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Development of small carbonate banks on the south Florida platform margin: response to sea level and climate change

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Abstract

Geophysical and coring data from the Dry Tortugas, Tortugas Bank, and Riley's Hump on the southwest Florida margin reveal the stratigraphic framework and growth history of these carbonate banks. The Holocene reefs of the Dry Tortugas and Tortugas Bank are approximately 14 and 10 m thick, respectively, and are situated upon Pleistocene reefal edifices. Tortugas Bank consists of the oldest Holocene corals in the Florida Keys with earliest coral recruitment occurring at ∼9.6 cal ka. Growth curves for the Tortugas Bank reveal slow growth (< 1 mm/yr) until 6.2 cal ka, then a rapid increase to 3.4 mm/yr, until shallow reef demise at ∼4.2 cal ka. Coral reef development at the Dry Tortugas began at ∼6.4 cal ka. Aggradation at the Dry Tortugas was linear, and rapid (∼3.7 mm/yr) and kept pace with sea-level change. The increase in aggradation rate of Tortugas Bank at 6.2 cal ka is attributed to the growth of the Dry Tortugas reefs, which formed a barrier to inimical shelf water. Termination of shallow (< 15 m below sea level) reef growth at Tortugas Bank at ∼4.2 cal ka is attributed to paleoclimate change in the North American interior that increased precipitation and fluvial discharge. Reef growth rates and characteristics are related to the rate of sea-level rise relative to the position of the reef on the shelf margin, and are additionally modified by hydrographic conditions related to climate change.

Keywords: carbonate bank; reefs; Dry Tortugas; Florida Keys; multibeam bathymetry; coral reef growth; Holocene climate

1. Introduction

A complex framework of modern and relict carbonate geomorphic features dominates the south Florida margin (Fig. 1). The Holocene reef tract in the Florida Keys is represented by a thin (< 6 m) veneer of active ('keep-up') reef that was initially recruited upon Pleistocene reef rock (Enos and Perkins, 1977). The islands comprising the upper Florida Keys (Fig. 1B) are constructed of Marine Isotope Stage (MIS) 5 reef deposits (∼110–125 ka; Shinn et al., 1989). Recently, outlier reefs were identified seaward of the main reef tract, which grew during MIS 5a, at approximately 80

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ka (Lidz et al., 1991; Ludwig et al., 1996). The lower Florida Keys (Fig. 1B) consist of cemented ooid tidal shoals (Hoffmeister et al., 1967) that also developed during MIS 5. Progressing westward from Key West, the reef tract is interrupted and extensive carbonate grainstone shoals occur surrounding the Marquesas (Fig. 1B). The last islands and 'keep-up' Holocene reefs in a westward direction are situated in the Dry Tortugas (Fig. 1). Smaller, deeper carbonate banks that occur near the Dry Tortugas include Tortugas Bank and Riley's Hump (Fig. 1B). The morphology of these three banks suggests that they are all reefal edifices. However, the Dry Tortugas carbonate bank (the largest) supports non-reefal sedimentary environments such as islands, dunes, beaches and submarine sand shoals, in addition to modern active reefs.

The Dry Tortugas, Tortugas Bank, and Riley's Hump are an integral component of this carbonate margin. Though relatively small (<25 km across), these reefs represent localized carbonate factories and framework producers that should exert a fundamental control on the regional geologic framework, and perhaps the long-term evolution of this margin. It is apparent that Tortugas Bank and Riley's Hump have not kept pace with sea-level change, and are therefore considered to be 'drowned' or 'give-up' reefs, indicating that the significance of these features as carbonate producers varies in relation to sea level and perhaps paleoclimate conditions.

Fundamental knowledge gaps exist regarding the age of these carbonate banks, the antecedent geology upon which they are recruited, and how they have responded to sea level and paleoclimate change. The structure of these banks and the role that these small banks play in the overall development of this margin, are unknown. In addition, there are other questions that need to be resolved. Are these carbonate banks aggradational or progradational? Do they support carbonate sedimentary facies other than coralgal reefs? Did these banks coalesce from smaller features?

Geophysical surveys and coring activities were performed in the Dry Tortugas area to gain an understanding of the geologic development of this region, and the response of these carbonate banks to sea level and climate change. Although we do not have sufficient geophysical data and core data to address all of the questions presented above (e.g. we have no cores from Riley's Hump), this investigation provides the foundation for future, more detailed research.

2. Regional geologic and oceanographic setting

The Dry Tortugas is a series of carbonate banks and sand shoals situated on the southwest Florida continental margin (Fig. 1A). The banks define a roughly circular pattern and were described as an atoll by Vaughan (1914). The shallow rim of the atoll is discontinuous and consists of Holocene corals and several sandy islands including Loggerhead Key, Bush Key and Garden Key (Fig. 1B) (Shinn et al., 1977). These banks occupy a transitional zone between the south and east facing rimmed margin (to the east) and the west facing ramp margin (to the north) of the Florida Carbonate Platform. The Holocene reefs that comprise the Dry Tortugas are approximately 14–15 m thick, are composed of massive head corals such as *Montastrea* sp., and are situated upon an antecedent high of the Key Largo Limestone Formation, a Late Pleistocene reef also composed of massive head corals (Shinn et al., 1977). The reefs surrounding the study area represent windward reef margins in regards to their orientation relative to the dominant wind and wave energies (Hine and Mullins, 1983). Tidal energy is also important in the study area with exchange occurring between the southwest Florida shelf (Gulf of Mexico waters) to the north, and the Straits of Florida to the south (Fig. 1) (Shinn et al., 1990).

Two additional significant carbonate banks are situated in close proximity to the Dry Tortugas. These include Tortugas Bank and Riley's Hump (Fig. 1B). Tortugas Bank crests at ~18–22 m below sea level (m bsl), and is located directly west of the Dry Tortugas reefs. A NE–SW trending channel, ~34 m deep and 5 km wide, separates Tortugas Bank from the Dry Tortugas reefs. Riley's Hump is a carbonate bank cresting at ~30 m bsl directly southsouthwest of Tortugas

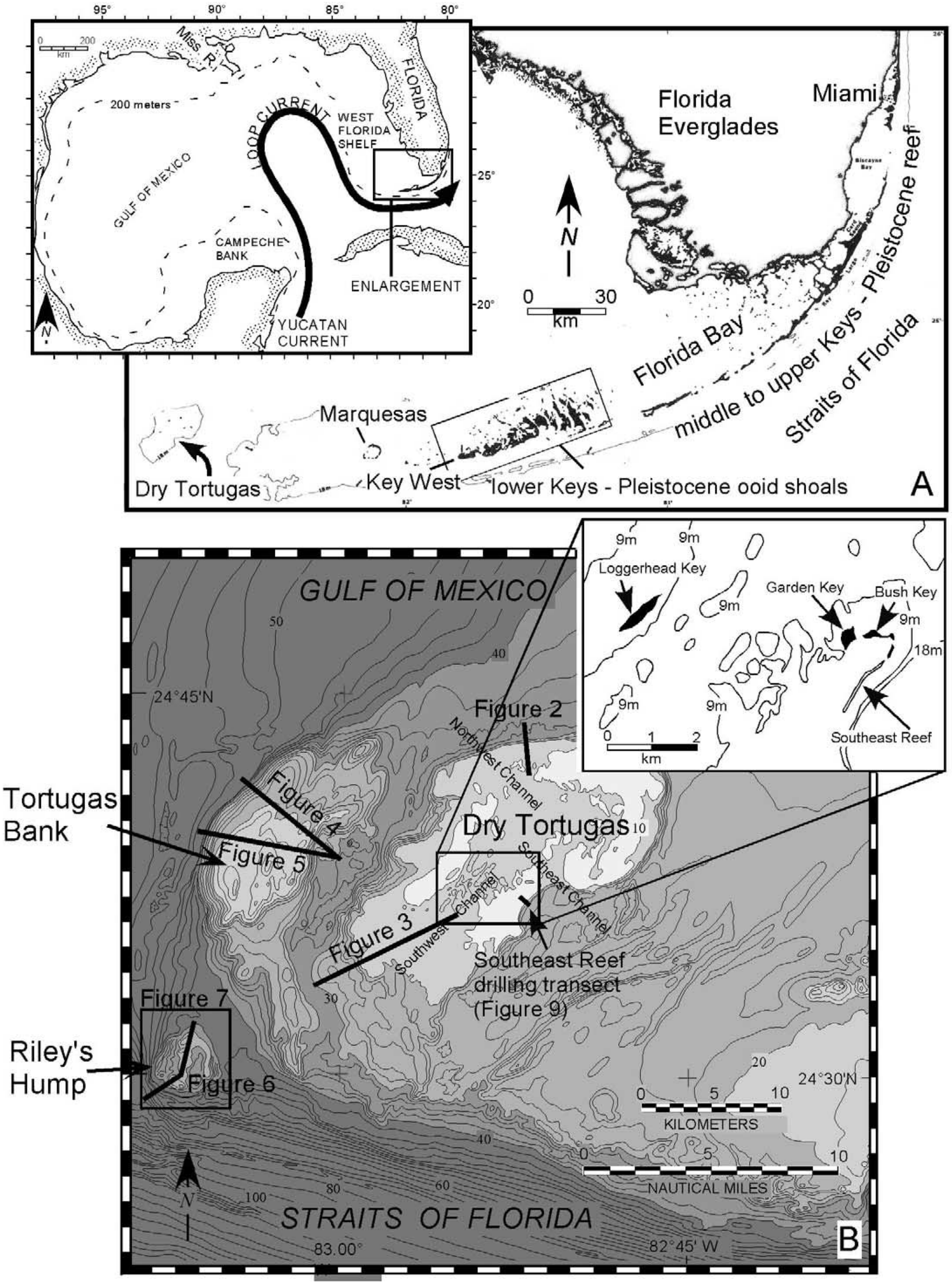

Fig. 1. (A) Maps showing the location of the Gulf of Mexico and Florida Keys, and illustrating the general Pleistocene framework. (B) Maps showing the location of the Dry Tortugas and associated Florida Keys, Tortugas Bank, and Riley's Hump on the southwest Florida margin. Locations of seismic profiles and side-scan sonar data presented in this manuscript are also shown.

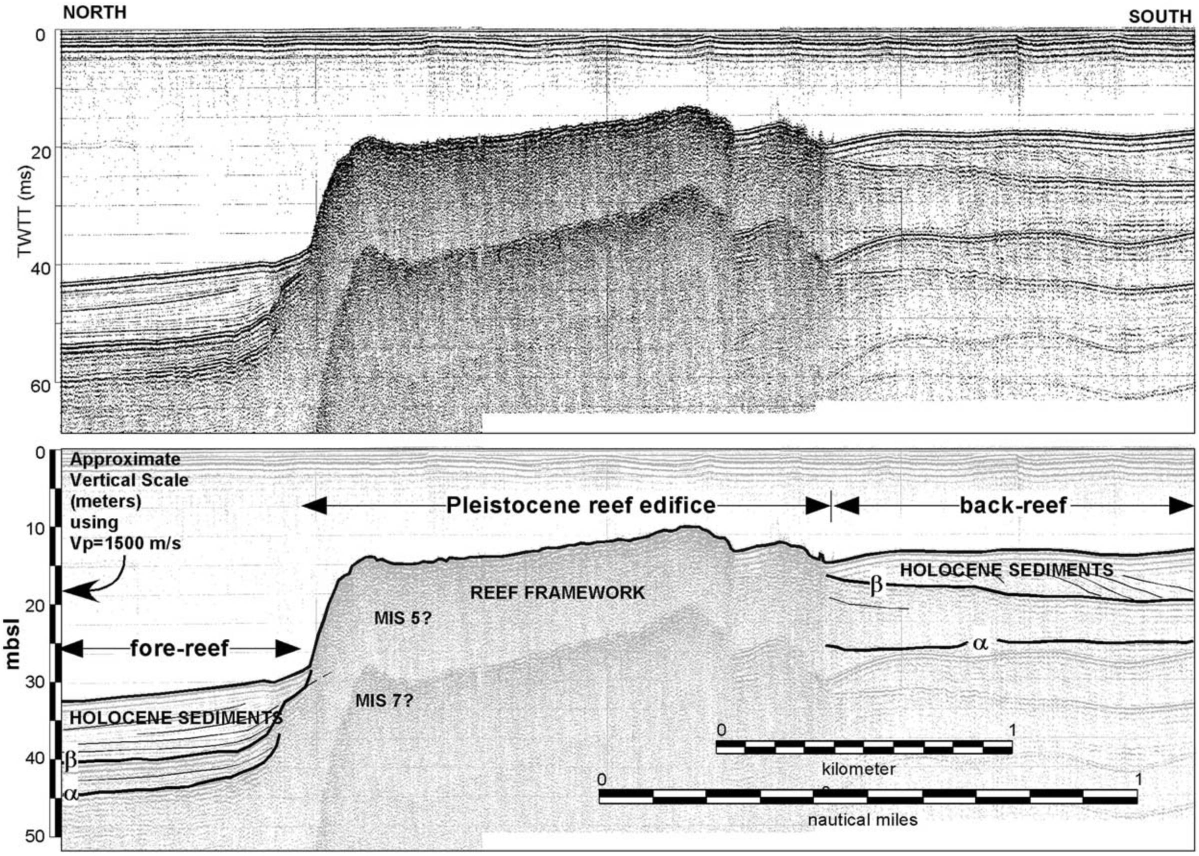

Fig. 2. Uniboom seismic profile with interpretation, of a portion of the Dry Tortugas carbonate bank in Northwest Channel (see Fig. 1B for the location).

Bank (Fig. 1B). The southern face of the bank exhibits a 20-m escarpment situated at the shelf/slope break. Thick sedimentary deposits fill a trough separating Riley's Hump from Tortugas Bank to the north.

Water mass characteristics in the vicinity of the Dry Tortugas are controlled by interactions of the Loop Current and west Florida shelf water (Fig. 1A). The Yucatan Current emerges from the Yucatan Channel and enters the eastern Gulf of Mexico as a narrow boundary current constrained by the Campeche Bank (Fig. 1A) (Fratantoni, 2001). The current then turns northwest and assumes a clockwise circulation, becoming the Loop Current, to flow southward along the steep escarpment of the west Florida shelf before entering the southern Straits of Florida near the Dry Tortugas, and becoming the Florida Current (Maul, 1977; Vukovich, 1988; Molinari and Morrison, 1988). The Florida Current ultimately becomes the Gulf Stream in the North Atlantic.

The Gulf of Mexico is unique in that it is a tropical to subtropical basin with direct links to temperate, high latitude climate conditions via fluvial conduits. This position places carbonate environments on the west and south Florida shelf directly in the path of effluent from the Mississippi River, via entrainment in the Loop Current (Gilbert et al., 1996). It is likely that the effects of Mississippi River discharge, consisting of high nutrient, low salinity waters, are largely to blame for the lack of actively aggrading reefs on this carbonate ramp (Hallock, 1988). The effects of fluvial discharge are diminished southward such that extensive coralgal reefs are encountered on the south margin.

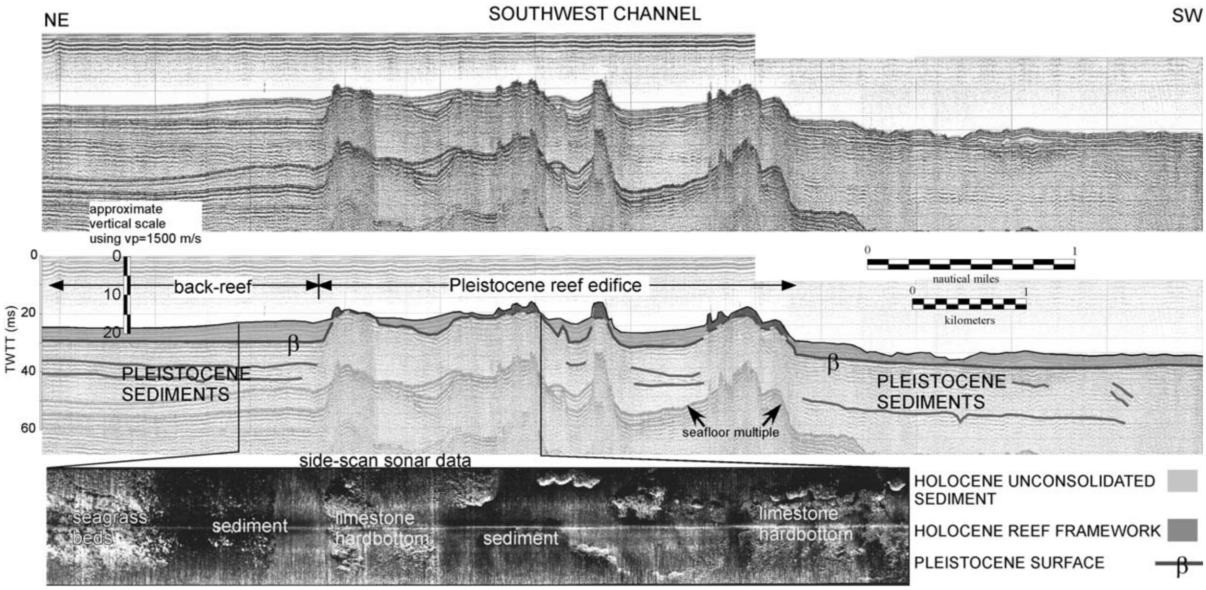

Fig. 3. Uniboom seismic profile and side-scan sonar data with interpretation, from the Dry Tortugas carbonate bank in Southwest Channel (see Fig. 1B for the location). Dark shades on the side-scan data represent low acoustic backscatter corresponding to muddy sands. Lighter shades represent high acoustic backscatter and correspond to live-bottom communities, sand, exposed rock, or seagrass beds.

Seasonal variability in sea surface temperature and salinity (SST and SSS, respectively) at the Dry Tortugas has been monitored since 1991 by an enhanced National Data Buoy Center C-MAN instrument package. SST at the Dry Tortugas varies from a low of ∼22°C in winter to a high of ∼30°C in summer. Seasonal variability of SSS in the Dry Tortugas is large, with maximum values reaching 36–37 psu and minimum values reaching 32–33 psu. This large range in surface salinity results from significant dilution by Mississippi River discharge into the northeastern Gulf of Mexico (Ortner et al., 1995; Gilbert et al., 1996).

3. Methods

Side-scan sonar data (100 kHz) were acquired along seismic profile lines using an EG&G Model 272 TD side-scan sonar towfish and DelphSonar acquisition system. High-resolution single-channel seismic data were acquired using a Huntec uniboom sled, ITI 10-channel streamer, and DelphSeismic acquisition system (Figs. 2–6). Multibeam bathymetry data (300 kHz) were acquired using a Kongsberg Simrad EM 3000 multibeam sonar mounted on a pole on the port side of the R/V *Suncoaster* at ∼9 knots aided by a TSS (now Applanix) POS/MV 320 attitude and positioning system that provided submeter accuracy in positions. A SeaBird (SBE-19) CTD was cast in the deep area of the survey to obtain sound velocity in the water column, but slight variations of the sound velocity structure appear to exist in the shallower waters causing slight track-parallel artifacts that run NW–SE (Fig. 7). Data were post-processed using the Kongsberg Simrad Neptune software to flag out bad pings using an automated standard deviation method with a grid cell size of 4 m. Sea-level height was predicted using a global tidal and hindcast wind program (He and Weisberg, 2002), which uses mean sea level as the chart datum. The post-processed bathymetry data were then gridded at a 5-m cell size in a visual display program called Fledermaus (IVS) which was used to generate plan (Fig. 7A) and perspective (Fig. 7B) views and to generate ESRI ARC files that are being used by biologists for fish habitat studies.

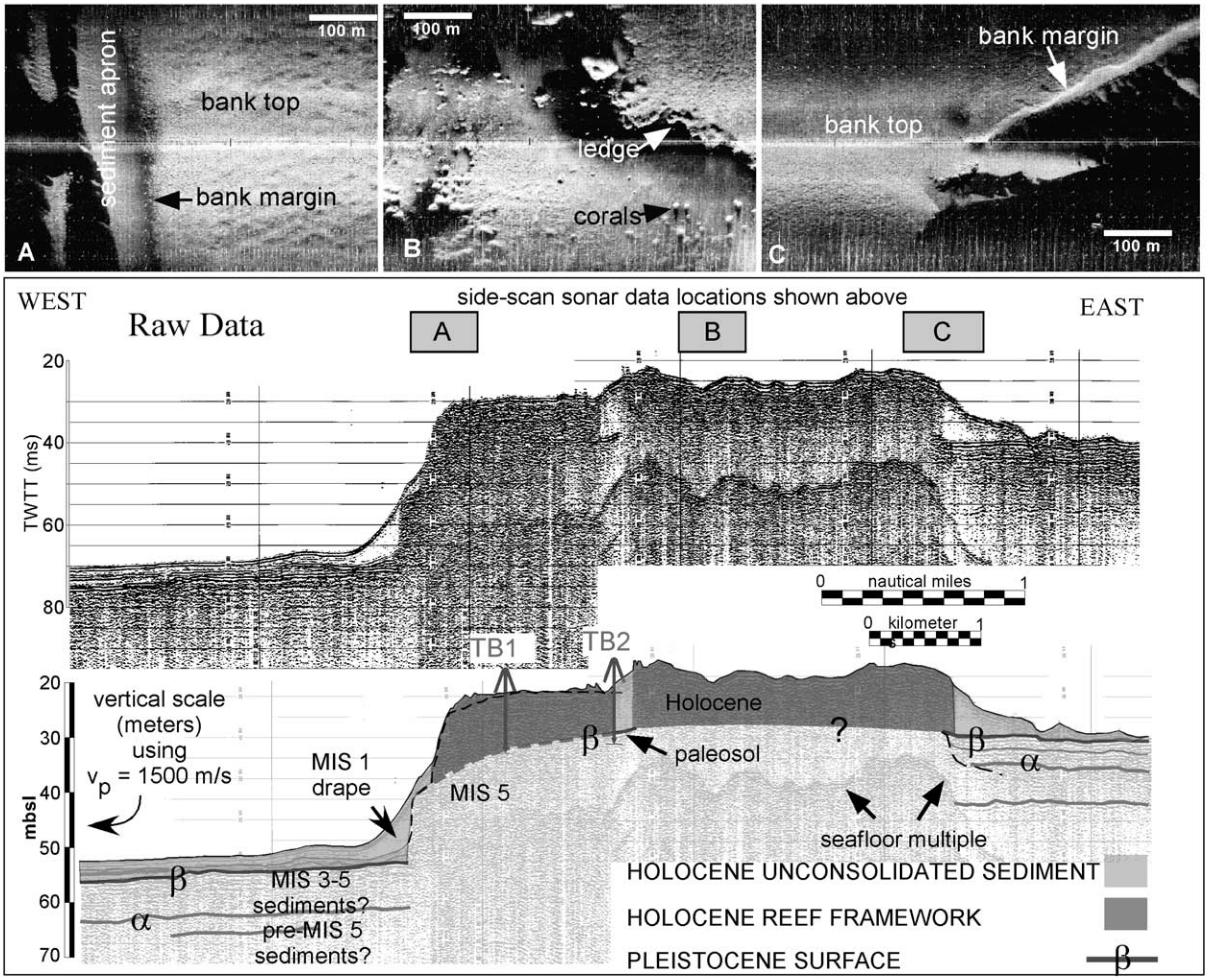

Fig. 4. Uniboom seismic profile of Tortugas Bank with interpretation and location of drill sites TB1 and TB2 (see Fig. 1B for locations). Also presented are selected 100-kHz side-scan sonar data (A, B, and C). Side-scan sonar data locations are indicated on the seismic profile as gray boxes. Dark shades on the side-scan data represent low acoustic backscatter corresponding to muddy sands. Lighter shades represent high acoustic backscatter and correspond to live-bottom communities, sand, or exposed rock.

Coring sites were chosen to target reflectors based on seismic data (Fig. 4). Five sites were cored on Southeast Reef in the Dry Tortugas in 1976 (Shinn et al., 1977). Three sites (TB1A, TB1B, and TB2) were cored on Tortugas Bank using a diver-deployed rotary rock drill provided by the USGS-Center for Coastal Geology, with support by the National Undersea Research Center, Wilmington. Underwater drilling of this type is based on the principle of the hydraulic underwater coring device pioneered by Ian MacIntyre and is described in Shinn et al. (1977), and Miller (1979). The drill uses an 18-hp Briggs and Stratton engine as a power source to run an Eaton hydraulic drill head. Sites TB1A and TB1B were drilled at 24 m water depth. Site TB2 was drilled at 19 m water depth.

Cores were logged and sampled at the College of Marine Science, University of South Florida, and the Center for Coastal Studies, United States Geological Survey, St. Petersburg, FL. X-ray diffraction analyses to determine mineralogy were performed on bulk powder samples using a Scintag XDS-2000. These data were used to assess the

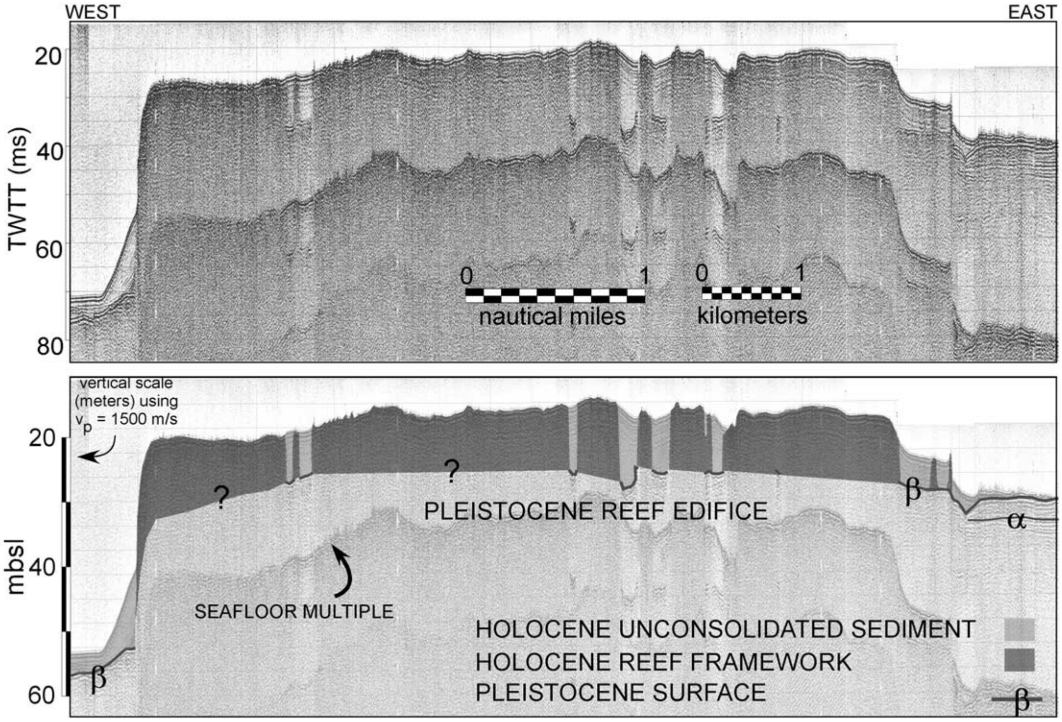

Fig. 5. Uniboom seismic profile of Tortugas Bank with interpretation (see Fig. 1B for the location).

degree of recrystallization of the samples. Uranium-series analyses (α-spectrometer) were performed on unaltered coral samples by Dr. Lawrence Edwards at the University of Minnesota. AMS ^{14}C analyses were performed on unaltered coral samples and one organic sample by the National Ocean Sciences AMS facility at Woods Hole, MS, and by Beta Analytic Laboratories. Conventional radiocarbon dates were acquired on samples from the Dry Tortugas (Shinn et al., 1977) at the University of Miami ^{14}C laboratory. Radiocarbon dates were corrected for reservoir effect and calibrated using the CALIB rev.4.3 software (copyright Stuiver and Reimer, 2000) and the INTCAL98 calibration curve of Stuiver et al. (1998).

4. Results

4.1. Geophysical framework

Seismic data reveal the stratigraphic framework and acoustic facies of the Dry Tortugas, Tortugas Bank and Riley's Hump (Figs. 2–6). The Dry Tortugas exhibits a zone of high signal attenuation characteristic of reef framework facies (Figs. 2 and 3). This reef facies occurs at a water depth of 15 m in the channels between the Holocene reefs (Northwest Channel, Southwest Channel; Fig. 1). The seaward side of the reef facies is characterized by seismic sequences bounded by high amplitude, continuous horizontal reflectors (reflectors α and β; Figs. 2 and 3). These sequences consist of multiple low-amplitude, discontinuous to continuous, subhorizontal, parallel reflectors that onlap the reef facies (Fig. 2). In the Northwest Channel (Fig. 2), a terrace is present in the subsurface associated with the reef facies, at a depth of ∼32 m bsl. The back-reef facies are characterized by seismic sequences similar to those found on the seaward side, but contain steeply inclined clinoforms that downlap onto the underlying sequence boundary (β), and prograde away from the reef facies.

Tortugas Bank has a 30-m escarpment on the

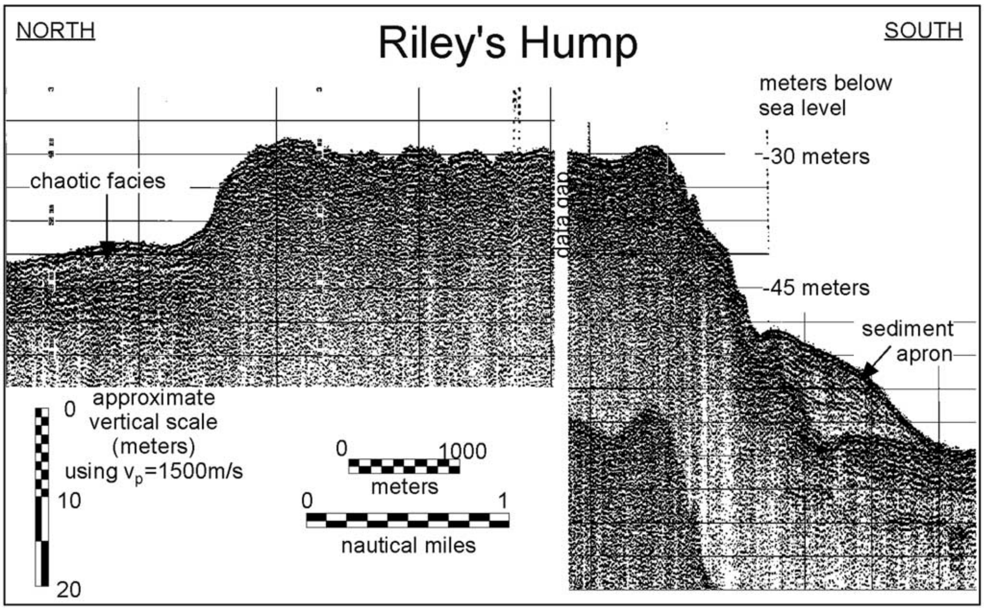

Fig. 6. Uniboom seismic profile of Riley's Hump (see Fig. 1B for the location).

west side and a 15-m face on the east side (Figs. 4 and 5). Sediment aprons drape the flanks of the bank and small patch reefs occur on top of the bank. Seismic data reveal the presence of some internal structure within Tortugas Bank. A high amplitude reflector (β) is intermittently observed and occurs at a depth of approximately 10 m below the top of the bank (∼30 m bsl) and in adjacent sedimentary deposits, and a subtle reflector occurs in the shallow subsurface (∼1 m) near the edge of the bank where TB1A and TB1B were drilled. Reflector β slopes seaward and may correlate with a terrace, buried under drape sediments, on the seaward face of the carbonate bank (Fig. 4).

Seismic data from Riley's Hump appear more chaotic, and exhibit higher attenuation than data from Tortugas Bank or the Dry Tortugas (Fig. 6). No internal structure is evident within the bank. The bank top is relatively flat; however, there is variable relief of up to 5 m associated with NNW–SSE trending linear bathymetric features (Fig. 7). There is a ∼20-m escarpment (from 30 to 50+ m bsl) on the south flank, where reefal limestone appears to be exposed (Fig. 6). A sediment apron, with seaward dipping internal reflectors, extends southward from ∼50 to ∼60 m bsl. Sedimentary deposits exhibiting poorly resolved, chaotic stratigraphy occur to the north of Riley's Hump in the trough adjacent to Tortugas Bank (Fig. 6). Multibeam bathymetry data also reveal NE–SW trending bedforms in both the NE and SE corners of Fig. 7A. The bedforms in the SE corner have large amplitudes and range in depth from 40 to 55 m.

Side-scan sonar data reveal distinctive acoustic backscatter facies that have been interpreted for the Dry Tortugas and Tortugas Bank (Figs. 3 and 4). Some of these acoustic facies have also been ground-truthed by diver observations. The Dry Tortugas back-reef environment is characterized by low backscatter areas with intermittent high backscatter patches (Fig. 3). The seabed in channels (i.e. the Northwest and Southwest Channel) (Fig. 1B) is characterized by high backscatter (Fig. 3). In general, the eastern margin of Tortugas Bank is characterized by high uniform backscatter (Fig. 4C); the western margin of Tortugas Bank is characterized by high backscatter with a dimpled pattern (Fig. 4A); and the majority of Tortugas Bank is characterized by complex, high contrast backscatter patterns with numerous spherical returns and lineations (Fig. 4B).

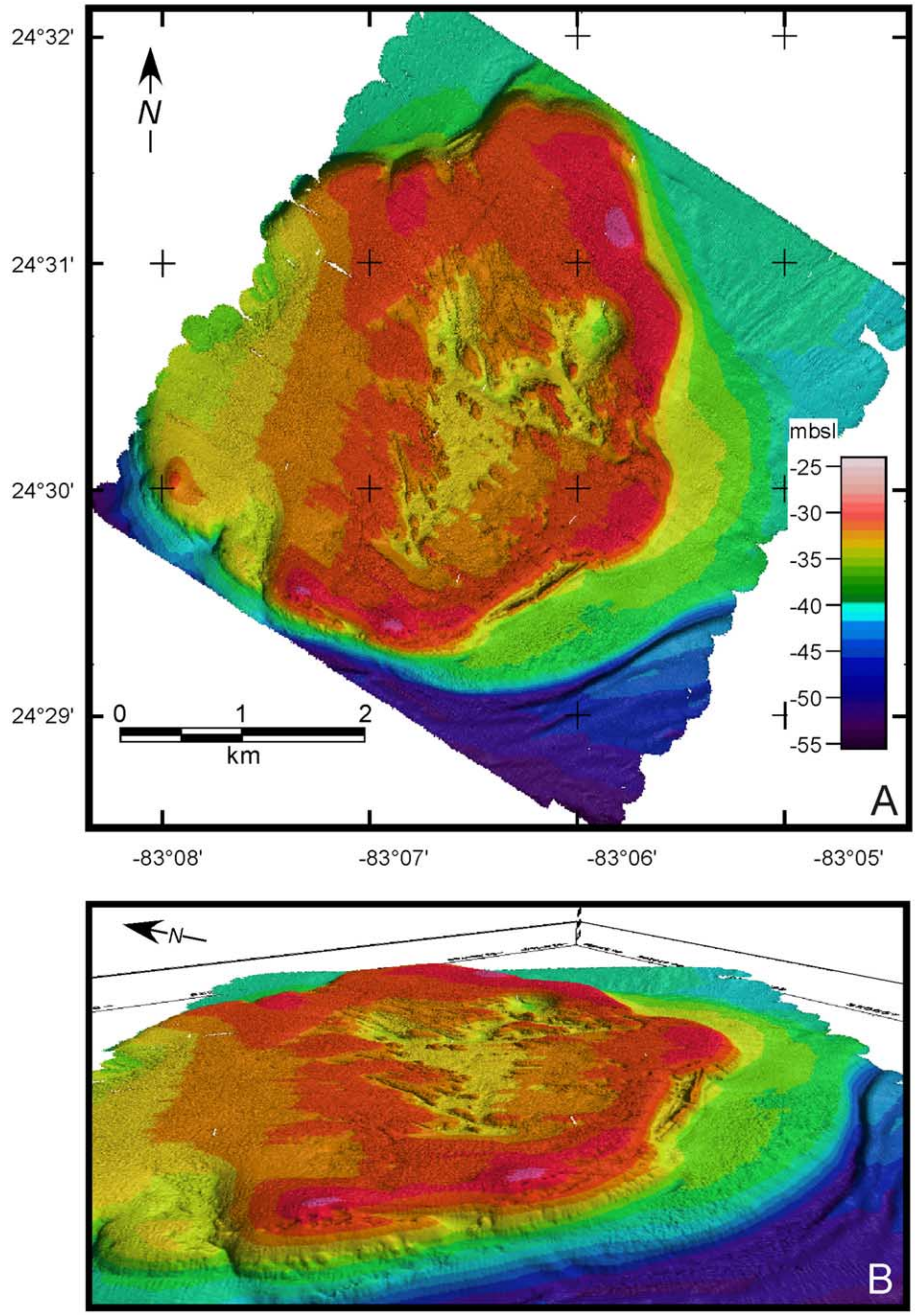

Fig. 7. (A) Plan view of high-resolution 300-kHz multibeam bathymetry over Riley's Hump with shading resulting from an artificial light source from the southeast. (B) 3-D perspective view of the same data looking towards N55E with 10× vertical exaggeration.

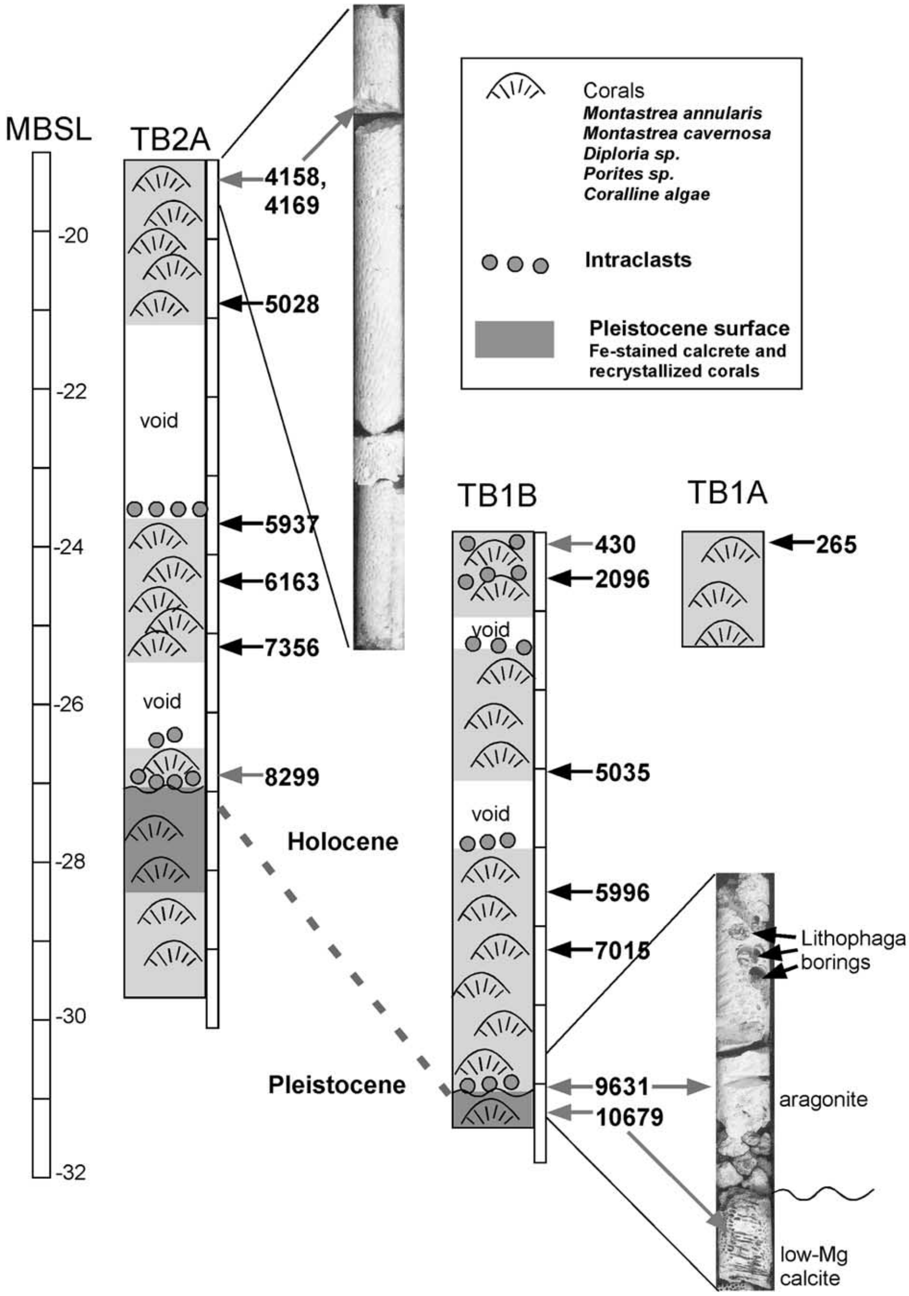

Fig. 8. Generalized logs of the Tortugas Bank cores, TB1A, TB1B, and TB2, with selected photographs and ages.

4.2. Cores

Cores from Tortugas Bank were acquired at 5-foot intervals to subsurface depths of 1.52, 7.62 and 10.67 m. These subsurface depths correspond to absolute depths of 25.3, 31.4 and 29.9 m bsl, respectively. Cores from these sites yielded coral reef framework sediments (various genera and species of coral; Fig. 8), coralline algae, and carbonate intraclasts and cements. A paleosol ho-

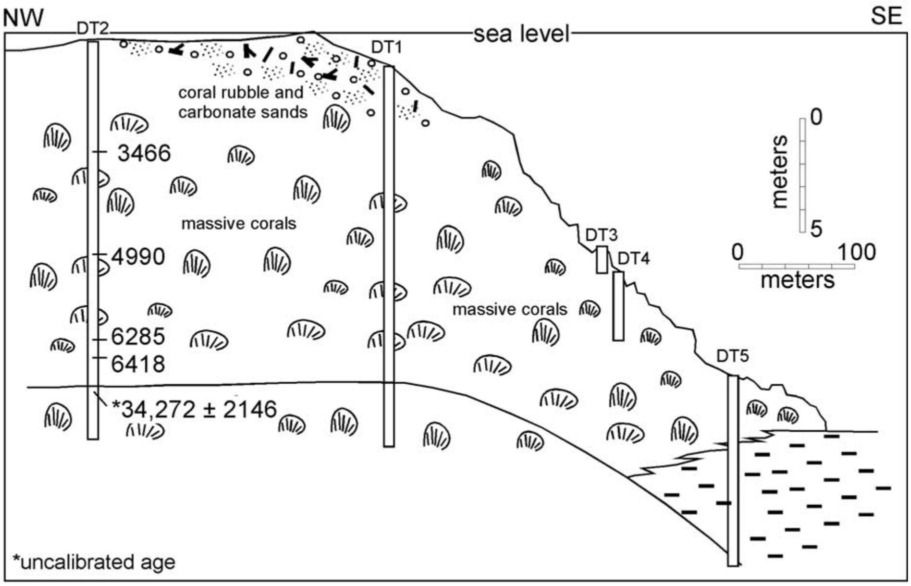

Fig. 9. Cross-section of Southeast Reef in the Dry Tortugas with calibrated radiocarbon ages (modified from Shinn et al., 1977). See Fig. 1B for the location of the transect.

rizon was penetrated at 26–31 m bsl and corresponds to the position of the prominent reflector in seismic data. Several voids were encountered and were noted based on the rapid advance of the drill and zero recovery in at least one core. Cores acquired at Southeast Reef (Fig. 1B) are similar in composition to the Tortugas Bank cores. These cores are described in Shinn et al. (1977) and a profile of the coring transect is illustrated in Fig. 9.

4.3. Ages

Age data are presented in Table 1 and Figs. 7–9. All ages are presented as calibrated years Before Present (yr BP), or calibrated thousands of years Before Present (cal ka). The earliest age that was acquired from the core material is a radiocarbon date of peat associated with the paleosol. This organic material provides an age of approximately 10.7 cal ka (Fig. 8). ^{230}Th and radiocarbon dates of the corals indicate initial coral recruitment occurred on the Pleistocene paleosol at ∼9.6 cal ka. Minimum coral ages are 265 (uncalibrated) yr BP (at the −24-m site) and ∼4.2 cal ka (at the −19-m site). The maximum average growth rate for this relict reef is 3.6 mm/yr. Reef aggradation rates were quite low at both sites between 9.6 and 6.2 cal ka (0.6–1.2 mm/yr), but increased three-fold between 6.2 and 4.2 cal ka. It is interesting to note that the seabed at the shallow site is a hiatal surface representing some 4200 years, whereas the deeper site continued aggrading until recently. There may be a discontinuity in the deep site record between approximately 430 and 2096 yr BP. A discontinuity is also indicated in the seismic data (Fig. 4).

Five radiocarbon dates were acquired from corals in cores from Southeast Reef in the Dry Tortugas (Shinn et al., 1977) (Fig. 9). Dates presented in Shinn et al. (1977) are conventional radiocarbon dates without any corrections. Newly calibrated dates are presented as DT samples in Table 1 and Fig. 8. The oldest age is from the Pleistocene substrate and is not considered reliable. The first Holocene corals in these cores date at 6.4 cal ka. Although the tops of these cores were not dated, we assume that they would yield modern ages as they were taken in an active reef environment.

5. Discussion

5.1. Surficial geology

The Dry Tortugas back-reef environment is characterized by muddy sands with intermittent seagrass beds (Fig. 3). The seabed in channels (i.e. Northwest and Southwest Channel; Fig. 1) is characterized by exposed Pleistocene limestone hardbottom, with scattered Holocene patch reefs (Fig. 3).

Side-scan sonar data and diver observations indicate that the western margin of Tortugas Bank (Fig. 4A) is dominated by an extensive cover of head corals (*Montastrea* spp., *Siderastrea* spp., *Diploria* spp.) with infrequent sand patches ranging in size from 5 to 10 m in diameter. Head corals rise approximately 1–2 m above the sand patch areas. Site TB1 was drilled in one of these patches. Coralgal patch reefs with up to 5 m of relief occur primarily in the central regions of the bank (Fig. 4B). The eastern margin (Fig. 4C) is characterized by a coarse carbonate sand sheet with widely scattered soft corals and sponges.

Multibeam bathymetry data and ROV data (Jarrett, 2003) reveal Riley's Hump to be a rimmed bank with a shallow depression in the center, which contains NNW–SSE trending bioherma structures (Fig. 7). These structures are aligned approximately perpendicular to the flow of the Florida Current that sweeps the outer shelf in this area. Deep (40–55 m bsl) bedforms to the east and south of Riley's Hump also indicate a current-swept environment, and are oriented approximately parallel or oblique to the prevailing current.

These data reveal a gradation of environments, from sandy back-reef type facies on the east side of Tortugas Bank and within the Dry Tortugas central basin, to scattered, high-relief patch reefs at the crest of Tortugas Bank, to prolific head corals on the west margin of Tortugas Bank.

5.2. Stratigraphic framework

5.2.1. Depositional sequences

Seismic reflectors that bound sequences surrounding the carbonate banks appear to be un-

Table 1
Age data from corals and organic matter in the Tortugas Bank (TB) and Dry Tortugas (DT) cores

Core	m bsf	m bsl	Method	Laboratory/Number	^{14}C age	cal yr BP[a]	2σ range
TB1A	0.10	24.2	Conv.	Beta Analytic/134665	590 ± 80	265	420–0
TB1B	0.20	24.3	Th/U	U. Minn.		430	± 5
TB1B	0.62	24.7	AMS	NOSAMS/OS26083	2450 ± 30	2096	2152–1999
TB1B	3.05	27.2	AMS	NOSAMS/OS26084	4790 ± 35	5035	5222–4940
TB1B	4.64	28.7	AMS	NOSAMS/OS26085	5640 ± 35	5996	6158–5927
TB1B	5.30	29.4	AMS	NOSAMS/OS26086	6530 ± 35	7015	7151–6935
TB1B	7.05	31.2	Th/U	U. Minn.		9631	± 30
TB1B[b]	7.60	31.7	AMS	Beta Analytic/134405	9430 ± 60	10670	11045–10970
							10760–10515
TB2	0.10	18.7	Th/U	U. Minn.		4158	± 21
TB2	0.10	18.7	Th/U	U. Minn.		4169	± 18
TB2	1.82	20.4	AMS	NOSAMS/OS26142	4780 ± 35	5028	5207–4907
TB2	4.69	23.3	AMS	NOSAMS/OS26400	5580 ± 45	5937	6099–5881
TB2	5.29	23.9	AMS	NOSAMS/OS26401	5730 ± 60	6163	6272–5979
TB2	6.15	24.8	AMS	NOSAMS/OS26402	6830 ± 80	7356	7480–7207
TB2	7.85	26.4	Th/U	U. Minn.		8299	± 28
DT2	5.3	5.3	Conv.	U. of Miami ^{14}C lab	6017 ± 90	6418	6639–6263
DT2	9.8	9.8	Conv.	U. of Miami ^{14}C lab	5883 ± 224	6285	6779–5837
DT2	13.4	13.4	Conv.	U. of Miami ^{14}C lab	4762 ± 85	4990	5281–4814
DT2	14.3	14.3	Conv.	U. of Miami ^{14}C lab	3593 ± 88	3466	3687–3305

[a] Radiocarbon ages were calibrated using CALIB rev.4.3 software (copyright Stuiver and Reimer, 2000; and Stuiver et al., 1998). All samples (except TB1B-7.60) include a 400-yr reservoir correction.
[b] Organic matter.

conformable surfaces and probably represent erosion and cementation during sea-level lowstands corresponding to glacial periods. These sequences may be equivalent to the Pleistocene Q sequences defined by Enos and Perkins (1977). Groundtruth data for the upper sequence (Mallinson et al., 1997) indicate that sequences consist of carbonate sandy muds and muddy sands. In the region to the southeast of the Dry Tortugas, the sediments are, on average, approximately 97% carbonate, with quartz, biogenic silica, and organic matter comprising the remainder. Sediments are dominated by aragonite and high-Mg calcite (HMC), with lesser amounts of low-Mg calcite (LMC) and trace amounts of dolomite within the silt fraction. Scanning electron microscope observations reveal the composition of the mud as primarily aragonite needles from green algal sources such as *Penicillus* and *Halimeda*, and from coral and mollusk shells. Aragonite chips from the bioerosion of coral by Clionid sponges are also apparent. HMC from the degradation of foraminiferal tests, coralline red algae, and perhaps from direct precipitation is abundant throughout. LMC is present in the form of coccoliths. Sands are primarily composed of benthic and planktonic foraminifera, pelecypod, gastropod, echinoderm, coral, bryozoan, and Halimeda plate fragments, worm tubes, nondescript skeletal material, and carbonate lithoclasts (Mallinson et al., 1997).

5.2.2. *Reef framework*

Based upon the depth to the prominent reflector (β) noted in seismic data from Tortugas Bank (Figs. 3 and 4), and the depth of the paleosol encountered in cores, it is clear that this reflector represents a subaerial exposure surface. This surface occurs at approximately 30 m bsl (29–31 in the cores) at Tortugas Bank, and 14 m bsl at the Dry Tortugas (Shinn et al., 1977).

Although no ages of the recrystallized coral at the base of the Tortugas Bank cores were obtained, the presence of iron staining and meteoric diagenetic properties, including recrystallization to LMC and formation of a calcrete, provide clear evidence that this is Pleistocene substrate that was altered during subaerial exposure associated with a sea-level lowstand. The extent of recrystallization precludes a reliable date by uranium-series or radiocarbon methods.

The Holocene reef was recruited upon the Pleistocene substrate beginning at ∼9.6 cal ka. By comparison to sea level proxy data (*Acropora palmata* stands) from Barbados (Fairbanks, 1989), initial coral growth at TB1 (the deeper site) occurred immediately upon inundation in very shallow water depths. This coral is a *Montastrea cavernosa* with several lithophaga borings (Fig. 8). The oldest coral at TB2 (the shallow site) is a *Porites* sp. with an age of ∼8.3 cal ka, suggesting initial coral recruitment in approximately 5 m of water (Fig. 10).

Tortugas Bank exhibits a structure characterized by extensive development of reef framework, interspersed with zones of unconsolidated sediment. Coralgal patch reefs exhibiting high acoustic attenuation rise vertically from reflector β, the Pleistocene substrate (Figs. 4 and 5). Acoustic facies with lesser attenuation and poorly resolved minor reflectors are characteristic of the sediment accumulation zones between patch reefs (Figs. 4 and 5). The overall framework represents a history of vertical patch reef growth and sediment fill within intrabank lows, to produce the present carbonate bank.

A similar situation occurs in the Dry Tortugas. However, reef growth is limited to the rim of the Dry Tortugas. Unconsolidated sediment fills the back-reef basin of the Dry Tortugas and aggrades as a succession of depositional sequences (Figs. 2 and 3). Limestone hardbottom exposed at 15 m bsl within the Dry Tortugas channels (e.g. Northwest and Southwest Channels) is estimated to be the Pleistocene substrate upon which the adjacent Holocene reefs have developed. Holocene patch reefs and live-bottom communities have also been recruited upon the Pleistocene substrate within the channels.

Seismic data suggest that Riley's Hump consists of reef framework sediments with no apparent significant intrabank depositional basins along the seismic transect. The antecedent substrate is not resolved as a result of the high signal attenuation. The high attenuation and chaotic nature of sedimentary deposits surrounding the bank suggest that these deposits consist of poorly bedded, coarse sediments.

5.2.3. Chronostratigraphic framework and growth history

The earliest date (10.7 cal ka) within the core sediments from Tortugas Bank comes from the organic material associated with a recrystallized coral from TB1B (Fig. 8; Table 1). This organic material has a $\delta^{13}C$ value of −22.4 per mil; characteristic of marginal marine, marsh organics (Sackett, 1964; Middelburg and Nieuwenhuize, 1998). It is unlikely that marsh sediments would develop on this carbonate bank unless the depositional horizon was at or very near sea level. The occurrence of these organic sediments at this depth and time suggests that sea level was approximately 5 m higher at 10.7 cal ka than indicated by coral positions from Barbados, Tahiti, and New Guinea (Fairbanks, 1989; Bard et al., 1996). However, it is difficult to assess the true significance of this single data point as a result of possible calibration errors associated with marsh peats, and the uncertainty of the vertical position of this peat relative to sea level at the time of formation.

By comparison of the position of corals in our cores to the sea-level curves of Fairbanks (1989) and Bard et al. (1996) (Fig. 10), water depth variations over the banks, and the general style of reef aggradation may be inferred (Schlager, 1981; Neumann and Macintyre, 1985). Reef growth at the deep site (TB1) appears to have begun immediately upon inundation of the preexisting reef edifice (Fig. 10). Initial coral growth at the shallow site (TB2) appears to have lagged sea-level rise, such that corals began growing in ∼5 m of water. However, prior to 6.2 cal ka, both sites on Tortugas Bank were in ‘start-up’ mode, with sea-level rise significantly outpacing reef aggradation (Fig. 10). In general, sea level was rising at ∼8–9 mm/yr prior to 6.2 cal ka, while reef aggradation occurred at 0.6–0.7 mm/yr. Following 6.2 cal ka, sea-level rise slowed to an average rate of ∼1.5 mm/yr (Fairbanks, 1989; Bard et al., 1996), and reef aggradation at the shallow site increased significantly to approximately 3.2 mm/yr (Fig. 10). This increase in aggradation, and

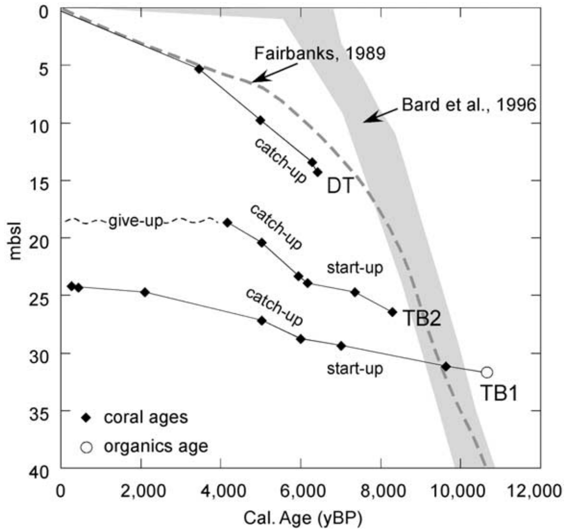

Fig. 10. Graphs illustrating carbonate bank aggradation relative to sea level for sites TB1 and TB2 on Tortugas Bank, and site 2 (DT) on Southeast Reef in the Dry Tortugas (Shinn et al., 1977). The sea-level curves are from Fairbanks (1989) and Bard et al. (1996), and are based on coral reefs from Barbados, Tahiti, and New Guinea.

decrease in sea-level rise, resulted in a brief ‘catch-up’ mode on Tortugas Bank. Given the rate of sea-level rise vs. reef aggradation, the shallow reef could have aggraded another 12.8 m over 4000 years, bringing the reef to a present water depth of 5.8 m, as opposed to the actual depth of 18.6 m. At 6.4 cal ka, reef growth was initiated at Southeast Reef at 3–7 m bsl, and aggradation occurred at a constant rate of 3.5 mm/yr. At approximately 4.2 cal ka, the shallow site (TB2) on Tortugas Bank gave up completely, while the deeper site maintained very slow aggradation rates (0.6 mm/yr). Overall, Tortugas Bank may be characterized as a ‘give-up’ reef, while Southeast Reef may be considered a ‘catch-up’ to ‘keep-up’ reef.

The sudden increase in aggradation rate at Tortugas Bank at 6.2 cal ka could not have been a response to the decrease in the rate of sea-level change, as the water depth over the bank was already approximately 15–22 m, and the slowest aggradation rates correspond to the shallowest water over the reef. A possible explanation for this increase in aggradation rates may be the contemporaneous recruitment of coral reefs at a more landward position on the Dry Tortugas edifice at 6.4 cal ka (Shinn et al., 1977) (Figs. 8 and 9). As the Dry Tortugas reefs grew, they would likely have formed a barrier to the effects of inimical shelf waters that suppressed reef growth on Tortugas Bank. However, given the topographically higher position of the Dry Tortugas reefs, and the correspondingly slower rate of sea-level rise following ∼6 cal ka, the Dry Tortugas reefs were able to maintain high aggradation rates and catch up with sea level (Fig. 10).

It is notable that the Tortugas Bank reef gave up suddenly at approximately 4.2 cal ka at the shallow water site while experiencing high rates of growth. Concurrently, the deep-water site maintained steady but slow aggradation rates. This indicates that the demise at ∼4.2 cal ka was not a function of sea-level change, but must have been in response to a sudden change in water quality, or disease, expressed over a vertical gradient. Likely candidates include an increase in the frequency of low salinity water incursions, or an increase in nutrients, or both. Nutrient resources are at least as important as temperature in limiting coral-reef development (Margalef, 1968; Kinsey and Davies, 1979; Wiebe et al., 1981; Hallock and Schlager, 1986). Hallock (1988, p. 281) proposed that 'suppression of reef development and stimulation of bioerosion by excess nutrients' might explain the lack of modern coral reefs on the west Florida shelf. On the Nicaraguan Rise, the reef turn-on/turn-off transition appears to occur over a narrow range of chlorophyll concentrations (∼0.15–0.20 mg Chlor a/m^3) (Hallock et al., 1988).

Recent work on Holocene marine deposits in the Gulf of Mexico has led to the development of a proxy (peaks in siliciclastic grain size, planktonic faunal turnover and negative $\delta^{13}C$ excursions) for the identification of North American megafloods during the Mid- to Late Holocene (Brown et al., 1999). Multidecadal episodes of high continental precipitation and large Mississippi River floods have been identified using this signature at ∼4.7–4.2, 3.5, 3.0, 2.5, 2.0, 1.2, and 0.3 cal ka (Brown et al., 1999). Holocene alluvial records in the Upper Mississippi Valley indicate an increase in overbank flooding at ∼3.3 cal ka (Knox, 2000). Generally, the climate picture emerging for the North American interior is one of aridity from ∼10 cal ka to ∼4 cal ka (Knox, 2000; Forman et al., 2001). The Mississippi River is known to be a major source of fresh water to the Gulf of Mexico, and ultimately to the Gulf Stream (Gilbert et al., 1996). Several processes are responsible for the production and transport of large volumes of low salinity water to the Florida Straits. Meteorological conditions are responsible for producing overbank flooding in the Mississippi River valley. Favorable winds may then drive the outflow to the southeast to be entrained in the Loop Current and advected to the vicinity of the Dry Tortugas (Gilbert et al., 1996).

The concurrence of the demise of the shallow reef, and the increase in precipitation and megaflood events at ∼4 cal ka suggests that the demise of the shallow reef was a result of intermittent low salinity, mesotrophic waters bathing Tortugas Bank; a process that continues today (Ortner et al., 1995; Gilbert et al., 1996). A well-documented megaflood event occurred in 1993 and affected the Tortugas area. The average position of the halocline separating low salinity, mesotrophic effluent from high salinity, oligotrophic marine water must have been such that the deeper reef was not as severely affected. The respective depths of the deep and shallow reefs at 4 cal ka were ∼23 m and 13 m (Fig. 10). Salinity data from offshore Looe Key (40 km east of Key West; Fig. 1) indicate that the steepest salinity gradient associated with the 1993 flood occurred at a depth of 10–15 m (Gilbert et al., 1996). A similar plume of fresh water occurring at 4 cal ka would have placed the deep reef under full marine conditions (psu of 35–36) while bathing the shallow reef with mesotrophic waters with salinities of 32–33 psu. These data suggest that continental-scale paleoclimate change and megaflood events (both past and future) play a critical role in the health and demise of coral reefs on the south and west Florida shelf. More arid conditions with less fluvial discharge to the Gulf of Mexico prior to 4 cal ka may have allowed the development of the Florida Middle Ground relict reefs in the northeast Gulf of Mexico as well.

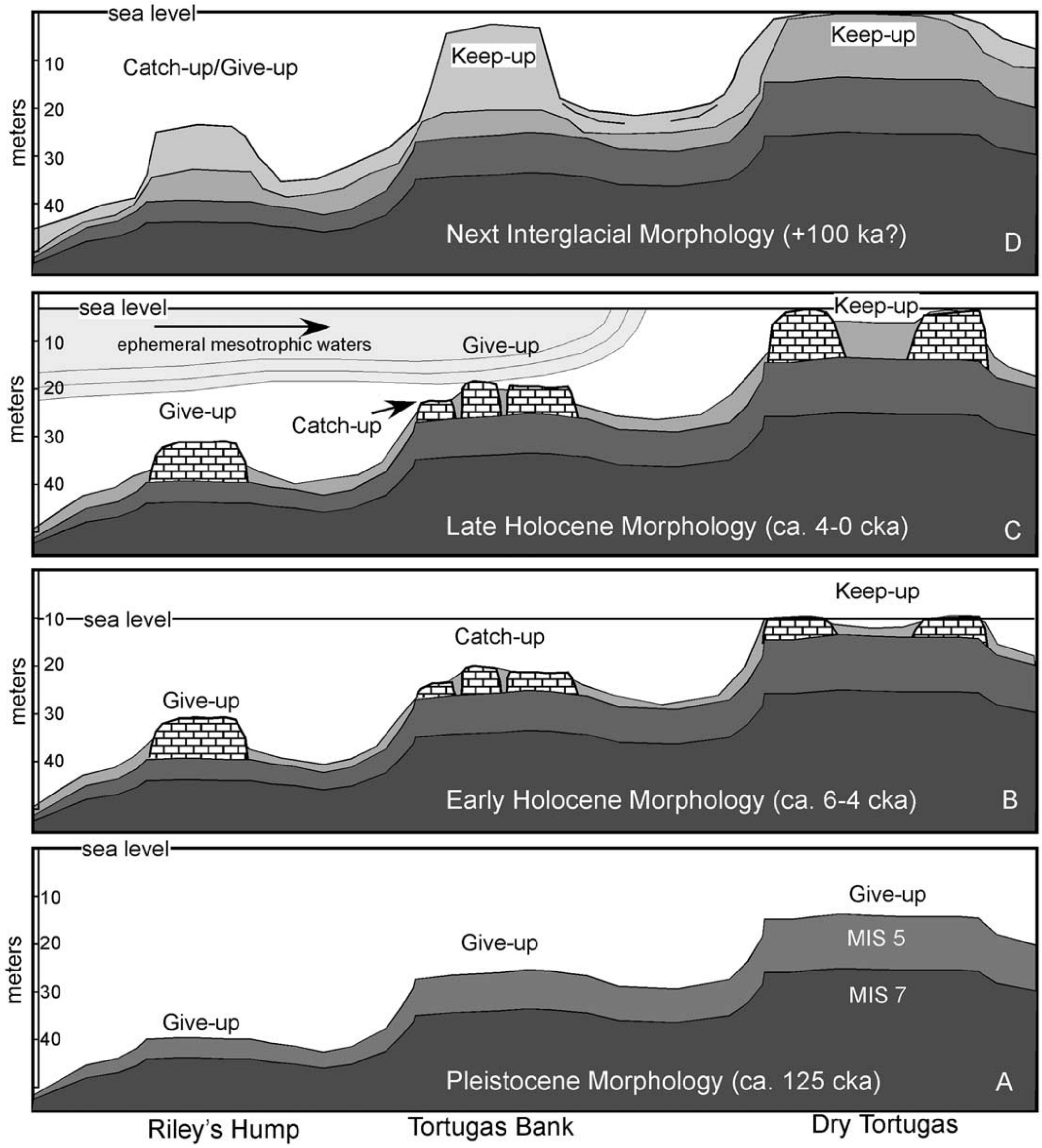

Fig. 11. Cross-section of Tortugas Bank, Dry Tortugas and Riley's Hump with the chronostratigraphic framework indicated (framework is speculative for Riley's Hump). The cross-section illustrates the successive phases of development of this margin in response to sea-level fluctuations. Each bank aggrades incrementally during successive sea-level events. Upon failure of the topographically lower bank (Riley's Hump and Tortugas Bank) corresponding to high rates of sea-level rise, the reef back-stepped to an available edifice occurring at an elevation commensurate with slower sea-level rise (the Dry Tortugas). Tortugas Bank is also modified by the incursion of mesotrophic water from Mississippi River discharge.

5.3. Implications for carbonate margin evolution

The age data and seismic data support a model of stepwise margin aggradation and progradation in response to Milankovitch-scale sea-level cycles (Fig. 11), modified by local and regional changes in hydrographic conditions. This model may only apply where trophic conditions are such that reefs are near the turn-on/turn-off threshold. Under more oligotrophic conditions reef aggradation may not necessarily be limited by high rates of sea-level rise.

During initial flooding of the margin associated with a Pleistocene sea-level rise, reef growth occurred on existing edifices, but failed to keep pace with the rapid rise due to marginal trophic conditions. This resulted in a series of give-up reefs (e.g. the Pleistocene morphology; Fig. 11A). During the subsequent Holocene rise, reef growth occurred once again on the now more elevated edifices. However, the lower edifice (Riley's Hump) corresponded to high rates of sea-level rise, and gave up. The reef back-stepped to the topographically higher edifice of Tortugas Bank and the Dry Tortugas (Fig. 11B–C). Aggradation at Tortugas Bank was further modified by paleoclimate change and the ephemeral incursions of low salinity mesotrophic waters from the Mississippi River discharge (Fig. 11C), causing the shallow reef to give up.

During successive rises, each reef edifice aggrades incrementally, until it reaches a level commensurate with slow sea-level change associated with the peak of an interglacial highstand (Fig. 11D). At such a point, the bank may be able to keep-up with the sea-level rise (the modern Dry Tortugas), and off-bank shedding may begin a progradational phase with deposition occurring in surrounding topographic depressions. Aggradation of a bank may be easily suppressed, interrupted, or terminated by adverse water column conditions from inimical shelf waters, or low salinity/nutrient enriched water masses from megaflood events. This model results in a series of back-stepping carbonate banks (Schlager, 1992) reflecting the combined impact of sea-level rise rates and trophic conditions. Given multiple successive sea-level events, as each bank eventually aggrades to a highstand level, progradation may ensue causing the banks to coalesce and step the margin seaward. Thus, the back-stepping provides the multiple reefal edifices that allow aggradation of individual carbonate banks, and eventual progradation of the margin. However, margin progradation seaward of Riley's Hump is probably severely limited by the occurrence of the Florida Current, which actively transports off-bank sediments toward the east.

Eberli and Ginsburg (1989) proposed a similar, but larger-scale mechanism for margin progradation and bank coalescence in the Bahamas. They found the Bahama Banks aggrading and prograding in response to sea-level change on scales of millions of years (third-order cyclicity) during the Cenozoic. Our observations are on a smaller spatial and temporal scale, and incorporate high frequency sea level and hydrographic changes. Lidz et al. (1991) developed a similar interpretation for margin progradation by filling of troughs behind the MIS 5a outlier reefs in the lower Keys. Lighty (1985) defined the growth and demise of Holocene reefs on the southeast Florida shelf. These reefs grew rapidly between ~9.4 and 7.1 ka (uncalibrated radiocarbon years), then abruptly 'gave up' in response to sea-level rise and the development of back-reef inimical waters (turbid, cool water) that were episodically advected across the reef during storm events. Our findings on the southwest Florida margin reveal that the margin morphology reflects the response to all of these processes (i.e. sea-level driven carbonate production and margin progradation and aggradation; coalescence of small carbonate banks; reef responses to inimical waters) in combination with climate change and boundary current processes.

Our interpretations indicate that carbonate sequence stratigraphic and sea-level models using reef step-back as an indicator of very rapid sea-level change may be oversimplified. It is important to consider the interregional relationship of the carbonate system, fluvial systems, boundary currents, and paleoclimate change at scales well beyond the local level.

6. Summary and conclusions

This investigation reveals the development of small, back-stepping carbonate banks on the south Florida margin. Small carbonate banks form on preexisting coralgal reef edifices during rising sea level. Banks are the product of the coalescence of smaller patch reefs by sediment fill within lows between reef framework areas. Tortugas Bank represents the oldest known Holocene reef in the Florida Keys, with initial coral recruitment occurring at 9.6 cal ka. Coral reef growth began in the Dry Tortugas at ~6.4 cal ka. Accelerated aggradation of Tortugas Bank at 6.2 cal ka is likely the result of reef growth at the Dry Tortugas, which blocked inimical shelf waters. The general demise of the shallow reef at Tortugas Bank at 4.2 cal ka may have been related to a paleoclimate transition over North America that was manifested in the Dry Tortugas area as an increase in exposure to low salinity, high nutrient waters. The Dry Tortugas reefs were able to keep up with the late Holocene sea-level rise simply because of their topographically higher elevation that coincided with the slow rate of rise following ~6 cal ka.

Our data indicate that under conditions of marginal reef range, the morphology of the margin is controlled by a diverse and far-ranging combination of factors. These factors include the initial rate of sea-level rise as the margin is flooded, changes in the rate of sea-level rise, the depth of the initial substrate, the position with respect to the trophic resource continuum (Hallock and Schlager, 1986; Hallock, 1988; Hallock et al., 1988), ephemeral adverse water column conditions, and the presence of a boundary current.

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