Caribbean Reef Drowning During Slow Mid-Holocene Sea-Level Rise

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Abstract

Predicting if reefs can keep pace with future sea-level (SL) rise is problematic because accretion occurs over geological timescales. For example, although meltwater pulses drowned reefs during postglacial SL rise, drowning has also been reported during the mid Holocene, when SL rise was slower and meltwater pulses unlikely. Here we report the discovery of a drowned incipient reef-crest on the widest part of northeast Yucatan shelf. Our data show the reef is an array of closely-spaced patches that crest at -14 m. These patches consist of 3 m-thick stands of *Acropora palmata* that grew over a Pleistocene dune ridge ~8 ka ago, but subsequently failed to keep pace with rising SL. We hypothesize that this failure is due to the suppression of coral recruitment by high sediment flux on wide shelves. Although recruitment does occur as the surf zone crosses topographic residuals during the transgression, suppression in sandy reef-fronts and back-reefs limits accretion of these incipient crests, causing their slow drowning during SL rise. We conclude that although reefs can slowly develop breakwaters in such settings, they may be incapable of vertical accretion and thus vulnerable to drowning. Identifying reefs with this vulnerability will be key to managing future SL rise.

Introduction

Coral reefs produce linear breakwaters that play a key role in protecting tropical coasts from high-energy wave events generated by storms or tsunamis¹. To retain this breakwater function, reefs must accrete vertically at a rate that matches or exceeds that of relative SL rise². With an increasing rate of SL rise³, metre-scale projections of future SL rise⁴ and declines in reef health⁵, there is considerable uncertainty about the potential of reefs to match these rises and hence continue to protect coastlines from wave erosion⁶.

A significant part of this uncertainty relates to quantifying long term reef-accretion rates. Accretion is mediated by processes that occur on both ecologic and geologic timescales. Over shorter ecologic timescales, accretion is controlled by coral growth rate, productivity and bioerosion⁷, which vary both biogeographically and also due local changes in wave exposure, slope, and sediment flux⁸. Over longer timescales accretion is modified by tropical cyclones, which locally destroy and reposition shallow-coral on a regular basis over thousands of years⁹. As a result, reefs show significant spatial variation in accretion rates, implying that there maybe a subset of reefs with low accretion potentials that are naturally vulnerable to future global climate and SL changes¹⁰.

A geologic approach to identifying reefs with low accretion potentials is to investigate those that drowned during postglacial SL rise. In the Caribbean-Atlantic reef province, drowned reefs have been discovered at several locations¹¹ based on the presence of submerged crests composed of monospecific frameworks of *A. palmata*, which only develop in the surf/breaker zone less than 5 m deep¹². Most of these reef crests drowned during accelerations in SL rise known as meltwater pulses, which resulted from rapid deglaciation of northern Hemisphere ice sheets^{13,14,15}. Yet recent reports¹⁶ of reef-crest drowning during the mid-Holocene (4-8 ka), when SL and ice sheets had begun to stabilize close to their present positions, suggest that meltwater pulses are unlikely to be the cause. In these cases, changes in local climate or sub-optimal environmental conditions may have suppressed the accretion potential of reefs so that they could not keep pace with gradually rising SL. Investigating mid-Holocene reef drowning may therefore help identify natural environmental causes of low accretion and the subset of modern reefs that may be at risk of drowning.

Results

To investigate the cause of mid-Holocene reef drowning, we searched for submerged relict reef-crests along the northeast-Yucatan section of the Mesoamerican Reef tract, which is developed over a 3-4 km wide sand-covered shelf¹⁷. A semi-continuous reef ridge was discovered between the 18-14 m isobaths along the inner part of this shelf (Fig. 1). To document the morphology of this feature we mapped the sea floor bathymetry over a ~1 km section with an area of 10 ha at sub-meter vertical resolution (Methods). These data show an irregular asymmetrical ridge that parallels the modern reef higher up-slope (Fig. 1B). The width of the reef is irregular and varies from 70 to 130 m. It has a relief of ~5 m and rises sharply from a sand-covered terrace at a depth of ~18 m, levelling off to form a crest at ~14 m, before sloping steeply back down to 16 m on its landward side. The maximum relief of the ridge is 6 m along the northern part, due to lower sand accumulation on its landward side, and the development of isolated peaks on the crest that reach depths of 12 m (Fig. 1C). The size of the ridge is thus comparable to the modern reef in shallower water which forms a tract ~130 m wide, but does not share the same variations in width and height.

Figure 1. Configuration and morphology of submerged reef ridge. (A) Bathymetry of the Mesoamerican Reef off Puerto Morelos, NE Yucatan (centered on 20.878186° -86.844745°), showing the modern reef along inner part of a 3-km wide sandy terrace. Inset shows location of submerged reef ridge and depth-sounder tracks. (B) Bathymetric reconstruction of reef ridge shows it consists of a linear series of closely-spaced patches which crest at -14 m (contour interval 0.5 m). Note location of *A. palmata* samples (orange circles) and underlying Pleistocene dune (white circles). (C) Depth profiles generated from boxed areas in panel B, along the reef ridge, showing the minimum, mean and maximum depth profiles in each area (Methods). Profiles show an ~5 m maximum relief (arrow) which likely reflects the amount of reef accretion developed over the Pleistocene substrate.

To establish the age and composition of the ridge, and its underlying substrate, core and surface samples were taken from sub-vertical surfaces where reef framework was

visible (Methods). Three short core-samples were taken from substrates on the front slope of the ridge below the 18 m isobath (BD1,2 and 7: Fig. 1C). All consist of a well-sorted fine-grained carbonate sandstone (grainstone) with low-angle laminations typical of low-energy coastal dune or beach deposits. This interpretation is supported by the presence of micrite-filled rhizoliths which are consistent with root penetration by dune vegetation (Fig. 2A). These samples imply that the reef ridge grew over the apex of a relict coastal beach/dune ridge of late Pleistocene or early Holocene age.

Figure 2. Submerged reef-ridge samples. (A) Core sample of Pleistocene dune substrate underlying reef ridge: highlighted are low-angle cross lamination (dashed lines) and micritic rhizoliths (solid circle). Scale in cm. (B) Well preserved palmate-shaped clast of *A. palmata*, with little bioerosion or encrusting epibionts. (C) Core sample BD6 taken from an area of the reef with visible in-place *A. palmata* framework. Sample shows low-relief forms of *Homotrema rubrum* (Hr), *Entobia* isp (E), *Trypanites* isp (Try) and *Gastrochaenolites torpedo* (Gt), all typical of the surf zone in shallow-reef environments¹⁸.

The other 8 short cores and samples consist of the reef-crest coral, *A. palmata*. Most of these were taken from surfaces dominated by loose or poorly consolidated cobble-sized clasts, which included intact branch fronds with palmate shapes and low levels of encrustation and bioerosion (Fig. 2B). These samples returned ²³⁰Th ages between 6.8 and 6.1 ka (Table 1). However the core sample BD6, which was taken from visibly in-place coral framework exposed beneath the ridge-crest, returned an older ²³⁰Th age of 7.9 ka (Table 1). This framework sample consists of a robust cylindrical branch of *A. palmata* that is associated with low-relief forms of *Homotrema rubrum* and macro-boring ichnospecies such as *Entobia* isp, *Trypanites* isp, and *Gastrochaenolites* isp (Fig. 2C). This suite of encrusters and bioeroders is consistent with taphonomically defined surf-zone environments (<2-3 m) from the reef-front and reef-crest facies¹⁸.

Table 1. ^{230}Th age of coral samples

Sample Species Type	Coords. (Latitude/ Longitude)	Recorded Depth (Interpolated depth) (m)	^{238}U (ppm) +/-	$^{230}\text{Th}/^{238}\text{U}$ +/-	$^{234}\text{U}/^{238}\text{U}$ +/-	$\delta^{234}\text{U}$ +/-	$^{238}\text{U}/^{232}\text{Th}$ +/-	Age (Ka) +/-	$\delta^{234}\text{U}^\circ$ +/-
PM-BD5 <i>A. palmata</i> Stump	516347/ 2308673	14.5 (14.0)	3.094 0.003	0.0699 0.0008	1.1452 0.0007	145.2 0.7	5371 34	6.84 0.075 0.076	148.1 2.3
PM-BD6 <i>A. palmata</i> Colony	516373/ 2308705	15.6 (14.4)	3.168 0.001	0.0795 0.0006	1.1374 0.0046	137.4 4.6	12433 44	7.87 0.073 0.073	141 5.0
PM-BD8 <i>A. palmata</i> Clast	516449/ 2308620	18 (17.1)	3.037 0.001	0.0669 0.0017	1.1448 0.0011	144.8 1.1	8814 172	6.54 0.170 0.160	147.5 2.5
PM-MM1 <i>A. palmata</i> Clast	516367/ 2308627	15 (15.4)	3.560 0.002	0.0657 0.0006	1.1446 0.0010	144.6 1.0	13730 124	6.42 0.058 0.055	147.2 2.4
PM-MM2 <i>A. palmata</i> Clast	516386/ 2308615	15 (15.5)	3.122 0.002	0.0626 0.0013	1.1446 0.0007	144.6 0.7	1951 33	6.10 0.130 0.130	147.2 2.5

These results are consistent with the brief development of an immature reef crest ~8 ka ago. The lack of a normal morphological zonation similar to the modern reef, together with the irregular surface morphology and the limited 5 m relief, suggests that the reef developed as a single, but patchy layer of *A. palmata* within its monospecific depth habitat of 0-5 m¹². Furthermore, the presence of colonies with large cylindrical branches and surf-zone epibionts implies that the upper part of this layer developed within 2-3 m of the water surface. However, this immature reef-crest did not keep pace with SL rise and was slowly submerged. The presence of younger palmate-shaped clasts over parts of its surface signifies that, during this submergence, it was partially colonized by younger acroporids that grew in deeper water over a more extended period of time. These colonies did not remain in place, however, and their clasts filled depressions in the irregular surface of the ridge.

The interpretation that deeper-water corals later colonized an inactive reef crest, can be tested by comparing their age-elevation data against independent SL curves, as illustrated in Figure 3.

Figure 3. Drowned reef crests and Holocene SL rise. Comparison between a local relative SL curve from the Mississippi Delta¹⁹ (red curve) and ice-volume equivalent far-field SL²⁰ (black curve). The Mississippi peat curve caps age-elevation data from in-place monospecific *A. palmata* framework^{11,18,21,22} (grey band). Positions of drowned reefs reported¹¹ from Grand Cayman, Barbados, and Florida are shown superimposed over these SL data. Position of incipient reef-crest reported here (site 5) shows that it developed within 3 m of mean SL ~8 ka ago. Plotting the age-elevation data of the younger clasts from its surface show that, when they grew ~6-7 ka ago, the incipient reef crest was in 8-9 m of water (3-4 m below the monospecific habitat range).

This figure shows that a local relative SL curve reconstructed from Mississippi basal peats¹⁹ is similar to ice-volume-equivalent SL derived from far-field data corrected for glacio-isostatic adjustment²⁰, with only a minor 2-3 m offset in magnitude that could be attributed to local glacio- or hydro-isostatic processes. The Mississippi curve caps age/depth data from Caribbean reef-crest framework^{11,18,21,22}, and the position of drowned reefs¹¹, confirming the 0-5 m monospecific depth habitat for *A. palmata*¹². By superimposing our ²³⁰Th age/depth data on this reconstruction, it is clear that the 7.9 ka framework sample from the immature reef crest (BD6) developed within the normal 0-5 m depth habitat of modern reef-crest corals (shown by the grey band in Fig. 3), supporting the interpretation that it formed in the surf zone. But when the younger clasts grew ~6-7 ka ago (shown as clasts in Fig. 3), the reconstruction shows that the incipient reef crest was submerged in 8-9 m of water, some 3-4 m below the monospecific depth habitat, supporting the interpretation that they grew on, and were later deposited over, an inactive or drowned reef crest.

Discussion

The comparison with SL supports our claim that a single stand of *A. palmata* initiated reef-crest development close to sea level ~8 ka ago. Although our data do not allow an assessment of accretion rates per se, it is clear from the limited thickness and irregular morphology, that the stand of *Acropora* underwent little vertical accretion. The failure to accrete and extend outside its biological habitat shows that, when it drowned, the reef crest was at an incipient stage of development²³. The key question is why this incipient reef crest was unable to develop further and keep-up with SL rise? There are two main possibilities: first, SL rise was too fast to allow reef-crest development or, second, reef accretion was suppressed by environmental factors.

Considering the first possibility, there are several reports of reef-crest drowning in the Caribbean during postglacial SL rise^{11,13,16,24-26}. The drowning of these reefs have been associated with pulses of meltwater discharge that produced brief accelerations in postglacial SL rise^{13,14}. Several reports, for example, have linked the demise of fully

developed and actively accreting early Holocene reefs to an acceleration in the rate of SL rise centered around ~8.4 ka ago, produced by the final disintegration of the Laurentide Ice Sheet^{11,27,28}. Rise rates during these pulses have been estimated at ~40 mm/yr or more^{11,13,15,29} and have been corroborated by dating of basal-peat sequences from coastal marshes and mangroves^{19,30}. Nevertheless, such pulses caused only brief cessations in reef development, and reef crests back-stepped to locations further up-slope as soon as the rate of rise had returned to previous levels. Indeed, during nearly the entire postglacial SL rise, reef-crests in some areas kept pace with rise rates of 10-12 mm/yr, producing vertically accreting sequences of *A. palmata* framework as thick as 30 m in less than 3 ka^{13,29,31}.

In the case of our incipient reef, Figure 3 shows that it postdates any meltwater pulse centered at 8.4 ka, which was likely responsible for drowning actively-accreting Caribbean reefs¹¹. And in the thousand-year interval following its initiation at ~8 ka, the reconstructions show SL rose at a rate of only ~7 mm/yr. As a consequence, it is unlikely that SL rise was too fast to permit reef-crest development, and more likely that it drowned due to suppression of reef-accretion rates. The question therefore becomes what environmental conditions can simultaneously allow reef communities to initiate, yet suppress their vertical accretion on geological timescales as SL rises?

Considering the second possibility, several studies have reported climatic cooling as a possible environmental factor causing reef demise. Along the Pacific coast of Costa Rica, for example, radiometric dating of several dead reefs returned radiocarbon ages of ~600-700 years³². Although subtracting a 465 yr marine-reservoir age gave dates that coincided with the Little Ice Age, the reservoir age in this area is now known to range between 260-560 yrs due to upwelling³³, giving low confidence in the timing of reef demise and it's postulated Little Ice Age cause. Cooling-induced reef demise has also been postulated following the discovery of a mid-Holocene drowned reef in Florida¹⁶. Exposed in a trench formed by a submarine grounding, the reef consisted of a single stand of *A. palmata* framework with calibrated radiocarbon ages between 6.8-7.4 ka (inner reef of ref. 12). LIDAR data showed the stand had a crest at ~8 m and was essentially an amalgamation of patch reefs that formed a linear structure¹⁶. Later drilling confirmed these data and suggested that reef development terminated at ~6 ka possibly as a result of climate cooling following the end of the Holocene Thermal Maximum³⁴.

The morphological similarity between the inner Florida structure and the incipient reef crest reported here is striking. They both initiated development over topographic highs on wide sandy shelves, both formed single stands of *Acropora* aligned in irregular patches, and both failed to undergo any significant vertical accretion. Given the tropical location of one, and differences in the timing of their demise, we suggest that neither of these incipient reefs were terminated by climatic cooling but, instead, simply failed to develop as a result of the generally unfavourable conditions for reef accretion on wide sandy shelves^{9,35}. We hypothesize that on such wide low-gradient shelves, recruitment of *Acropora* is suppressed due to high sediment flux³⁶ and only occurs sporadically when topographic highs are inundated during the transgression. In our case, the apex of a Pleistocene dune ridge provided a suitable substrate for coral recruitment because it trapped and removed sand from the surf-zone and therefore afforded the recruits relief from wave-suspended sediment. However, the lack of recruitment in adjacent sandy back-reef and reef-front zones suppressed the accretion potential of the incipient reef crest and prevented a full breakwater structure from developing. Thus, as slow SL rise continued, the *Acropora* stand was left to slowly drown.

This suppressed-accretion hypothesis can therefore account for the drowning of incipient reefs on wide sandy shelves during slow Holocene SL rise. This model can be tested because it predicts that reef development is dependent on the geomorphology of the shelf¹⁷. As a consequence, reef crests that drown on wide shelves with high sediment flux should therefore survive in areas where the shelf is narrower. More importantly, the model implies that reefs can initiate and perhaps develop in suboptimal environments where only low rates of accretion are possible. The repercussion of suppressed accretion is that there may be modern reefs that were only able to develop slowly during the last 7 ka when SL rise was minimal (rising only 4-5 m at rates of <3 mm/yr). If true, then the order-of-magnitude increase in the rate of SL rise predicted to occur by the end of the Century^{4,37} means that such reefs would be unable to keep pace and drown. The possibility exists, therefore, that a subset of modern reefs may be inherently vulnerable to drowning, even if their condition can be restored to a pristine state of health^{38,39}. Identifying which reefs are vulnerable, however, will require a more detailed analysis of their chronological structure so that the timing and rates of lateral accretion and breakwater-reef development can be quantified. Failure to identify this vulnerability may compromise the protection of coastal zones dependent on reefal breakwaters.

Methods

Bathymetry

General bathymetric data for the shelf down to ~15 m was derived from satellite imagery⁴⁰. To delineate the morphology of the submerged reef ridge, we collected additional depth/position data using a Garmin GPSMAP 178C single-beam Sounder. To minimise error due to wave-induced sensor movement, we ran profiles during calm sea-surface conditions with minimal wave activity. In total, 32 depth transects were run perpendicular to the long axis of the reef structure, spaced approximately 25 m apart, with sonar data points recorded every ~6 m along the transects, generating a total of 2800 distinct data points. A gridded digital elevation model (DEM) at a sample spacing of ~9 m was produced by localised ordinary kriging of the sonar data with a linear variogram, using Surfer version 13.3.493. For comparison, a similarly gridded DEM was produced using Global Mapper version 10.02, which uses simple bilinear interpolation over a triangulated mesh. Graphics and interpolated depths were derived by convolution of the gridded DEM with a linear filter. The filter kernel was dynamically instantiated at each interpolation point, taking into account the relative positions of the interpolation point and the contributing sample points, with a radius of 20 m chosen to remove visible artifacting. The filter has strictly no overshoot and hence is unable to generate minima or maxima absent in the input data, and responds from 10% to 90% of a step input over a distance of 17 m. After filtering, the results from both gridding methods were visually indistinguishable. The depths at each of the 2800 sonar points were interpolated from the filtered kriged DEM and compared with the originally recorded depths, with mean and root mean square (RMS) errors being 1.8 mm and 23 cm. The standard deviations of the recorded and interpolated depths over the 2800 sonar points were 2.43 m and 2.39 m, consistent with our filtering having had little impact on the data. Boxes in Figure 1(b) show areas used to generate profiles i to iv. For each profile we plotted the minimum, arithmetic mean and maximum elevation above the baseline of the box.

Sampling

To establish the composition and age of the reef feature, and its underlying substrate, surface samples were taken from vertical and sloping surfaces where reef framework was visibly exposed. Samples from large in-place coral colonies, or their substrate, were taken with either a 3-speed hydraulic drill unit and a 12 cm diameter core barrel, or a portable pneumatic drill with a 5 cm diameter core barrel. Using these drills, core samples were collected up to ~50 cm into the reef and underlying substrate. This surface sampling approach can be more reliable at identifying in-place corals than vertical drill cores where there can be considerable uncertainty in distinguishing in-place framework from large detrital clasts¹⁸. Sample depths were measured using a scuba depth gauge. Comparison of recorded depths with interpolated sonar depths at 11 sample points gave a mean difference of 0.4 m (depth gauge deeper), an root-mean-square error of 0.79 m, and a maximum difference of 1.38 m (BD7, depth gauge deeper). At the average sample depth of 16 m, gauge miscalibration between freshwater and seawater will give rise to 0.4 m reported depth variation (an instrument calibrated for freshwater reporting a deeper physical depth). Tides are also a source of error and are mainly within ± 10 cm of mean at this location but, in conjunction with geostrophic effects from the Yucatan Current and possible wind effects, ocean level may vary by several dm at extrema⁴¹.

Dating

The samples were dated by isotope-dilution MC-ICPMS using a Thermo-Finnigan Neptune Plus at Centro de Geociencias, UNAM, using a high-purity ²²⁹Th spike obtained from Oakridge National Laboratory, and ²³³U from IRMM 051a reference material⁴². All sample preparations were carried out in a class 100 clean-lab, with blanks typically lower than 3pg of ²³⁸U and 1 pg of ²³²Th. Uranium and Thorium were measured independently. ²³⁴U was measured with an ion-counter (SEM) behind a retardant potential quadrupole (RPQ) filter, providing an abundance sensitivity of 0.5 ppm at m-1 which, nevertheless, is unable to fully remove the tailing contributions from ²³⁸U and ²³⁵U upon ²³⁴U. Consequently, we added a fast magnet jump in the measurement routine to monitor at m/Z+ = 233.5 and 234.5 on the SEM and remove any contribution by linear interpolation. ²³⁰Th was measured with the SEM behind the RPQ filter. Because all samples measured here produced low ²³²Th signals (> 0.1 V), no tailing corrections on ²³⁰Th were necessary. All ages were calculated with Isoplot⁴³ v. 3.75 using half-lives from ref. 44 for ²³⁸U and ref. 45 for ²³⁴U and ²³⁰Th.

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Contributions

PB, JE initiated the study, collected the geological data, and >15 m bathymetric data. J-PB dated the samples, SC-E, RM-D collected the <15 m bathymetric data, SR analysed and rendered the bathymetry, PB analysed the data and wrote the manuscript. All authors contributed to the editing of the manuscript.