

Diving into the Past: Scuba and the Temporal Dimension of Coral Reefs

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ABSTRACT. A variety of sampling techniques afforded by scuba diving have made it possible to study the Holocene history of coral reefs in detail. This paper describes results of three geological techniques and illustrates them with examples from our own work in the Caribbean. First, cores extracted with a hydraulic drill from cemented reef frameworks provided the complete history of a fringing reef off the Caribbean coast of Panama and documented a relict reef stranded by rising sea level off St. Croix. Second, surface samples collected from a coral death-assemblage helped explain the demise of an algal-dominated reef off the southern coast of Barbados. Third, push-cores from uncemented reefs in the Belizean barrier-reef lagoon and a coastal lagoon in Panama revealed that 3,000 or more years of compositional stasis were followed in recent decades by precipitous turnover events, in which the previously dominant corals were replaced by a different species. Understanding the geological history of coral reefs over the last several thousand years is critical to predicting their response to climate change, alterations in land use, and other natural and anthropogenic perturbations.

INTRODUCTION

Among its many contributions to marine science, scuba diving has enabled researchers to collect vital information on the Holocene history of coral reefs. Historical information can be compared to the reefs' present-day status to explain current conditions and predict the future. In this paper we explore the contribution of scuba to the historical analysis of reefs by describing three methods of geological sampling. The geology of coral reefs has been reviewed in detail elsewhere (Aronson, 2007; Montaggioni and Braithwaite, 2009); here we focus on scuba-based techniques, which we illustrate with examples from our own research. The salient point is that without the technology of scuba diving much of this critical information would remain inaccessible.

ROTARY DRILLING

With the introduction of an underwater, hydraulically powered drill in the early 1970s (Macintyre, 1978), it became possible to collect cores from cemented frameworks across an entire reef, not only above water but underwater on scuba as well (Figure 1). Drilling revealed the complete Holocene history of a fringing reef off Galeta Point, Panama (Macintyre and Glynn, 1976). Cores collected at water depths of 0–10 m showed a reef about 14 m thick, with six distinct reef facies (Figure 2).

1. Back-reef sediment facies: This facies consists of skeletal debris composed mainly of *Acropora palmata*, *Acropora cervicornis*, *Porites furcata*, *Agaricia agaricites*, and

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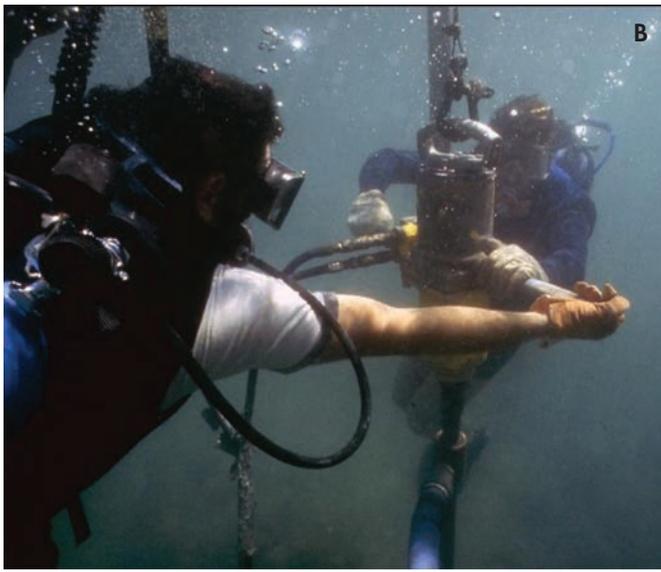


FIGURE 1. Collecting cores from Galeta Reef, Panama, above (A) and below (B) the sea surface with a hydraulically operated drill (photos courtesy of Ian G. Macintyre).

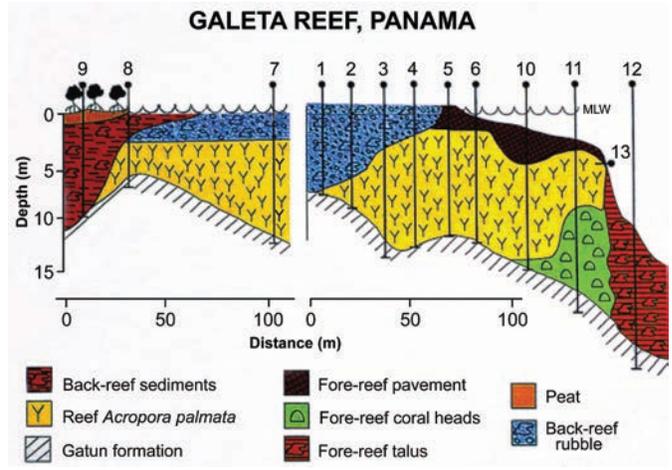


FIGURE 2. Transect across Galeta Reef showing the six reef facies and peat accumulation.

- mollusks in a *Halimeda*-rich muddy sand. The top of this facies grades into a calcareous mangrove peat.
2. Reef-flat rubble facies: The rubble derives from a variety of coral species, including *Acropora palmata*, *Diploria* spp., *Agaricia agaricites*, *Millepora complanata*, and *Porites astreoides*. Most of this skeletal debris is water-worn, extensively bored, and encrusted.
 3. Reef *Acropora palmata* facies: This main structural framework of Galeta Reef ranges from 3 to 11 m thick and consists primarily of well-preserved *Acropora palmata*. Growth patterns indicate that most of the *Acropora palmata* has not been overturned.
 4. Fore-reef pavement facies: This facies is heavily indurated by submarine cement and extends from the reef crest to the drop-off at the outer edge of the reef. It contains a high-energy assemblage consisting of crustose coralline algae, *Millepora complanata*, *Agaricia agaricites*, and *Porites astreoides*. Much of this skeletal material has been obliterated by multicyclic boring and cementation.
 5. Fore-reef coral-head facies: This facies occurs only at the base of the outer edge of the reef framework and consists of a mixed assemblage of massive corals, including *Dichocoenia stokesi*, *Siderastrea siderea*, *Porites astreoides*, and the *Orbicella annularis* species complex. Most of these corals show extensive bioerosion and are in-filled with submarine cement.
 6. Fore-reef talus facies: The principal components here are fragments of coral, crustose coralline algae, bryozoans, mollusks, and *Millepora* spp. in a matrix of mud and sand.

As confirmed by eighteen radiocarbon dates, the Galeta Reef has gone through several stages of development (Figure 3):

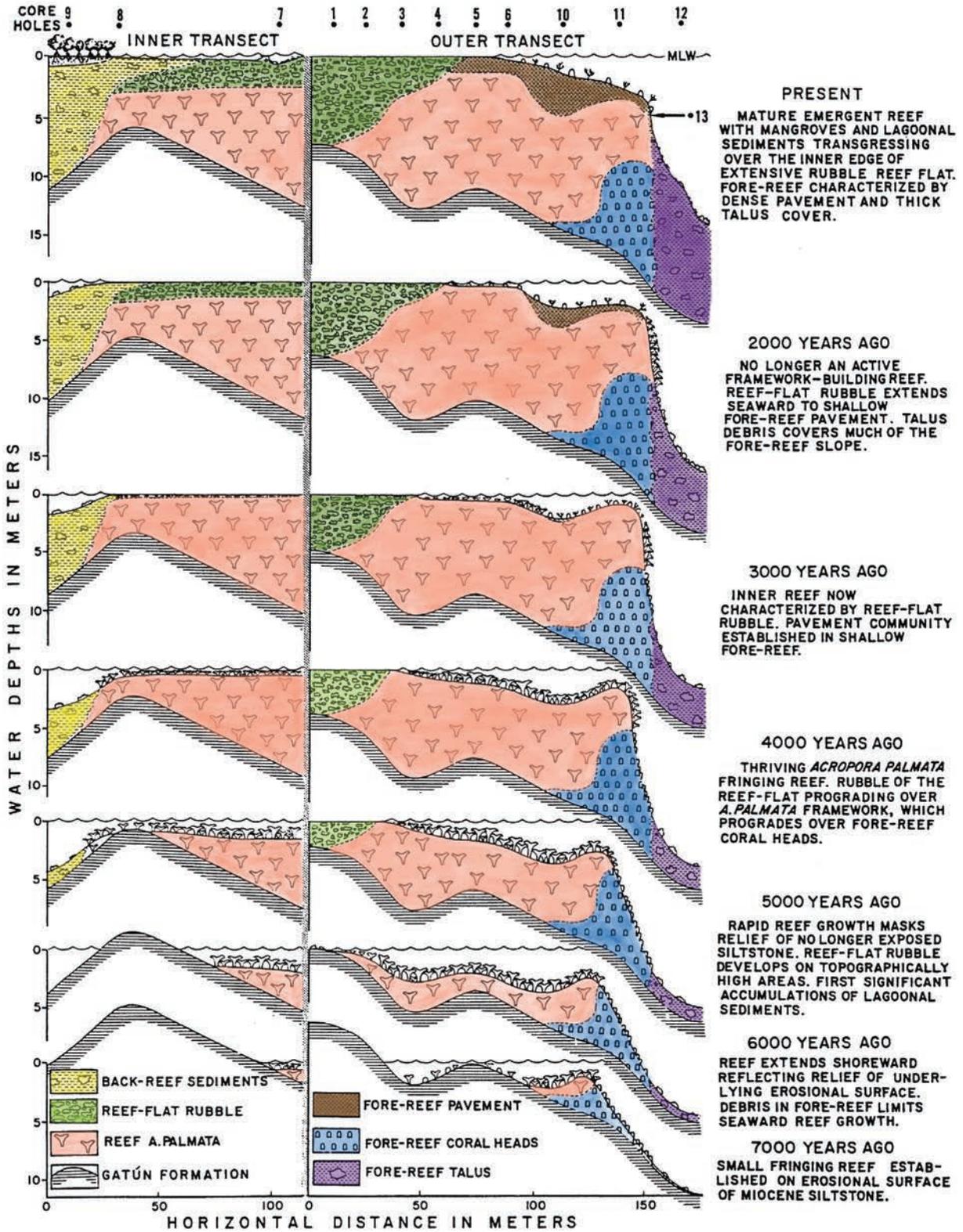


FIGURE 3. Stages of accumulation of Galeta Reef over the past 7,000 years in relation to the Western Atlantic sea-level curve (Lighty et al., 1982). Numbers at top indicate the core-hole locations.

- Beginning slightly more than 7,000 years ago, a small reef consisting of *Acropora palmata* and coral heads established on the mid-Miocene siltstone Gatun Formation.
- 6,000 years ago, the reef extended shoreward, taking on the relief of the underlying Gatun Formation.
- 5,000 years ago, rapid accumulation of *Acropora palmata* masked the substrate relief; the reef-flat rubble facies, back-reef sediment facies, and fore-reef talus facies began to form.
- 4,000 years ago, a mature reef with five facies had become well developed.
- 3,000 years ago, the reef continued to accumulate with the start of the formation of the fore-reef pavement facies.
- 2,000 years ago, all six facies were well developed, but the reef framework was no longer accumulating.
- At present, the mature, emergent reef has mangroves and lagoonal sediments transgressing over the reef-flat rubble, and the fore reef is characterized by dense pavement and a thick talus cover.

Galeta is a classic example of a catch-up reef (Neumann and Macintyre, 1985). It has reached sea level and any new vertical accretion will depend on the provision of new accommodation space through further sea-level rise.

In a subsequent project off the southeast coast of St. Croix (Adey et al., 1977), scuba made it possible to collect three cores from a shelf-edge system in water depths of 11–15 m (Figure 4). These cores all contained a deeper-water coral-head facies with radiocarbon dates ranging from 7,000 to 5,000 years BP (before present; see blue sections in Figure 5). The outermost core, however contained a section of shallow-water *Acropora palmata* below the coral heads, which yielded a date of 9,075 years BP.

When the date of this core was compared with the positions of rising sea level, it became apparent that the shallow-water *Acropora palmata* community died during flooding of the insular shelf about 7,000 years ago (Figure 5). Erosion of the sediment cover on the shelf likely produced turbid conditions at the shelf edge, which exceeded the tolerance of the sensitive *Acropora palmata*. Supporting evidence from X-ray diffraction analysis indicated a marked increase in terrigenous minerals trapped in the cement crusts of the coral-head facies, in contrast to the clean crusts of the *Acropora palmata* facies. By the time turbidity had declined and water quality had improved, sea level at the shelf edge had risen beyond the depth at which the shallow-water *Acropora palmata* could become reestablished. As a result, the massive-coral (or coral-head) assemblage became dominant on the outer shelf. The common occurrence of relict shelf-edge reefs in the Caribbean indicates that during the later stages of the Holocene Transgression most of these reefs succumbed to stress associated with shelf flooding and high turbidity.

The geological patterns illuminated by scuba-based studies in Panama and St. Croix hold lessons for the trajectory of reefs in our present era of rapid climate change. As rising sea levels associated with climate change flood terrestrial habitats, water quality will decline as it did off St. Croix 7,000 years ago and we

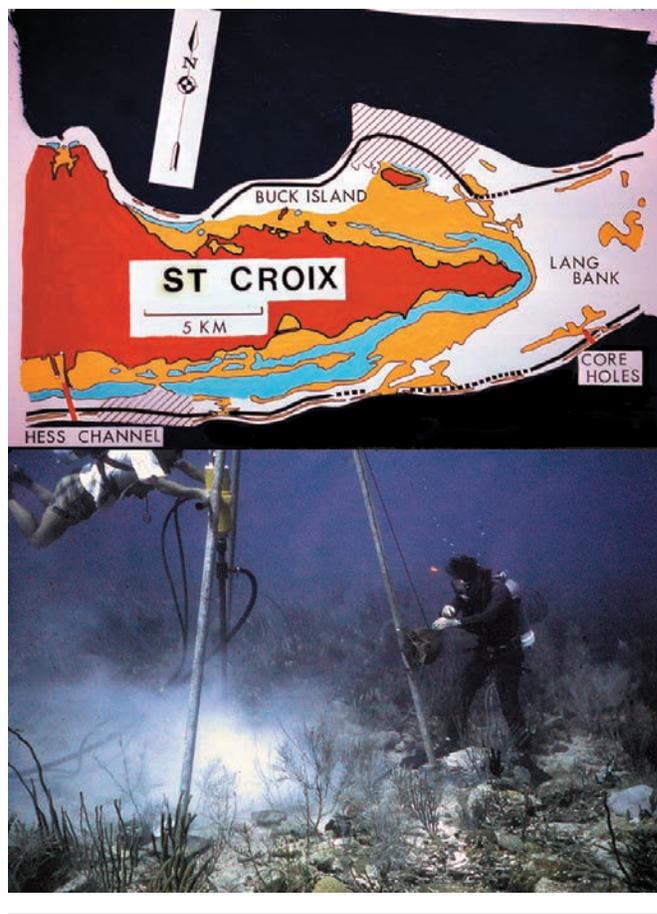


FIGURE 4. Map of the east end of St. Croix showing location of core-hole drilling on a bottom of scattered coral heads and octocorals (modified from Adey et al., 1977; photo courtesy of Ian G. Macintyre).

can expect similar negative impacts on modern reefs. Continued sea-level rise, however, will provide the accommodation space necessary for reefs that have caught up with sea level to begin growing vertically again.

SURFACE SAMPLING

Geological samples collected from reef surfaces also provide valuable information on reef growth and the timing of inimical conditions that stop that growth. Another of our scuba-assisted studies took place on a “dead,” algae-covered, bank-barrier reef off the southeast coast of Barbados (Figure 6). Because the reef lies in an area of constant and heavy wave energy driven by the trade winds, we could only work on it in September, a time of year when storm activity interrupts the otherwise persistent wind pattern (Macintyre et al., 2007).

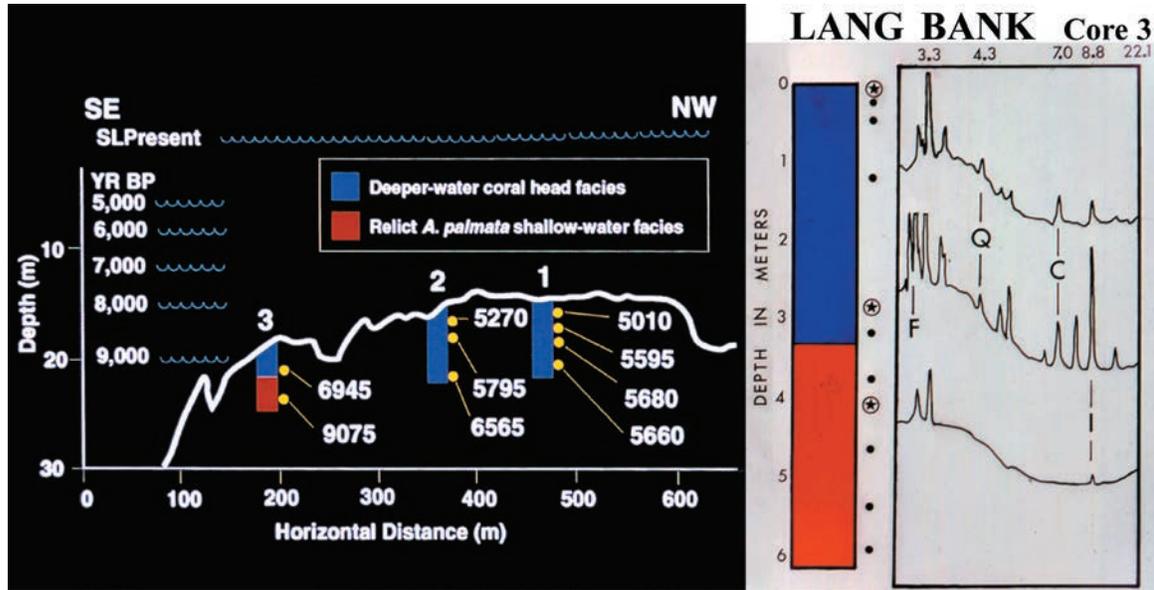


FIGURE 5. Transect of three core holes across the shelf edge off the south coast of St. Croix. Both coral-head and *Acropora palmata* facies are shown with radiocarbon dates. Note the relationship of the end of *Acropora palmata* accumulation to the flooding of the shelf 7,000 years ago. X-ray diffraction patterns of cement crusts from the outermost core show a marked increase in terrigenous material in the upper coral-head facies (modified from Adey et al., 1977).



FIGURE 6. Satellite photograph of Barbados showing Cobbler's Reef, a bank-barrier reef off the southeast coast (courtesy of Digital-Globe).

We reached nine study sites along the 15-km crest of this bank-barrier reef (Figure 7). We completed ten-meter chain-transect surveys, along with digital photography, and collected samples of subfossil corals for radiocarbon dating. Although this was clearly a robust, *Acropora palmata*-dominated reef at one time, we found no living colonies. Instead, we encountered occasional small colonies of *Porites astreoides*, *Diploria* spp., and *Millepora complanata* (Figure 8). The substrate was dominated by macroalgae, crustose coralline algae, and turf algae on dead plates of *Acropora palmata*.

Although the demise of *Acropora palmata* populations in Barbados was previously thought to be partially related to human activity in the seventeenth century (Lewis, 1984), radiocarbon dates of 27 samples of *Acropora palmata* indicated that reef accumulation stopped 3,000 years ago, with 11 dates plotting above the sea-level curve (Figure 9). These dates, along with the taphonomic observation that the subfossil *Acropora palmata* was broken and flattened, indicate that severe storms around 4,000–3,000 years ago destroyed most of the reef. The few *Acropora palmata* colonies that survived until 400–300 years ago may have been killed off by the clearing of land for sugar cane in the late 1600s; however, there has been no reef-framework accumulation for the past 3,000 years. Apparently physical conditions, not human activity, were responsible for the demise of this bank-barrier reef.

Why did this reef not recover? There are at least two hypotheses, which are not mutually exclusive. One explanation is

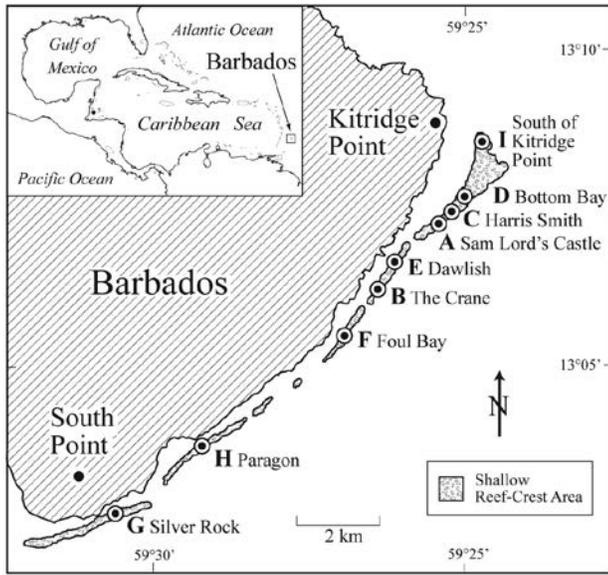


FIGURE 7. Index map showing the nine study sites (A–I) on Cobler’s Reef (Macintyre et al., 2007).



FIGURE 8. Harrismith site (site C) on Cobler’s Reef showing scattered and flattened *Acropora palmata* with a cover of crustose coralline algae, *Millepora complanata* (M), and macroalgae (modified from Macintyre et al., 2007; photo by Allan G. Macintyre).

that wave energy in this area may be too high and constant to allow herbivores to keep macroalgae in check (Steneck, 1988); once the corals died and the macroalgae rose to dominance, the macroalgae prevented corals from recruiting successfully. Alternatively, or in addition, the initial flattening of reef topography prevented recolonization by *Acropora palmata* (cf. Precht et al.,

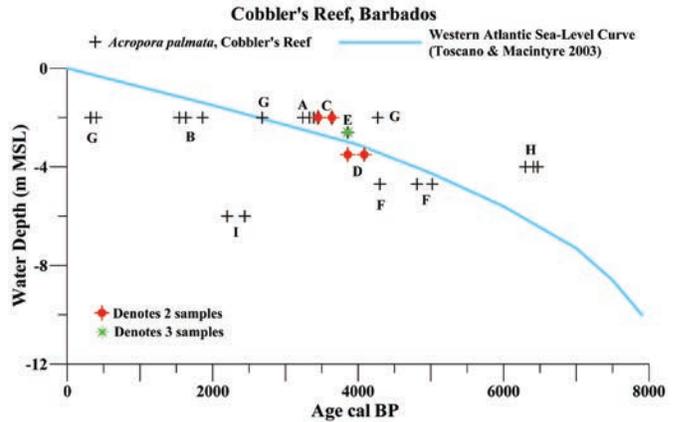


FIGURE 9. Radiocarbon dates of *Acropora palmata* from the crest of Cobler’s Reef plotted in relation to the Western Atlantic sea-level curve (Toscano and Macintyre, 2003). Note the samples that plot above the sea-level curve, which indicate storm damage. There has been no additional reef accumulation for the past 3,000 years (Macintyre et al., 2007). Letters refer to the sites in Figure 7.

2001), due either to high turbulence or to the loss of sheltered microhabitat for herbivores (Szmant, 1997).

PUSH-CORING

Push-coring is an alternative to rotary drilling for reconstructing the Holocene history of coral reefs in lagoonal settings. The ribbon reefs, or rhomboid shoals, in the central shelf lagoon of the Belizean barrier reef; the patch and fringing reefs in Bahía Almirante, a coastal lagoon at Bocas del Toro in northwestern Panama; and certain lagoonal reefs elsewhere in the Caribbean and in the Indo-Pacific are uncemented, consisting essentially of accumulations of skeletal fragments of branching and foliose corals packed in an unconsolidated, sandy-mud to muddy-sand matrix (Aronson et al., 2002, 2004; Wapnick et al., 2004; Toth et al., 2012). Low-energy conditions and the abundant matrix are primarily responsible for the lack of submarine cementation on these reefs.

For the push-coring method, divers force a 5 to 6 m aluminum tube into the unconsolidated reef framework, rotating it in using adjustable core-slips with handles and pounding with a hammer-weight sleeved over the top of the tube (Figure 10). Once the tube has penetrated 4–5 m, the free end is sealed with a plastic cap and electrical tape. The core is then extracted from the reef. Its bottom is sealed and it is then brought to the surface for laboratory analysis. A team of three or four scuba divers can collect a core in a dive of 30–45 minutes. Push-coring is an inexpensive, highly portable alternative to drilling and other mechanized techniques such as percussion vibracoring (Dardeau et al., 2000). Expense and portability are not the sole reasons for

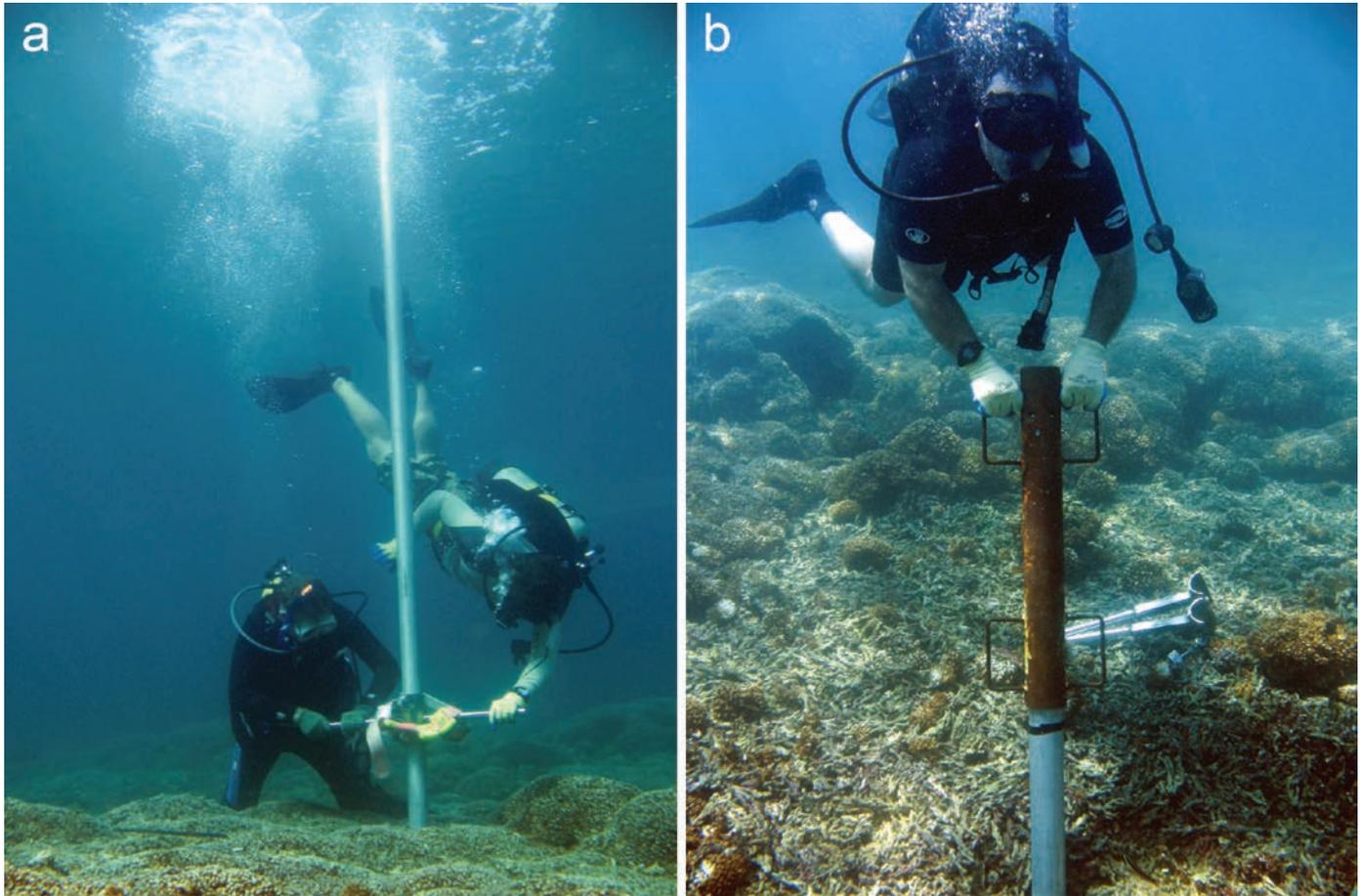


FIGURE 10. Push-coring technique: (a) two divers rotating a core tube into an uncemented reef, using adjustable core slips with handles (photo by Richard B. Aronson); (b) a diver pounding from the top of a core tube using a sliding hammer-weight (photo by Steven V. Vollmer, reproduced courtesy of Richard B. Aronson). Core slips are visible in the background (b), resting on dead coral on the reef surface below the diver.

the high value of push-coring in lagoonal environments. Drilling is inappropriate because the process itself pulverizes delicate corals and blows them and the unconsolidated fine sediments out of the core tube, destroying the very materials that are the focus of study.

Thirty-eight push-cores extracted from 20 sites in Belize at 3–12 m water depth, distributed over 375 km² of the central shelf lagoon, revealed a striking and remarkably consistent pattern of dominance and turnover during the past 3,000–4,000 years (as determined by radiocarbon dating). *Acropora cervicornis* dominated throughout the last several millennia until the late 1980s. Turnover events were highly localized in time and space, consisting of small-scale shifts in dominance between *Acropora cervicornis* and the lettuce coral *Agaricia tenuifolia* (Aronson et al., 2002). After 1986, virtually the entire population of *A. cervicornis* on the rhomboid shoals was wiped out by white-band disease, an infectious bacterial disease that killed acroporid populations throughout the Caribbean from the late

1970s through the early 1990s (Aronson and Precht, 2001). High levels of herbivory from the sea urchin *Echinometra viridis* controlled algal growth on the dead skeletons of *Acropora cervicornis* in the Belizean shelf lagoon, so that by the mid-1990s the reef surfaces at all 20 sites had switched to dominance by *Agaricia tenuifolia*. This large-scale, recent turnover event was recorded as a layer of *Agaricia* plates at the top of each of the cores (Figure 11, left).

The pattern of stasis and turnover was similar in Bahía Almirante in Panama, but the long-term dominant and the cause of turnover were different from the Belizean case. Thirty-six cores were extracted from 12 sites at 5–10 m water depth, distributed over an area of 128 km². In this case, branching *Porites* spp. were the continuously dominant corals for the last 3,000–4,000 years (Figure 11, right). Small-scale turnover events, localized in time and space as in Belize, consisted of transitions to *Agaricia tenuifolia* or *Acropora cervicornis*. Around 1970, the reefs of the Bahía switched to dominance by *Agaricia tenuifolia*. Aronson et

al. (2004) attributed the transition in Bahía Almirante to deteriorating water quality from changing patterns of land use in Bocas del Toro and surmised that the turnover event was precipitated by massive flooding from unusually heavy rains in 1970. These hypotheses were corroborated by geochemical analysis (Hilbun,

2009). The convergence of lagoonal reef systems in Belize and Panama on dominance by *Agaricia tenuifolia* is a remarkable example of the biotic homogenization that is affecting marine ecosystems worldwide.

The push-cores from the Belizean lagoon and Bahía Almirante consisted of a sandy-mud to muddy-sand matrix containing up to 50% Mg-calcite in the clay-size fractions (<4 mm). The consistent mineralogy of 12–13 mole% MgCO₃ and the lack of significant Mg-calcite skeletal material in both the silt-size (4–63 μm) and sand-size (>63 μm) fractions indicate that most of the fine Mg-calcite is precipitated (Table 1). By contrast, authors of previous studies in Belize had speculated that the fine Mg-calcite had a skeletal source. Interestingly, the same Mg-calcite composition found in the lagoonal mud fraction was observed in lithified geopetal deposits on serpulid projections in a lagoonal cave in Belize (Figure 12). Lithification in the cave suggests that exposed sediments may become lithified, whereas the cores indicate that trapped sediments may not.

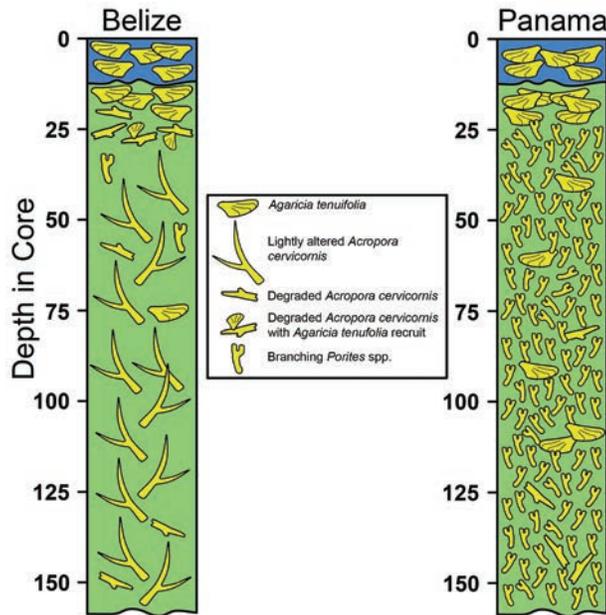


FIGURE 11. Generalized logs of push-cores from the central shelf lagoon of the Belizean barrier reef and Bahía Almirante, Bocas del Toro, Panama. Light green fill indicates a sandy-mud to muddy-sand matrix. Blue fill at the tops of the core logs indicates open framework that has not yet been in-filled with sediment (adapted from Aronson et al., 2002, 2005).

TABLE 1. Concentrations of magnesium calcite in three size fractions of the matrix in lagoonal cores from Belize and Panama (from Macintyre and Aronson, 2006). Note Mg-calcite values in the clay-size fractions. There was no evidence of a source of coarser skeletal Mg-calcite that could break down to form clay-size concentrations of Mg-calcite.

Lagoon location	Average percent Mg-calcite in substrate		
	Sand	Silt	Clay
Belize	9.4%	13.8%	38.2%
Panama	12.6%	16.0%	50.2%

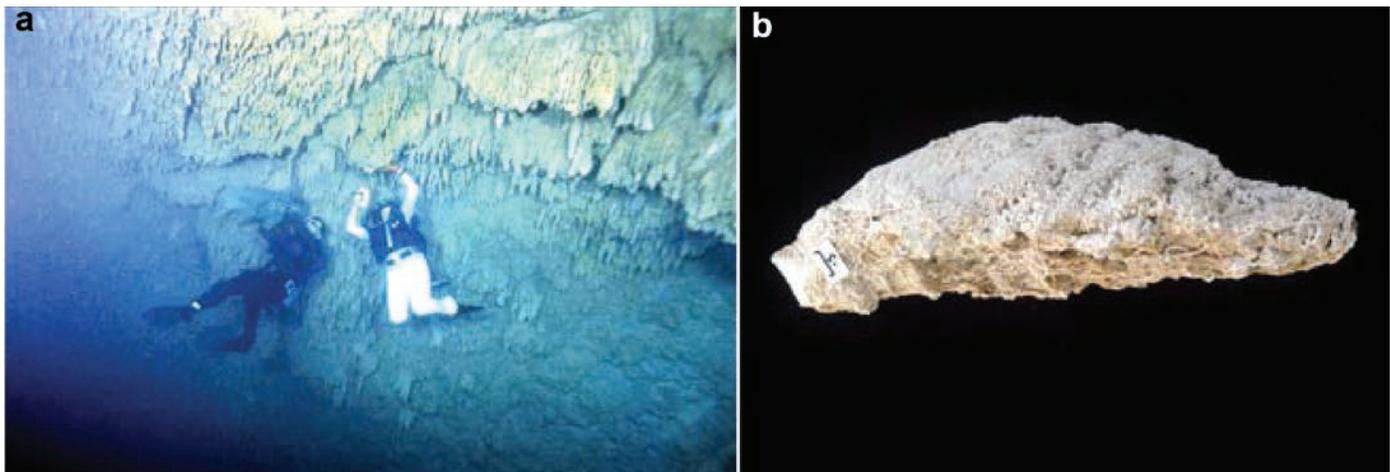


FIGURE 12. (a) Divers sampling serpulid projections on the ceiling of Columbus Cay cave, located in the Belizean barrier reef lagoon. (b) Sample of serpulid projection with thick surface deposit of lithified Mg-calcite (after Macintyre, 1984; photos courtesy of Ian G. Macintyre).

CONCLUSIONS

The ecological and geological responses of coral reefs to natural and human perturbations can only be understood in a historical context. We have presented examples of research on the Holocene history of Caribbean reefs that could not have been accomplished without scuba. The studies highlight the value of a millennial-scale perspective for distinguishing signal from noise in the trajectories of coral reefs. Predicting how reefs will grow and what they will look like in the future will continue to be both an ecological and a geological enterprise, with scuba-based methodologies figuring prominently.

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