringing reefs are likely to be directly affected by river plume water at low frequency and short duration.

High SSC in Rockingham Bay (70% of the maximum recorded during the 1990 flood) was measured while the river was at baseflow prior to commencement of the 1988 wet season. SSCs at fringing reef sites are also consistently higher than those at adjacent deep water sites. These results indicate that, although SSCs at the sites where coral cores were extracted are affected by the river plume, bottom sediment resuspension also has a significant effect.

Although no vertical SSC gradient measurements were made, some inferences can be drawn by analogy with other sites. Firstly, gradients resulting from bottom sediment resuspension have SSC maxima at the sea bed. Secondly, vertical gradients in marine waters with buoyant freshwater sediment plumes have SSC maxima at, or near, the sea surface. Consequently, over the period of vertical coral growth, the calcifying part of the skeleton, which "records" environmental conditions, has changed its position in relation to sediments derived from both sources.

Coral colonies sampled must be located close to the coast because, as this and other studies show, sediment plumes are generally confined to nearshore waters. In order to trap suspended fluvial sediments, the sediment traps (coral heads) must also be in the nearshore zone. Furthermore, the further offshore the site is located the greater the risk of mixing with sediment plumes from other streams.

The nearshore location, although essential, has adverse consequences:

(a) Most nearshore sites are associated with continental island fringing reefs, leading to some risk of contamination from island runoff.

(b) Nearshore sites are more susceptible to contamination by bottom sediment resuspension.

(c) As a result of high turbidity, nearshore coral growth generally occurs only at shallow depths, thereby limiting the maximum age of coral colonies and, therefore, the period of record available. In Rockingham Bay, fringing reefs closest to the

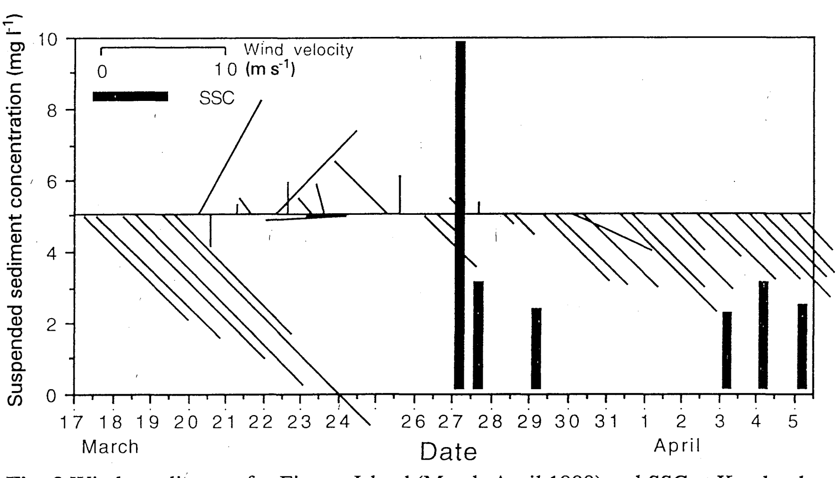

Fig. 3 Wind ray diagram for Fitzroy Island (March-April 1990) and SSC at Kumboola Island.

river, with some prospect of measurable sediment inclusions, have no coral colonies of sufficient age to monitor the entire history of land use change in the Tully basin. This is important, given that land use change took place more recently in the Tully basin than in most others in the region for which older coral heads would be required.

(d) Nearshore sites are more susceptible to partial or total mortality, due to the direct or indirect effects of sediment resuspension and/or river plumes. The coral head cored at Bedarra Island, and several smaller colonies which were sectioned, all had a break in growth for some unknown period. This renders chronological interpretation using the annual growth bands unreliable and allows entry of contaminants.

(e) Nearshore sites are more susceptible to endolithic boring than offshore sites, rendering the sediment inclusion records vulnerable to contamination and, therefore, to misinterpretation.

(f) Variations in skeletal void ratios are likely to be greatest in coral skeletons at nearshore sites, possibly affecting the accuracy of all determinations using surface analysis techniques.

Ion beam analysis results

The results of time series ion beam determinations on coral skeletal material were compared with an inferred time series of annual sediment yield from the Tully River. The sediment yield record was estimated from spatial variation in SSC in relation to land use, the known sediment yield for a wet season which was monitored, the land use history of the basin, and the long-term history of rainfall erosivity in the basin calculated using a power function of daily rainfall above a threshold. Details of these calculations are given in Neil (1994). An example of the relationship between the sediment yield time series and typical ion beam results is given in Fig. 4. The results are for gamma emissions at 0.844 MeV, consistent with Al but also Na and Mg which are naturally

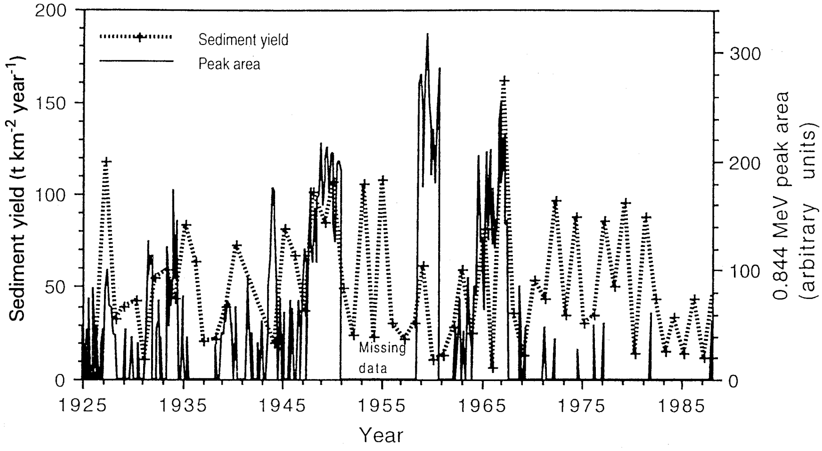

Fig. 4 Time series of Tully River sediment yield and $E_T = 0.844$ MeV (Al) peak areas (Coomb Island core).

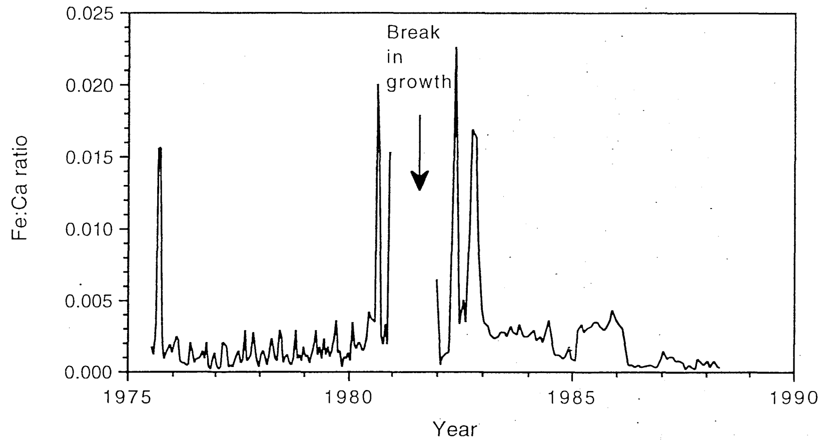

Fig. 5 Time series of Fe:Ca peak area ratio for the Bedarra Island core, showing high Fe concentrations in the coral skeleton both above and below the break in growth.

present in coral skeleton, on a coral core from Coomb Island. It is clear that there is no relationship between the inferred sediment yield time series and the ion beam results. Detailed examination of the coral cores used and the ion beam results for all cores analysed and elements determined leads to the following conclusions:

(a) PIGME and PIXE peak areas consistent with Al, Si and Fe are generally too low, and the associated errors too high, for precision analysis.

(b) Inability to adequately discriminate Al gamma emissions from those of Mg and Na, both present in significant concentrations in coral skeleton, render interpretation of the already inadequate emissions difficult.

(c) When peaks in the concentrations of target elements occurred in the respective time series they were associated with contamination via endolithic borers or following a break in growth (Fig. 5).

(d) The ion beam results, particularly PIXE, are apparently affected by variation in coral skeletal morphology which is itself affected by changes in water chemistry due to land use change (Rasmussen & Cuff, 1990).

Resuspended sediment is a major source of noise in nearshore water quality. Because of the irregularity of this noise, large numbers of measurements in a continuous time series are needed to discriminate between resuspended sediment and fluvial sediment. The PIXE/PIGME method is suited to the high frequency time series analyses necessary, but does not have the sensitivity to detect the relevant elements at the concentrations at which they occur in the coral skeleton. Furthermore, sediments which are incorporated are often contamination, that is not derived from runoff. The results presented suggest that ion beam determination of the rate of direct sediment inclusion in massive corals does not provide a high temporal resolution record of the sediment yield response to land use intensification in tropical basins.

Acknowledgement Generous support was provided by the Department of Biogeography and Geomorphology, ANU, the Australian Institute of Marine Science, and the Australian Institute of Nuclear Science and Engineering.

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