Journal of Coastal Research	29	4	971–983	Coconut Creek, Florida	July 2013

Sedimentary History of Mangrove Cays in Turneffe Islands, Belize: Evidence for Sudden Environmental Reversals

Terrence A. McCloskey and Kam-biu Liu

Department of Oceanography and Coastal Sciences
School of the Coast and Environment
Louisiana State University
Baton Rouge, LA 70803, U.S.A.
tmcclo1@tigers.lsu.edu

ABSTRACT

McCloskey, T.A. and Liu, K.-B., 2013. Sedimentary history of mangrove cays in Turneffe Islands, Belize: evidence for sudden environmental reversals. *Journal of Coastal Research,* 29(4), 971–983. Coconut Creek (Florida), ISSN 0749-0208.

The Holocene history of the continental margin of Belize has frequently been interpreted as being very straightforward, controlled almost entirely by postglacial sea level rise. Depending upon location, the dominant depositional environment, whether coral or mangrove, is either able to keep up with the rising sea level and thereby maintain its integrity through the present, or becomes drowned. Here we present sedimentary evidence from four mangrove cays situated on Turneffe Islands that shows an unusual pattern wherein early mangrove development is replaced by carbonate sedimentation before reverting back to mangroves in the relatively recent past. The bracketed carbonate layers, up to >2 m thick and resembling lagoon-floor material, display both a rough temporal coincidence across sites and a distinctive geographic signature, thinning landward irrespective of relative elevation. The carbonate sections are often underlain by a mixed sediment layer characterized by a jumble of stratigraphically incoherent mangrove clumps intermingled with carbonates. The replacement of mangrove peat with bottom-style carbonate deposition suggests a lowering of island surface elevation. Seismic activity is identified as the most likely cause, although hurricanes cannot be excluded. In either case the elevational reduction is probably amplified by peat collapse associated with mangrove mortality. The occurrence of such activity and the resulting catastrophic ecological/geomorphic change indicate a need for incorporating these geological perturbations in risk assessment for Turneffe Islands.

ADDITIONAL INDEX WORDS: *Atlantic atolls, Turneffe Islands, Belize, mangroves, sea level rise, seismic activity, hurricanes, tsunamis.*

INTRODUCTION

The paleoenvironmental history of the continental margin of Belize is well known in the broad scale. Histories have been developed from sediment cores extracted from numerous mangrove cays both along and inside the barrier reef as well as the coral rims and lagoon floors of all three offshore carbonate platforms (Gischler, 1994, 2003; Gischler and Hudson, 1998, 2004; Gischler and Lomando, 2000; Gischler *et al.*, 2008; Halley *et al.*, 1977; Jones and Dill, 2002; Littler *et al.*, 1995; Macintyre, Littler, and Littler, 1995; Macintyre *et al.*, 2004; McKee and Faulkner, 2000; Monacci *et al.*, 2009; Wooller *et al.*, 2004, 2007, 2009). The inferred regional environmental history is straightforward, with both coral and mangrove cays falling into one of two categories. Where vertical accretion rates have kept up with sea level rise the cays have maintained their respective compositional character, whereas when sea level rise has surpassed accretion rates, islands have become permanently submerged, with the mangrove peat or coral formation being replaced by unconsolidated bottom deposition.

Here we present sedimentary evidence from six mangrove cays covering a 30 km transect that suggests that the environmental history has not been so uniformly simple for Turneffe Islands, but that dramatic biological and geomorphic perturbations have affected the atoll over the late Holocene, and attempt to identify the causes of these unusual stratigraphies.

ENVIRONMENTAL SETTING AND GEOLOGICAL HISTORY

The continental shelf of Belize consists of a shallow marine lagoon extending from the mainland to the barrier reef. The continental slope begins immediately east of the barrier reef, marked by rapidly increasing water depths, interrupted by three isolated carbonate platforms: Turneffe Islands, Lighthouse Reef, and Glovers Reef (Figure 1). These platforms are rare Atlantic atolls, accreted coral reefs that rise from deep water to the surface, forming coral rims surrounding central lagoons.

Turneffe Islands is located on a fault ridge, separated from the barrier reef to the west by water depths of >400 m, while

DOI: 10.2112/JCOASTRES-D-12-00156.1 received 17 August 2012; accepted in revision 1 November 2012; corrected proofs received 24 January 2013
Published Pre-print online 27 February 2013.

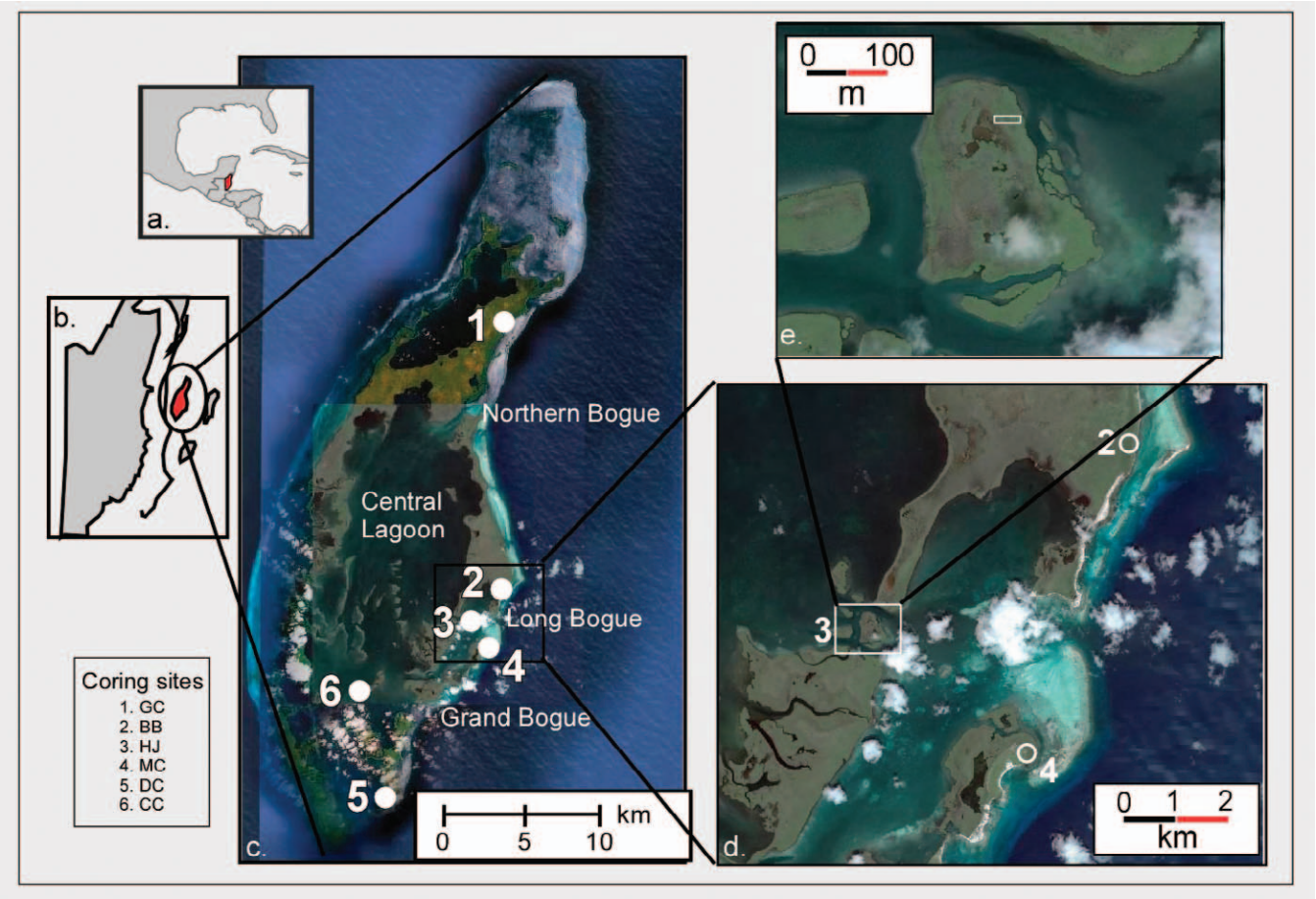

Figure 1. (c) Map of Turneffe Islands atoll, showing (a) geographical relation to the Caribbean, and (b) the Belize mainland. (d) The area around Long Bogue is shown in greater detail, displaying the locations of sites 2, 3, and 4. (e) The three-core transect for site 3 is marked by numbers: corresponding site designations are listed in the box on the left.

depths of >1000 m occur immediately to the east. The atoll is somewhat elliptical with the long axis running north–south. Maximum distances are ~50 km north to south and 16 km east to west (Figure 1). The eastern face of the atoll is a vertical wall hundreds of meters in height, topped by a wave-breaking rim of coral, broken by a small number of openings, the most important of which are, from north to south, Northern Bogue, Long Bogue, and Grand Bogue. Lying behind the rim is a reef flat generally <400 m wide covered by a few tens of centimeters of water. The center of the atoll is the Central Lagoon, dotted with mangrove cays that rise steeply from the lagoon floor. Circulation is restricted. Maximum lagoon depth is 8 m; the floor is densely covered by sea grass (*Thalassia*), the calcareous algae *Halimeda*, sponges (*Spheciospongia* species), and occasional coral, mainly *Porites* species and *Manicina areolata*. Seafloor sediments are dark, stained by the decaying organic matter washed off the mangrove cays and are dominated by *Halimeda* debris (Gischler, 2003; Gischler and Hudson, 1998). Mangroves, which dominate atoll vegetation, typically display zonation, with fringing red mangroves (*Rhizophora mangle*) at the lowest levels, and bands of first black (*Avicennia germinans*) and then white mangroves (*Laguncularia racemosa)* forming inland, and dwarf *Rhizophora* forests developing in areas of higher salinity (McKee, 1995; McKee and Faulkner, 2000; Murray *et al*., 2003). Sand is produced by the powdering of coral on the reef face and flats. Subaerial sand is most common on the eastern reef flat, either in piles as sandy cays along the inside coral rim or as beaches on the eastern edges of the facing mangrove islands. Beaches are commonly lacking on the interior mangrove islands, which generally rise steeply from the lagoon floor and consist of muddy peat right to the island edge. Carbonate production, mainly by *Halimeda*, dominates the lagoon-floor sediments (Gischler, 2003; Gischler and Hudson, 1998).

During the last glaciation the Belize shelf (the current shallow marine lagoon) and the three carbonate platforms were all subaerial (Gischler and Hudson, 1998, 2004). The platforms were dish-shaped limestone islands. The limestone shelf was connected to the mainland, cut by river channels, the topography controlled at depth by faults, and more superficial-

ly by the antecedent topography imposed by a series of Pleistocene reefs, themselves possibly sited on top of earlier topographic highs based on siliclastic river deposits (Choi and Ginsburg, 1982; Choi and Holmes, 1982; Dillon and Vedder, 1973; Ferro *et al*., 1999; Halley *et al*., 1977; Lara, 1993; Shinn *et al*., 1979). Glacial melting and eustatic sea level rise drove a rise in the water table leading to soil formation in most locations. As sea level continued to rise, both the shelf and the platforms flooded, leading to mangrove development in intertidal areas and vertical accretion by coral along the rims (Gischler, 2003; Gischler and Hudson, 1998, 2004). As the coral rims built up, interior water depth increased, drowning the mangroves in lower areas and where accretion was slow. These flooded areas formed the floor of either the shelf or atoll lagoons, depending on location. With the replacement of mangrove peat deposition by the slower accretion rate associated with carbonate production, the drowned areas fell farther below sea level. On the carbonate platforms accommodation space has increased since flooding, with lagoonal floor sedimentation lagging far behind the vertical accretion of the coral rim (Gischler, 2003; Gischler and Hudson, 1998, 2004). On the other hand, "keep-up" mangroves, often starting on antecedent highs (Halley *et al*., 1977), have kept pace with sea level, building ever thicker peat sequences (up to 10 m thick, Macintyre, Littler, and Littler, 1995; Wooller *et al*., 2009) that support the steep-sided mangrove cays that presently dot the shelf lagoon and atolls. This results from continuous near sea level mangrove production as the cays accrete upward, remaining within the upper tidal zone as the sea level rises (Ellison, 1993; Macintyre, Littler, and Littler, 1995; McKee and Faulkner, 2000; Woodroffe, 1981; Wooller *et al*., 2004, 2007, 2009). In most cases mangroves have dominated from their establishment through the present, although small changes in forest assemblage and canopy height have been recorded, probably driven by changes in hydrology (Wooller *et al*., 2004, 2007, 2009).

This regional environmental progression has led to two standard stratigraphic sequences:

Sequence 1. Limestone, brownish/greenish clay, mangrove peat ("keep-up" mangroves)
Sequence 2. Limestone, brownish/greenish clay, mangrove peat, carbonates ("drowned" mangroves)

Where mangroves have kept up with sea level (mangrove islands), peat deposition continues to the present (sequence 1); where they have not (subaqueous locations), an abbreviated peat layer becomes overlaid by carbonate-dominated sand and silt (sequence 2). These are the common sequences, well documented in the literature (Gischler, 1994, 2003; Gischler and Hudson, 1998, 2004; Gischler and Lomando, 2000; Gischler *et al*., 2008; Halley *et al*., 1977; Jones and Dill, 2002; Littler *et al*., 1995; Macintyre, Littler, and Littler, 1995; Macintyre *et al*., 2004; McKee and Faulkner, 2000; Monacci *et al*., 2009; Wooller *et al*., 2004, 2007, 2009).

Although two of the mangrove cays studied display the well-known sequence 1 pattern, four other cays display a distinctly different history in which mangrove peat occurs above the submerged carbonate phase of sequence 2. The only similar sequences recorded in the literature for Belize occur in cores from Twin Cays, inside the barrier reef (Macintyre *et al*., 2004). This peat–carbonate–peat sequence, suggesting rapid relative sea level rise, followed by gradual recovery, probably occurs twice in the Turneffe Islands cores. The candidate mechanisms responsible for driving such dramatic environmental perturbations are discussed in this paper, in order to assess the possibility that the risk of similar future occurrences needs to be considered in respect to the management and development of Turneffe Islands.

METHODS

In total 23 cores were extracted from six mangrove cays: four sites (GC, BB, MC, and DC) facing the reef flat along the eastern edge of the atoll, one (HJ) in the Long Bogue channel, and one (CC) in the Central Lagoon (Figure 1). With the exception of sites CC and DC where only one core was taken, multiple cores were retrieved from each site along a transect generally landward from the coast in order to trace the spatial variation of sediment layer thicknesses. The overall distance between the northernmost (GC) and southernmost (DC) sites (sites 1 and 5, respectively in Figure 1) is about 30 km.

Within each individual site the transect of cores extends up to 165 m inland (site BB). Apart from a 90-cm section of core GC1, which was obtained by a modified Livingstone piston corer, all sediment was extracted in 50-cm sections by a 2-inch diameter Russian peat borer. With the exception of 11 short cores from site BB, all cores were pushed until refusal, with a slight offset and a minimum overlap of 5 cm between sections. Locations were marked with a handheld GPS unit. Photos were taken and sketches made capturing all relevant biological and geomorphic features of the sites. Peat borer cores were photographed and described in the field. Cores were sealed in the field and transported to a cold room at Louisiana State University. When opened all cores were photographed, described, and subjected to loss on ignition (LOI) analysis at 1-cm intervals continuously, following the methodology described by Liu and Fearn (2000). A single core, HJ1, was selected for focused study and radiocarbon dating. Plant macrofossils were collected from HJ1 to provide materials for accelerator mass spectrometry (AMS) radiocarbon dating.

Three bulk sediment and two plant detrital samples were radiocarbon dated by the National Ocean Sciences AMS lab at Woods Hole Oceanographic Institutions and Beta Analytic in Miami. These dates were calibrated to calendar years using the Calib 6.0 program (Stuiver, Reimer, and Reimer, 2010), based on the datasets of Reimer *et al*. (2009). An age–depth model was created using a single calendar date for each sample by averaging the midpoints of all sigma date ranges, weighted by probability (McCloskey and Liu, 2013).

RESULTS

Here we present detailed data from HJ1, our main core, which fully captures the important sedimentological features of all the cores collected. Stratigraphic information from the other cores and sites is also presented to illustrate regional variations among different sites on the atoll.

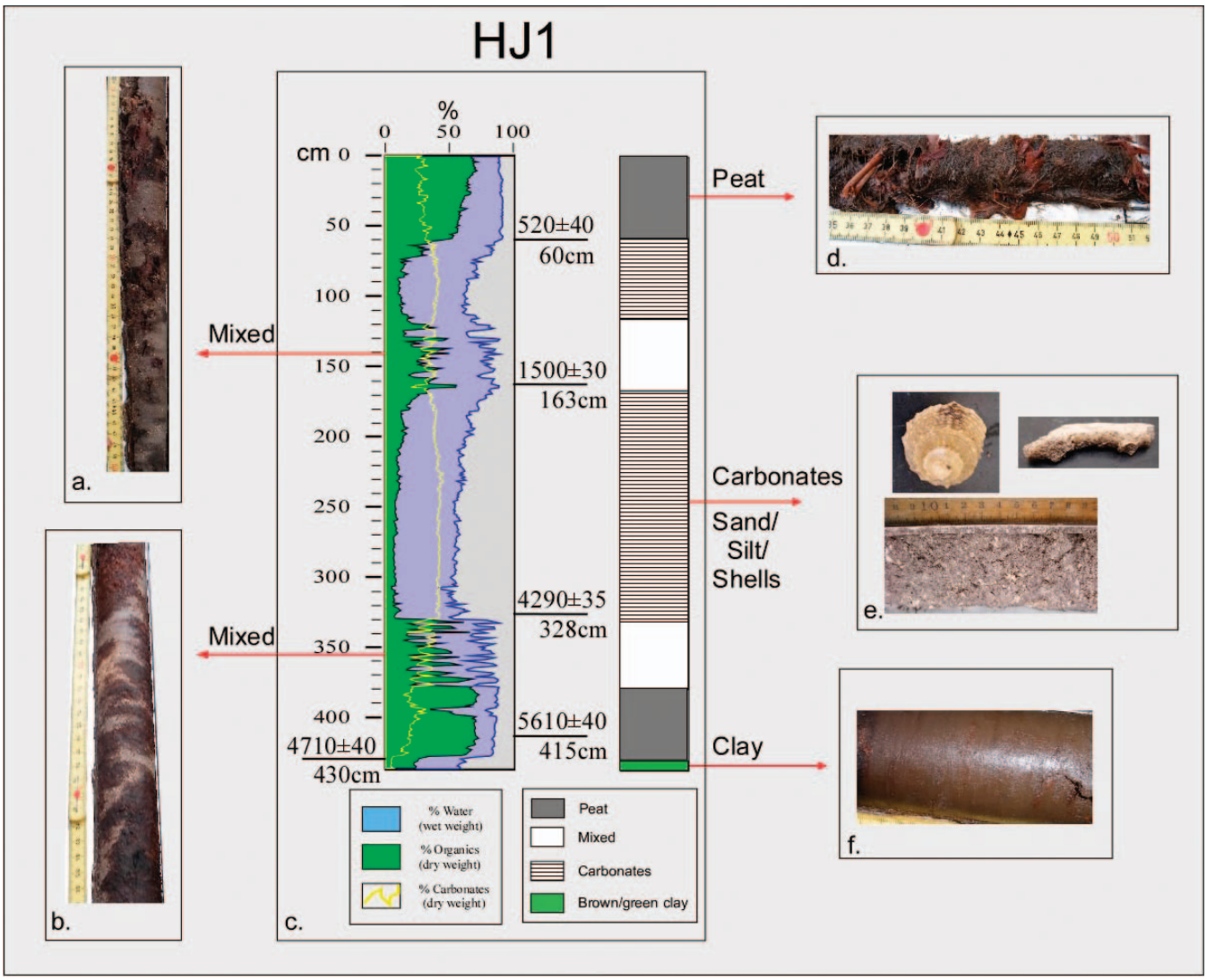

Figure 2. HJ1 sedimentological units. (c) The combined LOI curve, litholog, depth, and radiocarbon dates for five dated samples. Pictures and identifying LOI characteristics are presented for the four sedimentological units present in HJ1: (d) peat; (e) carbonates, consisting of shells/silt/sand; (a, b) mixed (a chaotic combination of the two previous units); and (f) basal clay.

HJ (Site 3 in Figure 1)

The HJ site is located on a small mangrove cay approximately 3 km west of the coral rim in Long Brogue (Figure 1). This cay rises steeply from the lagoon floor, with water depth reaching 4 m less than 10 m offshore zone. Cores HJ1 and HJ2 were located under thick, medium height (<5 m), monospecific *Rhizophora* forest at 1 and 29 m inland, respectively. Core HJ3 was extracted from a flooded dwarf *Rhizophora* zone at 69 m inland. The cores show a common pattern, with a thin basal clay overlain by a peat layer, then a thick carbonate layer (which may or may not be sandwiched between a chaotic mixture of interbedded peat and inorganic layers), followed by peat, which extends to the surface.

Core HJ1 consists of nine 50-cm peat borer sections that penetrated to a depth of 433 cm. The LOI curves and core litholog are presented in Figure 2. Four basic sedimentary units are encountered in this core, clearly distinguishable both visually and by characteristic LOI values (Figure 2c). These units are

(1) Peat (high water and organic and moderate carbonate values). This unit occurs from 1 to 59 and from 379 to 425 cm. An example from 35 to 52 cm is shown (Figure 2d).
(2) Carbonates (decreased water and organic and increased carbonate values). These layers are relatively unconsolidated, structureless mixtures of sand, silt, and shells. These sections occur from 60 to 114 and from 163 to 329 cm (Figure 2c). The interval from 208 to 220 is shown,

Table 1. *Radiocarbon results for core HJ1.*

Depth (cm)	Material	Lab	Sample No.	^{14}C Age	Error Bar	Calibrated YBP (2δ)	Probability (%)	Calibrated y AD/BC (2δ)
60	Plant/wood	Beta	234828	520	±40	503–562	0.780	1388–1447 AD
						595–634	0.220	1316–1355 AD
163	Plant/wood	WHOI	63006	1500	±30	1312–1417	0.934	533–638 AD
						1466–1490	0.045	460–484 AD
						1495–1508	0.021	442–455 AD
328	Plant/wood	WHOI	63028	4290	±35	4825–4893	0.868	2944–2876 BC
						4897–4960	0.132	3011–2948 BC
415	Bulk sed	Beta	234829	5610	±40	6305–6468	1.000	4519–4356 BC
430	Bulk sed	Beta	234830	4710	±40	5321–5420	0.487	3471–3372 BC
						5438–5487	0.222	3538–3489 BC
						5506–5582	0.291	3633–3557 BC

displaying characteristic shells and a coral fragment (Figure 2e).

(3) Mixed. This unit is marked by repeated transitions between the two previously described materials, marked by abrupt dips/spikes in the LOI values, with water and organic values rising/falling in parallel, inverse to the carbonate values. The two sediment types are not interbedded horizontally, and specific sediment types rarely occur across the width of the cores (Figures 2a and b). Rather, small, angular peat clasts are embedded in a carbonate matrix. Generally the mixing appears more extreme in the lower part of the intervals, with clast frequency and volume occupied decreasing rapidly up-core. Because this stratigraphy does not seem to represent a succession of quickly changing depositional environments but rather the simultaneous deposition of two dramatically different sediment types, these mixed layers are treated as a single zone, reflecting a particular deposition style. This unit occurs from 115 to 162 and from 330 to 378 cm (Figure 2c).

(4) Clay (low organic and carbonate percentages, intermediate water). A brown/green clay occurs below 425 cm. The interval from 425 to 432 is shown (Figures 2c and f).

The AMS ^{14}C dating results obtained from the three plant/organic and two bulk sediment samples are listed in Table 1 and shown graphically in Figure 2.

The age/depth model (Figure 3), based on the calibrated (cal) calendar dates, shows slower sedimentation during the carbonate deposition, as expected. Although the upper three dates are in stratigraphic order, there is an age reversal between the two samples from the basal clay, with the sample at 430 cm producing a date 900 ^{14}C years younger than that for the sample at 415 cm. The question as to which of the two bottom dates is correct is problematic, but not of great significance. Using the older date (5610 ± 40 ^{14}C years before present [YBP] at 415 cm) and eliminating the younger date (4710 ± 40 ^{14}C YBP at 430 cm) results in a calculated basal date of ~6700 cal YBP, whereas using the younger date and eliminating the older results in a calculated basal date of ~5500 cal YBP. We have decided to reject the younger date (circle, Figure 3), since this results in both a more constant sedimentation rate and an age more consistent with previously dated basal material from Turneffe Islands (Gischler, 2003; Gischler and Lomando, 2000).

Some combination of the four sedimentary units described for HJ1 can be used to describe all the cored material recovered across the atoll. Cores HJ2 and HJ3 are very similar to HJ1 (Figure 4), except that HJ2 does not reach the basal clay and HJ3 lacks the mixed sediment layers. A consistent spatial pattern is displayed with the carbonate and mixed intervals thinning in a landward direction.

GC (Site 1 in Figure 1)

The GC site is situated on the eastern edge of a large mangrove cay in the northern part of Turneffe Islands (Figure 1). A group of small sand cays lies directly to the east, up

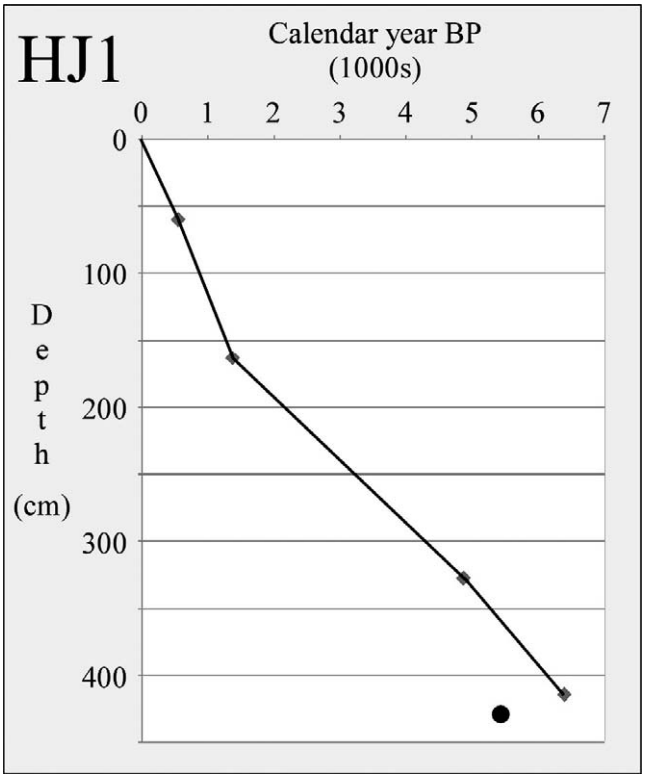

Figure 3. HJ1 depth–age graph. As discussed in the text, our chronology is based on four dates and rejects the date associated with the sample from 430 cm (circle).

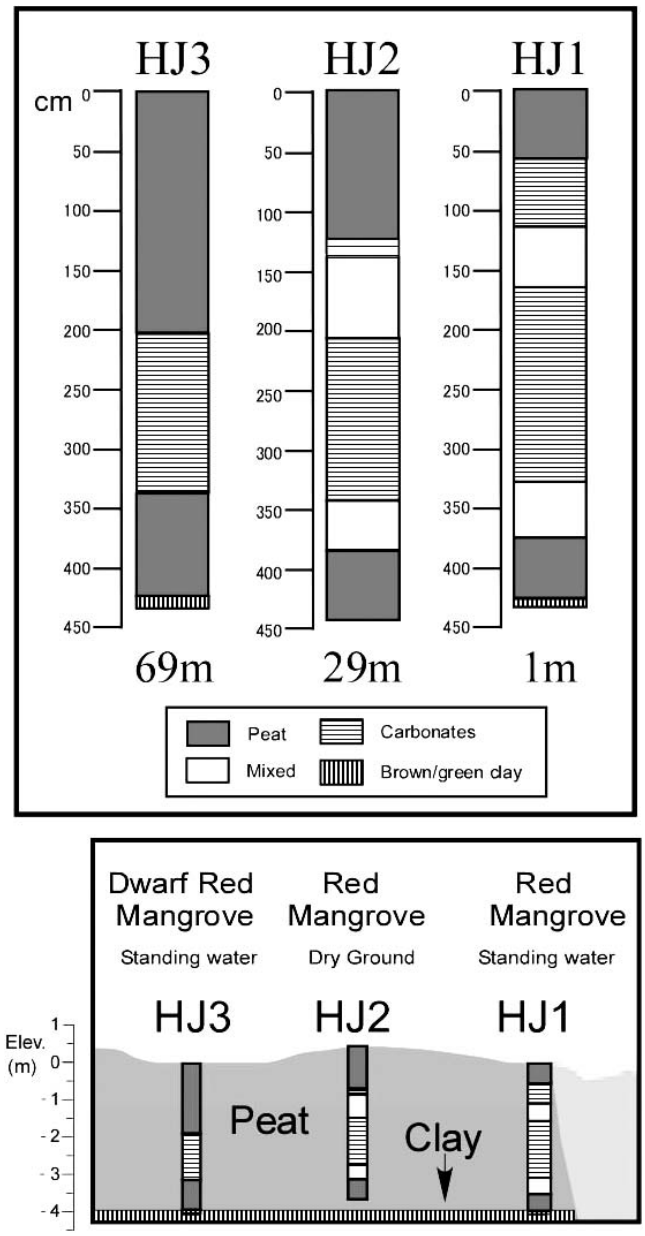

Figure 4. HJ transect. Top box displays the lithologs for the three-core transect, the bottom box displays the topography, hydrological conditions, and dominant vegetation for each core.

against the inside rim of the fringing coral, across the rather wide reef flat (>750 m). Very tight fringing *Rhizophora* stands extend into the water beyond the edge of the island; there is no beach. Cores were extracted at 64, 89, and 125 m inland. GC1, the most seaward core at 64 m inland, shows a stratigraphic sequence (from bottom to top) of peat–carbonate–peat. Core GC2 at 89 m inland reaches the basal clay, overlain by peat–carbonate–mixed–carbonate–peat. GC3, cored at a slightly higher elevation 125 m inland, is consistently peat throughout (Figure 5).

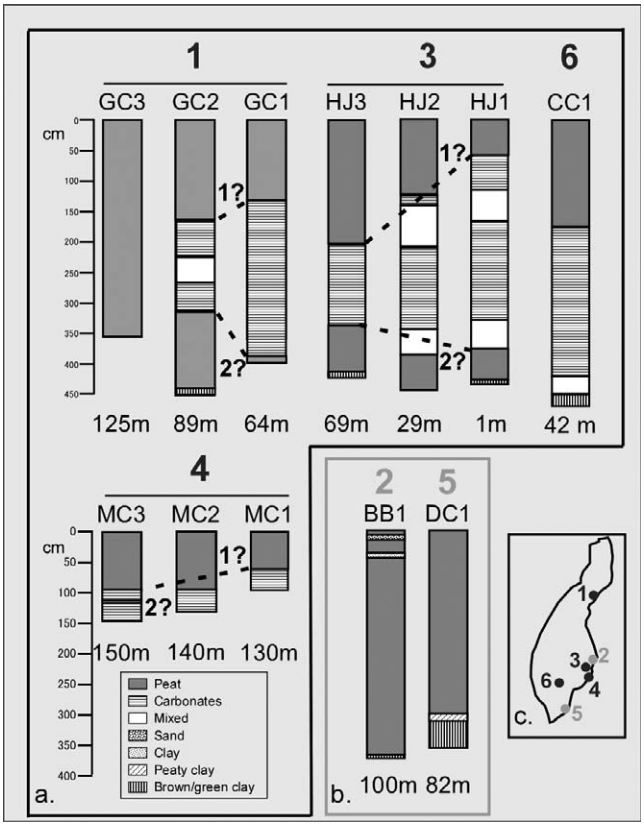

Figure 5. Combined transects. (a) The lithologs from four study sites (GC, HJ, CC, MC) display thick carbonate layers, (b) while lithologs from two sites (BB, DC) do not. (a) A landward thinning of the carbonate layers is noticeable across the GC, HJ, and MC transects, as is the separation of the layers into upper and lower units. (c) Transects that do/do not contain these carbonate layers do not fall into distinct geographic groupings.

MC (Site 4 in Figure 1)

This site is located on a sandy cay on the western edge of the reef flat, just south of the mouth of Long Bogue (Figure 1). Three short cores (<150 cm) were taken within the *Avicennia* zone along a cuspate transect paralleling the northern rim of the cay. Cores MC1 (130 m) and MC2 (140 m) consist of a bottom carbonate section, topped by peat, while the MC3 (150 m) shows a bottom upward sequence of carbonates–peat–carbonates–peat (Figure 5).

CC (Site 6 in Figure 1)

The CC site is located on a small mangrove cay in the southern section of the Central Lagoon (Figure 1). A single core 463 cm in length was extracted from the *Rhizophora* zone, 42 m inland. This core reaches the basal clay, followed by a mixed section, then a thick carbonate section, capped by >1.5 m of peat (Figure 5).

BB (Site 2 in Figure 1)

The BB site is located on the eastern edge of a large mangrove island just to the north of Long Brogue behind a wide reef flat that forms an elbow in the islands' eastern rim (Figure 1). The

cay is fronted by a sandy beach, behind which our transect passed through the *Rhizophora–Avicennia*–mixed hardwoods forest zones. Canopy height was ~10–15 m. A total of 12 cores reaching 165 m inland were taken, but only core BB1 at 100 m was pushed until refusal (373 cm); thus, only the stratigraphy from this core is presented here. Above the basal clay, this core consisted entirely of peat, with the exception of two clastic layers within the top meter. Eleven short cores, from 50 to 150 cm in length, were taken to trace these clastic layers. Both layers thin and fine inland. At BB1, the top layer, at 10–15 cm depth, is visible as a dramatically distinct light-colored coarse sand layer 5 cm thick. By 130 m it is a barely visible clay, later becoming undetectable farther inland. The lower clastic layer, a 3-cm brown clay band centered at 48 cm depth in BB1, is only identifiable to 115 m inland.

DC (Site 5 in Figure 1)

This site is on a medium-sized mangrove cay near the south end of the atoll (Figure 1). The reef flat is narrow at this location: ~40 m width of shallow (~1.5 m deep) water separates the cay from a group of small sand cays on the seaward edge of the reef flat. A single core (353 cm) was extracted from the *Rhizophora* zone, 82 m inland from the sea. This core is all peat above the basal clay and a thin transitional peaty clay section (Figure 5).

Intersite Comparison

The lithologs of all cores are shown in Figure 5. Cores from four of the locations contain thick carbonate layers; cores from the other two locations do not. All three multicore transects (GC, HJ, MC) display landward thinning of the carbonate layers. Mixed layers occur at HJ, GC, and CC, in all three locations underlying carbonate layers. Two separate mixed-carbonate sequences occur at HJ, and a single sequence at GC and CC.

DISCUSSION

A rough paleoenvironmental history for core HJ1 can be reconstructed from the ^{14}C dated sediment stratigraphy. The bottom of the core consists of a brownish-green clay that began accumulating around 6700 BP when rising sea levels drove the water table high enough to support vegetation. This is in keeping with previously published descriptions of the Turneffe Islands atoll as a mud-covered limestone island prior to the middle-Holocene transgression (Gischler, 2003; Gischler and Hudson, 1998; Gischler and Lomando, 2000; Wooller *et al.*, 2009). By ~6400 BP the clay was replaced by a highly organic peat deposition, which probably represents an environment very similar to the present. By ~4900 BP a marine environment developed, which continued until ~600 BP when the present *Rhizophora* forest was formed.

Both the distinctive brownish-green clay and the reddish mangrove peat are easily recognized in cores across the atoll. Common basal stratigraphies suggest a common early history for all sites, namely, a progression from bare limestone through a sparsely vegetated terrestrial environment, followed by forests, most likely *Rhizophora*, paralleling the standard environmental succession for the continental margin of Belize. At this point, however, the histories for the different cays diverge as the forested vegetation continues at BB and DC through the present, while the GC, HJ, MC, and CC sites show thick carbonate intervals, which were eventually replaced by peats. The processes responsible for producing the stratigraphies occurring at BB and DC seem straightforward (sequence 1: mangrove cays keeping up with sea level). Identifying the processes involved in creating the bracketed carbonate layers is not, but it is essential for understanding the atoll's environmental history.

Figure 6. Mixed layers. Sections of cores HJ1 (315–330 cm), HJ2 (325–340 cm), and GC2 (255–270 cm) displaying the random orientation and physical nonconnectivity of peat clasts embedded in the carbonate matrix.

These bracketed carbonate stratigraphies are unusual, with the resumption of peat deposition after a period of carbonate deposition being extremely rare in the literature. Macintyre *et al.* (2004) report similar peat–carbonate–peat sequences from a few cores extracted from two long transects across Twin Cays. They attribute the sequence to lagoonal transgression followed by the recolonization of mangroves, suggesting hurricanes as the causative agent. In addition, the mixed layers occurring in GC, HJ, and CC seem to be unique in the literature. Visually, they are quite dramatic, consisting of unconnected, angular clumps of dark organic material embedded in a light-colored carbonate matrix of silt, sand, shell and coral fragments, and *Halimeda* flakes (Figure 6). The minimum spatial coverage of this peat–carbonate–peat stratigraphy is 25 km on Turneffe Islands, the distance that separates sites 1 (GC) and 6 (CC) (Figure 5). The spatial distribution of the peat–carbonate–peat groups does not correspond with atoll environments. Sites GC,

BB, MC, and DC are all located on the western edge of the reef flat, yet two contain the carbonate layers and two do not. Neither does spatial proximity control the occurrence of the carbonate layers. BB, HJ, and MC are located within a few kilometers of each other (Figure 1d), yet HJ and MC contain carbonate layers while BB does not (Figure 5). The carbonate layers display inland thinning. At HJ Cay and GC there is a narrowing of the layer, with the bottom and top of the layer converging across the transects. At MC the short length of the cores only permits examination of the top of the carbonate layer, which deepens from 60 to 90 cm moving inland. There is some indication in these three transects of upper and lower carbonate layers, with the ability to distinguish the two increasing landward. The initiation and termination of these layers is often abrupt, with a chaotic mixing of peat and carbonate clumps preceding carbonate layers at HJ, GC, and CC (Figures 2a and b). The depth of the bottom of the carbonate layers (presumably related to time of initiation) is similar for GC1, HJ1, HJ2, and HJ3, and only slightly deeper for CC1.

Carbonate and Mixed Layers

The classification of these carbonate layers is problematic. The material is structureless and unconsolidated, with peat borer extraction (typically stopped by a few centimeters of sand) proceeding through >2 m of material. The material contains large amounts of *Halimeda* flakes and foramnifera tests, with the carbonate intervals in HJ1 and MC2 beginning above a basal shell and/or *Halimeda* flake layer. These are all typical lagoon-floor depositional features (Gischler, 1994, 2003). These analyses suggest a location receiving bottom-style deposition in water too deep for mangroves. However, the bottom of these intervals is well above the level of the lagoon bottom and must have been deposited in shallow water as they replaced an environment (mangroves) that was at or near sea level. These layers, therefore, most likely represent submerged island tops. The submerged edges of mangrove cays do not presently exhibit this depositional environment, as evidenced by the top sections of core HJ1, which was cored in ankle deep water within a meter of the cay edge, but consists of highly organic peat (organic content >65 %) (Figures 2c and d).

Although regional records identify significant ecological and climatic changes that have occurred over the middle-to-late Holocene, these changes are not large enough to explain the gross sedimentological reversals exhibited in our cores. Wooller *et al*. (2009) shows both hydrologic and vegetative changes occurring on Turneffe Islands, with increased freshwater inundation ~4100 BP resulting in an increase in *Rhizophora* density and height, followed by a dryer period beginning ~3900 BP during which *Rhizophora* was replaced by *Salicornia*. Records from mangrove cays located inside the barrier reef demonstrate ecological changes with concentrations of *Myrsine* and *Avicennia* pollen peaking during various time periods (Wooller *et al.,* 2004, 2007), as well as possible changes in wind strength/direction (Monacci *et al*., 2009; Wooller *et al.,* 2004, 2007). However, these are all examples of alterations to the plant community (changes in composition, species dominance, and plant stature) and not its destruction. Except for small changes in peat density, none of the environmental changes mentioned above significantly affected sedimentary structure. In particular, there was no shift in the dominant depositional mode; as in all the cited studies, all cores consist entirely of peat above the basal clay. Relatively small changes in precipitation and inundation regimes, though ecologically significant, are not capable of turning a highly organic environment into one devoid of vegetation receiving lagoon-floor style deposition. The one instance of gross sedimentary change in the regional literature occurs in a core extracted from a mainland *Rhizophora* forest at the mouth of the Sibun River in central Belize, wherein the basal peat is replaced by mud ~2500 BP (Monacci *et al*., 2011). This mud, however, is fluvial and primarily allochthonous, attributed to increased upstream erosion resulting from precipitation changes and/or the effects of ancient Maya agriculture (Monacci *et al*., 2011). Such upland erosion, of course, is irrelevant for Turneffe Islands, which is an isolated carbonate platform separated from the mainland by water depths of >400 meters.

The bracketed carbonate layers sit directly over peat sequences, suggesting a sudden increase in relative sea level. In locations where accumulation rates are low, a rapid rise in sea level can erode the edges of mangrove forests and result in their local extinction (Soares, 2009). This is the standard sequence 2 scenario that has occurred in many places along the continental shelf of Belize, resulting in drowning of mangroves and replacement by carbonate sedimentation. However, eustatic sea level change is an unlikely cause in this case, since the drowning of mangroves in the HJ1 begins ~5000 YBP, just as sea level rise began slowing (Gischler and Hudson, 2004). In any event, eustatic sea level rise should be reflected in all locations across the atoll.

This argues that these layers occur as a result of dramatic reductions in island elevation on a local scale. The mixed layers that underlie several of the carbonate layers support this view. It is very unlikely that these layers result from rapidly alternating intervals of peat and carbonate deposition. The material is not horizontally bedded, and individual sediment types do not extend across the width of the cores; rather, irregularly shaped, randomly orientated organic chunks are scattered throughout a carbonate matrix, with many of the dark peat clasts entirely surrounded by the light-colored carbonate material (Figure 6). This depositional framework indicates that the small peat clasts were deposited simultaneously with large amounts of carbonate material, a highly unusual condition. Because the peat clasts most likely originated from tops or sides of the mangrove cay and the carbonate material from the lagoon bottom, their simultaneous deposition suggests a high-energy event capable of eroding the island, resuspending large amounts of bottom sediment, and transporting both materials to new locations. Significant peat erosion could lower island elevation (at least along the edges), thereby forming a new depositional environment below sea level, too deep for mangrove development. After the event, a reduced form of this mixed deposition could continue along these submerged edges if peat clumps continued to erode from the island's edge (now transgressed inland), were transported outward, and were subsequently buried under the gradually accumulating carbonates. This is in accordance with the standard mixed-layer depositional pattern. Clast frequency is typically highest at the bottom of the mixed layers, above which

clast frequency decreases rapidly upcore above before transitioning into typical bottom-style carbonates, free of organic clumps.

Slumping has been recorded for the floor of Turneffe Islands' central lagoon (Stoddart, 1963) and inside the barrier reef near the Tobacco Range fracture zone, ~40 km to the SW (Littler *et al.*, 1995; Macintyre, Littler and Littler, 1995). In both cases the initiation of the slumping was attributed to wave action associated with extreme events, with hurricanes or earthquakes being named as the most likely candidates. The slumping near the Tobacco Range fracture zone is characterized by large blocks of fossil peat jumbled chaotically on the lagoon bottom offshore from a mangrove cay. The investigators believe that the slumping continued after the initiating event because of undercutting and structural differences in the peat (Littler *et al.*, 1995).

Seismic Activity

Although several types of high-energy events are potentially capable of reducing island elevation, seismic activity is the most likely candidate in this case. Studies from the Patía River delta on the Pacific coast Colombia have shown that tectonic-induced activity has led to subsidence, erosion, and the retreat and death of mangroves (Restrepo and Cantera, 2011), while "most" of a large mangrove forest in the Dominican Republic was destroyed as a result of an earthquake-generated waves in 1946 (Sherman, Fahey, and Martinez, 2001). Turneffe Islands is a free-standing tower, >1000 m in height, situated only ~150 km north of the North American/Caribbean plate boundary, making it subject to tectonic disturbances, such as the 7.3 submarine earthquake that occurred 125 km NNE of La Ceiba, Honduras, on 28 May 2009 (USGS Earthquake Hazards Program 2009). Some evidence exists that significant seismic settling has occurred in the past. The tops of the Pleistocene reefs for the first three fault blocks offshore of Belize (Turneffe Islands is on the second) all show a distinct southern dip, possibly the result of tilting, although direct neotectonic evidence is lacking, and differential weathering is an alternative explanation (Gischler and Hudson, 1998, 2004; Gischler and Lomando, 2000). More direct evidence of movement is provided by a speleothem gallery in the Great Blue Hole, a submerged sinkhole in Lighthouse Reef, ~25 km east of Turneffe Islands. Stalactites in this gallery display a northern tilt of 5–10°, some with bends and spiral structure, probably indicating a tilt of the platform as they formed (Dill, 1977; Jones and Dill, 2002). During recent times earthquakes "have occurred and continue to be reported" for the area (Littler *et al.*, 1995).

The response of individual mangrove cays to gross platform movement could be spatially inconsistent, with magnitude and direction of movement varying by site. Idiosyncratic responses would be particularly relevant in regard to slumping occurring on cay edges, with the top of some cays dropping below the mangrove depth threshold, while others are unaffected. Platform structure could also be a factor, with a tilt to the north resulting in lowering elevations in the north (thick carbonate layer at GC) and higher elevations in the south (no carbonate layer at DC). The exceptionally broad reef flat in front of the BB transect, perhaps indicating greater structural strength and less vertical mobility, may explain the lack of carbonate layers in the BB transect.

Mangrove Die-offs

Mangrove mortality provides a possible amplifying mechanism. Tree death can result in a lowering of cay surface elevation, as demonstrated by the documentation by McKee and Faulkner (2000) of several large stumps of *Avicennia*, which typically occur at higher elevations, submerged in an interior pond on a Belizean cay, indicating surface subsidence following tree death. On Guanaja, off the coast of Honduras, the die-off of mangroves associated with Hurricane Mitch (1998) resulted in an elevation loss of >7 cm in the first 2 years, with an additional predicted short-term loss of ~6 cm (Cahoon *et al.*, 2003). These studies suggest that the peat collapses associated with die-offs are capable of significantly reducing surface elevation and increasing water depth.

This process provides a potential explanation of the HJ1 stratigraphy (Figure 7). Under this scenario mangrove development began shortly after the middle-Holocene transgression ~6500 BP, resulting in peat deposition. Seismic movement then dropped the island's outer edge below water level, which triggered a massive mangrove mortality and a subsequent peat collapse (A) that eroded the surface along the edge of the island to 378 cm core depth. The increased water depth prohibited mangrove growth, and deposition shifted to lagoon-floor style carbonates mixed with clumps of mangrove peat eroded from the island edge during and/or after the event (B). Around 5000 cal YBP the island stabilized, peat stopped eroding from the cay edges (C), and normal carbonate deposition dominated for the next 3500 years. This was followed by a second large event and die-off, and the process was repeated, with peat clumps eroded from the vegetated sections of the cay (farther toward the center) mixing with the resuspended/deposited carbonates (D, E), resulting in a second mixed layer, after which carbonate sedimentation reinitiated. The 1 m of sedimentation associated with the mixed material and the carbonates between ~1400 and 600 BP far surpassed the sea level rise during the period (Gischler and Hudson, 2004; Toscano and Macintyre, 2003). This shallowing permitted mangroves to reestablish themselves ~600 BP, after which they developed rapidly (F).

Hurricanes

Hurricanes frequently pass through the area. Since 1955 five hurricanes (Janet, 1955; Hattie, 1961; Carmen, 1974; Keith, 2000; Iris, 2001) have passed within 65 nautical miles of the atoll at category 4 or 5 strength, with Janet and Hattie both achieving category 5 strength. Three hurricanes (Unnamed, 1931, category 3; Hattie, 1961, category 5; Keith, 2000, category 4) have passed within 10 km at category 3 strength or higher during the last 80 years. Long-term hurricane landfall records indicate that the average strike probability has been ~one major storm *per* decade for the coast of Belize over the last 500 years (McCloskey and Keller, 2009) and that such storms have been frequent occurrences for at least the last 7000 years (McCloskey and Liu, 2013). The effects of Hurricane Hattie, which crossed Turneffe Islands as a category 5 hurricane in 1961, are described in detail by Stoddart (1963). These effects included widespread mortality and defoliation of trees, large-scale sand movement, including the building/

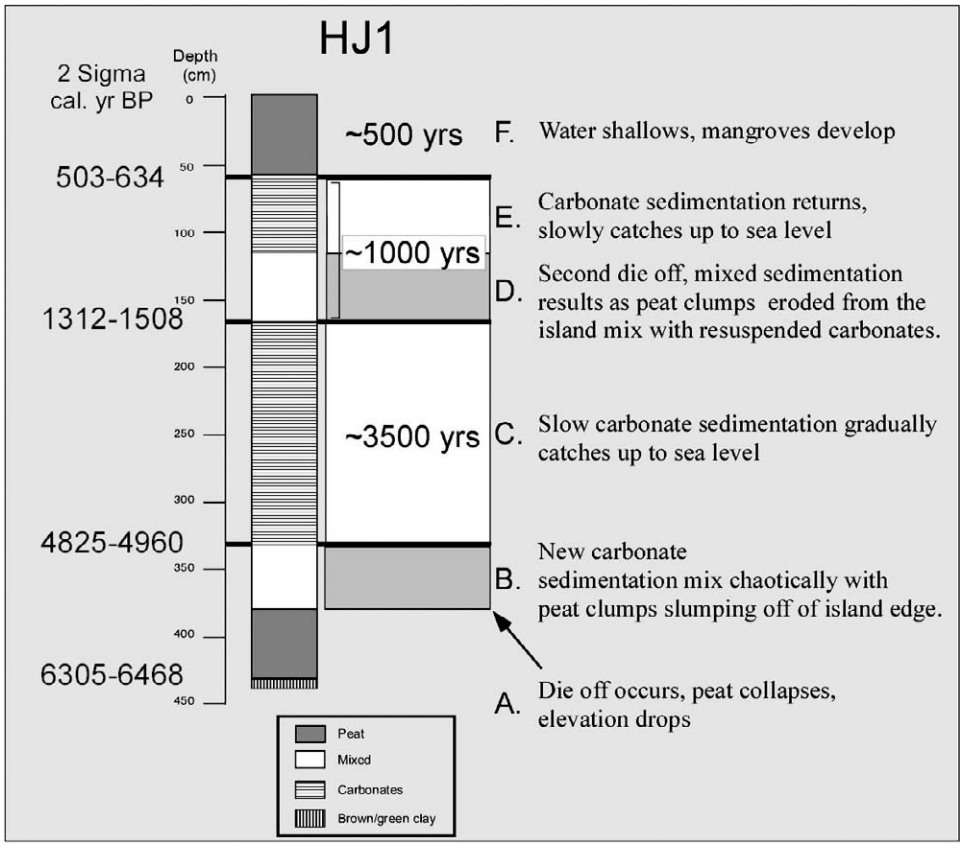

Figure 7. Conceptual model of HJ1 sedimentology based on peat collapse. In this model an event-driven peat collapse substantially reduces island elevation, thereby switching sedimentation from mangrove peat to a mixed deposition followed by subaqueous carbonate material. This process occurs twice.

removal of beach ridges, and extensive erosion, including beach retreat, the creation of extensive scour pits, and the disappearance/submergence of small sand cays. Despite the magnitude of these effects, this storm is barely recognizable in our cores, which were intentionally extracted in the areas cited as having suffered the heaviest damage from Hattie (Stoddart, 1963). Of our six sites, only BB displays a clear record of the event, marked by a thin clastic layer at ~15 cm depth, which extends only 130 m inland. A second clastic layer, occurring at 48 cm depth in the same core, is attributed to the unnamed hurricane of 1931 (McCloskey, 2009). Since both layers are markedly different from the bracketed carbonate layers in size, structure, solidarity, and composition, the possibility that the carbonate layers were deposited as hurricane overwash layers is unlikely. Nevertheless, hurricanes cannot be eliminated as a possible causative agent, since hurricane-generated erosion and the associated mangrove mortality provide a plausible mechanism for lowering island elevation and thereby changing the normal deposition from peat to carbonate sands, as suggested by Macintyre *et al*. (2004). However, given the near total lack of sedimentary signatures for historical storms, hurricanes seem an unlikely candidate for producing the long-term changes seen in our cores, particularly the multimillennial suppression of mangroves observed at HJ1.

Tsunamis

It is also unlikely that the carbonate layers are tsunami deposits. A study conducted on a Maldivian atoll following the 2004 Sumatra tsunami demonstrates that steep atoll bathymetry and restricted atoll entrances tend to severely dampen the geomorphic effects of tsunami waves (Kench *et al*., 2006, 2008). Both of these inhibiting conditions apply to Turneffe Islands. The sedimentary signatures of the Maldivian tsunami deposits and Turneffe Islands' carbonate layers exhibit distinct differences in composition, structure, grain size, layer thickness and extent, and the presence of terminal drapes. Importantly, the Maldivian tsunami did not lead to island instability, and the event is not expected to be preserved in the sedimentary record (Kench *et al*., 2006, 2008).

Regional Correlation

The dramatic sedimentary changes that dominate this core make chronological correlation of paleoenvironmental/climatic events with regional records problematic. The recording sensitivities for environmental proxies during the period of carbonate deposition, which covers at least 4500 years in HJ1, are very different from the sensitivities occurring during peat deposition. During the carbonate period HJ1 is basically insensitive to features such as changes in precip-

itation and inundation regimes, ecosystem dynamics, and plant assemblages that have been noted in peat-based proxy records such as Wooller *et al*. (2004, 2007, 2009) and Monacci *et al*. (2009, 2011), thereby severely limiting the utility of HJ1's contribution to regional correlations. Because the shifts in depositional modes most likely result from instantaneous events and not climatic conditions, the timing of these shifts also provides no climatic information and cannot be matched with regional records. HJ1 does show a correlation with local records in one regard, as it displays a marked increase in sedimentation rate ~1000 BP, as noted in nearby locations (Monacci *et al*., 2009, 2011; Wooller *et al*., 2004). However, in this case the higher sedimentation rate probably merely reflects the change in deposition from slow bottom-style carbonate deposition to the faster mangrove-driven peat accumulation.

Carbonate Layers Summary

Sedimentologically, the carbonate layers do not appear to be event layers, since they generally lack the chaotic nature, the occasionally vertical deposition, and the overall structure (upward fining) usually associated with instantaneous high-energy deposition (Goff, McFadgen, and Chague-Goff, 2004; Morton, Gelfenbaum, and Jaffe, 2007; Peters, Jaffe, and Gelfenbaum, 2007; Williams, 2009, 2010). The thickness is also beyond the usual event parameters, as is the unconsolidated nature of the material. The most likely depositional environment for the layers is a subtidal surface too deep to permit mangrove development.

However, the layers do resemble event layers stratigraphically in regard to landward thinning, the rough atoll-wide temporal correspondence, and the chaotic nature of the lower contact between the peat and carbonate layers, especially the mixed layers occurring in HJ1 and HJ2, GC2, and CC1. The simultaneous deposition of two sediment types originating in separate environments, their extreme vertical mixing, complete lack of sorting, and general incoherency of these mixed layers argues for some type of high-energy perturbation.

A likely resolution to this paradox is to view the carbonate layers as event initiated, although the major portions of the layers (the purely carbonate sections) predominately represent normal deposition in a changed environment. The important effect of the event was a rise of relative sea level for the sites, with increased water depth shifting the depositional mode from organic to carbonate. In some cases, this depositional shift was preceded by a period of chaotic mixed deposition associated with erosion and biogeological processes resulting from the event. Since water depth can control mangrove viability, small changes in relative sea level can result in an abrupt switch in depositional environments. An event that causes water depth to surpass the maximum mangrove depth threshold can switch sedimentation from organic to carbonate, while gradual shallowing will at some point lead to an abrupt switch back to organic. The peat clasts found in the distinctive mixed layers probably result from the disintegration of the edges of the peat platform, an important amplifying mechanism contributing to the reduction of island elevation.

The size and random orientation of the clasts indicate a sudden and powerful precipitating event. Gradually changing boundary conditions do not seem capable of producing either such chaotic deposition or the required amplitude of water depth changes. Nor do hurricanes. Although the hurricane-driven amplification of surface elevation decreases through peat collapse has been recorded in the region, this response has not been observed for historical events on Turneffe Islands and does not seem capable of operating at the necessary spatial scale. Tsunamis also seem an unlikely candidate. Not only does atoll geology limit their geomorphic effects, the lack of corresponding events, both regionally and across the atoll, argues against tsunamis as the proximate cause. Local seismic activity, probably resulting from the shifting of all or part of the platform, is the process that can most successfully explain both the abrupt (probably repeated) relative sea level rise in a widespread but spatially spotty manner and the distinctive depositional mixing of carbonates and peat.

Dating of the initiation of the carbonate layers is uncertain. The top of the bottom peat layer in HJ1 was not dated because of the view that erosion associated with the precipitating event removed an unknown amount of material directly below the mixed layer. Although no other cores were dated, mangrove accumulation and island elevation are so closely tied to sea level that stratigraphic correlation across the atoll can be expected to be fairly accurate for peat intervals. The elevations of the bottoms of the carbonate layers do, in fact, display a rough correlation. However, owing to erosion such correlations are only useful if erosion is assumed to be similar across sites, which, given the spatial variability seen in our cores, is unlikely. Thus, the dating and chronological correlation of events across Turneffe Islands is very uncertain. However, only a large, platform-wide movement would have resulted in simultaneous events across the atoll; smaller movements resulting in slumping of individual mangrove cays could display great temporal variability.

If these carbonate layers do indeed result from small-scale subsidence, then the apparent repetition of the peat–carbonate–peat sequence in the GC, HJ, and MC transects suggests that such events may be a repeating phenomenon. If so, there are fairly significant potential societal consequences, especially given the increasing use of the atoll as a tourist destination (Pat, 2001).

CONCLUSIONS

(1) Sedimentary evidence indicates that the Turneffe Islands mangrove cays share a common initial ecological history, with basal clay, probably representing a species-poor terrestrial environment being replaced by a mangrove forest ~6500 BP. The rising water table associated with postglacial sea level rise is the probable causative mechanism.

(2) At two sites the peat deposition continues through the present, having maintained a roughly static elevation relative to sea level over the middle-to-late Holocene.

(3) At four sites the peat deposition is interrupted by thick carbonate intervals, probably lasting several thousands of years. This depositional environment resembles lagoonal floor conditions, under a water depth surpassing the maximum threshold for mangrove survival. However,

these conditions occur at elevations above the contemporary lagoon floor.

(4) The most likely explanation for the stratigraphic change from peat to carbonate-rich sand and silt is an event-initiated drop in local surface elevation, resulting in an increase in relative sea level. Candidate events include hurricanes, tsunamis, and seismic activity. Hurricanes probably lack the necessary geomorphic power. Not only are appropriate tsunamis missing in the regional record, but geologic factors, principally the atoll's vertical structure and intact rim, also reduce tsunami energy below the requisite levels. Seismic activity that lowered island surface level, amplified by the associated island slumping resulting from peat collapse following massive mangrove mortality, produced by a movement of all or parts of the carbonate platform, is the most likely explanation.

(5) If seismic activity is the responsible agent, there is a need to incorporate this factor in risk assessment for coastal Belize, since sedimentological evidence suggests at least two such events over the last 5000 years.

ACKNOWLEDGMENTS

This research was supported by grants from the Inter-American Institute for Global Change Research (IAI-CRN2050), the U.S. National Science Foundation (BCS-0213884), and a NSF Graduate Research Fellowship to T.A.M. Assistance in the field was provided by Faustino Chi, Adria Hussein, and Emily Byers.

LITERATURE CITED

Cahoon, D.R.; Hensel, P.; Rybczyk, J.; McKee, K.L.; Proffitt, C.E., and Perez, B.C., 2003. Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. *Journal of Ecology,* 91, 1093–110.

Choi, D.R. and Ginsburg, R.N., 1982. Siliclastic foundations of Quaternary reefs in southernmost Belize Lagoon, British Honduras. *GSA Bulletin*, 93, 116–126.

Choi, D.R. and Holmes, C., 1982. Foundation of Quaternary reefs in south-central Belize lagoon, British Honduras. *American Association of Petroleum Geologists Bulletin*, 66, 2663–2671.

Dill, R.F., 1977. The blue holes: geologically significant submerged sinkholes and caves off British Honduras and Andros, Bahamas Island. *In:* Taylor, D.L. (ed.), *Proceedings of the Third International Coral Reef Symposium,* Vol. 2. Miami, Florida: Rosenstiel School of Marine and Atmospheric Sciences, pp. 237–242.

Dillon, W.P. and Vedder, J.G., 1973. Structure and development of the continental margin of British Honduras. *Geological Society of America Bulletin*, 84, 2713–2732.

Ellison, J.C., 1993. Mangrove retreat with rising sea-level, Bermuda. *Estuarine, Coastal and Shelf Science*, 37, 75–87.

Ferro, C.E.; Droxler, A.W.; Anderson, J.B., and Mucciarone, D., 1999. Late Quaternary shift of mixed siliclastic-carbonate environments induced by glacial eustatic sea-level fluctuations in Belize. *In:* Harris, P.M.; Saller, A.H., and Simo, J.A. (eds.), *Advances in Carbonate Sequence Stratigraphy: Application to Reservoirs, Outcrops and Models,* Vol. 63. Tulsa, Oklahoma: Special Publications—Society of Economic Paleontology Mineralogists, pp. 385–411.

Gischler, E., 1994. Sedimentation on three Caribbean atolls: Glovers Reef, Lighthouse Reef and Turneffe Islands, Belize. *Facies,* 31, 243–254.

Gischler, E., 2003. Holocene development in the isolated carbonate platforms off Belize. *Sedimentary Geology,* 159, 113–132.

Gischler, E. and Hudson, J.H., 1998. Holocene development of three isolated carbonate platforms, Belize, Central America. *Marine Geology,* 144, 333–347.

Gischler, E. and Hudson, J.H., 2004. Holocene development of the Belize Barrier Reef. *Sedimentary Geology,* 164, 223–236.

Gischler, E. and Lomando, A.J., 2000. Isolated carbonate platforms of Belize, Central America: sedimentary facies, late Quaternary history and controlling factors. *In:* Insalco, E.; Skelton, P.W., and Palmer, T.J. (eds.), *Carbonate Platform Systems: Components and Interactions*. London: The Geological Society of London, Special Publications 178, pp. 135–146.

Gischler, E.; Shinn, E.A.; Oschmann, W.; Fiebig, J., and Buster, N., 2008. A 1500-year Holocene Caribbean climate archive from the Blue Hole, Lighthouse Reef, Belize. *Journal of Coastal Research,* 24, 1495–1505.

Goff, J.; McFadgen, B.G., and Chague-Goff, C., 2004. Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine Geology*, 204, 235–250.

Halley, R.B.; Shinn, E.A.; Hudson, J.H., and Lidz, B., 1977. Recent and relict topography of Boo Bee Patch reef, Belize. *In:* Taylor, D.L. (ed.), *Proceedings of the Third International Coral Reef Symposium,* Vol. 2. Miami, Florida: Rosenstiel School of Marine and Atmospheric Sciences, pp. 29–35.

Jones, A.T. and Dill, R.F., 2002. Great Blue Hole of Lighthouse Reef Atoll, Belize, Central America: deep technical diving to collect sea-level records. *In:* Jackson, T.A. (ed.), *Caribbean Geology: Into the Third Millennium. Fifteenth Caribbean Geological Conference*. Kingston, Jamaica: University of the West Indies Press, pp. 181–193.

Kench, P.S.; McLean, R.F.; Brander, R.W.; Nichol, S.L.; Smithers, S.G.; Ford, M.R.; Parnell, K.E., and Aslam, M., 2006. Geological effects of tsunami on mid-ocean atoll islands: the Maldives before and after the Sumatran tsunami. *Geology,* 34, 177–180.

Kench, P.S.; Nichol, S.L.; Smithers, S.G.; McLean, R.F., and Brander, R.W., 2008. Tsunami as agents of geomorphic change in mid-ocean reef islands. *Geomorphology,* 95, 361–383.

Lara, M.E., 1993. Divergent wrench faulting in the Belize southern lagoon: implications for Tertiary Caribbean plate movements and Quaternary reef distribution. *American Association of Petroleum Geologists Bulletin*, 77, 1041–1063.

Littler, M.M.; Littler, D.S.; Macintyre, I.G.; Brooks, B.L.; Taylor, P.R., and Lapoint, B.E., 1995. The Tobacco range fracture zone: a unique system of slumped mangrove peat. *Atoll Research Bulletin,* 29, 73–91.

Liu, K.-B. and Fearn, M.L., 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research*, 54, 238–245.

Macintyre, I.G.; Littler, M.M., and Littler, D.S., 1995. Holocene history of Tobacco Range, Belize, Central America. *Atoll Research Bulletin,* 430, 1–18.

Macintyre, I.G.; Toscano, M.A.; Lighty, R.G., and Bond, G.B., 2004. Holocene history of the mangrove islands of Twin Cays, Belize, Central America. *Atoll Research Bulletin,* 510, 1–16.

McCloskey, T.A., 2009. Proxy Records of Paleohurricane Activities for the Western and Southern Caribbean. Baton Rouge, Louisiana: Louisiana State University, Ph.D. dissertation, 728p.

McCloskey, T.A. and Keller, G., 2009. 5000 year sedimentary record of hurricane strikes on the central coast of Belize. *Quaternary International*, 195, 53–68.

McCloskey, T.A. and Liu, K.-B, 2013. A 7000-year record of paleohurricane activity from a coastal wetlands in Belize. *Holocene*, 23, 276–289.

McKee, K.L., 1995. Mangrove species distribution patterns in a Belizean mangrove forest: an exception to the dominance-predation hypothesis. *Biotropica*, 27, 334–345.

McKee, K.L. and Faulkner, P.L., 2000. Mangrove peat analysis and reconstruction of vegetation history at the Pelican Cays, Belize. *Atoll Research Bulletin*, 468, 45–58.

Monacci, N.M.; Meier-Grünhagen, U.; Finney, B.P.; Behling, H., and Wooller, M.J., 2009. Mangrove ecosystem changes during the Holocene at Spanish Lookout Cay, Belize. *Paleogeography, Palaeoclimataology, Palaeoecology*, 280, 37–46.

Monacci, N.M.; Meier-Grünhagen, U.; Finney, B.P.; Behling, H., and Wooller, M.J., 2011. Paleoecology of mangroves along the Sibun River, Belize. *Quaternary Research*, 76, 220–228.

Morton, R.A.: Gelfenbaum, G., and Jaffe, B.E., 2007. Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedimentary Geology*, 200, 184–207.

Murray, M.R.; Zisman, S.A.; Furley, P.A.; Munro, D.M.; Gibson, J.; Ratter, J.; Bridgewater, S.; Minty, C.D., and Place, C.J., 2003. The mangroves of Belize: Part 1: distribution, composition and classification. *Forest Ecology and Management,* 174, 265–279.

Pat, W., 2001. *Case Study: Tourism and Biodiversity: Ecotourism—a Sustainable Development Tool, a Case for Belize*. Belmopan, Belize: Ministry of Tourism and Youth, Government Printers.

Peters, R.; Jaffe, B.E., and Gelfenbaum, G., 2007. Distribution and sedimentary characteristics of tsunami deposits along the Cascadia margin of western North America. *Sedimentary Geology*, 200, 372–386.

Reimer, P.J.; Baillie, M.G.L.; Bard, E.; Bayliss, A.; Beck, J.W.; Blackwell, P.G.; Bronk Ramsey, C.; Buck, C.E.; Burr, G.; Edwards, R.L.; Friedrich, M.; Grootes, P.M.; Guilderson, T.P.; Hajdas, I.; Heaton, T.J.; Hogg, A.G.; Hughen, K.A.; Kaiser, K.F.; Kromer, B.; McCormac, F.G.; Manning, S.; Reimer, R.W.; Richards, D.A.; Southon, J.R.; Talamo, S.; Turney, C.S.M.; van der Plicht, J., and Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51, 1111–1150.

Restrepo, J.D. and Cantera, J.R., 2011. Discharge diversion in the Patía River delta, the Colombian Pacific: geomorphic and ecological consequences for mangrove ecosystems. *Journal of South American Earth Sciences*, doi: 10.1016/j.jsames.2011.04.006.

Sherman, R.E.; Fahey, T.J., and Martinez, P., 2001. Hurricane impacts on a mangrove forest in the Dominican Republic: damage patterns and early recovery. *Biotropica*, 33, 393–408.

Shinn, E.A.; Halley, R.B.; Hudson, J.H.; Lidz, B., and Robbin, J., 1979. Three dimensional aspects of Belize patch reefs (abstract). *Bulletin of the American Association of Petroleum Geologists,* 63, 528.

Soares, M.L.G., 2009. A conceptual model for the responses of mangrove forests to sea level rise. *In:* Furmanczyk, K. (ed.), *Proceedings of the 11th International Coastal Symposium*, Journal of Coastal Research, Special Issue No. 64, pp. 267–271.

Stoddart, D.R., 1963. Effects of Hurricane Hattie on British Honduras reefs and cays. *Atoll Research Bulletin,* 95, 1–120.

Stuiver, M.; Reimer, P.J., and Reimer, R. 2010. *CALIB ^{14}C Radiocarbon Calibration*. http://calib.qub.ac.uk/calib/.

Toscano, M.A. and Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated C-14 dates from *Acropora palmate* framework and intertidal mangrove peat. *Coral Reefs*, 22, 257–270.

USGS Earthquake Hazards Program. 2009. http://earthquake.usgs.gov/earthquakes/eqinthenews/2009/us2009heak.

Williams, H.F.L., 2009. Stratigraphy, sedimentology, and microfossil content of Hurricane Rita storm surge deposits in southwest Louisiana. *Journal of Coastal Research*, 25, 1041–1051.

Williams, H.F.L., 2010. Storm surge deposition by Hurricane Ike on the McFadden National Wildlife Refuge, Texas: implications for paleotempestology studies. *Journal of Foraminiferal Research* 40, 510–519.

Woodroffe, C.D., 1981. Mangrove swamp stratigraphy and Holocene transgression, Grand Cayman Island, West Indies. *Marine Geology,* 41, 271–294.

Wooller, M.J.; Behlig, H.; Guerrero, J.L., Jantz, N., and Zweigart, M.E., 2009. Late Holocene hydrologic and vegetation changes at Turneffe Atoll, Belize, compared with records from mainland Central America and Mexico. *Palaios,* 24, 650–656.

Wooller, M.J.; Behlig, H.; Smallwood, B.J., and Fogel, M., 2007. A multiproxy peat record of Holocene mangrove palaeoecology from Twin Cays, Belize. *The Holocene,* 17, 1129–1139.

Wooller, M.J.; Morgan, R.; Fowell, S.; Behlig, H., and Fogel, M., 2004. Mangrove ecosystem dynamics and elemental cycling at Twin Cays, Belize during the Holocene. *Journal of Quaternary Science,* 19, 703–711.