

The maintenance of reef islands

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Abstract. Low coral reef islands are known to comprise biogenic sediments but the processes whereby these islands are nourished are poorly understood. This paper argues that the sediment system of large reef platforms can be strongly compartmentalised, at sub-kilometre scales, so that contemporary island maintenance and growth depends on organisms and processes operating within a small physiographic and ecological sector of the reef flat. Evidence is provided through a study of the origins and pathways of island-nourishing sediments on Warraber Reef, using textural, compositional and selected dating analyses of surface sediments. Results reveal that the mollusc-algae covered sand flats of the emergent, inner reef flat are the dominant contemporary source of island sediment. In contrast, deeper, more-distant and leeward reef-flat zones are functionally isolated from the island beach deposit. This is despite the order of magnitude greater productivity, more-frequent submergence, and more-energetic wave environment of the latter areas, but in-line with reef flat sediment transport directions and the proportionately-greater particle production rates of organisms living in the windward, near-island zones. The key findings of this study are summarised in a theoretical model of the source-to-sink journey of skeletal biogenic sediments in low island environments, which is applicable to reef-island management.

Key words: Reef islands, Carbonate sediment, Platform reef, Reef flat.

Introduction

By 2015 half the world's population will live in coastal zones, including on low coral reef islands. These reef-surface features are described as particularly vulnerable to changing environmental conditions such as sea level rise (Woodroffe *et al.* 2007). They are constructed of accumulations of biogenic sediment primarily from the surrounding reef platform (Hart and Kench 2007). Beaches form the crucial interface through which these islands are nourished, built and eroded with reef platform sediments.

Little detail is known about the relationship between the different bio-physiographic zones of reef platforms and the ultimate nature of island sinks. A number of seminal papers have demonstrated that the character of reef sediments depends on: the carbonate producing and eroding organisms present (Stearn *et al.* 1977, Scoffin *et al.* 1980, Scoffin 1987); the contributing organisms' skeletal structure (Scoffin 1992, Ginsburg *et al.* 1963, Chave 1964, Enos and Perkins 1977); and on their interaction with biological, physical and chemical processes of breakdown and transport within reef environments (Folk and Robles 1964, Maiklem 1968, Gourlay 1988).

This paper contributes to this discourse through an investigation of how spatial variations in sediment processes across large reef platforms can influence the nature of a low-island beach. Comparisons

between beach and reef-flat deposits reveal functional relationships between the island sink and reef sources for Warraber Reef, an intertidal platform in central Torres Strait, Australia. The differing spatial and organism contributions to contemporary beach nourishment found are used to model the functioning of reef sediment systems and discuss their importance in understanding reef island futures.

Study Site

A large platform (11 km²) and small, oval-shaped sand cay (1.1 km²) form the Warraber Reef system (Fig. 1). Warraber is middle of 3 platforms called The Three Sisters, situated at the northern end of the Great Barrier Reef in central Torres Strait (10°12'S, 142°49'E). The Strait is characterized by 3.5 m spring tides, tidal currents up to 4 ms⁻¹, and a monsoonal wind and wave regime. Strong winds from the southeast (~15 ms⁻¹) dominate the dry season (March-Sept) while weaker northwesterlies (0-5 ms⁻¹) occur during the wet season.

Warraber (or Sue) Island stands 2 to 8 m above mean sea level (MSL) on the northwestern reef platform. It is thought to have developed incrementally over the last 3500 years while the reef surface (0.5 to 2.3 m above MSL) and much of its outer structure grew during the Holocene, around a Pleistocene reef core (Woodroffe *et al.* 2007). Rimmed by a young coral-algal rim, the platform's

contemporary reef flat has two distinct areas: the large, elevated central and eastern section with sand flats covering fossil microatolls and branching corals; and the smaller, lower, western reef flat characterized by muddy-sand flats near the beach and coral patches separated by sand channels towards the rim. The boat channel, constructed in 1991, divides the western reef flat in two. On low tides more than half of the reef flat drains fully while water ponds across deeper, western and outer-eastern, areas.

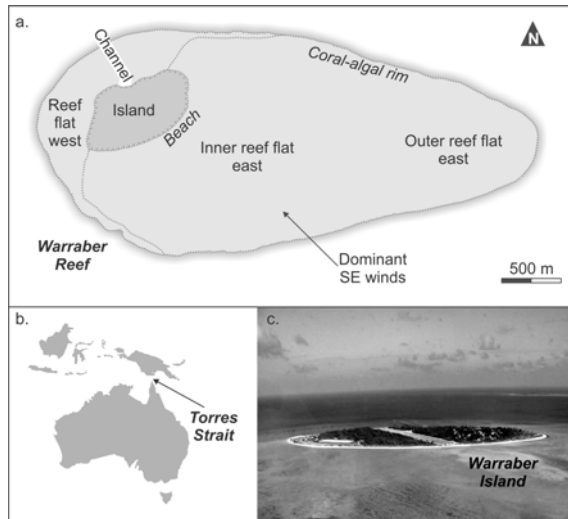


Figure 1: Warraber Reef (a), in central Torres Strait (b), with an oblique aerial photograph from the south side of the island (c)

Material and Methods

218 surface sediment samples were hand scooped along 15 beach to inner reef flat profiles and 5 transects radiating out from the island to reef rim. 3 additional samples were dredged from the boat channel at 11 m below MSL. Samples were cleaned of organic matter, and the fines were removed by wet sieving (particles <0.063 mm). The remainder was split into 15 and 70 g subsamples.

The 70g subsamples were settled through a 6.5 m long water column into a collection core, which was then separated into 4-6 visually-distinct fractions (after Kench and McLean 1996). 100 grains were grid-sampled from each fraction and their constituent origins determined using a reflected-light binocular microscope. Constituent weights were summed across all fractions to determine their % in each sample. For constituents comprising >1% of samples, Wilcoxon rank-sum tests were used to determine if variation between the beach and reef flat sample groups was significant (Zar 1999). Agglomerative, hierarchical cluster analysis was performed on the complete sample constituent data using the *S-Plus* software programme *Agnes* (Everitt 2002) and the sample constituent clusters mapped across the reef platform.

The 15 g subsamples were settled through a rapid sediment analyzer. Sample settling distributions and statistics were calculated using Middleton's (1967) negative \log_2 Psi parameter (ψ) and Folk's (1965) graphic formulae. Cluster analysis was performed separately on the textural data using *Agnes* and the textural cluster trends mapped across the reef flat.

Results

Table 1 shows the main constituents ($\geq 1\%$) that made up the reef flat and island beach sediments. The commonest sediment constituent was mollusc (mostly gastropod), comprising 55% and 35% of beach and reef-flat samples respectively. The next commonest constituents were coralline algae (16-26%, mostly encrusting) and coral (8-13%). On the beach this was followed by *Halimeda* (7%), foraminifera (5%), and fragments of beachrock (2%) while on the reef flat, the fourth commonest constituent was foraminifera (10%), followed by *Halimeda* (8%), crustacean (4%), and vermetid mollusc (2%).

Amounts of the two main constituents, mollusc and coralline algae, were significantly different ($P > 0.01$) between the beach and reef flat sample groups. Of the less-common constituents, beach and reef-flat sediments contained differing amounts of foraminifera, crustacean and beachrock material but significantly similar amounts of coral, *Halimeda* and vermetid mollusc. The mean sediment compositions reveal that, on average, the beach comprised more mollusc and beachrock fragments while the reef flat had more coralline algae, foraminifera and crustacean sediment than occurred on the beach (Table 1).

Table 1: Variation in the mean constituent composition of beach versus reef flat (RF) sediments (* indicates $P < 0.01$ in Wilcoxon rank-sum variance tests). Reef flat cover and carbonate production are included for comparison, where cover represents the 24% of the reef flat occupied by carbonate producers (Hart and Kench 2007)

Organism type	Mean % sediment composition		Mean % of live cover	
	Beach	RF	RF	RF
Mollusc (gastropod)	54.9* (47.7%)	34.8* (27.8)	3	4
Coralline algae (encrusting)	15.6*	25.6*	47 (46.5)	18 (16.2)
Coral	8.2	13.1	43	74
<i>Halimeda</i>	6.9	8.4	6	1
Foraminifera	4.8*	10.2*	1	2
Vermetid mollusc	0.6	1.5	<1	<1
Crustacean	0.6*	3.5*	<1	<1
Beachrock fragment	1.9*	0*	-	-

Comparisons between these sediment results and reef flat ecology data from Hart and Kench (2007) reveal that, on average, *Halimeda* and the minor constituents (<4%) were represented in the two sediment sinks in similar proportions to their reef flat cover and/or carbonate budget contributions (Table 1).

However, the occurrence of the other, major constituents in the sediments contrasted their parent organisms' reef flat cover and carbonate productivity. Coral, and to a lesser extent, coralline algae, appear to be under-represented as sediment constituents, while molluscs and, to a lesser extent, foraminifera appear over-represented, relative to their reef flat cover and productivity. In order to investigate explanations for these differences, surface-sediment spatial patterns were mapped based on the cluster analyses of % constituent compositions, and the textural properties.

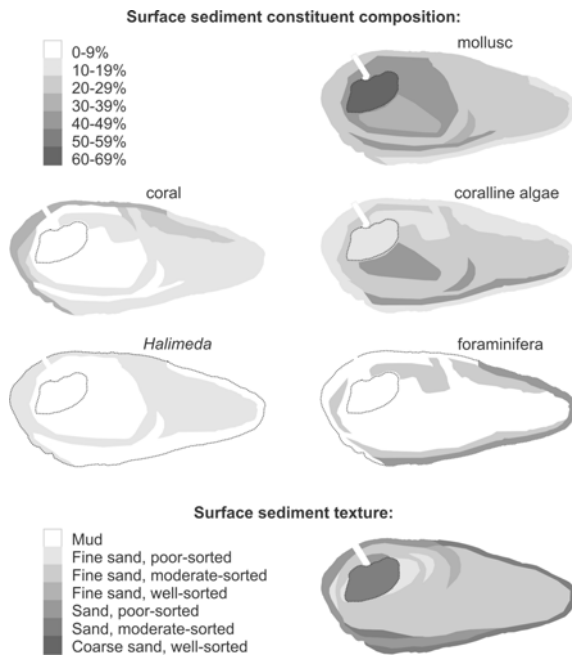


Figure 2: Trends in the concentrations of the five main sediment constituents in the beach deposit, represented by the island shape, and across the reef flat (top); and corresponding textures (bottom)

Fig. 2 shows that mollusc sediment concentrations generally increased from deeper-outer areas, towards central-emergent areas of the reef flat, and were greater in the beach deposit than anywhere on the reef flat. Almost the exact reverse pattern was evident for coral sediments. Coralline algae content decreased gradually south to north across the reef flat, and between the reef flat and beach deposits. *Halimeda* constituents were slightly more concentrated in deeper reef flat areas compared to on the beach and inner, emergent reef flat. The concentration of foraminiferal tests was high around the eastern and southern reef rim and patchy across the rest of the platform. Fig. 2 also reveals that sediment texture was coarser and better-sorted in the beach deposit and on the reef rim, relative to across most of the reef-flat surface. The boat channel sediments were dominated by poorly-sorted mud of indistinct origin.

Discussion

Two key results requiring explanation are that Warraber beach appears to contain disproportionately high concentrations of mollusc sediment and low amounts of most other constituents.

Textural results revealed the island shore as a high-energy setting relative to much of the surrounding reef flat. Mollusc shells are ideally suited to transport to, and retention within, such a deposit as they are buoyant and transportable as well as durable compared to the majority of other reef constituents (Chave 1964, Force 1969). Further, for most molluscs on Warraber (which were small gastropods) the translation of live-parent organisms into sediment particles suitable for nourishing the beach simply entails death. This contrasts coral and encrusting coralline algae, which require the additional step of skeletal breakdown to form particles suitable for beach nourishment.

The dominance of mollusc in the beach deposit is also due to the concentration of suitable mollusc sediments on the inner reef flat surrounding the island (Fig. 2). This corresponds to a concentration of live molluscs in this area (Hart and Kench 2007). Dating of individual particles by Woodroffe et al. (2007) reveals that molluscs form the youngest fractions of Warraber's island and reef-flat deposits, aged between modern and 2700 y, supporting the idea of a link between contemporary mollusc production on the inner reef flat and the concentration of mollusc sediment in the island beach.

Like molluscs, foraminifera have tests that are highly-transportable, durable, and simply translated into sediment upon death of the parent organism. Unlike molluscs, however, they form the oldest constituents in Warraber's island and reef-flat deposits (6600-4500 y old, Woodroffe et al. 2007). This indicates that, while foraminiferal material can persist in this reef environment, there may have been a decrease in the generation of new material over time. Today most foraminifera live far from the island on the reef rim, with a few living nearshore, east of the island (Hart and Kench 2007). This live-assembly pattern is similar to the observed foraminiferal sediment pattern (Fig. 2). Accordingly, the slightly-lower average concentration of foraminifera in the beach relative to reef-flat sediments found in this study (Table 2) is explained by the location of concentrated foraminiferal sediments either far or up-drift from the island shore (according to the dominant-southeasterly wind wave regime) as well as by the dilution of the beach constituents with the abundant mollusc material.

The proportions of *Halimeda* and coral constituents in the island beach reflect their average concentration in reef flat deposits (Table 2). *Halimeda*'s role in the

sediment budget reflects its minor role as a reef flat cover type and in carbonate productivity. This is not the case for coral, which was shown by Hart and Kench (2007) to be the second commonest live-carbonate-producer cover type and, by far, the dominant carbonate producer. Reasons as to why this extensive coral cover and carbonate production does not translate into dominant sediment contributions in either the reef-flat or island deposits include, first and foremost, that even in this emergent-platform environment, the bulk of coral carbonate produced is retained within the reef framework upon tissue death and not broken into sediment particles. Coral only grows where there is accommodation space. On Warraber, coral growth is concentrated in outer-reef-flat and reef-rim environments, where there is horizontal and vertical accommodation space respectively. Also, when coral skeletons do break down, their skeletal architecture, in combination with bioerosion processes, commonly leads to the production of a bimodal sediment population: that is, gravels which are readily worn into silts and muds (Scoffin 1987). The former are ill-suited to transport across the reef flat to the island shore, particularly from the western areas (where coral sediments are most concentrated) as this is against the dominant wave regime. The latter, fines cannot be retained in the high-energy, coarse beach deposit (Fig.2).

The path of coralline algal sediment generation is slightly different again. This carbonate producer is the most-extensive living-cover type on Warraber Reef, after the non-carbonate producing brown algae (Hart and Kench 2007). But this cover translates into far-less carbonate per unit live cover than for coral, so that there is less coralline algal material available for potential sediment generation. Compared to its role in the carbonate budget, coralline algae makes up a slightly-greater proportion of the reef flat, and slightly-smaller proportion of the island-beach, sediment budgets. Its reef-flat sediment contributions may be explained by its consistently-high cover across the reef flat, including growth on existing sediment particles - characteristics which predispose it to key sediment contributions. The slightly lower concentration of coralline algae in the beach may, in turn, be the product of winnowing of this not-so-durable constituent (Chave 1964).

Implications

The International Coral Reef Symposium (ICRS 2008, 3) scientific outcomes overview states that recent evidence indicates tropical reef systems are “primarily connected at scales of tens of kilometers”. This comes from a biological perspective and is counter to previous beliefs that reefs are highly interconnected at scales of thousands of kilometers. The present

research suggests that low-reef islands are connected to reef ecosystems at even-more-local scales. That is, in terms of beach nourishment (and thus island-building), the sediment system of the large, emergent Warraber reef platform is highly compartmentalized in space and time. The most-important beach constituent (mollusc) is largely locally (<1 km) and recently (≤ 2700 y) produced while the dominant carbonate producer (coral) and live-cover types (brown algae, coralline algae, coral) on the wider reef platform contribute far less to the maintenance and development of the contemporary island shore.

Based on these findings, Fig. 3 outlines the source-to-sink journey of skeletal biogenic sediments in low island environments. This model combines carbonate and sediment-particle production stages with the morphodynamic concept of low islands as the product of reef-flat sediment transport and nodal-point deposition. It shows that reef platform deposits, including cays, are inextricably linked to their surrounding ecosystems, and that this relationship is highly compartmentalized via the complex set of biological and physical processes involved in the creation, alteration and transport of reef and reef-island sediments.

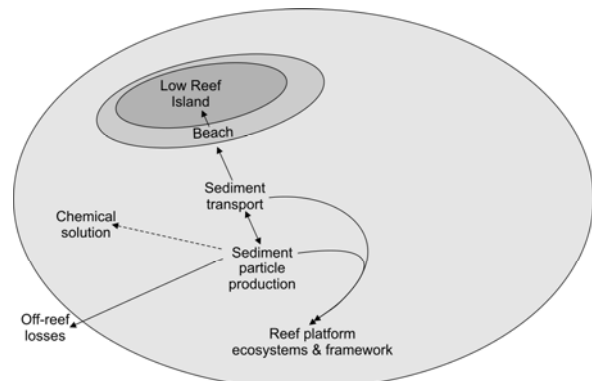


Figure 3: Theoretical schematic of a reef island sediment system, including carbonate production in surrounding platform ecosystems; its translation into sediment via producer-organism death and/or biological or mechanical erosion; and sediment transport to the beach for island nourishment and development, deposition in the reef edifice, or losses offshore and via chemical solution.

Current models indicate that reef-flat widths, elevations, current strengths and directions, and sediment volumes are all important in determining the rate and nature of island development (e.g. Gourlay 1988, Kench and Brander 2006, Barry et al. 2007). These factors are largely outside of the control of reef managers. The model developed in this study indicates that the amounts, and constituent and textural natures, and spatial distributions of sediments produced in reef flat environments today are crucial in

determining the island-beach sediment budgets and, thus, island maintenance, development or erosion. One major implication of this model is that it is necessary to understand the carbonate and sediment production systems of reefs in order to understand the future of their islands under changing environmental conditions such as those brought about by climate change, increased pollution and resource pressures. On Warraber, the reef-island sediment budget depends on production by a limited set of organisms, across a limited area of reef surface. The particular organisms and reef flat zones responsible for island maintenance will differ from reef to reef and change over time - establishing these locally can help reef managers to forecast the future of islands and empower them with information about the importance of conserving particular reef-flat ecosystems for island maintenance.

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