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Incremental accretion of a sandy reef island over the past 3000 years indicated by component-specific radiocarbon dating

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[1] Low-lying reef islands appear particularly threatened by anticipated sea-level rise, and determining how they formed and whether they are continuing to accumulate sediment is essential for their sustainable management. Depositional chronology of Warraber Island, a small sand cay in Torres Strait, Australia, is re-examined based on AMS radiocarbon dating of specific skeletal components. Whereas radiometric dating of bulk sand samples indicated one or more discrete phases of mid-late Holocene deposition, component-specific AMS radiocarbon dating of sand grains indicates sustained incremental growth over the past 3000 years. Ages on gastropods that lived on the reef flat around the island indicate continuing sediment production and island progradation, in contrast to bulk ages and other components produced at greater distances. Growth of sand cays depends on the rate and pattern of sediment supply, which are functions of the local ecology of the surrounding reef and reef flat, and hydrodynamic constraints. **Citation:** Woodroffe, C. D., B. Samosorn, Q. Hua, and D. E. Hart (2007), Incremental accretion of a sandy reef island over the past 3000 years indicated by component-specific radiocarbon dating, *Geophys. Res. Lett.*, *34*, L03602, doi:10.1029/2006GL028875.

1. Introduction

[2] Sand cays, small sandy islands formed on the surface of coral reefs, and in many cases forming the only habitable land for indigenous communities, appear particularly vulnerable to the impacts of sea-level rise anticipated as a consequence of global warming [*McLean and Tsyban*, 2001]. For more sustainable management of these fragile environments in the face of climate change, it is necessary to understand the history of their accumulation.

[3] Patterns of mid to late Holocene reef growth have been interpreted primarily on the basis of radiocarbon dating [*Hopley*, 1994; *McLean and Woodroffe*, 1994]. In contrast, relatively little effort has been directed toward deciphering the depositional history of sand cays on the surface of these reefs [*Roy and Connell*, 1991; *Stoddart*, 1969]. Carbonate sand is amenable to radiometric dating, but interpretation of radiocarbon ages appears problematic because of the disparity between time of death of skeletal organisms (coral, coralline algae, foraminifera or mollusc) and time of deposition. A radiocarbon age yields an estimate of the former, whereas the latter may occur some time thereafter, following an undefined period of transport, breakdown, mixing and re-deposition [*Roy*, 1991]. Hence radiocarbon ages represent maximum ages in terms of sand deposition.

[4] Radiocarbon dating of coral shingle ridges on a reef island and coral boulders on a gravel spit in areas subject to tropical cyclones has shown an incremental pattern of development with increased age of each successive ridge [*Chivas et al.*, 1986; *Hayne and Chappell*, 2001]. Systematic dating of sequences of ridges appears to record accumulation of storm-generated coral rubble with only limited subsequent redistribution and cementation of boulders [*Maragos et al.*, 1973; *Scoffin*, 1993]. In relation to sand cays, at least two phases of sand-cay formation have been inferred on the Great Barrier Reef, one around 3000 ^{14}C years BP and a second around 1500 ^{14}C years BP [*McLean and Stoddart*, 1978]. In the Maldives, low-lying sandy reef islands at the southern end of the archipelago were interpreted as initially formed around 3000 years ago when the reef rim was believed to have caught up with sea level [*Woodroffe*, 1992]. A recent study by *Kench et al.* [2005] of cays to the north of the Maldives chain, on the other hand, inferred that the islands had developed over a long period of time with progressive accretion, on the basis of a series of bulk radiocarbon dates on sand.

[5] However, depositional history of sand cays based on bulk dates may be misleading as a result of sediment reworking and re-deposition [*McLean et al.*, 1978; *Stoddart et al.*, 1978]. In this paper the depositional history of Warraber Island is determined based on radiocarbon ages on samples from a series of pits across the island. Although bulk dates indicate a discrete phase of deposition, 4000–2500 years ago [*Woodroffe*, 2002], accelerator mass spectrometry (AMS) radiocarbon dating of specific carbonate grains indicates that different components within the island and reef flat sand yield different ages. One specific component, gastropods originating from the reef flat around the island, yields ages that imply continual sand accumulation over the past 3000 years.

2. Area of Study

[6] Warraber Island is a sand cay at the northeast of a reef platform 5.4 km long and 2.6 km from north to south, situated in central Torres Strait (Figure 1). The Strait is outside the tropical cyclone belt, and is dominated by southeasterly winds for most of the year, except for several months during the Austral summer (November–March) when northwesterly winds blow. Torres Strait is dominated by strong tidal currents, and the island experiences a tidal

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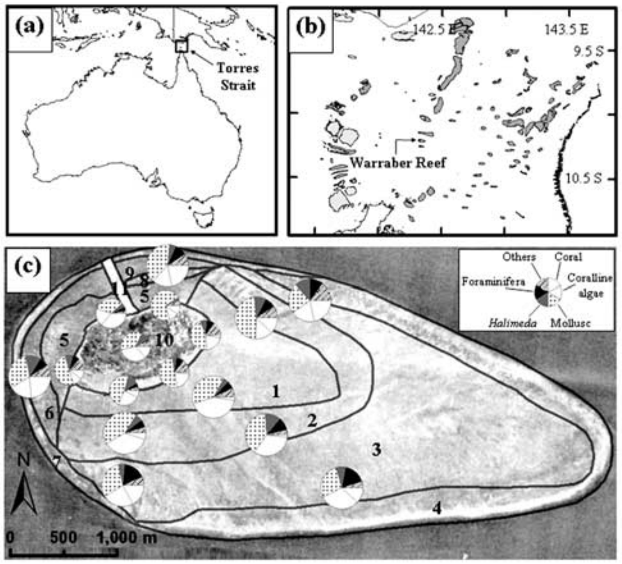

Figure 1. Locations of (a) Torres Strait and (b) Warraber Reef and (c) ecological zones on the reef flat and sediment composition for samples from the reef flat, beach and island (small circle): sandy reef flat dominated by molluscs (zone 1), sandy reef flat dominated by algae (zone 2), sandy reef flat dominated by coral (zone 3), raised algal rim (zone 4), fine sandy reef flat (zone 5), mixed coral zone (zone 6), lower algal rim (zone 7), dense branching coral (zone 8), dense mixed coral (zone 9), Warraber Island (zone 10), and boat channel (zone 11).

range of around 2.5 m. Much of the reef-flat surface is exposed at low tide, because it formed about 5800 years ago when sea level at this site was around 0.8 m higher than present, as shown by radiocarbon dates on a series of fossil *Porites* microatolls [*Woodroffe et al.*, 2000]. The largely barren reef flat is veneered by a discontinuous and generally thin sediment cover, generally <20 cm thick [*Hart*, 2003]. The distribution of ecological zones and the relative contribution of different components within the sediment is summarised in Figure 1c, and is described in greater detail by *Hart and Kench* [2007]. The bare reef and sediment veneer, especially of Zone 1, are grazed by gastropods, particularly species of *Turridrupa* and *Mitra*. Coral occurs as sparse colonies only, except around the reef crest (Zone 3) and across the lower, northwestern margin of the platform (Zones 6 and 9) whereas coralline and brown algae are abundant on the reef crest (Zones 4 and 7).

[7] The island comprises a sequence of forested beach ridges of <1 m amplitude, discernible on aerial photographs taken before recent modification of the island surface and construction of a runway along a NW-SE axis. These subtle ridges are identifiable on a digital terrain model (DTM) of the island (Figure 2) derived photogrammetrically from 1998 colour vertical aerial photography.

3. Materials and Methods

[8] Sand samples were collected from backhoe pits along a transect across Warraber Island [samples labelled A were from <1 m, and B >1 m depth], and conventional ^{14}C ages on several of these samples were reported by *Woodroffe* [2002]. In order to investigate the validity of the bulk dates, individual component sand grains of coral, mollusc and foraminifera were selected for AMS radiocarbon dating after examination under a binocular microscope. Pristine grains were preferentially selected in order to minimise the potential age bias due to reworking and contamination; individual foraminifers were selected which retained their original spines, and gastropod shells that showed little sign of abrasion, generally retaining their colouration and a sharply pointed spire. Only very small coral fragments were found (generally <1 mm).

[9] A set of 32 single grain samples (10 coral, 18 gastropod shells and 4 foraminifera) was dated by AMS ^{14}C. Each single grain was washed several times with deionised water in an ultrasonic bath, and leached in dilute HCl to remove any surface contamination and possible secondary carbonate. The cleaned samples were hydrolysed to CO_2 using 85% phosphoric acid, and then converted to graphite using the Fe/H_2 method [*Hua et al.*, 2001]. AMS ^{14}C measurements were undertaken on each single grain using the ANTARES facility at ANSTO [*Fink et al.*, 2004].

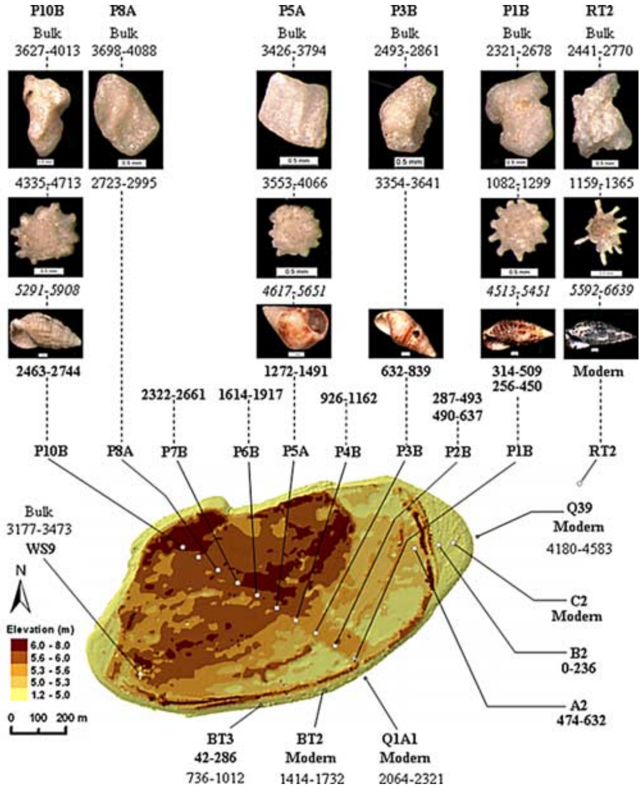

Figure 2. A photogrammetrically-derived digital terrain model (DTM) of Warraber Island, showing ridges that record incremental progradation of the island, and the distribution of bulk sample and AMS dates from pits as well as reef flat and active beach. All ages are reported with range of 2σ in years cal BP. Dates are in plain text for corals, in italic for foraminifera and in bold for shells. Note that the scale bar for photomicrographs of (top) coral and (middle) foraminifera is 0.5 mm, and for (bottom) molluscs it is 1 mm. There are two dates of shell samples at P1B and P2B.

Table 1. Radiocarbon Ages and Their Associated Calibrated Ages for Bulk Sand and Individual Grains From Warraber Island and Reef Flat

Sample Code	Lab Code	Description	δ^{13}C, ‰	Conventional ^{14}C Age, years BP ± 1σ Error	Cal BP 2σ Age Ranges
P10B[a]	Wk8213	Bulk sand from the island	0.7	3910 ± 60	3627–4013
P10B Coral	OZG563	Coral from P10B	−1.6	4410 ± 50	4335–4713
P10B Shell	OZG564	Shell from P10B	−0.9	2920 ± 40	2463–2744
P10B Foram	OZG565	Foraminifer from P10B	0.0[b]	5290 ± 140	5291–5908
P8A[a]	Wk8212	Bulk sand from the island	1.9	3970 ± 60	3698–4088
P8A Coral	OZG562	Coral from P8A	0.8	3120 ± 50	2723–2995
P7B Shell	OZH751	Shell from P7B	1.8	2790 ± 50	2322–2661
P6B Shell	OZH750	Shell from P6B	2.8	2230 ± 50	1614–1917
P5A[a]	Wk8211	Bulk sand from the island	2.3	3730 ± 60	3426–3794
P5A Coral	OZG559	Coral from P5A	−3.1	3890 ± 90	3553–4066
P5A Shell	OZG560	Shell from P5A	1.1	1870 ± 40	1272–1491
P5A Foram	OZG561	Foraminifer from P5A	0.0[b]	4930 ± 210	4617–5651
P4B Shell	OZH749	Shell from P4B	2.9	1540 ± 40	926–1162
P3B[a]	Wk8210	Bulk sand from the island	2.4	2990 ± 60	2493–2861
P3B Coral	OZG557	Coral sample from P3B	−4.0	3650 ± 50	3354–3641
P3B Shell	OZG558	Shell from P3B	0.6	1220 ± 40	632–839
P2B Shell	OZH748	Shell from P2B	2.4	810 ± 50	287–493
P2B Shell	OZI554	Shell from P2B	3.6	1010 ± 40	490–637
P1B[a]	Wk8209	Bulk sand from the island	2.7	2800 ± 60	2321–2678
P1B Coral	OZG554	Coral from P1B	−2.1	1700 ± 40	1082–1299
P1B Shell	OZG555	Shell from P1B	0.3	850 ± 40	314–509
P1B Shell	OZI553	Shell from P1B	1.6	740 ± 40	256–450
P1B Foram	OZG556	Foraminifer from P1B	0.0[b]	4780 ± 180	4513–5451
RT2[a]	Wk10830	Bulk sand on the reef		2930 ± 52	2441–2770
RT2 Coral	OZG566	Coral from RT2	0.0[b]	1760 ± 40	1159–1365
RT2 Shell	OZG567	Shell from RT2	0.3	Modern	Modern[c]
RT2 Foram	OZG568	Foraminifer from RT2	0.0[b]	5770 ± 240	5592–6639
WS9[a]	Wk9421	Bulk sand on the reef		3505 ± 50	3177–3473
A2 Shell	OZH752	Shell from the eastern spit	2.3	990 ± 40	474–632
B2 Shell	OZH753	Shell from the eastern spit	0.9	540 ± 40	0–236
C2 Shell	OZH754	Shell from the eastern spit	3.3	200 ± 40	Modern[c]
BT3 Coral	OZH883	Coral from the beach	1.4	1390 ± 50	736–1012
BT3 Shell	OZH884	Shell from the beach	3.9	600 ± 50	42–286
BT2 Coral	OZH881	Coral from the beach	1.5	2070 ± 50	1414–1732
BT2 Shell	OZH882	Shell from the beach	2.2	490 ± 50	Modern[c]
Q1A1 Coral	OZH887	Coral from the reef flat	0.5	2580 ± 40	2064–2321
Q1A1 Shell	OZH888	Shell from the reef flat	0.7	Modern	Modern[c]
Q39 Coral	OZH885	Coral from the reef flat	−1.8	4330 ± 60	4180–4583
Q39 Shell	OZH886	Shell from the reef flat	2.0	Modern	Modern[c]

[a] Samples were dated by conventional ^{14}C dating, whereas all other samples were dated by AMS.
[b] Assumed value as the sample size is too small and no δ^{13}C measurement was carried out.
[c] Modern samples whose radiocarbon ages are out of the range of Marine04 curve.

[10] Conventional ^{14}C ages (in years BP) were calibrated to calendar BP ages (cal BP) using the online calibration program, CALIB Rev 5.0.2 html [*Stuiver and Reimer*, 1993] and the marine calibration data set Marine04 [*Hughen et al.*, 2004] with a marine reservoir correction (ΔR) of 50 ± 31 ^{14}C years for northeastern Australia derived from Marine Reservoir Correction Database [*Reimer and Reimer*, 2000].

4. Results and Discussions

[11] The radiometric dates on bulk samples from a transect across the island, and from site WS9 (Table 1 and Figure 2), implied progradation of beach ridges to the southeast during the mid Holocene, consistent with the concentric ridges detected on aerial photographs. However, the bulk date from the southern shore of the island (P1) was >2000 years cal BP. On the basis that bulk ages represented the time of deposition of the sand, it was inferred that the island had switched from dynamically accreting 4000–3000 years ago, to a steady state with negligible addition of sediment over the past 2000 years [*Woodroffe*, 2002]. If the reef flat provides a current source of sediment for nourishing the island, then sediment from its surface might be expected to yield modern ages. However, a radiocarbon age on bulk sediment from site RT2 on the reef flat yielded an unexpectedly old age (2441–2770 cal BP).

[12] The AMS results show that different components yield substantially different ages. Coral dates were the least consistent in pattern, and lend further support to the contention that coral grains, or individual pieces of coral shingle, from reef islands on the rim of atolls in the Indian and Pacific Oceans can be anomalously old and poor indicators of time of deposition [*Woodroffe et al.*, 1999]. Coral grains from P10, P5 and P3 were older, whereas those from P8, P1 and RT2 were younger than the associated bulk samples (Figure 2). Sand samples appear to comprise relict coral material; in addition coral may break down in several stages requiring a longer period of transport and reworking than simpler, smaller grains derived from other material.

[13] Individual tests of the foraminifer *Calcarina spengleri* yielded the oldest ages from the island (4510–5900 cal BP),

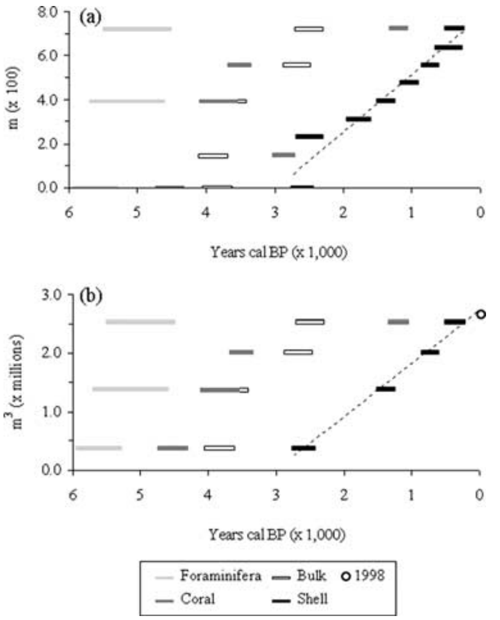

Figure 3. Calibrated ages on different components of island sediment (2σ): (a) rate of island progradation along the NW-SE transect and (b) rate of increase in island sediment volume, derived from DTM. The distance for estimating the rate of island progradation along the NW-SE transect is measured from P10. Only dates that are associated with four time intervals of volumetric calculation are presented in Figure 3b. The shell ages indicate gradual, sustained progradation.

and the oldest date for any individual grain was for a *Calcarina* from the surface sediment at RT2 on the reef flat (5592–6639 cal BP). The central part of the reef flat is no longer conducive to foraminiferal production; foraminifera presently live in habitats of lower elevation and more persistent tidal inundation around the reef margin, and from here tests are carried only a short distance onto the reef platform [*Hart and Kench*, 2007]. We infer that the foraminifera dated from the reef flat around Warraber Island are relict, having grown in conditions associated with the mid-Holocene fossil reef and undergone episodic entrainment and re-deposition over mid-late Holocene, in contrast to earlier studies on Pacific reefs where foraminifera living on the adjacent reef flat comprise a major component of island beaches and account for much of the volume of the reef island [*Woodroffe and Morrison*, 2001].

[14] In every case, ages determined for shell represent the youngest component for each sand sample, indicating that these would be better indicators of time of deposition than other older components. A shell from the contemporary reef flat surface (RT2) yielded a modern age, in contrast to all other components. Shells are easily entrained and carried to shore by the short-period waves that dominate the reef top [*Brander et al.*, 2004; *Hart and Kench*, 2007]. In addition, gastropod shells are relatively durable with a greater chance of being preserved for dating. Shell sand, often conspicuous as a swash-line ridge, is prominent on the beach and shell contributes a large proportion to both reef-flat and beach sediments (33–95%, see Figure 1c). Although there is a time interval between the death and deposition of shells, the sequence of shell ages across the island implies continual addition of sediment to the island. Mixing and reworking occur, but the relatively rapid rate of progradation (averaging around 0.3 m/yr, see below) implies that deposition and burial are likely relatively soon after death of the gastropod.

[15] Shell dates appear to be the most appropriate component to indicate timing of sand deposition and imply that the island began to form around 2473–2739 cal BP (P10) with successively younger AMS dates on shell samples from pits P7B, P6B, P5A, P4B, P3B, P2B and P1B, consistent with a pattern of sustained accretion of the island (Figure 2). This pattern of ongoing island progradation is also supported by dating results of shell grains from the modern beach (BT2: Modern and BT3: 42–286 cal BP) and the reef flat adjacent to the beach toe (Q1A1: Modern and Q39: Modern). By contrast, dates on coral grains from these locations are anomalously older (BT2: 1414–1732, BT3: 736–1012, Q1A1: 2064–2321 and Q39: 4180–4583 cal BP) and appear inconsistent with patterns of island formation. Dates on shell samples on the eastern end of the island (A2 to landward: 474–632 cal BP, B2: 0–236 cal BP and C2, nearest the shore: Modern) also indicate progressive accretion at the eastern end of the island.

[16] Selection of the most appropriate component from within sand samples is likely to substantially improve the estimate of depositional chronology, because the time of death of the component derived from radiocarbon dating is closer to time of deposition of the sediment. In the case of Warraber Island, gastropod shells, sourced from the largely exposed reef flat around the island (Zone 1 in Figure 1c), appear particularly appropriate. In other situations, the sea-level history and ecology of the surrounding reef means that other components may be more appropriate. For example, previous studies suggest that foraminifera are the most appropriate component for the determination of sediment depositional history for reef islands rimming mid-ocean atolls where prolific foraminiferal production occurs on the adjacent reef flat [*Woodroffe and Morrison*, 2001] as well as for parts of the Great Barrier Reef that have suitable habitat for foraminifera [*Yamano et al.*, 2000].

[17] This reassessment of earlier dating results leads to a significant revision of the geomorphology of island formation; instead of a relatively discrete episode of accretion followed by steady state, the island appears to be in dynamic equilibrium, commencing around 3000 years ago and growing incrementally as a result of continuing sediment supply. The island, presently 920 m wide along this transect, has accreted at an average linear rate of 0.30 m/yr (Figure 3a). Based on a photogrammetrically-derived digital terrain model (DTM) of the island [*Samosorn and Woodroffe*, 2003], a volumetric addition of sediment to the island of approximately 1,000 m^3/yr is estimated (Figure 3b). Paradoxically, the time at which the island was inferred to have ceased accreting according to the bulk dates (P1B bulk: 2321–2678 cal BP) corresponds to the time around which deposition commenced (P10B Shell: 2463–2744 cal BP). Our results indicate that some sand cays grow as a result of sustained input of sediment that is sourced from the surrounding reef flats in a manner which is similar to the protracted, though punctuated, accretion demonstrated by

radiocarbon dating of corals from coral rubble and shingle ridges in storm-prone areas [*Nott and Hayne*, 2001].

5. Conclusions

[18] Targeted dating of selected sediment components is a better indication of whether reef islands are continuing to accumulate than bulk dating of a range of grain types. Gastropod shells that lived on the reef flat immediately adjacent to the island appear to be the most appropriate component to date on Warraber Island to determine its depositional chronology. AMS radiocarbon dates on these shells indicate that the island has been continuing to accrete sand. The ecology of the adjacent reef appears to be a prime factor in determining the nature of the sediment, and hence which components to date to reliably estimate the rate of sediment addition. There are a number of factors that might result in a decrease in the productivity of prolific sediment producers on the adjacent reef and reef flat, including response to global climate change, anthropogenic impacts or intrinsic geomorphological thresholds of reef development. Sustainability of islands in the face of environmental stresses, exacerbated by climate change, will depend upon a continuing supply of sediment, with islands more susceptible to erosion if any factors diminish sediment production or transport.

[19] **Acknowledgments.** We are grateful for funding from the Australian Research Council to support field research and the Australian Institute for Nuclear Science and Engineering (AINSE grants 03/129 and 04/174) for AMS measurement. Fieldwork was supported by the Warraber Island Council; aerial photography and photogrammetry were undertaken by Schlencker Mapping. We thank the Warraber Island community for their hospitality.

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