Fringing reef growth over a shallow last interglacial reef foundation at a mid-shelf high island: Holbourne Island, central Great Barrier Reef

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Abstract

Fringing reefs are rare on the mid-shelf of the central Great Barrier Reef, with Holocene development histories established for a few examples. The paucity of reef growth records from mid-shelf fringing reefs has limited opportunities for comparisons with inshore fringing reef growth records to better understand the influence of changes in environmental conditions on reef growth with distance offshore. The long-term development of the mid-shelf fringing reef at Holbourne Island was reconstructed using nine percussion and drill cores that captured the entire Holocene period of reef growth. The cores were chronologically constrained by 16 high-precision ²³⁰Th ages. A weathered, Pleistocene reef substrate was U-Th dated as last interglacial (open system age of $131,100 \pm 1,000$ cal yBP) and this provides the underlying foundation upon which the Holocene reef initiated prior to $\sim 7,520 \pm 20$ cal yBP. The last interglacial reef was encountered 5.9 m below the present reef surface and is the shallowest confirmed last interglacial reef in the central GBR region to date. Most of the Holocene reef structure was

emplaced within 1,000 years of initiation. The chronostratigraphy and contemporary geomorphology of the fringing reef at Holbourne Island preserve evidence of re-working and stripping of the reef structure by cyclones. This evidence includes: 1) an age hiatus in core data of $\sim 3,500$ years ($6,238 \pm 18$ to $2,683 \pm 10$ cal yBP); 2) the abundance of detrital branching coral rubble material within the core facies; 3) the surface elevations and ages of fossil microatolls, which reveal that storm-induced ponding of water during low tidal stages up to 55 cm deep has been active (but intermittent) across the reef flat for at least 600 years and is still active today; and 4) long-standing shingle ridges onshore and modern shingle ridges on the reef flat.

1.0 Introduction

Fringing reefs on Australia's Great Barrier Reef (GBR) have developed directly attached to the mainland coast or attached to the shorelines of high continental or volcanic islands on the inner-shelf (within the 20 m isobath) or mid-shelf (between the 20 and 50 m isobaths: Hopley et al. 2007). Environmental settings where fringing reefs develop include headlands or rocky shores, within embayments, sandy coastlines, and in the nearshore where they may initially develop as shoals not directly attached to the shoreline (Smithers, 2011). Fringing reefs on the GBR are considered vulnerable to degradation caused by direct anthropogenic pressures because they are often located relatively close to human populations and river discharge from anthropogenically modified coastal catchments (Fabricius et al. 2005; Roff et al. 2012). Other natural stressors to fringing reef health include cyclones (Done, 1992; Scoffin, 1993), sea-level change (Woodroffe and Webster, 2014) and elevated sea surface temperature (Hughes et al. 2017) and these will be compounded by climate change. Due to their location further offshore, mid-shelf fringing reefs are less exposed to direct anthropogenic impacts than their inner-shelf counterparts (Hopley et al. 2007), but could be more exposed to other natural impacts such as cyclones.

Understanding how and when fringing reefs developed over millennia (and under what environmental conditions) provides important baseline information for interpreting present reef condition and predicting future reef trajectories. Long-term reef records can be constructed by coring into the reef structure and characterising the internal reef framework and matrix in the context of dated *in situ* coral material (Kennedy and Woodroffe, 2002; Montaggioni, 2005). Ideally, reef cores should attempt to capture the entire Holocene reef sequence, terminating in the underlying, pre-Holocene foundation to reveal the details of reef initiation, including when reef growth began and upon what substrate type. Most fringing reefs on the GBR initiated during the early- or mid-Holocene ~7,000 years before present (cal yBP), where present is 1950 AD, once the continental shelf had been flooded at the end of the post-glacial marine transgression (PGMT) (Hopley et al. 2007). Unlike the outer-shelf reefs of the GBR (located beyond the 50 m isobath), which developed exclusively upon Pleistocene reef limestone foundations (Marshall and Davies, 1984; Dechnik et al. 2017a), fringing reefs have developed upon a wide variety of consolidated and unconsolidated substrates. These substrates include unconsolidated transgressive sands and gravels (Hopley et al. 1983; Perry et al. 2011; Lewis et al. 2012; Ryan et al. 2016a), mangrove muds, coffee rock (Roche et al. 2011), consolidated terrigenous clay (Hopley et al. 1983; Johnson and Risk, 1987), a terrigenous boulder beach (Hopley and Barnes, 1985), and last interglacial (Pleistocene) reef (Hopley et al. 1978). Of the mid-shelf reefs for which reef growth records are known, most are platform reefs which developed upon last interglacial reef antecedent substrates (Marshall and Davies, 1984; Davies et al. 1985; Dechnik et al. 2015, 2017a).

A comprehensive reef growth dataset for the GBR has been developed over the past few decades, comprising reef core records from ~29 nearshore and fringing reefs (Smithers and Larcombe, 2003; Perry et al. 2008, 2009, 2011, 2012, 2013; Palmer et al. 2010; Perry and Smithers, 2010, 2011; Smithers et al. 2006; Hopley et al. 2007). This has been augmented by more recent studies on the inner GBR shelf (Lewis et al. 2012; Perry et al. 2012, 2013; Roff et al.

2012, 2015; Ryan et al. 2016a, b, c; Johnson et al. 2017). Comparatively few detailed chronostratigraphic records from GBR mid-shelf fringing reefs exist (Kleypas, 1996; Dechnik et al. 2017b), as mid-shelf fringing reefs are themselves rare (particularly in the central GBR region north of the Whitsunday Islands) and they are more difficult to access than reefs close to the mainland. Chronostratigraphic records from mid-shelf fringing reefs are needed to contribute to a better understanding of the role of cross-shelf environmental variability in reef development and the influence of natural acute events, such as storms and cyclones over millennial and centennial scales (Blanchon and Jones, 1997; Blanchon et al. 1997; Braithwaite et al. 2000; Ryan et al. 2016b).

Here we present a detailed chronostratigraphic record of fringing reef development at Holbourne Island, an exposed mid-shelf fringing reef located on the central GBR (Figure 1). The novel record was developed using a combination of percussion and rotary drill cores that extend deep through the Quaternary reef structure, combined with high-precision uranium-thorium (U-Th) dating of *in situ* coral framework to obtain an accurate chronology. The cores capture last interglacial reef development at 5.9 m below the present reef surface, as well as a 6-8 m thick Holocene reef. The Holocene reef framework captured in the cores represents ~7,500 years of accretion, with the majority of reef development occurring within 1,000 years of reef initiation. The mode of reef development, average reef accretion rates and timing of reef flat formation are reported. Results of precise topographic surveys combined with geomorphic and ecological assessments of contemporary benthic cover reveal complex zonation on the contemporary reef flat. Radiocarbon (^{14}C) and ^{230}Th ages of fossil microatolls preserved on the Holbourne Island reef flat reveal a complex history of storm effects over the past 500 years.

2.0 Background and regional setting

2.1 Study site

Holbourne Island (148°21'E, 19°43'S) is a relatively isolated, continental high island situated ~40 km offshore on the mid-shelf of the central GBR (Figure 1). Marshall et al. (1925) first described the geomorphology of Holbourne Island, with Hopley (1975) and Hopley and Isdale (1977) providing more detail, especially on the reef flat. Holbourne Island is relatively exposed to prevailing south-easterly waves and currents generated by trade winds, with a fetch distance of ~60–70 km to the southeast. The reef flat is partially protected from easterly swells by the granitic outcrops located at the south-eastern margin of the reef flat, but is exposed to northerly and north-westerly swells. Tides are semi-diurnal with a spring tidal range of ~3.6 m in this part of the GBR. The water depth around the island and reef reaches ~45 m (Hopley, 1975). Holbourne Island lies ~80 km east of the Burdekin River mouth (the largest river in the region) and is far enough offshore that it is rarely (1–3 times per decade) affected by riverine flood plumes containing suspended particulate matter, nutrients and pollutants flushed from coastal catchments (Devlin et al. 2012). The reef is therefore less influenced by turbid water associated with flood plumes or the re-suspension of the inshore terrigenous sediment wedge (Larcombe and Woolfe, 1999b) compared to most other fringing reefs on the GBR, which are generally located further inshore.

Holbourne Island is 1.1 km long by 0.6 km wide and comprises two major granitic outcrops fringed by Quaternary sedimentary deposits. These deposits include a series of shingle ridges, sand/shingle beach ridges, and a series of elevated Holocene beachrock terraces (Hopley, 1975; Figure 1c). Hopley (1975) dated shell and coral within two of these beachrock terraces and reported respective conventional ^{14}C ages of $6,020 \pm 130$ and $3,350 \pm 95$ yBP. Calibration of these dates results in median ages of 6,450 cal yBP (with a 2-sigma age range of 6,170 to 6,760 cal yBP) and 3,190 cal yBP (with a 2-sigma age range of 2,920 to 3,440 cal yBP), respectively (see section 3.3 for the details of age calibration of the marine ^{14}C dates discussed in this paper).

A 440 m-wide reef flat has developed on the southern side of Holbourne Island, bounded by several granitic outcrops at the south-eastern extent. A boulder beach borders the landward extent of the eastern reef flat, while the western half is bordered by a 20–25 m-wide beachrock exposure in front of a sand/rubble beach (Figure 1c). Hopley (1975) and Hopley and Isdale (1977) noted the complex geomorphology of the reef flat, which is sub-aerially exposed during lower tidal stages. Fields of fossil coral microatolls form part of this complex geomorphology. Microatolls are discoid corals that have flat upper surfaces, constrained by sub-aerial exposure during low tide (Scoffin and Stoddart, 1978). On the GBR, fossil microatolls of mid-Holocene age are often preserved on reef flats (Hopley and Isdale, 1977; Chappell et al. 1983). Conspicuous groups of elevated, well-preserved fossil microatolls on the reef flat at Holbourne Island (Figure 2b) were initially interpreted as a raised reef by Marshall et al. (1925). Rainford (1925) suggested that the reef flat corals on Holbourne Island (presumably including the microatolls) were killed by freshwater exposure associated with a large cyclone in 1918. Alternatively, Hopley (1975) and Hopley and Isdale (1977) suggested that the microatolls died when a shingle rampart that moated water over the reef flat above the open-water low tide level (allowing the microatolls to grow) was destroyed during this cyclone. Based on the size and inferred age of many of the microatolls killed, the moat must have been stable for ~200 years prior to the cyclone. Hopley (1975) argued that a ^{14}C age (uncalibrated) of 60 ± 90 yBP from one of these emerged fossil microatolls on Holbourne Island supported the view that the 1918 cyclone event killed these microatolls. However, the error associated with the conventional age is too large to link the mortality to a specific cyclone, and a calibrated median age of -11 cal yBP (2 sigma age range from -8 to -14 cal yBP; see section 3.3 for detailed age calibration) suggests that the coral died between 1958 and 1964 AD.

2.2 Reef development

Fringing reefs on the GBR can develop in a variety of ways (Chappell et al. 1983; Partain and Hopley, 1989; Kennedy and Woodroffe, 2002; Smithers et al. 2006) according to the size, shape and composition of the underlying substrate (Woodroffe et al. 2000) and the availability of accommodation space, which is a function of relative sea level and the rate of reef growth (Kennedy and Woodroffe, 2002). At least seven fringing reef growth modes/styles have been identified and summarised by Kennedy and Woodroffe (2002) and Smithers et al. (2006). These growth modes are: seaward progradation from a shoreline; vertical accretion; vertical accretion followed by seaward reef flat progradation; episodic seaward reef crest advance; and offshore vertical accretion followed by shoreline-reef coalescence through either rubble/sediment backfilling, seaward lateral accretion, and/or landward lateral accretion. Typically, vertical reef accretion occurs until the reef reaches sea level and exhausts all vertical accommodation space, forcing lateral accretion to prevail and, eventually, reef flat formation.

Geographic variations in relative sea-level history across the continental shelf exert a strong control on reef growth and morphology (Davies et al. 1985; Chappell et al. 1982, 1983). The continental shelf of the GBR was flooded during the PGMT by ~8,000 cal yBP. At the end of the PGMT, a highstand was reached ~7,000–6,000 cal yBP, where sea level was about 1.0–1.5 m higher than present (Chappell et al. 1983; Lewis et al. 2013). The highstand lasted a few thousand years, after which sea-level fell gradually to its present level. However, the nature and precise timing of this post-highstand sea-level fall on the GBR remains unresolved (Perry and Smithers, 2011; Harris et al. 2015; Lewis et al. 2015; Leonard et al. 2016; Dechnik et al. 2017b). The effects of late-Holocene sea-level fall are likely to be more pronounced on the inner GBR, due to spatial variations in hydro-isostatic shelf deformation associated with water loading during the PGMT (Chappell et al. 1982; Lambeck and Nakada, 1990). However, precise sea-level data from the mid-shelf are lacking (Harris et al. 2015) and thus the importance of cross-shelf variations in relative sea level for reef development remains poorly understood. Many fringing reef flats in the GBR were formed during the sea-level highstand, at elevations ~1.0 m above the

level for modern reef flat formation. Large areas of these reef flats are today emergent during lower tidal stages due to this late Holocene sea-level fall (Smithers et al. 2006).

3.0 Materials and methods

3.1 Core recovery and analysis

Nine cores were collected from Holbourne Island reef flat (Figure 1b) using a combination of two standard coring techniques: percussion coring (Perry and Smithers, 2006) and rotary diamond drilling (Partain and Hopley, 1989) along a single transect (transect 2) perpendicular to the shore. Percussion cores penetrated up to 2.0 m below the present surface and captured both reef framework and matrix (sand and rubble). Compaction throughout the percussion cores varied between 13–20%. The solid nature of the cemented reef framework and the time available for field work (days on the island were limited and the reef flat could only be accessed safely during lower tidal stages) meant that retrieving percussion cores >2.0 m depth was not logistically feasible. Four cores drilled using a rotary drill rig (similar to the rig described in Partain and Hopley, 1989) achieved deeper penetration (up to 8.0 m) into the reef structure. Recovery rates of the drill cores varied between 18–75%. Low recovery rates were due to the open framework nature of the reef structure; similar to the fringing reef flats in the Northumberland Island Group, around 140–240 km south of Holbourne Island (Kleypas, 1996). Cores were visually logged to differentiate reef facies, as described in Ryan et al. (2016a), and 16 *in situ* coral clasts were dated using U-Th techniques at the Radiogenic Isotope Facility at The University of Queensland (see section 3.3). Carbonate and mud content was determined for matrix sediments in the percussion cores at 20 cm (uncompacted) downcore intervals, following standard acid digestion and wet sieving procedures described in Ryan et al. (2016a). Fine-grained material (muds and fine sands) not flushed out during rotary drilling was visually described according to Udden-Wentworth nomenclature.

3.2 Topography and contemporary ecology

A Real Time Kinematic (RTK) Global Positioning System (GPS) was used to map geomorphological zones across the reef flat and shoreline (Figure 1c) and to obtain high precision elevation data (horizontal and vertical precision typically 0.01–0.005 m). All elevation data were reduced to lowest astronomical tide (LAT) at the Abbot Point tide gauge (port number 59300: BOM, 2016b) relative to datum RTK GPS base station values obtained from AUSPOS 2.1, an online GPS processing service provided by the Commonwealth of Australia (Geoscience Australia, 2015). The high-precision RTK-GPS surveying allowed for the most accurate geomorphological survey and mapping of Holbourne Island to date, extending previous work by Hopley (1975) and Hopley and Isdale (1977). Three shore-perpendicular transect lines were mapped across the reef flat (Figure 1c), along with the location and elevation of shingle ridges, basset edges, the upper surfaces of fossil and living microatolls, and other geomorphic features or zones on the reef flat or shoreline. Eco-geomorphological zones were differentiated across each transect based on variations in the elevation of the reef flat surface, substrate, live coral cover and vegetation cover. Within each zone, ten 1 m² quadrats were photographed and analysed in Coral Point Count with Excel Extensions (Kohler and Gill, 2006) to determine average percent benthic composition for each zone (Ryan et al. 2016a). Along the reef slope and parts of the reef flat not exposed at low tide, spatially-referenced video-photography was captured using an underwater SeaViewer drop camera paired with a Trimble Juno GPS. The video survey extended from the reef crest at transect two and terminated approximately half way down the reef slope (Figure 1c).

3.3 Fossil microatolls and dating

Small cores (~2.5 cm diameter and ~3.0 cm length) of coral skeleton were recovered from the surface outer edge of seventeen fossil microatolls. Five were dated using U-Th techniques and 12 were ^{14}C dated using accelerator mass spectrometry (AMS). All samples were pre-screened using scanning electron microscopy for diagenetic alteration to ensure that all dated samples were pristine. The samples for AMS ^{14}C dating were analysed using the method described by Fink et al. (2004) at The Australian Nuclear Science and Technology Organisation (ANSTO). Calibration of AMS ^{14}C ages was performed using OxCal program version 4.2.3 (Bronk Ramsey, 2009) and ^{14}C data (1951-2010 AD) from Heron Island, Abraham Reef and Holmes Reef (see Dawson et al. 2014) extended back in time using the Marine13 calibration dataset (Reimer et al. 2013) with a ΔR (regional offset from the “global” marine reservoir age) of 4 ± 40 years (Druffel and Griffin, 2014) for samples older than 1950 AD. For AMS ^{14}C ages of fossil microatoll samples younger than 1950 AD, the median age is reported with $\pm 2\sigma$ age range in calendar years AD (Supplementary Material). For samples older than 1950 AD, calibrated ^{14}C ages are reported in cal yBP.

Core samples and fossil microatoll samples selected for U-Th dating were rigorously cleaned and prepared for dating using techniques described in Clark et al. (2014a) and Ryan et al. (2016a). Samples were U-Th dated at the Radiogenic Isotope Facility at The University of Queensland using a Nu Plasma I multi-collector inductively coupled plasma mass-spectrometer (MC-ICP-MS). U-Th dating procedures were similar to those described in detail by Clark et al. (2014a,b). ^{230}Th ages of core samples are presented as calibrated calendar years before present (cal yBP), where present is defined as 1950 AD (Supplementary Material) to facilitate direct comparison with previously published ^{14}C ages. ^{230}Th ages of fossil microatoll samples are presented as calendar years AD for direct comparison with the AMS ^{14}C ages of fossil microatoll samples.

4.0 Results

4. 1 Holocene reef development

The nine cores from across the Holbourne Island reef flat, extending 1.5–8.0 m depth, captured a record of Holocene reef matrix and framework. Four Holocene reef facies were differentiated in the cores (facies A–D: Table 1). The percussion cores captured the upper ~2 m of reef matrix sediments, which were differentiated into facies A, B and C (Table 1). Although the percussion cores did not penetrate beyond 2 m depth into the reef structure, the cores are spread across the width of the reef flat and contain *in situ* coral material aged between $7,178 \pm 20$ and 517 ± 48 cal yBP (Figure 3), covering the majority of the Holocene period of reef development.

Therefore, it is likely that the cores have captured reef matrix sediments that are representative of the entire period of reef growth. Facies A was characterised by contemporary intertidal sands (Table 1) and comprised the upper ~10–15 cm of the percussion cores (Figure 3). Facies B (reef framework with a sandy matrix) and C (reef framework with a muddy matrix) comprised the remainder of the percussion cores, where coral material (framework and detrital) varied in age from $7,178 \pm 20$ cal yBP in P-3 to $1,326 \pm 15$ cal yBP in P-5 (Figure 3). Facies D (*Acropora* rubble assemblage) was dominated by re-worked branching *Acropora* clasts largely encrusted with coralline algae. Facies D formed units in the drill cores up to 4.5 m wide and is likely to have included a sediment matrix similar to that observed in facies B and C, but the sediment matrix was not recovered as the rotary drill coring process flushed sediments from the cores. In general, the reef matrix sediments coarsened upwards, with mud content (the $<63 \mu\text{m}$ fraction) being greatest in the lower muddy facies C, comprising $18.0 \pm 8.3\%$ (mean $\pm 1\sigma$ standard deviation), compared with just $6.5 \pm 2.0\%$ mud in facies B (Table 1). Terrigenous components in the reef sediment matrix were very limited ($<7.2\%$) and throughout the cores the matrix sediments were primarily composed of carbonate (reef-derived) material, averaging between 92.8 ± 3.9 and $97.3 \pm 0.7\%$ (Table 1).

Cores D-1 (~80 m from the contemporary shoreline) and D-2 (~170 m from the contemporary shoreline) penetrated the entire (6–8 m thick) Holocene reef sequence and terminated in the substrate over which the reef developed: igneous rock in D-1 and Pleistocene reef in D-2 (Figure 3). The ^{230}Th age of $137,778 \pm 608$ cal yBP obtained from facies E 6.2 m below the present surface (Figure 3) indicates that this material is Pleistocene reef that would have been growing during the last interglacial period (Figure 4). Using the Thompson open system model (Thompson et al. 2003) to further correct for minor diagenesis, as indicated by elevated initial $^{234}\text{U}/^{238}\text{U}$ (Supplementary Material), the resulting open system age is $131,100 \pm 1000$ cal yBP. Basaltic rock, presumably derived from dykes associated with the granitic outcrops that dominate the interior of Holbourne Island, was encountered at the base of core D-1 (facies F) at a depth ~8.2 m below the present reef flat surface. An *in situ* faviid coral located ~6 m down core D-1 (and therefore ~2 m above the initiation substrate) was dated at $7,520 \pm 20$ cal yBP, the oldest of any age obtained from the cores (Figure 3). This faviid coral is located above ~2 m of reefal material that was classified as rubble (not *in situ*) and thus the reef community must have initiated some time prior to $7,520 \pm 20$ yBP.

The chronostratigraphy of the reef based on the ^{230}Th age data, reveals that after initiation upon last interglacial reef or igneous rock foundations, the reef rapidly accreted vertically towards palaeo-sea level over a period of ~1,000 years. The reef approached within 1 m of palaeo-LAT by $6,406 \pm 19$ cal yBP, as indicated by the ^{230}Th age in P-3 from a coral clast ~50 cm downcore. Reef flat formation probably began shortly after this time once the reef reached sea level and further vertical accretion was restricted (Figure 3). The spread of ^{230}Th ages between $7,520 \pm 20$ and $6,238 \pm 18$ cal yBP throughout the majority of the cores from the back and central reef flat indicates that most of the reef was constructed during this time period. Average vertical reef accretion rates between ~7,500 and 6,500 cal yBP varied from 1.7–3.2 mm.yr⁻¹ (Figure 3). The palaeo-ecology of the core facies indicates the reef slope during this time supported a hard coral assemblage that included branching *Acropora* and massive faviid corals, such as *Favites* and

Platygyra (Figure 3) growing in palaeo-water depths of 3–5 m. No ages between $6,238 \pm 18$ and $2,683 \pm 10$ cal yBP were recovered from the cores. However, two ^{230}Th ages of $2,683 \pm 10$ and $1,326 \pm 15$ cal yBP were obtained in the two most seaward cores within 1.2 m of the present reef flat surface (Figure 3). This suggests that the outer ~100 m of reef flat (at least the upper 1.5 m) has developed over the past ~2,500 years.

4.2 Contemporary geomorphology

Eco-geomorphological surveys using high-precision RTK GPS revealed complex zonation across the reef flat (Figure 1c, Table 2). Generally, the backreef flat extended from the Holbourne Island shoreline at an elevation ~1.0–1.3 mLAT and sloped seaward towards the reef crest, which was elevated close to LAT at transects 1 and 2 and 0.7 m above LAT at transect 3 (Figure 5). The backreef flat extended ~120–190 m from the shoreline and was largely characterised by two moated areas, where during low tidal stages, water was trapped and remained moated (~0.1–0.4 m deep) on the reef flat due to the presence of elevated shingle ridges and/or higher sections of cemented reef flat. The eastern moat corresponds to zones 1 and 2 on transect 3 and the western moat corresponds to zone 1 and the first half of zone 2 on transect 2 (Figure 1, Figure 5). Coral rubble ($46.2 \pm 24.1\%$) and sand ($20.0 \pm 13.8\%$) dominated the substrate of the western moat, while coral rubble ($53.4 \pm 30.9\%$ in zone 1) and turf algae upon the reef pavement ($47.7 \pm 27.4\%$ in zone 2) dominated the substrate of the eastern moat. The presence of ponded water allows living *Porites* and *Goniastrea* microatolls to grow across these backreef zones (Figure 2a) at elevations 0.5–1.0 m above open-water coral growth. The widespread moated microatolls varied between 0.6–3.0 m in diameter. The living upper rims of the *Porites* microatolls in the western ponded area were elevated between 0.9–1.0 mLAT (~0.2 m above mean low water spring [MLWS] level) and those in the eastern moated area were ponded at a slightly higher level, between 1.2–1.3 mLAT (within 0.1 m of mean low water neap [MLWN] level). Fossil microatolls, interspersed between the living microatolls, were the most

conspicuous features in the moated areas (Figure 2b). The fossil microatolls were generally tall and large, reaching up to 3.6 m in diameter and elevated around 0.1–0.4 m (or more) above their modern live moated counterparts. The fossil microatolls in the western moat were up to 0.4 cm taller than those in the eastern moat. Seventeen of these fossil microatoll samples were dated using a combination of U-Th and AMS ^{14}C techniques, yielding calibrated ages (calendar years AD) between 1361 and 1984 AD (Supplementary Materials). The relatively young ages coupled with their elevations on the reef flat indicate the fossil microatolls grew in a moated setting. Thus, groups of fossil microatolls with similar ages and elevations may reflect the timing of shingle ridge lowering or removal during cyclones and associated moat draining.

The outer reef flat was largely characterised by an algal turf zone (zone 3 on transects 2 and 3: Figure 2e), which began ~190 m offshore and extended ~120–150 m seaward (Table 2). The surface of zone 3 was elevated ~0.5–0.8 mLAT on transect 2 and was slightly higher on transect 3 (~0.7–1.0 mLAT). An algal turf zone was absent on transect 1. On the algal turf, the reef flat was relatively featureless and turf algae growing upon consolidated reef pavement dominated the substrate ($41.3 \pm 12.7\%$ on transect 2 and $50.8 \pm 27.7\%$ on transect 3), along with scattered coral rubble and sparse living corals (live coral cover $2.0 \pm 1.9\%$ and $7.1 \pm 15.9\%$ on transects 2 and 3, respectively). Amongst and seaward of the algal turf, live coral from six genera (*Acropora*, *Porites*, *Goniastrea*, *Favites*, *Montipora* and *Platygyra*) were surveyed in open-water (not moated) environments on the outer reef flat (Figure 2f) at elevations below ~0.64 mLAT (i.e. below MLWS level, which is 0.67 mLAT at the Abbot Point tide gauge). Live coral cover averaged $27.7 \pm 7.4\%$ in zone 2 on transect 1, $38.1 \pm 32.0\%$ in zone 4 on transect 2, and $7.1 \pm 15.9\%$ in zone 3 on transect 3 (Table 2). Open-water live coral cover was highest on the lower elevation western side of the outer reef flat (transects 1 and 2, ~0.4–0.0 mLAT) than the higher elevation eastern part (transect 3, ~0.7 mLAT). Living open-water microatolls (*Porites*) were located on the outer reef flat, with upper living rims elevated 0.37 mLAT on average.

From the reef crest, the reef sloped steeply down the fore-reef, where three zones were differentiated from the video survey of the upper half of the reef slope. Depths were not measured and thus the zones that were differentiated must be considered as generalisations. Nevertheless, six genera of live hard coral were confidently identified (*Acropora*, *Montipora*, *Fungia*, *Porites*, *Stylophora* and *Turbinaria*) in the video survey (Figure 7). Within ~2 m of the reef crest in the shallow zone 5, only robust branching and plate corals (including *Acropora*, *Porites* and *Montipora*) were surveyed, covering $47.6 \pm 38.1\%$ of the substrate. Living corals were more abundant and diverse (in terms of their structural morphology) in zone 6 between approximately 2–4 m below the reef crest. In zone 6, live coral cover averaged $74.0 \pm 22.4\%$ and branching, massive, plate, foliaceous, columnar and free-living coral growth forms existed, including *Acropora*, *Fungia* and *Montipora* and up to eight other un-identified genera. The deeper zone 7 (that was still on the upper half of the reef slope) was comprised of branching, foliaceous and plate corals (including *Acropora*, *Stylophora* and *Turbinaria*, along with soft corals) covering on average $64.7 \pm 41.6\%$.

Storm-derived geomorphological features were surveyed overlaying the reef flat survey and on the modern shoreline, indicating a long history of cyclone occurrence and associated impacts at Holbourne Island. These features include: basset edges (the cemented remnants of storm-deposited shingle ridges: Figure 1, Figure 2d) and coral blocks (~1.5 m high) emplaced on the reef flat; and storm-deposited shingle ridges on the reef flat (Figure 2c) and on and above the modern shoreline (Figure 1). The crest of the highest ridge on the shoreline reached 7.0 m above LAT. The four shingle ridges, numbered 1–4 (Figure 1) surveyed on the reef flat were comprised of storm-deposited coral rubble, where the material had been either stripped from the living fore-reef and deposited by waves on the reef flat or mobilised from pre-existing detrital rubble stores and re-worked by waves (Figure 2c). Similar sized and shaped ridges have been observed elsewhere on the GBR and in the Pacific and termed ‘rubble spits’ (Shannon et al. 2013) or ‘gravel tongues’ (Etienne and Terry, 2012). The reef flat shingle ridges were all

elongated in a roughly similar direction perpendicular to the reef crest (north-south) and were analogous in shape and size; generally 19–21 m in width and 140–200 m long (Figure 1). The ridge deposits had a steep landward slope and a gentle seaward slope and were lowest in elevation and widest near the seaward edge, where the coral rubble that comprised the ridges splayed out, covering the surrounding reef flat in coral rubble. The landward edges were abrupt and taller (higher elevation), with curved ends (Figure 2c). The maximum elevation of the shingle ridge crest varied between the reef flat ridges, generally increasing eastward: 1.0 mLAT on ridge 1 (equivalent to ~0.3 m below mean low water neap [MLWN] level); 1.4 mLAT on ridge 2; 2.3 mLAT on ridge 3; and 2.1 mLAT on ridge 4 (equivalent to mean high water neap [MHWN] level). Cemented remnants of an older shingle ridge (basset edges, Figure 2d) were located on the south-eastern part of the reef flat, oriented in the same direction as the modern shingle ridge 4 (Figure 1). The upper surface of the basset edges reached an elevation of 1.6 mLAT.

5.0 Discussion

5.1 Last interglacial reef foundation

Our precisely dated chronostratigraphy of fringing reef development reveals a new record of last interglacial reef from the mid-shelf region of the GBR. Eustatic sea level reached a maximum of ~6 m above present between 120,000 and 116,000 cal yBP, but was close to the present level (+1.0–2.0 m) ~131,000 cal yBP (Muhs et al. 2002; Murray-Wallace and Woodroffe, 2014), allowing reefs to grow on the GBR at comparable locations and depths to contemporary reefs. However, the precise age of the Pleistocene-Holocene reef boundary in the GBR remains unclear (but see Dechnik et al. 2017a) with a wide range of ages reporting a time period between $172,000 \pm 12,000$ to $107,000 \pm 8,000$ cal yBP (Marshall, 1983; Marshall and Davies, 1984; Kleypas, 1996; Braithwaite et al. 2004). Dechnik et al. (2017a) determined the timing of major last interglacial reef growth on mid-outer shelf platform reefs in the southern GBR to between

~129,000 and 121,000 cal yBP. The variability in ^{230}Th ages reported from last interglacial corals on the GBR may be due to varying degrees of sub-aerial erosion of last interglacial reef surfaces during the glacial sea-level lowstand prior to the most recent sea-level transgression (Marshall and Davies, 1984). Alternatively, variable ages may be due to the dated corals being diagenetically altered to different extents (Johnson et al. 1984). Nevertheless, the identification of last interglacial reef from a U-Th dated coral clast with an open system age of $131,100 \pm 1000$ cal yBP at 5.9 m below the present Holbourne Island reef flat surface (~5.0 m below present LAT) is an important discovery, as accounts of last interglacial coral are rare along eastern Australia (Murray-Wallace and Belperio, 1991). Moreover, this age conforms to the colonisation phase (phase 1) of GBR last interglacial reef growth (>129,000 yBP) identified by Dechnik et al. (2017a).

To date, last interglacial reef foundations have been recovered beneath few fringing reefs in the GBR (Hopley et al. 1978; Kleypas, 1996) and the Torres Strait (Woodroffe et al. 2000). Last interglacial reef provides the foundation for all Holocene reef growth so far investigated on the outer shelf of the GBR (Marshall and Davies, 1984) as well as mid-shelf platform reefs (Thom et al. 1978; Marshall and Davies, 1984; Dechnik et al. 2017a). On the central GBR, last interglacial reef is the known foundation for just one other fringing reef, at Hayman Island (Hopley et al. 1978; Kan et al. 1997), located ~25 km offshore on the inner-mid-shelf margin ~65 km south-east of Holbourne Island (Figure 1). At Hayman Island the depth to the last interglacial reef surface (~20–15 m below the surface: Harvey et al. 1979; Kan et al. 1997) was much deeper than at Holbourne Island (5.9 m below the surface). At ~5.0 m below present LAT, the last interglacial reef recovered at Holbourne Island is the shallowest confirmed last interglacial reef recovered beneath a fringing reef on the GBR. Indeed, the depth to the last interglacial reef boundary at Holbourne Island is by far the shallowest known of all reefs in the central GBR region (Dechnik et al. 2017b), where Hopley et al. (2007) suggested this boundary was much deeper than on reefs to the north and south because of possible outer-shelf subsidence

associated with postglacial hydroisostasy or longer-term structural movement. Kleypas (1996) encountered last interglacial reef substrates beneath two mid-shelf fringing reefs on the southern GBR: Cockermouth Island (~40 km offshore) at a minimum depth of 8.4 m below LAT; and Penrith Island (~70 km offshore) at a minimum depth of 6.4 below LAT. Weathered reef material assumed to be last interglacial reef was exposed at the surface of Digby Island (also in the southern GBR ~45 km offshore: Kleypas, 1996), however this assessment of age was based on the appearance of the material and is yet to be confirmed by radiometric dating. In comparison, the Pleistocene-Holocene reef boundary at Britomart Reef, a mid-shelf platform reef in the central GBR, was recovered ~20–25 m below LAT (Johnson et al. 1984). Although last interglacial reef provides the foundation for all mid-shelf fringing reefs in the GBR studied so far (Hopley et al. 1978; Kleypas, 1996), last interglacial reef foundations have not yet been recovered beneath reefs within ~20 km of the mainland. Whether this reflects a paucity of data is unknown, but will be revealed in future studies. However, the possibility that inshore fringing reefs similar to those that have developed in the mid- and late-Holocene (Smithers et al. 2006) grew during the last interglacial period cannot be ruled out. Their remnants may have been eroded, particularly given the detrital and ephemeral nature of some Holocene inshore reefs (Smithers and Larcombe, 2003), which contrasts with their offshore counterparts that developed solid, cemented limestone structures.

Basaltic rock (facies F) was encountered at the base of core D-1 beneath the Holocene reef (Figure 3). Based on observations of the contemporary shoreline at the base of the granite island outcrop and reports from other similar settings (e.g. Hopley and Barnes, 1985), facies F is probably representative of a Pleistocene boulder beach over which the Holocene fringing reef has later developed (Figure 1). Hopley and Barnes (1985) established that a terrigenous boulder beach formed the foundation for Holocene fringing reef growth at Iris Point, Orpheus Island on the inshore central GBR. This boulder beach was also exposed at the surface landward of the reef flat at Iris Point and was estimated to be of last interglacial age (Hopley and Barnes,

1985). Indeed, Hopley (1975) reported a boulder beach beneath Holbourne Island buried ~1.5 m below the surface of the sand ridge located on the island behind transect 2. This finding supports the inference that facies F forms part of a boulder beach that extends from the island beneath the back part of the reef flat. Alternatively, the basaltic rock underlying reef material in core D-1 could be representative of an *in situ* rock outcrop situated underneath the reef or a rubble deposit. These alternative possibilities cannot be ruled out, as rock outcrops currently adjoin the eastern side of the reef flat and areas on the modern reef flat contain lithic rubble that has been re-distributed alongshore from these outcrops and the boulder beach at the shoreline (Figure 1). The lack of last interglacial reef material in D-1 may be a result of either burial of last interglacial reef by the Pleistocene boulder beach, erosion, or simply because a reef did not grow in this position during the last interglacial period.

5.2 The Holocene reef chronostratigraphy

The chronostratigraphy of the cores from Holbourne Island reef reveals four key stages in reef development (Figure 3): 1) initiation over last interglacial reef foundations ~7,500 cal yBP; 2) vertical accretion towards sea level by ~6,500 cal yBP; 3) mid-Holocene reef flat progradation around 6,000 cal yBP; and 4) late-Holocene reef flat progradation from ~2,700 cal yBP continuing to the present. Initiation of the Holocene reef occurred upon a weathered last interglacial reef or over an igneous rock substrate at or prior to $7,520 \pm 20$ cal yBP in a subtidal environment ~6.2–9.0 m below palaeo-LAT (Figure 3, Figure 8). In the 1,000-year period after Holocene reef initiation, the reef accreted vertically towards sea level and reef flat formation began once the reef reached (palaeo) sea level (Figure 8) and all vertical accommodation space was occupied. The majority of reef development occurred between 7,500 and 6,000 cal yBP. The earliest known Holocene age from Holbourne Island of $7,520 \pm 20$ cal yBP indicates this reef initiated approximately 3,000 years after initiation of the mid-shelf fringing reef at nearby Hayman Island, which occurred ~10,160 cal yBP (2-sigma age range between 12,161 and 8,350

cal yBP, where a conventional uncalibrated ^{14}C age of $9,320 \pm 730$ yBP was presented in Hopley et al. 1978 and calibrated herein; see section 3.3 for ^{14}C age calibration). Earlier initiation of Hayman Island reef might be expected because the deeper substrate at Hayman Island was flooded earlier during the PGMT. Hayman Island reef is situated in a more protected environment than Holbourne Island, largely sheltered from prevailing south-easterly swells (Figure 1) and these conditions may have been favourable for earlier reef start up. A ^{14}C age from a core collected at Hayman Island reef of 5,730 cal yBP (2-sigma age range from 6,280 to 5,190 cal yBP; uncalibrated ^{14}C age of $5,360 \pm 240$ yBP presented by Hopley et al. 1978 and calibrated herein; see section 3.3 for ^{14}C age calibration) was from coral material recovered at an approximately equivalent depth to the earliest age from Holbourne Island ($7,520 \pm 20$ cal yBP ~ 5.0 m below present LAT). The shallower pre-reefal substrate beneath Holbourne Island reef (6.0 m depth compared with 15–20 m depth at Hayman Island) means that Holbourne Island reef had less accommodation space to vertically accrete until it reached sea level, while Hayman Island reef accreted over a greater depth in ‘catch-up’ mode (Neumann and MacIntyre, 1985). Hopley et al. (1978) determined average rates of reef accretion at Hayman Island to be 4–5 mm.yr^{-1} ; much faster compared to estimated rates at Holbourne Island (2–3 mm.yr^{-1}). This is not surprising given that reefs growing from deeper foundations often have much faster average annual vertical accretion rates (Davies et al. 1985).

Only one age reversal was encountered in the chronostratigraphy of Holbourne Island reef in D-1 (Figure 3) where an age ~ 820 years older ($7,520 \pm 20$ cal yBP) was encountered ~ 1.7 m above the basal age ($6,697 \pm 19$ cal yBP). Easton and Olsen (1976) suggest age gaps in reef cores can be due to irregularities in the shape of the growing reef. However, the younger, lower age could alternatively be due to storm re-working or mixing during coring (Johnson and Risk, 1987). The lower, younger coral clast was selected for dating because it was the most suitable clast for U-Th dating (most likely to be *in situ*) within the lower 1.5 m of the core and it was anticipated that this clast would provide a minimum age for reef initiation. Nevertheless, the age

reversal does not significantly alter the general age structure of reef development. It is likely the lower clast is a re-worked rubble deposit, given the prevalence of re-worked branching rubble material throughout the cores (e.g. facies D) and the presence of large storm-deposited shingle ridges onshore and on the present reef flat.

5.2.1 The role of cyclones over millennial and centennial scales

Storms have played an important role in shaping both the Holocene chronostratigraphy and the contemporary geomorphology of Holbourne Island reef over millennial to centennial timescales. Evidence for storm effects is present in the chronostratigraphy in two main forms. First, the core facies were dominated by *Acropora* rubble material encrusted on all sides with coralline algae (facies D), indicating the clasts have undergone substantial re-working. While the scarcity of well-preserved *in situ* coral material for dating in some sections of the reef cores (e.g. D-1, D-2, D-3) may limit the accuracy of the calculated reef accretion rates (Figure 3), this in itself is an interesting feature of the chronostratigraphy of Holbourne Island reef. Given the considerable amount of storm-deposited, encrusted rubble characterising the modern reef flat (Figure 1) the branching rubble material comprising facies D is likely to be imported detrital material (transported by storms/cyclones) rather than *in situ* rubble. Indeed, it is possible that this bottom layer of rubble could correspond to an old shingle ridge. Second, no ^{230}Th ages were recovered in the chronostratigraphy between $6,238 \pm 18$ to $2,683 \pm 10$ cal yBP. The large age gap in the internal reef structure could simply reflect gaps in the dating strategy, however it could also be a result of cyclone stripping during the mid-Holocene. Indeed, a similar age gap between $6,439 \pm 19$ and $1,617 \pm 10$ cal yBP was observed in the internal structure of the fringing reef at Middle Island (Ryan et al. 2016b), located 28 km south of Holbourne Island (Figure 1). Based on the abundance of re-worked rubble material in the chronostratigraphy and the nature, size and age of shingle ridge deposits located onshore at Middle Island, Ryan et al. (2016b) attributed the age gap to cyclone waves stripping the upper and outer reef structure during the mid-Holocene and redistributing this material onshore in the form of shingle ridges.

The maximum shingle ridge crest elevation at the Holbourne Island shore was very similar (7.0 mLAT) to that at Middle Island (6.3 mLAT) and it is reasonable to assume they were deposited during the same cyclone(s), due to the similar height and nature of both ridges (heavily vegetated at the time of this study) and the similar timing of the age gap in reef cores. The shingle ridge at Middle Island was dated to 4,570 cal yBP (median age with a 2-sigma age range between 4,830 and 4,280 cal yBP), where a conventional uncalibrated ^{14}C age of $4,410 \pm 100$ yBP was presented in Hopley (1975) and has been calibrated herein; see section 3.3 for ^{14}C age calibration. This age of 4,570 cal yBP lies within the age gaps in the chronostratigraphies of both Middle Island and Holbourne Island reefs, supporting the hypothesis that coral material was transported from the reef onshore around this time. The calibrated median age from a coral fragment (3,190 cal yBP, with a 2-sigma age range of 2,920 to 3,440 cal yBP) within a beachrock terrace deposit on Holbourne Island (Hopley, 1975; see Section 2.2) also suggests that coral growth on the reef must have persisted during this age gap in the core record. Interestingly, a shingle ridge at Curacoa Island in the central GBR has a similar crest elevation (~ 6.8 mLAT) to that at Holbourne and Middle Islands and was ^{14}C dated and interpreted to have been deposited during intense cyclones $\sim 4,000$ yBP by Hayne and Chappell (2001) and Nott and Hayne (2011). This reveals that intense cyclones occurred in the GBR during this time, and deposited shingle ridges onshore that remain well-preserved in more sheltered locations than Holbourne Island. The similarities in the chronostratigraphy of the reefs at Holbourne and Middle Islands, and the presence of large Holocene-aged shingle ridges (up to 7.0 mLAT) composed of mainly branching rubble material above the shoreline at both islands provides sufficient reason to infer that the cyclone-stripping concept may also apply at Holbourne Island for explaining the mid-Holocene chronostratigraphic age gap. The effects of historical cyclones on reef framework development differ in nature on mid-shelf fringing reefs (erosive) compared with their inner-shelf counterparts (depositional, Ryan et al. 2016a). Cyclones have played an erosive role in Holocene reef flat development on mid-shelf reefs, whereby it is interpreted that material was stripped from the fore-reef and transported shoreward (Ryan et al. 2016b). While this erosive process

can certainly occur at inner-shelf reefs, mid-Holocene storms have also been shown to have a depositional role in the Holocene development of reefs located on the inner-shelf close to the mainland. Ryan et al. (2016a) suggested that layers of terrigenous sediments in the chronostratigraphy of Bramston Reef (a mainland fringing reef located 30 km towards the Queensland coast from Holbourne Island) were attributable to storm-associated riverine discharge events.

Cyclones have continued to play a role in the geomorphic development and ecology of Holbourne Island reef in the past millennium. The nature and age of geomorphological features surveyed on the modern reef flat (fossil microatolls and reef flat shingle ridges) provide insights into the effects of cyclones over centennial scales. The fossil microatolls on the Holbourne Island reef flat reached 0.6 m tall and 3.6 m in diameter, indicating that ponded water up to 0.55 m deep must have existed on the reef flat for a period of up to ~180 years, based on average growth rates of *Porites* corals in this region of ~1 cm.yr⁻¹ (Lough and Barnes, 2000). The range of fossil microatoll ages from 1361 to 1984 AD indicates that moating of water up to 1.0 m above the low tide level has been active (but intermittent) on this reef flat for at least 600 years. The majority of dated samples were taken from the outer rims of the fossil microatolls and hence provide the time of mortality that likely coincided with a cyclone/disturbance event. Moating of water on the reef flat still occurs today, allowing microatolls to grow above elevations of open-water coral growth by ~0.6–1.0 m. Rainford (1925) initially proposed that a cyclone event in 1918 was responsible for the mortality of all the corals on the Holbourne Island reef flat, which Hopley (1975) confirmed based on just one ¹⁴C age from a fossil microatoll that corresponded with this 1918 event (see also Hopley and Isdale, 1977). In fact, the fossil microatoll data presented here (including five precise ²³⁰Th ages with extremely low error margins between 4 and 10 years) show that the 1918 cyclone was not solely responsible for microatoll mortality. The ages indicate that it is possible that the 1918 cyclone killed some of the fossil microatolls, but mortality of others occurred up to 600 years earlier than this (Figure

6). In that regard, our data suggest that at the very least, four major cyclones impacted Holbourne Island over the past 600 years, and caused considerable geomorphological and ecological change over the reef flat.

6.0 Conclusions

The percussion and drill cores coupled with ^{230}Th ages allowed the chronostratigraphy of the fringing reef at Holbourne Island to be established. Last interglacial reef was encountered 5.9 m below the reef surface (~ 5.0 m below present LAT) at Holbourne Island. This is the shallowest confirmed record of last interglacial reef beneath a mid-shelf fringing reef in the GBR to date. Holocene coral colonies at Holbourne Island developed upon this last interglacial reef (or directly upon a basaltic rock foundation) at or prior to $\sim 7,500$ cal yBP. The reef then accreted vertically towards sea level and began to form a reef flat by around 6,400 cal yBP. Reef flat formation occurred when sea level was ~ 1.0 – 1.5 m higher than present. Due to late-Holocene sea-level fall, the majority of the Holbourne Island reef flat is now exposed at low tidal stages. An age gap of $\sim 3,500$ years exists in the chronostratigraphy of the reef, which is attributed to cyclones. The case for cyclone stripping of the upper/outer reef structure in the mid-Holocene and deposition as shingle ridges onshore as suggested by Ryan et al. (2016b) is strengthened by the chronostratigraphy and geomorphology of Holbourne Island reef. However, a further detailed investigation of the ages of the shingle ridges located onshore at these sites would complement the chronostratigraphic records of mid-shelf fringing reef development and cyclone history. Cyclones have long had catastrophic and abrupt impacts on reef flat ecology and geomorphology at Holbourne Island, through the deposition, movement, or removal of shingle ridges. Ponding of water above the low tide level occurs today (due to shingle ridges) and has occurred at various times over the last 600 years, creating complex fields of fossil microatolls of different ages. Holbourne Island is a unique fringing reef due to its relatively exposed and isolated location on the mid-shelf of the central GBR and our chronostratigraphic

and eco-geomorphic study presents an important addition to a very small dataset of fringing reef development on the mid-shelf GBR.

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List of figure captions:

Figure 1. (a) Location of Holbourne Island and other reefs mentioned in this manuscript, central Great Barrier Reef, Australia; (b) aerial image of Holbourne Island showing core sites on the reef flat; (c) geomorphological map of Holbourne Island and reef flat, using survey data augmented with a previous map presented by Hopley (1975), showing important zones across the reef flat, transect locations (labelled T1-T3), and surveyed fossil microatolls and storm deposits (reef flat shingle ridges numbered 1–4).

Figure 2. Photographs of some of the geomorphological features or zones on the reef flat at Holbourne Island. a) moated backreef zone with living *Porites* microatolls; b) moated backreef zone with high fossil microatolls; c) landward edge of a coral shingle ridge on the reef flat; d) basset edges (photo looking towards the north-west); e) outer reef flat algal turf zone; f) outer reef flat living coral zone showing live branching, massive and plate coral morphologies.

Figure 3. Profile of transect 2 at Holbourne Island reef flat extending seaward, with reef age indicated by the uranium-thorium (U-Th) ages ($\text{cal yBP} \pm 2\sigma$) from the percussion cores (P1–P5; core locations shown by black rectangles) and drill cores (D1–D4). Percussion core logs are shown in the inset below the profile, indicating the reef facies and the carbonate and mud content of the sediment matrix. Vertical arrows indicate average reef growth rates. Elevation is relative to lowest astronomical tide (LAT).

Figure 4. a) photograph of the lower section of core D-2 showing the last interglacial reef material and the Holocene reef branching rubble material above it, and b) photograph of the last interglacial reef material.

Figure 5. Profiles of transects 1, 2 and 3 at Holbourne Island extending seaward showing elevation of the reef flat surface relative to lowest astronomical tide (LAT) and the benthic composition for each eco-geomorphological zone (numbered) in pie charts. TOB: Toe of beach. The upper surfaces of high, moated fossil microatolls (FMA) are shown. Examples of the high FMA, reef flat shingle ridges and basset edges are shown in Figure 2b, c, d, respectively. Note that the depth of the reef slope on transect 2 is estimated.

Figure 6. Microatoll ages (note that ages are presented as calendar years AD) and elevations (relative to lowest astronomical tide [LAT]). Black markers represent fossil *Porites* microatolls, with triangles indicating radiocarbon ages and squares indicating uranium-thorium ages. 2σ age errors are shown by bars. Grey circular markers represent modern living *Porites* microatolls at Holbourne Island.

Figure 7. Collection of photographs from Holbourne Island reef slope taken in 2014 by E. Ryan using an underwater drop camera showing various live coral morphologies including plate (a, g), branching (b, e, h), foliaceous, (c–d, f), free-living (e).

Figure 8. ^{230}Th ages (cal yBP) and elevations (relative to lowest astronomical tide [LAT]) of coral samples from percussion and rotary cores. Error bars are too small to warrant inclusion on the plot. A sea-level envelope is superimposed (shaded grey) to indicate relative palaeo-sea level; the envelope is drawn from palaeo-sea level data presented in Lewis et al. (2013).

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Table 1: Reef core facies descriptions with average percent mud and carbonate (CaCO₃) values of the sediment matrix.

Facies			A	B	C	D	E	F
Facies name			Contemporary intertidal sands	Reef framework, sandy matrix	Reef framework, muddy-sand matrix	<i>Acropora</i> rubble framework	Pleistocene reef	Bedrock
Description			Sandy matrix with encrusted coral rubble and shell hash	Sandy matrix with coral clasts, shell hash, bivalves	Muddy sand matrix with coral clasts, bivalve, shell hash	Recovered in drill cores, coral rubble dominated by branching <i>Acropora</i>	Cemented and altered reef framework	Granite
Environmental interpretation			Contemporary intertidal reef flat	Lower intertidal reef environment where most fine material remains in suspension	Subtidal reef environment where fine sediments can settle		Reef that was growing during the last interglacial	Underlying bedrock substrate that the present reef grew upon
Matrix component	% mud	Mean	2.1	6.5	18.0	-	-	
		SD	0.8	2.0	8.3	-	-	
	% CaCO ₃	Mean	97.3	97.4	92.8	-	-	
		SD	0.7	1.3	3.9	-	-	

Table 2: Holbourne Island reef flat eco-geomorphological zones at transect 1 (T1), transect 2 (T2) and transect 3 (T3).

	Zone	Description	Width (m)	Approximate elevation relative to LAT (m)	Average live coral cover (%)	Notes	Coral genera present (order of dominance)
T1	1	Back reef flat with coral and lithic rubble	120	~-0.4-1.2	2.8	Living microatolls present	<i>Porites, Goniastrea, Favites</i>
	2	Outer reef flat live coral zone	135	~-0.0-0.4	27.7	Living microatolls common, branching and massive corals present	<i>Porites, Goniastrea, Acropora, Platygyra, Favites</i>
T2	1	Moated back reef flat	40	~-0.7-1.0	10.3		<i>Porites, Goniastrea</i>
	2	Moated high fossil microatoll zone with coral rubble	150	~-0.7-1.4	0.6	Shingle ridge crosses this zone. Living microatolls	<i>Porites</i>
	3	Outer reef flat algal turf zone	120	~-0.5-0.8	2.0	Small coral recruits	<i>Goniastrea, Acropora, Porites</i>
	4	Outer reef flat live coral zone	130	~-0.0-0.5	38.1	Branching and massive corals dominant	<i>Acropora, Montipora, Goniastrea, Porites, Soft coral, Favites</i>
T3	1	Moated back reef flat with microatolls	40	~-1.1-1.3	5.6	Living microatolls	<i>Porites, Goniastrea</i>
	2	Moated reef flat with turf algae and rubble	150	~-1.0-1.1	0.2		<i>Goniastrea, Porites</i>
	3	Outer reef flat algal turf and living microatolls	150	~-0.7-1.0	7.1	Small coral recruits	<i>Porites, Goniastrea</i>

HIGHLIGHTS

- Holbourne Island fringing reef initiated in the early-Holocene, prior to 7,500 yBP
- Reef flat formation began around 6,500 yBP under higher sea level
- Last interglacial reef foundations underlie the Holocene reef at Holbourne Island
- Cyclones have influenced Holbourne Island reef development throughout the Holocene
- Moating of water on the reef flat has been active for at least several centuries

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Accepted Manuscript

Fringing reef growth over a shallow last interglacial reef foundation at a mid-shelf high island: Holbourne Island, central Great Barrier Reef

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