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Corresponding Author	Family Name	**CT**
	Particle	
	Given Name	**Perry**
	Suffix	
	Division	Geography, College of Life and Environmental Sciences
	Organization	University of Exeter
	Address	Exeter, EX4 4RJ, UK
	Phone	
	Fax	
	Email	c.perry@exeter.ac.uk
	URL	
	ORCID	http://orcid.org/0000-0001-9398-2418
Author	Family Name	**PS**
	Particle	
	Given Name	**Kench**
	Suffix	
	Division	School of Environment
	Organization	The University of Auckland
	Address	Private Bag 92019, Auckland, New Zealand
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Author	Family Name	**SG**
	Particle	
	Given Name	**Smithers**
	Suffix	
	Division	School of Earth and Environmental Sciences
	Organization	James Cook University
	Address	Townsville, QLD, 4811, Australia
	Phone	
	Fax	
	Email	
	URL	

	ORCID	
Author	Family Name	**BR**
	Particle	
	Given Name	**Riegl**
	Suffix	
	Division	National Coral Reef Institute
	Organization	Nova Southeastern University
	Address	8000 N. Ocean Drive Dania, Fort Lauderdale, FL, 33004, USA
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Author	Family Name	**P**
	Particle	
	Given Name	**Gulliver**
	Suffix	
	Division	NERC Radiocarbon Laboratory
	Organization	Scottish Enterprise Technology Park
	Address	Rankin Avenue, East Kilbride, G75 0QF, Scotland, UK
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Author	Family Name	**JJ**
	Particle	
	Given Name	**Daniells**
	Suffix	
	Division	School of Environment
	Organization	The University of Auckland
	Address	Private Bag 92019, Auckland, New Zealand
	Phone	
	Fax	
	Email	
	URL	
	ORCID	

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Abstract

Low-lying coral reef islands are considered highly vulnerable to climate change, necessitating an improved understanding of when and why they form, and how the timing of formation varies within and among regions. Several testable models have been proposed that explain inter-regional variability as a function of sea-level history and, more recently, a reef platform size model has been proposed from the Maldives (central Indian Ocean) to explain intra-regional (intra-atoll) variability. Here we present chronostratigraphic data from Pipon Island, northern Great Barrier Reef (GBR), enabling us to test the applicability of existing regional island evolution models, and the platform size control hypothesis in a Pacific context. We show that reef platform infilling occurred rapidly (~4–5 mm yr^{-1}) under a “bucket-fill” type scenario. Unusually, this infilling was dominated by terrigenous sedimentation, with platform filling and subsequent reef flat formation complete by ~5000 calibrated years BP (cal BP). Reef flat exposure as sea levels slowly fell post-highstand facilitated a shift towards intertidal and subaerial-dominated sedimentation. Our data suggest, however, a lag of ~1500 yr before island initiation (at ~3200 cal BP), i.e. later than that reported from smaller and more evolutionarily mature reef platforms in the region. Our data thus support: (1) the hypothesis that platform size acts to influence the timing of platform filling and subsequent island development at intra-regional scales; and (2) the hypothesis that the low wooded islands of the northern GBR conform to a model of island formation above an elevated reef flat under falling sea levels.

Keywords (separated by '-')	Coral reefs - Reef islands - Reef platform - Great Barrier Reef - Terrigenous sedimentation
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REPORT

Terrigenous sediment-dominated reef platform infilling: an unexpected precursor to reef island formation and a test of the reef platform size-island age model in the Pacific

Perry CT[1] · Kench PS[2] · Smithers SG[3] · Riegl BR[4] · Gulliver P[5] · Daniells JJ[2]

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Abstract Low-lying coral reef islands are considered highly vulnerable to climate change, necessitating an improved understanding of when and why they form, and how the timing of formation varies within and among regions. Several testable models have been proposed that explain inter-regional variability as a function of sea-level history and, more recently, a reef platform size model has been proposed from the Maldives (central Indian Ocean) to explain intra-regional (intra-atoll) variability. Here we present chronostratigraphic data from Pipon Island, northern Great Barrier Reef (GBR), enabling us to test the applicability of existing regional island evolution models, and the platform size control hypothesis in a Pacific context. We show that reef platform infilling occurred rapidly (~4–5 mm yr^{-1}) under a "bucket-fill" type scenario. Unusually, this infilling was dominated by terrigenous sedimentation, with platform filling and subsequent reef flat formation complete by ~5000 calibrated years BP (cal BP). Reef flat exposure as sea levels slowly fell post-highstand facilitated a shift towards intertidal and subaerial-dominated sedimentation. Our data suggest, however, a lag of ~1500 yr before island initiation (at ~3200 cal BP), i.e. later than that reported from smaller and more evolutionarily mature reef platforms in the region. Our data thus support: (1) the hypothesis that platform size acts to influence the timing of platform filling and subsequent island development at intra-regional scales; and (2) the hypothesis that the low wooded islands of the northern GBR conform to a model of island formation above an elevated reef flat under falling sea levels.

Keywords Coral reefs · Reef islands · Reef platform · Great Barrier Reef · Terrigenous sedimentation

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✉ Perry CT
c.perry@exeter.ac.uk

[1] Geography, College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4RJ, UK

[2] School of Environment, The University of Auckland, Private Bag 92019, Auckland, New Zealand

[3] School of Earth and Environmental Sciences, James Cook University, Townsville, QLD 4811, Australia

[4] National Coral Reef Institute, Nova Southeastern University, 8000 N. Ocean Drive Dania, Fort Lauderdale, FL 33004, USA

[5] NERC Radiocarbon Laboratory, Scottish Enterprise Technology Park, Rankin Avenue, East Kilbride G75 0QF, Scotland, UK

Introduction

Low-lying coral reef islands, composed of reef-derived carbonate sands and coral shingle, have exceptionally high socio-economic and ecological value, since they are commonly used for human habitation (e.g. Maldives, Tuvalu and Kiribati, Torres Strait; Perry et al. 2011), and provide critical habitat for terrestrial and marine species (Fuentes et al. 2010). These landforms form atop coral reef platforms, frequently around atoll margins (Yamano et al. 2005), and above lagoon infill sequences (Kench et al. 2005), and their formation has thus been strongly influenced by sea-level fluctuations and the timing of reef development since the mid-Holocene (since ~7000 yr ago) (Perry et al. 2011). In this context, four models of island formation have been proposed: (1) a model that shows that some Pacific islands formed above elevated reef surfaces during the late stages of the mid-Holocene sea-

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level rise and subsequent highstand ~5–4000 calibrated years BP (cal BP) (Kench et al. 2014a; Yamano et al. 2014); (2) a model based on data from several Indian and Pacific Ocean sites showing islands forming since ~5000 cal BP atop either elevated conglomerate platforms (e.g. Woodroffe et al. 1999) or reef flats (Kench et al. 2012), as sea level fell post the mid-Holocene highstand; (3) a model showing some Pacific islands forming on sea-level-constrained reef flats over the past 2000 yr under relatively stable sea-level conditions (e.g. McKoy et al. 2010; Kench et al. 2014b); and (4) a model based on studies from the Maldives (central Indian Ocean), showing lagoonal reef platform islands forming above lagoon infill sequences between 4500 and 3000 cal BP, coincident with latter stages of Holocene sea-level rise (Kench et al. 2005; Perry et al. 2013).

These models provide a framework for understanding inter-regional timescale variability in reef island formation. More recently, however, data have been presented from the Maldives suggesting that reef platform size, as a key control on the timing of underlying reef flat formation or lagoon infilling, may act as an important second-order control that influences intra-regional (or intra-atoll) timescales of island formation (Perry et al. 2013). However, our ability to test these hypotheses is currently constrained by the paucity of chronostratigraphic datasets that establish, on a same-site basis, not only the timing of underlying reef and/or lagoon infilling, but also of (where present) reef flat formation, and then of island establishment. Here we present such a dataset from Pipon Island, northern Great Barrier Reef (GBR), and use this to specifically test: (1) the validity of recent island formation models proposed for the northern GBR (Kench et al. 2012); and (2) in a Pacific context, the importance of reef platform size as a control on the timing of island initiation (Perry et al. 2013). Pipon Island is one of the GBR island types classified as a "low wooded island", of which 44 occur along the inner-shelf north of Cairns (Hopley et al. 2007). Despite being the best-studied to date of the GBR's island types, chronostratigraphic datasets that resolve the history and timing of reef platform development and how this relates to the timing of island emplacement remain limited. What data exist suggests these islands probably formed at various times post the mid-Holocene highstand, i.e. in the period from ~6000 to 3000 cal BP (McLean et al. 1978), and, at least at one site, Bewick Island, that this occurred above an established reef flat dating to ~6000 cal BP (Kench et al. 2012) (model 2 above). This study thus contributes to a wider understanding of how and when these important reef-associated landforms developed, which are considered at high risk from future climate, and specifically sea-level, change (Woodroffe 2008).

Materials and methods

Study site

Pipon Island (14°07′S; 144°30′E) is a reef platform located about 4 km offshore from Cape Melville and about 30 km east of Princess Charlotte Bay, northern GBR (Fig. 1a). The platform is roughly oval shaped (2.6 × 1.9 km) with a surface area of 3.3 km^2 (Fig. 1b). As a low wooded island the platform surface, which has an elevation of between +0.5 and +1.3 m relative to present lowest astronomical tide (LAT), comprises several characteristic components: a set of shingle ridges that parallel and occur on the exposed eastern platform margin; an area of mangrove leeward of the shingle ridges (approximately 0.75 km^2 or 19.2% of platform area); and a small (0.03 km^2) vegetated sand cay on the leeward western platform margin (Fig. 1b, c). The central expanse of the platform is sediment dominated and comprises of bare sand and rubble flats (Fig. 1d). The platform surface is devoid of living coral, although the upper surfaces of fossil *Porites* microatolls are commonly exposed, and extensive stands of living *Acropora* sp. are visible close to LAT around the seaward platform flanks (Fig. 1e). In the context of the evolutionary development of low wooded islands, whereby the entire platform surface is colonised by mangrove complexes, Pipon is at a young-to-intermediate stage of maturity (Stoddart et al. 1978).

Core recovery and analysis, and microatoll sampling

To determine reef platform chronostratigraphy, we recovered seven cores from along a transect running broadly north-west to south-east (Fig. 1b). The cores (PC1-7; Fig. 1b) were recovered using percussion coring following the method described by Smithers and Larcombe (2003). Aluminium core pipes (6 m long, 9.5 cm internal diameter) were manually driven into the reef, with rates and depths of penetration recorded to allow reconstructions of subsurface stratigraphy and to account for core compaction. Several cores stalled at 0.3–0.5 m below the contemporary surface, with the cores hitting impenetrable in situ coral colonies (where these could be examined they appeared to be *Porites* and are assumed to have formed a field of microatolls given their widespread occurrence). Cores PC1 and PC3 encountered these colonies but successfully penetrated this horizon, capturing the in situ colonies in the cores. The cores were split with a circular saw and then logged to record the major facies units on the basis of the following biosedimentary attributes: (1) the ratio of coral clasts to matrix, and framework fabrics (following Embry and Klovan 1971); (2) visual coral species identification (to genus and based on Veron and Stafford-Smith 2002); (3) a

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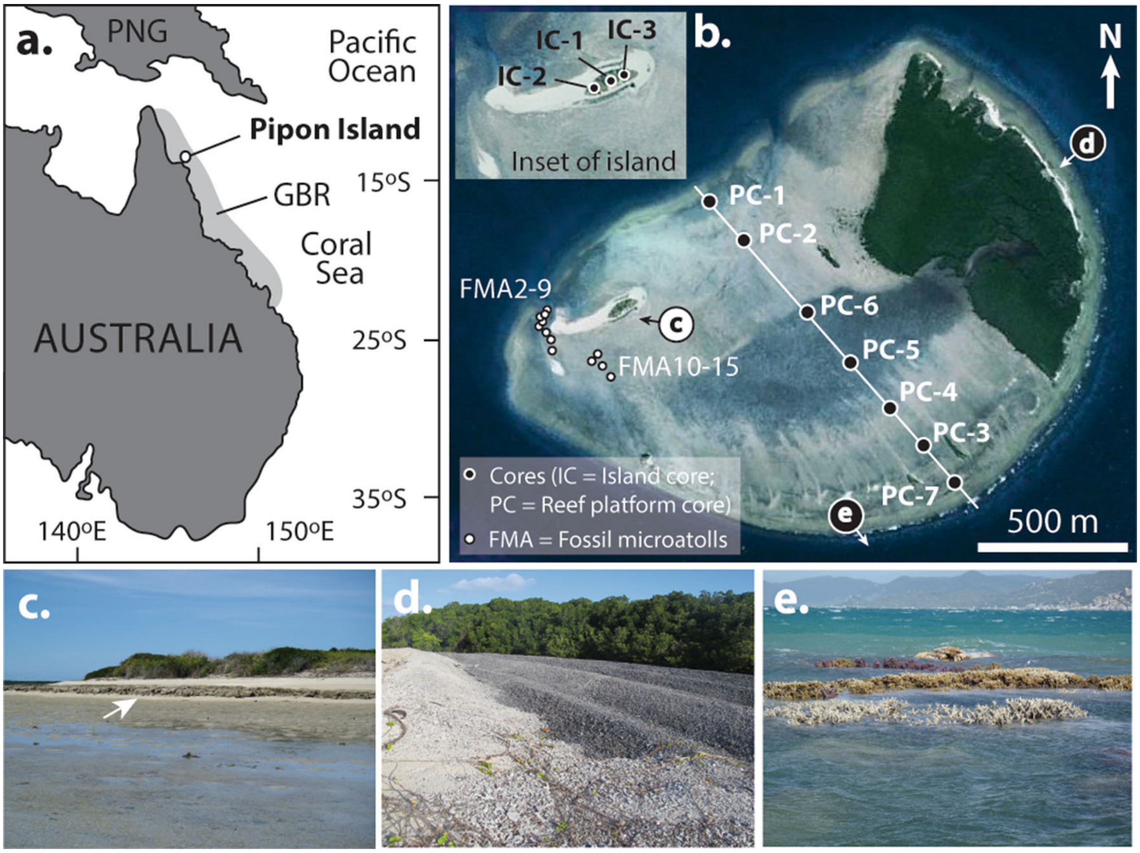

Fig. 1 **a** Regional context and location of Pipon Island. **b** Aerial image showing the location of core and fossil microatolls and (*inset*) the location of cores from the vegetated sand cay. **c** View of the sand cay on Pipon Island. Note the well-developed beachrock (*arrowed*) cropping out around the island margin; **d** View across one of the sequences of shingle ridges that flank Pipon Island along its eastern margins; **e** View eastwards to mainland showing thriving *Acropora* colonies along seawards of the contemporary platform rim which are exposed close to lowest astronomical tide (LAT). Locations of images **c**–**e** are shown in the *arrowed circles*

visual assessment of sediment textural characteristics (using the Udden–Wentworth nomenclature); and (4) a visual assessment of sediment composition. To constrain the timing and rate of platform infilling, 19 well-preserved coral samples from the cores were selected for radiocarbon dating. To further constrain the timing of reef flat development, small plugs (30 mm × 20 mm) were recovered using a hand-held brace and bit from the upper surfaces of 12 fossil microatolls exposed along the western side of the platform (Fig. 2; Table 1). To determine the age and internal composition of the vegetated sand cay, we recovered subsurface samples initially by digging pits to a depth of ~75 cm and then by hand augering and percussion coring (IC-3). Island sedimentary facies were determined by visually assessing composition and textural properties in samples recovered in discrete 10 cm units either from the exposed sides of the hand-dug pits or as material was recovered from auger/percussion cores. To constrain the elevations of dated core samples, microatoll surfaces, and the topography of the island to a common datum (local LAT; see Table 1), we used a combination of real-time kinematic and standard auto-level survey techniques.

Samples for radiocarbon dating were sent to one of the following laboratories: NRCF-EK, NERC Radiocarbon Dating Facility-East Kilbride; AINSE, ANSTO-ANTARES AMS Facility; or Beta Analytic Inc., Miami, (see Table 1). Prior to dating, selected samples were sectioned, surficial calcareous encrustation removed, subjected to ultrasonic agitation in distilled water to remove detrital particles, oven-dried (40 °C) and then sealed in plastic bags. Results from all labs were normalised to $\delta^{13}C_{VPDB}$ ‰ = −25 and are presented in Table 1 as conventional years Before Present (yBP) and calibrated years Before Present (cal BP) where present is defined as 1950. Conventional dates were calibrated to calendar years using the Calib 7.1 calibration program, (http://calib.qub.ac.uk/calib/; Stuiver and Reimer 1993) and the Marine13 calibration curve (Reimer et al. 2013). The conventionally employed marine reservoir correction in Australian waters is 450 ± 35 yr (http://calib.qub.ac.uk/marine; Gillespie

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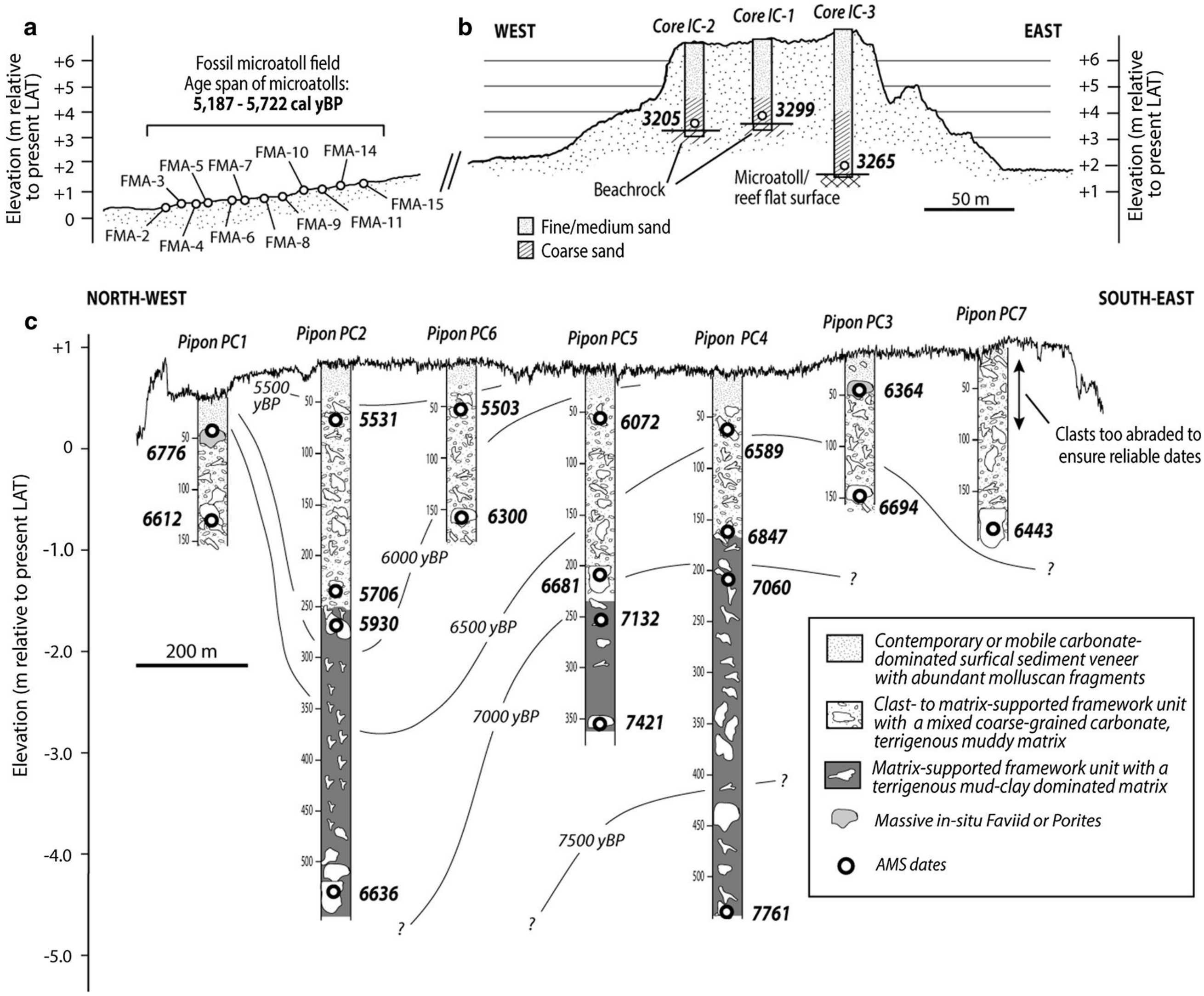

Fig. 2 **a** Schematic cross sections showing the elevations relative to lowest astronomical tide (LAT) and radiocarbon ages (shown as median probability age in calibrated yr BP) from **a** the field of fossil microatolls, **b** the vegetated sand cay, and **c** the reef platform. See Fig. 1 for core locations

1977). However, various studies have indicated significant deviations in regional marine reservoir signatures. Therefore, a weighted mean ΔR value of 78 ± 68, currently the best estimate of variance in the local open-water marine reservoir effect for the northern Queensland coast (Gillespie and Polach 1979), was applied. Resultant calibrated AMS radiocarbon dates were used to determine the depth–age relationship of the cross-platform cores and the minimum age of island initiation.

Results

Platform and reef island cores, along with dated fossil microatolls, capture the history of mid-to-late Holocene platform infilling, reef flat formation and subsequent sand cay evolution at Pipon Island. Reef cores penetrated up to 5.5 m below the contemporary platform surface, which is at an elevation of $\sim$+0.7 m LAT (Fig. 2c). Radiocarbon dating of coral clasts indicates that platform infilling was well advanced by $\sim$7500 cal BP and that eastern/south-eastern areas had infilled to a level some $\sim$+ 0.5 m LAT by $\sim$6000 cal BP (Fig. 2c). Central and north-western areas appear to have infilled a little later, but complete platform infilling (to an elevation of $\sim$+0.7 to 0.8 m LAT) was essentially complete by $\sim$5500 cal BP (Fig. 2c). Age-depth analyses from the longer cores (PC2 and PC4; Fig. 2) indicate that infilling rates during these later stages of platform evolution were relatively high, in the range 4.3–4.5 mm yr^{-1}.

The timing of sea-level constraint, and of complete platform infilling, can be independently corroborated by

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Table 1 Radiocarbon dates from cores from Pipon Island

Core/sample code	Material	Radiocarbon laboratory ref.	$\delta^{13}C_{VPDB}$ (‰)	Elevation (m relative to LAT)	^{14}C age (yr BP)	^{14}C age error (yr BP)	Calibrated age range (1σ)		Probability distribution (68%)	Median probability age (cal BP)
							Min	Max		
PIP-IC1	Coral sand	Beta-417690	+2.8	+3.90	3510	30	3205	3389	1	3299
PIP-IC2	Coral sand	Beta-417688	+2.8	+3.50	3430	30	3118	3320	1	3205
PIP-IC3	Coral sand	Beta-417687	+0.8	+1.70	3480	30	3174	3358	1	3265
PIPON-FMA2	*Porites*	OZR872	−0.4	+0.54	5295	25	5486	5645	1	5578
PIPON-FMA3	*Porites*	OZR873	−1.3	+0.64	5310	30	5511	5678	1	5595
PIPON-FMA4	*Porites*	OZR874	−0.8	+0.58	5320	30	5533	5697	1	5607
PIPON-FMA5	*Porites*	OZR875	−0.4	+0.57	4975	30	5076	5103	0.094	5202
PIPON-FMA6	*Porites*	OZR876	−0.7	+0.77	5045	30	5237	5436	1	5313
PIPON-FMA7	*Porites*	OZR877	−0.5	+0.72	4965	30	5074	5293	1	5187
PIPON-FMA8	*Porites*	OZR878	−1.8	+0.82	5240	30	5444	5594	1	5518
PIPON-FMA9	*Porites*	OZR879	−1.6	+0.95	5430	30	5631	5810	0.987	5722
PIPON-FMA10	*Porites*	OZR880	−1.2	+1.17	5055	30	5252	5439	1	5327
PIPON-FMA11	*Porites*	OZR881	−0.9	+1.19	5070	30	5269	5443	1	5347
PIPON-FMA14	*Porites*	OZR882	−1.4	+1.23	5330	30	5548	5708	1	5617
PIPON-FMA15	*Porites*	OZR883	0.9	+1.26	5185	30	5393	5568	1	5465
PIPON-PC1/25	*Porites*	SUERC 45027	−2.6	+0.20	6391	37	6677	6867	1	6776
PIPON-PC1/65	*Faviid*	SUERC 45028	−0.7	−0.75	6254	38	6515	6707	1	6612
PIPON-PC2/70	*Acropora*	SUERC 45029	1.9	+0.30	5253	37	5449	5608	1	5531
PIPON-PC2/165	*Acropora*	SUERC 45030	−0.5	−1.40	5415	35	5599	5781	1	5706
PIPON-PC2/200	*Galaxea*	SUERC 45031	−1.2	−1.75	5618	37	5837	6041	1	5930
PIPON-PC2/390	*Porites*	SUERC 45032	−2.6	−4.40	6274	36	6539	6730	1	6636
PIPON-PC3/18	*Faviid*	SUERC 54048	−1.9	+0.60	6025	37	6280	6435	1	6364
PIPON-PC3/75	*Porites*	SUERC 45049	1.1	−0.45	6322	36	6598	6791	1	6694
PIPON-PC4/42	*Acropora*	SUERC 45042	−1.5	+0.20	6234	37	6487	6675	1	6589
PIPON-PC4/105	*Montipora*	SUERC 45045	−1.3	−0.80	6452	35	6745	6938	1	6847
PIPON-PC4/168	*Acropora*	SUERC 45046	0.4	−1.30	6626	36	6966	7155	1	7060
PIPON-PC4/355	*Acropora*	SUERC 45047	0.2	−4.60	7375	38	7672	7837	1	7761
PIPON-PC5/45	*Acropora*	SUERC 45037	1.4	+0.30	5746	37	5983	6169	1	6072
PIPON-PC5/105	*Faviid*	SUERC 45038	1.2	−1.25	6311	37	6585	6780	1	6681
PIPON-PC5/140	*Stylophora*	SUERC 45040	1.3	−1.65	6691	38	7043	7233	1	7132
PIPON-PC5/170	*Acropora*	SUERC 45041	0.5	−2.75	6990	38	7346	7496	1	7421
PIPON-PC6/40	*Acropora*	SUERC 45035	1.8	+0.40	5224	35	5431	5589	1	5503

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Table 1 continued

Core/sample code	Material	Radiocarbon laboratory ref.	$\delta^{13}C_{VPDB}$ (‰)	Elevation (m relative to LAT)	^{14}C age (yr BP)	^{14}C age error (yr BP)	Calibrated age range (1σ)		Probability distribution (68%)	Median probability age (cal BP)
							Min	Max		
PIPON-PC6/98	*Porites*	SUERC 45036	0.8	−0.65	5958	37	6224	6382	1	6300
PIPON-PC7/53	*Porites*	SUERC 45050	0.0	−0.75	6101	37	6345	6530	1	6443

See Fig. 1 for core/sample codes. Radiocarbon laboratories codes are: SUERC: NRCF-EK, NERC Radiocarbon Dating Facility, East Kilbride; OZ: AINSE, ANSTO-ANTARES AMS Facility; Beta: Beta Analytic Inc., Miami

the ages obtained from dated fossil microatolls exposed along western sides of the platform (Fig. 1). The surfaces of these microatolls span an elevational range from +0.5 to +1.2 m LAT (Table 1) and have ages that cluster between 5100 and 5700 cal BP (Fig. 2a). By ~5000 cal BP, complete platform infilling and reef flat formation thus appears to have been complete. Cores also indicate that platform infilling was strongly influenced by the influx of terrigenous sediments, with all the cores that penetrated deeper than ~1.5 m below present LAT recovering a consistent matrix-supported facies dominated by fragments of branched *Acropora* spp. and *Montipora* sp., as well as *Turbinaria* sp., *Porites* sp. and faviids, within a fine-grained terrigenous mud matrix. This facies, and the coral assemblages associated with it, is typical of those identified in many nearshore turbid-zone reefs in the central GBR (e.g. Palmer et al. 2010; Perry and Smithers 2011; Roche et al. 2011). In contrast to these more southerly inner-shelf reefs, the morphology of Pipon Island and its infill history is more consistent with the concept of a "bucket-fill" (sensu Schlager 1981). However, instead of being a product of entirely locally sourced (autochthonous) carbonate sediments derived from the adjacent reef rim, as is the norm for such bucket-fill models (Purdy and Gischler 2005; O'Leary and Perry 2010), a high proportion of the infilling is allochthonous, fine-grained terrestrially derived sediment.

Radiocarbon dating of samples from close to the base of the sand cay cores suggests a minimum island initiation age of ~3200 cal BP (Fig. 2b; Table 1). The deepest core (IC-3) terminated on an indurated surface at a depth of ~1.6 m LAT, i.e. at an elevation consistent with the heights of the adjacent fossil microatolls (Fig. 1c), an observation that suggests the sand cay at Pipon Island fits the depositional model established for Bewick Island to the south (Kench et al. 2012). The other two cores (IC-1 and IC-2) both terminated in a hard beachrock horizon (Fig. 2b) at elevations of ~3.2–3.5 m LAT, which is consistent with the height of the beachrock horizons exposed around the island (Fig. 1c).

Discussion

Analysis of cores from Pipon Island indicates a strong terrigenoclastic sediment influence on reef-lagoon infilling history during reef platform development. Indeed, the age-independent distribution of core facies with depth suggests that progressive platform infilling (i.e. shallowing towards sea level) has probably acted as a key influence on the composition of the accumulating sediments inside the platform "bucket", with shallowing to a depth of within ~1.5–2 m of the present platform surface leading to reduced accumulation of fine-grained terrigenous muds, presumably due to increased suspension and flushing as wave-driven sediment resuspension increased (Wolanski et al. 2005). Such vertical facies transitions have been reported from a number of nearshore GBR turbid-zone reefs (see Palmer et al. 2010), such that near-surface facies are increasingly dominated by coarse-grained, bioclastic sediments.

At Pipon Island, the contemporary platform surface is devoid of living coral and is instead dominated by a medium- to coarse-grained carbonate-rich sand, with abundant large (up to ~5 cm), and often highly abraded molluscan fragments, and heavily bioeroded and coralline algal-encrusted coral fragments. However, the shallow subtidal margins of the outer platform rim still support flourishing communities of (especially) branched *Acropora* (Fig. 1e), which can episodically supply large volumes of branched coral rubble to create complex sequences of coral gravel ridges (Fig. 1d). However, both lateral and vertical accommodation space for active reef framework accumulation is limited, and this condition has probably persisted over the last ~5–6000 yr under conditions of falling sea levels following the mid-Holocene highstand (Perry and Smithers 2011). The present surface of the reef platform thus expresses a senescent, sea-level-constrained reef flat, with no further accommodation space for vertical reef accretion on the platform top. Instead, landform and habitat development has shifted to become dominated by intertidal, subaerial and terrestrial processes, as evidenced by

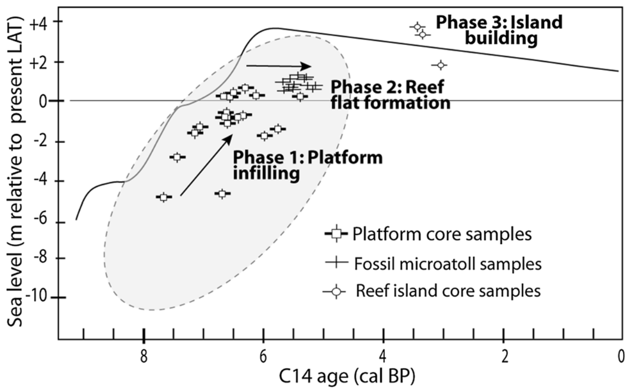

Fig. 3 Age-depth plot showing the different stages of platform infilling, reef flat formation and reef island building as interpreted from core and microatoll samples at Pipon Island. Samples are plotted as the median probability ages in calibrated years BP (cal BP). *Horizontal error bars* are the 68% probability range of the calibrated dates, and the *vertical error bars* are 0.25 m for in situ corals and 0.5 m for in-site rubble samples. Dates are shown in relation to the best-fit mid-Holocene sea-level curve for eastern Australia (after Larcombe et al. 1995) superimposed on the sea-level regression plot of Chappell (1983), and in relation to the mid-Holocene window of nearshore turbid-zone reef development delineated by Perry and Smithers (2011)

the expansive mangrove stands that have developed along the eastern platform and, on the western side, by sand cay formation (Fig. 1b).

Stratigraphic data thus point to defined stages of reef platform development and of subsequent sand cay formation at Pipon Island. As outlined above, platform infilling, under "bucket-fill" type conditions, was strongly influenced by terrigenous sediment accumulation, which probably increased accretion rates. Ages returned from core-top coral samples and from fossil microatolls suggest complete platform infilling had occurred by ~5500 cal BP, with the later stages of sediment infill defined by reduced terrigenous sediment accumulation. This timing of platform infilling coincides with the late stages of the Holocene transgression (Fig. 3) and is also contiguous with a mid-Holocene turbid-zone reef growth "window" previously delineated for the inner-shelf areas of the GBR (Perry and Smithers 2011). Reef flat formation occurred from ~5500 to ~5000 cal BP under conditions of stable or slightly falling sea level after the mid-Holocene highstand (Fig. 3). This provided a substrate, as sea levels continue to fall, for a shift towards intertidal and subaerial-dominated sedimentation. No dates are available from the base of the

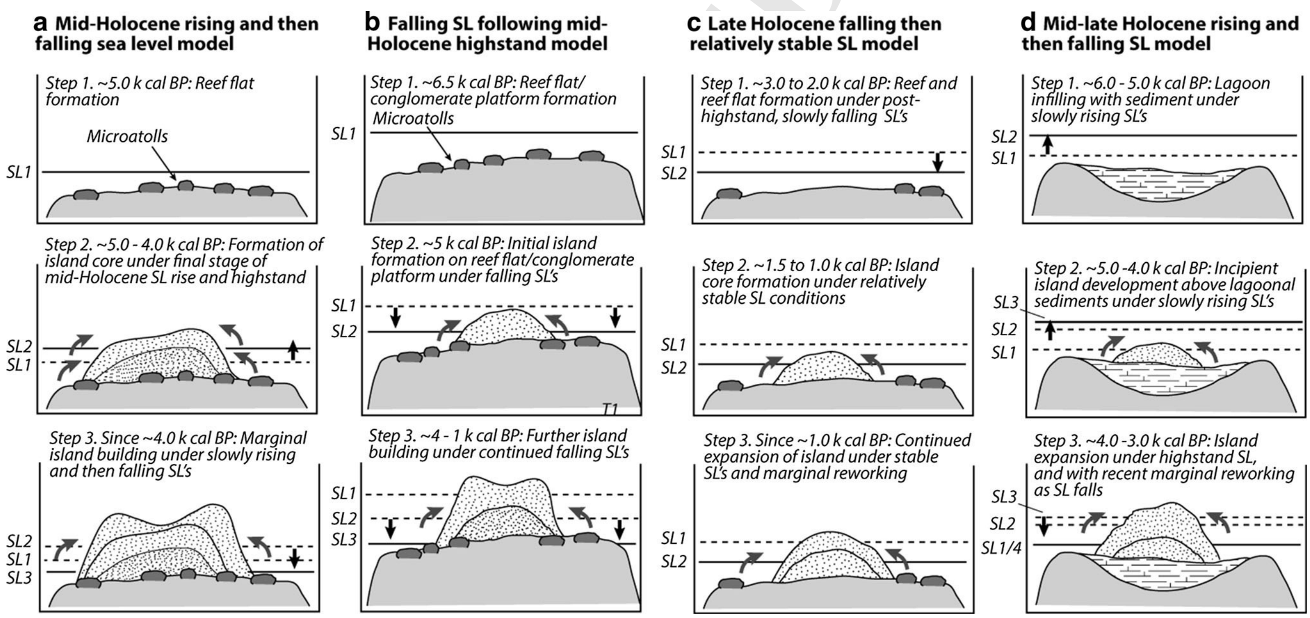

Fig. 4 Schematic diagram showing different models proposed for reef island development. **a** Model for sites where islands have formed above elevated reef flat surfaces during the late stages of the mid-Holocene sea-level rise and subsequent highstand ~5–4000 calibrated years BP (cal BP), based on data from specific Pacific island settings (e.g. Kench et al. 2014a; Yamano et al. 2014). **b** Model for sites where islands have formed since ~5000 cal BP atop elevated conglomerate platforms or reef flats as sea level fell after the mid-Holocene highstand, based on data from Indian Ocean and Pacific sites (e.g. Woodroffe et al. 1999; Kench et al. 2012). This model is consistent with the data from Pipon Island (this study). **c** Model for sites where islands have formed on sea-level-constrained reef flats over the last ~2000 yr, based on data from some Pacific islands settings (e.g. McKoy et al. 2010; Kench et al. 2014b). **d** Model for sites where islands have formed above lagoon sediment infill sequences between ~4500 and 3000 cal BP, coincident with late stages of Holocene sea-level rise. Based on data from the Maldives (e.g. Kench et al. 2005; Perry et al. 2013). *Grey arrows* = sediment input from reefs to islands, *black arrows* = direction of sea-level (SL) change

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mangrove developed on the eastern side of the platform, but dated bulk sediment samples from the base of the island on the western side suggest a lag of ~1500 yr before island initiation, or at least stabilisation. Island establishment and morphological change and, by inference given the elevation, mangrove colonisation and expansion are likely to have occurred over the subsequent ~3000 yr, probably following shingle ridge emplacement. It may also be reasonable to hypothesise that mangrove development post-dated that of island establishment given the asymmetry of the platform infilling suggested in the core records.

Chronostratigraphic data from Pipon Island thus not only provide important insights into the relationship between reef platform and reef island age in this region, but also to our understanding of some of the key controls on the timing of platform infilling and of island initiation. Indeed, our data clearly corroborate the model of island development proposed for Bewick Island to the south (Kench et al. 2012), with island formation occurring above an established reef flat (Fig. 4b), a generic model that differs from that proposed for other reef island regions under different sea-level stages (Fig. 4). However, a comparison of microatoll dates from the two sites suggests slightly earlier reef flat formation at Bewick Island, which was in the window ~6000–6500 cal BP (Kench et al. 2012), compared to around 5000–6000 cal BP at Pipon. Our data also suggest a more significant time lag and a later initiation age of the vegetated sand cay on Pipon, where the island is unlikely to have started to accumulate much before ~3200 cal BP (~1500 yr later than island initiation at Bewick). However, Bewick Island is a much smaller platform (~1.5 km^2) than Pipon (3.9 km^2), and thus the later timing of both reef flat formation and of island formation is consistent with recent ideas proposed from the Maldives whereby smaller (but proximal) platforms infill faster, experience earlier island formation, and presently exist in more mature evolutionary stages (sensu Perry et al. 2013). In this context, it is pertinent to note that on the smaller Bewick Island platform, mangroves cover nearly 80% of the platform top. However, an additional potential factor that may interact with platform size to influence infill timescales is the depth to, and structure of, any antecedent topography (e.g. Purdy and Winterer 2006). This has been shown to be a contributing factor to between-platform infill histories elsewhere on the GBR (e.g. Hopley et al. 2007). While any such differences cannot be constrained with the existing records from these sites, the recovery of cores constraining the full Holocene infill histories of these platforms and/or shallow seismic surveys would provide a useful source of data for further hypothesis testing around these questions.

This study thus provides not only further evidence of the significant and long-term (millennial timescale) influence of terrigenous sediments on the evolution of inner-shelf reefs along the GBR, but also critically: (1) confirms that the low wooded island development model of Kench et al. (2012) has regional consistency; and (2) establishes the basis of a conceptual framework about the links between reef size, infill timing and reef island development (analogous to that identified in the Maldives; Perry et al. 2013) that now needs wider testing at sites both on the GBR, and across the wider Pacific, and that can also ideally account for any intra-regional antecedent topographic variability.

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References

Chappell J (1983) Evidence for smoothly falling sea level relative to north Queensland, Australia, during the past 6000 yr. Nature 302:406–408

Embry AF, Klovan JE (1971) A late devonian reef tract on Northeastern banks island, Northwest territories. Bulletin of Canadian Petroleum Geology 33:730–781

Fuentes MMPB, Dawson J, Smithers S, Limpus CJ, Hamann M (2010) Sedimentological characteristics of key sea turtle rookeries: potential implications under projected climate change. J Mar Freshw Res 61:464–473

Gillespie R (1977) Radiocarbon dating of marine mollusc shells. Australian Quaternary Newsletter 9:13–15

Gillespie R, Polach HA (1979) The suitability of marine shells for radiocarbon dating of Australian prehistory. In: Berger R, Suess HE (eds) Radiocarbon dating. Proceedings of the 9th international ^{14}C conference, Las Angeles and La Jolla. University of California Press, Berkeley, pp 404–421

Hopley D, Smithers SG, Parnell KE (2007) The geomorphology of the Great Barrier Reef: development, diversity and change. Cambridge University Press, Cambridge

Kench PS, McLean RF, Nichol SL (2005) New model of reef-island evolution: Maldives, Indian ocean. Geology 33:145–148

Kench PS, Smithers SG, McLean RF (2012) Rapid reef island formation and stability over an emerging reef flat: Bewick Cay, Northern Great Barrier Reef, Australia. Geology 40:347–350

Kench PS, Owen SD, Ford MR (2014a) Evidence for coral island formation during rising sea level in the central Pacific Ocean. Geophys Res Lett 41:820–827

Kench PS, Chana J, Owen SD, McLean RF (2014b) The geomorphology, development and temporal dynamics of Tepuka Island, Funafuti atoll, Tuvalu. Geomorphology 222:46–58

Larcombe P, Carter RM, Dye J, Gagan MK, Johnson DP (1995) New evidence for episodic post-glacial sea-level rise, central Great Barrier Reef, Australia. Mar Geol 127:1–44

McKoy H, Kennedy DM, Kench PS (2010) Sand cay evolution on reef platforms, Mamanuca Islands, Fiji. Mar Geol 269:61–73

McLean RF, Stoddart DR, Hopley D, Polach H (1978) Sea level change in the Holocene on the northern Great Barrier Reef. Philos Trans R Soc Lond A 291:167–186

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O'Leary M, Perry CT (2010) Holocene reef accretion on the Rodrigues carbonate platform: an alternative to the classic 'bucket-fill' model. Geology 38:855–858

Palmer SE, Perry CT, Smithers SG, Gulliver P (2010) Internal structure and accretionary history of a Holocene nearshore, turbid-zone coral reef: Paluma Shoals, central Great Barrier Reef, Australia. Mar Geol 276:14–29

Perry CT, Smithers SG (2011) Cycles of coral reef 'turn-on', rapid growth and 'turn-off' over the past 8500 yr: a context for understanding modern ecological states and trajectories. Glob Chang Biol 17:76–86

Perry CT, Kench PS, O'Leary M, Riegl BR, Smithers SG, Yamano H (2011) Implications of reef ecosystem change for the stability and maintenance of coral reef islands? Glob Chang Biol 17:3679–3696

Perry CT, Kench PS, Smithers SG, Yamano H, O'Leary M, Guilliver P (2013) Timescales and modes of reef lagoon infilling in the Maldives and controls on the onset of reef island formation. Geology 41:1111–1114

Purdy EG, Gischler E (2005) The transient nature of the empty bucket model of reef sedimentation. Sed Geol 175:35–47

Purdy EG, Winterer EL (2006) Contradicting barrier reef relationships for Darwin's evolution of reef types. Int J Earth Sci 95:143–167

Reimer PJ, Bard E, Bayliss A, Beck JB, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 yr cal BP. Radiocarbon 55:1869–1887

Roche R, Perry CT, Johnson KG, Saltana K, Smithers SG, Thompson AA (2011) Mid-Holocene coral community data as a baseline for understanding contemporary reef ecological states. Palaeogeog Palaeoclim Palaeoecol 299:159–167

Schlager W (1981) The paradox of drowned reefs and carbonate platforms. Geol Soc Am Bull 92:197–211

Smithers SG, Larcombe P (2003) Late Holocene initiation and growth of a nearshore turbid-zone coral reef: Paluma Shoals, central Great Barrier Reef, Australia. Coral Reefs 22:499–505

Stoddart DR, McLean RF, Hopley D (1978) Geomorphology of reef islands, northern Great Barrier Reef. Philos Trans R Soc Lond B Biol Sci 284:39–61

Stuiver M, Reimer PJ (1993) Extended 14C data base and revised CALIB 3.0 14C calibration program. Radiocarbon 35:215–230

Veron JEN, Stafford-Smith M (2002) Coral ID—key to the zooxanthellate scleractinian corals of the world. CD-Rom. Australian Institute of Marine Sciences, Townsville

Wolanski E, Fabricius K, Spagnol S, Brinkman R (2005) Wet season fine sediment dynamics on the inner shelf of the Great Barrier Reef. Estuar Coast Shelf Sci 77:755–762

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

Woodroffe CD, McLean RF, Smithers SG, Lawson EM (1999) Atoll reef-island formation and response to sea level change: West Island, Cocos (Keeling) Islands. Mar Geol 160:85–104

Yamano H, Kayanne H, Chikamori M (2005) An overview of the nature and dynamics of reef islands. Global Environmental Research 9:9–20

Yamano H, Cabioch G, Chevillon C, Join J-L (2014) Late Holocene sea-level change and reef-island evolution in New Caledonia. Geomorphology 222:39–45 **(Amst)**

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