Holocene reef accretion along the north side of Bahia Enriquillo (western Dominican Republic): unique insights into patterns of reef development in response to sea-level rise

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Abstract. Well-exposed reef outcrops along the northern side of the Enriquillo Valley record continuous reef accretion between ca. 9,000 and 5,000 CalBP, when the bay was closed off from the open Caribbean. All the zones of present-day Caribbean reefs are well represented, and facies geometry provides valuable information about both paleo-environmental conditions and changing sea level. Suppressed coral-growth rates, coral distribution/shape, and patterns of bioerosion all point to elevated sedimentation and nutrient influx. Radiocarbon dates, combined with careful stratigraphic analysis, tell a story of early transgression under a regime of rapidly rising sea level followed by regression as sea level slowed and the shallow reef built out over deeper mixed- and massive-coral zones.

Key words: Holocene; fossil reef; reef accretion; sea level, bioerosion

Introduction

The Enriquillo Valley sits on the south-central coast of Hispaniola near the border between the Dominican Republic and Haiti (Fig. 1). During the early Holocene (ca. 9,000 CalBP), the embayment was open to the Caribbean, and coral reefs flourished in a low-energy setting that was exposed to at least periodic intervals of high sedimentation from the steep mountains flanking the bay. By 5,000-4,000 years ago, the bay had closed off due to sedimentation from the Rio Yaque del Sur and possible landslide activity (Mann et al. 1984; Greer and Swart, 2006). Evaporation lowered lake level to its present –42m, exposing the reefs. Arroyos have exposed continuous outcrops that span the entire zonation scheme from shallow, branching corals to deeper-water platy species. This paper describes the general character of the reefs, using a 450-m long exposure at Cañada Honda as the primary example. It then considers the possible environment of deposition based on both reef-community structure and characteristics of individual corals. Finally, it uses the three-dimensional facies pattern, along with radiocarbon ages from the outcrop to address the response of the Enriquillo reefs to rising sea level.

Methods

The outcrop was surveyed using a LaserTech Impulse200 instrument that determined vertical and horizontal intervals to within 1-3 cm. The survey was referenced to permanent markers located by differential GPS (Delorme Earthmate receiver and PostPro softwatre). Reef facies (Fig. 2) were initially defined based on visual estimation of species and point counting of corals at 20-cm vertical intervals along six transects. More detailed measurements were made in 53 meter-square quadrats (4870 data points) along 16 vertical transects. Coral statistics were analyzed within facies to verify or adjust the original boundaries.

Massive corals were divided into three primary shapes: hemispherical (the most common shape on modern reefs), conical and columnar. The shape of the colonies encountered in the quadrats were recorded and used to tie shape preference by species and overall within particular outcrops. A well-defined storm layer within the outcrop (Fig. 3) provides a time line that was used to characterize the morphology of the reef. It also provided an instantaneous surface below which we examined coral taphonomy and bioerosion by coral species and shape. Radiocarbon dates from corals just beneath the storm layer across the outcrop confirm the synchronicity of the event and date it at 9,500-9,000 CalBP.

Results

A total of 27 coral species (plus two *Millepora* species) were identified in the Enriquillo Valley reefs. The relative abundance of the most important species
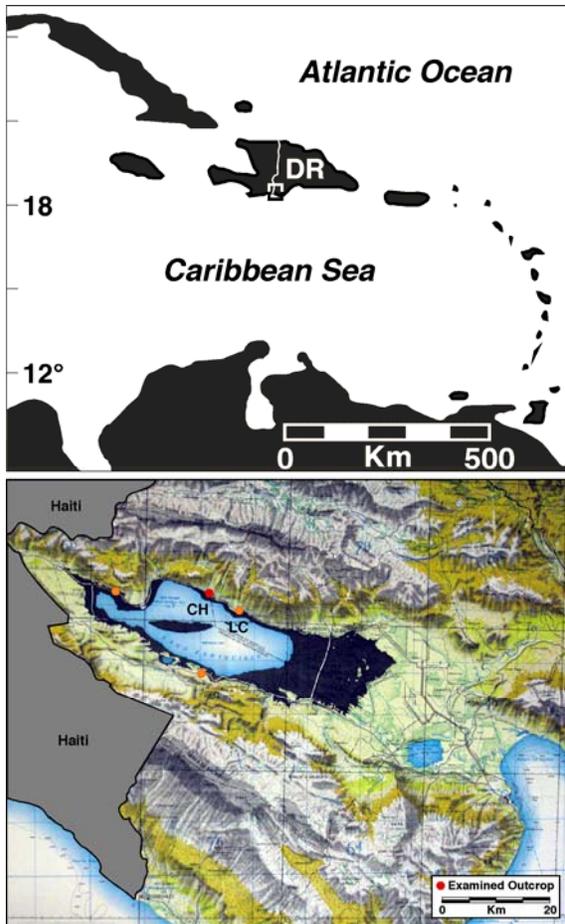
Figure 1: Map showing the location of the location of the Enriquillo Valley (box in upper) and the outcrops at Cañada Honda (CH) and Las Clavellinas (LC) in the Enriquillo Valley (lower).

Table 1. Summary of major species and overall coral diversity by facies.

Facies	Massive	Mixed	Platy	M3
Agaricia spp.	0.7	2.7	2.4	1.7
C. natans	3.7	8.7	0.9	1.5
Dichocoenia sp.	1.1	0.9	0	0.4
Madracis spp. (2)	1.2	0.2	1.0	1.6
*M. faveolata**	10.9	4.6	7.4	3.8
M franksii/cavernosa	0.1	0.0	0.0	23.7
Eusmilia spp. (2)	0.3	0.4	0.7	0.4
S. radians	0.8	4.6	0.6	2.9
S. siderea	43.2	35.5	14.7	21.1
Stephanocoenia sp.	3.0	0.1	4.4	0.5
Total Other Coral	2.3	1.7	2.0	0.0
Total Molluscs	0.4	0.3	0.0	0.2
Total Sed/Rubble	32.3	40.5	65.7	42.1
No. of Species	14.0	18.0	12.0	12.0
Avg. Species/Transect	8.1	7.3	5.5	3.8

* includes a variant with smaller polyps: aka Mini-*Montastraea*

is summarized in Table 1. The facies exposed in the outcrop represent all the major coral zones found on modern Caribbean reefs (Fig. 2). Within the branching coral zone, *Acropora palmata* is replaced by *A. cervicornis*, probably because of the low wave
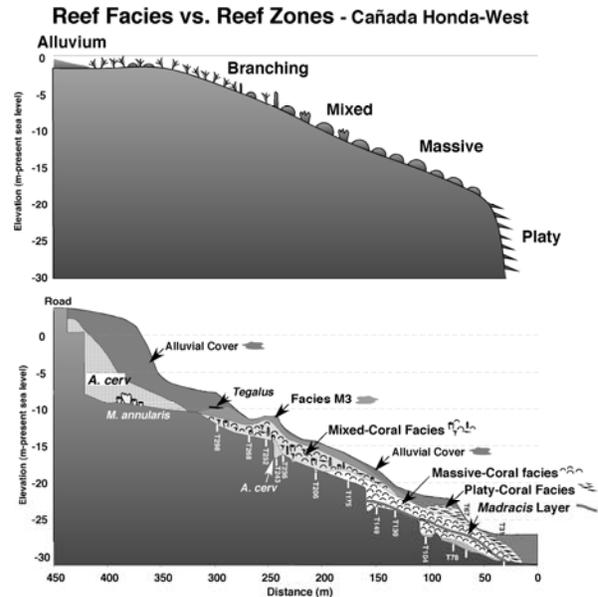

Figure 2: Cross-sections of a modern Caribbean reef (upper) and facies within the outcrop at Cañada Honda (lower)

Figure 3. Photograph of a storm layer dominated by *Madracis* spp. Note how many of the corals lean toward the right (i.e., downslope), reflecting disruption as the detrital layer was put in place.

energy in the protected embayment. Most of the coral appears to be either in place or simply compressed by collapse and burial. The oldest *A. cervicornis* colonies are found midway along the outcrop and the species extends to the uppermost part of the exposure, reflecting gradual transgression as sea level rose. Coral diversity was greatest in the mixed-coral zone, which was dominated by *Siderastrea siderea* and lesser amounts of *Colpophyllia natans* and *Montastraea* spp. (Table 1; Fig. 4). Corals in the deeper massive-coral zone were more evenly split between *Montastraea* spp. and *Siderastrea* spp. In the platy coral zone, the dominant species are *S. siderea* and *M. franksii*. Sediment made up 32-66% of the reef interior.
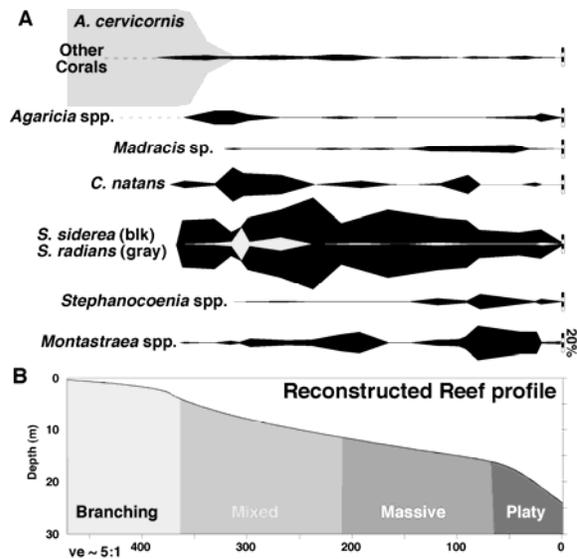
Figure 4: Reconstructed reef profile for the reef exposed in Cañada Honda (below). The coral abundance within facies and in the corresponding environments on open Caribbean reefs is shown by the Mae West diagrams at the top.

The massive-coral zone is interrupted by a layer of *Madracis* sp. (Fig. 3) that was initially deposited during a storm event 9,400-9,000 years ago. While there is evidence of recolonization and possibly additional debris emplacement later on, the base of the layer undoubtedly reflects a short-lived interval that represents a time line through the reef. This layer allows us to reconstruct the morphology and paleo-depths along the reef at that time. It also provides an opportunity to assess the relative importance of live versus dead coral along the reef at any one time. Preliminary studies based on the taphonomic condition of the buried corals (pristine or near-pristine corals are assumed to have been alive at the time of burial; those with significantly altered or encrusted surfaces were scored as "dead") infer that approximately half of the coral community was alive before the storm event that buried the entire forereef profile. We can use this value to "adjust" the quadrat data shown in Table 1 to approximate live-coral cover on an equivalent modern reef. Based on these numbers, live coral cover probably ranged from nearly 50% in the branching-coral zone to between 16 and 33% along the rest of the reef. Whether we use the raw quadrat data or the numbers adjusted by the taphonomic estimates, the percent cover along the Enriquillo Valley reefs approaches what is seen on modern Caribbean reefs, despite the protected nature of the embayment and the high likelihood of elevated sedimentation and nutrient loading.

Higher sedimentation is supported by three lines of evidence. First, the growth rates of *Siderastrea* spp. and *Montastraea* spp. are generally depressed
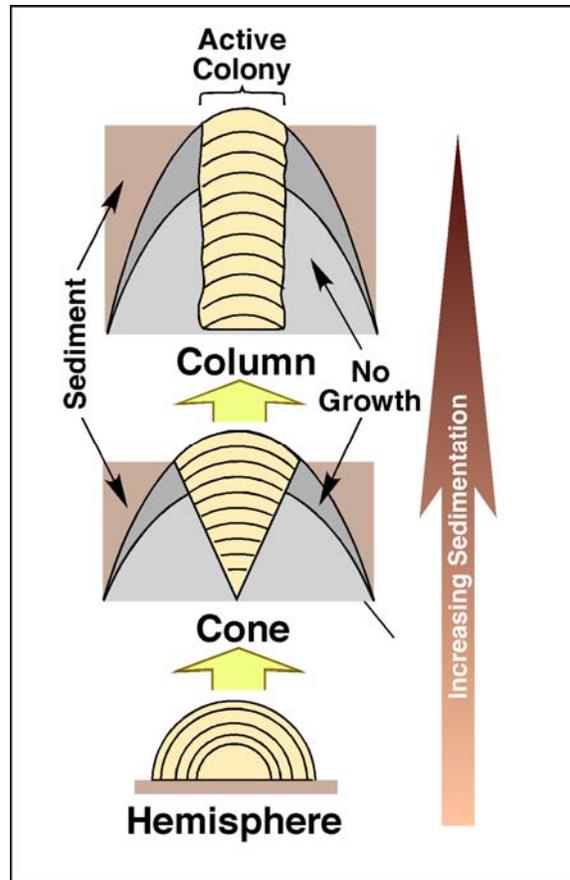

Figure 5. Effects of increasing sedimentation on coral shape in Bahia Enriquillo. On normal, oligotrophic reefs exposed to less sediment, hemispheres dominate. As the rate of sedimentation increases, polyps near the base of the colony will increasingly be overcome and lateral colony extension will be reduced. As a result, coral shape will gradually shift toward conical and columnar forms until a point at which sedimentation becomes so severe that the colony ceases to be viable and is totally overwhelmed.

(1-3 mm/yr) compared to the published rates for the same species at similar depths in the open Caribbean (5-10 mm/yr). Second, coral shapes are rarely hemispherical in outcrop. Conical and columnar growth forms are much more common. It is presumed that as sedimentation increases, lateral colony extension will be more difficult (Fig. 5). As a result, coral shape will shift from hemispherical to conical to columnar as coral bases are increasingly buried by sediment. In Cañada Honda, *Montastraea* spp. tends to be columnar, compared to a more conical growth form for the more sediment-tolerant *Siderastrea* spp. (Fig. 6). In an outcrop near Las Clavellinas (LC in Fig. 1), sedimentation rates are higher. In response, *Siderastrea* spp. shifts to a columnar form and *Montastraea* spp. is virtually absent, following the expected relationship between form and sedimentation. Finally, bioerosion in the Cañada Honda corals is higher and involves different
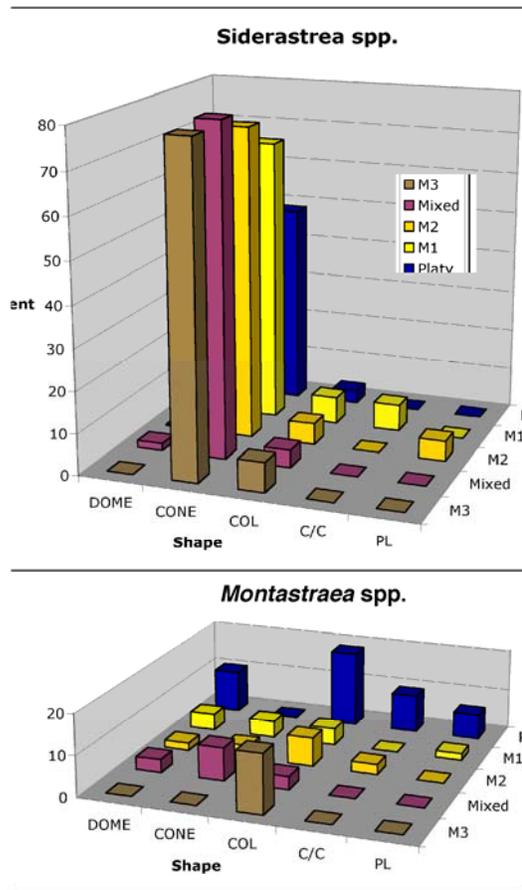
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Figure 6. Graphs of coral shapes associated with the two dominant genera in the reef. The more sediment-tolerant species of *Siderastrea* tend to be conical, reflecting some difficulty with sedimentation. *Montastraea* spp. are even less tolerant and show a greater tendency toward columnar forms.

Figure 7. Photographs of coral slabs from Cañada Honda (left) and Cane Bay (St. Croix, USVI – right). In the more protected and higher-sediment/nutrient environment of Bahia Enriquillo, lithophagid molluscs dominated, compared to a borer community dominated by sponges in the open Caribbean.

organisms than are typical of open-Caribbean settings. Bioerosion showed a general decrease with paleo-depth, similar to what has been found on open-Caribbean reefs. However, on a more general level, the difference between the borer communities at the two sites were statistically different at a value of α<.001. The dominant borers in the Bahia Enriquillo corals were lithophagid molluscs. This contrasts dramatically with the greater importance of sponges in corals sampled from the US Virgin Islands (Fig. 7). This is consistent with past studies that have tied boring bivalves to well-documented high-nutrient environments (Highsmith 1980; Sammarco and Risk 1990; Perry and Hepburn 2007). Another indication of both high and episodic sediment stress is the abundance of colonies the reflect periods of burial separated by intervals in which the coral could build laterally over the remaining surface (Fig. 8).

On a larger scale, the overall facies geometry that is preserved in the outcrop (Fig. 2) reveals a change in accretionary style over time. Along the lower and

central portions of the outcrop, coral date between 9,000 and 7,000 CalBP, a time when sea level was rising very rapidly (Fig. 9). Facies generally deepen upward (from massive to platy). This pattern is repeated in the central part of the outcrop, where facies change upward from massive to mixed corals– see Fig. 9 lower right photo). Later on, as sea level slowed, a gradual shift toward a regressive pattern emerges.

Discussion

The spectacularly exposed reefs in the Enriquillo Valley provide a unique opportunity to examine the internal structure of Holocene reefs at a level of detail impossible in cores. The species diversity within these reefs was surprisingly high, given the low energy and high sedimentation they experienced. This presumption is supported by the shift from *A. palmata* (which has no biological mechanism for sediment removal and relies on wave energy) to *A. cervicornis,* as well as retarded growth rates (1-3 mm vs 5-10 mm), the general lack of hemispherical colonies (except in *Colpophyllia natans*), and the dominance of lithophagid molluscs that require high nutrient levels to support their metabolic needs.

This high diversity flies in the face of modern paradigms that stress low coral abundance and diversity on reefs exposed to high sedimentation. The "pancake" morphology (Fig. 8) that is common

Figure 8. Photograph of "pancake" coral morphology. Each interruption in upward extension is interpreted as partial burial by sediment during storms that either delivered more sediment from land or, less likely, shifted it in from adjacent environments.
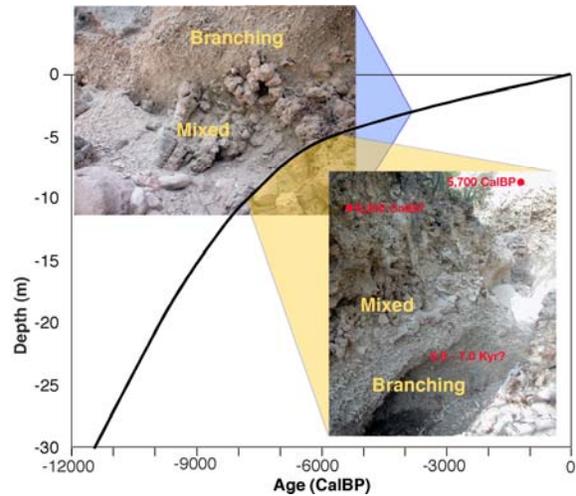

Figure 9. Facies patterns versus sea-level rise (black curve). When sea level was rising more rapidly, paleo-environments deepened upward (lower right photograph). As sea-level rise slowed, the shallow branching facies migrated seaward over the deeper mixed-coral facies. This demonstrates a pattern of transgression before 6-7,000 years ago, gradually shifting to regression.

in all outcrops reflects high but periodic sedimentation. The present climate is very dry, but is seasonally interrupted by intense, flashy rains typical of a desert region. If this climate prevailed in earlier Holocene times, the high coral diversity may reflect clearer water in the intervals between rains. Greer and Swart (2006) have proposed variable rainfall on a decadal scale. If this extends to shorter periods of time, then the higher-than-expected diversity and abundance numbers may reflect "longer intervals of boredom separated by brief episodes of terror". Superimposed on this were the much larger events reflected in the storm-debris layer that is dominated by *Madracis* sp. (Fig. 3). Alternately, we may have to re-examine our existing ideas about sedimentation and coral diversity. Perhaps reefs that developed in a regime of long-term sediment stress were able to adapt, in contrast to the situation on modern reefs exposed to anthropogenically induced conditions.

Whatever the answer to this dilemma, the exposures at Cañada Honda allow us to address these and similar questions at a level of detail that was previously impossible. On a larger scale, the pattern of early transgression followed by a shift to regression as the rate of sea-level slowed provides strong support for the new and simplified Holocene reef model proposed by Hubbard (this volume).

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