Rapid vertical accretion on a 'young' shore-detached turbid zone reef: Offshore Paluma Shoals, central Great Barrier Reef, Australia.

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Abstract

We report on the age structure and net accretion rates determined for an open water turbid-zone reef, known as Offshore Paluma Shoals, located on the inner central Great Barrier Reef. Twenty-eight radiocarbon dates from 5 cores through the reef structure indicate this reef began growing ~1,700 years ago, and that net vertical accretion through the main phase of reef development was rapid (averaging 7.8 mm yr^{-1}), this despite the reef growing in highly turbid waters. The most rapid growth phases coincided with the accumulation of mud-rich terrigenoclastic sediments within the reef fabric. The study emphasises the capacity of turbid-zone reefs to vertically accrete at rates matching or exceeding many clear water reefs despite seemingly detrimental water quality conditions.

Keywords

Great Barrier Reef, inner-shelf, turbid zone reefs, reef accretion

Introduction

Australia's Great Barrier Reef (GBR) includes a varied range of reef types that differ geomorphologically and ecologically due to the influence of both geological and environmental factors such as: geographical variations in relative postglacial sea-level history, and the variable depth, size and shape of substrates on which modern reefs have grown (Hopley et al. 2007). These factors have determined when and where postglacial seas inundated the continental shelf, resulting in local variations in the extent of reef-building. Strong latitudinal and cross-shelf gradients for important environmental controls, such as depth and water quality, also exist and are especially evident cross-shelf in terms of sedimentation and turbidity regimes. Inner-shelf waters typically have high suspended sediment loads and high (but fluctuating) turbidity regimes (Browne et al. 2012). These result from: (i) resuspension, by wind-generated waves, of sediments reworked shoreward during the postglacial transgression to form an inshore sediment prism ('ISP'; Woolfe and Larcombe 1999), and (ii) sediments exported from terrestrial catchments (Neil et al. 2002). Distance and depth below wave base largely isolate mid and outer shelf reefs from these influences (Lough et al. 2002), and thus reef-building taxa on inshore and offshore reefs experience very different growth conditions. Longstanding paradigms that coral and reef growth are impaired by high turbidity regimes would thus predict that reef growth is typically more restricted on the inner GBR compared to mid- and outer shelf sites.

Contrary to these predictions, however, a variety of coral reef types - many with impressive accretion rates - have been documented from shallow (< ~6 m depth) high turbidity inner-shelf settings. These include land-attached and detached shoal reefs (Smithers and Larcombe 2003; Perry et al. 2009; Browne et al. 2010), mainland-attached fringing reefs (Partain and Hopley 1989; Roche et al. 2011; Lewis et al. 2012), and inshore reef platforms (Frank 2008). Detailed analysis of dated cores from turbidity-affected reefs of the GBR inner-shelf reveals two discrete age cohorts, with one flourishing during the late stages of the Holocene transgression but senescing once the mid-Holocene highstand had been reached, and a younger cohort initiated during the past ~2,000 years (Perry and Smithers, 2011). Here we report chronostratigraphic data from a relatively poorly studied inner-shelf reef type - a coalescing open-water shoal reef - known as Offshore Paluma Shoals (OPS) (19°6·18’ S, 146°33·20’ E). This shoal complex is located in an exposed, open water setting, ~3 km offshore from the mainland coast at Halifax Bay, central GBR (Fig. 1). The limited extent and low elevation of the reef flat suggest OPS has only recently caught up to sea level. Here we describe the geomorphic structure and chronostratigraphy of OPS, calculate rates of accretion, and consider how its growth history relates to regionally identified periods of inner-shelf reef establishment.

Materials and Methods

Three coalescing reef structures occur at OPS, rising from the shallow (~ -4 m below Lowest Astronomical Tide (LAT)), low gradient (<1:1000) seafloor to be near sea level on the lowest spring tides (Figs. 1c, 2a). Within Halifax Bay the ISP is shore-detached, with the inner limit located < ~1 km seaward of OPS, corresponding approximately with the 5 m isobath. High suspended sediment loads and turbidity regimes in this area (Browne et al. 2013) result from wave-driven resuspension of sediment deposited on the inner-shelf (mostly a legacy of the post-glacial transgression), augmented by sediments recently transported from coastal catchments. The Burdekin River ~100 km south of OPS is the main source, with minor contributions from the closer, but smaller, Ross, Bohle and Black Rivers (Fig. 1a) (Neil et al. 2002). Long-term net sediment accumulation rates decrease away from the river mouths but are estimated to be ~0.1 mm yr^{-1} within central Halifax Bay (Woolfe and Larcombe 1999). At nearby Paluma Shoals, high turbidity events occur throughout the year (>10 NTU for 46 % of the time) and are especially elevated following >12 hrs of strong winds (> 20km hr^{-1}) and wave activity (*Hs* >0.5m) (see Browne et al. 2013).

To investigate the geomorphic structure and age history of OPS, 5 cores were collected along an approximately offshore-onshore transect in July 2010 (Fig. 1c). Coring occurred over two short (~2 hour) winter Low Spring Tides when the reef top was nearly exposed. Cores were recovered using percussion techniques with 6 m aluminium pipes (internal diameter 9.5 cm). Rates and depths of core penetration were recorded to ensure reliable depth chronologies and to constrain for compaction. Cores were later split longitudinally, photographed, and logged for basic bio-sedimentary facies information. Coral framework constituents and fabrics, including coral clast to matrix ratios and coral species, were described and calculated. Corals interpreted as being *in situ* based on growth position and preservation were selected for radiometric dating to determine age structure and accretion rates. Samples were prepared by removing encrustations with a dentist drill, and subject to ultrasonic agitation in distilled water to evacuate infilled pores.

Results and Discussion

The 'coalescing open-water shoal' type reef represented by OPS is relatively common in Halifax Bay and possibly other inner GBR locations - numerous equivalent shoals with small reef flat patches close to sea level were observed during fieldwork. Upper parts of these shoals have relatively high (but unquantified) live coral cover, dominated by *Montipora* sp. and *Turbinaria* sp. All cores penetrated to 5 m depth and had 100% recovery. Four cores penetrated the entire reef sequence to terminate in Pleistocene clay (Fig. 2b), indicating the reef established over this substrate. The clay was encountered at ~3.8 to 4.1 m below present LAT (Fig. 3), and is a regionally consistent unit identified as underlying other inner-shelf reefs (Smithers and Larcombe 2003; Perry et al. 2009, 2012). A transgressive lithic dominated coarse-sand and pebble unit commonly overlies the clay, above which a transitional bioclastic-lithic sand facies containing isolated (often large, up to 10 cm diam.) coral clasts (Fig. 2b) and isolated oysters and bivalves occurred in all cores. Coral clasts are generally well preserved, with *Acropora* sp., *Lobophyllia* sp., and *Turbinaria* sp. the most common taxa.

A matrix-supported coral-rich unit that is the dominant reefal facies (Fig. 3) overlies the bioclastic-lithic sand facies. Occurring between ~1.0 to ~3.0 m below LAT, this facies contains abundant, exceptionally well-preserved corals, within a mud-clay-rich sediment matrix (Fig. 2c). Dominant coral taxa include *Acropora*, *Goniopora* and *Lobophyllia*. In all cores this mud-rich unit is overlain by a clast-supported coral unit (mostly *Acropora*, *Montipora* and *Turbinaria*), with a muddy bioclastic sand matrix and then, in the central (and slightly higher) areas of the reef, by an open clast-supported unit. This uppermost layer has little sediment matrix and forms the contemporary reef surface. This is a vertical facies sequence comparable to that described from other GBR inner-shelf turbid-zone reefs (Perry et al. 2009, 2011), with the main phase of reef accretion interpreted as an open coral fabric that promoted the settling and accumulation of siliciclastic mud-rich sediments.

Twenty-eight coral samples were radiometrically dated to establish the growth history of OPS. Dated corals from the basal (transitional) facies indicate reef initiation occurred between ~1,700 to ~1,000 yBP (calibrated years before present), with the oldest dates from the central core (OPS-PC3) (Fig. 3) and the youngest dates from the base of OPS-PC5. Dates from close to the base of the main mud-rich reef unit are younger, ranging from ~750 yBP in the central reef core to about ~300 to 250 yBP in the adjacent cores (Fig. 3). Dates from samples towards the tops of all cores are much younger, less than ~170 yBP, and many return “modern” ages.

The main phase of reef development (that associated with mud-dominated siliciclastic sediment accumulation) was characterised by net vertical accretion rates that were very high relative both to the underlying incipient reef growth phase (Fig. 3), and compared to reefs globally (Dullo 2005). Net vertical accretion rates of between 0.8 mm and 1.3 mm yr^{-1} (average 1.0 mm yr^{-1}) are calculated for the incipient reef phase (the “transitional facies”; Fig. 3), whereas rates between 4.1 to 10.8 mm yr^{-1} (average 7.8 mm yr^{-1}) are calculated for the overlying reef units (Fig. 3). These rapid accretion rates coincide with the accumulation of mud-rich sediment and are comparable to similarly high rates recently reported from Middle Reef, another inner-shelf reef subject to high turbidity, where rapid burial by mud was argued to enhance coral preservation and promote high vertical accretion rates (Perry et al. 2012).

Core facies and radiometric dates suggest reef development at OPS occurred in several stages. Coral communities (or “coral carpets”; *sensu* Riegl and Piller 1999) initially developed over a seafloor dominated by muddy, siliciclastic sediments between ~1,700 to 1,000 yBP, with low vertical accretion rates (Fig. 4a). These coral communities then progressively coalesced before metamorphosing into reefs by building persistent topographic structures. Evidence for these early reef developmental stages is seen in the sub-tidal shoals and reef patches we have observed to be relatively common in Halifax Bay (Fig. 2d), and which are the focus of on-going investigations. One possible interpretation of the early age structure at OPS is that vertical reef growth may have been interrupted by a hiatus, represented by a possible unconformity (indicated by a poorly constrained gap between upcore radiometric ages) between the “transitional” facies and the overlying reefal units. The age structure may alternatively be interpreted as reflecting persistently difficult initiation conditions punctuated by episodic set-backs before sustained reef growth could occur. Regardless, later phases of reef growth were rapid (Fig. 4a), and our interpretation is that the developing reef structure enhanced mud deposition and biogenic carbonate preservation, which together increased net vertical accretion rates. Radiometric ages indicate that OPS has reached sea level in the past ~100 years. The negligible mud content of near-surface facies can be attributed to increased hydrodynamic reworking and resuspension of sediments. Age-reversals downcore in OPS-PC3 suggest episodic reworking of near-surface deposits may also occur, presumably during storms. The morphology and age-structure of OPS conform to a late juvenile-early mature stage of development *sensu* Hopley et al. (2007).

The timing of reef growth in the context of regional inner-shelf reef development is also interesting. Two discrete periods of Holocene reef ‘turn-on’ and ‘turn-off’ on the GBR inner-shelf have been proposed (Perry and Smithers 2011): the first during the Holocene transgression-early highstand (~8.5–5.5k yBP); the second since ~2k yBP (Fig. 4b). OPS established only in the late Holocene (since ~1700 years ago), but grew rapidly to sea level from a shallow clay-dominated substrate. Coral communities and incipient reefs similar to OPS commonly rise from the shallow seafloor of the inner central GBR, and those examined in detail so far are amongst the most actively accreting reefs on the GBR at present (Perry et al. 2012). Future research on similar marginal reefs will undoubtedly continue to challenge thinking on reef growth conditions and performance, but the identification of inner-shelf reefs with often high live coral cover and high accretion rates raises questions about the assumed ‘degraded’ state of these reefs and suggests they are worthy of higher conservation status.

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Figure Captions

Fig. 1. (A) Location of Offshore Paluma Shoals (OPS), central Halifax Bay. (B) Oblique aerial view north across mainland-attached Paluma Shoals (foreground) to OPS (arrowed). (C) View west across OPS showing location of core sites.

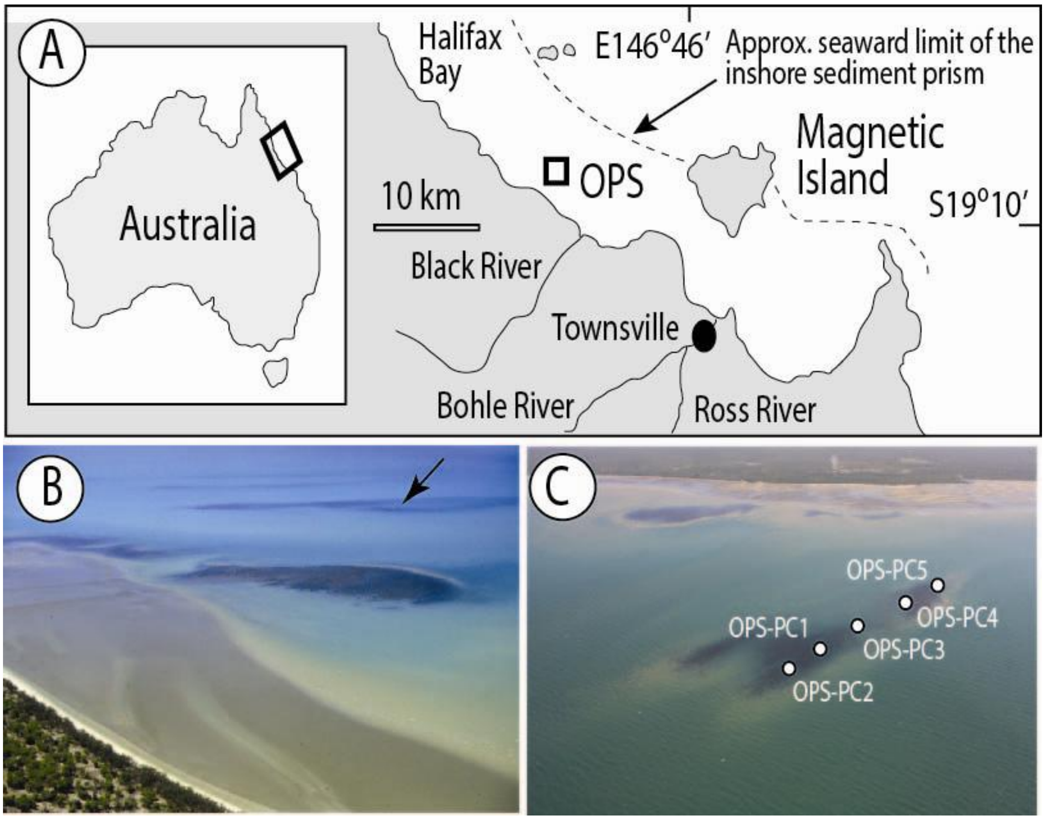
Fig. 2. (A) View east across Offshore Paluma Shoals (OPS) showing the near emergent reef flat at ~0.2 m LAT tide level. (B) Basal core sequence showing transition from Pleistocene clay, through the transgressive lithic unit into the early stages of reef development. (C) Main matrix-supported mud-rich unit with large, well-preserved *Favid* and *Goniopora* colonies. Scale bars in cm. (D) Prolific cover of *Turbinaria*, *Acropora* and *Montipora* that is typical across the shallow (~3-4 m below mean sea level) seafloor surrounding OPS. Note photo was taken after Cyclone Yasi in Feb 2011.

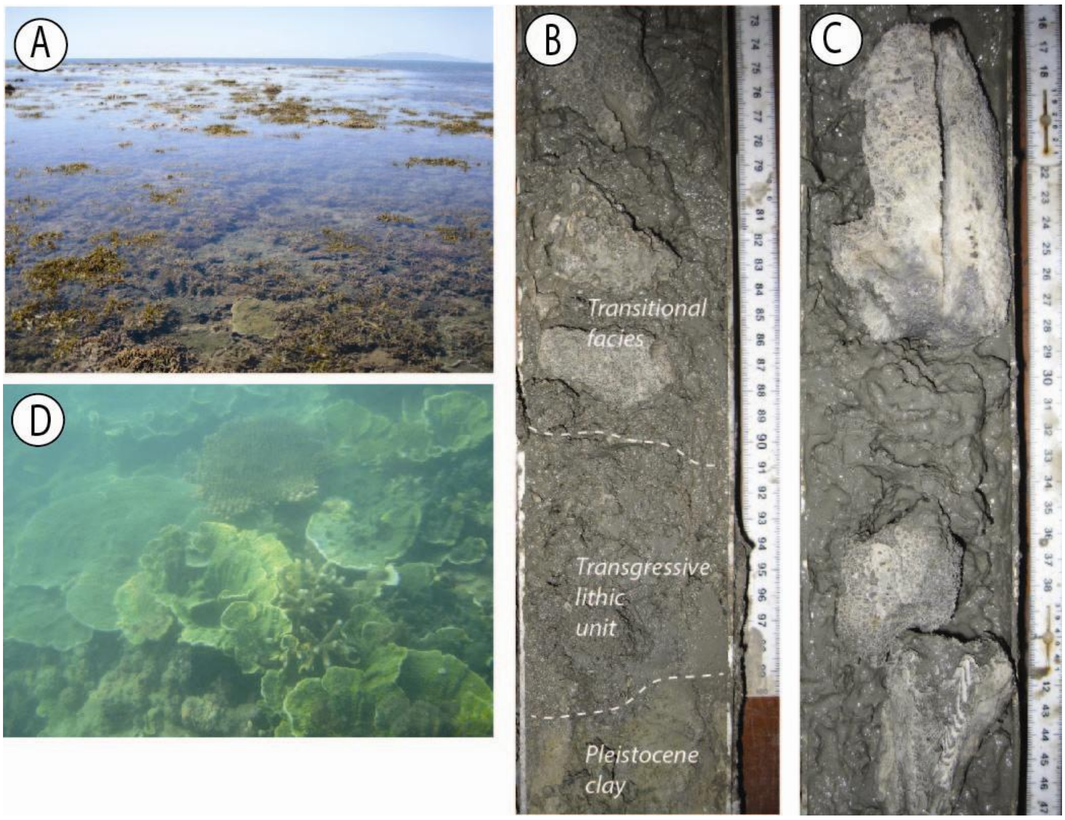
Fig. 3. Core logs and chronostratigraphy of Offshore Paluma Shoals showing net vertical accretion rates calculated for the transitional and main phases of reef accretion.

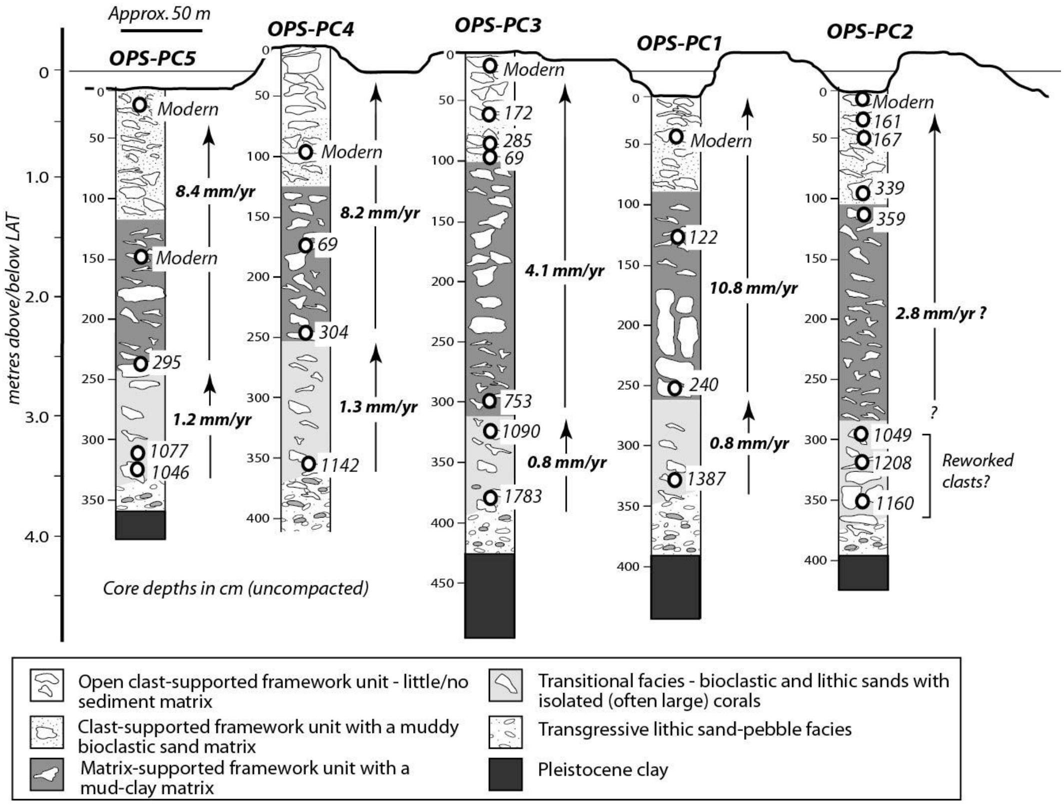
Fig 4. (A) Net accretion rate trendlines derived for individual cores from Offshore Paluma Shoals (OPS). White circles denote the age and depth relative to Lowest Astronomical Tide (LAT) of dated corals in individual cores. (B) Age-depth plots for the calibrated radiocarbon dated samples from OPS. Dates are shown in relation to a plot of the best-fit Holocene sea-level curve (bold line) for eastern Australia (see discussion in Perry and Smithers 2011) and the regionally delineated mid-late Holocene reef growth ‘windows’ (grey zones) on the inner-shelf of the Great Barrier Reef (after Perry and Smithers 2011).

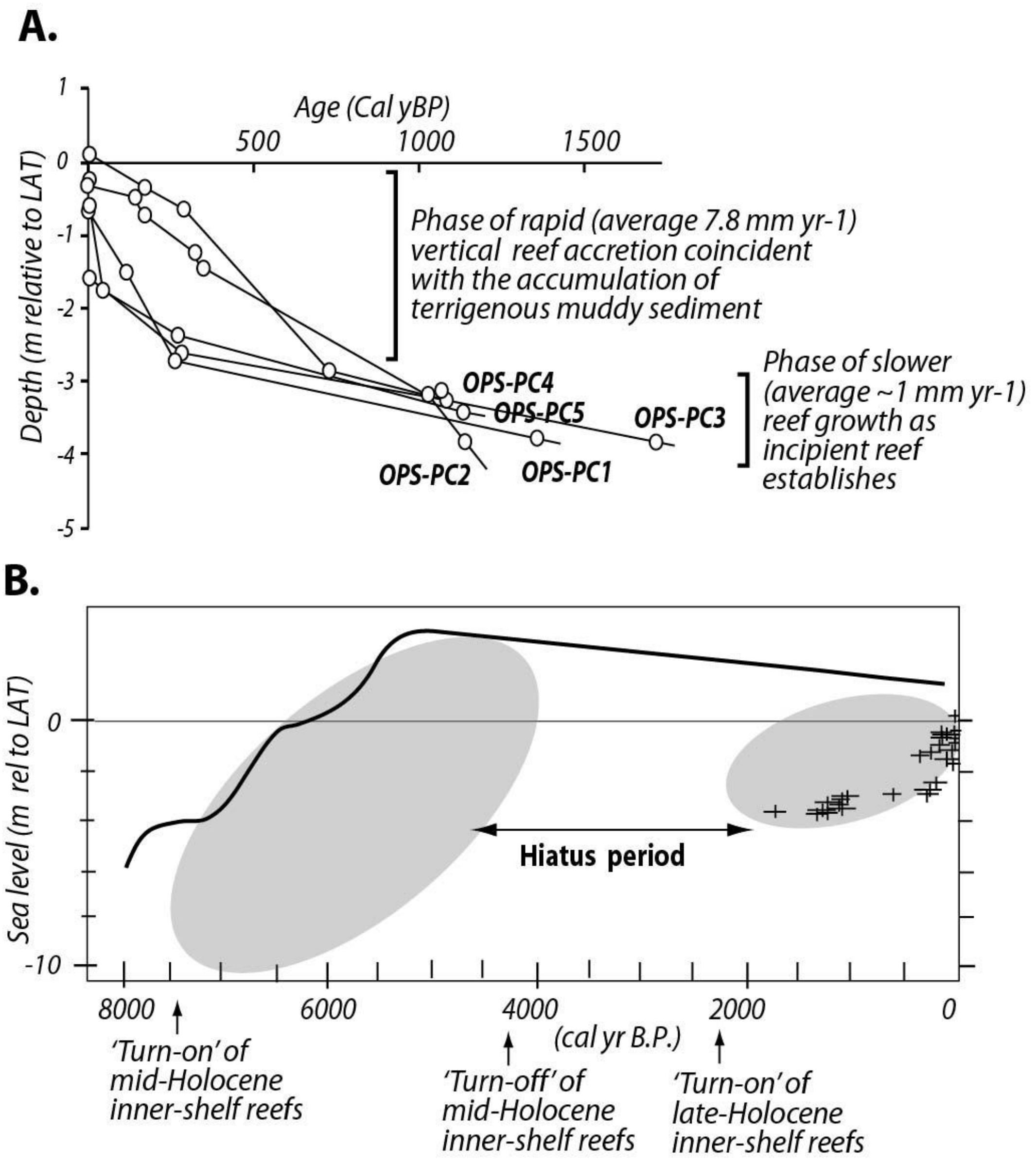
Table captions

Table 1. Radiocarbon dates from cores collected at Offshore Paluma Shoals. Samples were dated at the Waikato Radiocarbon Dating Laboratory, New Zealand and SUERC (NERC Radiocarbon Dating Facility, UK). Conventional dates were calibrated using Calib 6 and calibration curve Marine09 (http://calib.qub.ac.uk/marine). A weighted mean ΔR value of +10 ± 7, currently the best estimate of variance in the local open water marine reservoir effect for the central Queensland coast (Ulm 2002), was applied. Nb. ‘Modern’ denotes clasts formed between 1955 and 2010 AD.




A
B
C
D
Transitional facies
Transgressive lithic unit
Pleistocene clay


Approx. 50 m
OPS-PC5
OPS-PC4
OPS-PC3
OPS-PC1
OPS-PC2
metres above/below LAT
0
1.0
2.0
3.0
4.0
Modern
8.4 mm/yr
Modern
295
1.2 mm/yr
1077
1046
Modern
8.2 mm/yr
69
304
1.3 mm/yr
1142
Modern
172
285
69
4.1 mm/yr
753
1090
0.8 mm/yr
1783
Modern
122
10.8 mm/yr
240
0.8 mm/yr
1387
Modern
161
167
339
359
2.8 mm/yr ?
?
1049
1208
1160
Reworked clasts?
Core depths in cm (uncompacted)
Open clast-supported framework unit - little/no sediment matrix
Clast-supported framework unit with a muddy bioclastic sand matrix
Matrix-supported framework unit with a mud-clay matrix
Transitional facies - bioclastic and lithic sands with isolated (often large) corals
Transgressive lithic sand-pebble facies
Pleistocene clay


A.
Age (Cal yBP)
500
1000
1500
1
0
-1
-2
-3
-4
-5
Depth (m relative to LAT)
Phase of rapid (average 7.8 mm yr-1) vertical reef accretion coincident with the accumulation of terrigenous muddy sediment
Phase of slower (average ~1 mm yr-1) reef growth as incipient reef establishes
OPS-PC4
OPS-PC5
OPS-PC3
OPS-PC2
OPS-PC1
B.
Sea level (m rel to LAT)
0
-10
Hiatus period
8000
6000
4000
2000
0
(cal yr B.P.)
'Turn-on' of mid-Holocene inner-shelf reefs
'Turn-off' of mid-Holocene inner-shelf reefs
'Turn-on' of late-Holocene inner-shelf reefs

Core/sample code	Material	Lab Ref.	Elevation (m rel to LAT)	^{14}C age (yr BP)	^{14}C age error (yr BP)	Calibrated age range (1σ)		Median probability age (cal yBP)
						Max	Min	
Core OPS-PC1								
OPS-PC1-35	*Porites*	Wk-26568	-0.7	456	42	Modern		Modern
OPS-PC1-88	*Acropora*	Wk-26569	-1.5	510	41	236	0	122
OPS-PC1-198	*Favid*	Wk-26570	-2.8	617	54	398	86	245
OPS-PC1-252	*Turbinaria*	Wk-26571	-3.5	1848	70	1538	1257	1387
Core OPS-PC2								
OPS-PC2-29	*Montipora*	SUERC-32473	-0.3	280	35	Modern		Modern
OPS-PC2-30	*Acropora*	SUERC-32474	-0.45	537	37	261	49	161
OPS-PC2-31	*Acropora*	SUERC-32475	-0.6	543	35	265	53	169
OPS-PC2-32	*Cyphastrea*	SUERC-32476	-1.15	697	37	425	264	339
OPS-PC2-33	*Acropora*	SUERC-32477	-1.3	722	37	442	279	359
OPS-PC2-34	*Acropora*	SUERC-32478	-3.2	1510	37	1156	951	1049
OPS-PC2-35	*Favid*	SUERC-32481	-3.35	1654	37	1284	1113	1208
OPS-PC2-36	*Lobophyllia*	SUERC-32482	-3.75	1606	37	1250	1058	1160
Core OPS-PC3								
OPS-PC3-21	*Acropora*	SUERC-32462	+0.1	Modern	--	Modern		Modern
OPS-PC3-22	*Acropora*	SUERC-32463	-0.5	547	37	269	53	172
OPS-PC3-23	*Acropora*	SUERC-32464	-0.7	648	35	404	220	285
OPS-PC3-25	*Acropora*	SUERC-32466	-1.0	465	37	149	0	69
OPS-PC3-26	*Acropora*	SUERC-32467	-2.9	1224	35	859	671	753
OPS-PC3-27	*Lobophyllia*	SUERC-32468	-3.2	1544	37	1189	971	1090
OPS-PC3-28	*Turbinaria*	SUERC-32472	-3.75	2136	37	1819	1595	1714
Core-OPS-PC4								
OPS-PC4-43	*Acropora*	Wk-31814	-0.8	Modern	--	Modern		Modern
OPS-PC4-98	*Montipora*	Wk-31815	-1.75	472	30	148	0	69
OPS-PC4-147	*Goniopora*	Wk-31816	-2.3	668	32	406	249	304
OPS-PC4-240	*Favid*	Wk-31817	-3.3	1590	30	1231	1052	1142
Core-OPS-PC5								
OPS-PC5-19	*Acropora*	SUERC-32458	-0.3	Modern	--	Modern		Modern
OPS-PC5-95	*Acropora*	Wk-31819	-1.7	424	30	Modern		Modern
OPS-PC5-185	*Lobophyllia*	Wk-31820	-2.65	660	28	395	246	295
OPS-PC5-248	*Turbinaria*	Wk-31818	-3.1	1532	25	1161	986	1077
OPS-PC5-260	*Turbinaria*	SUERC-32461	-3.25	1508	37	1154	949	1046