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A New Caribbean Reef Model: A View From Ye Shoulders of Giants

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Abstract. For geologists, three cores from Lang Bank described at the 1977 ISRS meeting in Miami, FL set the direction of the coral-reef discussion for the next three decades. High accretion rates from this and other Caribbean sites led us to ask why reefs capable of outpacing even the fastest sea-level rise could be abandoned. A possible gap in accretion on Lang Bank at 10,000 CalBP attributed to dirty water flowing off the recently flooded bank provided a solution to this "drowning paradox", and the Lang Bank story was extrapolated to the entire Caribbean. Recent studies suggest that some of the foundational ideas upon which our models were built may warrant reexamination. *Acropora palmata* reefs not only continued to build, but thrived across the presumed Caribbean-wide gap. Caribbean reef building can generally be characterized as transgressive between 11,000 and 7,000 CalBP due to a steady and rapid rise in sea level, and regressive thereafter, as sea-level rise slowed to below 4 m/Kyr. However, two millennial-scale lapses remain for *A. palmata*, starting at ca. 6,000 and 3,000 CalBP, respectively, well after sea-level rise had slowed to below the average rate of reef accretion. Their origins remain unknown, but could bear on the species' recent decline.

Key words: Caribbean; Reef Models, Reef Accretion, Holocene, *Acropora*

Introduction

Our earliest coring studies were designed primarily to address Darwin's subsidence hypothesis. The reef and underlying limestone intervals atop the epic cores through the Marshall Islands (Ladd and Schlanger 1960) were catalogued as "reefal limestone" and set in storage once the basalt intervals that vindicated Darwin were encountered. This focus was changed by the development of a small and cost-effective drilling system that provided access to the interiors of modern reefs (Macintyre 1975). Early descriptions for the Caribbean (Adey 1975; Macintyre and Glynn 1976; Shinn 1980) were quickly followed by studies along the Great Barrier Reef (Hopley 1982; Davies et al. 1985), the Indo-Pacific region (e.g., Camoin et al. 1997; Montaggioni et al. 1997), and numerous other locales throughout the tropics.

At the Coral Reef Symposium in Miami, Adey et al (1977) described reef accretion along the southwestern corner of Lang Bank east of St. Croix in the US Virgin Islands (Fig. 1). *Acropora palmata* dominated early shelf-edge reefs that built rapidly until ca 10,000 CalBP, when the reefs suddenly died off. Adey et al proposed that the sudden demise was caused by turbid water flowing from the recently flooded bank. Water depth over the failed reefs increased as sea level rose over the ensuing 2,000 years. As the waters cleared, massive corals dominated the new reef community, now in water too deep for branching acroporids. The sequence of events at Lang Bank provided the foundation for Caribbean-wide models of Holocene reef development (Adey 1978; Macintyre 1988) that

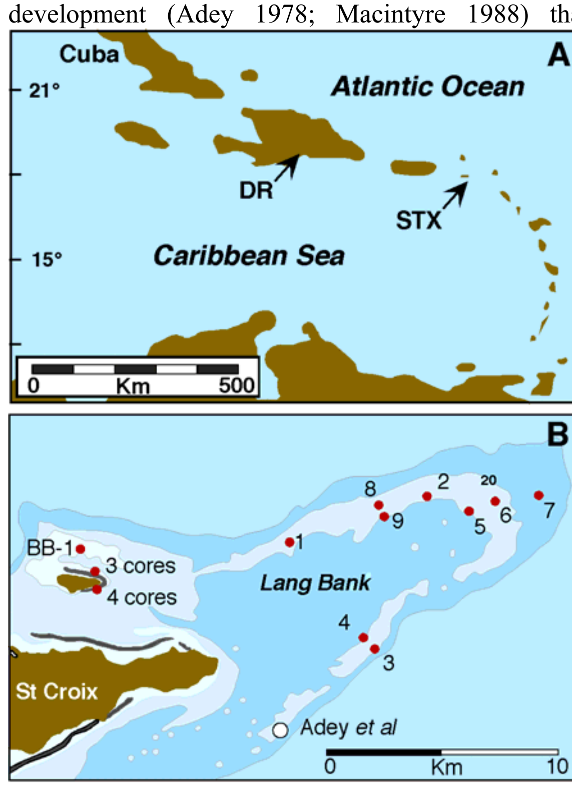

Figure 1: Location of cores (closed circles) on Lang Bank. TheSmithsonian core site described in Adey et al (1977) is shown by the open circle.

envisioned "inimical bank waters" related to platform flooding creating similar scenarios throughout the region.

This paper describes more recent core data from Lang Bank and elsewhere across the Caribbean. These data show that the interval of non-accretion within the early Lang Bank cores was largely absent elsewhere on the bank and the larger Caribbean region. An alternative and simpler Holocene Reef model based on the rate of sea-level rise and moderated accretion reef rates is proposed.

Material and Methods

On Lang Bank, four cores (LB1-LB4: Fig. 1) were recovered using a small drilling system similar to the one described by Macintyre (1875). Five additional cores on Lang Bank and eight from Buck Island were recovered using the SCARID Drilling System. In separate studies, cores were recovered from shelf-edge environments off SW Puerto Rico (Hubbard et al. 1997) and Florida (Toscano and Lundberg 1998). Cores were recovered in 1.5-m intervals, and notes during drilling permitted logging accuracy within a few centimeters. Samples were slabbed longitudinally and corals were identified to species level. Fresh-looking samples were used for radiocarbon dating, following XRD analysis to confirm their pristine nature. Methods are described in more detail in Hubbard et al. (2005).

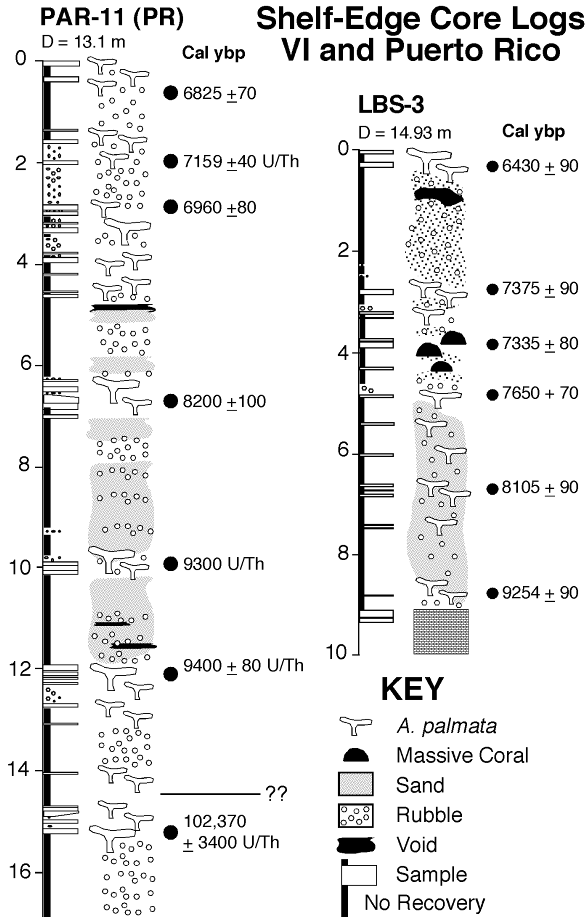

Figure 2: Core logs from the shelf edge of Lang Bank and SW Puerto Rico. Note the abundance of *A. palmata* over the interval between 10,000 and 8,000 CalBP when reefs quit at the Adey et al site. The left column shows recovery. The right log is interpreted.

Results

The Lang Bank cores provide a record of vigorous reef accretion around Lang Bank starting ca. 11,000 years ago (oldest ages are from Adey et al. 1977), and continuing until ca 5,000 CalBP (limited to massive corals after 6,300 CalBP). Along the northern platform margin, *A. palmata* reefs started up later (ca. 8,100 CalBP), a timing consistent with the scenario proposed by Adey et al. (1977). However, at core site LB-3 located east of the Smithsonian site (Fig. 1) reefs dominated by *A. palmata* started as early as 9,250 CalBP (i.e., in the middle of the proposed hiatus: Fig 2), and continued to accrete until 6,400 years ago. In core LB-6 on the eastern end of the bank, there is over 5 meters of reef between the Pleistocene surface and a sample that dated at 8048 ± 70 CalBP (Table 1). It therefore seems likely that both *A. palmata* and massive-coral reefs along at least the southern and eastern margins continued to build through the 10-8 Kyr interval when inimical bank waters were previously assumed to have shut down reefs all around Lang Bank.

If we examine reefs elsewhere in the Caribbean, similar patterns emerge. Reefs along the southern shelf edge of nearby Puerto Rico (e.g., PAR-11: Fig.2) were similarly dominated by *A. palmata* and continued to build through the proposed gap that was subsequently incorporated into the Caribbean reef models of Adey (1978) and Macintyre (1988).

Figure 3 summarizes the occurrence of *A. palmata* reefs over the past 11,000 years. The data are derived from a variety of water depths and reef types across a wide geographic range within the Caribbean. The number of dated *A. palmata* samples within Box A shows no significant decrease in the density of the branching species between 10,000 and 8,000 CalBP. Furthermore, *A. palmata* remained as an important component of Caribbean reefs immediately after 8,000 CalBP.

Discussion

Ian Macintyre's submersible drill provided our first real opportunity to chronicle Holocene reef history. Starting with the hallmark Panama study (Macintyre and Glynn 1976), coring investigations spread first across the Caribbean and eventually to every major tropical ocean. The earlier studies focused on the

Table 1. Lang Bank Core Statistics. All age errors are less than 100 years.

Core	Oldest	Youngest	Corals	Comments
1	6476	6215	Mixed	Not to Pleistocene
2	8075	6625	*A. pal*	To Pleistocene
3	9250	6340	*A pal*	To Pleistocene
4	8060	5885	Mixed	Not to Pleistocene
5	6740	6130	Mixed	Not to Pleistocene
6	8050	4860	Mixed	5m to Pleistocene
7	6615	5035	*A. pal*	To Pleistocene
8	7310	6350	A pal	To Pleistocene
9	7145	6350	Mixed	Not to Pleistocene

internal fabric of modern reefs, with an eye toward comparisons with their ancient counterparts. The Smithsonian study on SW Lang Bank was a turning point inasmuch as it looked, for the first time, at the relationships between processes and products – relating larger-scale patterns of reef development to both local (sedimentation) and global (sea level) controls.

Citing reports of accretion rates near 10m/Kyr, Schlager (1981) argued that it was problematic that shallow-water reefs, most of which were capable of building at rates faster than the rise of Holocene sea level, could have been abandoned. He resolved this "drowning paradox" by invoking either sudden (and usually short-lived) jumps in sea level or a local deterioration of water quality sufficient to slow or kill corals. The Lang Bank story provided the best example of the impact of "inimical bank waters" related to the flooding of long-exposed shelves.

It was further argued that carbonate banks existed at similar depths throughout the Caribbean, and the scenario of early start up by *Acropora*-dominated reefs, followed by abandonment as platform tops flooded could be generalized to the region. From this, it was proposed that high-energy Caribbean shelf margins would host "relict *give-up reefs* along the upper slopes and shelf edges, and relatively young late Holocene reefs fringing most coastlines" (Macintyre 1988).

More recent data from this and other Caribbean sites do not support this scenario. Recent compilations of reef-accretion rates throughout the Holocene (Indo-Pacific and Indian Oceans: Dullo 2005; Caribbean: Hubbard 2008) show that accretion rates near 10m/Kyr are the exception and that most reefs built at half this rate or below. Hubbard (2008) computed an average accretion rate for Caribbean reefs of 3.5 m/Kyr. The long-assumed decrease in accretion with depth was not supported by the data. Furthermore, the accretion rate for reefs dominated by branching *A. palmata* (3.83 m/Kyr) was not significantly different from the rate of building for reefs with mostly massive corals (3.07 m/Kyr). This was tentatively

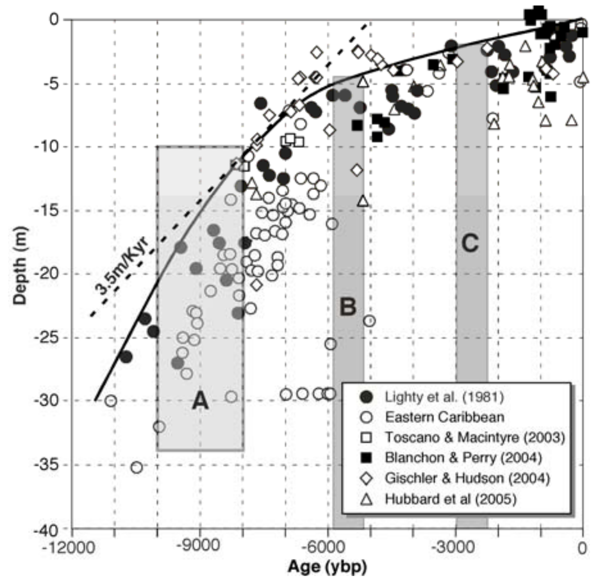

Figure 3: Summary of depth and age data for *A. palmata* in Caribbean cores (sources are provided in the legend). Box A outlines the interval across which *A. palmata* are supposed to be absent based on existing Caribbean reef models. Note that *A. palmata* not only survives but thrives across this predicted gap. Shaded intervals B and C represent times for which dated *A. palmata* samples are either rare or absent. While *A. palmata* reefs have generally occurred since 11,000 years ago, those on the left side of Box B sit near shelf margins and have not been active since ca. 6,000 years ago. Those to the right are shallower reefs, closer to shore, throughout the region. The two millennial-scale intervals of poor *A. palmata* development both occurred after sea-level rise had slowed, and some other mechanism must be invoked to explain the apparent difficulty that this rapidly growing species had encountered. The dashed line represents the average Caribbean reef-accretion rate proposed by Hubbard (2008) and intersects the sea-level curve at ca. 7,500 CalBP. Before this time, reefs would have had a more difficult time keeping up with rising sea level than after sea-level rise slowed. Modified from Hubbard et al (2005).

explained by depth-related patterns of bioerosion and down-slope transport that mirrored calcification.

If we discount the anomalously high rates cited by Schlager (1981) as typical of reef accretion, then a simpler model emerges – one that does not involve a "drowning paradox" or a need to resolve it. Figure 4 illustrates the accretion patterns for several reefs on St. Croix and Puerto Rico. Apart from a few examples, reef accretion was close to 3.5 m/Kyr and was independent of the coral species recovered in the cores.

Based on accretion near 3.5m/Kyr, early shelf-edge reefs were building at rates slower than sea-level rise. Presumably these were initially being outpaced. However, the rise of sea level was gradually slowing, and by 7,500 years ago sea-level rise and accretion were roughly balanced (dashed line in Figure 3). After this time, the balance between sea-level rise and accretion gradually reefs tipped in favor of the reefs.

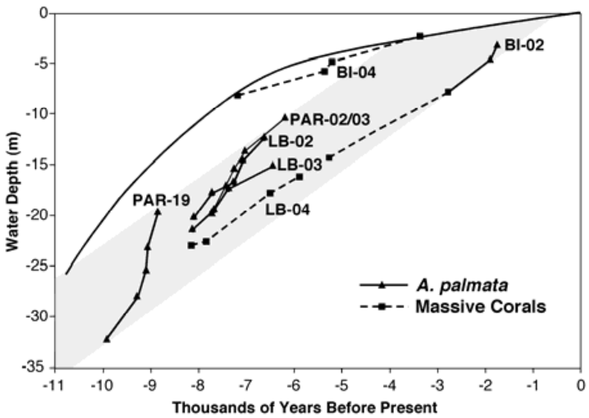

Figure 4: Accretion curves for several cores from St. Croix and Puerto Rico. These data are for single cores contained within the data base used to construct Figure 3, and most other reefs exhibited similar accretionary histories. Note that the apparent gap between ca. 8,500 and 8,000 CalBP is an artifact of the cores chosen to illustrate the accretionary pattern of eastern Caribbean reefs. Other than the deeper reef off Puerto Rico (PAR-19) and the reef constrained by sea level (BI-04), reef accretion generally conforms to the average Caribbean rate of 3.5 m/Kyr (shaded envelope). The dashed line in Figure 3 corresponds to this rate and intersects the Caribbean sea-level curve at ca. 7,500 CalBP.

All the Caribbean shelf-edge reefs cored to date remained active after 7,500 CalBP. Based on their initial accretion rates, they should have caught up with rising sea level between 6,000 and 3,000 years ago.

Reefs that are presently emergent sit closer to shore and started up by 8,000 CalBP. Their emergence reflects the fact that sea level rose close to or slower than the reefs built. Those reefs that were at sea level (e.g., core BI-04 from Buck Island: Fig. 4) were producing carbonate faster than accommodation space was being created. As a result, they built now only upward but also seaward. At Buck Island (the small island north of St. Croix in Figure 1b) the reef that rims the eastern half of the island built seaward by more than 60m over the past 8,000 years (Fig. 5). Similar patterns have been documented for Tague Reef on northeastern St. Croix (Burke et al. 1989).

Holocene reefs exposed in the western Dominican Republic (Fig. 6) provide a unique opportunity to examine the facies architecture in much greater detail than is possible from cores. Along a 450-m long outcrop, the older section (10,000 - ~6,000 CALBP) reflects a deepening-upward sequence. In the deeper and older part of the outcrop, shallow tidal molluscs give way to massive corals and finally platy corals found at depths over 25 m on modern reefs. The shallower end of the transgressive facies bundle yielded dates as young as 5,700 CalBP (Fig. 6b), after sea level had started to slow down. Facies still deepen upward (branching → mixed coral facies). Higher (and younger) in the outcrop, the pattern is reversed,

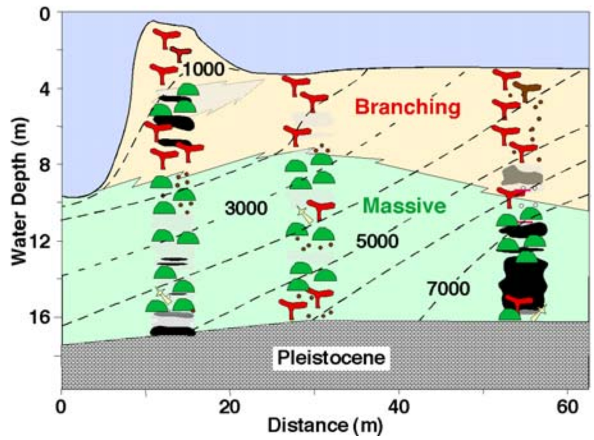

Figure 5: Cross section through the northern reef at Buck Island. Throughout its history, this reef had an accretionary potential that was greater than accommodation space being created by slowing sea-level rise. As a result, the reef built not only upward but also seaward. The initial position of this reef was roughly midway across the lagoon at a point not on this cross section. Thus, the reef has built more than 60m seaward over the past 8,000 years. Modified from Hubbard et al. (2005).

and the shallow-water branching facies builds out over the deeper mixed-coral facies (Fig. 6c) in response to even slower sea-level rise. This is analogous to the conditions seen in Figure 5 for Buck Island in the US Virgin Islands.

Collectively, these examples illustrate a simpler model for Caribbean coral-reef accretion (Fig. 7). Prior to ca. 7,500 CalBP, sea level was rising faster than shelf-edge reefs could build and they tended to gradually lag behind. By the time sea level slowed, most of them were still in water depths favorable to *A. palmata*, and reef-building gradually matched and eventually exceeded the rate of sea-level rise. Reefs closer to shore started later (9,000 – 7,000 CalBP) and in shallower water. As a result, they were able to either keep up or catch up to sea level, which they have successfully tracked ever since. As sea level continued to slow and accommodation became increasingly inadequate, these reefs have generally built both upward and seaward.

One problem emerges from all of this. As discussed above, shelf-edge reefs throughout the region should have been able to reach sea level by 4-3,000 years ago. For reasons that remain unexplained, every shelf-edge reef that has been sampled stopped accreting between 7,000 and 6,000 CalBP. This includes reefs from Lang Bank (this study), SW Puerto Rico (Hubbard et al. 1997), northern Florida (Lighty et al. 1982) and the Florida Keys (Toscano and Lundberg 1998). This occurred well after sea level slowed, and some other mechanism must be invoked – and it recurred at ca. 3,000 CalBP, again for unknown reasons. The question remains whether/how this might bear on the recent decline of *A. palmata*.

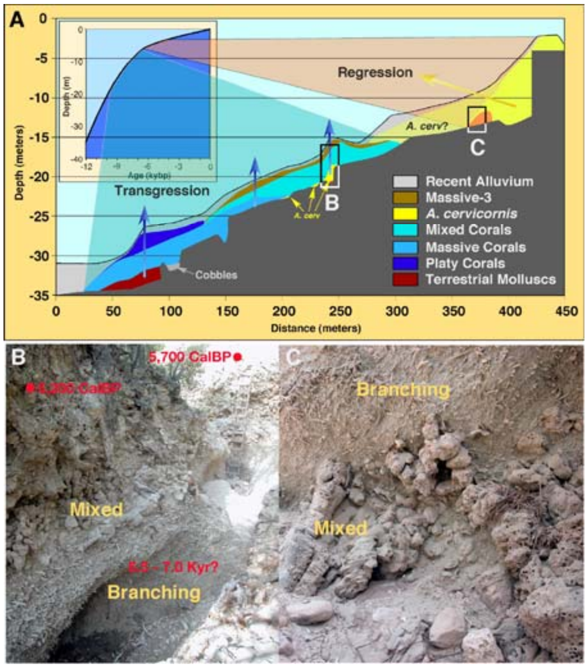

Figure 6: Facies distribution in Cañada Honda, western Dominican Republic. A) Cross section along the outcrop showing the facies distribution. Note that in the lower part of the outcrop, environments deepen upward (massive→ mixed), while in the upper outcrop the reverse occurs. Photo locations for B and C are indicated. B) Photo looking up-canyon. The sequence still deepens upward shortly after sea level has slowed down. C. Photo of a younger section near the upper end of the outcrop. Note that the section shallows upward as the branching *A. cervicornis* facies builds out over the deeper mixed-coral facies. This shift from transgressive to regressive facies architecture reflects the slowing of sea-level rise and the outbuilding of the younger section of the reef, similar to what was seen in the Buck Island reefs (Fig. 5). For outcrop location, see "DR" in Figure 1.

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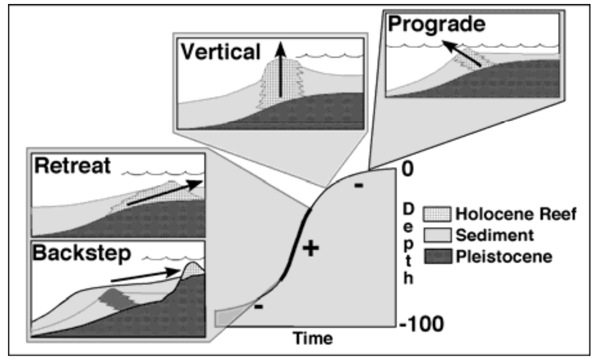

Figure 7: Facies model for Holocene sea-level rise. Prior to 7,500 Cal BP, sea level was rising at a rate faster than average accretion (+ on the curve). In this scenario, reefs either retreated upslope, backstepped (Hubbard et al, 1997) or drowned. As sea-level rise slowed around 7,500 CalBP, reefs first built vertically as accretion matched sea-level rise, and eventually started to build out over deeper mixed- and massive-coral facies (Figs. 5, 6). Presently emergent reefs closer to shore initiated as sea level was slowing, and accretionary potential quickly exceeded accommodation space. As a result, they have typically built seaward over their history.

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