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Coral-reef Geology: Puerto Rico and the US Virgin Islands

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7.1   Introduction

7.1.1   Regional Geology

The distribution of Holocene coral reefs around Puerto Rico and the US Virgin Islands reflects the tectonic history of the region. By best estimates, the present-day Caribbean formed between 200 and 130 million years (MY) ago, when North and South America pushed apart and Pacific crust moved northeastward (Pindell 1994). By late Cretaceous time (80 MY: Fig. 7.1), Caribbean plate motion was starting to turn eastward, the Aves Ridge (presently southeast of St. Croix) was forming, and rudistid molluscs were the dominant reef fauna throughout the region (Fig. 7.2). By Oligocene time, the geography of the Caribbean looked much like it is today, and the Greater Antilles lay along a major fault separating the Caribbean and Atlantic plates. Caribbean coral reefs were populated by a much more cosmopolitan fauna than what exists today (Frost 1977; Frost and Weiss 1979). Throughout the Miocene, the Greater Antilles were being torn apart and twisted by both tensional and compressive forces between the opposing Caribbean and Atlantic Plates (Pindell and Barrett 1990; Masson and Scanlon 1991). This has resulted in a left-lateral offset of similar formations on different islands (e.g., the Ponce/Aymamon Formations on Puerto Rico and the Kingshill on St. Croix), as well as counterclockwise rotation of many individual islands (Reid et al. 1991; Gill et al. 2002). On both St. Croix and Puerto Rico, transtensional basins received shallow-water carbonates derived from shallow-water reefs of unknown origins. Movement along the more southerly Muertos Trough (Fig. 7.3) began some time around 10 MY years ago, widening the zone of interplate faulting to some 300 km. The resulting boundary between the Caribbean and North American plates is complex and may include a microplate sitting between the Puerto Rico Trench to the north and the Muertos Trough to the south (Fig. 7.3).

The result is a tectonically active region with generally narrow insular shelves and steep margins that plunge to oceanic depths (Fig. 7.4). The northern, fault-bound margin of St. Croix is one of the steepest submarine slopes in the world. A series of closely spaced faults results in a deep basin (5,500 m) that separates St. Croix from Puerto Rico and the northern Lesser Antilles. The Puerto Rico/Virgin Islands (PR/VI) Platform connects Puerto Rico and the northern Virgins, and was exposed during Quaternary glacial periods, allowing active mixing of terrestrial faunas. In contrast, St. Croix has been separate since its emergence some time after the Miocene and is geologically more related to the Aves Ridge (Fig. 7.3) than to the northern Virgin Islands. The latter are dominated by igneous rocks related to earlier collisional tectonics, whereas the basement rocks of St. Croix are sedimentary in origin (volcaniclastics), and are capped by Cretaceous and Neogene sediment -gravity flows containing numerous reef fossils.

Adey and Burke (1977) characterized St. Croix and the northern Virgin Islands as uplifted and subsided systems, respectively. While this resulted in differing platform histories over a longer timeframe,

both systems have been "inactive" more recently. Thus, the older underpinnings likely experienced different tectonic histories throughout Neogene time (23–1.8 million years), but Holocene reefs throughout Puerto Rico and the US Virgin Islands have probably developed under similar, and largely stable, tectonic conditions, with perhaps minor uplift (ca. 10–30 cm).
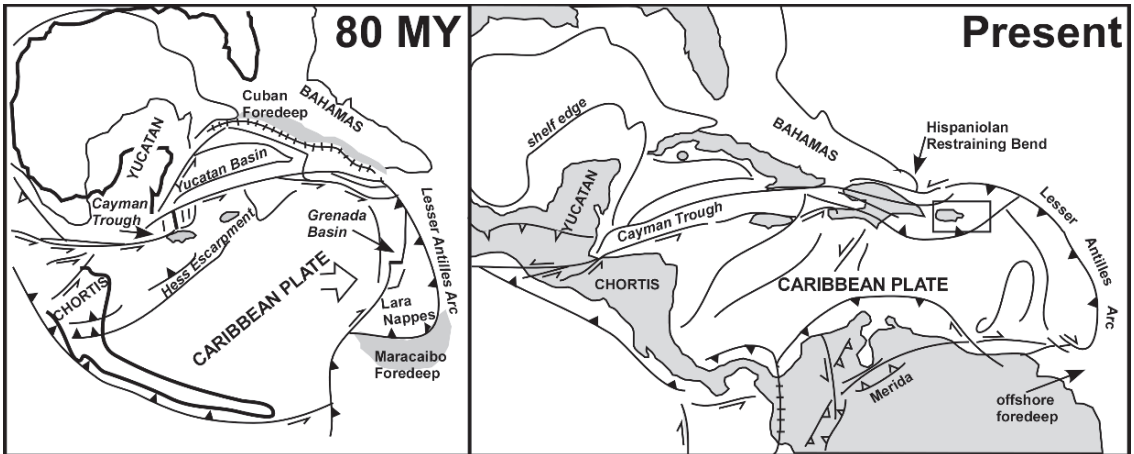

Fig. 7.1. The Caribbean Sea 80 million years ago and today. Before 80 million years ago, the Caribbean plate moved largely northeastward, but was eventually deflected to the east by the Atlantic Plate. The islands of the Greater Antilles lay along the northern boundary between the Caribbean and Atlantic Plates. Today, the Virgin Islands and Puerto Rico (box) lay between the Puerto Rico Trench to the north and the Muertos Trough to the south (Modified after Pindell et al. 1988 by permission of University of the West Indies Publishers)

Fig. 7.2. Photographs of Cretaceous rudists in central Jamaica. While the gregarious molluscs could reach 2 m across, most were more similar in size to those depicted here (coin ~2 cm)
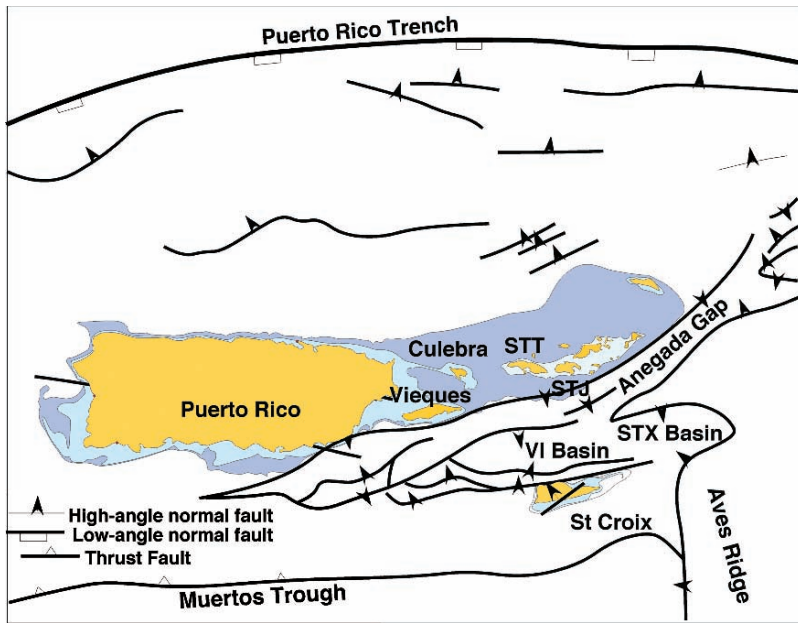
FIG. 7.3. Map of Puerto Rico and the Virgin Islands showing the major faults running through the region. Note the platform that connects Puerto Rico and the northern Virgin Islands (darker blue). This was exposed during glacial intervals, connecting Puerto Rico and the northern Virgin Islands. The V.I. Basin separates these islands from S. Croix and reaches depths of 5,500 m (Modified after Speed 1989 by permission of West Indies Laboratory)
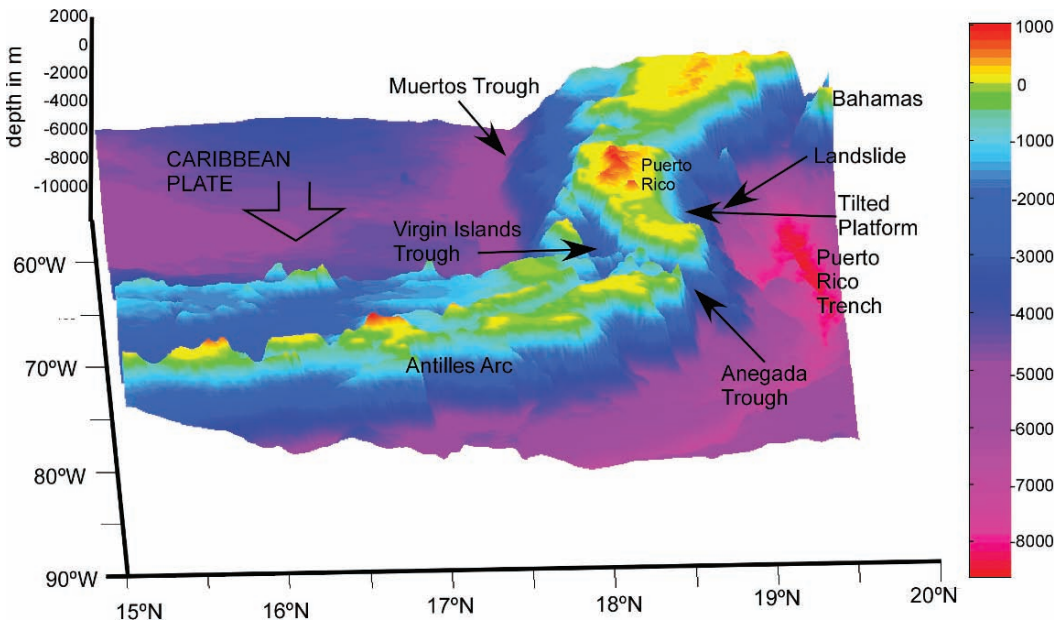

FIG. 7.4. Three-dimensional bathymetric view looking to the west across the eastern Greater Antilles and the northern Windward Islands. St. Croix sits on the ridge south of the Virgin Islands Trough and is separated by it from St. Thomas and St. John to the north. The Puerto Rico Trench (north: right) and the Muertos Trough (south: left) mark the extremes of the transition zone between the North American and Caribbean Plates. The Anegada Trough which cuts diagonally south of the PR/VI platform is the result of one of the many major faults that cut across the region. Diagram modified after Brink et al. (1999) using ETOPO2 data

7.1.2 Reef Types in the Area

Classification is the bane of every scientist, and agreeing on a common scheme for Caribbean reefs is no exception. The system of fringing reefs, barrier reefs and atolls (e.g., Darwin 1842) is unsatisfactory for a variety of reasons. The linear features on eastern St. Croix that are separated from the shoreline by a few kilometers fit the functional definition for barrier reefs. However, many might argue that their scale would relegate them to the fringing category when compared to reefs off Belize or eastern Australia. Horseshoe Reef off Anegada is of sufficient magnitude to qualify as a barrier reef, except much of the "lagoon" that is protected from northeasterly storms is in fact an open bank that is exposed to southeasterly swell and hurricanes passing along the main southerly track through the Caribbean. Circular reefs near South America owe their origins to decidedly different processes than those envisioned by Darwin. And finally, many of the reef buildups occurring near the shelf edge

have lagged behind rising sea level, and are not emergent "reef" features that easily fit into this ternary scheme.

Adey and Burke (1976) proposed a genetic classification based on their cores from reefs throughout the Caribbean. However, this approach suffers in many instances from a priori assumptions of internal reef character and underlying topography (e.g., a cemented terrace beneath "bench reefs", versus a largely unlithified bar associated with early "bank-barrier reefs"). Subsequent cores through at least some of the reefs considered below are not consistent with these earlier assumptions upon which this alternate classification was based. Also, we know less about others, and hesitate to speculate on their origins and histories without core data.

We have, therefore, chosen a morphologic approach that is based on large-scale reef geometry and location. This is used only for consistency with the discussion below, and is not proposed as an alernative classification that is any better than those just discussed; in fact, it is not without its own inherent flaws. Based on this system, the

FIG. 7.5. NOAA vertical photograph of St. Thomas and St. John. The steep nearshore slope extends from the shore to depths greater than 10m, resulting in fringing reefs close to land. The light-colored areas fringing the reefs are sand produced by bioerosion. Darker areas are either seagrasses or hardgrounds at ca. 15–20m, with widely scattered hard and soft corals, and sponges. Pillsbury Sound is deeper and is dominated by sand that moves generally from north (top) to south

reefs of Puerto Rico and the US Virgin Islands generally fall into three categories. Where the shelf slopes steeply to depths exceeding 10–15 m, narrow *fringing reefs* hugging the steep shore are the norm (Fig. 7.5). In many cases, the reef crest is difficult to identify, and the reef forms a continuous veneer that slopes into the immediate nearshore zone (Fig. 7.6a). While more robust communities can occur along steep rocky headlands away from watershed axes, reef cover is generally low and of limited diversity (Fig. 7.6b). The proximity of these features to shore and the steep slopes above have most likely discouraged significant accretion, and they are generally considered to be relatively thin and concordant veneers over the underlying bedrock.

Where nearshore slopes are gentler, *barrier reefs* are separated from the coast by shallow lagoons (<5–10 m) that typically reach maximum widths of 2 km (Fig. 7.7). While the scale is much different from similar features in Belize or the Indo-Pacific region, the term "barrier" is applied, as the lagoon provides a significant buffer from terrestrial sedimentation, and the reef provides a barrier to open-ocean conditions.

Where the shelf gives way to a steep insular slope, well-developed *shelf-edge reefs* often occur. It has only recently been realized that accretion on these deeper features has been significant, and often exceeds that of emergent reefs (Hubbard et al. 1997, 2001). Holocene reef building has resulted in a present-day reef morphology that can be significantly different from that of the underlying Pleistocene substrate. These reefs can sit atop elevate Pleistocene rims (e.g., Lang Bank, SW Puerto Rico) or along simpler slope breaks that take advantage of proximity to deep water (e.g., Cane Bay, Salt River submarine canyon). Reefs at the shelf break are characterized by alternating reef buttresses separated by sand channels (Fig. 7.8) that show a clear relationship to Holocene wave processes (Roberts et al. 1977). The sand channels serve as short-term repositories for bioeroded (and mechanically derived) sediment (Hubbard et al. 1990), and are the main conduits through which sediment is exported during storms (Hubbard 1992b). Shelf-edge reefs can have some of the highest coral cover found on PR/VI reefs (Fig. 7.9), owing to active currents near the shelf break (Roberts et al. 1977) and the separation from terrestrial sediment stress.
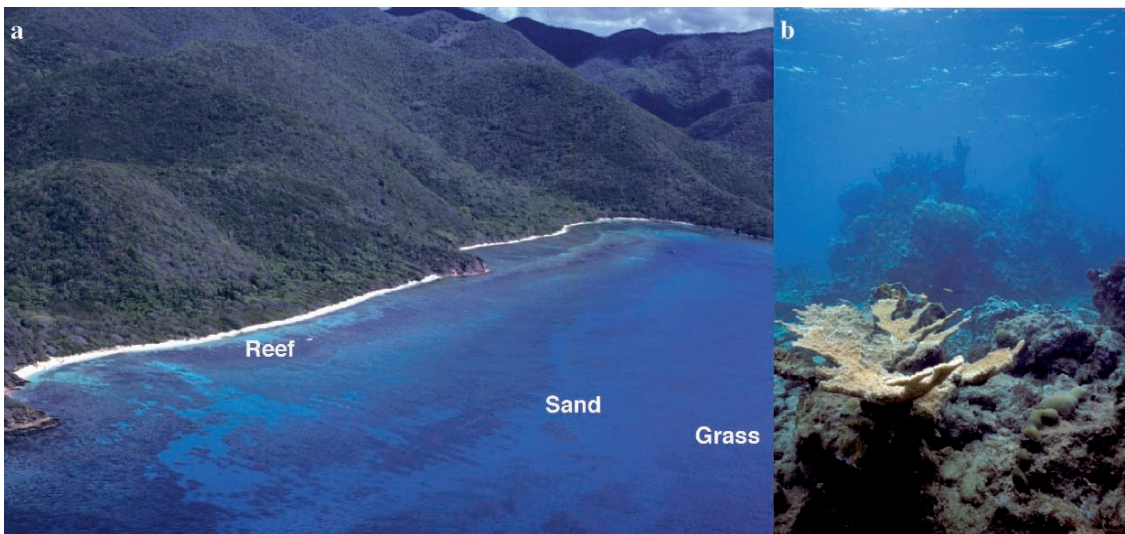

FIG. 7.6. (**a**) Oblique aerial photograph looking northeast along inner Reef Bay, St. John. The steep, continuous slope encourages reefs close to shore with sand and seagrass to seaward. (**b**) Underwater photograph of the forereef in Reef Bay (December 1985). Note the lower coral cover and diversity

Fig. 7.7. Oblique aerial photograph looking west over eastern St. Croix. Note the general shift from reefs closer to shore near the steeper East Point to barriers separated from the island to the west. Buck Island National Park is at the far right of the photo. Salt River and Cane Bay are located along the highland that is visible in the distant background
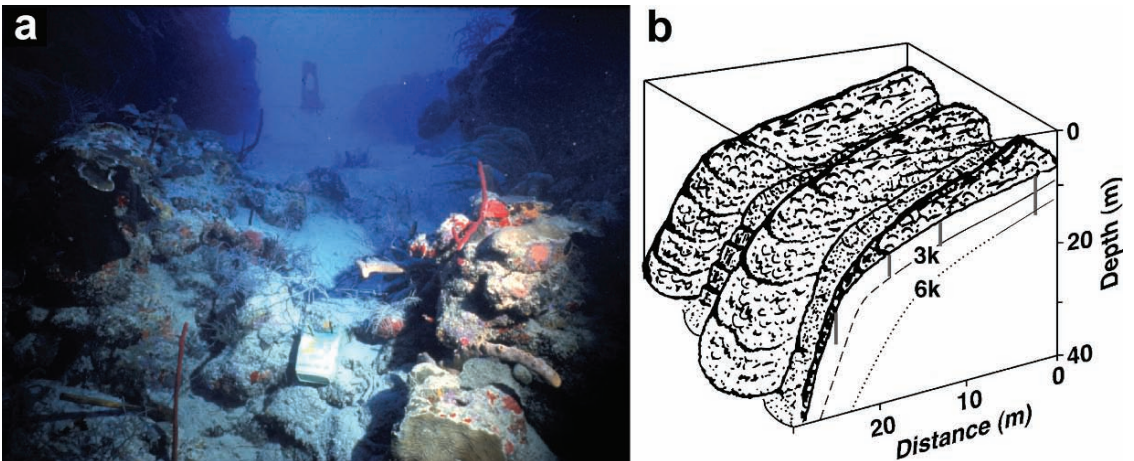

Fig. 7.8. Shelf-edge reef at Cane Bay on northwest St. Croix. (**a**) View looking up a sand channel that separates two reef buttresses (diver in background for scale). The sand channels are temporary storage areas for bioeroded sediment and are the main pathways for export during storms. The sediment trap in the foreground was part of a larger experiment to measure off-shelf sediment transport (Hubbard et al. 1981, 1990). (**b**) Diagram illustrating the character of the shelf edge at Cane Bay. The reef profile 6,000 and 3,000 years ago is shown (based on 4 cores). The present reef morphology reflects a progressive steepening of the forereef slope over time, but the main morphological control is still antecedent (After Hubbard 1989c by permission of West Indies Laboratory)
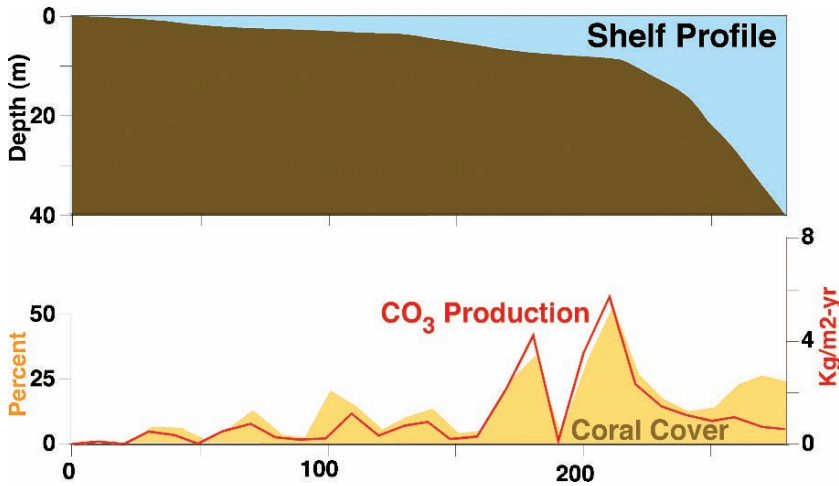
FIG. 7.9. Coral cover (yellow) and carbonate production (kg/m^2-year – red line) across the shelf at Cane Bay (top) on northwest St. Croix. Higher coral cover and carbonate production are a result of lower sediment stress and greater current action near the break in slope (After Hubbard et al. 1981 by permission of West Indies Laboratory)

7.1.3 Relationship to Other Caribbean Reefs

Connell (1978) proposed that reefs are not as temporally stable (or spatially partitioned on a large scale) as has been generally accepted. As a result, the greatest variability in reef types and the highest diversity in those systems would occur where reefs are perturbed at intermediate levels. Adey and Burke (1977) showed a systematic increase in wind strength from Florida and the Bahamas to the Windward Islands. They tied the regional variability in reef type that they observed to changes in wind strength (and, by extension, wave energy) along the same geographic gradient (see their Fig. 7.4). Geister (1977) proposed a similar relationship. Hubbard (1989a) added storm intensity and return frequency to the list of factors that might tie into Connel's classic treatment. The strongest relationship exists along the reef crest, where wave energy is more pronounced, but effects related to swell can extend well down the forereef.

Figure 7.10 combines data for fair-weather wave energy with information on the dominant storm paths, and compares these to changes in reefs type. In the eastern Caribbean, well-developed algal ridges dominate the reef crest (Adey and Burke 1976, 1977). Frequent and strong hurricanes preclude *A. palmata* on the reef crest, where thick algal ridges can form due to the exclusion of grazers by high fair-weather waves. The importance of algal ridges throughout the eastern Caribbean contradicts earlier claims that they do not occur in the region (Stoddart 1969; Milliman 1973).

At the other end of the spectrum, Florida and the Bahamas experience fewer and less extreme hurricanes (Hubbard 1989a). Also, wave energy is generally much lower in the intervals between storms (Adey and Burke 1977; Geister 1977; Hubbard 1989a), allowing for an active grazing population on the reef crest. While lower wave energy results in less breakage of *A. palmata,* this branching coral cannot efficiently clear sediment on its own. As a result, it flourishes on only those more-exposed reef crests where turbulence is sufficient to remove sediment. A dominance of massive species on the reef crest is often the norm.

Puerto Rico and the US Virgin Islands generally experience intermediate fair-weather wind/wave intensity, and storm frequency falls between the extremes seen at either end of the Caribbean (Hubbard 1989a). This results in both high coral diversity and varied reef types, from well zoned systems with *A. palmata* near the crest (e.g., Buck Island, Tague Reef) to algal-ridge dominated reefs
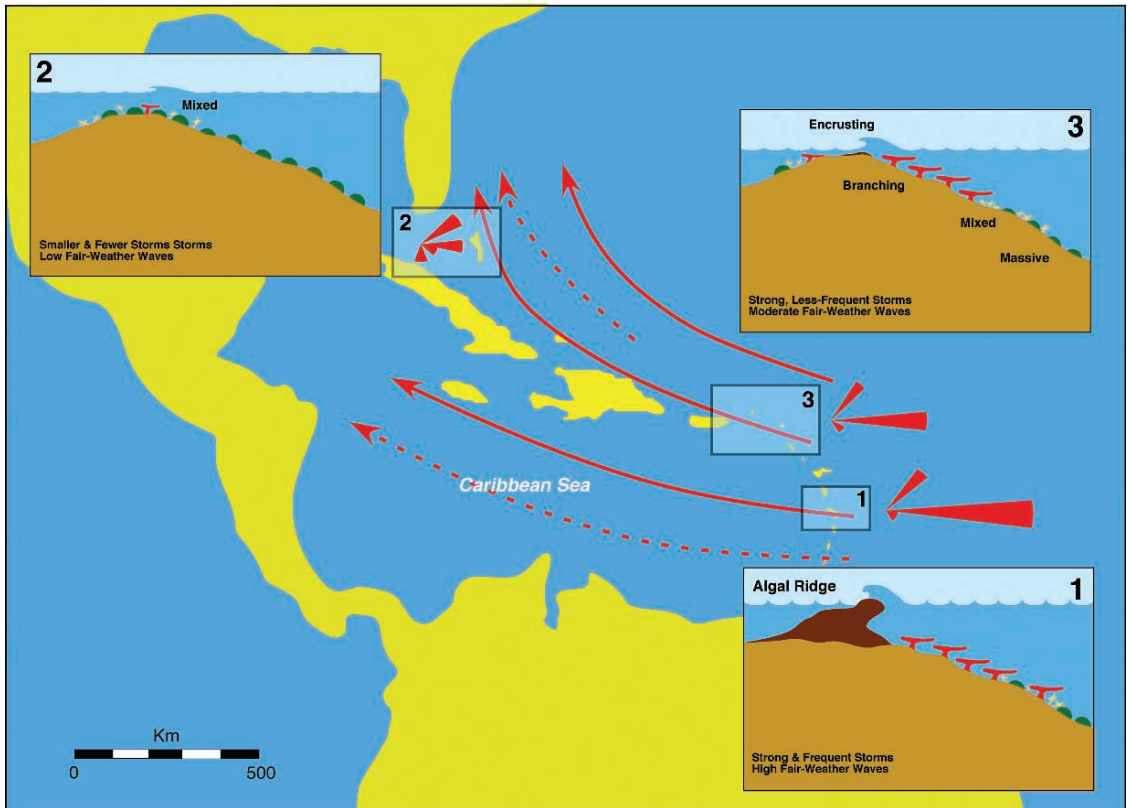
FIG. 7.10. Caribbean reef types relative to wave energy and hurricane intensity. Hurricane (solid) and tropical-storm (dashed) paths are shown by the red arrows. Note the main southerly path across the Windward islands and the secondary path just to the north. The arm lengths on the wave diagrams show the relative wave energy (fair-weather conditions) coming from that direction. The strong easterly trade-wind influence and northeasterly storm flow dominates. Wave energy generally decreases away from the Equator and from the Windward Islands toward Florida and the Bahamas. Algal ridges dominate the Windward Islands (Box 1), especially near Guadalupe and Marie Galante (Adey and Burke 1977) where frequent and strong storms break down *A. palmata,* while high intervening waves discourage grazing and allow thick coralline accumulations. In contrast, both storm and fair-weather conditions are more benign in the western Caribbean (Box 2). Without physical sediment removal by wave action, *A. palmata* has difficulty on all but the most energetic reef crests, and massive species often dominate. Intermediate disturbance levels and ambient wave energy in the northeastern Caribbean (Box 3) provide for high diversity of both organisms and reef types. The most complete Caribbean zonation is generally seen along these reefs (After Hubbard 1989a by permission of West Indies Laboratory)

facing southeasterly swell (e.g., Fancy Bay on St. Croix) or northeasterly storm waves (e.g., Boiler Bay; Adey 1975).

7.2 Pleistocene Reefs

The last time sea level was near its present elevation was ca. 125,000 years ago (125ka) (Fig. 7.11). Somewhat lower (10–20 m) high-

stands were centered on ca. 105 and 80 ka, with lower-yet oscillations in between (e.g., 55 and ca 40 ka). Both emergent and submerged Quaternary reef deposits have been described from Puerto Rico and St. Croix. The emergent reefs appear to be associated with the 125,000-year event (Hubbard et al. 1989; Taggart 1992; Muhs et al. 2005; Prentice et al. 2005) On western Puerto Rico, uplifted reefs at +2–3 m and + 10 m yielded ages of 114–134 ka (ka = thousand years)

(Taggart 1992). The lower terrace also contained Holocene corals, which Taggart interpreted as evidence for a regional sea-level highstand of 2–3 m above present between 1.4 and 3.3 ka. In this scenario, Pleistocene corals were eroded from the 10-m terrace just above. In contrast, Prentice et al. (2005) explained the elevated Holocene corals as a response to uplift. Based on the age and elevation of the emergent Pleistocene units, Taggart computed an average Quaternary uplift rate for Puerto Rico of 3.3 to 5.5 cm/ka. In-place corals from other elevated reef deposits along the northern and western coasts of Puerto Rico have been found between 0.5 and 1.5 m above sea level, and yielded dates ranging from ~127 to 114 ka. A *Strombus gigas* shell from the elevated (1–2 m) terrace on western St. Croix yielded a U/Th age of 125,000 years (Hubbard et al. 1989b). All these reefs fall within the timeframe of marine isotopic stage 5e and are consistent with a higher sea level at that time (Fig. 7.11).

Submerged Pleistocene strata underlying the shelf-edge reefs off Puerto Rico yielded a U/Th age of 102 ka (Hubbard et al. 1997), which is more consistent with substage 5c, as are similarly placed corals from other localities (Cutler et al. 2003;

Gallup et al. 1994; Toscano and Lundberg 1999). The present-day depth range of the Pleistocene sections in the Puerto Rico and St. Croix cores is likewise concordant with estimates of substage 5c sea-level elevations (Cutler et al. 2003; Toscano and Lundberg 1999). The character of these deposits varies from site to site. In some instances (e.g., the southern Puerto Rico shelf edge), the Pleistocene *Acropora palmata* appear identical, both macroscopically and microscopically, to those in the overlying Holocene section. In contrast, the Pleistocene deposits beneath many of the St. Croix reefs are often coral/mollusc grainstones and rudstones with a well-developed caliche cap, reflective of different environmental conditions at those sites.

7.3   Holocene Reefs

No reef cores have been recovered from the northern Virgin Islands. However, Adey and Burke (1976) provide observations on possible antecedent features that permit conjecture on the timing and extent of Holocene reef development in these areas. On St. Thomas and St. John, the proximity of reefs
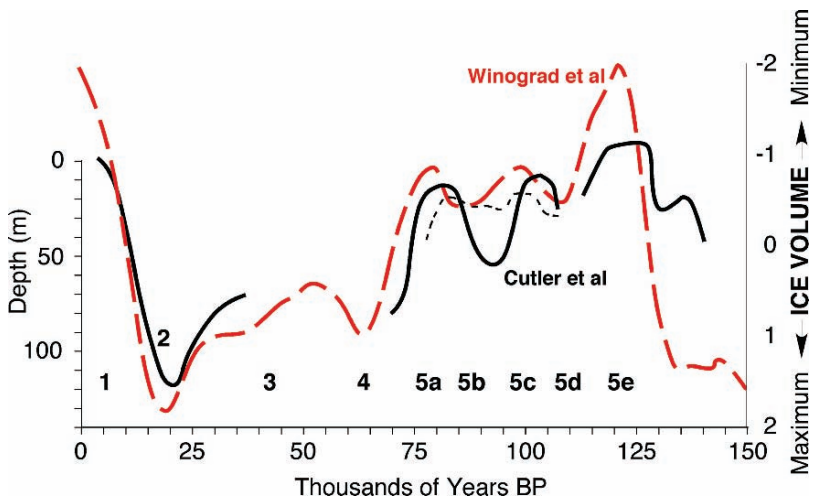

FIG. 7.11. Pleistocene sea-level record based on coral samples from the uplifted reefs of Barbados and New Guinea (Cutler et al. 2003: bold black) and submerged reefs in the Florida Keys (Toscano and Lundberg 1999: dashed, thin line). Also shown is the isotopic record from the SPECMAP foraminiferal ^{18}O time series of Imbrie et al. (1984: red dashed). Bold numbers above the abscissa are Shackleton's (1987) marine ^{18}O isotope stages (1–5) and substages (5a–5e). The known Pleistocene reefs on Puerto Rico and St. Croix are associated with substages 5c and 5e (After Winograd et al. 1997 by permission of Elsevier)

to shore and the steep watersheds immediately behind argue against vertically extensive reefs. Off Puerto Rico, most available cores come from the southwest corner of the island. In part, this is related to the convenience of a permanent marine lab on nearby Isla Magueyes. However, general reconnaissance studies confirm higher coral cover and diversity in this area. Reefs along the western (e.g., Mayaguez) and southern coastlines (e.g., Ponce and Guayanilla) are generally subjected to higher sedimentation levels than near La Parguera, where our cores were recovered (Acevedo et al. 1989). The development of such diverse reefs in the southwest is largely a result of the broad shelf that provides a buffer from intense coastal sedimentation.

A coring investigation off Vieques, just east of mainland Puerto Rico, concluded that there was "relatively little present day reef growth" (Macintyre et al. 1983), similar to what we propose for the northern Virgin Islands and northern Puerto Rico. Long, linear features that are obvious from the air near San Juan on the north coast (Fig. 7.12) are not biologically built reefs. Rather, they are drowned dunes left by the last sea-level highstand. Shelf-edge features analogous to those described below probably occur, but the steep inshore slope and high wave energy would make significant accretion more difficult.

7.3.1 Reef Building and Holocene Sea-level Rise

The locations of reef cores upon which this chapter is based are shown in Fig. 7.13. The patterns of reef building at these sites are dependent on shelf geometry, the nature and proximity of adjacent landmasses, and the relationship between antecedent topography and rising sea level. As progressively shallower sites were flooded, the success of subsequent generations of reefs was dependent on both the rate of sea-level rise at the time and environmental conditions as those reefs tried to keep up. It, therefore, seemed most logical to describe reefs within a temporal context, rather than tie the discussion to reef type or location. We start with shelf flooding, and work our way through progressively shallower and more landward reef development.

Because we tie our story to rising sea level, we start our discussion there. While there is some disagreement over the details, it is generally accepted that Holocene sea level rose rapidly (>5–6 m/1,000 years – m/ka) until ca. 8,000–6,000 years ago, when it slowed to ca. 1 m/ka (Fig. 7.14). As will be discussed later, this decrease in the rate of rise triggered major changes in Caribbean reef development. The most widely accepted curve for Caribbean sea level was compiled by Lighty et al. (1982), using all available depth/age data for
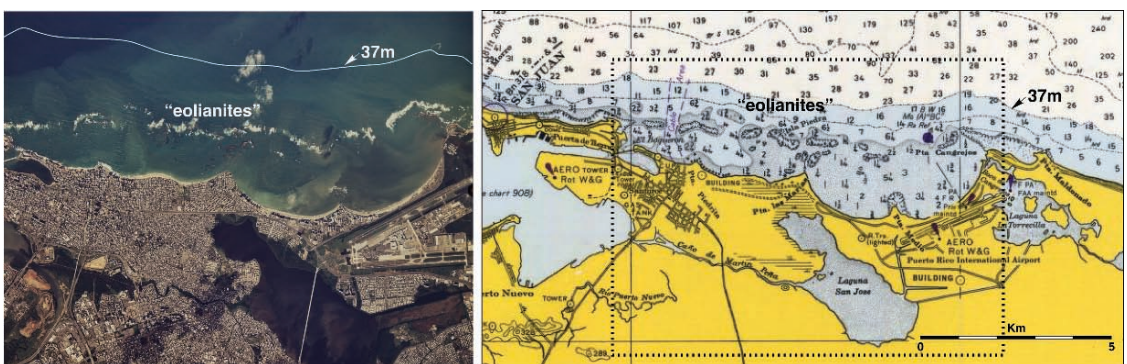

FIG. 7.12. NOAA Vertical air photo (left) and coastal chart (right) near San Juan, Puerto Rico. The breaking waves show the locations of remnant dunes ("eolianites") from the last sea-level highstand. The location of the air photo is shown by the dashed box on the chart. The steep nearshore slope (the 37 m contour is only 1–2 km offshore) makes it difficult to form extensive reefs with significant accretionary potential, a situation that is similar to the northern Virgin Islands. This is in contrast to the broad shelf along the southwestern insular margin of Puerto Rico, where some of the reefs described in this chapter were cored
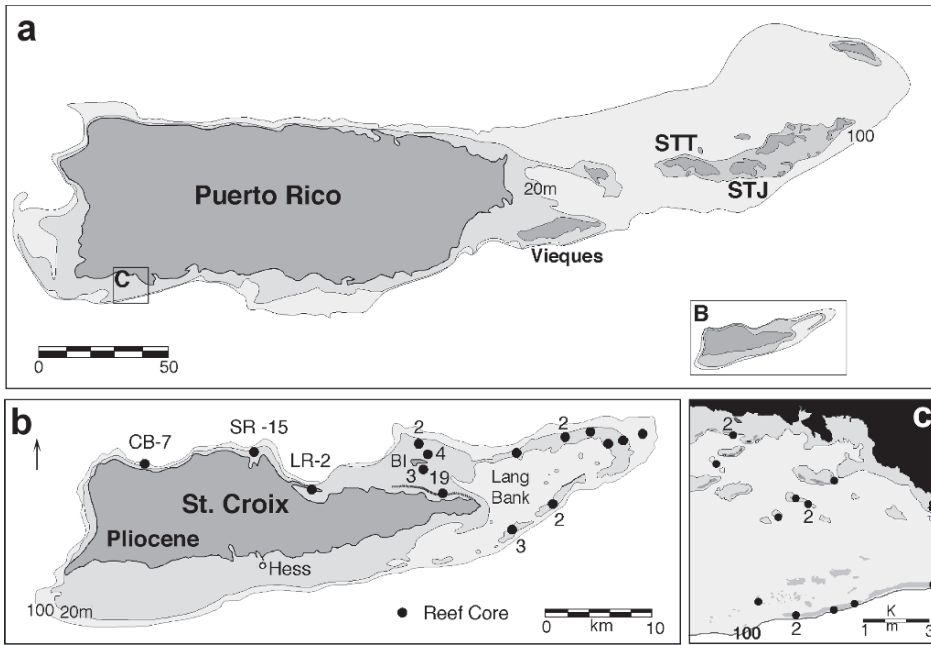
FIG. 7.13. (**a**) Map showing the locations of sites in Puerto Rico and the Virgin Islands discussed in this chapter. The boxes show the locations of B and C. (**b**) Core locations around St. Croix. Numbers next to black circles indicate multiple cores. The three cores along SW Lang Bank are those of Adey et al. (1977). BI = Buck Island; CB = Cane Bay; SR = Salt River. C) Cores off La Parguera on the southwest corner of Puerto Rico

A. palmata. They assumed that the upper boundary of the plotted samples represented sea level (i.e., reefs do not normally build above sea level), and the vertical spread in samples reflected either the depth range (ca. 5–10 m) of this fast-growing branching coral or down-slope transport. The curve shown in Fig. 7.14 is based on isotopic corrections of the Lighty et al. curve using either a proprietary algorithm developed by Beta Analytic, Inc. (Hubbard et al. 2000, 2005) or a similarly structured freeware program, *Calib* (Toscano and Macintyre 2003). The standard for referring to these corrected ages is "calendar years before present" (Cal. BP). All ages mentioned below refer to Cal. BP, even though the shorthand ka is used throughout the text for "thousand years".

The Lighty et al. curve is similar to a peat-based curve for Bermuda (Neumann 1977),[1] corrected

for differential biological fractionation (corals vs. mangroves) and ocean reservoir effects using the methods described above. However, recent challenges have come from Blanchon (2005), Gischler and Hudson (2004), and Gischler (2006). Blanchon (2005) argues for three steps in the curve, similar to the two "meltwater pulses" described for Barbados by Fairbanks (1989). However, Blanchon's curve (red in Fig. 7.14) in inconsistent with the number of radiocarbon dates that plot above it, as well as the lack of any interruption in reef accretion that such jumps should have presumably caused. Also, isotopic data do not support a sudden pulse of meltwater into the world ocean as was the case for the Barbados cores (Fairbanks 1989). Gischler (2006) reports a number of *A. palmata* samples from Belize that plot above the curve used here. These were accompanied by peat samples from Belize, Florida and Jamaica. Toscano and Macintyre (2003) interpreted these as intertidal to supratidal peat, and drew the curve beneath them, while Gischler (2006) argued for a subtidal origin, and a curve that sits above. Fortunately for the following discussion,

[1] This curve originally appeared in Adey (1975: Fig. 13), with the sole reference of "Neumann (in ms)". It subsequently occured in Adey and Burke (1976; Fig. 3) without citation. Bloom (1977) published it with the permission of the author, again citing it as "unpublished data".
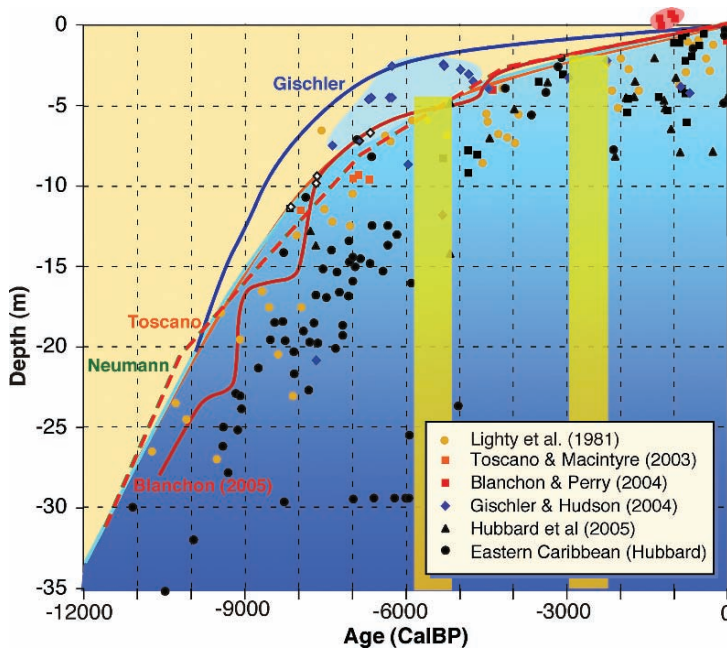
FIG. 7.14. Holocene sea-level curves for the Caribbean. Reef development described in this chapter is referred to the sea-level curve of Lighty et al. (1982), corrected for metabolic and sea-water effects (Hubbard et al. 2000, 2005: light blue; Toscano and Macintyre 2003: orange). Each data point reflects the corrected age of an *A. palmata* sample and its depth below present sea level (see legend for data source). Curves suggested by Neumann (1977: dashed green), Blanchon (2005: red) and Gischler (2006: dark blue) are also shown. The *A. palmata* samples used to derive the curves are provided (see key for sources). The yellow bars represent two intervals in which *A. palmata* is either rare (three samples between 5.9–5.3 ka) or absent (3–2.2 ka) from the record of dated samples for the entire region. After Hubbard et al. (2005) by permission of SEPM

whichever curve one chooses in Fig. 7.14, the general pattern remains the same: rapid sea-level rise before 8–6 ka and a much slower rise thereafter. We will take no side here, inasmuch as the change in the rate of sea-level rise between 8 and 6 ka is the only point that is critical to our arguments that follow.

7.3.2 Shelf Flooding

Prior to 12,000 years ago, most of the shelf margins around Puerto Rico and the Virgin Islands were exposed. The deeper southern margin near St. Thomas and St. John (at ca. 35 m) would have flooded earlier, when sea level was rising very quickly. Because Atlantic sea level is slightly higher than its Caribbean counterpart, tidal flow through Pillsbury sound is dominantly to the south, a pattern that probably also existed 12,000 years ago. The southerly off-shelf transport, in

combination with rapidly rising sea level, probably discouraged significant reef development along the southern edge of the PR/VI Platform, especially opposite breaks between islands. Today, these areas support scattered corals and large demosponges. A similar fauna is common along the southern and western margins of St. Croix at similar depths.

Where the shelf-edge reefs reach present depths less that 15 m, depths along the underlying Pleistocene surface generally fall between 20 and 35 m. Cores along deeper antecedent shelves yield older ages near their base, owing to earlier flooding. Overwhelmingly, these early reefs were dominated by branching *A. palmata* (Fig. 7.15). Based on the sea-level curve in Fig. 7.16, the underlying Pleistocene surface would have flooded between 12,000 and 10,000 years ago. The oldest radiometric ages for corals in the lower sections of the cores post-date flooding by ca. 1,500 years. Timelines
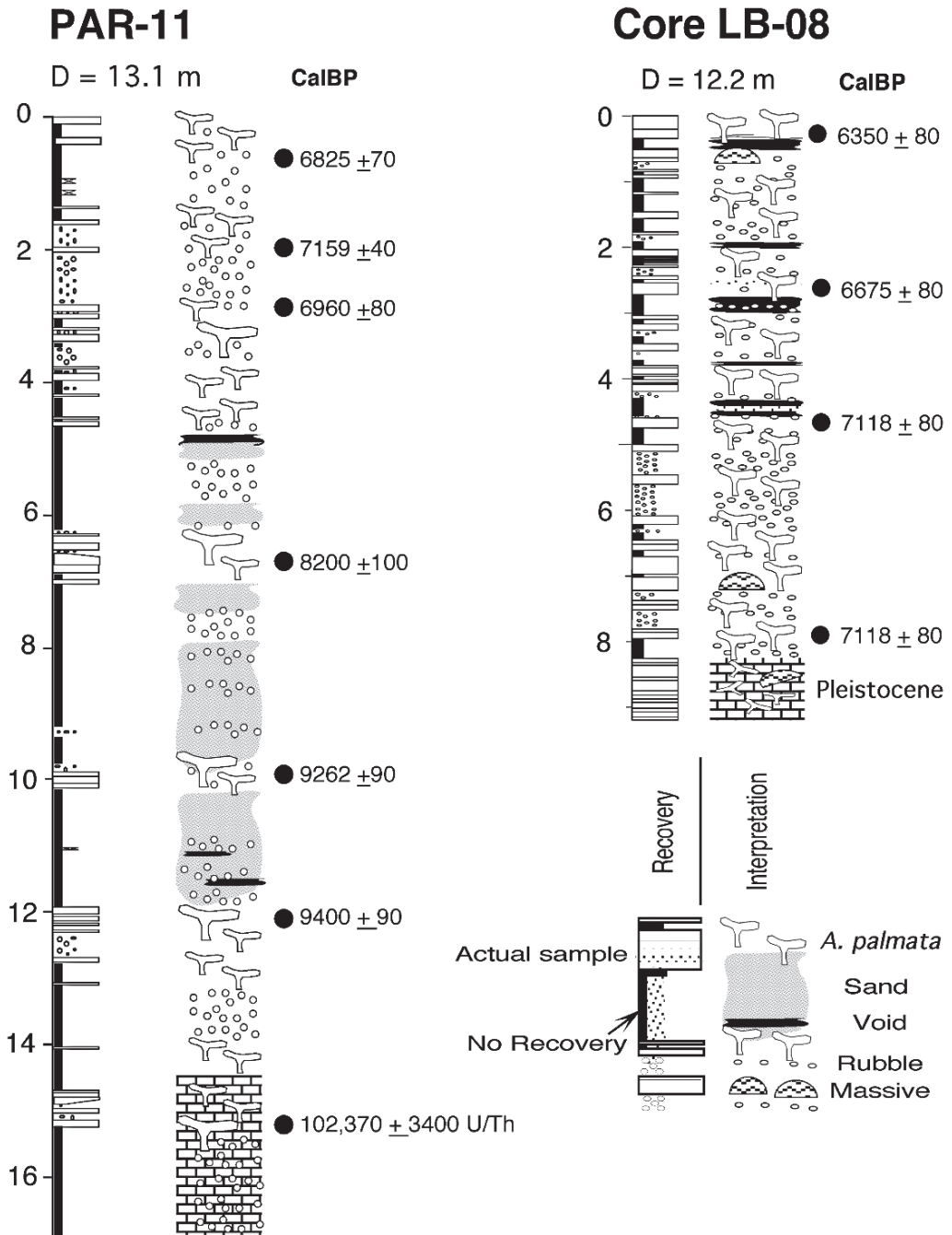
FIG. 7.15. Core logs from typical shelf-edge reefs off southwestern Puerto Rico near La Parguera (PAR-11) and eastern St. Croix (LB-08). Actual core recovery is summarized in the left column of each log; the interpreted section (including coral species and the character of intervening sections, i.e., void, sand, rubble) make up the right half. See key at lower right for details. The dominant corals at both sites were branching *A. palmata*. In general the antecedent shelf was shallower on St. Croix and, therefore, flooded later.
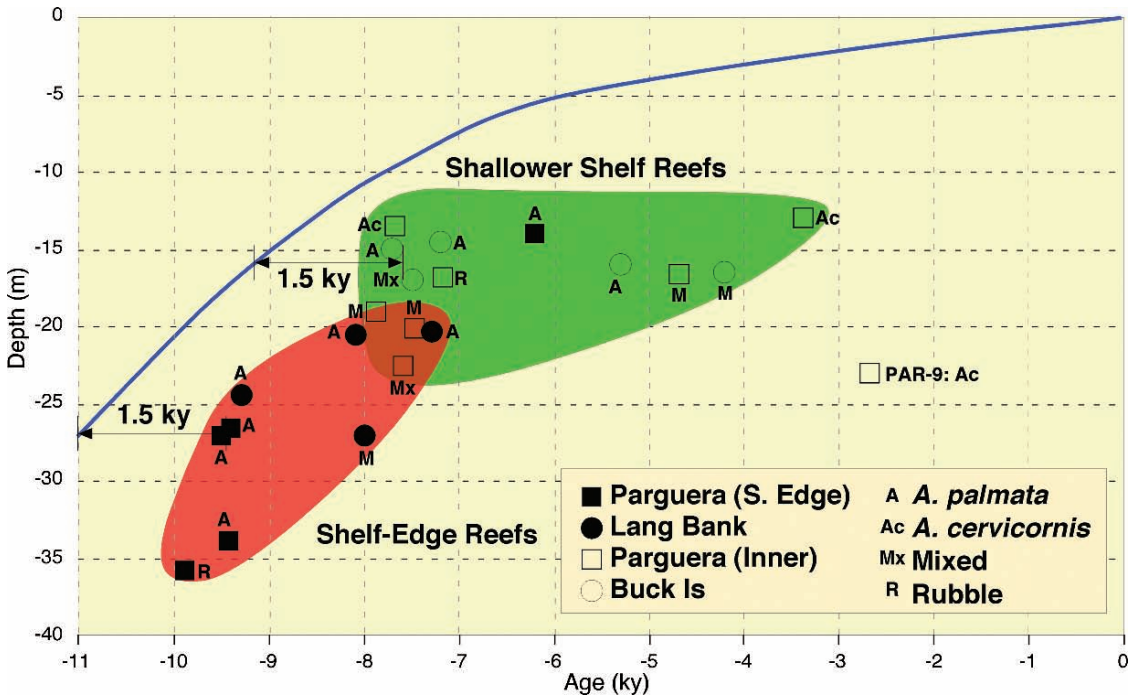
FIG. 7.16. "Start-up" ages and depths for reefs where cores penetrated through the entire Holocene section. Based on the corrected Lighty et al. curve (black line), the oldest preserved samples lag behind flooding by ca. 1,500–2,000 years. The lag associated with branching *A. palmata* (A) was roughly half that associated with more sediment-tolerant massive species (M). If this lag were a response to sediment stress, more tolerant massive corals should have been able to adapt more quickly, contrary to the pattern shown by the cores. Ac = *A. cervicornis*; Mx = mixed species.
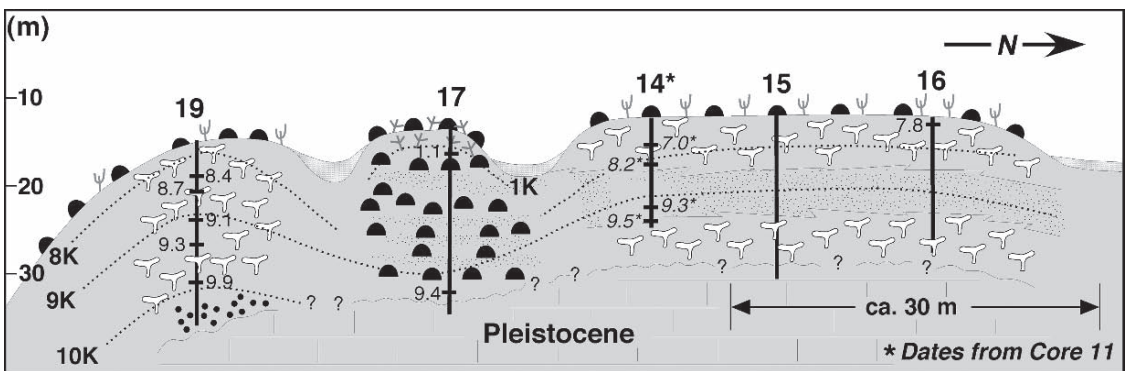

FIG. 7.17. Profile across the shelf-edge reef near La Parguera, SW Puerto Rico (Caribbean Sea is to the left). Reef composition and time lines across the feature are based on multiple cores (see Fig. 7.15 for coral key). The morphology at this site does not allow for significant downslope coral transport that might bias age/depth relationships discussed here. The innermost ridge (Cores 14–16) was cored at two other places along the shelf edge, and demonstrates along-shelf continuity of the lithology and timing shown here. The outer feature (C19) formed first, and was dominated by *A. palmata*. A reef inhabited by massive species formed ca. 20 m landward (C17). A broad platform (ca. 30 m across) covered by *A. palmata* formed the shallowest part of the reef complex. Water depth atop the reef (12–13 m) is identical to the rim around Lang Bank (St. Croix), where a nearly identical history was revealed. The *A. palmata* reefs quit around 6,800 – 6,500 years ago, but the intermediate ridge dominated by massive species continued to build more slowly after the *A. palmata* reefs had succumbed (note the 1.1 ka date 3 m below the present surface in core PAR-17). The present-day cover by massive and soft corals contrasts with the species found in the immediate subjacent strata except on the middle reef

drawn along core transects show that the reefs were relatively narrow and flat-topped features with deeper water both in front and behind (Fig. 7.17). This precludes samples having rolled down from upslope and younger reefs.

The lag between shelf flooding and the oldest ages in the cores has traditionally been related to the suppression of coral recruitment by turbid water, high sedimentation, and elevated nutrient levels derived from Pleistocene soil horizons that were eroded by wave action as the platform was overtopped (Adey et al. 1977; Schlager 1981; Neumann and Macintyre 1985; Macintyre 1988). While re-disturbed sediments undoubtedly played some role in discouraging early coral communities, it is difficult to envision this inhibition lasting on such a large scale for 1,500 years or longer. Also, in many cases massive-coral reefs lagged behind similar structures dominated by more susceptible acroporids by as much as 3,000 years. If this lag

were related to turbid water flowing off the flooded platform, then one would expect more tolerant massive species to be associated with shorter lag times, opposite to the pattern shown here.

An alternative scenario recognizes that "the oldest reef dates are simply the first *preserved* corals" (R. Buddemeier). Early shelf-edge reefs had to deal with not only turbid water, but also the possibility of an unstable substrate (Adey and Burke 1976). The slowly developing reefs were undoubtedly subjected to bioerosion that may have been more severe, given the elevated nutrient levels that probably existed during earliest flooding. Under this scenario, the lag reflects not so much poor water quality as it does a near balance between construction and destruction along fledgling shelf-edge reefs. Seven of the eight shelf-edge cores from St. Croix and Puerto Rico that penetrated into the underlying Pleistocene strata contained basal Holocene intervals dominated largely by sediment and reef rubble,
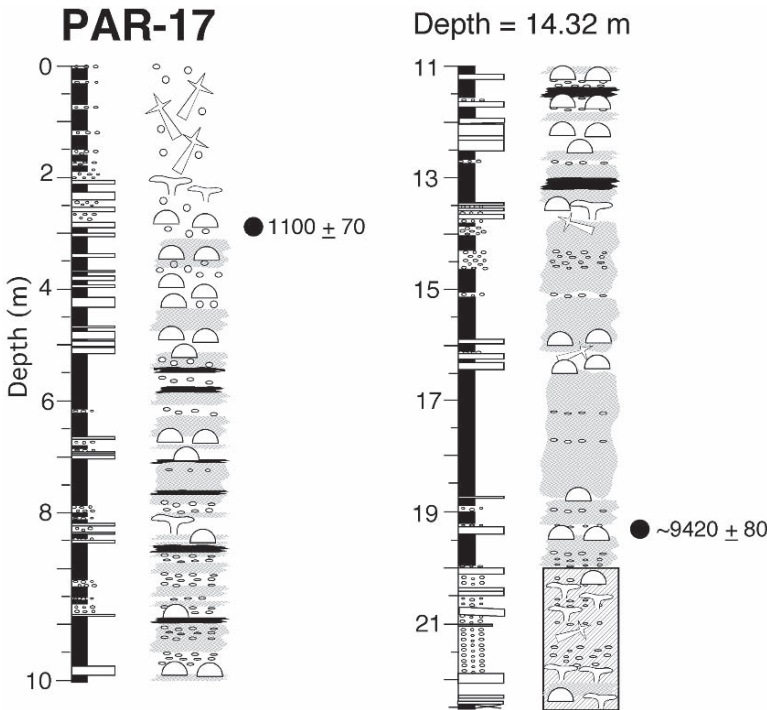
FIG. 7.18. Shelf-edge core from SW Puerto Rico illustrating the abundance of reef detritus in the lower 7 m of the reef that "started up" ca. 9,420 years ago (the black bar in the left column denotes no recovery; stippled pattern in right column is an interpretation of sandy sediment in the non-recovered interval). Note the general increase in recovered coral framework up-core. This pattern is typical of nearly all of the shelf-edge cores that penetrated through into the underlying Pleistocene strata. See Fig. 7.15 for key

in some instance several meters thick (Fig. 7.18). The abundance of bioclastic debris logically reflects a productive system being largely reduced to rubble. Whether this material was part of an allochthonous spit/bar that served as a focal point for reef development (e.g., Adey and Burke 1976; Burke et al. 1989) or a largely autochthonous reef fabric reflecting increasing coral preservation over time is not clear. Regardless of the origins of this bioclastic debris, something had to be there to bioerode, and the most likely sources are the antecedent Pleistocene surface and Holocene corals. The preserved caliche surface at the top of many Pleistocene sections precludes the antecedent surfaces as a bioclastic sediment source at these sites. Thus the "lag" after shelf flooding appears to have been related more to poor initial preservation than to delayed coral recruitment.

7.3.3 Shelf-edge Reef Building

Reef building throughout the early Holocene implies conditions that were ideal for *A. palmata*. Even though sea level was rising at its maximum rate, extensive branching-coral reefs had been able to form on deep topographic benches off Barbados (70–120 m below present sea level), and flourished intermittently between 20,000 and 11,000 years ago (Fairbanks 1989). It is likely that these features occur widely throughout the region. As upslope Caribbean shelf margins were flooded, this dominance of *A. palmata* continued.

The oldest radiometric age reported from Caribbean shelf margins (11.1 ka) comes from a reef in Salt River submarine canyon (Fig. 7.13) on the north shore of St. Croix at a depth slightly greater than 30 m below present sea level (Hubbard et al. 1986). The reef was dominated by branching corals and sat within 2–3 m of sea level at the time. Reefs also formed along an antecedent rim around Lang Bank (the 10.3 ka reef of Adey et al. 1977; see their Fig. 4) and an elevated shelf margin off southwestern Puerto Rico (Hubbard et al. 1997; Fig. 7.19, Table 7.1). These are coincident with *A. palmata* reefs forming in Florida (10,700 Cal. BP: corrected from Lighty et al. 1982) at similar depths along the edge of the Gulf Stream.

As sea level rose further, reefs formed along the tops of antecedent Pleistocene ridges (e.g. cores 14–16: Fig. 7.17). While massive corals did occur in more protected areas (Core 17: Fig. 7.17), the reef crest was generally dominated by *A. palmata* (only 4 of 18 cores through shelf-edge reefs in Puerto Rico and St. Croix yielded massive species, and all of these were landward of other cores dominated by *A. palmata*). By 9 ka, widespread branching-coral reefs flourished at both shelf-edge sites, and along other shelf margins at similar depths throughout the Caribbean. Water depth over the St. Croix and Puerto Rico reefs was generally less than 10 m, but did reach as much as 16 m (Fig. 7.16). Stands of *A. palmata* can be found at similar depths on Lang Bank today, but these are isolated colonies that are probably not contributing to in-place reef framework. However, modern reef pinnacles at similar depths off SW Puerto Rico supported well-developed stands of *A. palmata* that appear to have been contributing to a largely in-place reef structure until the colonies were killed by bleaching and/or disease, probably within the past 2–3 decades.

Despite the considerable depth over most of the early Holocene shelf-edge reefs, accretion rates averaged between 4 and 5 m/ka. These reefs were, therefore, capable of keeping pace with rapidly rising sea level, which was advancing at a similar rate. Thus, while the reefs were not shoaling over time, they were not falling further behind either.

7.3.4 Backstepping and the Formation of Shallower Reefs

7.3.4.1 Puerto Rico

By 8 ka, flooding of the inner shelf triggered the development of shallower reefs closer to shore (Fig. 7.19). These started from elevated, antecedent surfaces between 13 and 23 m below present sea level (most commonly between 14 and 17 m: Fig. 7.16: "shallower shelf reefs"; Table 7.1; Hubbard et al. 1997). There was a roughly 2,000-year overlap between the early development of inshore reefs 8,000 years ago and the subsequent demise of their deeper counterparts. Thus, the demise of the shelf-edge reefs logically had no causative effect on the shifting of reefs toward shore. Unlike the shelf-edge reefs that were largely dominated by *A. palmata*, the newly formed inshore structures were built by massive species, and only shifted to branching
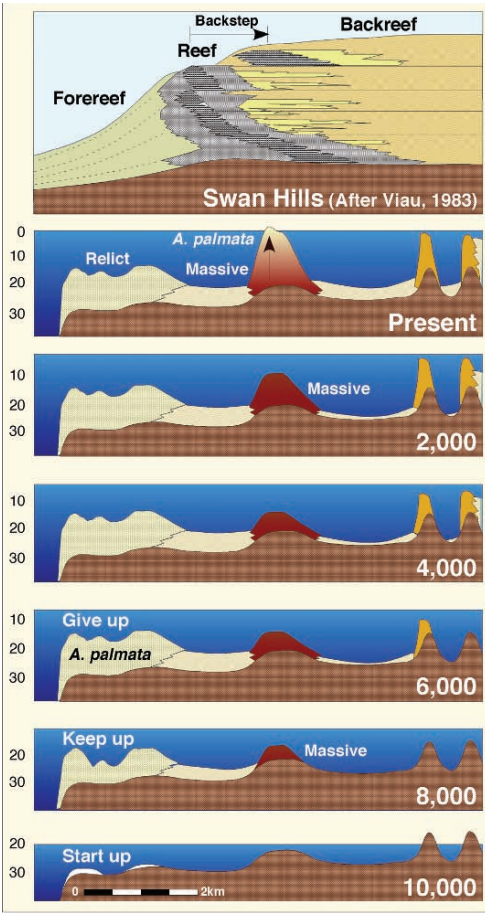
FIG. 7.19. Summary of Holocene reef development off La Parguera in SW Puerto Rico. The earliest reefs date to slightly before 10 ka, and were dominated by *A. palmata*. The next 4,000 years saw expansion of the shelf-edge reefs and the subsequent formation of new reefs closer to shore. The latter were dominated by massive corals, probably a response to higher levels of sedimentation closer to the island. Development along the shelf edge is shown in greater detail in Fig. 7.17. After 6 ka, the inshore reefs continued to build, but accretion near the shelf edge had ceased. The abandonment of shelf-edge reefs in favor of shallower and more landward sites was similar in both character and scale to reef "backstepping" that has occurred at many sites in the geologic past. The top panel shows initial outbuilding of Devonian reefs in Canada followed by a sudden "backstep", interpreted as a response to a sudden and rapid rise in sea level. The cross sections have all been drawn at the same vertical and horizontal scales. Similar phenomena occurred in Australia at about the same time (Playford 1980) (After Hubbard 1992a; Hubbard et al. 1997 by permission AAPG and ISRS)

acroporids much later. This difference was probably a response to higher terrestrial sediment influx closer to shore.

By 6,000 years ago, extensive inner-shelf reefs were well-established along two primary trends (Fig. 7.20), but the mid-shelf reefs had not yet caught up to rising sea level (Fig. 7.19). Antecedent topography played a significant role in where reefs developed. The larger mid-shelf reefs and reef islands (e.g., Turromote, Corral, Enrique: Fig. 7.20.) all sit atop elevated Pleistocene features that occupied the same locations the last time sea level was near its present elevation (Fig. 7.21). Similarly the series of inner shoals and mangrove islands appear to have nucleated on elevated features that were present 125,000 years ago. Our longest core through one prominent mud shoal ("Jack's Mound": Fig. 7.22) passed through the entire Pleistocene interval and penetrated older, well-indurated silts and clays. These lowermost sediments in the core are terrestrial in origin, and may have been part of an alluvial-fan complex built at the mouths of dissected watersheds that remain today (see the rugged upland areas in Fig. 7.20). The arcuate shape of the innermost reef-island trend is suggestive of such a feature beneath.

"Backstepping" is a common phenomenon throughout the geologic record of reefs. Between 370 and 350 million years ago, reefs generally built out under a regime of slow sea-level rise. It has been proposed that near the end of that interval, sea level suddenly rose quickly, causing the position of the dominant reefs to shift dramatically landward (Playford 1980; Viau 1983). This phenomenon has been described from other reefs at different times, and has likewise been attributed to sudden and dramatic increases in the rate of sea-level rise. Schlager's (1981) "Drowning Paradox" is based on similar assumptions. The top panel in Fig. 7.19 characterizes the reefs of northern Canada that backstepped in the late Devonian (after Viau 1983). The cross section is plotted at the same vertical and horizontal scale as the Holocene cross sections across the Puerto Rico shelf. Clearly, the spatial scales of the two scenarios are similar. However, the sudden rise in sea level used to explain backstepping in the fossil Canadian reefs was clearly not involved in the Holocene reefs off Puerto Rico.

7.3.4.2 Virgin Islands

The shelf-edge reefs around St. Croix have a history similar to that just described for Puerto Rico (Hubbard et al. 2000, 2001). On Lang Bank (Fig. 13b), the outermost ridge cored by Adey et al. (1977) yielded a maximum age of 10.3 ka, coincident with the start-up date for a similar feature off Puerto Rico (Core 19: Fig. 7.17). The Pleistocene surface beneath the shallow rim of Lang Bank sits at 25–30 m, slightly shallower than its counterpart off SW Puerto Rico (up to 34 m). As a result, the shelf-edge reefs off eastern St. Croix started slightly later than those sit-

ting off Puerto Rico at similar depths today (8–9 vs. 10 ka Fig. 7.23).

Inshore reefs dominated by massive species started to develop between 8 and 7 ka (Figs. 7.16, 7.24a, Table 7.1), while *A. palmata* reefs continued to flourish along the shelf edge. The Pleistocene rim around Lang Bank extended west past Buck Island (Fig. 7.13b), generally shallowing in that direction (ca. 15 m north of Buck Island, compared to 20–30 m to the east). As a result, accretion along the ridge north of Buck Island ("BI Bar" in Fig. 7.24) started much later than was the case on Lang Bank, and is more related to the inner reefs around

TABLE 7.1. Information on start-up conditions for reefs of Puerto Rico and the US Virgin Islands.

SHALLOW REEFS

Core	Location	D (m)	Age (Cal. BP)	Substrate	Source
PAR-01	SW PR	20.2	7,355	Massive	Hubbard et al. (1997)
PAR-04	SW PR	13.3	6,180	Sediment	
PAR-05	SW PR	19.5	7,910	Massive, *A. cervicornis*	
PAR-06	SW PR	13.5	7,725	*A. cervicornis*	
PAR-07	SW PR	13.3	3,350	Mixed coral	
PAR-08	SW PR	16.1	4,720	Mud	
PAR-09	SW PR	23.0	2700	Sand; massive	
PAR-10	SW PR	22.5	7,625	Massive; sand	
PAR-12	SW PR	16.7	7,150	Rubble	
BI-01	Buck Is (N)	15.9	5,270	Mixed	Hubbard et al. (2005)
BI-02	Buck Is (N)	16.0	5,270	*A. palmata*	
BI-04	Buck Is (S)	13.6	>7,175	Rubble; mixed	
BI-05	Buck Is (N)	16.5	4,210	Massive	
BI-07	Buck Is (S)	16.01	2,840	Massive; rubble	
BB-01	Buck Is Bar	15.3	7,770	*A. palmata*	
TB-17	Tague Reef	13.5	6,975	Massive; sand	Burke et al. (1989)

SHELF-EDGE REEFS

| Core	Location	D (m)	Age (Cal. BP)	Substrate	Source
PAR-11	SW PR	28.0	9,453	*A. palmata*	Hubbard et al. (1997)
PAR-14	SW PR	29.6	no date	*A. palmata*	
PAR-17	SW PR	34.2	9,420	Massive; rubble	
PAR-19	SW PR	~36.8	9,900	*A. palmata*	
LB-02	Lang Bnk (N)	20.9	8,075	*A. palmata*	Hubbard (unpublished)
LB-03	Lang Bnk (S)	24.2	9,254	*A. palmata*	
LB-06	Lang Bnk (E)	32.0	>8,048	Mixed	
LB-08	Lang Bnk (N)	20.5	7,310	*A. palmata*	
USGS-2	Sand Key	12.8	8,900	Massive	Toscano and Lundberg (1999)
CDR-3	Carysfort	20.0	6,600	Massive	
CSFT-4	Carysfort	15.5	6,300	Massive	
CDR-1	Carysfort	15.9	7,100	Massive	
GR-4	Grecian Rks	7.5	6,750	Massive	Shinn et al. (1989)
N/A	Looe Key	10.0	7,440	*A. palmata*	
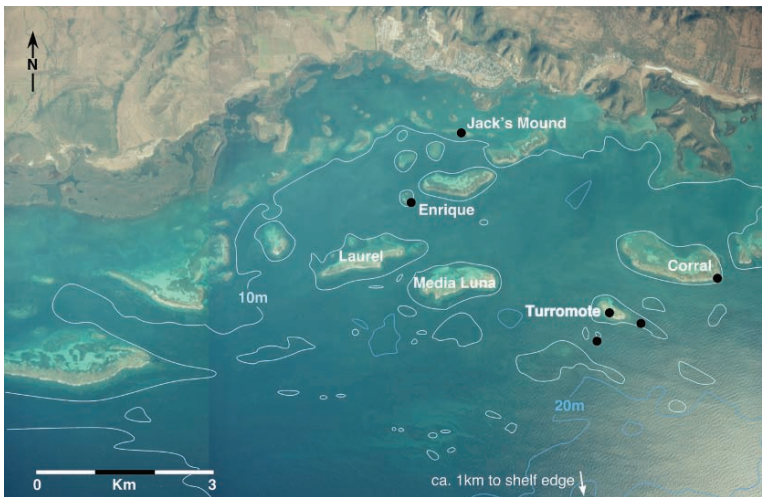
FIG. 7.20. Vertical NOAA aerial photograph of the mid-shelf reefs (Laural, Media Luna, Enrique and Corral) and inner reefs (just inside the 10-m contour) off SW Puerto Rico. Generalized bathymetry (10- and 20-m contours, based on soundings by Jack Morelock, in Hubbard et al. 1997) is provided for reference. The shelf-edge reefs are just off the bottom of the photo. Core sites are shown by the black dots. Antecedent topography is an important control of reef location. The mid-shelf reefs and the submerged shoals associated with them sit atop remnant Pleistocene highs (e.g., Fig. 7.21 on Turromote). The inner belt of muddier shoals and rubble islands that parallel the coast appear to sit on muddy, alluvial deltas which pre-date the Pleistocene (e.g., "Jack's Mound" near the northernmost black dot: Fig. 7.22)
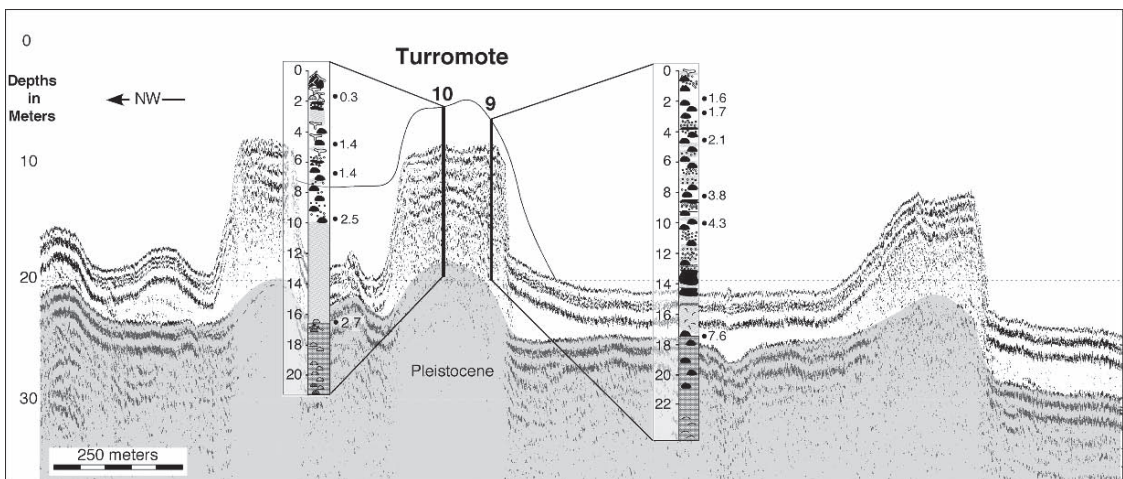

FIG. 7.21. Seismic line across the reef at Turromote (Fig. 7.20). Note the strong correspondence between the present-day reefs and highs in the antecedent Pleistocene surface beneath (gray shading). The seismic line was run over a low spot in Turromote Ridge; the generalized shape of the shallower reef where the cores were actually recovered is shown by the solid line above. Generalized core logs are also shown (after Hubbard et al. 1997). Massive corals dominated throughout, and ages ranged from ca. 7.6 ka to the present. See Fig. 7.15 for key to cores
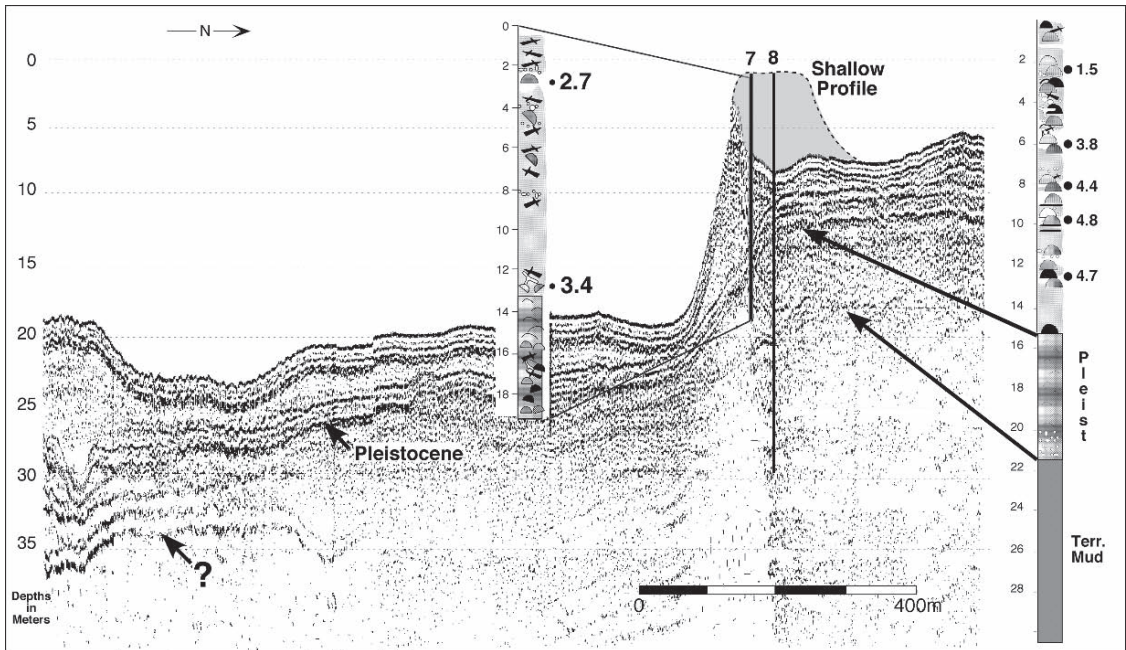
FIG. 7.22. Seismic line across the inner mud shoals near "Jack's Mound" (innermost core in Fig. 7.20). Massive corals and branching *A. cervicornis* dominated the Holocene section of the shoals, which range in age from ca. 4.7 ka to the present (cores after Hubbard et al. 1997 by permission of ISRS; see Fig. 7.15 for key). Note that the shoal sits atop an antecedent Pleistocene ridge. Beneath that, an older (Tertiary?) feature occurred at the same site (lower arrow), and was dominated by terrestrially derived mud. This is interpreted as an alluvial fan built by heavy runoff from the steep and heavily dissected watershed to the north. See Fig. 7.15 for key to logs

Buck Island (Hubbard et al. 2005), and Tague Reef on St. Croix (Burke et al. 1989) than to those along the Lang Bank shelf edge to the east. As the shallower reefs formed along the northern St. Croix shelf, the greater wave exposure and distance from shore allowed branching *A. palmata* to form along Buck Island Bar, in contrast to the massive-coral dominated reefs closer to shore. Reefs built steadily all across the northern shelf through to the present. As the reefs built and slopes steepened over time, zonation formed and was characterized by *A. palmata* near the reef crest, giving way to massive species below (Fig. 7.24b). This trend continued, except in the interval between 3 ka (Fig. 7.24c) and 2 ka, when *A. palmata* was absent for reasons that will be discussed below.

The general timing of the shallower St. Croix reefs (Burke et al. 1989; Hubbard et al. 2005) is strikingly similar to what has been documented

for similar reefs off Puerto Rico (Hubbard et al. 1997), Florida (Lighty et al. 1982; Shinn et al. 1989), the Bahamas, Antigua (Macintyre et al. 1985), Belize (Gischler and Hudson 2004) and Panama (Macintyre and Glynn 1976). The fringing reefs in the northern Virgins probably share a history starting after 7 ka and following the scenario just described. All of the shallower and now-emergent reefs throughout the Caribbean appear to have started at about the same time as sea level was slowing, and underwent the same general patterns of development.

7.3.4.3 St. Croix Algal Ridges

As described earlier, the character of reefs in the northeastern Caribbean is highly varied, owing to intermediate levels of fair-weather wave action and storm disturbance. Algal ridges
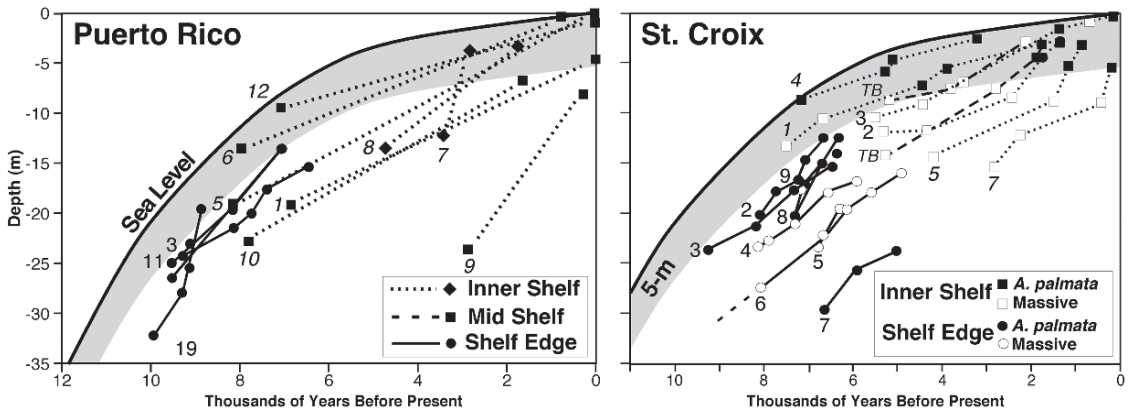
FIG. 7.23. Accretion by shelf-edge and inner-shelf reefs on Puerto Rico and St. Croix. Off Parguera (left), the oldest shelf-edge reefs, dominated by *A. palmata* (closed circles; solid lines) started 10,000 years ago and thrived until ca. 6,500 Cal. BP. Reefs closer to shore had already been actively building for ca. 1,500 years (closed squares and diamonds; dotted line). Similarly, the shelf-edge reefs around Lang Bank on eastern St. Croix (right – circles and solid lines) date back to ca. 9,500 Cal. BP. The reefs made up of *A. palmata* (closed circles) stopped accreting slightly later than those off Puerto Rico, but massive-coral reefs (open circles) continued to build for another 1,000 years. Inshore reefs around Buck Island (dotted lines; core numbers in *italics*) and Tague Bay (dashed lines: *TB*) started as early as 7,500 Cal. BP, but the oldest ages from most cores were on the order of 6,000–5,500 Cal. BP. Note that the accretion rates for *A. palmata* reefs are not significantly different than those for massive species, regardless of water depth. Also, when the shelf edge reefs quit, they were either no deeper (or, in some cases, shallower) than when they initiated. Clearly, they were not building slower that sea level was rising, despite being below the 5-m-depth envelope (gray shading) that is generally considered to be a threshold for *A. palmata*-driven accretion. Thus, being outpaced by sea level is clearly not an explanation for the demise of reefs at the shelf edge

can be found at many sites along the eastern end of St. Croix. On the north shore, at Boiler Bay (BB: Fig. 7.25), an inner series of degraded ridges sits near the beach in a protected lagoon behind eastern Tague Reef. In contrast, active algal ridges can be found at several sites along the south-facing shore where there is no seaward reef to block incoming wave energy (Robin Bay (RB): Fig. 7.25).

Adey and Burke (1976) proposed that the Boiler Bay algal ridges formed on alluvial fans in shallow water, and were still exposed to high waves 2,000–3,000 years ago (Fig. 7.25). As Tague Reef built up in front of Boiler Bay, wave energy over the algae ridges dropped, and they fell victim to increased grazing pressure and macroalgal buildup. They proposed a slow initial buildup along Tague Reef associated with slower-growing massive corals at greater water depths (see the tan "reef envelope" in Fig. 7.25).

In this scenario, Tague Reef built into shallower water, and *A. palmata* gradually took over the reef crest, triggering accelerated reef accretion. This concave-upward accretion curve reflects reef-accretion rates tied to water depth and coral type (i.e., branching *A. palmata* vs. massive corals). Once Tague Reef built to sea level, wave energy to the Boiler Bay algal ridges was cut off, and they began a cycle of degradation, characterized by increased bioerosion and overgrowth by fleshy algae.

Core data for Tague Reef (Burke et al. 1989) corroborate the general story of early algal-ridge development close to shore, followed by wave attenuation as Tague reef built to seaward. However, the accretionary patterns within Tague reef are substantially different than those summarized in Adey and Burke (1976; Fig. 7.25). Unlike the convex-upward accretion curve envisioned by Adey and Burke (1976), the reef
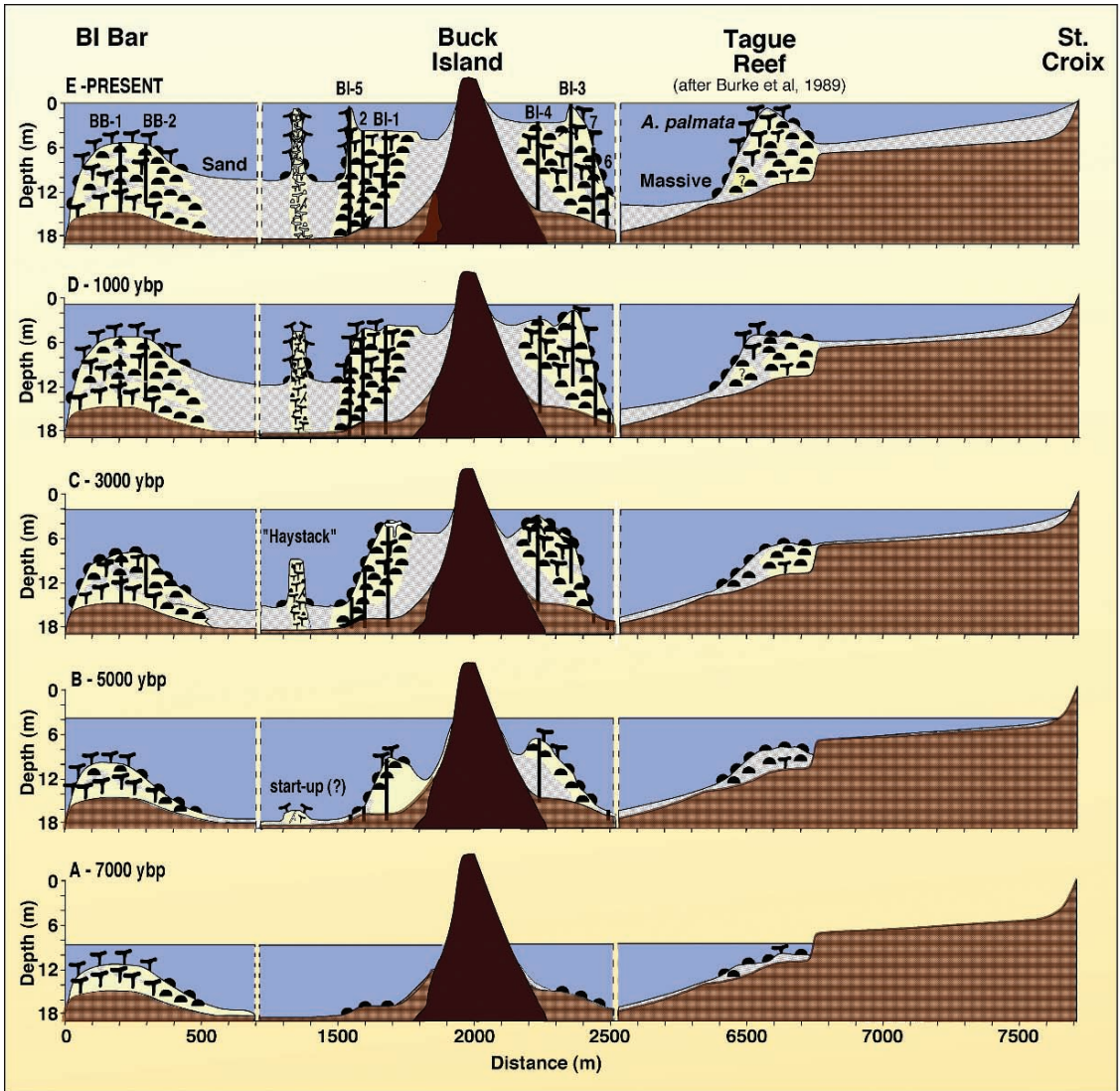
Fig. 7.24. Reef history on NE St. Croix. Reefs closer to the shelf edge generally started up first and were dominated by branching *A. palmata* (A). Reefs closer to Buck Island and St. Croix were subject to greater sediment stress, and were dominated by more resistant massive-coral species. Reefs along the south side of Buck Island (Hubbard et al. 2005) and northern St. Croix (Burke et al. 1989) reflect greater quantities of sediment than their higher-energy counterparts on northern Buck Island and Buck Island Bar (Macintyre and Adey 1990). As reef topography developed, zonation from *A. palmata* near the surface to massive species at depth became the norm, with the exception of the period starting 3,000 years ago (C). Today, the reefs have reached sea level with the exception of Buck Island Bar, which appears to have been depressed by high wave action along this more-exposed margin (Macintyre and Adey 1990) (Figure after Hubbard et al. 2005 by permission of SEPM)

appears to have built to sea level quickly and at a generally uniform rate, regardless of water depth or coral type (red curves in Fig. 7.25; based on data from Burke et al. 1989). This pattern is counter to widely held presumptions of species- and depth-dependant reef accretion.
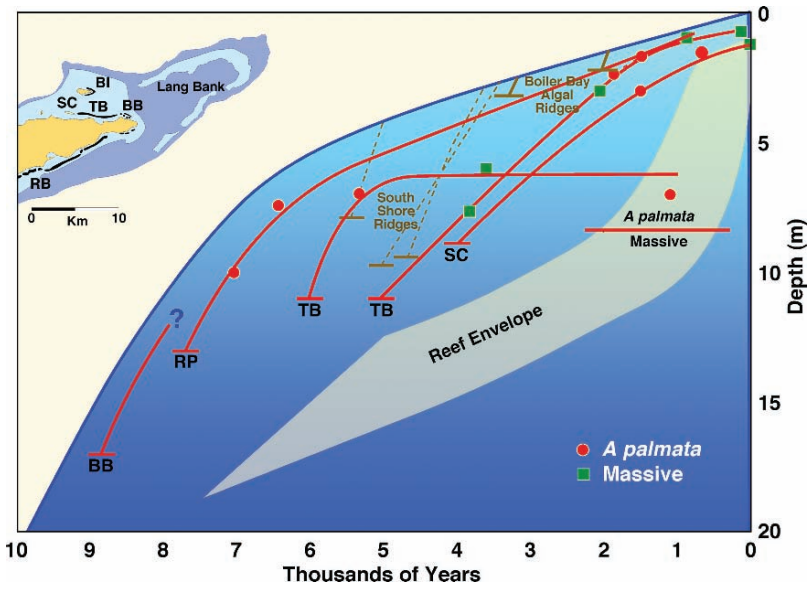
Fig. 7.25. Shallow-water reef development on northeastern St. Croix. General core locations are shown on the map inset (BB = Boiler Bay; TB = Tague Bay; RP = Romney Pt (between BB and TB); SC = Sandy Cay; BI = Buck Island; RB = Robin Bay). Sea level over the past 10,000 years is summarized by the blue curve. Reef accretion along northeastern St. Croix is shown in red (the horizontal bars are the measured or inferred Pleistocene basement; data from Burke et al. 1989). Dated core samples are differentiated between *A. palmata* (red circles) and massive corals (green squares). The brown dashed lines are inferred accretion patterns for algal ridges on the north (Boiler Bay) and south shore (Robin Bay). The concave-up "reef envelope" (tan-gray) summarizes the general pattern of accretion envisioned by Adey and Burke (1976) for Tague Reef. The envelope reflects different histories starting on a deeper substrate to the east (base of the "envelope") and a shallower antecedent surface to the west. They proposed that Tague Reef initially built slowly because it sat in deeper water, and was dominated by slower-growing massive corals. As the reef built into shallower water, faster-growing acroporids presumably took over, and the reef built quickly to sea level, cutting off wave energy to the algal ridges in Boiler Bay. Core data from Burke et al. (1989: red lines) show that Tague Reef actually built rapidly to sea level much earlier, and at rates that did not vary in response to either water depth or coral type

7.3.4.4 Cane Bay and Salt River

Two noteworthy and morphologically distinct reef systems occur at Salt River and Cane Bay along the narrow northwestern margin of St. Croix (SR and CB: Fig. 7.13b). Cane Bay sits along a narrow shelf that reaches depths of 20–30 m within 250 m from shore. From the shelf break, the bottom drops precipitously to abyssal depths (5,500 m), at an average slope of 45° (the upper 2,500 m are vertical). To the west, the slope break deepens to as much as 80 m.

The reefs along this insular margin share attributes of both fringing and shelf-edge reefs. Cores have not reached the underlying Pleistocene strata, but it appears that the shape of the present reef surface reflects both Holocene reef-building and antecedent topography (Fig. 7.8b; Hubbard et al. 1984, 1986). Steep hills overlook the bay, and sediment stress has been naturally high. As a result, massive corals have dominated the 6,400 years for which our core record exists. Because of constant terrestrial input, the high coral cover and carbonate production rates occur near the shelf edge (Fig. 7.9).

The reef at Cane Bay is organized into alternating reef buttresses and intervening sand channels (Figs. 7.8, 7.26). The channels occur at regular intervals, suggesting an extrinsic control on their periodicity.

A similar pattern has been identified off Jamaica (Goreau and Land 1974), in the Bahamas (Hubbard et al. 1976), and on Grand Cayman Island (Roberts et al. 1977). The latter authors proposed that channel patterns were responding to Holocene wave climate. More recently, Hubbard et al. (1981, 1982, 1990) and Sadd (1984) identified the role of the channels as short-term repositories for bioclastic sediment that might otherwise overwhelm the reef. Storms periodically flush these stored sediments from the reef (Fig. 7.26; Hubbard 1992b).

Salt River (SR in Fig. 7.13b), where Christopher Columbus made first landfall on his second voyage, sits at the head of a reef-lined submarine canyon (Figs. 7.27, 7.28). For a decade, this was home to *Hydrolab*, the world's longest-lived, open-water saturation-diving facility. It served as a base of operations to well over a hundred reef scientists from myriad research institutions. This program provided a wealth of baseline information on the biology, geology and oceanography of this unusual marine system.

Both the larger canyon morphology and the distribution of coral species along its walls are a response to the pathways of sediment movement under the influence of trade-winds circulation (Hubbard 1986). Sediment generally moves to the west and into the canyon along its eastern side (larger gray arrows in Figs. 7.27 and 7.28). As a result, coral recruitment is discouraged, and a rubble - and oncoid-covered slope occurs along the inner portion of the eastern margin (Fig. 7.28). In contrast, bioclastic sediment is moved either down-canyon (smaller arrows) or away from the west side of the canyon along the adjacent shelf, and a steep reef wall has formed in response to lower stress. Storm processes also play a profound role in the sediment budget of the canyon. Detailed transport measurements under a variety of conditions have demonstrated that nearly half of the sediment removed from the canyon in the past century was the result of a single storm, Hurricane Hugo in 1989 (Hubbard 1992b). Like the smaller reef channels at Cane Bay and similar shelf-edge sites throughout the Caribbean, the canyon acts as a temporary holding area for bioclastic and terrigenous sediment that could otherwise overwhelm reef development.

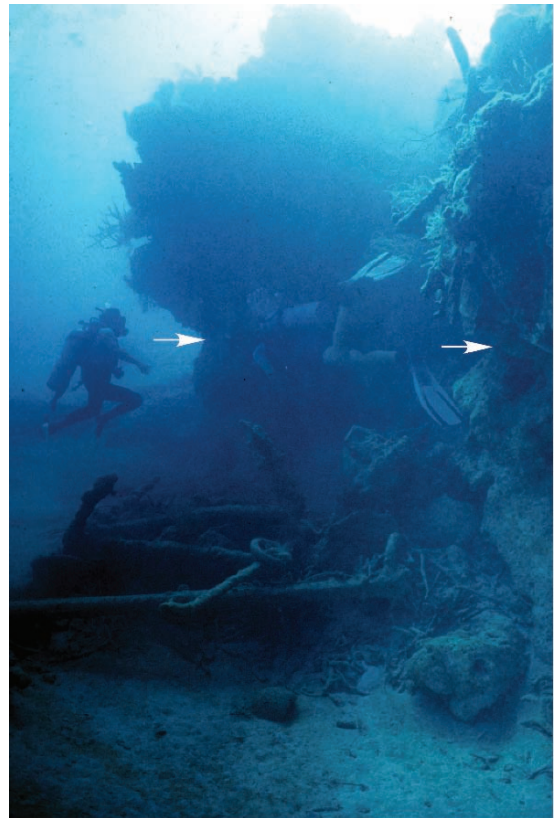Vertical cores along the western shelf (depth ~10 m), combined with horizontal cores into the

FIG. 7.26. Shelf-edge channel at Cane Bay 1 month after the direct it by Hurricane Hugo, a Category 4–5 storm. Strong return flows scoured most of the sand from this and other channels, exposing anchors that were probably left by eighteenth-century schooners picking up cane, molasses and rum from plantations along the shore. The arrows show the elevation of the sand before the storm. A small coral from a similar anchor in Salt River submarine canyon yielded an uncorrected age of 300 years before present (After Hubbard 1992b by permission of SEPM)

canyon wall (circles in Fig. 7.28) have been used to reconstruct reef development along the west side of Salt River submarine canyon over the past 11,000 years (Fig. 7.29). The oldest coral date from anywhere in the Caribbean (11,100 Cal. BP) comes from the deepest core on the west wall (present depth ~ 30 m). The first 7 m of this core reflects a reef dominated by branching *A. palmata* over the following 4,000 years (Hubbard et al. 1986, 1989b; Hubbard 1992a). After that, massive and platy corals took over. Shortly after 7 ka the shallow reef that separated Salt River Bay from the canyon was

FIG. 7.27. Air photo looking east across Salt River Bay (right) and the submarine canyon (dark reentrant) fronting it. The larger blue arrows show general sediment -transport in from the east and away from the canyon to the west. During storms, strong down-canyon flows (smaller arrows) export sediment along the base of the west wall and into the deep basin north of St. Croix. The small white "dot" near the head of the canyon is the support boat above *Hydrolab*

FIG. 7.28. Stylized block diagram looking up-canyon (south) at Salt River. This diagram is based on bathymetry and over 300 dives by the first author and colleagues. Sediment-transport pathways (gray arrows) and cores (black and white circles) are also shown. Figure 7.29 is based on the three seawardmost cores along the west (right) wall (After Hubbard 1989b by permission of West Indies Laboratory)

forming. This gradually created a sheltered lagoon environment in which both carbonate sediment and terrestrial silts and clays coming down Salt River were deposited. Tidal current increasingly moved this material into the canyon during the ebbing tide. As is the case today, easterly waves probably pushed this dirty water against the western canyon margin, signaling the end of *A. palmata* as the dominant reef builder in the canyon. At about the same time, this species was beginning to struggle throughout the region, so it is hard to separate the relative impact of local sedimentation and regional decline. However, when branching corals recovered at other sites around the Caribbean ca. 5,000 years ago, the reef on the west wall did not follow suit, implying a primacy of local sediment stress.
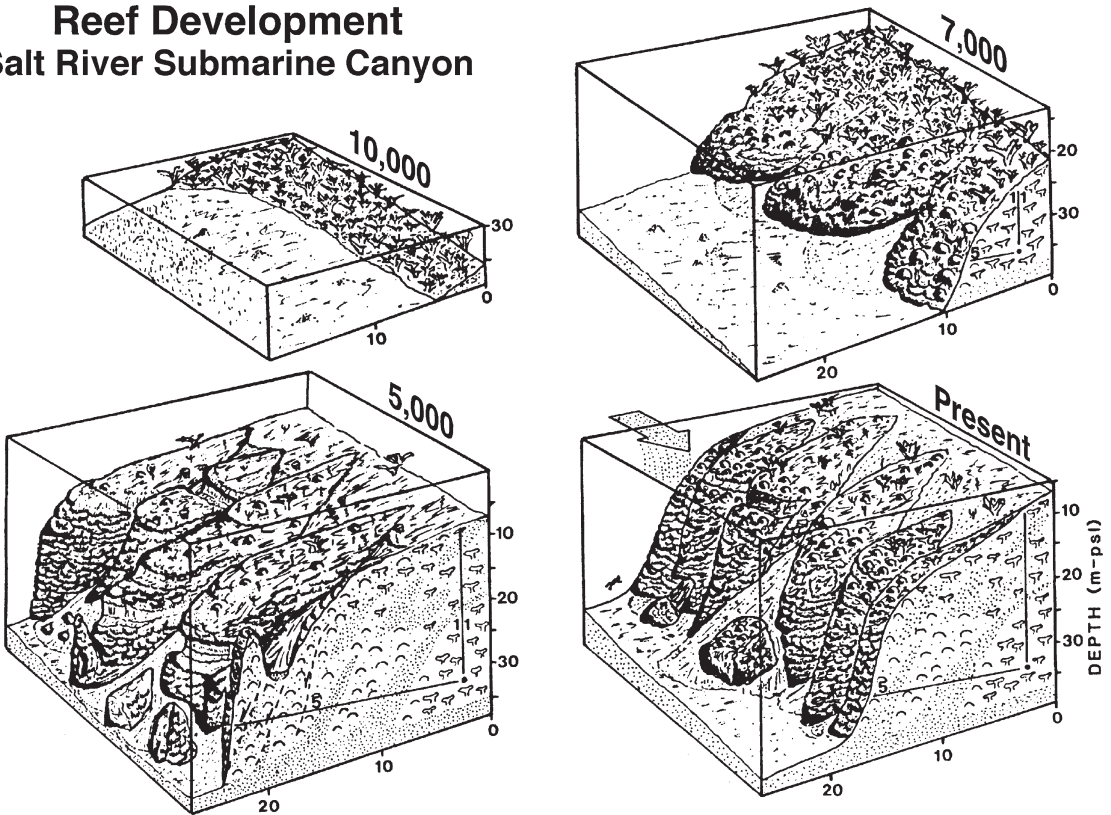

Reef Development
Salt River Submarine Canyon

FIG. 7.29. Geologic development along the west wall of Salt River Submarine Canyon. The canyon axis is a remnant channel that probably developed during the last lowstand of sea level, when Salt River crossed the shelf before emptying into the deep basin to the north. As the river valley flooded, *A. palmata* reefs developed along the western side, where sediment pressure from the adjacent shelf was lower (Figs. 7.27, 7.28). Over the next 3,000 years, an increasingly complex and steeper reef flourished, and was dominated by branching corals. By 6ka reefs had formed near the head of the canyon, creating a sheltered bay, behind which muddy sediments accumulated. Tidal flows increasingly carried fine-grained sediment into the canyon, and wave action pushed that toward the west wall, creating an environment that was increasingly inhospitable to branching *A. palmata*. At about the same time, *A. palmata* appears to have experienced difficulty throughout the region, contributing to the dramatic turnover in the reef community. When branching corals recovered throughout the Caribbean 5,000 years ago, the dominance of massive corals on the west wall persisted, due to their higher tolerance to elevated sedimentation that remains today (Hubbard et al. 1986) (From Hubbard 1989 by permission of West Indies Laboratory)

7.4 Revisiting Long-held Presumptions

7.4.1 The Role of Reef "Framework"

Considering that it has only been a little more than three decades since Ian Macintyre (1975) introduced his revolutionary portable drilling system, the advances in our understanding of coral-reef geology are remarkable. Virtually every coring system that has followed mimics his original design. We have all tinkered with power levels and changed core barrels or tripods to fit the particulars of our objectives and our field areas, but the fundamentals have remained largely unchanged. The development of this system remains as perhaps the single-most significant event in the evolution of our approach to studying Holocene reef geology.

In 1975, our perception of geologic reef s was still one of in-place and interlocking corals creating rigidity and structural framework (e.g., Lowenstam 1950; Newell et al. 1953). Thus, biological production enjoyed a position of primacy, with biological and chemical alterations relegated to subordinate roles. Discussions often focused on why modern reefs were so fundamentally different than their fossil forebears, and whether we should even use Holocene reefs as models for the past – hence, the comment (ca. 1960) "The Present is the Key to the Late Pleistocene … perhaps" (M. Lloyd, personal communication 2003).

These opinions were largely based on extrapolations from the surface of modern reefs to their interiors. The advent of affordable reef drilling and the myriad coring investigations that followed have provided a view of Holocene coral-reef interiors over a wide variety of oceanographic settings. What has emerged is a realization that 60–70% of the carbonate ending up in the reef is typically bioclastic debris (Hubbard et al. 1981, 1990, 1998; Burke et al. 1989; Conand et al. 1997). It is interesting that the notion of largely in-place reefs (Fagerstrom 1987) was not shaken until recently by the long list of cored reefs that inferred otherwise.

The occurrence of bioerosion has been recognized at least since the early nineteenth century (Grant 1826), but the magnitude of its importance has only recently been appreciated (Neumann 1966). As early as 1888, Johannes Walther (translated in Ginsburg et al. 1994) estimated coral abundance in raised reefs of the Sinai at only 40%, with the remainder being bioclastic sediment. Recovery from cores in Panama (Macintyre and Glynn 1976) averaged roughly 70% sand, rubble, and void (Ian Macintyre, personal communication 1998), as was the case in the reefs off Cane Bay, Salt River (Hubbard et al. 1984, 1986) and eastern St. Croix (Burke et al. 1989). Nevertheless, the popular "framework" models of Lowenstam (1950) and Newell et al. (1953) prevailed, despite an apparent later recantation by Newell in 1971. The idea of reefs built less by organisms in growth position than by the encrusted and cemented remains of broken and bioeroded corals was not widely embraced until the 1990s (Hubbard et al. 1990, 1998).

R.N. Ginsburg has provided us with an elegant analogy for reefs through time by way of a long-running Shakespearian play He pointed out that, despite the vagaries of changing taxonomy over evolutionary time, as well as the pervasive impacts of taphonomy, we can make useful comparisons between modern reefs and their fossil counterparts through an understanding of the "plot" and the "roles" of individual players – not in the form of specific actors, but rather the characters they played. This idea was echoed by the "reef guild" concept of Fagerstrom (1987). Looking at moderns reefs, calcification by corals is no longer the "star", but must share the billing with bioerosion (and physical breakage), transport, encrustation and cementation. Looking back through time, we can not only recognize these roles, but can use the varied reef fabric across deep time to consider the ever-changing roles of diversity and competition, ocean chemistry, and local paleoenvironment as they related to the "arms race" between organisms that built reefs and those trying to tear them down (Hubbard et al. 1990).

7.4.2 Coral Growth and Reef Accretion

Schlager (1981) proposed that reef accretion would mirror the fundamentally depth-related pattern of calcification. This was based on an assumption that, while bioerosion and sediment redistribution would occur in any reef, calcification would still dominate. In this scenario, "reef growth" would be roughly an order of magnitude slower than "coral growth", but would follow a pattern that was fundamentally linked to coral type (branching-coral reefs "grow" faster than massive-coral reefs) and water depth (lower light = less calcification = slower

accretion). Adey (1977) had asked the question, "If *A. palmata* is capable of rates of reef building of 8 m/1,000 years, then why is it that most shelf margins in the Caribbean are not built to sea level by Holocene reef frameworks?" Schlager's (1981) "Drowning Paradox" is based on these same rates of accretion, and asks the same question. He proposed that Quaternary reefs would drown ("give-up" reefs of Neumann and Macintyre 1985) only if the rate of sea level increased suddenly and dramatically (the "melt-water pulses" of Fairbanks 1989), or water quality suddenly degraded to the point where the potential for "reef growth" was significantly reduced. "Inimical bank waters" associated with sea level overtopping the platform provided the link between Schlager's "Drowning Paradox" and the models of Caribbean reef development based on the landmark study on Lang Bank by Adey et al. (1977). The fundamental principles shared by all these studies are: (1) reef accretion is irrevocably tied to water depth and coral species and (2) many (most?) Holocene reefs are capable of accretion rates in excess of sea-level rise, and must be otherwise compromised in order for them to be left behind.

A synthesis of available reef-accretion data from all across the Caribbean paints a fundamentally different picture (Hubbard 2005). Calibrated radio-carbon ages and paleo-depth reconstructions based on the corrected Lighty et al. (1982) sea-level curve (Fig. 7.14) were used to compute reef accretion in 151 core intervals from reefs off St. Croix, Puerto Rico and the larger Caribbean. The results of this synopsis clearly show a striking lack of dependence on either water depth or coral type within the upper 25 m of the water column (Fig. 7.30). It appears that depth-related patterns of bioerosion and sediment transport may effectively offset the well-documented decrease in carbonate production with depth (Hubbard 2005). Therefore, while the bulk of the raw materials is provided by corals, reef building is as much a physical process as it is a biological one. The term "reef growth" unrealistically implies a dominance of biological "growth" in controlling patterns of reef building. Recent findings argue for reconsidering the term "reef growth": in short, corals grow and reefs accrete.

7.4.3   The Present Caribbean Coral-reef Model

While this chapter focuses on local reefs, the studies detailed above have provided new data that inform our understanding of reef development
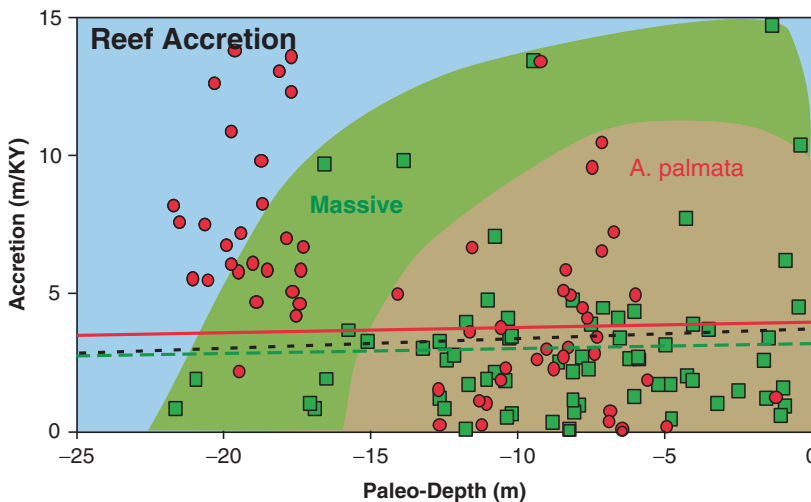

FIG. 7.30. Holocene reef accretion based on core data from Caribbean reefs. The greatest number of *A. palmata* reefs occurs in shallow water (red circles), but the depth range is broad and extends into paleo-water depths similar to those for massive species (green squares). The average accretion rates for *A. palmata* reefs (solid red line) and those dominated by massive corals (green dashed line) are not significantly different. Also, depth-related changes for all reefs (black dashed line) are not statistically significant ($r^2 \sim 005$) (After Hubbard 2005 by permission of GSA)

for the wider Caribbean. Our prevailing model began with three cores from southwestern Lang Bank (Fig. 7.31). According to Adey et al. (1977), reefs dominated by *A. palmata* first formed along the steep platform margins 11,000 years ago (Fig. 7.32a), when rising sea level was rapidly approaching the bank top. As the platform margin flooded, waves and currents mobilized soils that developed during the previous lowstand. Sediment-laden waters flowed off the platform, shutting down reef development (Fig. 7.32b). As sea level continued to rise quickly, once-thriving shelf-edge reefs were left behind. By the time the waters cleared (ca. 8 ka: Fig. 7.32c), water was too deep for branching acroporids, and slower-growing massive species dominated the recovery. The result was a slowly accreting reef that has yet to reach sea level (Fig. 7.32d). Reef "backstepping" was thus caused by compromised calcification in the face of rapidly rising sea level.

This study formed the fundamental underpinning of Caribbean reef models that were to follow. Adey (1978) proposed that for Cenozoic reefs "at depths greater than 10–20 m, a major shelf rim is likely to experience a significant period of minimal reef growth (1,000–2,000 years)". Following suit, Macintyre (1988) proposed a model for high-energy Caribbean reefs based on "relict give-up reefs along the upper slopes and shelf edges (due to 'inimical bank waters'), and relatively young late Holocene reefs fringing most coastlines". Rapid coral growth logically translated into rapid reef accretion (Schlager 1981), so much so that the failure of reefs to keep up with rising sea level could be explained only by short-lived, upward "sprints" of sea level or episodes of "inimical bank waters" that slowed down calcification and the reef accretion that depended on it. Our present Caribbean reef model relies on the latter scenario.

7.5 Lessons Learned

At the 1977 Miami meeting of the International Society for Reef Studies, Adey (1977) summarized our understanding of Caribbean coral-reef geology,
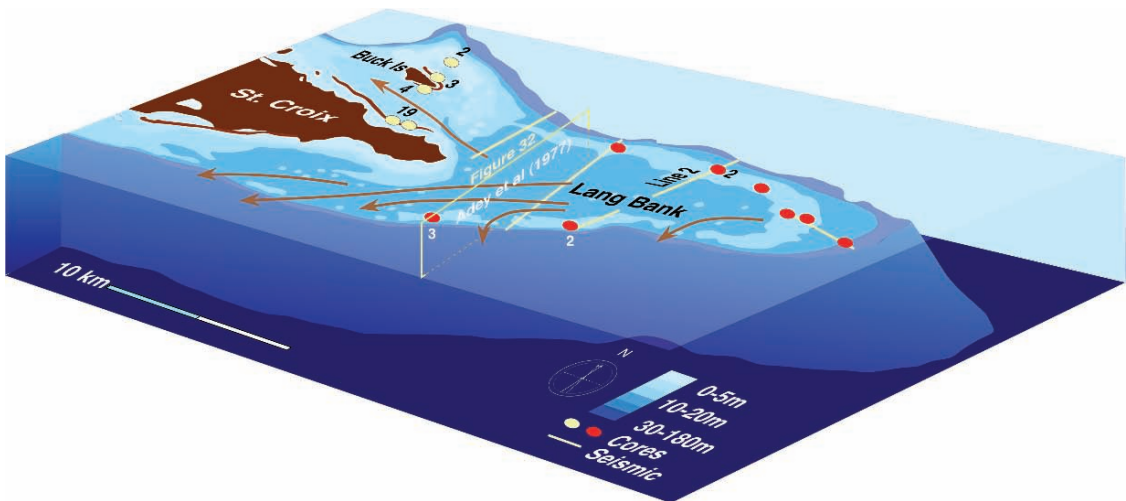

FIG. 7.31. Three dimensional view looking northwest across Lang Bank. Cores shown in red are from early (ca. 10 ka), shelf-edge reefs. Numbers next to core sites indicate multiple cores. The westernmost site on southern Lang Bank (marked "3") was described by Adey et al. (1977). Yellow circles show cores from inshore reefs that formed after 7 ka. Seismic lines are shown in yellow. The location of the cross section in Fig. 7.32 is shown by the yellow box. The brown arrows show likely pathways for turbid bank waters and bioclastic reef debris off the bank. Note how the elevated reef rim all around the bank (light blue) would have protected newly formed shelf-edge reefs from "inimical bank waters" derived from the deeper bank center, except where breaks occurred in the southern margin and along the large channels passing westward. It is likely that the hiatus described by Adey et al. (1977) was as much the result of terrestrial sediments from the bank interior as it was bioclastic debris from flourishing updrift reefs
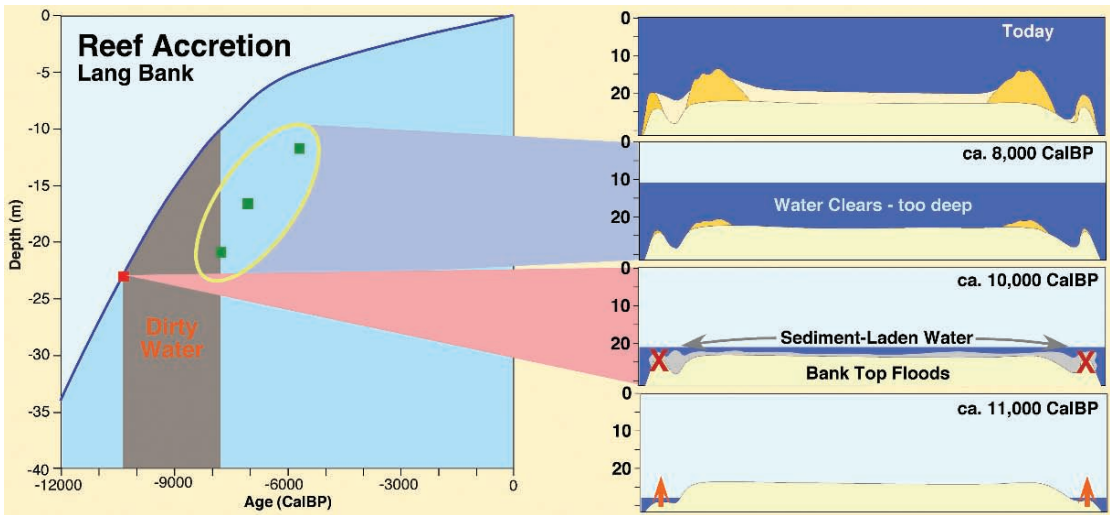
Fig. 7.32. Model of shelf-edge reef development on Lang Bank proposed by Adey et al. (1977). The profile described in panels A-D is located in Fig. 7.31 (yellow box). In this scenario, early *A. palmata* reefs were killed by turbid waters soon after bank flooding ca. 10,000 years ago. These "inimical bank waters" inhibited reef development until 8,000 years ago, by which time water depth was too deep for *A. palmata*. By that time, reef development had shifted to shallower areas closer to shore, as deeper reefs now dominated by massive corals reestablished on Lang Bank

and set the stage for integrating a growing body of information into an overarching reef model. Since then, Holocene reef-coring investigations have spread to virtually every tropical marine basin around the globe. Until then, studies had centered on petrographic textures associated with contemporaneous sedimentation and submarine cementation within Holocene and older reefs. Coring provided a view of the larger-scale reef interior, and allowed us to consider the processes that were responsible. The result has been a greatly improved understanding of the roles of biology, geology and chemistry under changing regimes of physical oceanography and rising sea level.

Reef-building is a complex process that can no longer be understood simply as the result of calcium carbonate set in place solely by the organisms that secrete it. Our prevailing models have focused on the role of in-place and interlocking organisms in providing the rigidity that is the central tenet of reef characterizations (e.g., Fagerstrom 1987). Our new-found ability to sample modern reef interiors has resulted in a realization that much more of the reef edifice is made up of detritus than has been widely held. And, not all of the recognizable coral

remains are demonstrably in life position (Hubbard et al. 1990, 1998).

The good news is that using Holocene reefs as models for ancient ones is far less difficult. The problem has not been that modern reefs are poor models for the geologic past. Rather, our *perceived* modern models have been poor approximations of what they actually look like inside. Structures dominated by in-place corals certainly occur. Algal ridges in the eastern Caribbean are largely in-place constructions of coralline algae that have formed in an environment that discourages branching-coral growth and grazing, in this case, one of high wave energy and frequent hurricanes. In the Dominican Republic, an exposed Holocene reef has a significant component of in-place massive corals (Hubbard et al. 2004).

Grazing has been a problem for reef builders (early stromatolites) since the advent of the articulated and skeletonized jaw. Likewise, infaunal bioerosion has reduced substrate to sediment, leaving a weakened skeleton that is more susceptible to breakage. The general absence of significant framework build-ups in the rock record no longer poses a problem. Modern reefs are no different;

they often comprise significant volumes of bound bioclastic debris – just like their ancient forebears.

What then does this say about our present model of Caribbean coral-reef development? As the bank margins of Puerto Rico and the US Virgin islands flooded between 12,000 and 10,000 years ago, wave action undoubtedly encountered sediments formed during the long interval of exposure associated with lower sea level. Based on the initial study of Lang Bank, it was assumed that once additional cores were recovered from other Caribbean sites, a picture akin to Fig. 7.33a would emerge: an earlier reef sequence dominated by *A. palmata* and separated by a 2,000-year hiatus from overlying and disconformable massive species. However, more recent core data paint a decidedly different picture (Fig. 7.33b). Neither the reef gap between 10 and 8 ka related to "inimical bank waters" nor the subsequent shift to massive corals occurred at other sites in the Caribbean. In fact, reefs all around Lang Bank thrived throughout the period when *A. palmata* was absent from the reefs at the Adey et al. (1977) site. New seismic data from eastern St. Croix (Fig. 7.34) show an elevated Pleistocene rim that would have directed turbid bank-top sediments from the deeper center of platform to the west and away from most of the reefs atop the elevated margin. The depression of central Lang Bank connected to Buck Island Channel north of St. Croix and a similar feature along the southern shelf (Fig. 7.31). The southern branch would have been an effective conduit to move sediment through breaks in the rim and toward the core site where our Caribbean shelf-edge model began (brown arrows in Fig. 7.31). As is the case with modern reefs, storm waves would have moved large volumes of water into what was then a deep lagoon behind the shelf-edge reefs. The transport of this water to the west would have carried terrestrial sediment languishing in the usually quiet and protected environment. Ironically, the reefs described by Adey et al. (1977) were probably impacted by not only this terrestrial sediment from the bank, but by bioclastic debris from thriving updrift reefs on Lang Bank as well.

Four important and new points emerge from Fig. 7.33. First, while the "inimical bank water" story of Adey et al. (1977) is a valid explanation for the reefs near the southwestern corner of Lang Bank, extrapolation to a larger scale seems unwarranted. The hiatus they described occurred neither elsewhere on Lang Bank nor at many other Caribbean and western Atlantic sites. This runs counter to the core principles upon which our pre-
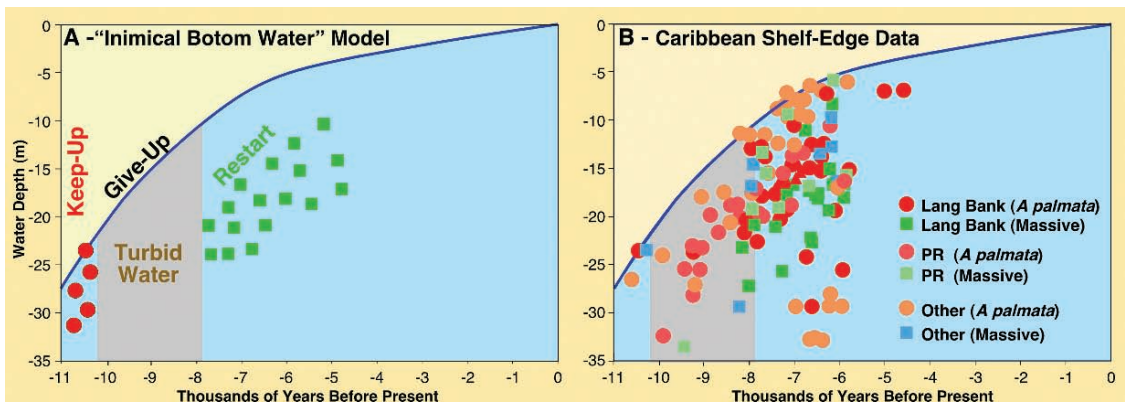

Fig. 7.33. Comparison between the "Inimical Bank Waters" model for Caribbean reef development extrapolated from Lang Bank (A: Adey et al. 1977) and more recent data from shelf-edge reefs throughout the Caribbean (B: Lighty et al. 1982; Hubbard et al. 1997, 2005; Toscano and Macintyre 2003; Hubbard, unpublished data). In contrast to the hiatus envisioned by Adey (1978) and Macintyre (1988) *A. palmata* flourished throughout the proposed "Lang Bank gap". Also, corals after the proposed hiatus (10–8 ka) were not confined to massive species, as was proposed on the southern bank. Most reefs around Puerto Rico and St. Croix were catching up throughout the proposed "turbid water" interval and, by 6,000 years ago, were facing a slowing sea level (After Hubbard 2005)
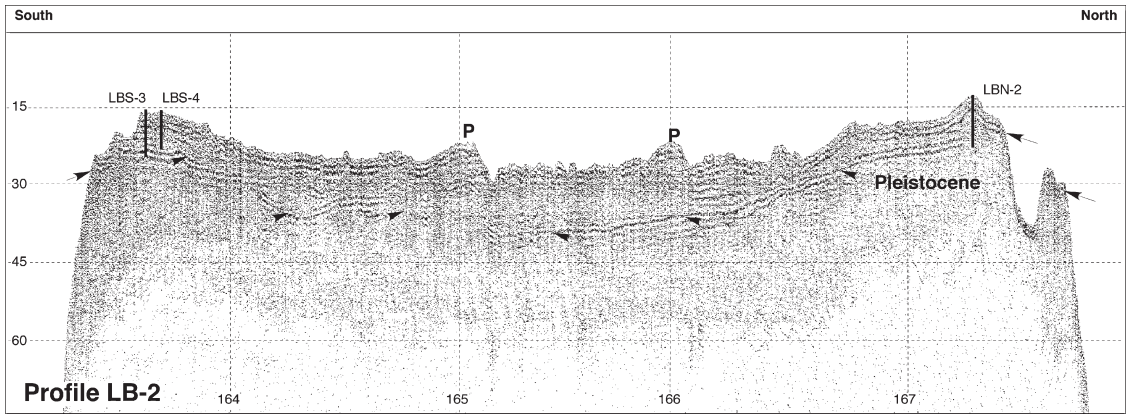
FIG. 7.34. North–south seismic line across Lang Bank showing the elevated Pleistocene rim that isolated the deeper, central lagoon from the outer reefs that were forming 10,000 years ago. Arrows show the Pleistocene surface, which has been confirmed by cores LBN-2 and LBS-3. The reefs, which have built to present depths of ca. 13 m, started along the top of this feature, and thrived until ca. 6,000 years ago, well after the proposed hiatus related to "inimical bank waters". Deeper reefs on the northern ridge appear thinner than those on the shallow rim. The location of this profile (yellow line labeled "Line 2") is shown in Fig. 7.31 (Data were collected with Chuck Holmes of the US Geological Survey)

vailing Caribbean reef models are based. Second, *A. palmata* built extensive reefs at water depths (up to 25–27 m) well beyond the 10-m figure we are used to seeing as the lower limit for extesive branching-coral framework. The deepest reported observation of live *A. palmata* to date is from 23 m of water in the Gulf of Mexico (Zimmer et al. 2006) and that colony subsequently died (William Precht, personal communication, 2006). Third, even the deeper branching coral reefs were capable of significant accretion and were either keeping up or catching up with rising sea level at a time when it was rising at rates of ca. 5 m/ka. Finally, these *A. palmata* reefs "quit" around 6,000 years ago, despite their having largely caught up to a then slowing sea level. A new model is needed that builds on the considerable foundations of earlier studies but takes these new findings into account.

We propose a model of Caribbean coral reef development that is far simpler than the current one. Shelf margins were flooded between 12 and 10 ka. Coral recruitment began soon after, with "inimical bank waters" having less impact than has been widely held. Carbonate production was high, but this was effectively offset by storm damage and bioerosion, as reflected in the abundant bioclastic

debris within the undated lower sections of most shelf-edge cores. Proximity to the shelf edge would have facilitated off-bank transport. Thus, initial carbonate production and subsequent degradation may have been even higher than what is reflected in the abundant sediment accumulation at the base of each core.

As bioclastic sediment progressively gave way to preserved corals, *A. palmata* was the dominant framework contributor, providing both in-place colonies and toppled branches. The rate of reef accretion was close to the rate of sea-level rise, despite most of the reefs being at what has been considered to be suboptimal depths (>5–10 m) for *A. palmata* growth and framework production.

As sea level continued to rise ever more slowly, progressively shallower sites closer to shore were colonized, in particular those sites that were topographically elevated above their surroundings. The dominance of massive species closer to shore was probably a function of sediment input from nearby highlands. Reefs at the shelf edge continued to be dominated by fast-growing acroporids, as were shallower reefs further removed from terrestrial effects (e.g., Buck Island Bar: Macintyre and Adey 1990; Hubbard et al. 2005). As waters cleared closer to shore, *A. palmata* increasingly took over

the role as the primary frame-builder. A major tipping point in this scenario was the slowing of sea-level rise ca. 7 ka. Most of the reefs closer to shore started around this time and built not only upward, but also outward (Fig. 7.35) as carbonate production exceeded accommodation space being created by an ever slower sea-level rise. This pattern can be seen in many other Caribbean reefs forming at the same time.

The one wrinkle in this otherwise simpler story is the appearance of two gaps in the recorded history of *A. palmata* during the Holocene development of Caribbean coral reefs (yellow bars in Fig. 7.14). Over 200 samples of *A. palmata* from virtually every region of the Caribbean reflect abundant branching corals over the past 10,000 years. Yet, only three samples have been dated between 5.8 and 5.2 ka. No dated samples have been reported between 3 and 2.2 ka (Hubbard et al. 2005).

The first of these two gaps coincides with the abandonment of shelf-edge reefs throughout the region. Based on available core data, reefs off

Florida appear to have started their decline earliest (8–6.8 ka), followed by those off Puerto Rico (7.9–6.9 ka), and eventually St. Croix (6.6–5.9 ka) (Table 7.2). Whether this temporal progression has any significance or simply reflects the vagaries of preservation or sampling, it appears that branching-coral reefs throughout the region had by-and-large given up by ca. 5.8 ka (at both shelf edge and inshore sites). A few areas already inhabited by massive species continued to accrete along the shelf edge until 5,000–3,000 years ago, but where *A. palmata* had dominated, a return to massive species was conspicuously absent. Inshore reefs switched to massive corals and never skipped a beat. Despite present-day coral cover up to 60% at some sites, little or no reef accretion has subsequently occurred at any of the shelf-edge sites where cores have been taken.

The widely accepted models of Adey et al. (1977) and Macintyre (1988) linked "inimical bank waters" at the time of platform flooding to the demise of the shelf-edge reefs and eventual backstepping. However, shelf-edge reefs cored on
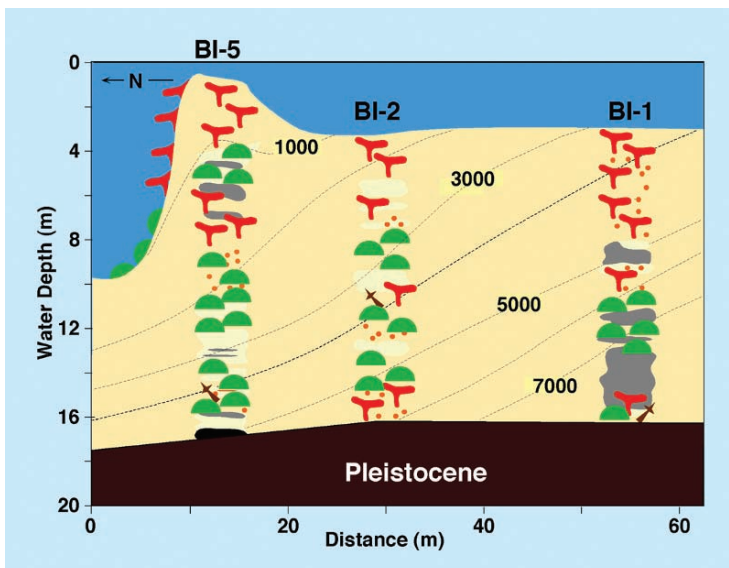

FIG. 7.35. Core transect across the northern Buck Island reef. Note that the reef built both upward and outward continually throughout its history. The slower sea-level rise after 7 ka allowed branching- and massive-coral reefs alike to produce carbonate at rates faster than accommodation space was being made available. Also note that the patterns of accretion appear to be independent of the dominant coral type. Similar patterns can be seen in many other Caribbean reefs formed in shallow water after 8 ka (After Hubbard et al. 2005 by permission of SEPM)

St. Croix and Puerto Rico (and elsewhere in the Caribbean) not only survived the period of bank flooding, but appear to have flourished throughout its presumed duration (Hubbard et al. 1997, 2001). Based on the sea-level curve and samples plotted in Fig. 7.14, water depth over the abandoned reefs varied from as much as 20–25 m off Puerto Rico and St. Croix to as little as 0.4–8.0 m off Florida. All had accreted at rates equal or close to sea-level rise. By the time the shelf-edge reefs quit, they had survived the "inimical bank waters" that were supposed to have killed them, had tracked rapidly rising sea level, and were entering a period of slowed sea-level rise that should have facilitated their catching up. Nevertheless, the apparently vibrant *A. palmata* community at each site stopped building framework, not only along the shelf edge but along shallower reefs closer to shore. Despite the absence of rapidly growing branching corals, shallow-water reefs not only continued to accrete at the same rate, but began to build seaward as accommodation space was decreasingly available.

By ca. 5.2 ka, *A. palmata* appears to have returned as a major frame-builder, but only along inshore reefs. The reasons for this recovery is as poorly understood as those responsible for earlier difficulties. If we invoke increased temperatures associated with the Holocene Thermal Maximum (Kaufman et al. 2004) to explain the sudden loss of *A. palmata* as a frame-builder, the timing does not appear to be coincident. Other possible causes are difficult to reconcile on other than a local scale. However enigmatic this *A. palmata* gap may have been, its repetition 3,000 years ago is even more so. No elevation of temperature is apparent in published climate records for this period, and not a single *A. palmata* date has been reported from this time interval (Hubbard et al. 2005).

The likelihood of these gaps being a sampling artifact seems small, considering the number of sites and investigators involved. Hubbard et al. (2005) concluded that local temperature variations, changing storm patterns and increased sedimentation or nutrients could not have occurred at all sites with the synchronicity required to explain these two gaps on a Caribbean -wide scale. Blanchon and Shaw (1995) and Blanchon (2005) have argued for a sudden jump in the rate of sea-level rise, but this is not supported by isotopic data, and is difficult to

envision given the position of sea level at the time (i.e., too close to present).

Regardless of the cause, major community shifts appear to have occurred at least twice in the late Holocene. Moreover, they involved the same species that signaled the start of the most recent reef decline – *A. palmata*. While we might be tempted to argue that the recent situation is simply the latest in a possibly cyclic phenomenon, this is most likely not the case. Even if the root causes were similar, the additional stresses today related to overfishing, increased sediment and nutrients, and probably rapidly rising global temperature were not present either 6,000 or 3,000 years ago. Thus, even if there are similarities in some of the triggering mechanisms of past and present events, factors that might limit or encourage subsequent recovery are assuredly greater today. Nevertheless, identifying the root causes of these past gaps is of considerable importance. How this might inform not only our understanding of why reef communities change, but also why and how they recover is critical and demands attention. The signal preserved in the recent geologic record is clearly sensitive enough to allow us to identify past turnover events on the scale of those occurring today. The challenge is to overcome largely taphonomic problems if we are going to provide a meaningful context for natural change that operates on a temporal scale longer than the attention span of legislators, funding cycles of NSF or scientific careers.

7.6   Conclusions

1. The reefs of Puerto Rico and the US Virgin Islands are widespread and varied in their morphology and community structure. The major controlling factors have been location, tectonic regime, sea level, depth of the antecedent substrate (and the timing of its flooding by rising sea level), and local patterns of current flow, sedimentation and nutrient flux.
2. Reefs along submerged shelf margins in Puerto Rico and the Virgin Islands started 10,000–12,000 years ago on antecedent rims or slope breaks 20–35 m below present sea level, and in paleo-water depths up to 25 m. These early reefs were dominated by branching *A. palmata*.

3. As sea level rose, reefs formed closer to shore 7,000–8,000 years ago. These reefs were largely dominated by massive corals, in response to higher levels of terrestrial sediment /nutrient input and possibly less stable substrates. Over time, their forereef slopes steepened, and *A. palmata* increasingly dominated the reef crest.

4. Reefs starting on shallower antecedent surfaces since 8 ka by and large accreted in a regime of slowing sea-level rise. They built continuously, and presently thrive at or near sea level. Exceptions include algal ridges in Boiler Bay (St. Croix) that were cut off by the subsequent development of Tague Reef (Adey and Burke 1976), and Buck Island Bar where unusually high wave energy has prevented the reef from building to sea level (Macintyre and Adey 1990).

5. Schlager's "Drowning Paradox" was built on the fundamental assumption that reef accretion follows a depth- and species-related pattern that mirrors coral growth (i.e., shallow *Acropora* reefs build faster than deeper reefs dominated by massive species). Also, most reefs are capable of accreting at rates faster than Holocene sea-level rise. Following these assertions, reefs should not "give up" unless sea level suddenly accelerates above ca. 10 m/ka or environmental conditions suddenly deteriorate to the point where calcification is compromised or terminated. Our prevailing Caribbean model invokes "inimical bank waters" as the solution to this "paradox", and presumes that abandonment of Caribbean shelf-edge reefs and backstepping to shallower sites was linked to this phenomenon.

6. Accretion data from all Caribbean cores reveal a pattern that contradicts Schlager's presumption that most reefs have been capable of outpacing even early Holocene sea-level rise. Regardless of water depth or dominant coral type, most reefs build at rates generally falling between 3 and 5 m/ka. Thus, reefs that were building prior to 7,000 years ago would have had difficulty keeping up with rising sea level under all but the most ideal conditions. The shelf edge apparently provided such an environment, and reefs on St. Croix and Puerto Rico kept pace with early an early Holocene sea-level rise on the order of 5 m/ka.

7. In contrast to earlier models, reef accretion continued throughout the flooding interval in Puerto Rico and the Virgin Islands. Core data from cored sites in Puerto Rico and the Virgin Islands, appear to invalidate the "inimical bank waters" scenario for all but a few specific sites. It seems more likely that, in the larger Caribbean, most shelf-edge reefs not only survived flooding, but thrived through it.

8. Commonplace and thick (up to several meters) detrital sequences at the base of most shelf edge cores imply that the lags of up to 3,000 years (more typically 1,500 years), previously attributed a lack of corals due to "inimical bank waters" (IBW) as the bank flooded, more likely represent poor framework preservation. High bioerosion related to elevated nutrient levels, combined with lower recruitment rates due to sedimentation and turbidity, may have been the cause. In this scenario, IBW had a bearing on reef accretion, but less so on coral recruitment. A flourishing community capable of reef building probably existed and gradually increased in its ability to build preservable framework. Most important, once reef building started, it was largely uninterrupted, and backstepping was unrelated to IBW developing along the platform margin.

9. Shallow reefs (barrier and fringing) started after 8 ka off Puerto Rico and the Virgin Islands, and throughout most of the Caribbean. They have developed under a regime of slowing sea level, and have had no difficulty in keeping up. As a result, they have built both vertically and laterally as carbonate production exceeded accommodation space.

10. Enigmatically, shelf-edge reefs eventually quit ca. 6,000 years ago when *A. palmata* ceased building framework. The loss of *A. palmata* framework rom the record also occurred on shallower reefs closer to shore, and apparently throughout the Caribbean. Many of the affected reefs continued to build, but the frame-building community was limited to massive species. Along the shelf edge, *A. palmata* reefs never recovered. The hiatus in *A. palmata* accretion lasted some 800 years and was repeated 3,000 years ago. The reasons for these changes in Caribbean community structure are unclear, but their synchronicity requires a regional explanation. Both sea level and "inimical bank waters" offer poor explanations. Whether or not these intervals of

TABLE 7.2. Data for "give-up" reefs along Caribbean shelf margins.

Core/site	Location	Age (ka)	D (m)[a]	SL (m)	PaleoD (m)	Source
LBN-1	Lang Bank	6.2	13.0	−6.0	7.0	Hubbard (unpublished)
LBN-2	Lang Bank	6.6	12.5	−6.5	6.0	Hubbard (unpublished)
LBS-3	Lang Bank	6.4	15.0	−6.3	8.8	Hubbard (unpublished)
LB-7	Lang Bank	5.9	25.5	−5.5	20.0	Hubbard (unpublished)
LB-8	Lang Bank	6.4	12.5	−6.3	6.3	Hubbard (unpublished)
LB-9	Lang Bank	6.4	13.7	−6.3	7.5	Hubbard (unpublished)
PAR-2	SW PR	6.9	14.0	−7.1	6.9	Hubbard et al. (1997)
PAR-3	SW PR	7.0	13.4	−7.5	5.9	Hubbard et al. (1997)
PAR-11	SW PR	6.9	13.5	−7.1	6.4	Hubbard et al. (1997)
PAR-16A	SW PR	7.8	12.5	−10.0	2.5	Hubbard et al. (1997)
PAR-A	SW PR	7.9	17.6	−10.3	7.4	Hubbard et al. (1997)
SR-5	Salt R	6.2	31.0	−6.0	25.0	Hubbard et al. (1985)
	Fla	7.0	7.9	−7.5	0.4	Precht (in Toscano and Macintyre 2003)
	Fla	8.0	17.5	−10.9	6.6	Lighty et al. (1982)
	Sand Key	6.8	9.5	−6.8	2.7	Toscano and Macintyre (2003)
	Carysfort	7.0	9.7	−7.5	2.2	Toscano and Macintyre (2003)

[a] Depth in meters below present sea level

poor *A. palmata* preservation share anything with the recent epidemic of branching-coral loss, understanding the causes of such large-scale community shifts provides both opportunities and challenges with respect to unraveling both natural and anthropogenic change.

In a larger sense, this paper owes everything to those earlier reef workers who challenged us to change the scale at which we view modern reefs. Walter Adey's broad view of Caribbean -wide patterns showed us the tremendous value of regional context. Our favorite reef no longer existed in a vacuum. Reefs varied along gradients of energy such that no single model was adequate. Not only was it OK that our reef didn't fit the Jamaica model – it shouldn't. Ian Macintyre's submersible coring system allowed, for the first time, access to modern reef interiors at a cost that was affordable and did not require a massive expeditionary force and a large, expensive drilling ship. This heralded a revolution in the way we have come to view modern reefs and their relationship to their ancient

forebears. Peter Davies and David Hopley carried the technique to Australia, and the focus gradually shifted away from who's reef was bigger or better – they were either different or similar, and what was important was understanding why. Names have been added to this list: Cabioch, Camoin, Dullo, Fairbanks, Fletcher, Geister, Grossman, Montaggioni, Shinn, my co-authors, and many more. But, whatever any of us might add to the revolutionary ideas laid out at the ISRS Meeting in Miami in 1977, we all draw from them.

References

Acevedo R, Morelock J, Olivieri RA (1989) Modification of coral reef zonation by terrigenous sediment stress. Palaios 4:92–100

Adey WH (1975) The algal ridges and coral reefs of St. Croix : their structure and Holocene development. Atoll Res Bull 187:1–67

Adey WH (1977) Shallow water Holocene bioherms of the Caribbean Sea and West Indies. Proc 3rd Int Coral Reef Symp 2:xx1–xxiv

Adey WH (1978) Coral reef morphogenesis: a multidimensional model: Science 202:831–837

Adey WH, Burke RB (1976) Holocene bioherms (algal ridges and bank barrier reefs) of the eastern Caribbean. Geol Soc Am Bull 87:95–109.

Adey WH, Burke RB (1977) Holocene bioherms of Lesser Antilles – geologic control of development, in: Frost SH, Weiss MP, Saunders JB (eds), Reefs and Related Carbonates – Ecology and Sedimentology, AAPG Stud Geol 4:67–81

Adey WH, Macintyre IG, Stuckenrath R, Dill RF (1977) Relict barrier reef system off St. Croix : its implications with respect to late Cenezoic coral reef development in the western Atlantic. Proc 3rd Int Coral Reef Symp 2:15–21

Blanchon P (2005) Comments on "Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmata* framework and intertidal mangrove peat". Coral Reefs 24:183–186

Blanchon P, Shaw J (1995) Reef drowning during the last deglaciation; evidence for catastrophic sea-level rise and ice-sheet collapse. Geology 23:4–8

Bloom AL (1976) Atlas of sea level curves. International Geological Correlation Programme, Project 61:C18

Burke RB, Adey WH, Macintyre IG (1989) Overview of the Holocene history, architecture and structural components of Tague reef and lagoon, in: Hubbard DK (ed), Terrestrial and Marine Geology of St. Croix,

U.S. Virgin Islands. Spec Publ No. 8, West Indies Laboratory:105–109

Conand C, Chabanet P, Cuet P, Letourneur Y (1997) The carbonate budget of a fringing reef in La Reunion Island (Indian Ocean): sea-urchin and fish bioerosion and net calcification. Proc 8th Int Coral Reef Symp 1:953–958

Connell JH (1978) Diversity in tropical rain forests and coral reefs. Science 199:1302–1309

Cutler KB, Edwards RL, Taylor FW, Cheng H, Adkins J, Gallup CD, Cutler PM, Burr GS, Bloom AL (2003) Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. Earth Planet Sci Lett 206:253–271

Darwin C (1842) The Structure and Distribution of Coral Reefs. Reprinted by the University of Arizon Press, 1984, 214 pp

Fagerstrom A (1987) The Evolution of Reef Communities, Wiley 600 pp

Fairbanks RG (1989) A 17,000 year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342:637–642

Frost SH (1977) Cenozoic reef systems of Caribbean: prospects for paleoecologic synthesis, in: Frost, S, Weiss M, Saunders J (eds), Reefs and Related Carbonates – Ecology and Sedimentology. AAPG Stud Geol 4:93–110.

Frost SH, Weiss MP (1979) Patch-reef communities and succession in the Oligocene of Antigua, West Indies. Geol Soc Am Bull 90:I 612–I 616

Gallup CD, Edwards RL, Johnson RG (1994) The timing of high sea levels over the past 200,000 years. Science 263:796–800

Geister J (1977) The influence of wave exposure on the ecology and zonation of Caribbean coral reefs. Proc 3rd Int Coral Reef Symp 1:23–29

Gill IP, Hubbard DK, McGlaughlin, PP, Moore CH (2002) Distribution and types of porosity within the Kingshill aquifer, in: Renkin RA et al. (eds), Geology and Hydrogeology of the Caribbean Islands Aquifer System of the Commonwealth of Puerto Rico and the U.S. Virgin Islands. U.S. Geol Surv Prof Pap 1419:123–131

Ginsburg RN, Gischler E, Schlager W (1994) Johannes Walther on reefs: Comparative Sedimentology Laboratory, University of Miami, Geological Milestones II, 141 pp

Gischler E (2006) Comments on "Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmata* framework and intertidal mangrove peat". Coral Reefs 25:273–279

Gischler E, Hudson JH (2004) Holocene development of the Belize barrier reef. Sedim Geol 164:223–236

Goreau TF, Land LS (1974) Fore-reef morphology and depositional processes, north Jamaica, in: Laporte LF (ed), Reefs in Time and Space. Soc Econ Petrol Mineral Spec Publ No. 18:77–98

Grant RE (1826) Notice of a new zoophyte (*Cliona celata* Gr.) from the Firth of Forth. Edinburg. New Philos J, Apr–Oct:78–81

Hubbard DK (1986) Sedimentation as a control of reef development : St. Croix, U.S.V.I. Coral Reefs 5:117–125

Hubbard DK (1989a) Modern carbonate environments of St. Croix and the Caribbean : a general overview, in: Hubbard DK (ed), Terrestrial and Marine Geology of St. Croix, U.S. Virgin Islands. Spec Publ No. 8, West Indies Laboratory:85–94

Hubbard DK (1989b) Depositional environments of Salt River estuary and submarine canyon, St. Croix, U.S.V.I., in: Hubbard DK (ed.), Terrestrial and Marine Geology of St. Croix, U.S. Virgin Islands. Spec Publ No. 8, West Indies Laboratory:181–196

Hubbard DK (1989c) The shelf-edge reefs of Davis and Cane Bay, northwestern St. Croix, in: Hubbard DK (ed), Terrestrial and Marine Geology of St. Croix, U.S. Virgin Islands. Spec Publ No. 8, West Indies Laboratory:167–180

Hubbard DK (1992a) A modern example of reef backstepping from the eastern St. Croix shelf, U.S. Virgin Islands. Proc Amer Assoc Petrol Geol, Ann Meet:57

Hubbard DK (1992b) Hurricane-induced sediment transport in open-shelf tropical systems – an example from St. Croix, U.S. Virgin Islands. J Sedim Pet 62:946–960

Hubbard DK (2005) Holocene reef development in the Caribbean, geologic perspectives revisited: abstracts with programs. Geol Soc Am:400

Hubbard DK, Ward LG, FitzGerald, DM (1976) Reef morphology and sediment transport, Lucaya, Grand Bahama Island. Proc Am Assoc Petr Geol Ann Meet, New Orleans, LA

Hubbard DK, Sadd JL, Miller AI, Gill IP, Dill RF (1981) The Production, Transportation and Deposition of Carbonate Sediments on the Insular Shelf of St. Croix, U.S. Virgin Islands : Technical Report No. MG-1, West Indies Laboratory, St. Croix, USVI, 145 pp

Hubbard DK, Sadd JL, Roberts HH (1982) The role of physical processes in controlling sediment -transport patterns on the insular shelf of St. Croix, U.S.V.I. Proc 4th Int Coral Reef Symp 1:399–404

Hubbard DK, Burke RB, Gill IP (1984) Accretionary styles in shelf-edge reefs, St. Croix, U.S.V.I. Proc Am Assoc Petr Geol Ann Meet, San Antonio, TX

Hubbard DK, Burke RB, Gill IP (1985) Accretion in shelf-edge reefs, St. Croix, U.S.V.I. in: Crevello PD, Harris PM (eds), Deep-water carbonates. SEPM Core Workshop No. 6:491–527

Hubbard DK, Burke RB, Gill IP (1986) Styles of reef accretion along a steep, shelf-edge reef, St. Croix, U.S. Virgin Islands. J Sedim Petrol 56:848–861

Hubbard DK, Venger L, Parsons K, Stanley D (1989) Geologic development of the west-end terrace system on St. Croix, U.S. Virgin Islands, in: Hubbard DK (ed), Terrestrial and Marine Geology of St. Croix. Spec Pub No. 9, West Indies Laboratory:73–84

Hubbard DK, Miller AI, Scaturo D (1990) Production and cycling of calcium carbonate in a shelf-edge reef system (St. Croix, U.S. Virgin Islands): applications to the nature of reef systems in the fossil record. J Sedim Petrol 60:335–360

Hubbard DK, Gill IP, Burke RB, Morelock J (1997) Holocene reef backstepping – southwestern Puerto Rico shelf. Proc 8th Int Coral Reef Symp 2:1779–1784

Hubbard DK, Burke RB, Gill IP (1998) Where's the reef: the role of framework in the Holocene. Carbonate Evaporite 13:3–9

Hubbard DK, Gill IP, Burke RB (2000) Caribbean -wide loss of A. *palmata* 7,000 yr ago: sea-level change, stress, or business as usual? Abstracts and Programs. 9th Int Coral Reef Symp:57

Hubbard DK, Gill IP, and Burke RB, 2001, The Coral Reefs revisited: inimical bottom waters turned friendly. Geol Soc Am Abstracts with Programs:A-408

Hubbard DK, Ramirez W, Davis A, Lawson GR, Oram J, Parsons-Hubbard K, Greer L, Cuevas D, and del Coro M (2004) A preliminary model of Holocene coral-reef development in the Enriquillo Valley, SW Dominican Republic. Geol Soc Am Abstracts with Programs:313

Hubbard DK, Zankl H, Van Heerden I, Gill IP (2005) Holocene Reef Development Along the Northeastern St. Croix Shelf, Buck Island, U.S. Virgin Islands. J Sedim Res 75:97–113

Imbrie J, Hays JD, McIntyre A, Mix AC, Morley JJ, Pisias NG, Prell W, Shackleton NG (1984) The orbital theory of Pleistocene climate : support from a revised chronology of the marine $\delta^{18}O$ record, in: Berger A, Imbrie J, Hays J, Kukla G, Saltzman B (eds), Milankovitch and Climate, Part 1. Reide, Boston, MA, pp 269–305

Kaufman DS, Ager TA, Anderson NJ, Anderson PM, Andrews JT, Bartlein PJ, Brubaker LB, Coats LL, Cwynar LC, Duvall ML, Dyke AS, Edwards ME, Eisner WR, Gajewski K, Geirsdottir A, Hu FS, Jennings AE, Kaplan MR, Kerwin MW, Lozhkin AV, MacDonald GM, Miller GH, Mock CJ, Oswald WW, Otto-Bliesner BL, Porinchu DF, Ruhland K, Smol JP, Steig EJ, Wolfe BB (2004). Holocene thermal maximum in the western Arctic (0–180 W). Quat Sci Rev 23:529–560

Lighty RG, Macintyr, IG, Stuckenrath R (1982) *Acropora palmata* reef framework : a reliable indicator of sea

level in the western Atlantic for the past 10,000 years. Coral Reefs 1:125–130

Lowenstam HA (1950) Niagaran reefs of the Great Lakes area geological society of America. Memoir 67:215–248

Macintyre IG (1975) A diver operated hydraulic drill for coring submerged substrates. Atoll Res Bull 185:21–25

Macintyre IG (1988) Modern coral reefs of western Atlantic : new geologic perspective. Amer Assoc Petrol Geol Bull 72:1360–1369

Macintyre IG, Adey WH (1990) Buck Island Bar, St. Croix, USVI: a reef that cannot catch up with sea level. Atoll Res Bull 336:1–7

Macintyre IG, Glynn PW (1976) Evolution of modern Caribbean fringing reef, Galeta Point, Panama. Amer Assoc Petrol Geol Bull 60:1054–1072

Macintyre, IG, Raymond, B, Stuckenrath R (1983) Recent history of a fringing reef, Bahia Salina del Sur, Vieques Island, Puerto Rico. Atoll Res Bull 268:1–9

Macintyre IG, Multer HG, Zankl H, Hubbard DK (1985) Growth and depositional facies of a windward reef complex (Nonsuch Bay, Antigua, W.I.). Proc 5th Int Coral Reef Symp 6:605–610

Masson DG, Scanlon KM (1991) The neotectonic setting of Puerto Rico. Geol Soc Am Bull 103:144–154.

Milliman JD (1973) Caribbean coral reefs, in: Jones OA, Endean R (eds), Biology and Geology of Coral Reefs, Academic

Muhs DR, Simmons KR, Taggart BE, Prentice, CS, Joyce J, Troester JW (2005) Timing and duration of the last interglacial period from U-series ages of unaltered reef corals, Northern and Western Puerto Rico. Abstracts of 17th Caribbean Geological Conference, San Juan, PR

Neumann AC (1966) Observations on coastal erosion in Bermuda and measurements of the boring rate of the sponge *Cliona lampa*. Limnol Oceanogr 11:92–108

Neumann AC (1977) A sea-level curve for Bermuda, in: Bloom AL (ed), Atlas of Sea Level Curves. International Geological Correlation Programme, Project 61, p C18

Neumann AC, Macintyre I (1985) Reef response to sea-level rise: keep-up, catch-up, or give-up. Proc 5th Int Coral Reef Symp 3:105–110

Newell ND (1971) An outline history of tropical organic reefs. Am Mus Novit 2465:1–37

Newell ND, Rigby JK, Fischer AG, Whiteman AJ, Hickox JE, Bradley JS (1953) The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico: A Study in Paleoecology. W.H. Freeman, San Francisco, CA, 236 p

Playford PW (1980) Devonian "Great Barrier Reef" of Caning Basin, Western Australia. Amer Assoc Petrol Geol Bull 64:814–840

Pindell JL (1994) Evolution of the Gulf of Mexico and the Caribbean, in: Donovan SK, Jackson T (eds), Caribbean Geology: And Introduction, University of W Indies Publishers Association/University of the West Indies Press, Kingston, Jamaica, pp 13–39

Pindell JL, Barrett SF (1990) Geologic evolution of the Caribbean region: a plate-tectonic perspective, in: Dengo G, Case JE (eds), The Caribbean Region. Geol Soc Am, Geol North Am Ser H:405–432

Pindell J, Cande S, Pitman W, Rowley D, Dewey J, Labrecque J, Haxby W (1988) A plate-kinematic framework for models of Caribbean evolution. Tectonophysics 115:121–138

Prentice CS, McGeehin J, Simmons KR, Muhs, DR, Roig C, Joyce J, Taggart B (2005) Holocene marine terraces in Puerto Rico: evidence for tectonic uplift?. Abstracts of 17th Caribbean Geological Conference, San Juan, PR

Reid JA, Plumley, PW Schellekens, JH (1991) Paleomagnetic evidence for Late Miocene counter-clockwise rotation of north coast carbonate sequence, Puerto Rico. Geophys Res Lett 18:565–568

Roberts HH, Murray SP, Suhayda JN (1977) Physical processes in a fore-reef environment. Proc 3rd Int Coral Reef Symp 2:507–515

Sadd JL (1984) Sediment transport and $CaCO_3 \simeq$ budget on a fringing reef, Cane Bay, St. Croix, U.S. Virgin Islands. Bull Mar Sci 35:221–238

Schlager W (1981) The paradox of drowned reefs and carbonate platforms. Geol Soc Am Bull 92:197–211

Shackleton NJ (1987) Oxygen isotopes, ice volume and sea level. Quat Sci Rev 6:183–190

Shinn EA, Lidz BH, Kindinger JL, Hudson JH, Halley RB (1989) Reefs of Florida and the Dry Tortugas. US Geological Survey, St. Petersburg, FL, 53 p

Speed R (1989) Tectonic evolution of St. Croix, Implications for tectonics of the northeastern Caribbean, in: Hubbard DK (ed.), Terrestrial and marine Geology of St. Croix, U.S. Virgin Islands, Spec Publ No. 8, West Indies Laboratory:9–36

Stoddart D (1969) Ecology and morphology of recent coral reefs, Biol Rev 44:433–498

Taggart BE (1992) Tectonic and eustatic correlations of radiometrically dated marine terraces in northwest Puerto Rico and Isla de Mona: Puerto Rico. Ph.D. dissertation, University of Puerto Rico, Mayagüez, 252 p

ten Brink, US, Dillon WP, Frankel A, Rodriguez R, Mueller C (1999) Seismic and tsunami hazards in Puerto Rico and the Virgin Islands. US Geological Survey Open-file Report 99–353

Toscano MA, Lundberg J (1999) Submerged late Pleistocene reefs on the tectonically stable S.E. Florida margin: high-precision geochronology, stratigraphy, resolution of substage 5a sea-level elevation, and orbital forcing. Quat Sci Rev 18:753–767

Toscano MA, Macintyre IG (2003) Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmata* framework and intertidal mangrove peat. Coral Reefs 22:257–270

Viau C (1983) Depositional sequences, facies and evolution of the upper Devonian Swan Hills buildup, central Alberta, Canada, in: Harris PD (ed), Carbonate Buildups – A Core Workshop. Soc Econ Petrol Mineral Core Workshop No. 4:113–143

Winograd IJ, Landwehr JM, Ludwig KR, Coplen TB, Riggs AC (1997) Duration and structure of the past four interglaciations. Quat Res 48:141–154

Zimmer B, Precht W, Hickerson E, Sinclair J (2006) Discovery of *Acropora palmata* at the Flower Garden Banks Marine Sanctuary, northwestern Gulf of Mexico. Coral Reefs 25:192