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1A Reef and reef island geomorphology

Benthic foraminifera: Their importance to future reef island resilience

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Abstract. The provenance, age and redistribution of sediments across Raine Reef (11°35’28”S 144°02’17”E), northern Great Barrier Reef (GBR) are described. Sediments of both the reef flat and sand cay beaches are composed predominantly of benthic foraminifera (35.2% and 41.5% respectively), which is a common occurrence throughout the Pacific region. The major contemporary sediment supply to the island was identified as *Baculogypsina sphaerulata*, a relatively large (1-2 mm exclusive of spines) benthic foraminifera living on the turf algae close to the reef periphery, and responsible for beach sand nourishment. Radiometric ages of foraminiferal tests of ranging taphonomic preservation (pristine to severely abraded) included in surficial sediments collected across the reef flat were remarkably young (typically <60 years). Results indicate rapid transport and/or breakdown of sand with a minimal storage time on the reef (likely $<10^2$ years), inferring a tight temporal link between the reef island and sediment production on the surrounding reef. This study demonstrates the critical need for further research on the precise residence times of the major reef sediment components and transport pathways, which are fundamental to predicting future island resilience.

Key words: Reef Island, Sedimentology, Foraminifera, Radiocarbon, Climate Change

Introduction

Coral reef islands are extremely important geomorphological features, forming the only habitable land for hundreds of thousands of people throughout the world’s oceans, providing refuge for endemic and/or threatened species of flora and fauna, and supporting significant economic services such as tourism. Their largely unconsolidated sediments are typically sand sized (0.063-2 mm) and composed almost entirely of the skeletal remains of reef biota, either as direct contributions (e.g. foraminifera, molluscs, *Halimeda*) or eroded framework material (e.g. coral, crustose coralline algae) from the surrounding reef. The future persistence of reef islands has been a subject of considerable global concern over the past 10-20 years (Roy and Connell, 1991; Khan et al., 2002; Smithers et al., 2007; Yamano et al., 2007; Woodroffe, 2008; Nichols and Cazenave, 2010), and was endorsed in the last IPCC assessment report (Mimura et al., 2007). Threats include land submergence, shoreline erosion and salt water intrusion into freshwater supplies (Nichols and Cazenave, 2010; Perry et al., 2011); beach erosion presents a particular hazard to coastal tourism facilities, which often provide the main economic thrust for small island nations. Additionally, rapidly increasing sea surface temperature (SST) and ocean acidification are stressing calcifying reef organisms that play a critical role in island development and maintenance (Hallock, 2000; Langdon and Atkinson, 2005; Fujita et al., 2011).

Reefs yield a supply of sediment that is selectively transported and deposited to reef islands depending on the hydrodynamic regime (waves and currents). 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 of permanent loss). Previous investigations have advocated negative shifts in island sediment budgets under future scenarios of ecological change (Perry et al., 2011); however, the details of the temporal scales at which islands may respond remain elusive.

This paper describes the general character of sediments across a reef platform in the northern Great Barrier Reef. It then focuses on the most important production and transport pathways on the reef flat. Finally it uses accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dating of single component grains as a tool to investigate patterns in age structure across a reef flat that will provide extremely important information for developing reef island sediment budgets and predicting future island resilience to climate change impacts such as sea level rise, increased storm intensity and significant changes to ocean chemistry.

Study Site

This study was conducted on Raine Reef (11°35'28"S 144°02'17"E), a planar reef situated on the far northern outer Great Barrier Reef (GBR) (Fig. 1). Wind-driven waves, from dominant south-easterlies and oceanic swells carry sediment from the reef flat to an island (Raine Island) close to the NW reef edge (Fig. 1C-D). The island is a moderate-sized (~275,000 m^2) vegetated sand cay (Fig. 2) and is an ideal location to investigate sediment age structure as patterns are not complicated by large-scale mixing of near-surface sediments from tropical storms or bioturbation (Dawson and Smithers, 2010). Maximum elevation is ~8 m above lowest astronomical tide (LAT) with an average elevation of about 5 m above LAT. It is thought that the island has formed over the past 4-4.5 kyr (Hopley et al., 2007). Raine Island is uninhabited but its sustainability is critical given its very high ecological status (world's largest population of nesting Green Sea Turtles and most significant sea bird population on the GBR).

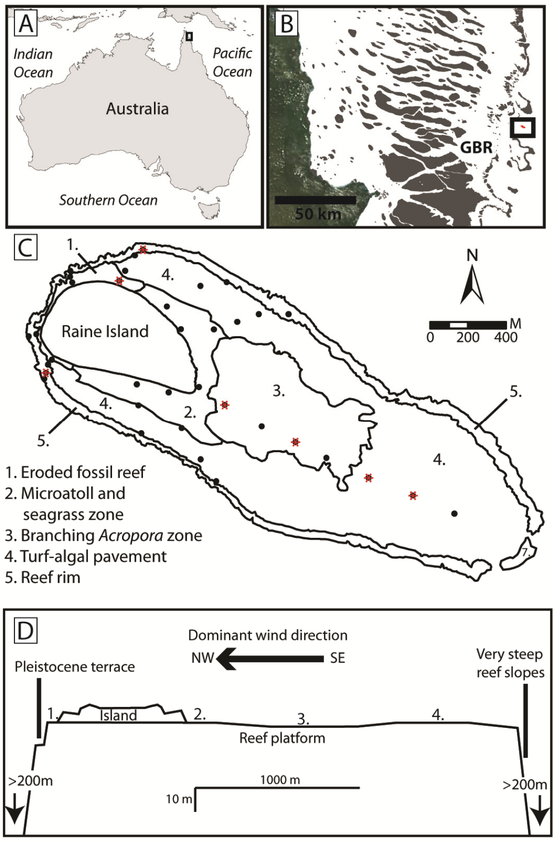

Figure 1: Locality map (A-B) and zonation of Raine Reef (C-D), northern GBR, Australia. The reefs position on the outer GBR is shown in (B) while the five major ecological reef zones and 33 reef sites (black dots) are shown in (C) – stars indicate sites selected for radiometric dating. A cross-section schematic (D) illustrates the topography of the reef platform.

Material and Methods

Sand samples were collected from 33 sites on the reef flat (Fig. 1D) and 13 sites on the contemporary beach from the upper 5-10 cm of surface sediment using plastic vials that were carefully capped to minimize any loss of finer sediments. In the laboratory, each sample was soaked in dilute sodium hypochlorite solution to remove salt and organic matter, repeatedly rinsed in fresh water through a 63µm sieve and oven dried at 40°C for 24 hours. Components were identified microscopically from a microsplit of each sample and tabulated as foraminifera, coral, crustose coralline algae (CCA), *Halimeda*, molluscs, or other bioclasts. The main groups of foraminifera were tallied according to species and *Baculogypsina sphaerulata* were grouped into three levels of preservation: 1) pristine; 2) moderately abraded; and 3) severely abraded based on the preservation or loss of test features identified using optical and scanning electron microscopy (SEM). In this paper we focus on the two end members: "pristine" and "severely abraded" (Fig. 3). In our classification, "pristine" samples represent the initial stages prior to any fragmentation or loss of spines, while "severely abraded" samples represent the end product of abrasion beyond which rapid destruction occurs. Using AMS-^{14}C measurements on individual foraminifera we dated two tests of each taphonomic end member at six sites plus two pristine samples from a seventh site (n=26 sites) (Fig. 1C). A further four tests were selected from the contemporary beach. Each test was washed several times with deionised water in an ultrasonic bath and leached in dilute hydrochloric acid (0.001M) for a few minutes to remove any possible surface contamination or residual secondary carbonate. The cleaned samples were hydrolysed using phosphoric acid and converted to graphite using the Fe/H2 method (Hua et al., 2001). AMS ^{14}C measurements were taken at the ANTARES and STAR facilities at ANSTO (Australian Nuclear Science and Technology Organisation), Sydney, Australia (Fink et al. 2004). All ^{14}C calculations were based on the conventions of (Stuiver and Polach, 1977) and calibrated using the Marine09 dataset (Reimer et al. 2009), a marine reservoir correction (ΔR) of 12 ± 13 ^{14}C years (weighted average derived from 14CHRONO: Reimer and Reimer, 2001) and the calibration software OxCal v4.10 (Bronk Ramsey, 2011).

Results

Based on the analysis of high-resolution satellite imagery (IKONOS), colour aerial photographs and field observations five major ecological zones can be differentiated across the contemporary reef flat (Fig. 1).

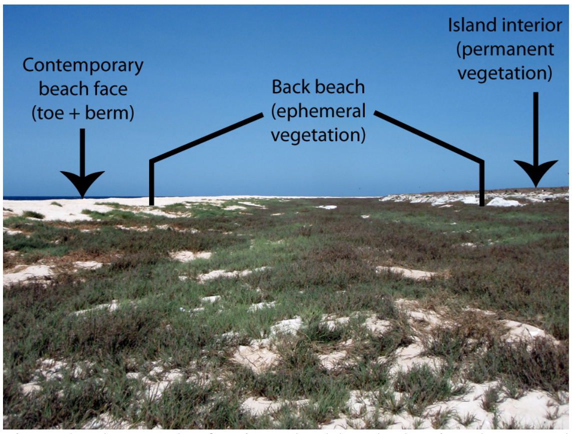

Figure 2: Photograph of Raine Island beach showing the general profile from shoreline (left) to a phosphate cliff that separates the ephemerally vegetated back beach and the permanently vegetated island interior. Vegetation is primarily tussock grasses.

The turf-algal pavement (zone 4) is the primary production zone of *B. sphaerulata* while most corals are restricted to the reef rim (zone 5) except for a few *Acropora* stands in zone 3 (Fig. 1C).

Sand Composition

Beach sands contain 42% foraminifera, 20% *Halimeda*, 17% mollusks and 16% coral; proportions of foraminifera were highest at the top of the active beach slope (berm) and lowest in the back-beach area (Fig. 4). *Baculogypsina* comprised over 72% of the foraminifera in beach sediments of which ~60% are severely abraded tests (Table 1). *Amphistegina* contributed a further 14%.

Relatively little sediment is stored over the reef-flat, with only thin (<20 cm thick) and sporadic patches of sand-sized sediments occurring mainly in topographic depressions. However, at various times, significant sand deposits occur closer to the cay as sand is periodically transported on and offshore. Sand deposits are exclusively bioclastic and dominated by foraminifera, coral, *Halimeda* and mollusks. The skeletal remains of foraminifera are found almost exclusively whole (with or without spines), while all other components typically occur as fragments. Like in beach sediments, the dominant component is foraminifera (35%) (Fig. 4) However, coral is the second most dominant component contributing 27% of reef flat sediments. An increased proportion of coral and decreased proportion of foraminifera is due to a prevalence of coral fragments found in zone 5 (44%) where living corals flourish. Percentages of *Halimeda* (15-20%), molluscs (10-15%) and CCA (5-6%) were similar to beach sediments (Fig. 4). Nearly 60% of foraminifera on the reef flat are *B. sphaerulata* with the highest proportions in zone 4 and zone 1 (Table 1). Most of these are severely abraded throughout all reef flat zones with the exception of zone 4 where sands contain a larger proportion of pristine tests (Table 1). There is also a progressive increase in test degradation from zone 4 towards the island.

Sediment Age (Radiocarbon Dating)

Table 2 and Fig. 5 summarise the radiocarbon age results for foraminifera collected from across the reef flat. All calibrated ages are expressed as calendar years AD (cal AD) as both a 2σ range (95% confidence interval) and a median (best estimate) age.

Remarkably, out of the 26 reef samples analysed, 22 (85%) of them returned a modern age (defined as post-1950AD) irrespective of their taphonomic grade or position across the reef flat. Consequently, the frequency distribution of test ages is strongly skewed towards older ages (i.e. mostly young). None of the 14 pristine samples and only a third of the poorest condition tests predates 1950AD. At sites closest to the reef island or towards the end of their sediment transport pathway (T1S7 and T7S4B) there is some indication that pristine tests are younger than severely abraded tests (Table 2).

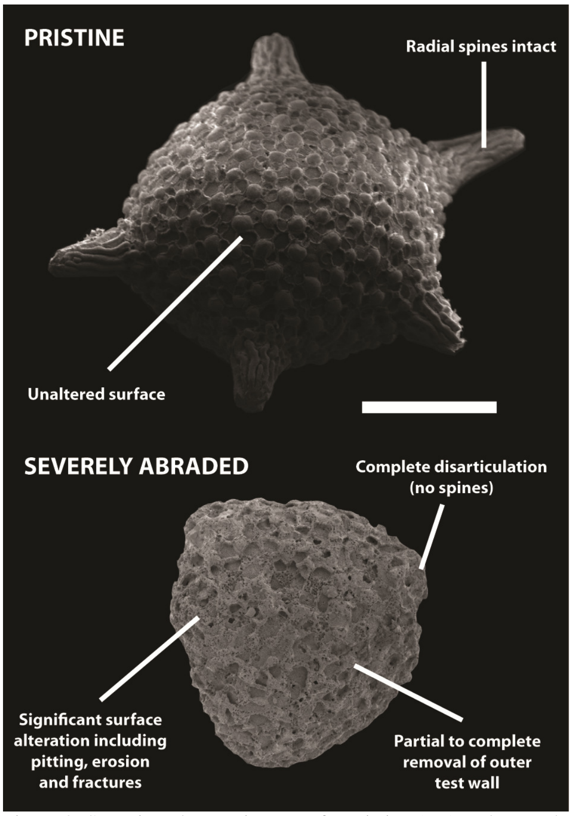

Figure 3: Scanning electron images of a pristine (top) and severely abraded (bottom) test of the large benthic foraminifera *Baculogypsina sphaerulata*. A 500µm scale bar pertains to both images.

Table 1: Average proportions of the main species of larger foraminifera in beach and reef flat sediments across Raine Reef. Proportions are shown as percentages of the total foraminifera found in each reef environment. Other species include minor contributions of *Homotrema rubrum*, *Calcarina hispida*, *Heterostegina depressa* and smaller miliolid species.

	Beach	Reef flat					
Species		Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Total
Baculogypsina sphaerulata	72.4	69.7	54.7	51.9	69.5	44.7	58.5
Pristine	0.4	5.2	7.0	8.4	26.4	10.0	11.1
Moderately abraded	11.4	9.0	12.0	17.1	24.7	11.8	16.3
Severely abraded	60.6	55.6	35.7	26.4	18.4	22.8	31.0
Amphistegina lobifera	13.9	9.7	13.5	2.3	8.7	6.0	8.4
Marginopora vertebralis	4.1	11.9	23.5	21.2	18.3	33.4	22.7
Other species	9.6	8.7	8.3	24.6	3.5	15.9	10.5

It is worth noting that with the exception of sample T7S4Bpr-B there is an age gap (~300-400 years) between the predominant modern-age population and a small cluster of distinctly older foraminifera towards the centre of the reef platform (Fig. 5). Interestingly, the four samples selected from the contemporary beach were also of modern age (Table 2) suggesting active transport of *B. sphaerulata* from the reef (source) to the island (sink).

The oldest age established for *B. sphaerulata* was 1580AD (95% confidence intervals: 1490-1675AD) representing the maximum duration an individual may be expected to persist in the active sedimentary environment (Flessa and Kowalewski, 1994).

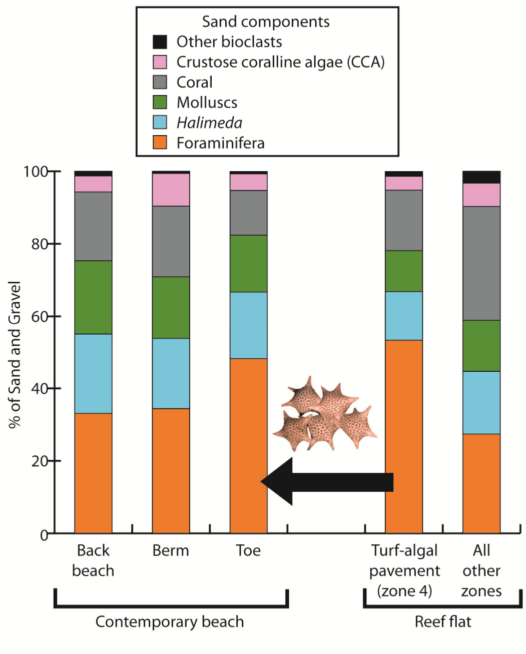

Figure 4: Average proportions (weight percent) of the main reef components in beach and reef flat sands and gravels. The contemporary beach consists of a beach toe rising to a berm that slopes down towards a back beach area (Dawson and Smithers, 2010; also see Fig. 2). Arrow denotes main transport pathway of foraminifera from the turf-algal pavement to the beach toe.

However, according to our data, we can expect most *B. sphaerulata* tests to completely break down over a much shorter time frame (possibly an order of magnitude quicker) as the majority are <60 years old. This is consistent with the rapid shell destruction observed in recent laboratory-based milling studies (Ford and Kench, 2011).

Discussion

The surface sediments across Raine Reef are entirely composed of the skeletal remains of marine organisms, particularly benthic foraminifera, which constitute between 30-50% of most beach and reef flat sands. At most locations across the reef, at least 20% of each sand sample is comprised of *B. sphaerulata* tests, but proportions may exceed 60% at some sites. The predominance of foraminifera sand at Raine Island is similar to many reef islands within the GBR and throughout the western Pacific: foraminiferal sediment production often exceeds that of any other calcifying organism including corals (Langer, 2008). Therefore, in such regions foraminifera are the critical source of beach nourishment. At Raine Island, foraminifera are well represented across the reef between the turf-algal pavement and the island. This is in marked contrast to the smaller proportions of coral sediments across the reef except in close proximity to zone 5 (zone of living coral). These patterns reflect the relative transport capacity of each component: foraminifera are easily transported while coral are produced and retained within the framework rather than broken down to sediments that are readily entrained (Harney et al., 2000; Hohenegger, 2006; Hart, 2008).

One of the aims of this study was to investigate the age range of *B. sphaerulata* in surface sediments across Raine Reef platform to better understand the residence time and to investigate a potential relationship between age and taphonomy (skeletal condition). AMS ^{14}C measurements obtained for 30 (26 reef flat + 4 beach) individual tests show that *Baculogypsina* sediments that dominate the reef surface are very young (Fig. 5; Table 2). These preliminary results suggest that the major source of sand to Raine Island is typically delivered within a 60 year time period (possibly much quicker) following the death of the organism indicating that the island has a tight temporal link to the production of calcareous tests by living *B. sphaerulata* close to the reef rim and the reef sediment stored (briefly) across the reef flat that surrounds the island.

The overall distribution of ^{14}C ages across the reef indicates that there may be a correlation between age, taphonomy and carbonate production. For example, Younger pristine tests occur close to the turf-algal pavement while older, comparatively poorer condition tests occur closer to the island. Although we are restricted to a modest sample size (n=30), a trend is suggested and further research is planned to investigate the intricacies of these relationships.

The skeletal tests of benthic foraminifera are ideally suited to transport across the reef due to their relative buoyancy, slower settling velocity and greater capacity for entrainment (Hohenegger, 2006). However, contrary to previous studies advocating a resistance to abrasion and dissolution and retention in carbonate environments for long periods of time (Kotler et al., 1992; Collen and Garton, 2004), we show that this does not apply to *B. sphaerulata*, an important reef island-building foraminifer on the GBR and throughout the western Pacific. In fact, we conclude that these foraminifera only have the capacity to persist in reef environments for short periods of time (e.g. <100 years). This is congruent with recent simulated milling experiments indicating *Halimeda* and *B. sphaerulata* are the least durable reef skeletal components and are removed from the sedimentary system in the shortest amount of time (Ford and Kench, 2011).

It is likely that islands dominated by *B. sphaerulata* are only able to persist because of the rapid transport and supply of newly produced foraminifera sediments.

The results of this study suggest that many Western Pacific reef islands (including within the GBR) could show extreme sensitivity (low capacity for adaptation) to continued anthropogenic stresses and climate change over the next century as ecologically driven sediment supply is altered or sediment transport pathways are interrupted (Perry et al., 2011). These results have very important implications for improving understanding of reef island sediment budgets that is critical for predicting the future sustainability of reef islands.

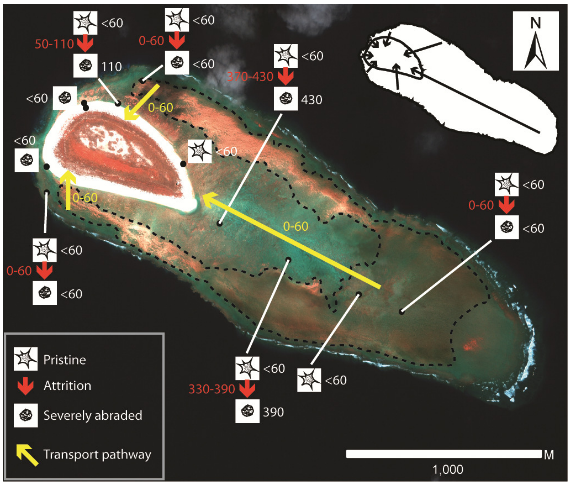

Figure 5: Radiocarbon age data for *Baculogypsina sphaerulata* across Raine Reef. An IKONOS satellite image (NrGB) shows the production zone of the foraminifer (dashed line). White values represent best estimate ages of pristine and severely abraded tests (oldest of each duplicate is given setting a maximum age). The red age ranges denote the maximum number of years required for the skeletal test to break down (attrition). The yellow arrows depict transport pathways all with estimated transport times of <60 years. Inset schematic (top right) illustrates incident wind and infragravity wave directions resulting from dominant SE trade winds.

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References

Bronk Ramsey C (2011) OxCal Program, Version 4.1 (https://c14.arch.ox.ac.uk/oxcal.html), Radiocarbon Accelerator Unit, University of Oxford, UK

Collen JD, Garton GW (2004) Larger foraminifera and sedimentation around Fongafale Island, Funafuti Atoll, Tuvalu. Coral Reefs 23:445-454

Dawson JL, Smithers SG (2010) Shoreline and beach volume change between 1967 and 2007 at Raine Island, Great Barrier Reef, Australia. Global and Planet Change 72:141-154

Fink D, Hotchkis M, Hua Q, Jacobsen G, Smith AM, Zoppi U, Child D, Mifsud C, van der Gaast H, Williams A, Williams M (2004) The ANTARES AMS facility at ANSTO. Nucl Instrum Meth B 223-224:109-115

Flessa KW, Kowalewski M (1994) Shell survival and time-averaging in nearshore and shelf environments: estimates from the radiocarbon literature. Lethaia 27:153-165

Ford MR, Kench PS (2011) The durability of bioclastic sediments and implications for coral reef deposit formation. Sedimentology doi: 10.1111/j.1365-3091.2011.01281.x

Fujita K, Hikami M, Susuki A, Kuroyanagi A, Sakai K, Kawahata H, Nojiri Y (2011) Effects of ocean acidification on calcification of symbiont-bearing reef foraminifers. Biogeosciences 8:2089-2098

Hallock P (2000) Larger foraminifers: Harbingers of global change? Micropaleontology 46:95-104

Harney JN, Grossman EE, Richmond BM, Fletcher CH (2000) Age and composition of carbonate shoreface sediments, Kailua Bay, Oahu, Hawaii. Coral Reefs 19:141-154

Hart DE (2008) The maintenance of reef islands. Proc 11th Int Coral Reef Symp 1:416-420

Hohenegger J (2006) The importance of symbiont-bearing benthic foraminifera for west Pacific carbonate beach environments. Mar Micropaleontol 61:4–39

Hopley D, Smithers SG, Parnell KE (2007). The geomorphology of the Great Barrier Reef: Development, Diversity and Change. Cambridge University Press, Cambridge, p 532

Hua Q, Jacobsen GE, Zoppi U, Lawson EM, Williams AA, Smith AM, McGann MJ (2001) Progress in Radiocarbon Target Preperation at the ANTARES AMS Centre. Radiocarbon 43:275-282

Khan TMA, Quadir DA, Murty TS, Kabir A, Aktar F, Sarker MA (2002) Relative sea level changes in Maldives and vulnerability of land due to abnormal coastal inundation. Mar Geod 25:133–143

Kotler E, Martin RE, Liddell WD (1992) Experimental analysis of abrasion and dissolution resistance of modern reef-dwelling foraminifera: implications for the preservation of biogenic carbonate. Palaios 7:244-276

Langdon C, Atkinson MJ (2005) Effect of elevated pCO2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. J Geophys Res 110:1–16

Langer MR (2008) Assessing the Contribution of Foraminiferan Protists to Global Ocean Carbonate Production. J Eukaryot Microbiol 55:163-169

Mimura N, Nurse L, McLean RF, Agard J, Briguglio L, Lefale P,Payet R, Sem G (2007) Small islands. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 687–716

Nicholls RJ, Cazenave A (2010) Sea-Level Rise and Its Impact on Coastal Zones. Science 328:1517-1520

Perry CT, Kench PS, Smithers SG, Riegl B, Yamano H, O'Leary MJ (2011) Implications of reef ecosystem change for the stability and maintenance of coral reef islands. Glob Change Biol 17:3679-3696

Reimer PJ, Reimer RW (2001) A marine reservoir correction database and on-line interface. Radiocarbon 43:461-463 (http://calib.qub.ac.uk/marine/)

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE (2009) INTCAL09 and MARINE09 Radiocarbon Age Calibration Curves, 0–50,000 Years CAL BP. Radiocarbon 51:1111-1150

Roy P, Connell J (1991) Climate change and the future of atoll states. J Coastal Res 7:1057-1075

Smithers SG, Harvey N, Hopley D, Woodroffe CD (2007) Vulnerability of geomorphological features in the Great Barrier Reef to climate change. In: Johnson JE, Marshall PA (eds), Climate Change and the Great Barrier Reef. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia, pp 667-716

Stuiver M, Polach A (1977) Reporting of 14C data. Radiocarbon 19:355-363

Woodroffe CD (2008) Reef-island topography and the vulnerability of atolls to sea-level rise. Global and Planet Change 62:77-96

Yamano H, Kayanne H, Yamaguchi T, Kuwahara Y, Yokofi H, Shimazaki H, Chikamori M (2007) Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. Global Planet Change 57:407-416

Table 2: AMS radiocarbon ages and calibrated calendar ages of *Baculogypsina sphaerulata* from Raine Reef measured using the ANTARES and STAR facilities at the Australian Nuclear Science and Technology Organisation (ANSTO).

Sample name	Skeletal condition [a]	ANSTO Lab code	Reef zone	^{13}C (‰)	Conventional age [c]		Calibrated age (years AD) [d]	
					(^{14}C years)	(±)	2σ age range	Median age (best estimate)
T1S2pt-A	P	OZM313	4	-1.0	Modern		0-60	<60
T1S2pt-B	P	OZM314	4	-2.2	Modern		0-60	<60
T1S2pr-A	S	OZM912	4	-3.1	Modern		0-60	<60
T1S2pr-B	S	OZM913	4	-3.4	Modern		0-60	<60
T1S3pt-A	P	OZM315	3	-2.8	Modern		0-60	<60
T1S3pt-B	P	OZM316	3	-3.5	Modern		0-60	<60
T1S5pt-A	P	OZM317	3	-2.0 [b]	Modern		0-60	<60
T1S5pt-B	P	OZM318	3	-2.0 [b]	Modern		0-60	<60
T1S5pr-A	S	OZN822	3	-2.3	Modern		0-60	<60
T1S5pr-B	S	OZN823	3	-1.2	685	45	1505-1710	1625
T1S7pt-A	P	OZM319	3	-2.0 [b]	Modern		0-60	<60
T1S7pt-B	P	OZM320	3	-2.0 [b]	Modern		0-60	<60
T1S7pr-A	S	OZM918	3	4.5	520	70	1685-1950	1815
T1S7pr-B	S	OZM919	3	-7.3	740	45	1485-1670	1580
T4S2pt-A	P	OZM321	5	-3.1	Modern		0-60	<60
T4S2pt-B	P	OZM322	5	-3.6	Modern		0-60	<60
T4S2pr-A	S	OZN824	5	-1.3	Modern		0-60	<60
T4S2pr-B	S	OZN825	5	-2.1	Modern		0-60	<60
T7S1pt-A	P	OZM323	5	0.4	Modern		0-60	<60
T7S1pt-B	P	OZM324	5	-2.0 [b]	Modern		0-60	<60
T7S1pr-A	S	OZM922	5	-4.9	Modern		0-60	<60
T7S1pr-B	S	OZM923	5	-2.0 [b]	Modern		0-60	<60
T7S4Bpt-A	P	OZM325	1	-2.0 [b]	Modern		0-60	<60
T7S4Bpt-B	P	OZM326	1	-2.2	Modern		0-60	<60
T7S4Bpr-A	S	OZN828	1	-1.5	Modern		0-60	<60
T7S4Bpr-B	S	OZN829	1	-2.0 [b]	400	50	1770-1950	1900
Q20096	S	OZM717	Beach	-2.6	Modern		0-60	<60
Q20097	S	OZM906	Beach	-2.0 [b]	Modern		0-60	<60
RIST1	P	OZM908	Beach	-1.7	Modern		0-60	<60
RIST4A	S	OZM733	Beach	-2.0 [b]	Modern		0-60	<60

[a] Skeletal condition: P = Pristine and S = Severely abraded

[b] Assumed $\Delta^{13}C$ value due to limited material. This assumed value is an average of all $\Delta^{13}C$ measurements made in this study

[c] Conventional ages and errors have been rounded according to Stuiver and Polach (1977)

[d] Calibration was performed using OxCal v4.10, Marine09 data set (Reimer et al., 2009) and a ΔR value of 12 ± 13 yr. Ages are reported in calendar years AD.