ATOLL RESEARCH BULLETIN

NO. 511

THE PLEISTOCENE LIMESTONE FOUNDATION BELOW TWIN CAYS, BELIZE, CENTRAL AMERICA

BY

IAN G. MACINTYRE AND MARGUERITE A. TOSCANO

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
SEPTEMBER 2004

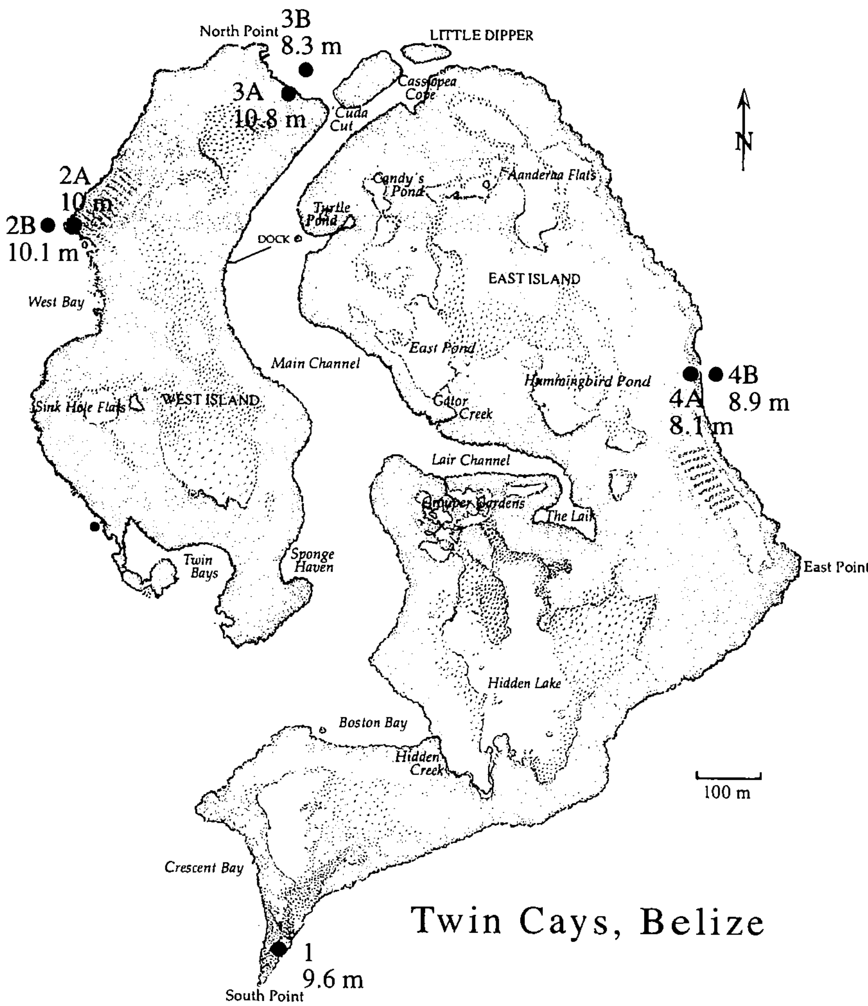

Figure 1. Location map of Twin Cays showing location of drill holes and depth of Pleistocene surface below mean sea level.

THE PLEISTOCENE LIMESTONE FOUNDATION BELOW TWIN CAYS, BELIZE, CENTRAL AMERICA

BY

IAN G. MACINTYRE and MARGUERITE A. TOSCANO

ABSTRACT

Seven core holes drilled around the perimeter of Twin Cays, Belize, penetrated the upper 1.58 m of the Pleistocene limestone, upon which 9m of Holocene mangrove peat and lagoonal sediments have accumulated. Despite extensive subaerial alteration, the cores reveal both a branching *Porites* facies and a *Thalassia*/sediment facies. X-ray diffraction analyzes indicate that all of this limestone has altered to calcite. The overall pattern consists of a mottled chalky limestone with numerous rhizolith tubules, which are scattered throughout a dense partially leached limestone. Over 70,000 years of subaerial exposure of this limestone has resulted in an extensive diagenetic alteration assisted by roots from a terrestrial plant system.

INTRODUCTION

Twin Cays, like Tobacco Range, Belize is a mangrove cay in the south-central area of the Belize Barrier Reef Platform. Since 8000 cal years BP, nine meters of Holocene mangrove deposits accumulated in this area of relief on the underlying Pleistocene limestone substrate and kept pace with rising sea level (Toscano and Macintyre, 2003; Macintyre et al., 2004).

Geologic studies of Pleistocene units underlying the Holocene reefs and mangroves of the Belize shelf include both broad-based, regional investigations (Purdy, 1974; Tebbutt, 1975; Choi and Ginsburg, 1982; Choi and Holmes, 1982; Lara, 1993) as well as incidental data obtained during Holocene reef studies (Halley et al., 1977; Shinn et al., 1982). Extensive subaerial exposures of Pleistocene limestones occur at the northern end of the Belize barrier reef complex, particularly at Ambergris Cay (18°N; Tebbutt, 1975; Macintyre and Aronson, 1997) where the Northern Belize Lagoon is shallow (<8 m) and further north along the Yucatan Peninsula. Structural investigations (Dillon and Vedder, 1973) revealed that the Pleistocene surface dips progressively to the south. As a result, south of the Belize River (approximately 17.5°N) Pleistocene limestone exposures or islands are not found above sea level in contrast with the exposures in northern Belize and the numerous Pleistocene islands throughout the wider Caribbean.

Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560

Structural Investigations of the Belize Shelf

The Campeche Bank became submerged during the Tertiary Period as the Yucatan block tilted northward. As a result, NNE-trending normal faults paralleling the eastern coast of Belize created a series of multiple-fault block ridges that controlled the alignment of coastal and shelf features including the Belize Barrier Reef and atolls. The Ambergris Cay Shoreline trend, Turneffe-Chinchorro trend, and Glovers-Lighthouse trend (from west to east respectively) have been maintained by continued extensional faulting and subsidence during the Cenozoic (Dillon and Vedder, 1973).

Purdy (1974) used seismic profile and core data to indicate that Holocene reef distribution is controlled by the underlying Pleistocene karst erosion surface, which varies from subdued relief on the northern shelf to high relief (tower karst) on the southern shelf. Halley et al. (1977) and Shinn et al. (1982) encountered Pleistocene reef and lagoonal mudstone deposits beneath cored Holocene sections approximately 20 km south of Twin Cays at Boo Bee Patch Reef (14 to 21 m below sea level) and Carrie Bow Cay (16.2 m below sea level). Both these studies cited evidence that the Holocene reefs and associated islands were formed on top of relict Pleistocene topographic highs including fossil reefs. Choi and Ginsburg (1982) interpreted from seismic reflection profiles and cores that the Quaternary carbonate section on the shelf in the southernmost Belize Lagoon (about 50 km south of Twin Cays) appears to be founded on elevations of siliclastic fluvial-deltaic coastal plain topography incised during early Pleistocene lowstands. Choi and Holmes (1982) interpreted reef distribution patterns in the south-central Belize lagoon as having been controlled by the fluvial geomorphology. Lara (1993) recognized the imperfect association between Holocene sedimentation patterns and long-lived troughs (forming channels) and ridges (acting as templates for carbonate deposition). She suggested that much older, deeper structural trends have influenced the locations of reefs and major channels and deep water in the Belize Southern Lagoon.

Age Dating of Pleistocene Deposits

Szabo et al. (1978) dated detrital corals from upper Pleistocene beach ridge deposits at 2 m to 10 m above present sea level along the northeastern tip of the Yucatan Peninsula (Cancun and Cozumel) north of Belize. The corals were inferred to have been reworked from reef facies seaward of the beach ridges. Six mineralogically pristine samples yielded an average alpha-spectrometric age of 122,000 ± 2000 yrs, with ^{230}Th and ^{231}Pa concordancy in one of the samples. Because the elevation range of the deposits is similar to those of other late stage 5 reef complex deposits on stable margins of the Caribbean (Florida: Broecker and Thurber, 1965; Hoffmeister and Multer, 1968; Coniglio and Harrision, 1983; Bahamas: Chen et al., 1991), the Northern Yucatan Peninsula was inferred to have been tectonically stable over the last 130 kyrs.

Gischler et al. (2000) dated seven Pleistocene coral samples from the upper 5 meters of Pleistocene section from cores in the offshore, isolated carbonate platforms seaward of the Belize barrier reef at Lighthouse Reef, Turneffe Islands, and Glovers Reef. One additional sample was taken from a subaerially exposed (+1 m) nearshore reef in northern Belize at Ambergris Cay (Ambergris Cay Shoreline trend; Dillon and Vedder, 1973). The latter was correlative, at 128.28 ka ± 1.33 kyrs, to Szabo et al.'s (1978) last interglacial dates from Cancun and Cozumel, while the deeper offshore samples ranged from 124.99 ka to 280.30 ka. In contrast to Szabo et al.'s (1978) virtually pristine aragonitic samples, only three of Gischler et al.'s (2000) seven samples contained greater than 97% aragonite. Two samples contained 86% and 89% aragonite and one contained only 5% aragonite. Recrystallization to low-Mg calcite excludes parent U from the calcite lattice thus concentrating Th and biasing the sample ages anomalously older. The sample from the +1m exposure at Ambergris Cay contained 98% aragonite. Its Substage 5e (128 ka) age was associated with a relatively reasonable initial $^{234}U/^{238}U$ activity ratio of 1.157 $^{o}/_{oo}$, which is just outside the accepted error range for the initial $^{234}U/^{238}U$ ratio in modern seawater (1.14-1.15 $^{o}/_{oo}$). Because elevated $^{234}U/^{238}U$ values are also known, like recrystallization, to be indicative of anomalously old analytical ages (Gallup et al., 1994), none of Gischler et al.'s (2000) deeper samples cored from the offshore platforms, all of which have $^{234}U/^{238}U_{init}$ values ranging from 1.157-1.71 $^{o}/_{oo}$, can be considered reliable age indicators of last interglacial highstand deposition. Despite these acknowledged issues with the accuracy of the dates, Gischler et al. (2000) concluded that the shallow-water limestones underlying the offshore atolls were deposited during the +6m highstand which peaked at 125 ka, and suggest that their current depth range of –4 m to –9 m is indicative of differential subsidence and variation in intensity of karst processes during the subsequent glacial period.

Sedimentary Facies Interpretations

Tebbutt (1975) described the geology, petrography and diagenesis of four facies in the exposed Pleistocene limestones on Ambergris Cay along the seaward edge of the continental shelf of northernmost Belize. Samples were obtained above sea level from discontinuous outcrops. Facies were distinguished by faunal content into reef crest (I), back reef (II), outer, middle and inner shelf (III a, b, c), and mudbank (IV) categories. The three shelf/lagoon subfacies (III a, b, c) were most extensive and consisted of mottled pelmicrites or biopelmicrites with varying amounts of coral, mollusks, *Halimeda*, and ooids. With the exception of the middle shelf zone, which consisted of ooids/ooliths in the Pleistocene, Pleistocene facies were faunally similar to analogous Holocene/modern environments in Belize, and retained some of the original aragonite and magnesium calcite skeletal mineralogy despite long-term exposure in the vadose zone. The Mudbank facies (IV), analogous to *Thalassia* beds in the modern system, may be most similar to the subsurface Pleistocene sediments encountered in this study. Halley et al. (1977) indicated that the Pleistocene mudstone found in three off-reef cores at Boo Bee Patch Reef was identical to typical Holocene lagoonal sediments of the Belizean lagoons. These mudstones showed evidence of subaerial exposure and subsequent burial by terrigenous clays (Halley et al., 1977).

Early descriptions of root casts in Quaternary limestones by Darwin (1895) preceded numerous reports of these organosedimentary structures (see Ward, 1975; Klappa, 1979; 1980; Esteban and Klappa, 1983; Bain and Foos, 1994). Northrop (1890) introduced the term "rhizomorphs" to describe these calcareous root structures, which were later termed "rhizocretions" by Kindle (1923, p. 631). However, despite the many reports of calcareous root casts, very little detailed attention was paid to these important paleoecological features until Klappa (1980) introduced a new term "rhizoliths" (p. 613) and described five basic types of rhizolith structures. Bain and Foos (1994) described a range of sedimentary structures that resulted from subaerial exposure, including rhizoliths, pedotubules, and calcified root hairs in Bahamian limestones, and documented the diagenetic environment created by root penetration and water migration. We will demonstrate that the Pleistocene limestone beneath Twin Cays exhibits the basic features of rhizolith structures described by Klappa (1979; 1980) and Bain and Foos (1994). It is therefore an excellent example of extensive diagenetic alteration of a well-lithified limestone by roots of a terrestrial plant system.

METHODS

In March and April of 1981 a total of seven core holes were drilled around the perimeter of Twin Cays (Fig. 1) with a hand-operated hydraulic drill (Macintyre, 1975; 1978). One hole was drilled on South Point and two holes, one onshore and the other a short distance offshore, were drilled along the east, west and north coasts (Fig. #2, a, b). Only peat debris and molluscan shell hash were recovered above the Pleistocene surface. On encountering the Pleistocene limestone, however, the core recovery was excellent, commonly reaching close to, or 100, percent (Table 1).

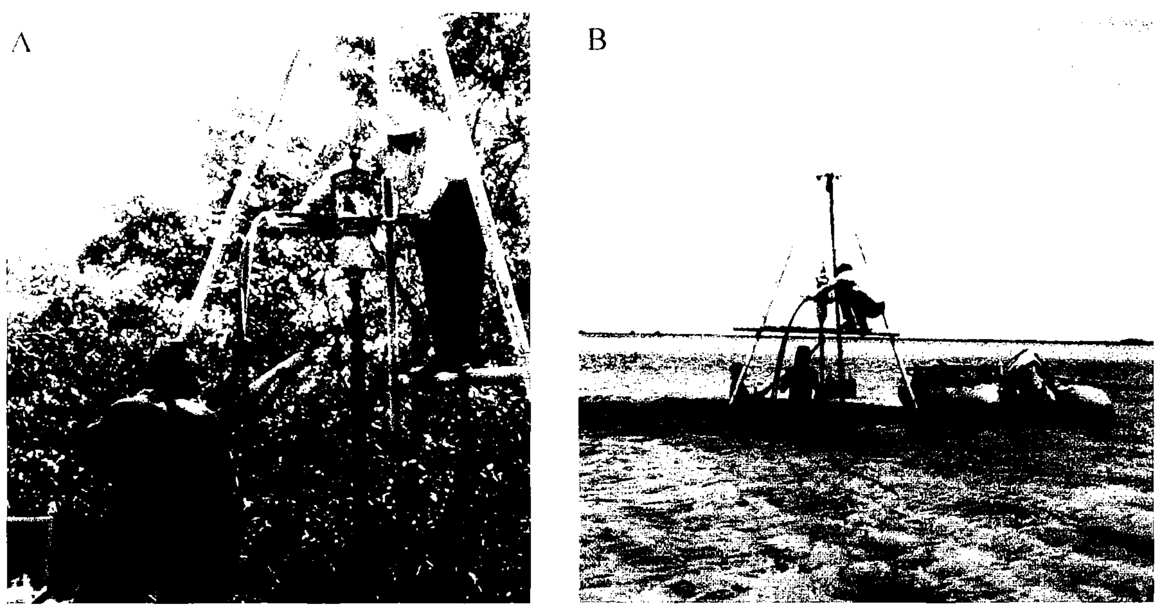

Figure 2. Drilling at site of core hole 2. A) Collecting a core on land. B) Collecting a core offshore.

Table 1. Core Hole Data for Seven Drill Sites, Twin Cays, Belize.

Borehole Number and Location	Core Number	Core Interval (m)	Recovery (m)	Recovery (%)	Core Top	Pleistocene Surface Elevation (m MSL)
#1 South Point	1	0-1.5	0	0	+0.4	-9.6
	2	1.5-10.0	0	0		
	3	10-11.6	1.57	98		
#2A NW Coast	1	0-10.5	0	0	+0.5	-10.0
	2	10.5-11.7	0.9	75		
	3	11.7-12.5	0.44	41		
#2B Offshore 38m from #2A	0*	0-9.4				
	1	9.4-10.6	0.83	69	-0.7	-10.1
#3A N Coast	0*	0-11.2				
	1	11.2-12.4	0.68	57	+0.4	-10.8
#3B Offshore 46m from #3A	0*	0-7.6				
	1	7.6-8.5	0.81	90	-0.7	-8.3
#4A E Coast	0*	0-8.2				
	1	8.2-8.3	0.10	100	+0.1	-8.1
	2	8.3-8.75	0.45	100		
	3	8.75-9.0	0.19	76		
#4B Offshore 40m from #4A	0*	0-7.8				
	1	7.8-9.4	1.58	98.8	-1.1	-8.9

*Holocene peat and unconsolidated *Halimeda* sands washed from core during drilling; not recovered.

Mineralogic analyses were carried out by standard X-ray diffraction techniques (Goldsmith and Graf, 1958; Milliman, 1974), using a Sintag X-ray diffractometer with Cu K radiation, a Peltier detector, and zero-background quartz mounting plates.

A total of five petrographic thin sections were prepared to study diagenetic textures and small samples of the extensively altered patches were mounted on aluminum stubs, gold plated, and examined with a Leica-440 scanning electron microscope.

We were very interested in establishing the age of the Twin Cays Pleistocene limestone by U-Th radiometric dating. However, our X-ray diffraction analyses of well-preserved coral samples all yielded pure calcite values (Fig. 3). This complete alteration of the original aragonite in all corals left us with no valid material to date.

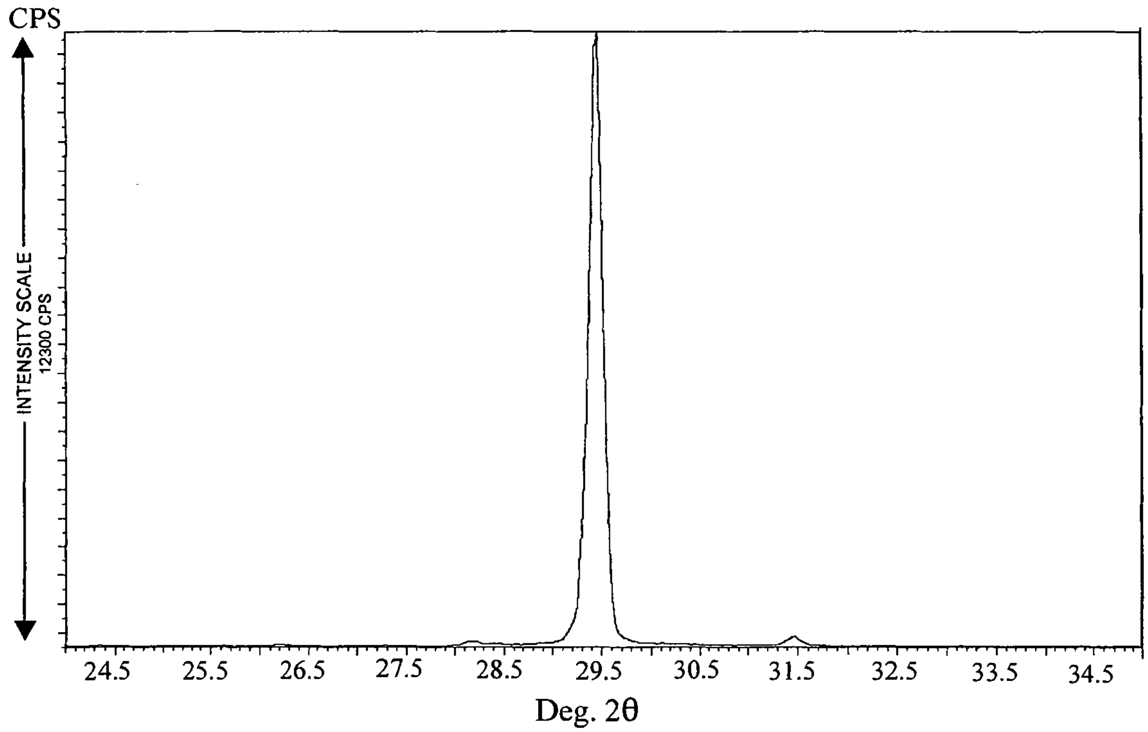

Figure 3. X-Ray diffractogram of a coral *Montastrea annularis* from core hole 2B showing complete recrystallization of biogenic aragonite to calcite. This and all other specimens analyzed were virtually completely recrystallized and unsuitable for radiometric dating.

RESULTS

Core Data

As can be seen in Figure 4, despite the high degree of diagenetic alteration with some loss of the skeletal record, there are two basic reef facies recognizable in these cores. A branching *Porites* facies consists of *Porites* branches in a microcrystalline matrix (Fig. 5). Other corals scattered throughout this facies include *Montastraea annularis* complex species, *Montastraea cavernosa,* and *Manicina areolata.* Molluscs, including both bivalves and gastropods, are common, often as leached casts as are well preserved echinoderm fragments.

The second molluscan facies consists basically of molluscan fragments, mostly bivalves but some gastropods, in various stages of preservation, in a dense microcrystalline matrix. Echinoid fragments are also well preserved in this facies. Corals scattered throughout this facies include *Manicina areolata* and some *Porites astreoides* (Fig. 6).

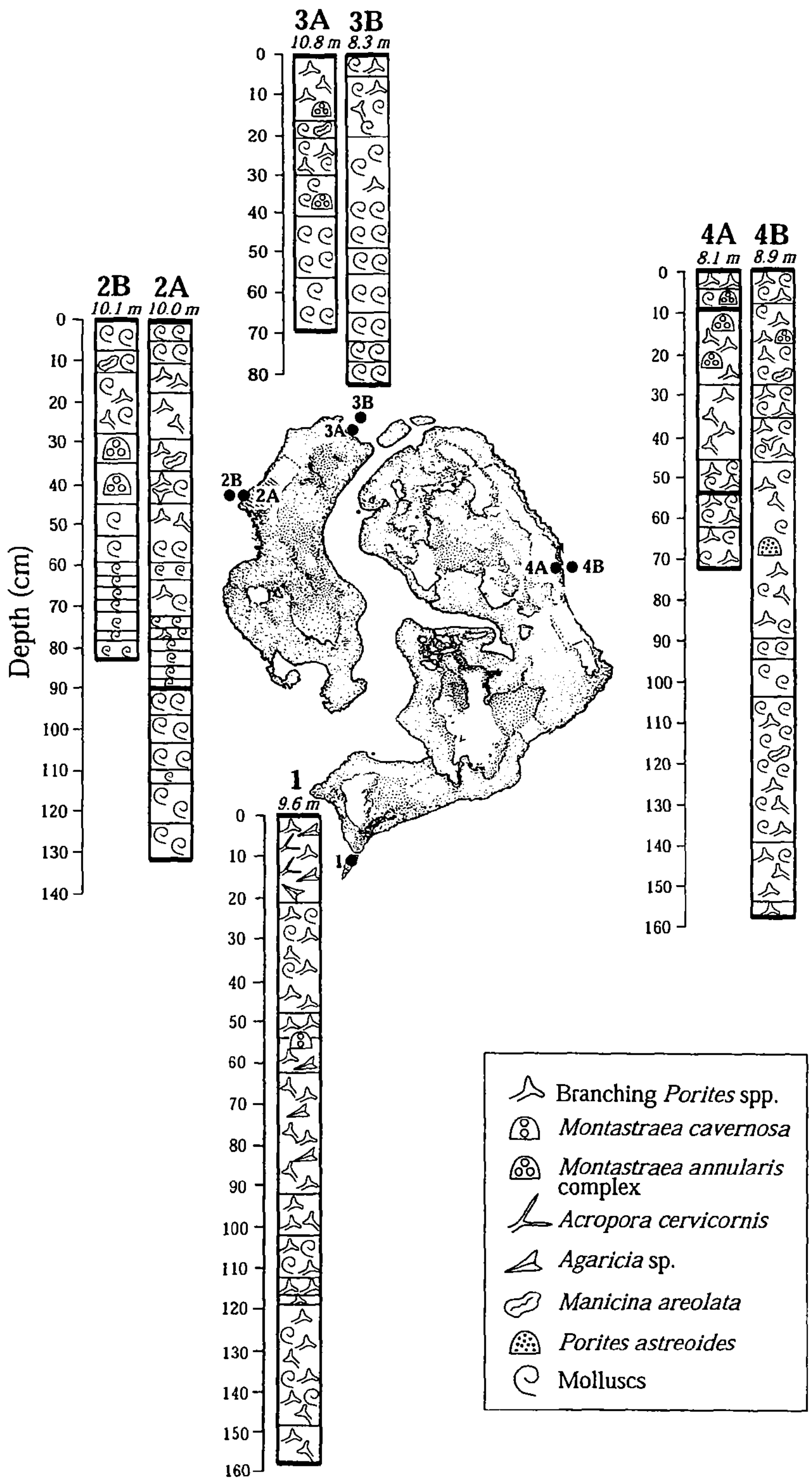

Figure 4. Map of Twin Cays core sites with core logs. Depths above cores in meters indicate depth of top of Pleistocene below mean sea level. Depths in cores marked in cm are depths below the top of the Pleistocene section. Darker lines mark core intervals.

Figure 5. Core photo showing *Porites* (each marked with "P") in muddy matrix.

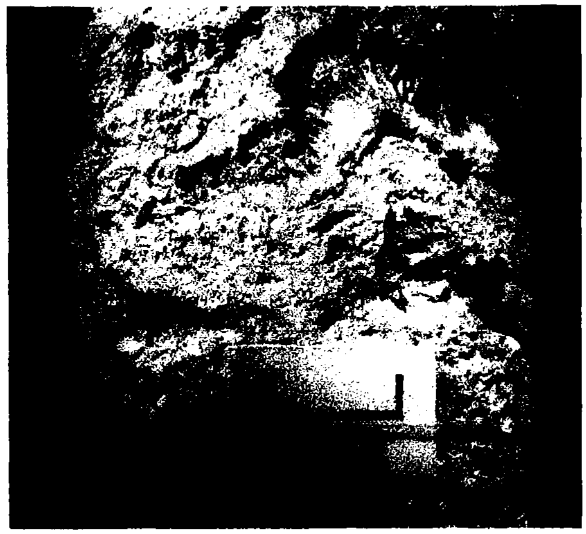

Figure 6. Core photo showing leached and recrystallized *Manicina areolata* in muddy matrix.

All of the cored samples collected in this study have been extensively altered in a subaerial environment. Most samples exhibit a mottled pattern of dense light gray microcrystalline limestone with random patches of chalky light brown-to-buff micrite containing a network of open unoriented tubules. These tubules range in diameter from 0.5 mm to 0.25 (Fig. 7) and are the only readily visible evidence of organic remains in these highly altered chalky patches. Coral, molluscan, and echinoid skeletons were found in various degrees of leaching in the dense grey areas. This extensive alteration, including the chalky patches, extends down to the base of the longest core of 1.58 m collected in Core Hole 4B (Figs. 1, 4).

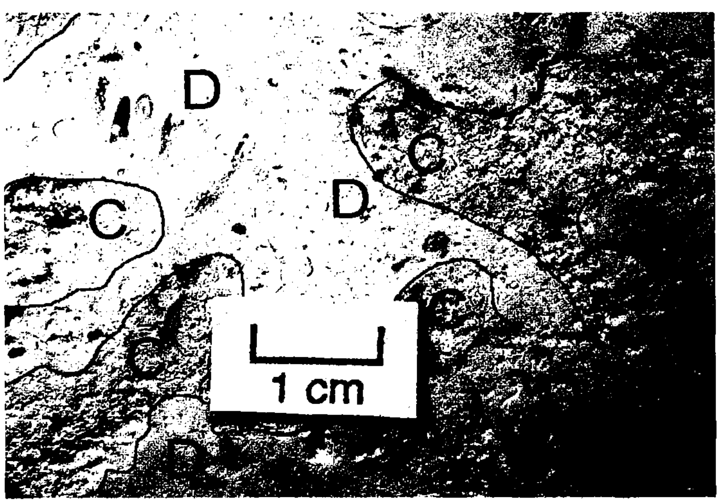

Figure 7. Close-up of core showing contact between dense (D) light gray microcrystalline limestone and chalky (C) light brown-to-buff micrite with unoriented tubules.

Thin Section Analysis

In the thin sections, the chalky areas consist of clotted microcrystalline (30 ηm to 4 ηm) to submicrocrystalline (< 4 mm) calcite with numerous 0.5 mm to 0.25 mm diameter tubules. Micro-tubules 5 ηm to 10 ηm in diameter radiate around the larger tubules (Fig. 8). Most of the skeletal grains in this very porous chalky material are leached out to form molds or are extensively recrystallized to blocky calcite crystals. Recognizable skeletal grains include coral, benthic foraminifera, molluscs, *Halimeda*, echinoid spines and worm tubes. Original Mg-calcite skeletal material such as echinoid spines and benthic foraminifera are generally well preserved. The contact between the chalky tubule calcite and the dense calcite is usually gradual, commonly leaving isolated remnants of the dense calcite surrounded by chalky calcite (Fig. 9). The tubules are also found penetrating the dense calcite and skeletal fragments, such as corals, at these contacts.

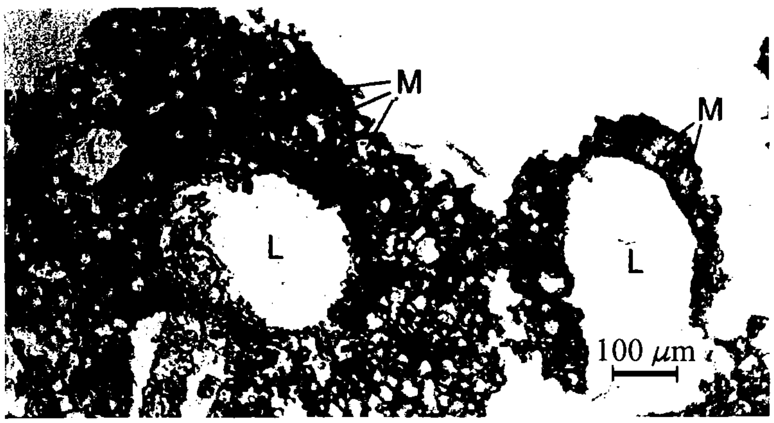

Figure 8. Thin section of core showing clotted microcrystalline to submicrocrystalline chalky calcite with tubules. Micro-tubules (M) radiate from larger tubules (L).

In the dense calcite the skeletal fragments are generally better preserved but there is still extensive leaching of this skeletal material, which results in scattered porosity and fossil molds (Fig. 10). Recognizable skeletal material is identical to that found in the chalky areas with the original Mg-calcite skeletons being the best preserved (Fig. 9).

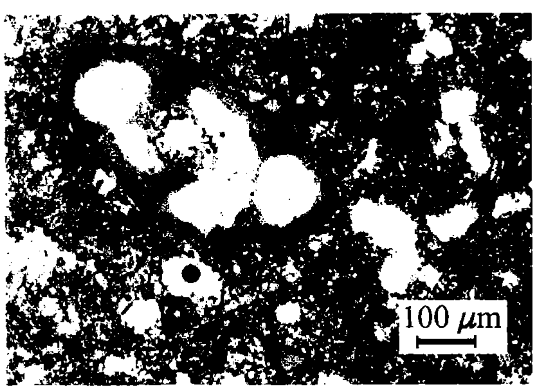

Figure 9. Thin section of core showing gradational contacts between chalky and dense limestone with preserved high-Mg calcite skeletal material (foraminifera).

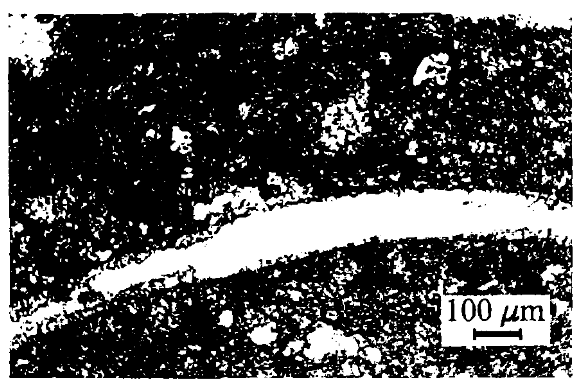

Figure 10. Cross section/mold of leached pelecypod shell in dense limestone.

Scanning Electron Microscopy

Scanning electron microscope (SEM) observations reveal that the chalky calcite crystals range in size from > 4 ηm to 50 ηm (Fig. 11 a, b). These crystals are most commonly anhedral micrite but, in some places, well developed platy calcite (Fig. 11a; Klappa, 1980) and random needle crystals (Fig. 11b; Supko, 1970) can be observed.

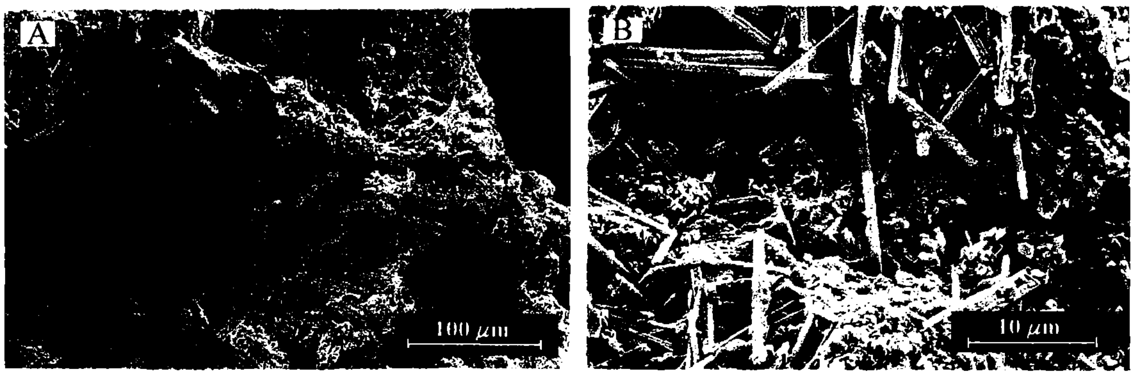

Figure 11. A) SEM image of chalky area showing well-formed platy calcite crystals. B) SEM image of chalky area showing random needle or whisker calcite crystals.

The diameters of the associated tubules vary widely from 5 ηm to 0.5 mm. As seen in thin sections, microtubule casts and molds are closely associated with the larger tubules (Fig. 12). In addition, these tubules commonly have a smooth lining or a secondary rim of dentate calcite crystals, or can be almost completely filled with euhedral crystals. As can be seen in Figure 13, tubules are sometimes found preserved within tubules. The tubules show no preferred orientation and penetrate the chalky calcite in winding random pathways. At contact with the dense calcite areas there is distinct decrease in the density of tubules but some do penetrate the dense areas (Fig. 14). In some cases calcified plant remains, consisting of a root epidermis with radiating root hairs, were found preserved within tubules (Fig. 15).

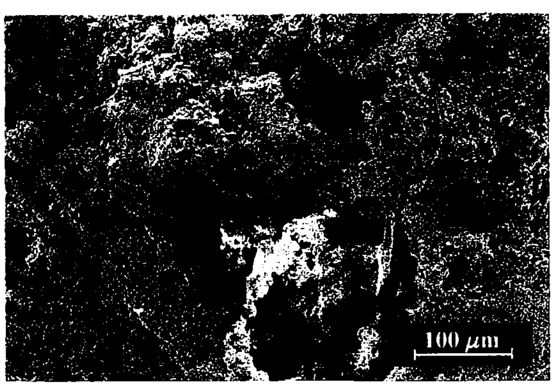

Figure 12. SEM image showing microtubules associated with a larger tubule in a chalky area.

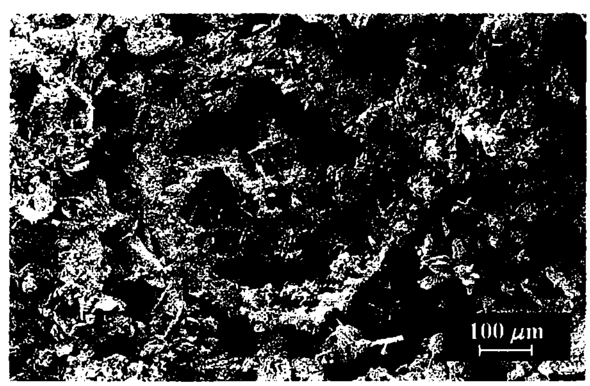

Figure 13. SEM image showing a cross section of a tubule, in which smaller tubules and needle calcite crystals are preserved. Platy calcite crystals surround the large tubule.

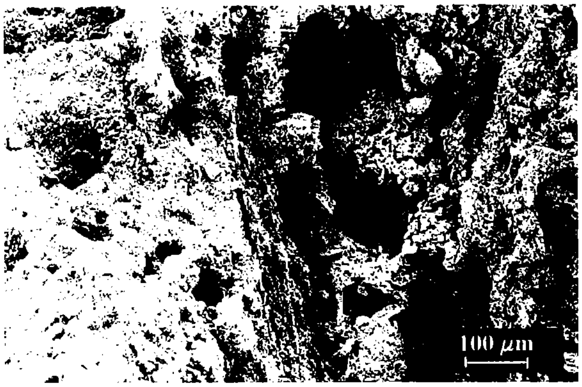

Figure 14. SEM image showing an area of dense limestone adjacent to an area of chalky calcite. The dense limestone contains fewer tubules than the chalky limestone.

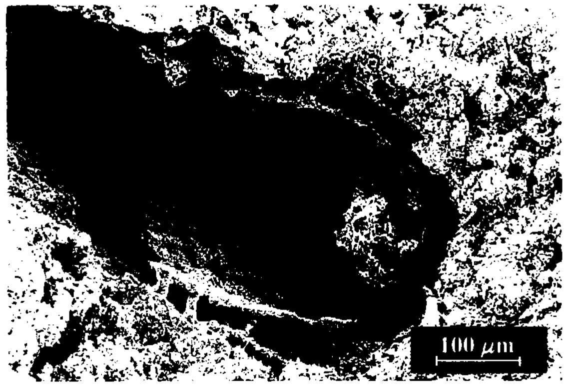

Figure 15. SEM image showing a calcified root epidermis with radiating root hairs.

DISCUSSION

The two reef facies (Fig. 4) consisting of branching *Porites* and scattered molluscs, both in a matrix of fine skeletal material in microcrystalline to submicrocrystalline calcite, are readably distinguishable despite the extensive subaerial recrystallization of this limestone. The branching *Porites* facies is characteristic of lagoonal environments and is well illustrated by the extensive accumulations of branching *Porites* in sandy mud and muddy sand in the Bahia Almirante off the Caribbean coast of Panama (Aronson et al. in prep). The "molluscs in muddy sand with occasional corals", particularly *Manicina areolata,* represent the *Thalassia* community that is still common to the Belize lagoons (e.g. Macintyre et al., 2000). Thus although this Pleistocene limestone has been greatly altered and much of the original texture lost in our cores, it appears that the Holocene mangroves of Twin Cays became established on a Pleistocene substrate formed by lagoonal accumulations of branching *Porites* mounds and *Thalassia* beds, when this substrate was flooded by the Holocene Transgression.

The most striking diagenetic feature in the alteration of this Pleistocene limestone is the widespread mottled chalkification (Constanz, 1989; Fig. 7) associated with a complex tubule pattern (Fig. 12). This appears to be related to the boring activity of a terrestrial plant community. The gradual contact between dense and chalky patches, which appeared to have similar lithology and tubule borings in dense areas, indicates a post-lithification alteration by a penetrating root system that has resulted in extreme recrystallization forming porous chalky patches in an original dense lagoonal limestone.

This Twin Cays altered limestone is an excellent example of what Klappa (1980, p. 613) termed "Rhizoliths — organosedimentary structures resulting in the preservation of roots of higher plants, or remains there of, in mineral matter." This is supported by the presence in this limestone of most of the characteristics that Klappa associates with rhizoliths including root molds, root petrifactions such as calcified epidermis, root tubules around root molds, and encrusted root tubules.

What is so impressive in the Twin Cays limestone is the extensive "rhizomicritization" (Klappa, 1980, p. 628) where solution and reprecipitation have converted a once dense lagoonal limestone into a porous chalky micrite with abundant root and rootlet molds and casts. This limestone, which had been subaerially exposed for a period of 70,000 years or more, was affected by root penetration to at least one and a half meters (our maximum core penetration). Root systems produced such extensive diagenetic alteration that no original Mg-calcite or aragonite remains.

Tebbutt (1975) reported a very similar tubule texture in the Pleistocene limestone of Ambergris Cay in northern Belize. He described this texture as a "puzzling vesicular structure" (p. 311). Interestingly, this texture was most pronounced in his lagoonal "Mudbank" facies, which is very similar to our lagoonal facies. He did not recognize these structures as rhizoliths and suggested that the tubules were primary features "incorporated in the mud" (p. 311) and goes on to speculate on a crustose coralline algal or encrusting foraminifera origin. Only a short distance north, Ward (1975) described rhizoliths, including root-hair sheaths (p. 520), in the carbonate eolianites of northeastern Yucatan Peninsula. Bain and Foos (1994) described the features of vegetative alteration of subaerially exposed late Pleistocene dune, beach and subtidal carbonates on San Salvador Island, Bahamas. Rootlet penetration into the Bahamian limestones resulted in anastomosing pedotubules, alveolar texture consisting of rootlet pores separated by thin micrite walls, and calcified root hairs (20µm diameter).

The greatest challenge in fully documenting the geologic history of this deposit is the lack of mineralogically pristine coralline material for high precision U-Th dating. Existing age data from other studies in Belize (Gischler et al., 2000) are problematic and unreliable. Without unequivocal dates, we cannot determine the definitive age of the deposit, the sea-level elevation during its deposition, or provide tectonic subsidence calculations. However, another possibility may be suggested if we assume minimal subsidence similar to the Bahamas and Florida (Toscano and Lundberg, 1999). Using the depth of the top of the deposit (-8 or more meters) and its location well offshore of potential 125 ka-aged deposits (expected to be exposed onshore, above present sea level), we can suggest a correlation to mineralogically pristine Pleistocene reef deposits from –9 to –21 m at the edge of the Florida Keys shelf. Corals forming these reefs were U-Th dated by Toscano and Lundberg (1999) and represent the final reef deposits of the last interglacial period (substage 5b and 5a, 95-79 kyrs BP). These reefs accreted well offshore of the 125 ka Florida Keys as a result of lowered sea levels (-7 m maximum) from 95-80 ka. The maximum sea-level estimate of –7 to –9 m is constrained by the elevation of concurrent speleothem (cave flowstone) growth in the Bahamas (Li et al., 1989). The undated Pleistocene shelf facies underlying Holocene mangroves of Twin Cays occurs over the same depth range as the Florida reef deposits and may have been deposited during the final substage of the last interglacial period, then subaerially exposed when sea level fell after 79 ka (Toscano and Lundberg, 1999), assuming no major subsidence. The deposits dated by Gischler et al. (2000) may also be correlative to latest stage 5 and a lower than present sea level.

CONCLUSIONS

1) The mangrove islands of Twin Cays were established on a lagoonal Pleistocene limestone consisting of branching *Porites* mounds and *Thalassia* beds.

2) This limestone has been totally altered to calcite with no evidence of original aragonite or Mg-calcite. As a result, the age of this limestone could not be reliably established by high-precision U-Th dating techniques. Based on previous work in Florida and the Bahamas, this deposit may best correlate with the outlier reefs of 95-79 ka age (Toscano and Lundberg, 1999; Li et al., 1989), which occur at similar water depths. This correlation may also be applicable to Gischler et al.'s (2000) samples from the offshore atolls, barring any major Pleistocene shelf faulting or significant subsidence.

3) The extensive subaerial diagenetic alteration of this limestone for a period of 70 kyrs by the penetration of terrestrial plant roots has resulted in widespread chalkification and resultant loss of original petrographic characteristics.

4) The presence of root molds, casts, tubules, and petrifications along with extensive chalky micritization in this altered limestone classifies it as an ideal example of rhizoliths.

ACKNOWLEDGEMENTS

We thank Anthony G. Macintyre, Michael R. Carpenter, Joseph Libby, and Robin G. Lighty for their assistance with the drilling, which took place in March and April of 1981. We gratefully acknowledge Patricia M. Gaydos for an initial description of the cores, Mary E. Parrish for help with graphics, and William T. Boykins for assistance with text and photographic layout (CCRE Contribution number 674).

REFERENCES

Bain, R., and A.M. Foos
1994. Carbonate microfabrics related to subaerial exposure and paleosol formation. Pages 19-27 in R. Rezak and D.L. Lavoie (eds). *Carbonate Microfabrics*. Springer-Verlag.

Broecker, W.S., and D.L. Thurber
1965. Uranium-series dating of corals and oolites from Bahamian and Florida Key limestones. *Science* 149:58-60.

Chen, J.H., H.A. Curran, B. White, and G.J. Wasserburg
1991. Precise chronology of the last interglacial period: ^{234}U-^{230}Th data from fossil coral reefs in the Bahamas. *Geological Society of America Bulletin* 103:82-97.

Choi, D.R., and R.N. Ginsburg
1982. Siliclastic foundations of Quaternary reefs in the southernmost Belize Lagoon, British Honduras. *Geological Society of America Bulletin* 93:116-126.
Choi, D.R., and C.W. Holmes
1982. Foundations of Quaternary reefs in south-central Belize Lagoon, Central America. *American Association of Petroleum Geologists Bulletin* 66:2663-2681.
Coniglio, M., and R.S. Harrision
1983. Facies and diagenesis of late Pleistocene carbonates from Big Pine Key, Florida. *Bulletin of Canadian Petroleum Geology* 31:135-147.
Constanz, B.R.
1989. The primary surface area of corals and variations in their susceptibility to diagenesis. Pages 53-75 in J.H. Schroeder and B.H. Purser (eds). *Reef Diagenesis*. Springer-Verlag, Berlin.
Darwin, C.
1844. *Geologic observations on the volcanic islands and parts of South American visited during the voyage of HMS Beagle. New York*, D. Appleton, 648 pp.
Dillon, W.P., and J.G. Vedder
1973. Structure and development of the continental margin of British Honduras. *Geological Society of America Bulletin* 84:2713-2732.
Esteban, M., and C.F. Klappa
1983. Subaerial exposure. Pages 1-96 in P. A. Scholle, D. Bebout, and C.H. Moore (eds). *Carbonate Depositional Environments*. American Association of Petroleum Geologists Memoir 153.
Gallup, C.D., R.L. Edwards, and R.G. Johnson
1994. The timing of high sea levels over the past 200,000 years. *Science* 263:796-800.
Gischler, E., A.J. Lomando, J.H. Hudson, and C.W. Holmes
2000. Last interglacial reef growth beneath Belize barrier and isolated platform reefs. *Geology* 28:387-390.
Goldsmith, J.R., and D.F. Graf
1958. Relation between lattice constants and composition of the Ca-Mg carbonates. *American Mineralogist* 43:84-101.
Halley, R.B., E.A. Shinn, J.H. Hudson, and B. Lidz
1977. Recent and relict topography of Boo Bee Patch Reef, Belize. Proceedings, *Third International Coral Reef Symposium Miami* 2 (Geology):29-35.
Hoffmeister, J.E., and H.G. Multer
1968. Geology and origin of the Florida Keys. *Geological Society of America Bulletin* 79:1487-1502.
Kindle. E.M.
1923. Range and distribution of certain types of Canadian Pleistocene concretions. *Geological Society of America Bulletin* 34:609-648.

Klappa, C.F.
1979. Calcified filaments in Quaternary calcretes: organo-mineral interactions in the subaerial vadose environment. *Journal of Sedimentary Petrology* 49:955-968.
Klappa, C.F.
1980. Rhizoliths in terrestrial carbonates: Classification, recognition, genesis, and significance. *Sedimentology* 27:613-629.
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.
Li, W.-X., J. Lundberg, A.P. Dickin, D.C. Ford, H.P. Schwarcz, R. McNutt, and D. Williams
1989. High-precision mass spectrometric uranium-series dating of cave deposits and implications for paleoclimate studies. *Nature* 339:534-536.
Macintyre, I.G.
1975. A diver-operated hydraulic drill for coring submerged substrates. *Atoll Research Bulletin* 185:21-26.
Macintyre, I.G.
1978. A hand-operated submersible drill for coring reef substrata. Pages 75-80 in D.R. Stoddart and R.E. Johannes (eds). *Coral Reefs: Research Methods.* UNESCO Monographs on Oceanographic Methodology No. 5, Paris.
Macintyre, I.G. and R.B. Aronson
1997. Field Guide to the Reefs of Belize. *8th International Coral Reef Symposium* 1: 203-222, Panama City, Panama.
Macintyre, I.G., I. Goodbody, K. Rutzler, D.S. Littler, and M.M. Littler
2000. A general biological and geological survey of the rims of ponds in the major mangrove islands of the Pelican Cays, Belize. Pages 13-34 (no. 467) in I.G. Macintyre and K. Rutzler (eds). *Natural History of the Pelican Cays, Belize. Atoll Research Bulletin.*
Macintyre I.G., M.A. Toscano and R.G. Lighty
2004. Holocene history of the mangrove islands of Twin Cays, Belize, Central America. *Atoll Research Bulletin* 510:1-16.
Milliman, J.D.
1974. *Marine Carbonates*. New York, Springer Verlag, 375p.
Northrop, J.I.
1890. Notes on the Geology of the Bahamas. *Transactions, New York Academy of Sciences* 10:4-22.
Purdy, E.G.
1974. Karst-determined facies patterns in British Honduras: Holocene carbonate sedimentation model. *American Association of Petroleum Geologists Bulletin* 58:825-855.

Shinn, E.A., J.H. Hudson, R.B. Halley, B. Lidz, D.M. Robbin, and I.G. Macintyre
1989. Geology and sediment accumulation rates at Carrie Bow Cay, Belize. Pages 63-75 in K. Rutzler and I.G. Macintyre (eds.). *The Atlantic barrier reef ecosystem at Carrie Bow Cay, Belize 1, Structure and Communities*. Smithsonian Contributions to Marine Sciences 12.

Supko, P.R.
1970. Whisker crystal cement in a Bahamian rock. Pages 143-149 in O.P. Bricker (ed), *Carbonate Cements*. Johns Hopkins University Press, Baltimore.

Szabo, B.J., W.C. Ward, A.E. Weidie, and M.J. Brady
1978. Age and magnitude of the late Pleistocene sea-level rise on the eastern Yucatan Peninsula. *Geology* 6:713-715.

Tebbutt, G.E.
1975. Paleoecology and diagenesis of Pleistocene limestone on Ambergris Cay, Belize. Pages 297-331 in K. F. Wantland and W.C. Pusey (eds.). *Belize shelf – carbonate sediments, clastic sediments, and ecology. American Association of Petroleum Geologists Studies in Geology* 2.

Toscano, M.A., and J. Lundberg
1999. Submerged Late Pleistocene reefs on the tectonically-stable southeast Florida margin: High-precision geochronology, stratigraphy, resolution of Substage 5a sea-level elevation, and orbital forcing. *Quaternary Science Reviews* 18:753-767.

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

Ward, W.C.
1975. Petrologic diagenesis of eolianites of northeastern Yucatan Peninsula, Mexico. Pages 500-571 in K. F. Wantland and W.C. Pusey (eds.). Belize shelf – carbonate sediments, clastic sediments, and ecology. *American Association of Petroleum Geologists Studies in Geology* 2.