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The importance of large benthic foraminifera to reef island sediment budget and dynamics at Raine Island, northern Great Barrier Reef

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ABSTRACT

Low-lying reef islands are among the most vulnerable environments on earth to anthropogenic-induced climate change and sea-level rise over the next century because they are low, composed of unconsolidated sediment that is able to be mobilised by waves and currents, and depend on sediments supplied by reef organisms that are particularly sensitive to environmental changes (e.g. ocean temperatures and chemistry). Therefore, the spatial and temporal links between active carbonate production and island formation and dynamics are fundamental to predicting future island resilience, yet remain poorly quantified. In this paper we present results of a detailed geomorphological and sedimentological study of a reef and sand cay on the northern Great Barrier Reef. We provide an empirical investigation of the temporal linkages between sediment production and reef island development using a large collection of single grain AMS ^{14}C dates. Large benthic foraminifera (LBF) are the single most important contributor to contemporary island sand mass (47%; ranging from 36% to 63%) at Raine Island, reflecting rapid rates of sediment production and delivery. Standing stock data reveal extremely high production rates on the reef (1.8 kg m^{-2} yr^{-1}), while AMS ^{14}C dates of single LBF tests indicate rapid rates of sediment transferral across the reef. We also demonstrate that age is statistically related to preservation and taphonomic grade (severely abraded tests > moderately abraded tests > pristine tests). We construct a contemporary reef and island sediment budget model for Raine Island that shows that LBF (*Baculogypsina*, *Marginopora* and *Amphistegina*) contribute 55% of the sediment produced on the reef annually, of which a large proportion (54%) contribute to the net annual accretion of the island. The tight temporal coupling between LBF growth and island sediment supply combined with the sensitivity of LBF to bleaching and ocean acidification suggests that islands dominated by LBF are likely to be very sensitive to short and long term climate change projections. Potential outcomes of this work relate to improving the understanding of the future change dynamics of reef islands in response to climate change.

1. Introduction

Reef islands are mostly low, unconsolidated accumulations of sands or gravels (shingle) that develop on coral reef platforms. They are extremely important geomorphological features, forming the only habitable land for hundreds of thousands of people throughout the world's oceans (Yamano et al., 2005), providing refuge for endemic and/or threatened species of flora and fauna (Turner and Batianoff, 2007; Fuentes et al., 2011), and supporting significant economic services such as tourism. Sediments are typically sand sized (0.063–2 mm) and composed entirely of the skeletal remains of reef biota, either as direct contributions of whole or disarticulated skeletal fragments (e.g. foraminifera, molluscs, *Halimeda*) or as detrital fragments eroded from the reef framework (e.g. corals, crustose coralline algae) and surrounding reef (Harney and Fletcher, 2003; Hart and Kench, 2007). These sediments accumulate over time at a focal point on their respective reef platform in response to wave refraction and convergence (Flood, 1986; Gourlay, 1988; Mandlier and Kench, 2012) and after initial development, hydrodynamic regimes, storms and sediment supply regimes interact and dictate their morphodynamic evolution leading to diversity in geomorphological characteristics (Woodroffe et al., 1999; Hopley et al., 2007; Perry et al., 2011). In particular, variations occur in sediment texture and composition, island shape (elongate, oval, circular), size, orientation and position on the reef platform (windward versus leeward). Numerous studies have shown that low-lying reef islands morphologically adjust to boundary conditions (e.g. sea-level, winds, waves and currents) at interdecadal (Flood, 1986; Frank and Jell, 2006; Dawson and Smithers, 2010; Webb and Kench, 2010; Rankey, 2011) and seasonal timescales (Hopley, 1981; Kench and Brander, 2006). However, the impacts of alterations to sediment production have received comparatively less attention (Kench and Cowell, 2002; Perry et al., 2011).

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Potentially disastrous impacts of recent and projected sea-level rise have been well documented, including land submergence, shoreline erosion and salt-water intrusion into freshwater supplies (Roy and Connell, 1991; Khan et al., 2002; Smithers et al., 2007; Yamano et al., 2007; Woodroffe, 2008; Dickinson, 2009; Nicholls and Cazenave, 2010). Furthermore, rapidly increasing sea surface temperatures and ocean acidification are reducing both the calcification of reef organisms and the $CaCO_3$ productivity of reef communities, as well as the durability of their sediments produced (Hoegh-Guldberg et al., 2007; Cohen et al., 2009; Yamamoto et al., 2012). Previous investigations have speculated negative shifts in island sediment budgets under future scenarios of ecological change (Perry et al., 2011). However, it is unclear what the magnitudes or rates of these changes, or the geomorphological consequences, may be.

Reefs yield a supply of sediment that is selectively transported and deposited to reef islands depending on the hydrodynamic regime (waves and currents) and characteristics of the sediment supply (e.g. density, size, durability). The formation of reef islands and their future sustainability are dependent upon this ecologically-driven sediment supply and in particular the sedimentary traits, rates of supply and residence times (time lags between sediment production and either final deposition or permanent loss). Recent coral reef studies have identified the need to incorporate sediment transport dynamics and taphonomic processes into sediment budgets (Yamano et al., 2000; Kench and Cowell, 2002; Harney and Fletcher, 2003; Hart and Kench, 2007; Ford and Kench, 2011; Perry et al., 2011). However, these processes are difficult to model over long periods because of their non-linearity and an incomplete knowledge of sediment production by components that contribute to reef-island accretion. Sediment budgets and specifically, the linkages between active carbonate production and sediment storage are critical to the understanding of the development and geomorphology of reef associated landforms (e.g. reef islands, beaches).

This study largely focuses on large benthic foraminifera (LBF) which are common on reefs throughout the Pacific Ocean and are often the chief source of sediment currently delivered and deposited on many reef island beaches (Yamano et al., 2000; Collen and Garton, 2004; Fujita et al., 2009; Dawson and Smithers, 2010). LBF are large symbiont-bearing calcareous organisms that, like corals, are extremely sensitive to some of the changes in ocean properties projected over the next century (Hallock, 2000; Kuroyanagi et al., 2009; Uthicke and Fabricius, 2012). Therefore, an appreciation of the spatial and temporal links between their production on the reef and accumulation on reef islands is critical to the understanding of future reef island resilience but remains poorly understood. Against this background, the current investigation presents a detailed analysis of the geomorphic and sedimentological importance of LBF to reef islands using quantitative measures of sediment production, transport and deposition. The specific aims of this study are to: (1) characterise carbonate sediment origin; (2) use radiocarbon dating techniques to empirically investigate the sediment transport dynamics of contemporary sand supply; (3) calculate a simple reef and island sediment budget using sedimentological and geomorphological data; and (4) investigate the importance of LBF to the reef sediment budget and their contribution to reef island accretion.

2. Study site

2.1. Setting

Raine Reef (11°35′S 144°02′E) is positioned on the outer edge of the far northern Great Barrier Reef (GBR), approximately 130 km off the NE coast of Australia (Fig. 1). It is a planar reef approximately 2.9 km long and 0.9 km wide that is probably built upon *Halimeda* bioherms of Pleistocene age (Orme and Salama, 1988; also see Hopley et al., 2007, pp. 276–278). It is one of a series of similar detached reefs along the outer northern GBR separated from the Australian continental shelf by water depths >300 m (Fig. 1). Much of the reef flat is 0.3–0.4 m above the lowest astronomical tide (LAT), corresponding with mean low water springs (Dawson and Smithers, 2010). Raine Island is a moderate sized (ca. 820 m long and 440 m wide) vegetated sand cay located toward the NW end of the reef flat. It is composed of well-sorted sand-sized sediments (mean grain size: 0.5–1 mm) dominated by foraminifera, molluscs and corals produced on the adjacent reef flat. Based on the age of the underlying reef surface (Hopley et al., 2007) the sand cay is believed to have formed after 5000–4000 yr BP (calendar years before present (1950 AD)). Maximum elevation reaches 8 m above LAT although it is mostly <5 m above LAT (Dawson and Smithers, 2010). Although the island was modified by guano mining between 1890 and 1892, it is currently recognised as a key habitat for seabirds and marine turtles (Fuentes et al., 2011).

2.2. Climate and oceanography

Raine Island is exposed to oceanic swell from the Pacific Ocean and experiences high solar radiation, air and sea surface temperatures and relative humidity throughout the year. According to the data collected from the weather station in Poruma (Coconut Island) (Australian Bureau of Meteorology, unpublished data), a sand cay located ~200 km north-northwest of Raine Island (10°03′S 143°04′E), strong southeast winds dominate for about 85% of the year, particularly from May to November when total rainfall is <200 mm. In contrast, a much shorter period (~15% of the year) of more variable (northerly to westerly) winds and total rainfall exceeding 1000 mm is typical during austral summer monsoons. Approximately 40% of southeast trade winds and 50% of monsoonal winds exceed 12.5 m s^{-1} and are responsible for the significant seasonal reversals in the orientation and position of the island on the reef flat (Dawson and Smithers, 2010). The north-eastern Australian coast is influenced by tropical cyclones during the summer months but Raine Island is situated north of the main cyclone belt of the Coral Sea and on average affected by <0.4 cyclones per year (Dawson and Smithers, 2010). At high tides waves propagate across the reef and are the major mechanism for sediment supply to the island. However, no waves travel across the reef at low tides (Gourlay and Hacker, 1991; Gourlay, 1995). The typical diurnal mesotidal range is about 1.8 m (mean sea level of ~1.3 m) and the highest astronomical tide (HAT) is 2.75 m LAT.

2.3. Reef flat zonation

Raine Island Reef is a planar reef that has reached a stage of senility, in which the antecedent lagoon has been completely infilled and a reef flat has formed across the reef platform (Hopley et al., 2007). The reef flat exhibits a relatively simple zonation pattern with six distinct zones identified from high resolution (IKONOS) satellite imagery and extensive field measurements and observations (Fig. 1; Table 1). These zones comprise a mostly continuous narrow (<50 m) band of luxuriant coral growth at the reef edge dominated by robust branching, tabular and massive morphologies (reef rim); a large zone (~0.86 km^2) of slightly higher elevation (0.6–0.9 m above LAT) and consisting of relatively flat reef substrate covered with an abundance of turf algae but few corals (algal turf zone); a zone of cemented rubble and corals sloping gently toward the western end of the reef (rubble zone); a central reef flat zone with a slightly lower elevation (0–0.3 m above LAT), *Acropora* thickets and patches of sand (central coral zone); and a zone of rocky substrate encompassing the island (nearshore reef flat), which is significantly eroded at the western end and characterised by patches of *Halimeda* and several microatolls (Poritids and Faviids) toward the eastern end (Fig. 1). The algal turf zone comprises the highest proportion of the reef flat (36%; see Table 1).

3. Methods

A map of the reef zones was created in a GIS using satellite imagery, colour aerial photography and ground-truthing and the area occupied