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COARSE-CLAST RIDGE COMPLEXES OF THE CARIBBEAN: A PRELIMINARY BASIS FOR DISTINGUISHING TSUNAMI AND STORM-WAVE ORIGINS

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ABSTRACT: **Coastal gravel-ridge complexes deposited on islands in the Caribbean Sea are recorders of past extreme-wave events that could be associated with either tsunamis or hurricanes. The ridge complexes of Bonaire, Jamaica, Puerto Rico (Isla de Mona), and Guadeloupe consist of polymodal clasts ranging in size from sand to coarse boulders that are derived from the adjacent coral reefs or subjacent rock platforms. Ridge-complex morphologies and crest elevations are largely controlled by availability of sediments, clast sizes, and heights of wave runup. The ridge complexes are internally organized, display textural sorting and a broad range of ages including historical events. Some display seaward-dipping beds and ridge-and-swale topography, and some terminate in fans or steep avalanche slopes. Together, the morphologic, sedimentologic, lithostratigraphic, and chronostratigraphic evidence indicates that shore-parallel ridge complexes composed of gravel and sand that are tens of meters wide and several meters thick are primarily storm-constructed features that have accumulated for a few centuries or millennia as a result of multiple high-frequency intense-wave events. They are not entirely the result of one or a few tsunamis as recently reported. Tsunami deposition may account for some of the lateral ridge-complex accretion or boulder fields and isolated blocks that are associated with the ridge complexes.**

INTRODUCTION

The 2004 Indian Ocean tsunami was a stark reminder of the devastating forces associated with these catastrophic events and their ability to cause widespread coastal change. Since then, attention has been focused on other regions of the world where active tectonic processes increase the probability of generating tsunamis that could cause loss of life and property. One such region is the Caribbean Sea and associated islands (Fig. 1), where historical tsunamis have been reported (Lander et al. 2002). The islands of the Caribbean region also are frequently impacted by tropical cyclones (Fig. 2), including extreme hurricanes. In recent years, attempts have been made to reconstruct histories of storm and tsunami hazards from the sedimentary record where local histories of these events are either short or incomplete. Because using paleo-event deposits is an accepted method of extending the historical record for coastal-hazard risk assessments (Bourgeois and Minoura 1997; Hayne and Chappell 2001; Jaffe and Gelfenbaum 2002), it is essential to recognize the depositional signatures of the two different extreme-wave processes where both coexist. The distinguishing characteristics of sandy storm and tsunami deposits have been reported recently (Morton et al. 2007a); however, diagnostic characteristics of coarse-clast features deposited by storms and tsunamis have not been compared.

To facilitate our assessment of extreme-wave hazards in the Caribbean, field data were collected in Puerto Rico (Isla de Mona), Jamaica, Guadeloupe, and Bonaire (Fig. 3), where historical hurricanes and tsunamis have inundated the coast (Lander et al. 2002) or interpreted paleo-tsunami deposits have been reported (Taggart et al. 1993; Scheffers 2002; Scheffers et al. 2005; Robinson et al. 2006). We used a combination of laser range finder, GPS receivers, field observations, historical aerial photographs, and satellite images to measure distances, elevations, and dimensions of the coarse-clast deposits and to document their morphologies, lateral extents, stratigraphies, and ages.

CARIBBEAN EXTREME-WAVE EVENTS

Historical Hurricanes

Tropical cyclones impact the shores of at least a few Caribbean islands each year. These intense storms, which commonly track from east to west (Fig. 2), exhibit counterclockwise wind circulation around centers of low barometric pressure (Simpson and Riel 1981). As a result of island orientations and storm movement and associated wind patterns, east- and north-facing shores typically experience the greatest impacts from high storm surge and wind-driven currents. South-facing shores are impacted when the storms pass south of the islands. Extremely rare exceptions to these paths and impact patterns are caused by storms that track from west to east, such as Hurricane Lenny in 1999. Because the zone of cyclogenesis is centered roughly 10° north of the Equator, frequency of impacts from hurricane-generated waves is highest in the northern Caribbean and decreases toward the south.

The coasts of Jamaica, Puerto Rico, and Guadeloupe are regularly flooded by storm waves because they lie within the zone of tropical

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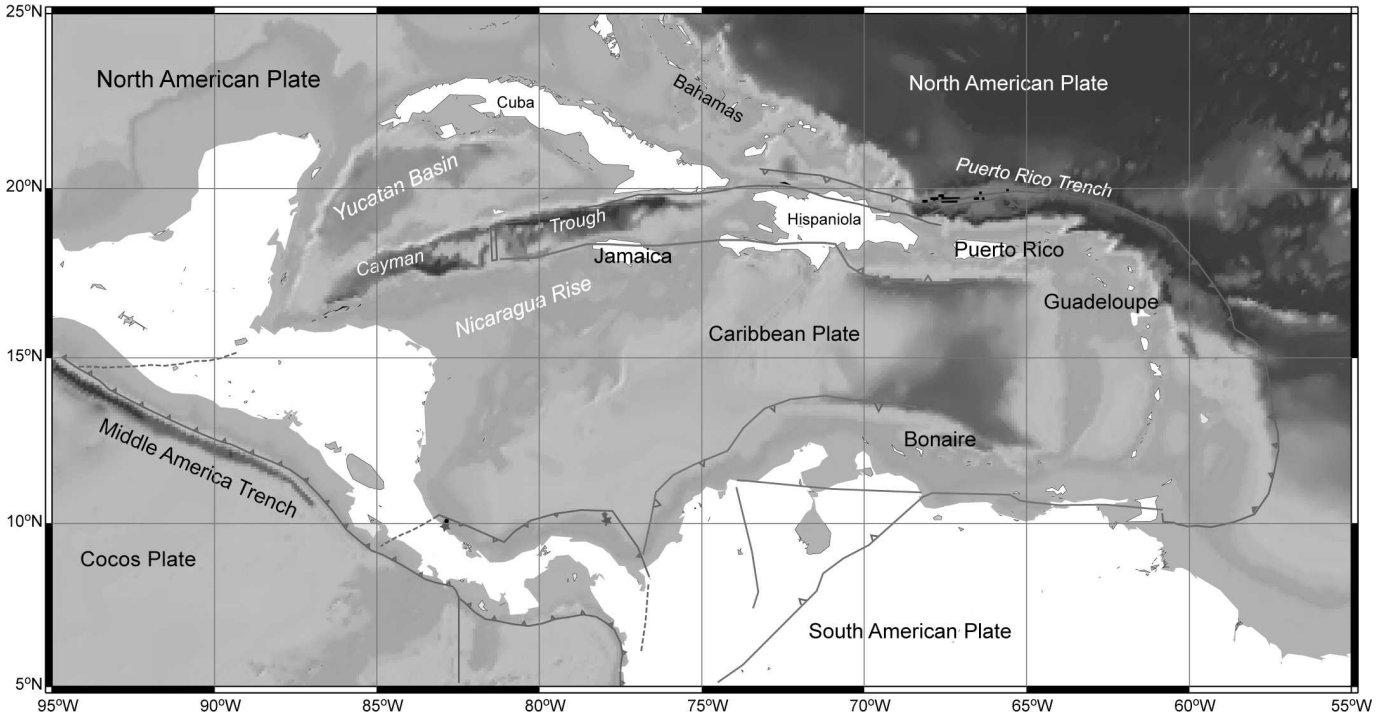

FIG. 1.—The Caribbean region, showing locations of Jamaica, Puerto Rico, Guadeloupe, and Bonaire relative to the major physiographic elements and tectonic plate boundaries.

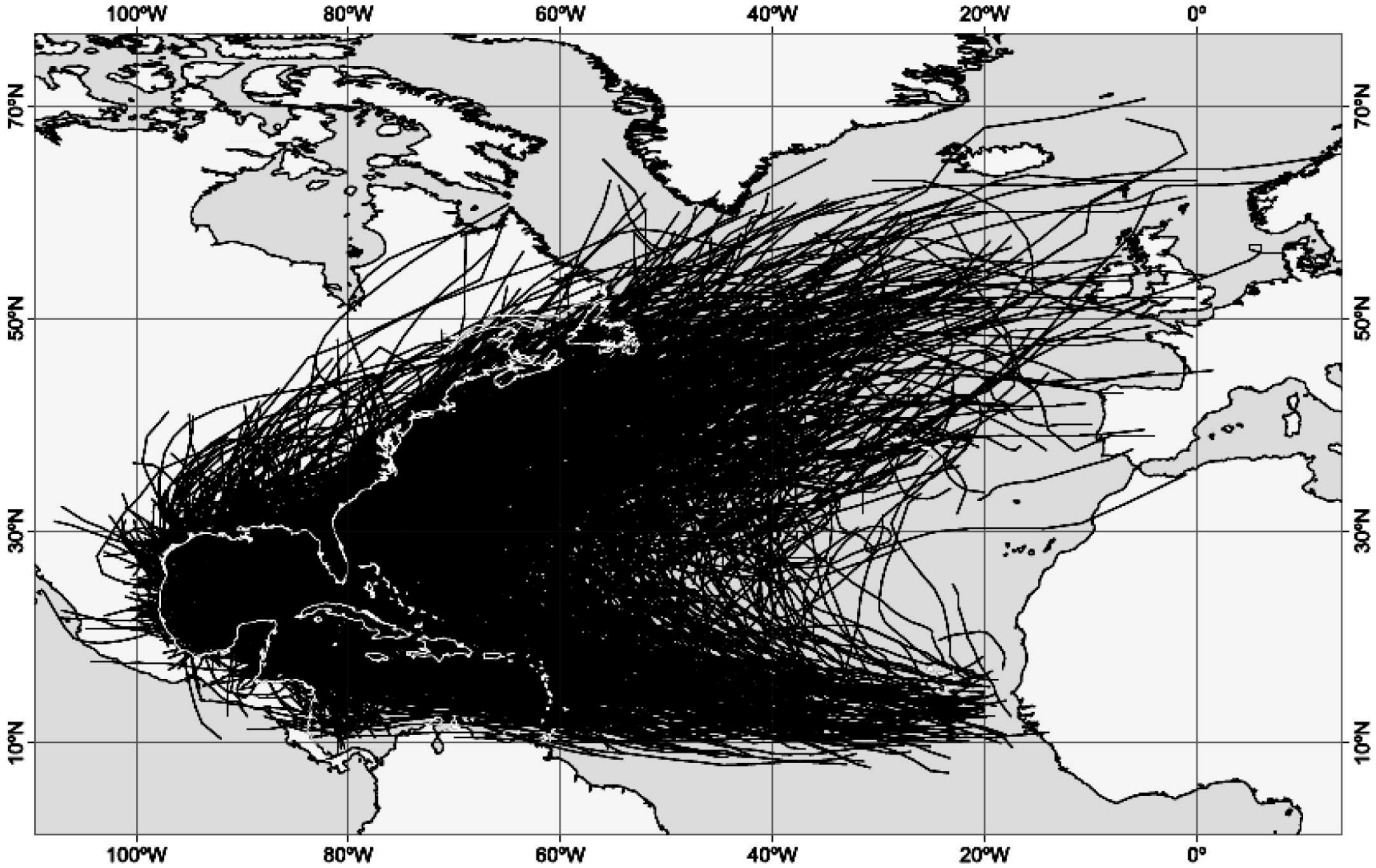

FIG. 2.—Tracks of all Atlantic tropical cyclones between 1851 and 2005. Obtained from the National Hurricane Center (http://www.nhc.noaa.gov/index.shtml).

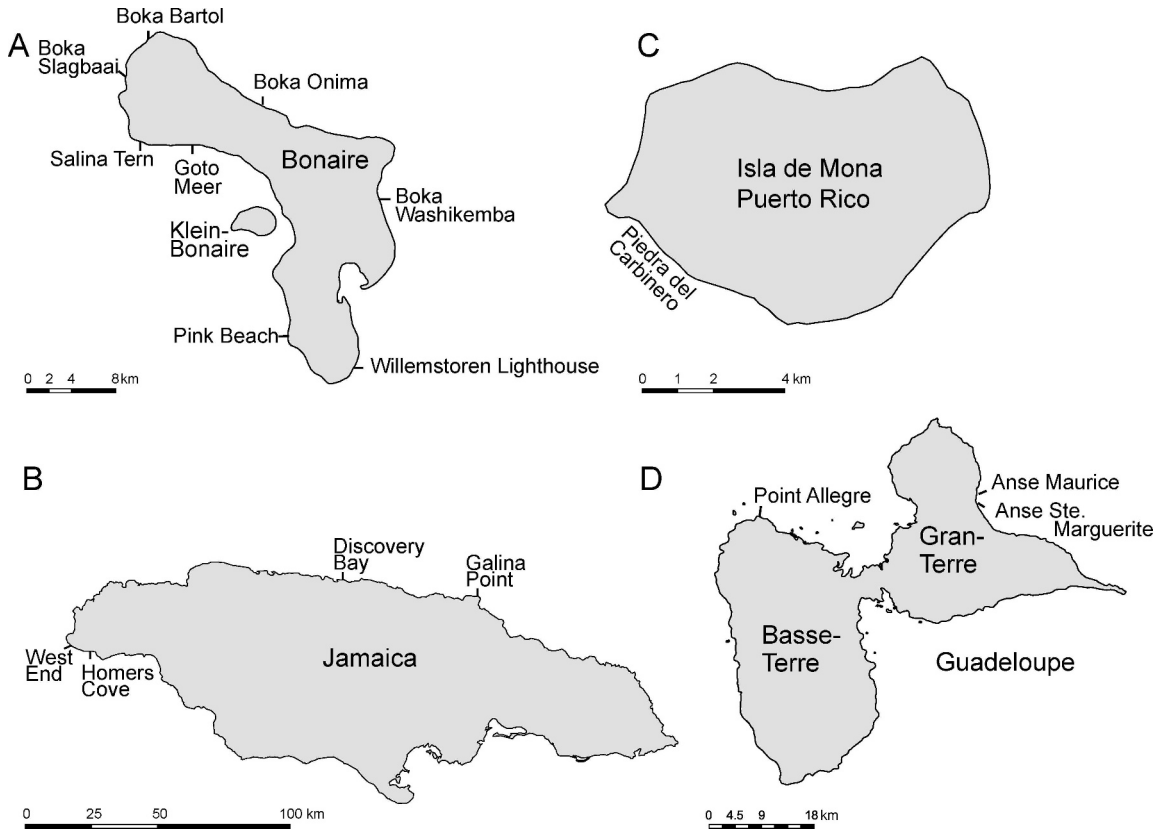

FIG. 3.— Locations of selected observation sites on **A)** Bonaire, **B)** Jamaica, **C)** Isla de Mona, Puerto Rico, and **D)** Guadeloupe. Sites listed in Tables 1 and 2 are labeled.

cyclone paths (Fig. 2). Prior to our field studies from 2005 to 2007, the most recent extreme storms to impact Jamaica were hurricanes Allen (1980) and Ivan (2004), whereas the most recent intense storms to cause widespread coastal change in Puerto Rico and the east coast of Guadeloupe were hurricanes Hugo (1989) and Georges (1998).

Hurricane winds generate deep-ocean swells that can cause substantial coastal change far from the storm center. Coastal impacts from distant storms are important for islands such as Bonaire. For example, hurricanes Ivan (2004) and Lenny (1999) came no closer than 110 km and 375 km, respectively, from Bonaire, and yet their waves constructed or reshaped coral-rubble ridges near sea level and moved boulders on rock platforms (Scheffers and Scheffers 2006).

Historical Tsunamis

All the common mechanisms for generating local tsunamis (earthquakes, volcanic eruptions, submarine landslides) are present in the Caribbean Sea. Island shores facing east toward the Atlantic Ocean also are at risk from teletsunamis generated by remote sources, such as the tsunami caused by the Lisbon, Portugal earthquake in 1755 (Lander et al. 2002). Nearly all islands within the Caribbean region have experienced a historical tsunami. The tsunamis tend to be highly focused, so their impacts are limited to short segments of only one or a few islands. Runup elevations of Caribbean tsunamis can be high, but they do not have the global impact of teletsunamis, such as the 2004 Indian Ocean event. Considering the historical tsunamis that impacted Puerto Rico in 1867, 1918, and 1946 (Lander et al. 2002), the 1918 event was the most devastating. This event, with a reported maximum runup height of 6 m (Reid and Taber 1919), inundated the northwest coast of the main island of Puerto Rico (Moya and Mercado 2006) and likely impacted Isla de Mona, which was near the tsunami source (Lander et al. 2002). Severe tsunami impacts were reported in Jamaica in 1692 and 1907. The 1907 tsunami inundated the north coast of Jamaica with 2.5-m waves (Lander et al. 2002).

The most significant historical tsunami to strike Guadeloupe occurred in 1867 and had a reported height of 18.3 m (Lander et al. 2002), but subsequent modeling and reinterpretation of eyewitness reports indicate that wave runup was probably less than 10 m (Zahibo and Pelinovsky 2001). No historical tsunamis have been reported on Bonaire, but that does not mean that the island is exempt from tsunami hazards. Earthquake-generated tsunamis have locally inundated the nearby northern coast of Venezuela, including some of the oldest reported tsunamis for the southern Caribbean Sea (Lander et al. 2002; Schubert 1994).

CARIBBEAN COARSE-CLAST DEPOSITS

Overview

Coastal deposits on the Caribbean islands are composed of sand, mixed sand and gravel, and blocks. We use the terminology of Blair and McPherson (1999), who defined the size ranges of clasts larger than sand, including boulders (0.25 to 4.1 m) and fine blocks (4.1 to 8.2 m). Gravel is a class that includes all particle sizes between coarse sand (2 mm) and very coarse boulders (4.1 m).

Morphologically the coarse-clast coastal deposits of the Caribbean can be grouped into ridges, ridge complexes, and boulder fields, depending on particle spacing and the resulting degree of clast concentration. Ridges and ridge complexes represent an accumulation several or more clasts

FIG. 4.—Sharp-crested ridge at sea level near Boka Slagbaai, Bonaire. The ridge was constructed by Hurricane Lenny in 1999 and subsequently modified by less energetic waves. The ridge is approximately 5 to 8 m wide at sea level. Location is shown on Figure 3A.

thick. The particles are in contact with one another and exhibit fitted (packed) fabrics that can be either matrix supported or framework supported. In contrast, boulder fields consist mainly of isolated clasts scattered across a surface. The particles are separated, and their respective positions do not necessarily influence subsequent movement of one another. The boulder fields also contain some blocks that are much larger than the sizes of clasts in the ridges and ridge complexes. Our detailed examination of isolated blocks and boulder fields in the Caribbean indicate that they have size and space distributions that are significantly different than those of the ridge complexes. Characterization of boulder fields requires measuring axial dimensions and orientations of individual clasts, determining the alongshore and cross-shore distribution of clasts, and determining the sizes and positions of the boulders relative to the shore or edge of a rock platform. Because different strategies are required to characterize and analyze the perched blocks and boulder fields, they are not addressed in this paper, although they too are important recorders of extreme-wave events.

The term ridge is restricted herein to a narrow, low, shore-parallel, wall-like feature a few meters high consisting of unconsolidated rubble that was deposited by waves during a single event (Fig. 4). A ridge may be modified by a few multiple-wave events while still retaining its individual identity. At time scales of years to decades, ridges are commonly reworked by other waves that cause them either to migrate landward or to be transformed into sheets (Blumenstock et al. 1961; Stoddart 1965; Baines and McLean 1976).

For our discussion, a ridge complex (Figs. 5–10) is a broad, composite, shore-parallel feature generally > 2 m thick consisting of unconsolidated rubble deposited by waves. A ridge complex represents an accumulation of many depositional events resulting from the long-term reworking and coalescence of multiple-event deposits, including former isolated ridges. At time scales of years to decades, ridge complexes near sea level are generally stable landforms that aggrade or prograde seaward as additional material accumulates on the crest and seaward side (Baines and McLean 1976; Woodroffe 1994).

Despite numerous storm and tsunami impacts recorded for the Caribbean islands, there are relatively few descriptions of the sediments deposited by these extreme-wave events. Boulders and blocks deposited on the Grand Caymans, Puerto Rico, Bahamas, Aruba, Curacao, Bonaire, Guadeloupe, Barbados, St. Martin, Anguilla, and Jamaica have captured the most attention because of their extraordinary size and the requirement of extremely powerful waves to transport them (Rigby and Roberts 1976; Jones and Hunter 1992; Taggart et al. 1993; Hearty 1997; Scheffers 2002, 2004; Kelletat et al. 2004; Scheffers 2005; Scheffers et al. 2005; Robinson et al. 2006). Although some of the authors interpret the

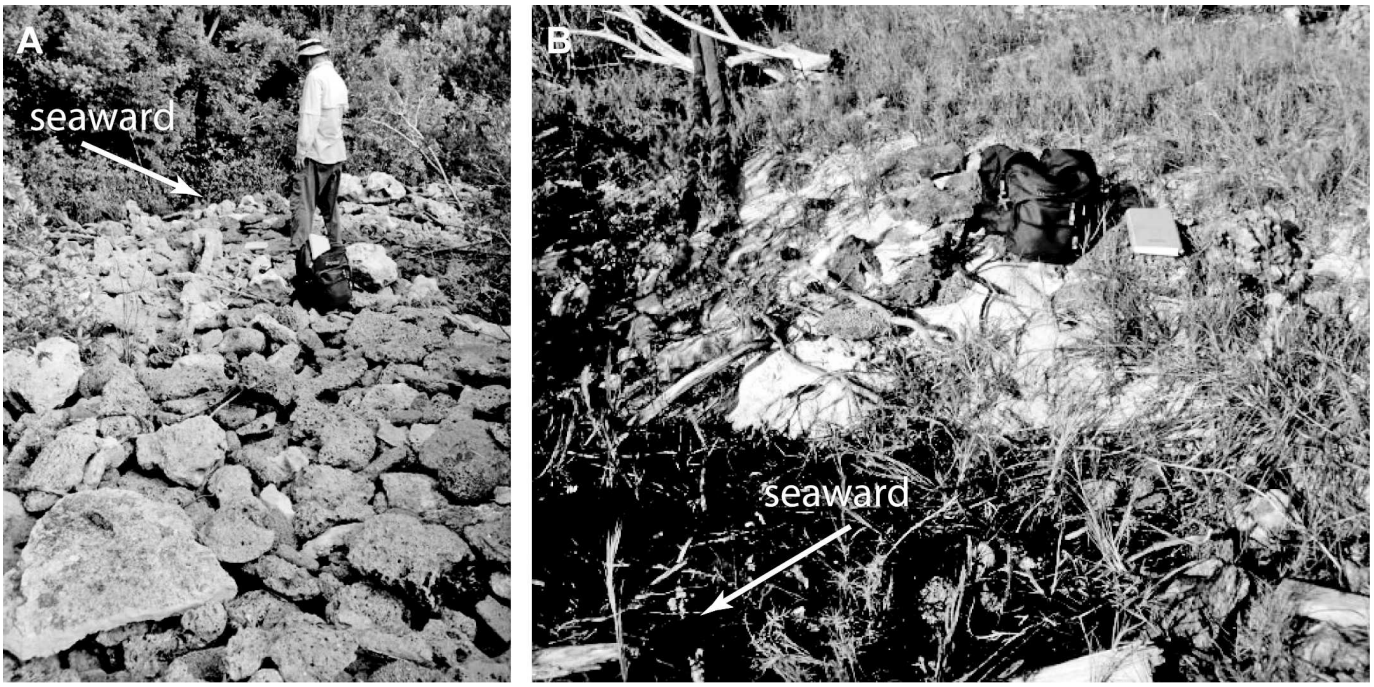

FIG. 5.—Reef-rubble ridge complex at Piedra de Carbinero on Isla de Mona, Puerto Rico, showing **A)** ridge-complex morphology and clast sizes approximately 30 m inland from the shore, and **B)** exposure of sand and gravel about mid-height of the ridge complex. Length of backpack is approximately 50 cm. Location is shown on Figure 3C.

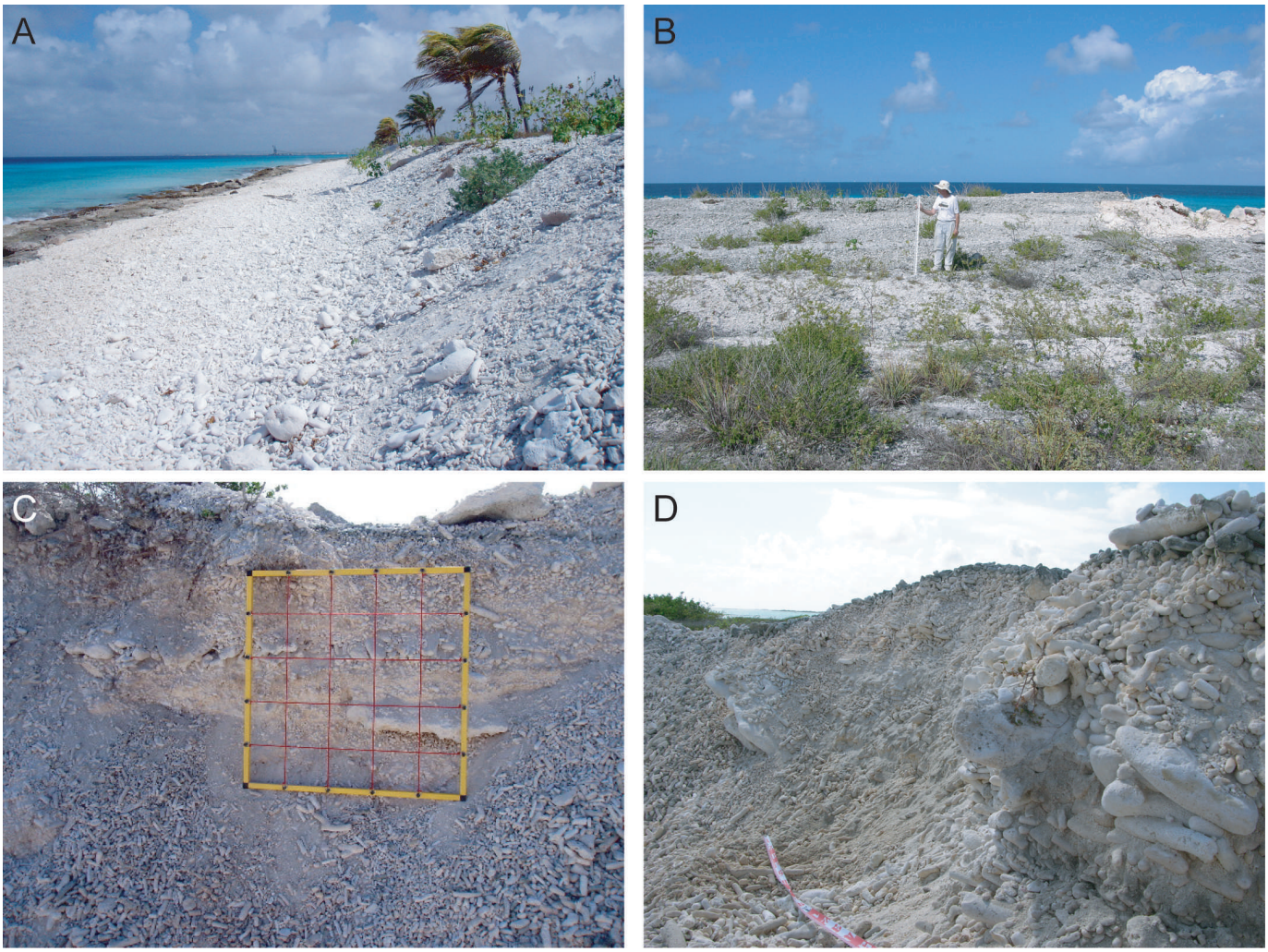

FIG. 6.—Representative views of a ridge complex near the shore and near sea level at Pink Beach, Bonaire, showing **A)** ridge-complex morphology (view is shore parallel), **B)** ridge-and-swale topography (view seaward), **C)** horizontal shore-parallel stratification, and **D)** seaward-dipping (to the right) shore-normal stratification. Grid shown in Part C is one meter square. Tape in Part D is 1.5 m long.

coarse-clast deposits as tsunamigenic (Jones and Hunter 1992; Scheffers 2002, 2004; Kelletat et al. 2004; Scheffers 2005; Scheffers et al. 2005; Robinson et al. 2006), they all acknowledge that either large tsunami or storm waves might have been responsible for the preserved boulder fields and polymodal ridge complexes.

Deposits Near Sea Level

Coarse-clast deposits of the Caribbean occur at different elevations relative to sea level as a result of island histories that were influenced by late Quaternary sea level fluctuations and tectonic processes. Where rock platforms and sea cliffs are absent and the seafloor is covered with sand, sand beaches and flat-crested or landward-sloping washover terraces characterize the shores. Beaches with well-developed sand dunes are also present where sand supply is abundant and the beach is relatively stable. Where washover terraces are predominant, terrace crests generally are 2 m or less above sea level (asl). At Point Allegre, Guadeloupe (Fig. 3D), where the 1867 tsunami flooded the coast, overwash sand is being transported across the beach and deposited into an adjacent pond that occupies a topographic low formed by upland drainage. On flanks of the uplands at elevations above the terrace are isolated fine boulders scattered across the surface. The relatively small size of the boulders, their low elevation, and their proximity to the shore make them likely candidates for storm-wave emplacement. Scheffers et al. (2005) also concluded that similar features were storm deposits and that there was no geological evidence of impacts from Holocene or historical tsunamis on Basse-Terre.

Where the coastal deposits contain more pebbles to fine boulders, they form either ridges or ridge complexes consisting of subangular to rounded reef rubble with an open framework at the surface (Figs. 4, 5A). The ridge complexes, which are commonly separated from the sea by a narrow, barren zone of beachrock (Fig. 6A), are a few tens of meters wide (Table 1) and have relatively steep seaward slopes that rise to intersect the flat or slightly rounded crests. The largest clasts are concentrated on the seaward sides and crests of the ridge complexes by wave reworking and removal of finer material. The platy shaped clasts commonly are imbricated and dip seaward. Most ridge complexes near the shore and sea level are 1.5 to 3 m thick and their crest elevations are 2 to 3.5 m asl (Table 1). Landward terminations of several of the ridge complexes are steep avalanche slopes or fan-like lobes projecting landward (Fig. 7). Mining exposures show the polymodal clasts are sorted into beds that

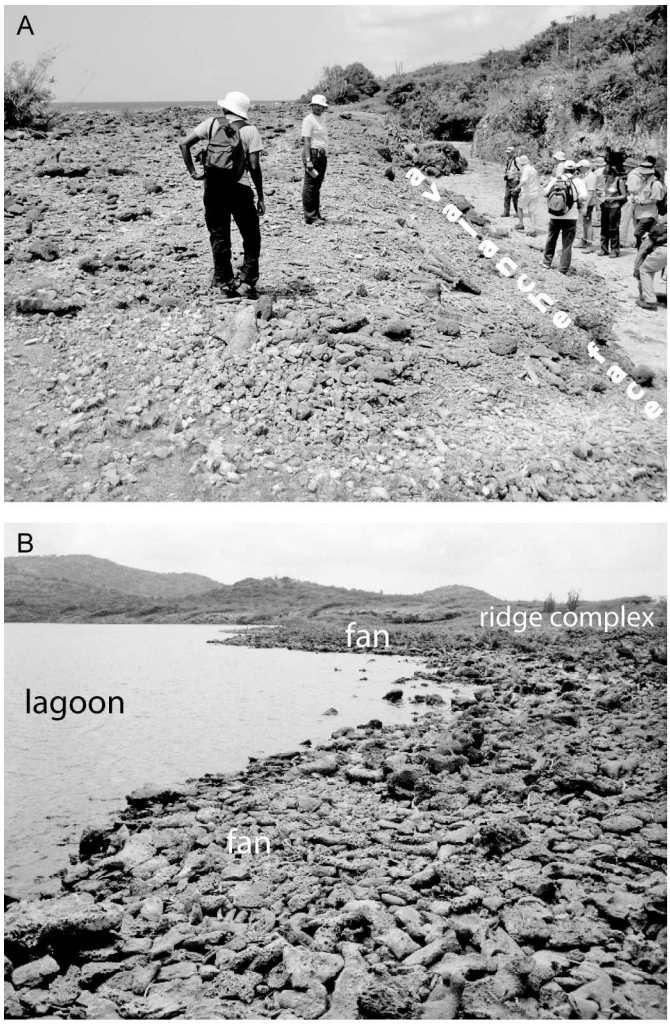

FIG. 7.—Examples of **A)** terminal avalanche face at Salina Tern, Bonaire, and **B)** terminal fans at Boka Bartol, Bonaire. Locations are shown on Figure 3A.

exhibit upward-fining and upward-coarsening textural trends, horizontal stratification in shore-parallel exposures, and seaward-dipping clasts and stratification in shore-normal exposures (Fig. 6C, D).

Deposits on Elevated Platforms

Sea cliffs and rock platforms are present throughout the Caribbean islands where fringing limestone outcrops are exposed to high-energy waves. The platforms and adjacent coral reefs are sediment sources for the elevated platform deposits. Wave-cut notches near sea level promote active cliff-face retreat that together with joint-controlled fractures make the cliffs unstable. Undermining beneath the notches causes boulders and blocks to fall into the sea or allows surging waves to quarry large clasts more easily by increasing the surface area exposed to uplift and air compression (Noormets et al. 2002).

At the elevated-platform sites, reef- and platform-derived rubble forms broad, wedge-shaped ridge complexes composed of polymodal sediments (Figs. 8–10). The ridge complexes are tens of meters wide and a few meters thick, and their crest heights range from 3 to 8 m asl (Table 2). A barren zone 20 to 130 m wide (Table 2) separates the ridge complex from the sea-cliff shoreline. The exposed platform is greatly to slightly karstified, and loose sediments are absent (Fig. 8), having been swept away by repeated storm-wave inundation (Scheffers 2005; Robinson et al. 2006). The coarsest clasts, including coarse boulders, typically are concentrated at the toes and on the seaward slopes of the ridge complexes (Fig. 8A), giving them asymmetrical shapes with steep seaward slopes and gentler landward slopes.

Mining exposures show that internally the clast-supported framework of cobbles and boulders is filled with sand (Fig. 9) that at the surface is unweathered. This indicates that the polymodal accumulation may be the result of framework deposition by extreme waves and subsequent framework infiltration of sand delivered by less powerful waves. The sediments are internally organized with crude stratification, vertical textural sorting, and bounding surfaces. Shore-normal exposures reveal internally imbricated clasts and seaward-dipping beds that exhibit upward-coarsening and upward-fining textural trends. The dip of the beds is similar to the slope of the ridge face exposed to waves (Fig. 9A). At Galina Point, Jamaica, the ridge complex is composed of polymodal sand and matrix-supported angular to slightly rounded cobbles (Fig. 10).

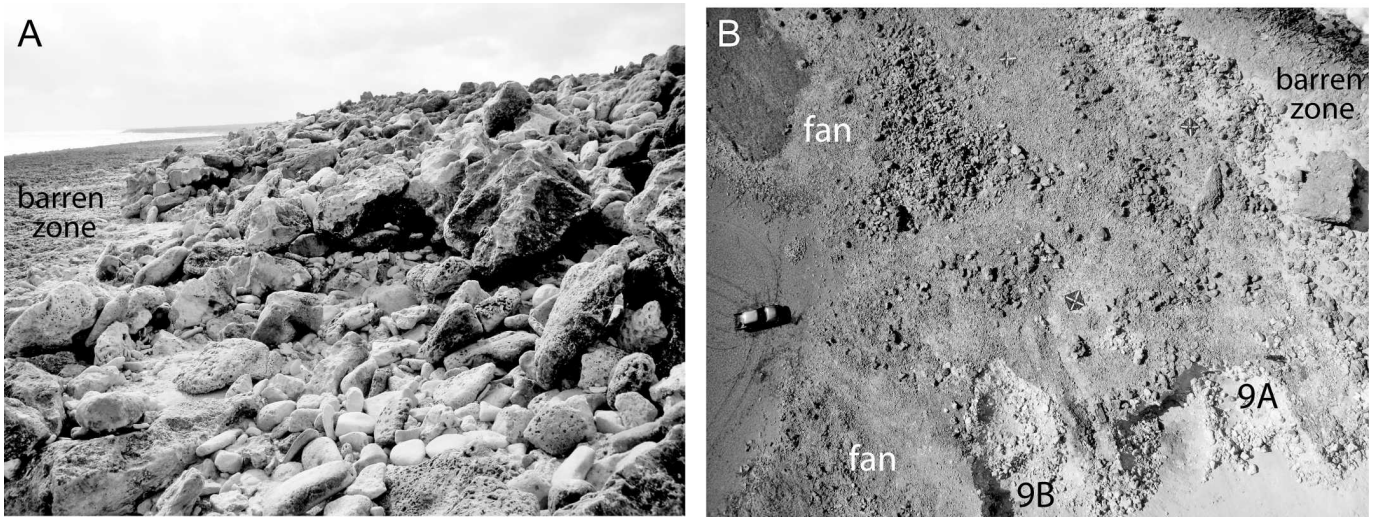

FIG. 8.—Ridge complex on wave-swept elevated platform at Boka Onima, Bonaire, showing **A)** a ground view of large clasts concentrated on seaward face and **B)** a vertical aerial view of the mining pits, locations of Figures 9A and 9B, and terminal fans on the landward side. Diagonal length of the black target with X near the center of Part B is 1.5 m.

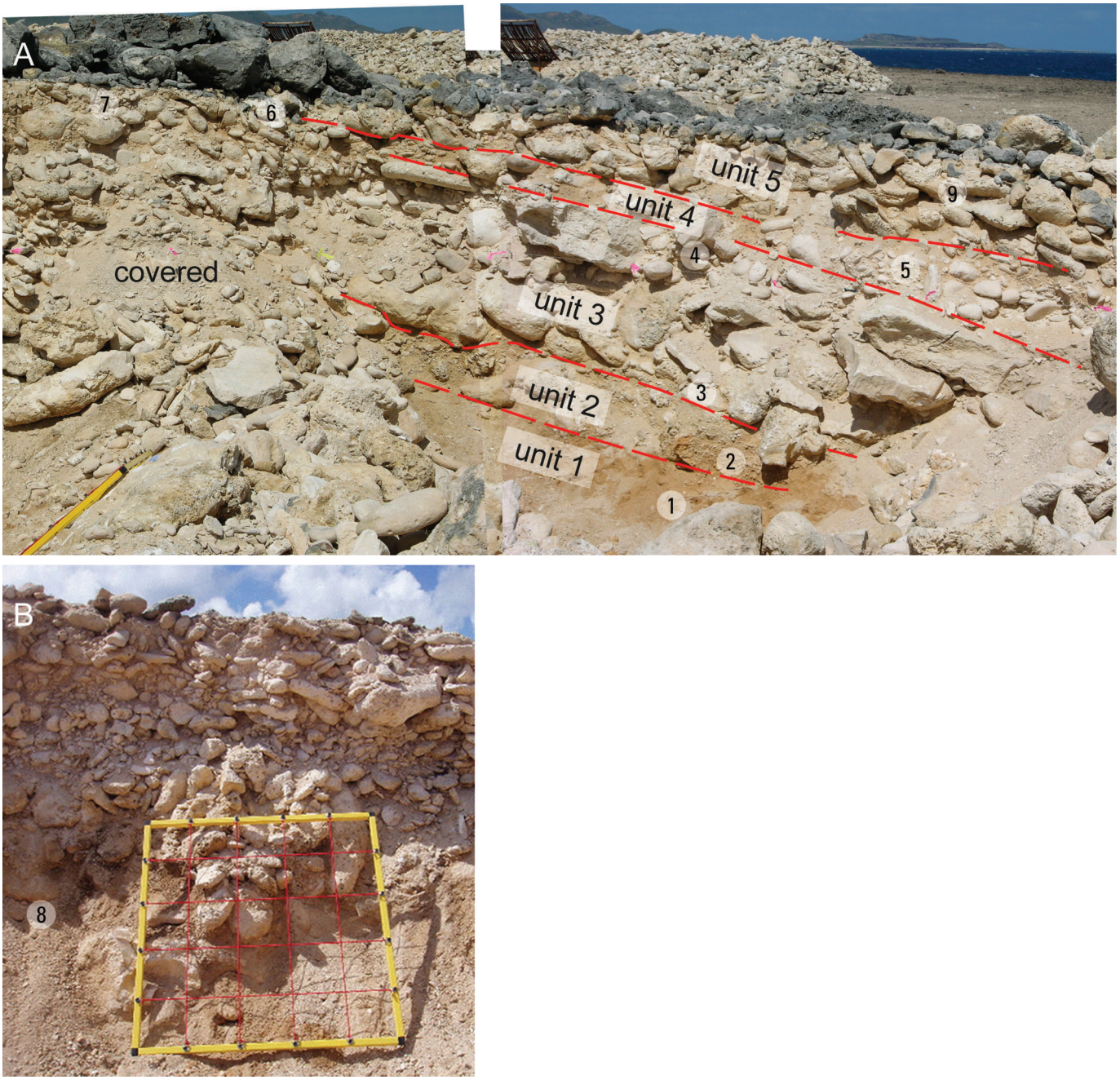

FIG. 9.—Mining exposures at Boka Onima, Bonaire, showing textural sorting, stratigraphic units, and radiocarbon sample locations (circled numbers) in **A)** seaward-dipping (to the right) shore-normal stratification, and **B)** horizontal shore-parallel stratification. Grid shown in part B is one meter square. Locations are shown in Figure 3A and Figure 8B.

Although the cobbles are only moderately sorted into layers, the largest platy clasts dip seaward. At Discovery Bay, West End, and Homers Cove, Jamaica, scattered exposures indicate that the ridge-complex cores are composed predominantly of sand with some gravel, and the surfaces are armored with boulders.

At Boka Onima, Bonaire, the ridge complex tapers landward, and terminates in fans (Fig. 8B), some with avalanche slopes. Near its seaward edge, the ridge complex consists of 4 or 5 stratigraphic units (Fig. 9A). Unit 1 consists of brown sand and pebbles that are partly iron stained and together form a paleosol. Unit 2 is an upward-coarsening deposit of sand and cobbles. Equant to platy, angular to subrounded clasts of overlying Unit 3 are substantially larger and imbricated and tend to coarsen upward. The largest clasts in Unit 3 are fine boulders. An abrupt change in clast size separates Unit 3 from Unit 4, which is composed of upward-coarsening sand and cobbles. Unit 4 pinches out in an onshore direction. Unit 5 is a clast-supported framework of cobbles and boulders filled with sand and pebbles. Texturally it is much coarser than Unit 4. Unit 5 also forms the ridge surface. Some of the largest clasts in the deposit at Boka Onima are isolated boulders resting on the ridge-complex crest, which is 6.5–8 m asl.

On the embayed east coast of Anse Ste. Marguerite, Guadeloupe (Fig. 3D) is an elevated shore-parallel terrace (Fig. 11) with

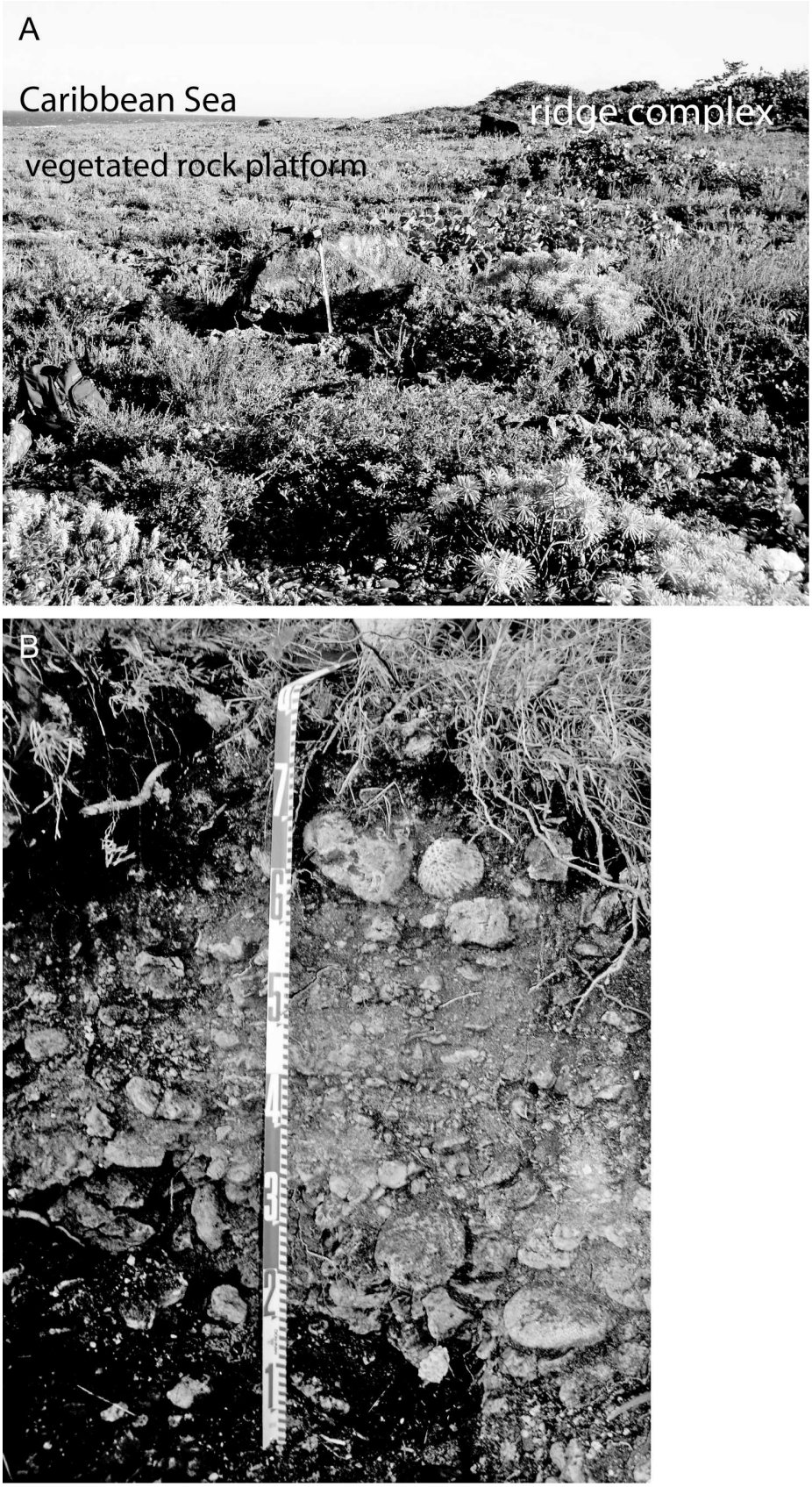

FIG. 10.—**A)** Ridge complex on vegetated elevated platform and **B)** associated textural sorting, crude stratification, and seaward-dipping (toward the viewer) clasts at Galina Point, Jamaica. Location is shown on Figure 3B.

TABLE 1.—*Characteristics and typical dimensions of some Caribbean coarse-clast deposits near sea level. Locations are shown in Fig. 3. R = ridge, RC = ridge complex, T = terrace, Y = yes, N = no, U = unknown because feature interior was not exposed.*

Location	Deposit type	Deposit width (m)	Deposit thickness (m)	Crest height above sea level (m)	Composition	Stratified	Imbricated
Boka Slagbaai, Bonaire	R	5–8	2.5	2	mostly cobbles with some fine boulders	U	Y
Boka Bartol, Bonaire	RC	60–70	3	3	cobbles and fine boulders	U	Y
Goto Meer, Bonaire	RC	30–60	3	3.5	mostly pebbles to cobbles with some sand and fine boulders	Y	Y
Salina Tern, Bonaire	RC	25–35	3	3	mostly pebbles to cobbles with some sand and fine boulders	U	Y
Pink Beach, Bonaire	RC	30–70	3	3	mostly pebbles to cobbles with some sand and fine boulders	Y	Y
Willemstoren Lighthouse, Bonaire	RC	60–80	1.5	2	mostly sand and cobbles with some fine boulders	Y	Y
Isla de Mona, Puerto Rico	RC	30–40	2+	2	mostly sand and cobbles with some fine boulders	U	Y
Point Allegre, Guadeloupe	T	40–50	1.5+	1.5	mostly sand with some cobbles and fine boulders	U	N

boulders scattered across the upper surface. Mining pits in the terrace show that the deposits are composed mainly of coarse sand with some shell and scattered cobbles to fine boulders (20–60 cm). Roots are abundant within the deposit, which may explain the apparent lack of stratification (Table 2). A low scarp separates the shrub- and tree-covered elevated terrace from a lower, presumably younger, shore-parallel surface of sand and cobbles that is covered by dense vines and grass (Fig. 11). Together the terrace deposits thin seaward and pinch out at the wave-washed barren zone of the rock platform.

ORIGINS OF COARSE-CLAST RIDGE COMPLEXES

Extreme waves capable of causing substantial coastal erosion and sediment transport are common in the Caribbean Sea. What remain unclear are the signatures of storm and tsunami deposits composed of polymodal sediments including sand and boulders. The following discussion presents criteria that were used to interpret origins of the coarse-clast ridge complexes in the Caribbean.

Historical Evidence

Evidence of historical inundation of coarse-clast deposits in the Caribbean includes eyewitness reports, deposition of anthropogenic material, and damage to man-made structures. For example, the ridge near sea level north of Boka Slagbaai, Bonaire (Fig. 4) was constructed by Hurricane Lenny in 1999 and later modified by Hurricane Ivan in 2004 (Scheffers and Scheffers 2006). Comparison of our 2006 photographs with the post-Ivan photograph of Scheffers (2005) shows subsequent ridge aggradation by small, non-hurricane waves that break, run up on the ridge, and deposit fine boulders.

In Jamaica, boulder-size concrete was deposited on the ridge complexes at Galina Point and West End, and at Homers Cove, boulder deposits of a ridge complex covered a road and sidewalk. Young trees bent and broken by fine boulders on the ridge-complex crest at Discovery Bay also indicate recent deposition. These artifacts of destroyed buildings and bioindicators of boulder transport are consistent with eyewitness reports of reef-rubble deposition on the rock platforms of northern and western Jamaica during hurricanes Allen (1980) and Ivan (2004), respectively (Robinson et al. 2006).

Ridge-complex erosion and deposition on Isla de Mona by Hurricane Georges, which crossed the island in 1998, is consistent with field evidence showing that fine boulders damaged a wire fence that in 2006 was less than 20 years old according to local property managers. Grass and vine vegetation on the lower surface at Anse Ste. Marguerite, Guadeloupe, also indicates relatively recent inundation, perhaps as a result of Hurricane Hugo, which came ashore there in 1989. Hugo's storm surge, estimated to be 3 m (Imbert et al. 1996), and runup from superimposed storm waves would have inundated the elevated terrace at Anse Ste. Marguerite (Fig. 11).

Coastal flooding from an oceanic storm includes a storm-surge component and a wave-runup component. The wave-runup component can be substantially higher than the storm-surge component if wave energy is not dissipated before coming ashore (Jaffe and Richmond 1992). The Caribbean islands are particularly vulnerable to coastal flooding by runup of extreme waves because their continental shelves are narrow and deep water allows high waves to come close to shore before breaking.

TABLE 2.—*Characteristics and typical dimensions of some Caribbean coarse-clast deposits on elevated platforms. Locations are shown in Fig. 3. RC = ridge complex, T = terrace, Y = yes, N = no, U = unknown because feature interior was not exposed.*

Location	Deposit type	Width of barren zone (m)	Deposit width (m)	Deposit thickness (m)	Crest height above sea level (m)	Composition	Stratified	Imbricated
Boka Onima, Bonaire	RC	30–35	40–80	3.5–4	6.5–8	mostly sand to fine boulders with some coarse boulders	Y	Y
Boka Washikemba, Bonaire	RC	20–50	100–150	3–3.5	5–5.5	mostly sand to fine boulders with some coarse boulders	Y	Y
Galina Point, Jamaica	RC	100–130	60–70	1.5–2	5.5–6	mostly sand to cobbles with some fine to coarse boulders	Y	Y
Discovery Bay, Jamaica	RC	30–40	40–50	3–3.5	3.5–4.5	mostly sand to cobbles with some fine to coarse boulders	Y	Y
West End, Jamaica	RC	10–40	30–50	2–2.5	3–3.5	mostly sand to cobbles with some fine to coarse boulders	Y	Y
Homers Cove, Jamaica	RC	10–30	30–35	2.5–3	4–4.5	mostly sand to cobbles with some fine to coarse boulders	Y	Y
Anse Marguerite, Guadeloupe	T	3–10	30–50	1.5+	2–3	mostly sand with some cobbles and fine boulders	N	N

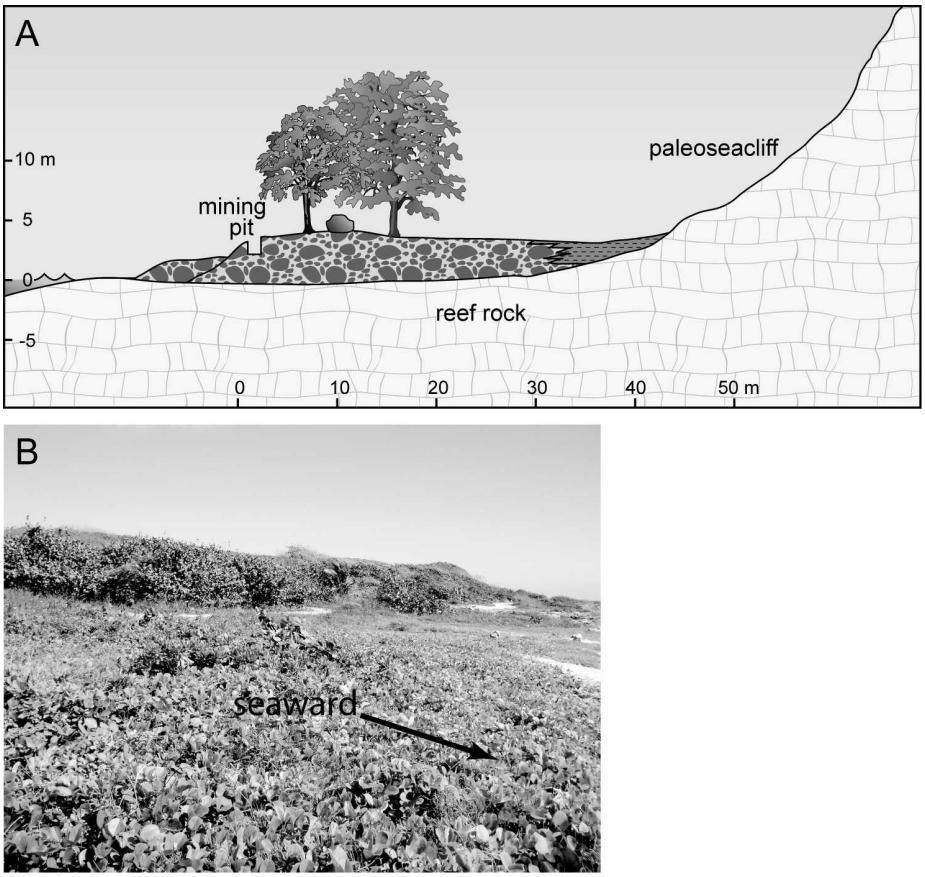

FIG. 11.—**A)** Schematic drawing and **B)** oblique alongshore view of elevated terrace at Anse Ste. Marguerite, Guadeloupe. Storm surge and waves from Hurricane Hugo in 1989 would have inundated the terrace. Location is shown on Figure 3D.

In 2004, Hurricane Ivan reached Category 5 intensities three times and set records for measured wave heights when it was a Category 4 storm (Wang et al. 2005). While Ivan impacted coasts throughout the Caribbean Sea extending from Bonaire to Cuba and along the north-central Gulf Coast of the United States, it produced maximum storm surges that ranged from 3 to 4.6 m (Franklin et al. 2006), significant wave heights that ranged from 16.1 to 17.9 m, and a maximum measured wave height of 27.7 m (Wang et al. 2005). Ivan's storm surge and wave runup inundated rock platforms and ridge complexes on Jamaica (Robinson et al. 2006) and its storm surge and superimposed waves clearly would have flooded ridge complexes on elevated platforms on Bonaire if the storm's track had been close to the island. Therefore, the historical evidence indicates that hurricanes with extreme waves that passed close to the Caribbean islands during the past 6000 years are reasonable explanations for construction of the coarse-clast ridge-complex deposits.

Deposit Textures

Clast imbrication and polymodal textures are common attributes of the ridge-complex deposits, so it is instructive to examine the origins of these characteristics and their applicability for distinguishing tsunami and storm deposits. The ability of storm waves to produce clast imbrication is well documented for particles up to cobble size. Bluck (1967) found that clast imbrication is a result of frequent wave swash and backwash and that it is best developed where the imbricated clasts form a zone near the upper limit of wave runup. After initial deposition and surficial clast imbrication, reworking by ocean swell or storm waves produces additional imbrication and tighter clast fitting (Shelley 1968). The resulting three-dimensional interpenetration and interlocking of clasts eventually provide framework stability that is more resistant to further reworking and helps preserve the older deposits and their associated fabrics (Bishop and Hughes 1989).

Our field observations in Bonaire, Puerto Rico, and Jamaica and those of Scheffers and Scheffers (2006) and Robinson et al. (2006) confirm boulder imbrication by historical storms. The few reports of boulder transport by historical tsunamis (Goff et al. 2006; Goto et al. 2007) do not mention clast imbrication. However, the lack of historical documentation does not necessarily rule out the possibility. Clast imbrication is a record of sediment accumulation influenced by antecedent topography where a pre-existing feature (beach or ridge complex) or particle (boulder) influenced the flow and impeded clast transport farther inland. For coastal deposits, imbrication of coarse clasts is clear evidence of wave deposition and reworking, but it does not appear to be a useful criterion for distinguishing tsunamis from storm waves.

At many beaches around the world, including the Caribbean region, bimodal and polymodal mixtures ranging in size from sand to boulders accumulate above the high tide line as a result of storm waves (Newell 1954; Bluck 1967, 1999; Kirk 1980; Woodroffe 1994; FitzGerald et al. 1994; Neal et al. 2003). However, Bryant et al. (1992) postulated that bimodal sediments were evidence of tsunami deposition. Since then, others have used mixtures of sand and gravel as evidence of tsunami processes (Kelletat et al. 2004; Scheffers et al. 2005; Scheffers 2005).

Polymodal coastal deposits are a function of available clast sizes and the history of transport and deposition of individual clasts. They are not diagnostic of a particular wave process, although clast textures (size, shape, and roundness) and internal organization (packing, sorting, and stratification) may provide important clues to their origins (Carr et al. 1970; Williams and Caldwell 1988). Furthermore, interstitial particles within gravel beaches tend to be smaller than those at the surface because

smaller particles infill the larger subjacent clasts that form the framework (Bluck 1967). Considering the number of modern beaches where bimodal and polymodal mixtures of sand and gravel are forming in the absence of tsunamis, it is clear that bimodal and polymodal textures are indicators of sediment sources and not a particular type of wave process.

Sorting and Stratification

Some ridge-complex deposits in Bonaire and Jamaica have been described as chaotic (Scheffers 2005; Scheffers et al. 2005; Kelletat et al. 2007) or unsorted (Robinson et al. 2006), implying that they have no internal organization and therefore lack textural gradients and stratification. However, mining exposures within those features show clear evidence of clast sorting and stratification (Figs. 6, 9). Similar internal organization and vertical textural trends are exhibited in a ridge complex on the Grand Caymans (Rigby and Roberts 1976).

The ridge-complex deposits also exhibit bedding-plane surfaces that separate sedimentary units that have distinctly different clast sizes and fabrics (Figs. 6, 8). The bounding surfaces separating the lithostratigraphic units are disconformities resulting from distinctly different depositional episodes. They also may represent substantial hiatuses in sedimentation (see section on Deposit Ages).

Deposit Morphology

There are no known reports of historical tsunamis depositing a laterally extensive, high ridge of coarse clasts near and parallel to the shore like the ridge complexes observed around the Caribbean islands. In fact, where the 2004 Indian Ocean tsunami encountered rubble-mound breakwaters on the west coast of Sri Lanka, it distributed cobbles and small boulders as debris fields of individual clasts without local concentrations (Morton et al. 2007b). The 2004 tsunami also constructed a field of reef-derived boulders across an intertidal flat in Thailand (Goto et al. 2007), but no ridge was constructed. Apparently the only ridge-like deposits were in densely vegetated backbeach areas where the tsunami-transported debris encountered pre-existing topographic highs with trees and prior accumulations of coarse clasts. Boulders entrained and deposited by the 1975 tsunami on the Big Island, Hawaii also were dispersed across a rock platform rather than being concentrated in a ridge (Goff et al. 2006). In contrast, storm waves commonly construct shore-parallel ridges and ridge complexes of coarse clasts (Umbgrove 1947; Cloud 1952; Newell 1954; McKee 1959; Maragos et al. 1973; Baines et al. 1974; Bayliss-Smith 1988; McLean and Hosking 1991; Scoffin 1993; McLean and Woodroffe 1994; Scheffers 2005). The coarse-clast ridges deposited by Tropical Cyclone Ophelia (McKee 1959), Tropical Cyclone Bebe (Baines et al. 1974), and Hurricane Lenny (Scheffers 2005) represent deposit morphologies of a single storm on a reef flat that had no antecedent topography (prior beach or ridge) to influence ridge construction.

The sand-and-gravel ridge complexes of the Caribbean exhibit morphological and sedimentological attributes that are consistent with storm-wave deposition. For example, the deposit surface at the Bonaire Pink Beach site exhibits low-amplitude ridge-and-swale topography (Fig. 6B). The ridge-complex surface increases in elevation seaward toward the deposit crest. These morphological features are evidence of lateral accretion and vertical aggradation, common depositional products of multiple wave events. A positive feedback cycle would have facilitated progradation and aggradation of the ridge complexes as wave-transported clasts were deposited at their bases or on their seaward faces because the antecedent topography prevented clast transport farther landward. It is unclear how long, straight-crested, wedge-shaped features with ridge-and-swale topography could be bedforms produced simultaneously by unidirectional flow during tsunami inundation.

Other diagnostic morphological features of storm-wave deposits are the steep avalanche slopes and terminal fans (Figs. 7, 8B) on their landward sides (McKee 1959; Baines and McLean 1976; Scoffin 1993; FitzGerald et al. 1994; Orford et al. 2002). An avalanche slope is constructed by bedload transport of clasts during overwash across the ridge and flow separation into shallow water landward of the ridge. The terminal fans are products of constructive wave interference that causes greater inland transport of sediments at some sites compared to others alongshore. Pre-mining aerial photographs of southwestern Bonaire show landward margins of the ridge complexes molded into bedforms that in planform were asymmetrical to the north. The asymmetry is consistent with shallow-water reworking by strong currents driven by hurricane-force winds at the time of backridge deposition (Morton 1979). These back-ridge morphological features are not consistent with ridge overtopping by a tsunami.

Finally, the geometries and dimensions of the coarse-clast deposits and total volumes of sediment stored in them are evidence of multiple wave events. The coarse-clast ridge complexes in the Caribbean region extend continuously inland tens of meters and they are several meters thick (Tables 1, 2). Although precise volumetric estimates of the deposits have not been made, the deposits seem to contain several hundred cubic meters per meter of beach. The total volume of ridge-complex debris coupled with the large size of some clasts likely exceeds the capacity of a few waves to entrain and transport that volume of sediment.

Deposit Ages

The ages of coarse-clast deposits can provide important clues regarding their origins and whether they are products of a few or many events. However, dating the specific constructional events can be problematic because there can be substantial elapsed time between the death of skeletal material and incorporation into the deposit. Woodroffe et al. (2007) compared radiocarbon ages of coarse-clast deposits in Australia and found that bulk ages provided an incomplete record that indicated discrete phases of deposition, whereas ages of individual grains provided better temporal resolution that indicated nearly continuous deposition. They also found that coral samples yielded ages that were anomalously old compared to those of shells.

To determine the range and spatial pattern of ages within the ridge complex at Boka Onima, Bonaire, individual molluscs were collected for AMS radiocarbon analyses along a transect from shore-perpendicular and shore-parallel exposures (Figs. 8B, 9). The molluscs, which inhabited the rock platform, rocky intertidal shores, or subtidal reef flat, were deposited in the sand component of the ridge complex when the rock platform was flooded. All samples, except C1, C2, and C5, were shielded by overlying large clasts so that possible contamination by young terrestrial gastropods falling into the deposit was eliminated. The terrestrial gastropods in the deposits helped constrain the ages of the depositional events because these specimens were either on the ridge complex at the time of inundation or were swept up from the adjacent platform during the wave event. The component-specific analysis better constrains the time of sediment deposition with the time of the organism's death because the life cycles of the molluscs (years to decades) are much shorter than the life cycles of corals (centuries).

The reported radiometric ages and calibrated values (Table 3), which span approximately 6000 yr, are distributed in a pattern that is consistent with ridge-complex progradation and aggradation (Fig. 9). For example, the most landward and lowest samples (C8 and C1) yielded some of the oldest ages (4069 cal yr BP and 5014 cal yr BP), whereas the most seaward and highest samples (C9 and C7) yielded some of the youngest ages (716 cal yr BP and 174 cal yr BP). The two dates that are at the same lithostratigraphic contact between finer-underlying and coarser-overlying sediments (C3 and C8) are essentially identical (4100 and 4069 cal yr BP), providing evidence of internal consistency. However, chronostratigraphic reversals indicate some reworking of older sediments and incorporation

TABLE 3.—*AMS radiocarbon ages for individual mollusc specimens from a ridge complex at Boka Onima, Bonaire. Sample locations within the deposit are shown in Fig. 9. Terrestrial samples were calibrated with intcal04.14c (Reimer et al. 2004) and marine samples were calibrated with the marine04.14c database (Hughen et al. 2004) using a standard 400-year global marine reservoir correction because no local data were available.*

Sample code	Material	Ecozone	δ^{13}C, %	^{14}C age yr BP	Median Cal yr BP	Cal yr BP 2σ Age Ranges
BOm-C1	*Pecten sp.*	subtidal	2.02	4765 ± 30	5014	4882–5141
BOm-C2	*Cerion sp.*	terrestrial	2.00	5275 ± 30	6067	5985–6127
BOm-C3	coral	subtidal	−0.04	4065 ± 30	4100	3982–4212
BOm-C4	*Tectarius sp.*	intertidal	−1.16	5315 ± 30	5668	5587–5744
BOm-C5	*Tectarius sp.*	intertidal	0.88	3615 ± 30	3510	3419–3609
BOm-C6	*Bulimulus sp.*	terrestrial	−15.64	275 ± 30	359	288–426
BOm-C7	*Tectarius sp.*	intertidal	−1.98	535 ± 30	174	60–263
BOm-C8	*Fissurella sp.*	subtidal	2.34	4045 ± 30	4069	3956–4181
BOm-C9	*Bulimulus sp.?*	terrestrial	−15.37	805 ± 30	716	677–770

into younger deposits. For example, C4 (5668 cal yr BP) is an anomaly, considering its age and stratigraphic position.

Other coarse-clast features in the Caribbean region have yielded a broad range of Holocene and Modern dates (Schubert 1994; Scheffers 2002, 2005; Scheffers et al. 2005; Robinson et al. 2006), but insufficient site-specific information has been provided regarding the distribution of ages within the deposits that would allow interpretation of deposit evolution and the history of events. The spatial distribution and range of radiocarbon ages from Bonaire (Fig. 9, Table 3) provide strong evidence that the ridge complex was constructed by multiple aggradational and progradational extreme-wave events spanning several millennia. These processes, when combined with the morphological and sedimentological evidence, are consistent with deposition by storm waves or a combination of storm waves that constructed a ridge and perhaps a few tsunamis that later deposited clasts on the seaward side and crest of the storm-constructed ridge.

Elevated Deposits

Throughout the Caribbean, rubble-ridge complexes and massive blocks are stranded on rock platforms several meters above sea level and above the reach of normal waves. Details of late Quaternary sea-level fluctuations and vertical movement of land masses are not well known, and yet that history of relative sea-level changes is critical to understanding the origins of elevated coastal deposits. Some may be the result of platform flooding by extreme-wave events under present sea-level conditions. Although extreme storm waves are capable of moving blocks on the platforms (Scheffers and Scheffers 2006; Robinson et al. 2006), not all the elevated ridge complexes show evidence of recent sediment accumulation or reworking by storm waves. The perched coarse-clast deposits also may be the result of tectonic uplift. For example, long-term uplift was reported for the northern part of Bonaire (Alexander 1961), but the platform elevations of 5 to 6 m asl and young ages of the deposits would require rapid rates of uplift that may be unrealistic.

The elevated deposits may have formed primarily during a middle-to-late Holocene highstand in sea level. However, results of glacial isostatic adjustment (GIA) models indicate that the mid-Holocene highstand is not manifest in the Caribbean region because it is located on the margin of the Laurentide forebulge and there are no sea-level records from the region that show a higher-than-present Holocene sea level. The GIA model results favorably matched the postglacial sea-level curves from the Caribbean, including curves from Jamaica and Curacao (Milne et al. 2005). However, the Caribbean sea-level curves are based on subtidal elevations that preclude establishing a Holocene sea level higher than present. Evidence from areas bordering the Caribbean, such as the northern Gulf of Mexico (Morton et al. 2000) and the tropical western Atlantic Ocean (Bourrouilh-Le Jan 2007), indicate a mid-to-late Holocene highstand.

At Galina Point, Jamaica, and Boka Onima, Bonaire, a paleosol separates the ridge-complex deposits from the underlying rock platform. The preserved stratigraphic successions record a history of prolonged platform exposure and development of a soil, subsequent platform inundation and deposition of the ridge complex, and then platform and ridge-complex exposure and development of an extant soil profile (Galina Point) or weathering surface (Boka Onima). Most of the coarse-clast ridge complexes in the Caribbean are less than 5500 years old (Table 3; Schubert 1994; Scheffers 2002, 2005; Scheffers et al. 2005; Robinson et al. 2006). The ages and stratigraphies of the elevated platform deposits are consistent with a mid-Holocene highstand in sea level, but they are also consistent with general stabilization of sea level and development of extensive reefs that served as sediment sources for the ridge complexes constructed by storm waves.

CONCLUSIONS

Field and laboratory evidence indicates that the Caribbean ridge complexes were deposited primarily by storms. For example, tropical cyclones, such as Bebe, Ophelia, and Lenny, constructed well-defined ridges of coarse clasts on intertidal reef flats, whereas the 2004 Indian Ocean tsunami constructed a field of boulders in the same geological setting. Ridge complexes of the Caribbean are composite recorders of long-term coastal processes spanning centuries to millennia. They have morphologic, sedimentologic, and stratigraphic attributes that favor deposition by multiple high-frequency intense-wave events. Evidence of storm-wave deposition includes ridge-complex morphologies, lateral and vertical textural trends, internal stratification, and the extremely large volumes of accumulated sediments. Hayne and Chappell (2001) used some of the same physical criteria to establish storm origins of beach ridges and to estimate storm frequency on the north coast of Australia. Merging of individual storm-rubble ridges with older storm features are part of the long-term sedimentation that constructs aggradational and progradational depositional complexes on some reef islands (Cloud 1952; McKee 1959; Baines and McLean 1976). After reviewing a number of reports of hurricane impacts on reef islands, Bayliss-Smith (1988) concluded that storm waves were the only marine process capable of large-volume emplacement of rubble ridges and ridge complexes, and more-frequent, less-intense waves reworked the storm deposits into more stable features.

Coarse-clast coastal ridge complexes of the Caribbean region were first attributed to storms (Stoddart 1965; Rigby and Roberts 1976; Hernandez-Avila et al. 1977; Schubert and Valastro 1976 among others), and only recently have they been interpreted as tsunamigenic. The low frequency of hurricanes impacting Aruba, Bonaire, and Curacao and the relatively minor deposition by hurricanes Ivan and Lenny were used by Scheffers (2002) to exclude storms as an agent of coarse-clast ridge-complex deposition. Also the narrow shape and low elevations of the

ridge deposited in Bonaire by Hurricane Lenny (Fig. 4) were considered evidence that the broad coarse-clast ridge complexes were either entirely tsunami deposits or a tsunami deposit that was later modified by storm armoring (Scheffers 2002). Radiocarbon dates that supposedly cluster around 3500 BP, 1500 BP, and 400–500 BP were used as evidence of three individual tsunami events. However, the distribution of radiocarbon dates grouped by shoreline sector around Bonaire (Scheffers 2005) spans thousands of years, which is compelling evidence of long-term coastal deposition by many extreme-wave events.

Scheffers et al. (2005) and Scheffers and Kelletat (2006) concluded that since 4500 BP, 3 to 6 separate megatsunamis impacted the Caribbean islands and those individual tsunamis were responsible for constructing the coarse-clast coral-rubble ridge complexes and boulder fields throughout the Caribbean region. However, the tsunami distribution map of Lander et al. (2002) does not easily support this conclusion of regional impacts by individual tsunamis. Instead, the map shows that during the past 500 years only the 1755 and 1867 tsunamis were reported at multiple locations in the Caribbean and there is no evidence that they were responsible for massive movement and organization of coarse coral-reef rubble. The historical, locally generated tsunamis have had limited geological impacts, both in their areal extent and in their ability to cause significant changes in the landscape.

Large-volume, coarse-clast accumulations and sand blankets interpreted as paleo-tsunami deposits, such as those described by Scheffers (2002, 2005), Scheffers and Kelletat (2006), and Robinson et al. (2006) that are several meters thick, internally exhibit multiple layers with bounding surfaces, and are tens to hundreds of meters wide are not likely products of a single or a few tsunamis. Tsunamis may have contributed to an existing reef-rubble ridge complex by depositing clasts in front of or on top of a pre-existing ridge, such as the large clasts that armor many ridge complexes. However, it is not likely that any tsunami was primarily responsible for ridge-complex initiation and subsequent construction.

Coarse-clast coastal deposits in the Caribbean region form a continuum of features the heights and shapes of which are controlled by clast size and their positions relative to the shore and to sea level. They range from small, flat-crested washover terraces composed of well-sorted sand to large, wedge-shaped ridge complexes composed of gravel and sand. The timing and mechanisms of wave emplacement of some blocks and extensive boulder fields on elevated platforms of the Caribbean region still are uncertain and will require additional investigation and analysis before their origins can be determined.

One line of future investigation would be modeling of sediment transport by waves where the clast size is cobbles through blocks. Considering the common use of results of the Nott (1997, 2003) equations as evidence for tsunami emplacement of coarse boulders and blocks, there is a clear need for evaluating the basic assumptions of the equations and applications of the results. This could lead to improved equations that rely on alternative assumptions, such as the critical forces and modes of boulder transport. For example, Noormets et al. (2004) compared the dynamic pressures and transport characteristics of storm waves and tsunami waves and applied their results to the historical emplacement and movement of megaclasts in Hawaii. The equations of Lorang (2000) may also have aspects that would improve overall prediction of boulder transport considering wave height, wave period, runup elevations, and swash velocities.

Other important issues that will require additional research and modeling are the volumes of polymodal sediments that can be emplaced by a single extreme-wave event (storm or tsunami) and the most likely geometries of the deposits produced by those events. This would involve identifying the theoretical upper limits of clast size (competence) and volume of sediment (capacity) for historical tsunami and storm waves. Some aspects of this research may be beyond current capabilities because it would require determining how particle-to-particle interference of large clasts in the bottom-boundary layer would influence sediment entrainment, transport, and deposition.

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