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Influence of hydrodynamic energy on Holocene reef flat accretion, Great Barrier Reef

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ABSTRACT

The response of platform reefs to sea-level stabilization over the past 6 ka is well established for the Great Barrier Reef (GBR), with reefs typically accreting laterally from windward to leeward. However, these observations are based on few cores spread across reef zones and may not accurately reflect a reef's true accretional response to the Holocene stillstand. We present a new record of reef accretion based on 49 U/Th ages from Heron and One Tree reefs in conjunction with re-analyzed data from 14 reefs across the GBR. We demonstrate that hydrodynamic energy is the main driver of accretional direction; exposed reefs accreted primarily lagoon-ward while protected reefs accreted seawards, contrary to the traditional growth model in the GBR. Lateral accretion rates varied from 86.3 m/ka–42.4 m/ka on the exposed One Tree windward reef and 68.35 m/ka–15.7 m/ka on the protected leeward Heron reef, suggesting that wind/wave energy is not a dominant control on lateral accretion rates. This represents the most comprehensive statement of lateral accretion direction and rates from the mid-outer platform reefs of the GBR, confirming great variability in reef flat growth both within and between reef margins over the last 6 ka, and highlighting the need for closely-spaced transects.

Introduction

A widely accepted, two-phase model of Holocene reef growth was developed from drilling investigations in both the Caribbean and the Great Barrier Reef (GBR) (Davies et al., 1985; Neumann and Macintyre, 1985). This model includes a rapid phase of vertical accretion, as reefs are forced to catch-up/keep-up with post glacial sea-level rise followed by a lateral accretion phase once sea level stabilized. Limited vertical accommodation as reefs approach sea level is thought to be the dominant controlling factor responsible for this shift into progradation (Marshall, 1982). For the mid-outer platform reefs of the GBR (Hopley et al., 2007), Davies, Marshall and others (Davies and Marshall, 1979; Marshall and Davies, 1982; Davies and Hopley, 1983; Davies et al., 1985; Marshall and Davies, 1985) used this basic reef growth model to demonstrate that the lateral accretion phase of reef growth was generally dominated by accretion in a lagoonal direction with less accretion seaward. Similar growth patterns were identified on many fringing reefs, including those of the Ryukyu Islands (Kan et al., 1995), Hawaii (Engels et al., 2004; Grossman and Fletcher, 2004) and Thailand (Scoffin and Le Tissier, 1998). Pre-Holocene slope morphology and exposure to strong wind and wave energy were identified as controlling factors, influencing the direction and extent of reef flat extension (Marshall and Davies, 1981; Hopley, 1982; Kan et al., 1995; Grossman and Fletcher, 2004).

Investigations of reefs with double-rimed windward fronts in the central GBR (Davies and Gable reefs) (Hopley, 1982) and recent data from closely-spaced transect cores at Heron Reef in the southern GBR (Webb et al., in press) show evidence of seaward accretion, inconsistent with traditional growth models in the region (Marshall and Davies, 1982, 1985; Hopley et al., 2007). Additionally, the few previous reef flat accretion rates calculated in the GBR represent inner shelf reefs (Hopley et al., 1983; Kleypas, 1996; Smithers et al., 2006; Palmer et al., 2010), where high turbidity and nutrient content associated with proximity to terrestrial sources have influenced reef development (Smithers et al., 2006; Palmer et al., 2010; Perry and Smithers, 2010). Furthermore, the majority of these inshore fringing reefs initiated growth on gently sloping Pleistocene sediments, as opposed to the mid-outer shelf reefs, which developed on broad antecedent platforms with steeply sloping antecedent fore-reefs (Smithers et al., 2006; Hopley et al., 2007). For the mid-outer platform reefs, accretion direction and rates were

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calculated from one or a few isolated cores distributed over a range of reef zones, commonly biased towards windward margins (Davies and Hopley, 1983). While isolated cores capture the chronologic and stratigraphic history of the transgressive growth phase, they do not necessarily distinguish vertical aggradation from lateral accretion (Blanchon and Blakeway, 2003). Only multiple, closely spaced (<50 m) core transects can capture the full response of reefs to the Holocene stillstand, including the rate and direction of lateral accretion.

Therefore, we present lithologic and chrono-stratigraphic data from 34 new, closely spaced short cores recovered from nine transects across One Tree Reef (OTR) and Heron Reef (HR), to assess the direction and rate of lateral accretion of exposed and protected reef flat margins, in response to Holocene sea-level stabilization. For the purposes of this discussion we define the reef flat as including the reef crest, coralgal flat, rubble band and coral windrows (adapted from Thornborough and Davies, 2011), and lateral accretion as including the seaward and/or lagoonal expansion of the reef flat, irrespective of the location on the windward or leeward margin. To produce a refined stillstand reef growth model, our specific objectives are to 1) establish the precise timing of when and where reefs in the GBR first approached modern sea level; 2) determine the effects of hydrodynamic exposure and fore-reef slope morphology on the rate and direction of reef flat accretion; and 3) investigate the effects of hydrodynamic exposure on reef flats at other mid-outer platform reefs in the GBR.

Field settings and methods

HR (23° 27′S, 152° 57′E) and OTR (23° 30′S, 152°05′E) represent two mid-shelf reefs in the southern GBR (Fig. 1). The dominant direction of hydrodynamic energy is from the southeast with an average significant wave height of 1.15 m, semi-diurnal tides and a spring tidal range of 3 m (Vila-Concejo et al., 2013). Southeast trade winds dominate most of the year (Marshall and Davies, 1982). HR is located approximately 6.5 km northwest of OTR and is protected from the dominant direction of wind and wave energy by Sykes Reef to the east, Wistari Reef to the west and OTR to the southeast. OTR is located closer to the shelf margin, with no proximal reefs on its borders to protect it from prevailing ocean swell.

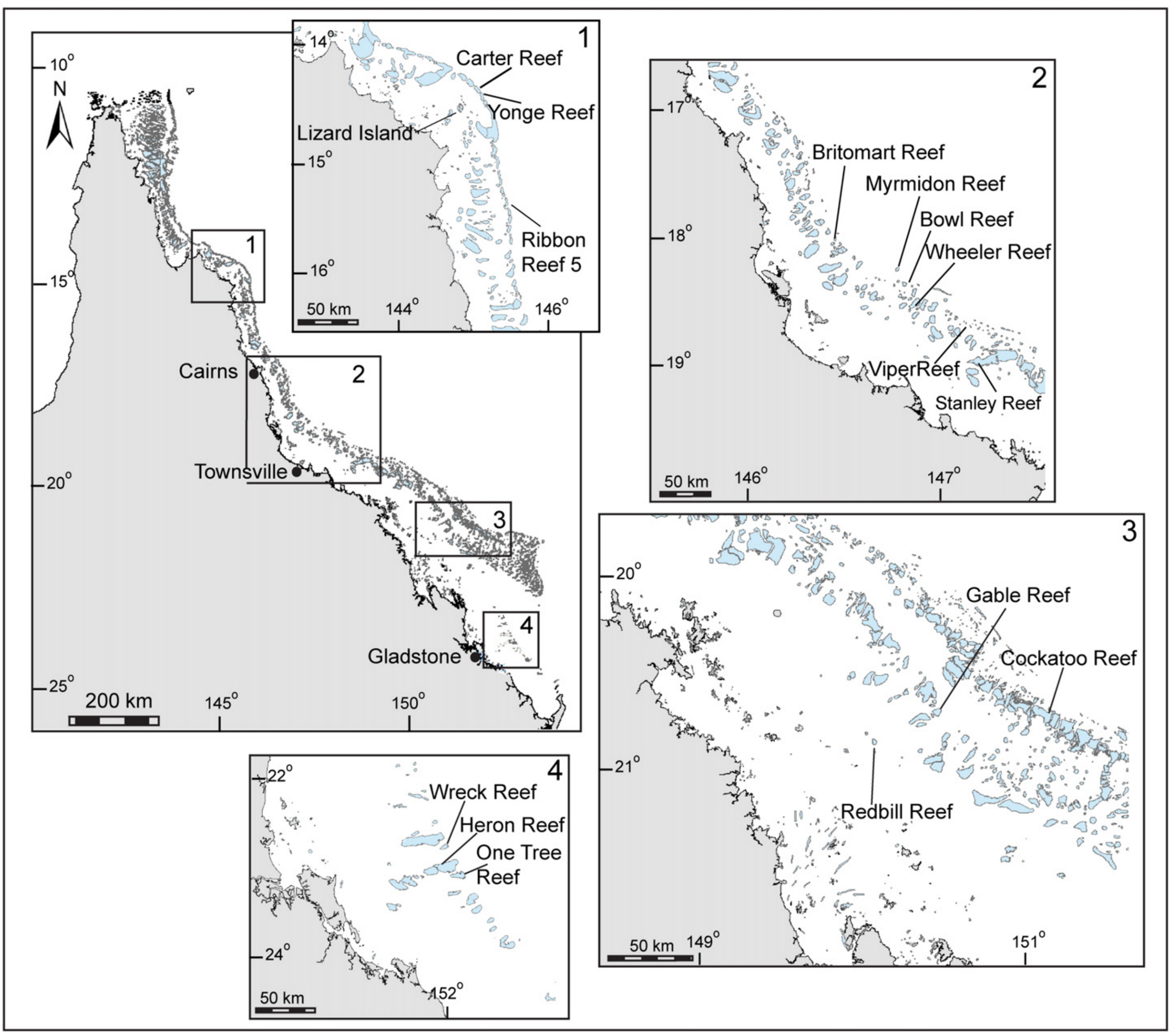

Figure 1. Location of the 16 reefs examined by this paper in the Great Barrier Reef, including Heron and One Tree reef.

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Thirty-four new short cores, approximately 1 m in length, were collected from HR and OTR, using a hand-held petrol powered drill attached to a 7-cm-diameter diamond core bit. Transects were drilled across the reef platforms to better capture the lateral accretion of the reef. Surface elevations of the short cores were determined using a Trimble R8Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) with a positional accuracy of ± 4 cm (Supplemental Table 1).

Lithologic facies and coralgal assemblages were logged in accordance with Camoin et al. (2007). The context of sampled coral colonies were classified as either in-situ (IS), not in-situ (NIS) or not enough information (NEI) based on criteria established by Abbey et al. (2011). Core chronology consisted of 49 new U-series dates and 30 previously published dates from HR and OTR (Supplemental Table 1, Figs. 1 and 2). All other previously cored mid-outer shelf reefs on the GBR were also investigated (N = 27), but only 14 additional reefs (Lizard, Cockatoo, Stanley, Younge, Bowl, Viper, Ribbon Reef 5, Gable, Carter, Myrmidon Britomart, Redbill, Wheeler and Wreck) could be included in the meta-analysis owing to the requirement for a minimum of two cores within a transect from a single margin (Supplemental Table 2).

Corals that were interpreted to be in growth position and free of obvious detrital contamination, microbialite encrustation or organic staining were cleaned in fresh water and vetted for dating using thin section petrography and scanning electron microscopy (SEM) (Nothdurft and Webb, 2009; Sadler et al., 2014). Corals with no microbial micrite and minimal syntaxial aragonite cement, microborings and dissolution were selected for dating using U-series techniques on a Nu Plasma multi-collector-inductively coupled plasma-mass spectrometer (MC-ICP-MS) in the Radiogenic Isotope Facility at the University of Queensland. Multiple subsamples were dated from selected corals (Supplemental Table 1).

Subsamples of vetted corals were crushed to chips (~1–2 mm in diameter) and inspected under a compound microscope. Only chips that lacked obvious cement, microbialite or staining were selected for dating. Chips were cleaned in 10% H_2O_2 for 24 h followed by rinsing in milliQ water with sonication for 15 min before three additional rinses in milliQ water. Samples (0.15 g) were spiked with a ^{229}Th–^{233}U mixed tracer and dated following a modified and simplified column separation procedure and a fully automatic MC-ICP-MS measurement protocol described in detail in Zhou et al. (2011) and Clark et al. (2014a,b). Ages were calculated using Isoplot Program EX/3.0 of Ludwig (2003) using decay constants of Cheng et al. (2000).

For the fourteen reefs included in the meta-analyses (Lizard, Cockatoo, Stanley, Yonge, Bowl, Viper, Ribbon Reef 5, Gable, Carter, Myrmidon Britomart, Redbill, Wheeler and Wreck), the previously published ages (Table DR2 in Data Repository) were recalibrated using calibration software (Calib7.0) (http://calib.qub.ac.uk/calib/; accessed June 2014). Marine reservoir correction value ΔR 12 $\pm$ 5 were used in all calculations, as this represents the best estimate of variance in marine reservoir effect for the mid-outer shelf reefs along the East Australian coast (Druffel and Griffin, 1999) (Supplemental Table 2). However, for ages older than ~5.4 ka there may be significantly larger ΔR, resulting in possible larger calibrated age errors (Hua et al., 2015). The new U-series ages produced in this study were adjusted to years before 1950 for easy comparison to previously published radiocarbon ages. To provide a neutral sea-level datum across all sites, all depths were replotted to mean sea level (MSL).

While only the ages from the top 1 m of the reef flat were reported in cores from this study, chronologic and stratigraphic comparisons were made with the previously published long cores where possible from both HR (Webb et al., in press) and OTR (Dechnik et al., 2015) in order to identify any age anomalies. Core distance from windward or leeward reef crests was calculated using high resolution aerial imagery. For the meta-analysis, distances were normalized as a ratio over the entire reef flat (from the edge of the crest to the inner end of coral windrows), so reefs with variable reef flat sizes could be more readily compared. Linear regressions using PRIMER 6 were used to assess the correlation between the age of the reef flat and the distance from the reef crest (Supplemental Tables 1 and 2). Mean lateral accretion rates were calculated on x-intercepts of lines of best fit for the top-most in-situ ages.

A GIS model (GREMO; Pepper and Puotinen, 2009) based on normalized wave fetch scenarios and typical wind patterns was used to classify reef margins as either exposed or protected (Fig. 2, Supplemental Table 3). Fetch distance was calculated in 30° increments at points spaced approximately every 500 m around the reef flat. Wind speed and direction statistics were calculated on the basis of wind data from the Bureau of Meteorology weather station, closest to each reef (Supplemental Table 3). Normalized values were calculated by dividing the wave exposure determined for a given site point by the theoretical maximum values that the site could possibly have, if 100% exposed in all directions at a wind speed of 16 m/s (just below cyclone strength). Thus wave exposure normalized to a theoretical maximum allows for comparisons between reefs.

Results

An overall pattern of lagoon-ward accretion is observed on both windward and leeward margins at OTR. The exposed outer windward margin, closest to the reef crest, reached MSL across transects 1, 2 and 3 at 6.65 $\pm$ 0.02 to 6.23 $\pm$ 0.01 ka, 6.07 $\pm$ 0.02 ka and 6.45 $\pm$ 0.02 to 6.15 $\pm$ 0.02 ka, respectively (Figs. 3A–E). However, on the protected leeward margin greater age variability and fewer in-situ dates from the inner coralgal rim make pattern determination more difficult. There the outer reef margin approached MSL at 5.86 $\pm$ 0.02 ka, and the most reliable in-situ ages for the inner coralgal rim range from 4.25 $\pm$ 0.42 ka to 6.18 $\pm$ 0.03 ka (Figs. 3A–E). Active accretion of the reef flat at OTR appears to have "turned-off" at approximately 2 ka, with the exception of one core date (1.25 ka) located on the inner reef margin. These results are consistent with the hiatus in reef growth after 2 ka identified by Harris et al. (2015), which coincided with a regional fall in sea level at approximately that time (Lewis et al., 2012). Results from the other exposed mid-outer platform reefs are consistent with the OTR model, with 80% of reefs showing a negative correlation between age and distance (R = 0.46), becoming younger to the lee with distance from the reef crest, indicating accretion in a lagoon-ward direction and little seaward accretion (Fig. 4).

An overall pattern of seaward accretion is observed on the leeward margins of HR, with reef flat ages becoming younger towards the crest. However, it remains unclear how far lagoon-ward the northern and southern leeward protected margins first approached MSL as transects did not extend that far from the margin. Long core data from Webb et al. (in press) suggest that the inner reef flat on the northern margin of HR first approached MSL between 6 and 7 ka and started accreting laterally by ~6.5 ka. Short core dates near the reef margin are as old as 5.63 $\pm$ 0.01 ka (Figs. 3A–C). Accretion continued seaward to near the modern reef crest between 1.86 $\pm$ 0.01 to 1.08 $\pm$ 0.01 ka on the southern margin and 4.10 $\pm$ 0.020 to 3.93 $\pm$ 0.10 ka on the northern margin. Similarly, all other mid-outer protected platform reefs showed a positive correlation (R = 0.40) between age and distance, with reef flats accreting seaward, becoming younger towards the crest, with all reefs conforming to this pattern (Fig. 5).

Reliable comparisons of reef flat accretion rates can be made between the windward margin of OTR and the leeward margin of HR (Fig. 6). Windward accretion rates at OTR vary from 86.3 m/ka at transect 1 to 42.4 m/ka at transect 2 to 54.9 m/ka at transect 3. The lower energy leeward margins of HR show even greater variation, averaging 15.7 m/ka, 68.4 m/ka, 58.3 m/ka and 19.6 m/ka (Webb et al., in press) at transect 1, 2, 3 and 4, respectively. The few in-situ dates recovered from the leeward margin of OTR make robust accretion rates difficult to establish (T4/5 = 473.8 m/ka); and while the leeward reef

Figure 2. Normalized wave exposure estimates for 16 reefs on the Great Barrier Reef (see also Supplemental Table 3). Wave exposure estimates were based on measurements of fetch at a series of individual locations around each reef (black dots — modal points) given typical wind patterns. Hollow circles show core locations.

flat appears to accrete in both directions, there is only one reliable age (5.86 ka) available on the outer coralgal rim (see Fig. 6).

Discussion

Hydrodynamic exposure and reef flat accretional direction

Using cores from the southern GBR, Marshall and Davies (1982, 1985) demonstrated that maximum lateral expansion of the reef flat occurs on the windward margin, towards the lagoon. This model has been shown to be widely applicable to many other reefs of the GBR (Hopley et al., 2007) and our data from One Tree and other exposed mid-outer platform reefs confirm and better constrain this model. In contrast, both HR, and other protected mid-outer shelf reefs in the GBR suggest a more complicated growth pattern, with the inner reef margin approaching MSL first and then continuing to accrete seaward.

For the mid-outer platform reefs of the GBR, Hopley (1982), Hopley et al. (2007) noted that pre-Holocene substrate parameters, including depth, shape and antecedent slope morphology, were strong controlling factors influencing Holocene reef growth and development. In particular, gently sloping fore-reefs with antecedent reef flat terraces were thought to enhance the extent of modern reef flat accretion, providing significant accommodation adequately shallow to allow prolific fore-reef growth, in some cases producing secondary windward reef rims (Hopley, 1982). In contrast, reef slopes with steep vertical scarps that lacked shallow fore-reef terraces, such as many of the Northern Ribbon reefs, were restricted to lateral accretion in a lagoon-ward direction (Hopley et al., 2007).

Pre-Holocene substrate at OTR has been identified in cores (Davies and Hopley, 1983; Dechnik et al., 2015) and seismic data (Marshall and Davies, 1981) to be approximately 13 m below sea level (MBSL) beneath the rims of both windward and leeward margins. Echo sounding profiles show a relatively steep reef slope (~10°) on the southern windward margin from low tide level to approximately −10 m (Davies and Marshall, 1979). Below this, a steep vertical scarp extends to approximately −40 m at its deepest point, with little to no coral cover. Davies and Marshall (1979) dated samples from this scarp and suggested that it was pre-Holocene in age, concluding that the reef flat had accreted in a primarily lagoon-ward direction with little seaward accretion on the windward fore-reef slope during the Holocene. While core data and morphologic fore-reef slope data suggest the southern windward reef flat first approached sea level near the current reef crest at 6 to

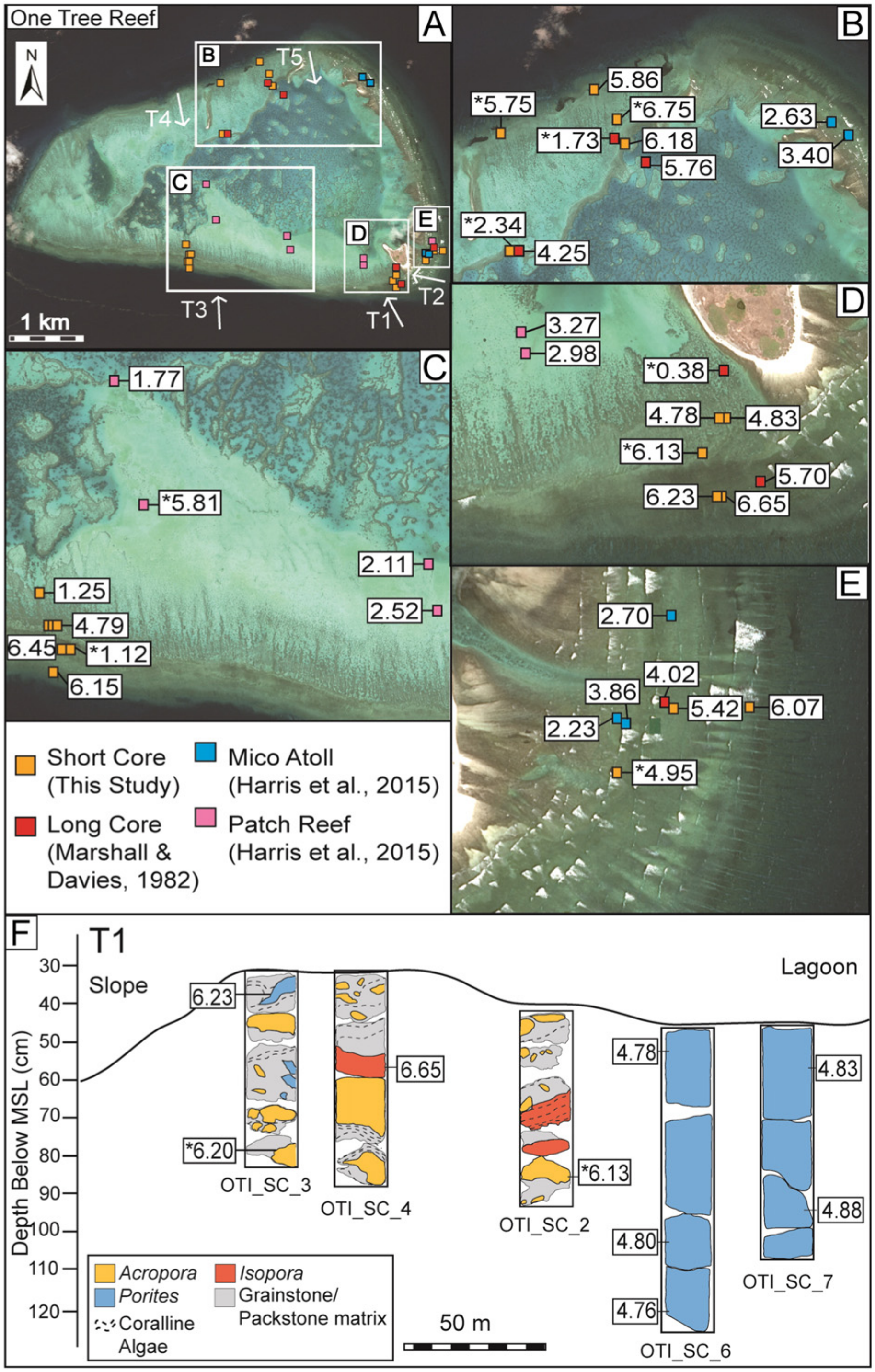

Figure 3. A) Location of the five transects analyzed, based on previously drilled and new short cores at One Tree Reef. B–E) Representative images of each of the core transects, with the top-most in-situ ages displayed for each core. F) Representative short core transect (T1), showing spatial and temporal chronologic and lithologic changes within each core. *Ages identified as not in-situ (NIS) or not enough information (NEI).

7 ka and then continued to accrete laterally in a largely lagoon-ward direction, little information is available for the eastern windward fore-reef slope. Nevertheless, a similar core age of 6.13 ka, situated less than 10 m from the eastern reef crest, suggests an analogous history of lateral accretion in a lagoon-ward direction.

Echo sounding profiles of the Pleistocene basement on the leeward southern margin at HR show a relatively gentle slope (~3°) with terraces at ~−9 and −15 m (Jell and Flood, 1978). In contrast, the northern leeward margin is generally much steeper with a slope of 15° from the crest to −25 m (Jell and Flood, 1978; Jell and Webb, 2012). While there is no evidence of reef terraces on this margin, a secondary reef rim occurs on its outer edge. Although no deep core was obtained from the outermost rim in the long core transect (Webb et al., in press), an in-situ coral from a short core from the secondary rim returned an age of 3.9 ka, suggesting very little seaward accretion of that section of reef flat since then. In contrast, on the opposing southern reef margin, the reef has continued to accrete to at least 1.08 ka and is presumably still accreting (Fig. 3). Therefore, we suggest that the northern leeward margin may have initiated reef growth closer to the edge of the antecedent platform than occurred at the southern margin, and thus

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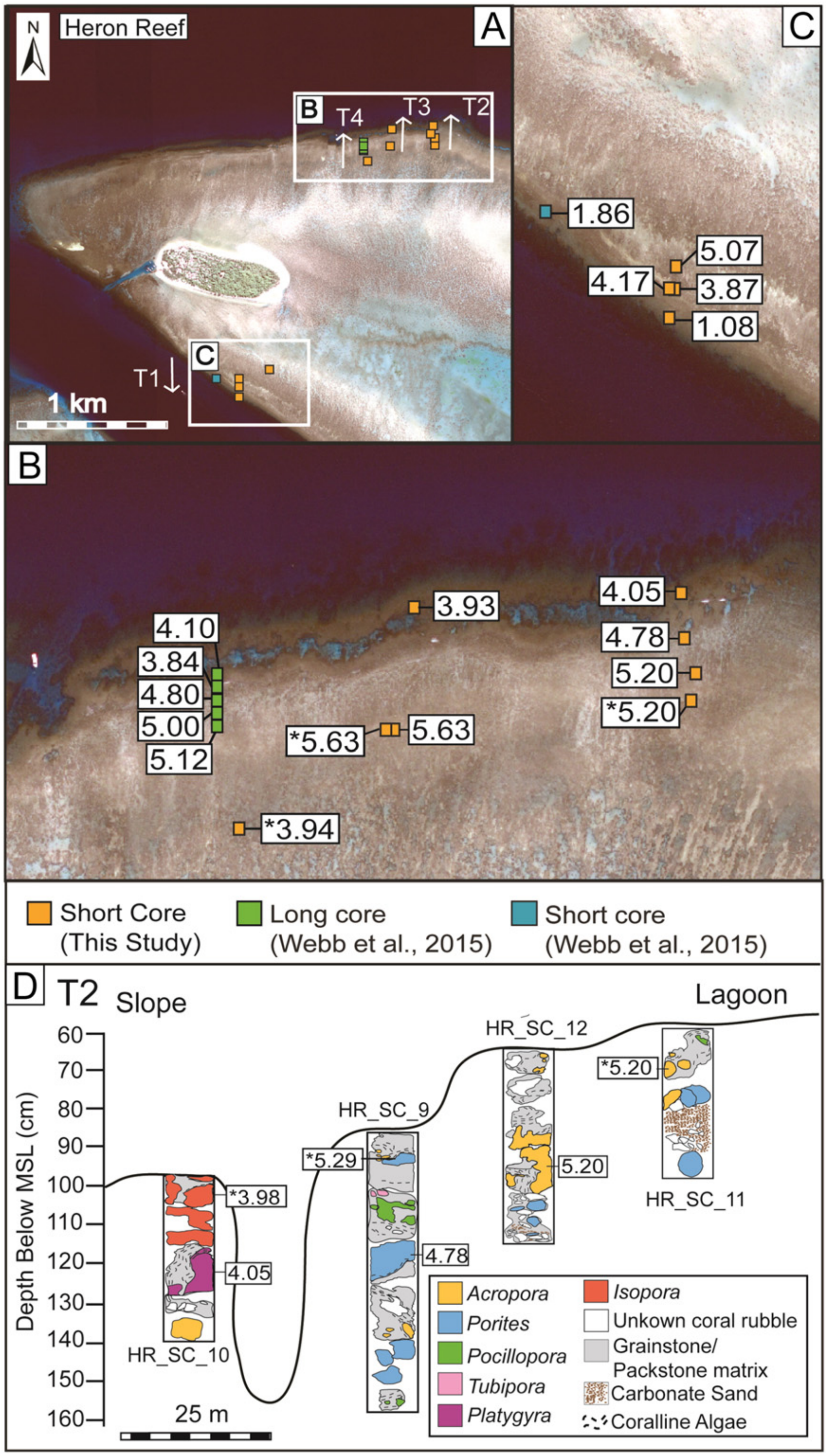

Figure 4. A) Location of the 4 transects analyzed based on previously drilled and new short cores at Heron Reef. B–C) Representative images of each of the core transects, with the top-most in-situ ages displayed for each core. *Ages identified as not in-situ (NIS) or not enough information (NEI). D) Representative short core transect (T2), showing spatial and temporal chronologic and lithologic changes within each core.

ran out of lateral accretionary space on the antecedent platform earlier. Alternatively, the steepness of the reef slope on the northern margin may have impinged lateral accretion of the reef flat after 4 ka, while the gently sloping southern margin allowed for continuous lateral accretion.

Both the northern margin of HR and the southern windward margin of OTR have similar fore-reef slope gradients, yet they accreted in opposite directions, suggesting that the morphology of the fore-reef slope may not be the dominant controlling factor. Alternatively, this may be attributed in part to differences in the direction of sediment transport and residence time between the exposed windward OTR margin and the protected southern HR margin. Braithwaite et al. (2000) observed similar differences in reef accretion patterns in Holocene cores from the Seychelles and devised a synoptic accretional model of reef growth. That model suggests that exposure of a reef to moderate to high hydrodynamic energy would be sufficient to flush sediment from

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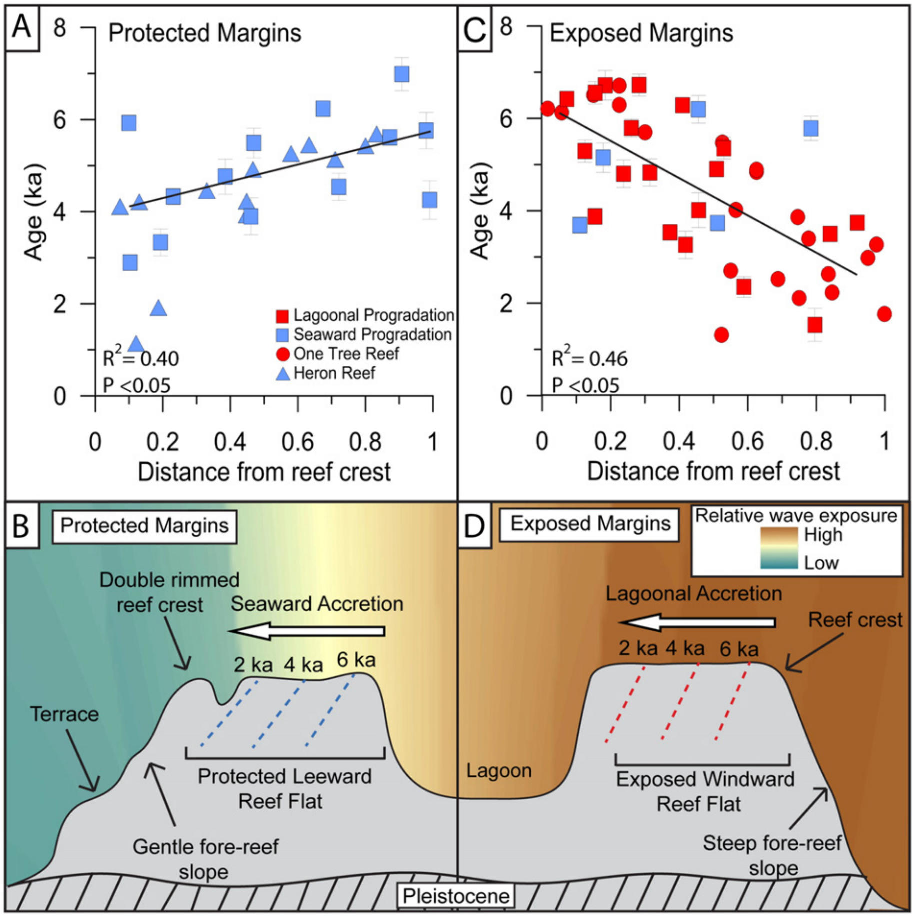

Figure 5. A) Linear regression showing correlation between age and distance (ratio) from the protected reef crest at HR and other protected mid-outer platform reefs. B) Conceptual model showing the predicted relationship between level of exposure of a protected reef margin and direction of lateral accretion. C) Linear regression showing correlation between age and distance (ratio) from the exposed reef crest at OTR and other exposed mid-outer platform reefs from the GBR. D) Conceptual model showing the predicted relationship between level of exposure of a protected reef margin and direction of lateral accretion. Error bars are smaller than symbols.

their systems but maintain reef framework growth, without significant breakage. Conversely, lower energy environments would experience longer residence time of sediments, with less energy available to flush the reef, resulting in retention of unconsolidated sediment, thus forming a substrate upon which lateral accretion could occur. Transport of isolated reef colonies and fragments would then provide important colonizing substrate for seaward accretion, analogous to the reef windrows clearly observed accreting over the southern sand sheet of OTR (Fig. 3). Hence, it is possible that a longer residence time of sediment on HR's protected northern margin allowed greater sediment accumulation, creating a sediment wedge upon which the leeward margin of HR has been able to accrete seawards. Conversely, the windward margin of OTR (Fig. 4) was restricted to accretion in a lagoon-ward direction because significant sediment thicknesses were unable to accumulate on the steep, high energy windward fore-reef slope. Exposure to strong wind and wave energy would have directed most sediment back into the lagoon, consistent with the original OTR model of windward to leeward lagoonal infilling (Marshall and Davies, 1982; Harris et al., 2015) and providing the shallow substrate necessary for reef flat colonization and accretion of the coral windrows. Hence, while the lack of vertical accommodation as the reef approaches sea level is widely accepted to produce an overall lateral accretionary response across most reef flat margins (Davies and Marshall, 1979), the level of exposure to hydrodynamic energy ultimately determines whether this will be seaward or lagoon-ward directed accretion.

No comparable echo sounding profiles exist for the other mid-outer platform reefs analyzed in this study, and thus we can only speculate about the steepness of the reef slopes of those reefs. However, in their review of inshore GBR reefs, Smithers et al. (2006) proposed a structural classification for fringing reefs, modified from Hopley and Partain (1987), which showed lateral accretion to occur almost invariably in a seaward direction, rocky foreshores being the exception, where the fore-reef morphology is much steeper. Kennedy and Woodroffe (2002) also developed generalized models for fringing reefs, with models B and C (Fig. 15 of Kennedy and Woodroffe, 2002) developed from accretion patterns observed at many inshore fringing reefs from the GBR. These models suggest that lack of vertical accommodation and gentle fore-reef morphologies allowed the reefs to accrete laterally in a seaward direction (Kennedy and Woodroffe, 2002). Whereas the basements upon which fringing reefs of the GBR develop are not directly analogous to the mid-outer platform reefs, a similar pattern of seaward accretion in relation to gentle fore-reef slopes was observed in this study. Furthermore, inshore reefs are significantly more protected from the prevailing wind and wave energy directed from the southeast than the mid-outer platform reefs (Hopley et al., 2007). In our study a correlation between wind and wave exposure and the direction of lateral accretion is apparent with all of the protected reefs recording a pattern of seaward accretion, suggesting a similar history for both the leeward margins of HR (Fig. 2) and the inshore fringing reefs of the GBR. Determination of the specific energy threshold that controls whether seaward or lagoon-ward directed accretion occurs is not possible (Roberts et al., 1977; Suhayda and Roberts, 1977), but our fetch model shows a clear correlation between relative wave exposure and direction of lateral accretion. The results from HR and OTR demonstrate that the traditional growth model of windward to leeward reef accretion does not hold true for lower energy, protected platform reefs.

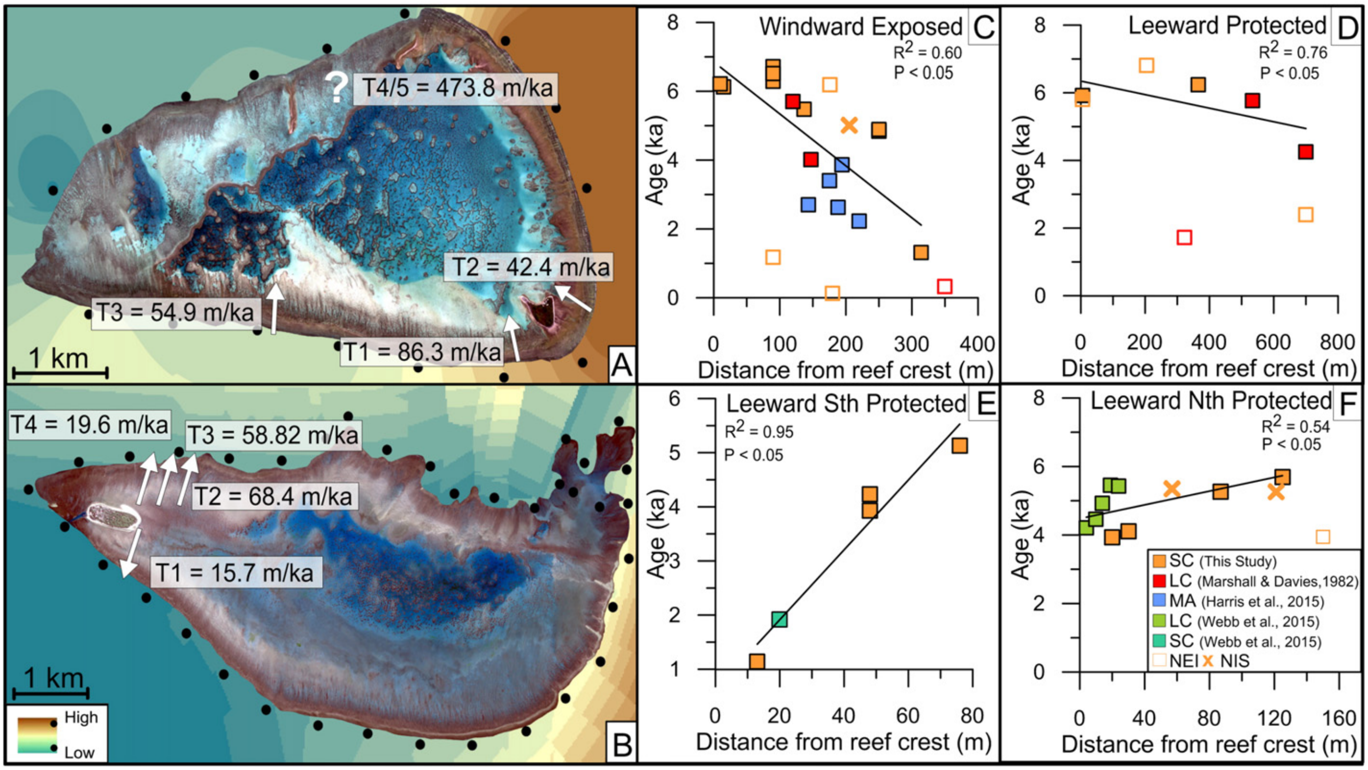

Figure 6. Rate and direction of reef flat lateral accretion at the various reef transects, superimposed on wave exposure data based on fetch measurements at A) OTR and B) HR (black dots — modal points, represent where individual fetch measurements were taken). Linear regression showing correlation between age and distance at C) Windward, D) Leeward margin of OTR, E) Southern leeward and F) Northern leeward margin of HR. Error bars are smaller than symbols.

However, more closely spaced reef core transects and age data, as well as bathymetric analysis of reef slopes, are required to further confirm the pattern.

Hydrodynamic exposure and rates of reef flat accretion

Rates of vertical reef accretion are relatively well established, particularly for the mid-outer platform reefs of the GBR (Marshall and Davies, 1982; Davies and Hopley, 1983; Hopley et al., 2007), where sufficient drill core material has been collected and dated. Rates of lateral accretion have received comparatively little attention, particularly on coral atolls and platform reefs (Masse and Montaggioni, 2001; Hopley et al., 2007). Yamano et al. (2003), provided one of the most comprehensive reviews of lateral accretion rates for fringing reefs in the Pacific and Indian Ocean, with rates ranging from 8 m/ka to 333 m/ka. In their review, reefs exposed to greater hydrodynamic energy were identified as having greater lateral accretion rates than protected reefs (Yamano et al., 2003). Conversely, Scoffin and Le Tissier (1998) found the highest rates of lateral accretion on fringing reefs in Thailand occurred on sheltered, low energy reefs (80 m/ka) compared to more exposed reef margins (17 m/ka). On the inshore reefs of the GBR a lateral accretion rate of 62 m/ka was reported for Orpheus Island (Hopley et al., 1983), whereas Johnson and Risk (1987) reported a rate of 111 m/ka for the nearby Fantome Island. Smithers et al. (2006) reviewed lateral accretion rates for inshore and fringing reefs of the GBR and found that approximately 50% of studied reef flats accreted rapidly, completely outgrowing their available lateral accommodation within a ~1.5-ka window between approximately 6 ka and 5.5 ka. The other 50% of reefs accreted much more slowly, taking as long as 6 ka to accrete a similar distance. Those authors suggested that optimal conditions for reef flat growth occurred in response to the Holocene "high energy window" (Hopley, 1984), prior to 5.5 ka, and that the higher energy conditions accounted for the rapid accretion on many of those reefs. However, they were unable to explain why other reefs, such as Dunk Island and Great Palm Reef, were unable to accrete at similar rates during the same time interval despite having sufficient seaward accommodation available (Smithers et al., 2006). They did note, however, that slower rates of lateral accretion after 5.5 ka were likely a response to falling sea level and or input of terrestrial sediments that may have limited carbonate production in nearshore environments (Smithers et al., 2006; Palmer et al., 2010; Perry and Smithers, 2010).

This study found no definitive relationship between reef accretion rates either within or between the margins at HR and OTR. Specifically, on the northern leeward margin of HR, lateral accretion rates vary from 19.6 m/ka to 68.4 m/ka despite the transects being less than 200 m apart. This is not surprising, however, as reefs are highly complex and dynamic ecosystems where numerous controlling factors, including wind and wave energy, turbidity, and facies and framework composition, may all influence the reef simultaneously, at local and regional scales (Kennedy and Woodroffe, 2002; Montaggioni, 2005). Additionally, heterogeneous topography on the antecedent platform may impart major local effects. Furthermore, establishing clear patterns in the rates of lateral accretion between transects of different sizes (e.g., 20 m at T3 and 100 m at T2 at HR) is challenging (Blanchon and Blakeway, 2003). Nevertheless, closely spaced core transects from HR and OTR provide some of the first robust lateral accretion rates calculated for the mid-outer shelf platform reefs, which broadly fall within ranges observed on the inner shelf and fringing reefs of the GBR. Based on the large variability in accretion rates both within and between the inner and mid-outer shelf reefs in the GBR, we suggest that exposure to hydrodynamic energy is not the strongest influence on lateral accretion rates, but it may be a primary control on the direction of reef accretion. The significant difference in accretion rates observed within and between these reef margins emphasizes the complex nature of reef flat development and the importance of using closely spaced core transects when interpreting reef flat accretion rates. These results further highlight, that caution must be taken when interpreting the timing, length and duration of past stillstand sea levels (e.g., Holocene and the last interglacial period) on the basis of isolated cores or outcrop samples, as there is significant variability in when and where different parts of the reef flat first approached MSL (Woodroffe and Webster, 2014).

Conclusions

The results from HR and OTR confirm that the traditional model of windward to leeward lateral accretion in the GBR does not hold true for lower energy protected reef margins. Protection from strong hydrodynamic forces is thought to increase sediment residence time on protected reefs, providing the shallow substrate necessary for the reef flat to extend laterally seawards. While slope morphology was also explored as a possible alternate mechanism for invoking the seaward extension of protected reef flats, greater analysis of the fore-reef slope gradient on mid-outer platform reefs is required before such conclusions can be made. Nevertheless, the analysis of other mid-outer platform reefs across the GBR confirms that reef exposure and accretion direction are closely correlated, with exposed reefs tending to accrete lagoon-ward and protected reefs seaward. Our results provide the most comprehensive lateral accretion rates for the mid-outer platform reefs of the GBR, which are broadly consistent with rates previously indentified on inshore fringing reefs. Significant spatiotemporal variations in reef flat accretion rates both within and between exposed and protected margins over the past 6 ka highlight the complex nature of reef flat development and suggest exposure to wind and wave energy is not the dominant driver of lateral accretion rates.

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