Rapid accretion of inshore reef slopes from the central Great Barrier Reef during the late Holocene

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ABSTRACT

Coral reefs from the inshore Great Barrier Reef (GBR) initiated in the early Holocene, and have undergone a period of quiescence in recent millennia after reaching sea level. However, the capacity for accretion in adjacent reef slopes that are unrestricted by sea-level constraints is largely unknown. To explore this potential, we recovered 38 sediment cores (2–5 m length) from the reef slope (5 m depth) from two inshore fringing reefs (Pandora and Havannah Reefs) from the central GBR. We obtained 115 high-precision U-series ages from the core record to reconstruct a detailed late Holocene accretion record from 1000 yr ago to the present. Computed axial tomography scans of intact cores revealed a coral matrix with voids infilled with fine-grained carbonate-siliciclastic sediment. Accretion within cores was highly constrained through time ($R^2 > 0.9$) with no evidence of age reversals, indicating continuous and rapid (average 8.8 ± 1.2 mm/yr) accretion throughout the late Holocene (i.e., 1000 yr ago to the present). Our results indicate rapid late Holocene accretion on reef slopes adjacent to senescent reef flats. Comparisons of these results with published reef accretion rates from Holocene reef flats on the inshore GBR indicate that where accommodation space is available, reef slopes continue to accrete at rates equal to and exceeding that occurring during the mid-Holocene climatic optimum.

INTRODUCTION

Throughout the Holocene, accretion rates of coral reefs (i.e., the vertical expansion of reefs by gradual accumulation) have varied substantially in time and space (Dullo, 2005). Rates of accretion are largely constrained by changes in sea level, but are influenced by a broad range of local and regional factors, including sea level (e.g., Grigg, 1998), nutrient loading (Hallock and Schlager, 1986), El Niño–Southern Oscillation (ENSO) events (e.g., Toth et al., 2012), and more recently, anthropogenic disturbances (e.g., Hoegh-Guldberg et al., 2007). Understanding rates of accretion throughout the geological past provides a baseline with which to assess future changes, and a geological context with which to interpret modern ecological trajectories of coral reefs (Perry and Smithers, 2010)

Reef accretion on the Great Barrier Reef (GBR) has been episodic throughout the Holocene, with reefs flourishing in various "turn on" and "turn off" phases of reef development (Perry and Smithers, 2010; Perry et al., 2008; Smithers et al., 2006). During the mid-Holocene climatic optimum (8000 to ~5500 yr ago), ocean temperatures and coral calcification rates were largely consistent with present-day conditions (Abram et al., 2009; Lough et al., 2014), and rising sea levels provided ample accommodation space for accretion (Lewis et al., 2013). Following this period of sustained accretion, minor sea-level fluctuations resulted in reef flats running out of vertical accommodation space (~5500–2500 yr ago; Smithers et al., 2006). Subsequently, modern inshore reefs (2500 yr ago to present) are described as being largely senescent, having undergone an apparent decline in accretion and a switch to lateral accretion following the closure of the mid-Holocene optimum window (Smithers et al., 2006).

To date, most published rates of accretion on inshore reefs of the GBR have been interpreted from cores extracted from accreting reef flat environments prior to reaching sea level (~8000 to ~2000 yr ago) or from modern shallow nearshore reefal shoals (e.g., Perry et al., 2008). Consequently, the potential for accretion in reef slopes adjacent to senescent reef flats without the constraints of sea level is largely unknown. We extracted cores from reef slopes at ~5 m depth from two inshore reefs from the Palm Islands region (central GBR; Fig. 1) and reconstructed the chronology of accretion throughout the late Holocene using high-precision thermal ionization mass spectrometry (TIMS) U-series dating (Clark et al., 2014; Roff et al., 2013). Our results indicate that rapid accretion occurs in modern reef slopes adjacent to senescent reef flats at rates equal to and exceeding those of the mid-Holocene optimum.

METHODS

Our study was conducted in the Palm Island group (central GBR) in the protected leeward sides of Pandora and Havannah Reefs. Havannah is a fringing reef surrounding a high island, and Pandora is a platform reef with a shingle cay on top that is submerged at high spring tide. Three sites were selected across leeward reef locations at Pandora Reef and two sites at Havannah Reef (Fig. 1) in 2007. Cores were extracted utilizing SCUBA and a simple open-barrel push-core technique using 10-cm-diameter aluminum tubes; at each site, seven or eight cores (two long cores, 5 m long, and five or six short cores, 2 m long) were extracted at a 90° angle to the reef slope at random along a 20 m transect (5 m depth; Fig. 2A). Compaction rates varied among cores, and ranged from 25% to 67%. Cores were sectioned lengthways in half and logged at 5 cm increments to record sedimentary facies. The remaining core halves were imaged using a multislice computed axial tomography (CAT) scan instrument (Lightspeed VCT, General Electric Healthcare). Images were

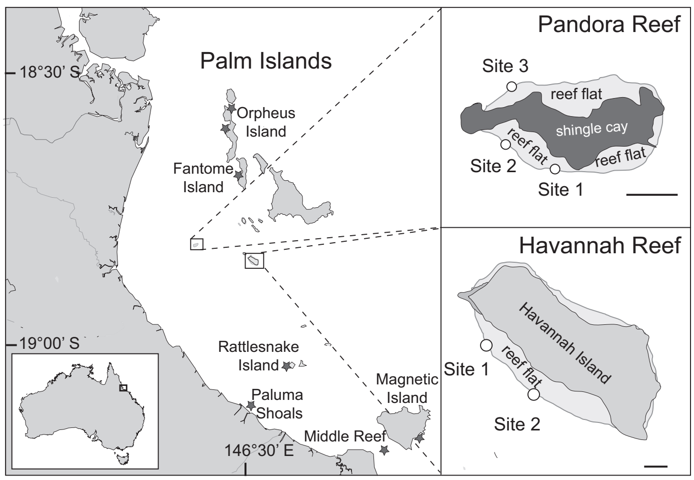

Figure 1. Palm Islands region, central inshore Great Barrier Reef (shingle cay—dark gray shading, land—gray shading, reef flat—light gray shading, continental shelf—white shading), showing locations of Pandora, Havannah, and Paluma Shoals; study sites at Pandora and Havannah Reefs are marked in inset (scale bars = 200 m). Sites of previous reef flat coring locations within the region (Orpheus Island, Fantome Island, Rattlesnake Island, Magnetic Island, Middle Reef, and Paluma Shoals) are marked with stars. Lower left inset is Australia.

GEOLOGY Data Repository item 2015125 | doi:10.1130/G36478.1
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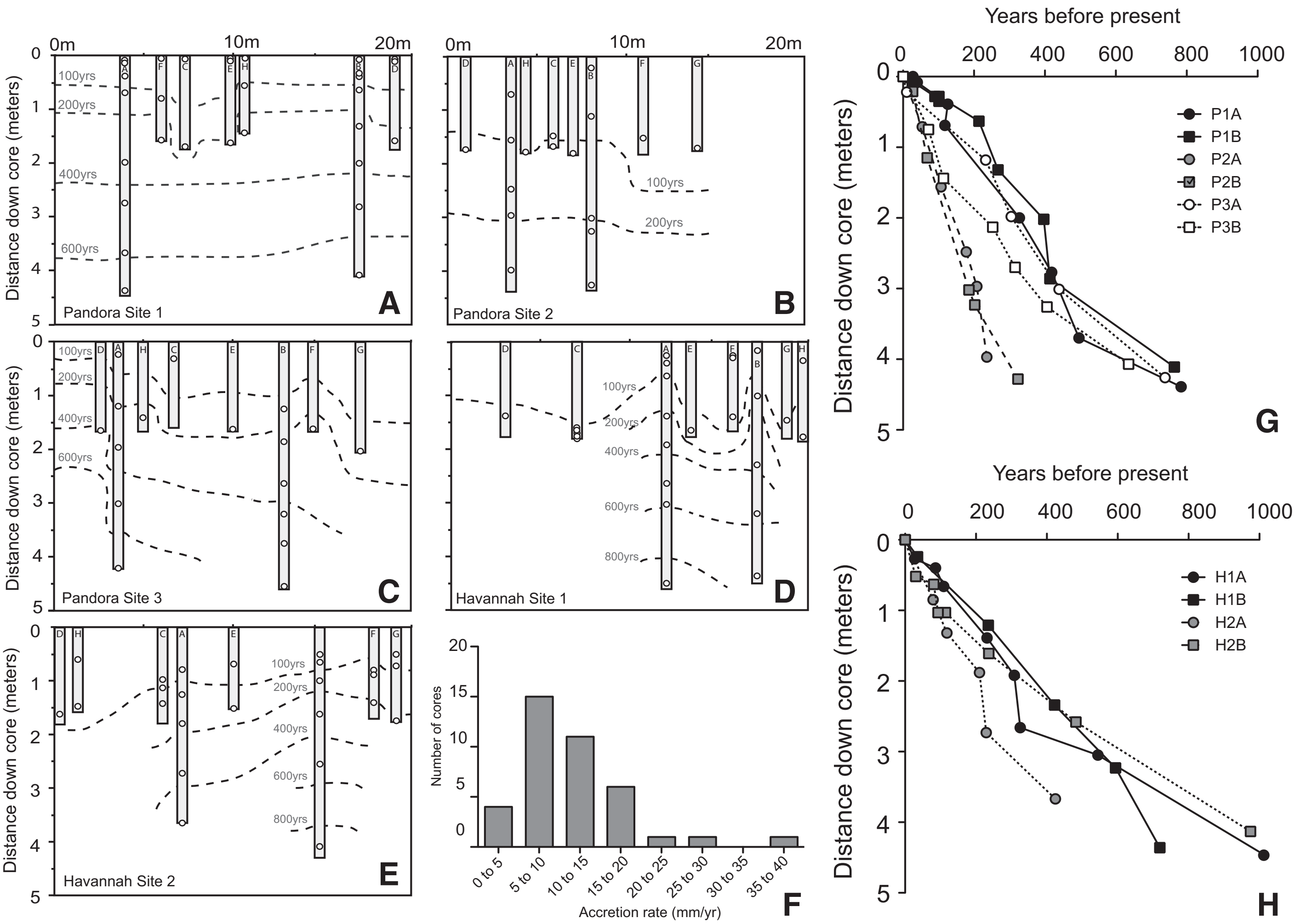

Figure 2. A–E: Reconstructions of 20 m parallel transects at each site on the Great Barrier Reef (5 m depth), with isochrons based upon U-series ages within cores recovered along each 20 m transect for Pandora and Havannah Reefs (in cores labeled A–H, depth represents uncompressed core lengths within sites; white circles within cores represent U-series dates). F: Frequency distribution of accretion rates (mm/yr) across all cores, and depth-age plots of long cores (multiple U-series ages). G: Pandora sites 1–3 (P). H: Havannah sites 1 and 2 (H).

taken in 625 µm axial slice increments using a 100 mm field of view, 110 kV, and 300 mAs. Images were reconstructed using a Bone Plus window and ultrasharp reconstruction, exported as DICOM (Digital Imaging and Communications in Medicine) files, and visualized in three dimensions using the average intensity projection mode of Osirix image software (64 bit v3.6.1; www.osirix-viewer.com).

To construct core chronologies, coral fragments were sampled for U-series dating from the bases of all cores and at intervals throughout the long cores to determine core chronologies. If live coral was present at the top layer of cores, 0 cm was considered as 0 yr, and where dead coral was present, an additional U-series age was obtained to constrain the age-depth relationship. Each dating sample was sectioned laterally and a subsample (2–3 g) was removed from the cleanest section in closest proximity to the growing margin; ~1 g of material from each subsample was used for U-series dating by TIMS at the Radiogenic Isotope Facility of the University of Queensland (Australia), following the methods described in Roff et al. (2013) and Clark et al. (2014).

A weighted least squares general linear model was used to determine the coefficient and slope within each core (stats package, R Software; www.r-project.org/foundation/). Differences between accretion rates among cores were determined using a nonparametric Kruskal-Wallis one-way analysis of variance test (stats package, R Software). Nonparametric post hoc multiple comparisons between sites were tested using the kruskalmc function (pgirmess package, R Software; cran.r-project.org/web/packages/pgirmess/index.html) to determine differences in accretion rate among sites.

RESULTS

Visual estimates of core logs and CAT scans revealed cores composed of 5%–35% carbonate and siliciclastic matrix supporting 65%–95% coral fragments from the Pandora and Havannah Reefs. In total, 115 U-series ages were obtained from multiple genera of corals among core depths (see Appendix DR1 in the GSA Data Repository[1]). Despite high levels of detrital thorium resulting from the inclusion of fine-grained siliciclastic sediments (<63 µm) embedded in coral skeletons, we obtained a relatively high level of age precision after detrital or nonradiogenic ^{230}Th correction (average of ±15 yr). U-series dating of a coral from the base of the longest core (451 cm depth) yielded an age of A.D. 1030 ± 12 yr, indicating that our analysis of accretion is constrained to within the past millennium of the Holocene.

Interpolation of U-series ages among short (~2 m) and long (~5 m) cores revealed nonuniform isochrons (successive stages of accretion)

[1]GSA Data Repository item 2015125, U-series ages and accretion data, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

within sites (Fig. 2A). Considerable variability was observed in accretion rates among cores, ranging from 3.5 to 35.2 mm/yr (average 11.5 ± 1.1 mm/yr; Fig. 2B). Significant differences in accretion rates were observed among sites (Kruskal-Wallis, $X^2 = 15.74$, $p < 0.01$). Post hoc tests (Fig. 3; Appendix DR2) revealed significantly higher accretion rates at Pandora site 2 (average 19.2 ± 2.9 mm/yr, $p < 0.05$) when compared with Pandora sites 1 and 3. No significant differences were observed among Havannah sites 1 and 2 (9.8 ± 1.2 mm/yr and 12.1 ± 1.6 mm/yr, respectively) and Pandora sites 1 and 3 (7.1 ± 1.4 mm/yr and 8.6 ± 1.3 mm/yr, respectively).

To test for patterns of change in rates of vertical accretion through time within cores, we obtained multiple U-series ages from long cores (n = 3–9 per core; Fig. 2C). Goodness of fit estimates obtained from linear regression of U-series ages within cores indicate consistent rates of accretion throughout the past 1000 yr (R^2 0.9–0.97; Appendix DR3). Multiple U-series samples from adjacent coral fragments revealed a continual record of overlapping coral accumulation within cores. No age reversals were observed within cores, with the exception of a single U-series date (7004 ± 75 yr ago) recorded from a core depth of 0.98 m.

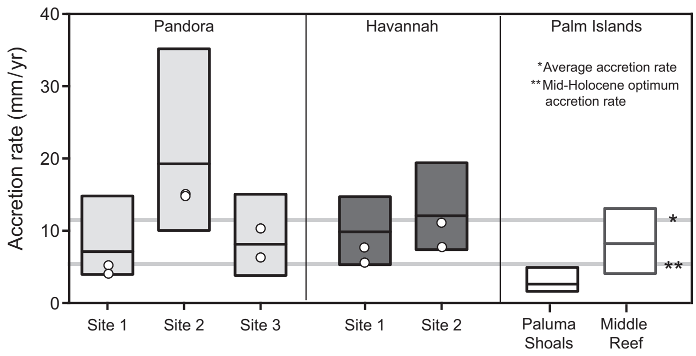

Figure 3. Average (± minimum and maximum) accretion rates for sites at Pandora and Havannah Reefs, Great Barrier Reef (long cores, n = 2, short cores, n = 5–6), and adjacent reefs within the region (Paluma Shoals and Middle Reef). Paired white circles represent accretion rates for each of the two long cores within sites at Pandora and Havannah Reefs. Mid-Holocene optimum accretion rate of 4.6 mm/yr based on published average accretion rates from inshore fringing reefs from the Great Barrier Reef (Smithers et al., 2006), and average accretion rate in our study derived from long and short cores (11.2 ± 1.1 mm/yr).

DISCUSSION

While the early Holocene history of Pandora and Havannah Reefs is unknown, fringing reefs in the Palm Islands region initiated between 8000 and 6500 yr ago upon transgressive siliciclastic sediment, or in the case of Pandora Reef, granitic foundations (Hopley et al., 2007). Reconstructions of reef sequences from these fringing reefs indicate rapid reef flat accretion and lateral expansion following initiation until the mid-Holocene (5000–3000 yr ago), when reef flats ran out of vertical accommodation space, and accretion ceased (Hopley and Barnes, 1985; Johnson and Risk, 1987). Previous studies of Holocene accretion on the GBR have largely focused on core records spanning ~8000 to ~2000 yr ago, and are almost exclusively based on ^{14}C dates that may have a compound age uncertainty of several hundred years due to nonanalytical errors related to temporal variations in atmospheric ^{14}C productions, uncertainties in local marine reservoir corrections, and terrestrial influence on fringing or inshore reefs. As such, this study is the first to document rates of accretion in modern reef slopes on the GBR. Using an unprecedented set of 115 high-precision U-series dates with mean 2σ error of only ±15 yr, our results indicate that rapid accretion of reef slopes occurred at both Pandora and Havannah Reefs from 1000 yr ago to the present day.

Despite regional-scale changes in temperature and salinity related to the Little Ice Age (Hendy et al., 2002), increased sediment flux following European settlement (McCulloch et al., 2003), and a high frequency of supercyclones throughout the Holocene (Nott and Hayne, 2001), our U-series reconstructions from short and long cores indicate that accretion was uninterrupted, consistent and rapid, averaging 11.2 ± 1.1 mm/yr. Accretion rates measured from long cores were predominantly lower than that of the average of all cores (short and long cores combined; Fig. 3). Such rapid accretion rates recorded in the short cores may reflect measurements of coral growth (i.e., short-term gross production of corals in the upper layers of cores) rather than measurements of longer term accretion (i.e., net accretion following transport and reworking). However, the average accretion rates in our study are lower than the growth rates of massive corals recorded at Pandora Reef (14.4 ± 3.50 mm/yr; Lough et al., 1999). Furthermore, the absence of rapid recent accretion in the upper layers of long cores (Fig. 2H) and the continuous accretion rates throughout the entire core lengths suggest that the chronologies obtained from long cores likely reflect patterns of net accretion over the past millennia (Fig. 2H). Alternatively, the apparent rapid accretion in short cores may reflect differential compression that occurred during the recovery of short cores. Therefore, a more conservative estimate based upon long cores alone indicates an average accretion rate of 8.8 ± 1.2 mm/yr.

By the late Holocene (1000 yr ago to present), average accretion rates of inshore fringing reef flats slowed to an average of 0.7 mm/yr (Smithers et al., 2006), primarily due to a lack of accommodation space, combined with a variable yet lower sea level within the GBR region compared to the early Holocene maximum (~1.5 m higher than present ~7000–5000 yr ago; Lewis et al., 2013). While current conditions may be suboptimal compared to that of the mid-Holocene climatic optimum (8000 to ~5500 yr ago; Smithers et al., 2006), comparisons of accretion rates reported herein (1000 yr ago to present) with previous published studies of GBR Holocene accretion rates (Smithers et al., 2006) indicate a higher average rate of accretion than that of the mid-Holocene optimum (4.6 mm/yr; Fig. 3). Comparison of reef slope accretion in our study with a late Holocene open-water reef within the region (Middle Reef; Fig. 1; Perry et al., 2012) that is similarly unconstrained by sea level revealed comparable rapid rates of accretion. Such results imply that the constraints of sea level and lack of accommodation space on adjacent fringing reef flats are primary drivers in reduced rates of accretion (Perry and Smithers, 2010).

While no reef flat cores were collected from the study sites, insights into the processes of accretion can be drawn from previous studies of accretion from reef flats within the region. While rapid rates of accretion were observed throughout the mid-Holocene at two adjacent reefs (Rattlesnake, >10 mm/yr; Fantome Island, >14 mm/yr), much of that accumulation was sedimentary and detrital rubble facies (Hopley et al., 1983; Johnson and Risk, 1987), rather than a coral-dominated matrix as described herein. The high frequency of coral fragments within our cores and highly ordered U-series ages from cores in our study indicate that reef slope accretion has continued in a consistent manner throughout the past millennium. Despite the closer proximity of Pandora Reef to the coastline and inshore sediment prism (Smithers and Larcombe, 2003) compared to Havannah Reef, no significant differences in accretion rates were observed between the two reefs, suggesting that in reef slopes, rates of accretion are independent of rates of terrigenous sediment deposition. Significant variability in accretion rates among sites at Pandora Reef may reflect higher rates of accretion and lateral expansion of reef slopes at more gradually sloping leeward sites (i.e., site 2) than adjacent sites (sites 1 and 3), and further high-resolution studies are needed to determine spatial patterns of accretion at local scales.

CONCLUSIONS

In summary, our findings indicate that rapid and consistent accretion occurred throughout the past ~1000 yr of the Holocene at both Pandora Reef and Havannah Reef slopes, and that this accretion occurred at rates exceeding the mid-Holocene optimum. Consistent with studies of nearshore reefal shoals (Perry et al., 2009, 2008) and open-water reefs (Perry et al., 2012) from the inshore GBR that exist in a similarly highly turbid environment, our results highlight the capacity for rapid accretion in habitats such as reef slopes that are unconstrained by sea level. These results highlight the importance of incorporating estimates of reef age and evolutionary state in interpreting current ecological states (Perry and Smithers, 2010), and provide a baseline for future studies documenting the changing dynamics of accretion on the inshore GBR.

ACKNOWLEDGMENTS

This project was partially funded by Marine and Tropical Science Research Facility Project 1.1.4 (Zhao and Pandolfi), an Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies grant (Pandolfi), and a Mia J. Tegner Memorial Research Grant and an International Society for Reef Studies fellowship (Roff).

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Manuscript received 25 November 2014
Revised manuscript received 22 January 2015
Manuscript accepted 26 January 2015

Printed in USA