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GEOMORPHIC AND SEDIMENTOLOGIC HETEROGENEITY ALONG A HOLOCENE SHELF MARGIN: CAICOS PLATFORM

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ABSTRACT: Reef-rimmed margins on isolated carbonate platforms are heterogeneous, and studying Holocene platforms provides a valuable means for characterizing the spectrum of facies variability and understanding the processes behind facies changes. In this study, insights from petrographic data, granulometric measurements, bottom observations, and remote sensing and subbottom profiler data from the northwestern part of Caicos Platform make this one of the more intensely studied shallow-marine carbonate systems in the Caribbean. Collectively, analyses of the thicknesses and heterogeneity of shallow-water Holocene carbonates and the platform margin reveal details of the considerable geomorphic variability present on this part of the margin, on which the orientation changes markedly.

In this area, the shelf margin arcs from northwest- to north- to northeast-facing, accompanied by changes in morphology as well as the distribution, thickness and type of sediments. The NW-facing margin has discontinuous reefs near the margin, flanked platformward by coarse sands in poorly developed aprons that transition to a deeper rocky bottom (interpreted as Pleistocene) with patches of sand to fine gravel sized sediment. Locally, lobate-to-arcuate shoals with medium sands ($<$ 500 μm mean size; peloids and skeletal grains) form discontinuous nearshore sediment wedges. Above the gently seaward-dipping surface of the interpreted top-Pleistocene surface on this part of the margin, the most pronounced bathymetric changes (greatest relief $\sim$ 3 m) occur around reefs and tidal deltas. In contrast, the NE-facing margin includes a continuous aggraded reef with just two passages to the open ocean (Sellar's Cut and Wheeland Cut). Just behind the reef, landward-fining coarse skeletal–peloidal sands ($>$ 500 μm mean size) form a reef apron that is continuous along strike and over 1000 m wide. Because the interpreted top-Pleistocene surface is gently dipping seaward, Holocene sediment thicknesses vary with changes in bathymetry and generally thin away from the reefs. Sediments in most areas are between 1.5 and 3 m thick but can reach over 6 m locally. Although the interpretation of the base of the Holocene can be ambiguous under shelf-margin reefs, subbottom profiles illustrate that backreef shelf patch reefs do not necessarily nucleate on Pleistocene bedrock highs.

Facies trends are interpreted to reflect a combination of physical oceanographic, sedimentologic, and biologic processes acting within the framework of Pleistocene bedrock configuration. The NE-facing margin, with the continuous reef and expansive sand apron, is interpreted to be more wave-dominated, influenced by swells from the open Atlantic, and by locally derived wind waves. Comparison with Bahamian platforms suggests that this trend is not unique; margins facing open Atlantic swells from the north–northeast have the best-developed reefs, not east-facing (windward) margins. In contrast, the beaches and tidal deltas on the NW-facing margin suggest tidal currents and longshore transport are more pronounced here, consistent with the nature of geomorphic changes through time. The enhanced tidal influence reflects the inlets open to the open bank interior, a factor which also may discourage growth of reefs on this part of the margin. Nonetheless, other Bahamian platforms with fewer tidal passes have comparable discontinuous reefs, suggesting that island continuity is not the most influential parameter on leeward reef development. Collectively, these results illustrate the nature, scale, and causes of along-strike heterogeneity and provide a conceptual model for ancient carbonate platform margins, some of which may be equally complex in their facies architecture.

INTRODUCTION

Reefs and associated sands form important geomorphic and sedimentologic components of many Holocene and ancient carbonate platforms. Not only do they record biotic evolutionary change (James 1984), but also their sensitivity to climatic and environmental changes makes them important reflections of paleoceanography (Camoin 2001), paleoclimate

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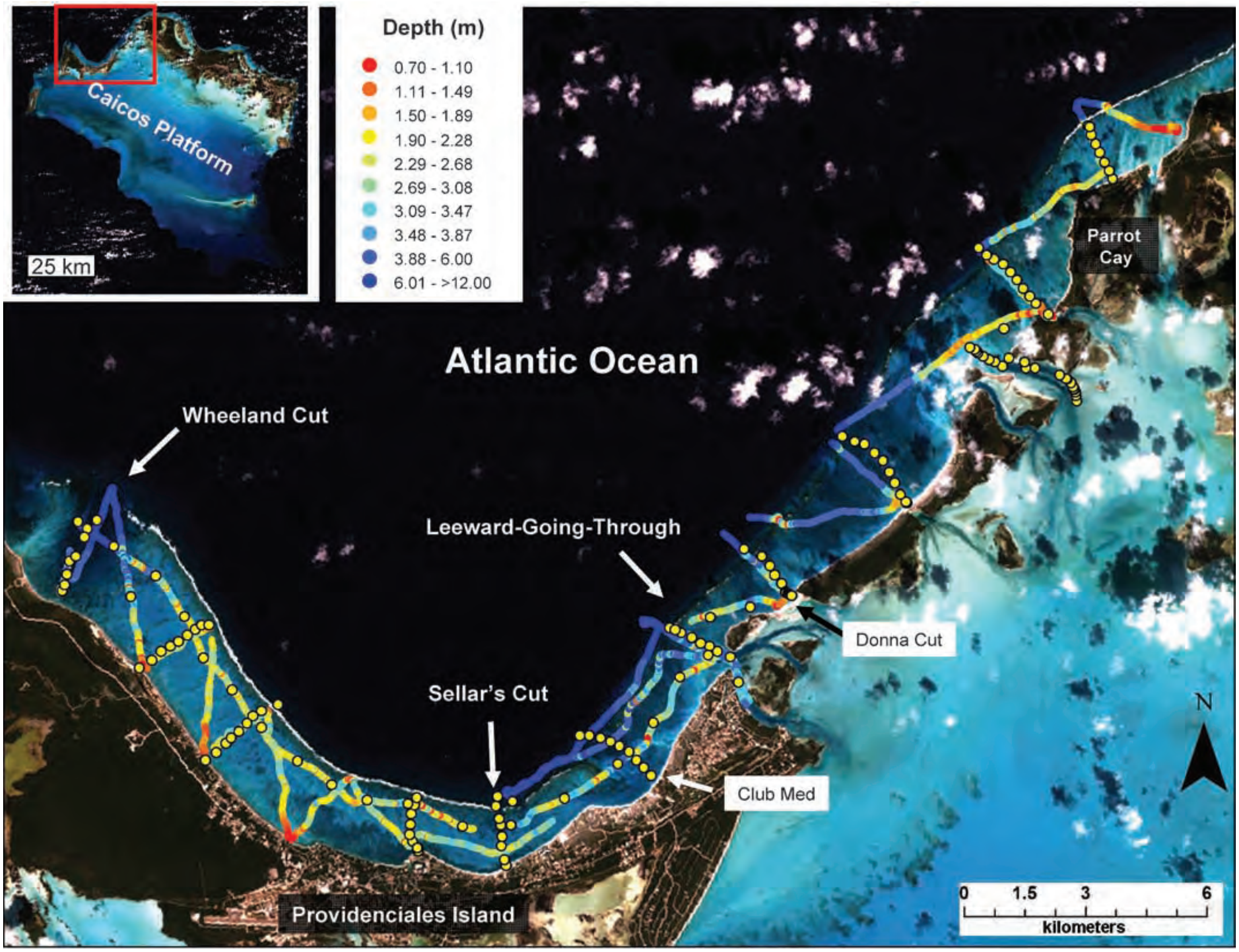

FIG. 1.—Location of study focus area on Caicos platform (inset). Yellow dots with black rims on remote sensing image represent sample locations, the non-rimmed rainbow-hued dots are water-depth measurements along many Chirp subbottom profiles. Locations mentioned in the text are noted. Modified from Rankey et al. (2008).

(Swart and Grottoli 2003), and sea-level change (Kendall and Schlager 1981). Similarly, reefs and sand aprons can form important hydrocarbon or water reservoirs. Thus, understanding their origin and dynamics is of fundamental importance for both practical and academic reasons.

Reefs and reef aprons commonly are best developed along the margins of platforms, in areas of shallow water (with the greatest light, and commonly maximum wave energy), low nutrients, normal-marine salinity, and carbonate-supersaturated waters, all aspects essential for reef growth (Kleypas et al. 1999). Many platforms exhibit a pronounced windward–leeward differentiation, where reefs and aprons are fully developed and continuous on windward flanks but less continuous on the leeward margin (Darwin 1889; Wiens 1962). Beyond the gross simplification of windward–leeward differentiation, however, lie the depositional patterns found on many reef-rimmed margins, on which there can be considerable along-strike heterogeneity. This depositional variability can be reflected in the stratigraphic record of analogous reef-rimmed margins.

Studying modern analogs provides one means to better understand spatial variability in sedimentary depositional systems. Although not perfect representations of any ancient system, Holocene sedimentary systems provide the opportunity to observe both patterns and processes. Through this, they offer a unique means to develop conceptual understandings and testable predictive models. The purposes of this paper are to describe and interpret the sedimentologic and geomorphic variability in Holocene reefs and sediments along a shelf margin on the western, leeward, side of the Caicos platform. Through analysis of bottom observations, remote-sensing data, and subbottom-profiling data, the results of this study illustrate the complex three-dimensional architecture (spatial patterns plus thickness) patterns and internal geometries that are the result of interactions of the physical and biological components of this shelf margin, providing conceptual insights into controls on potential variability on ancient analogs.

BACKGROUND

Study Area and Setting

The ~ 100 km by 70 km Caicos Platform, located approximately 900 km southeast of Miami, Florida, represents the southernmost shallow platform of the Bahamas–Turks and Caicos archipelago (Fig. 1). The platform lies within a semiarid, subtropical climate, characterized by pronounced seasonal variability in rainfall (Milliman 1967; Ahrens 2008). The dominant winds are from the east, although passage of winter cold fronts can be accompanied by winds from the north and west.

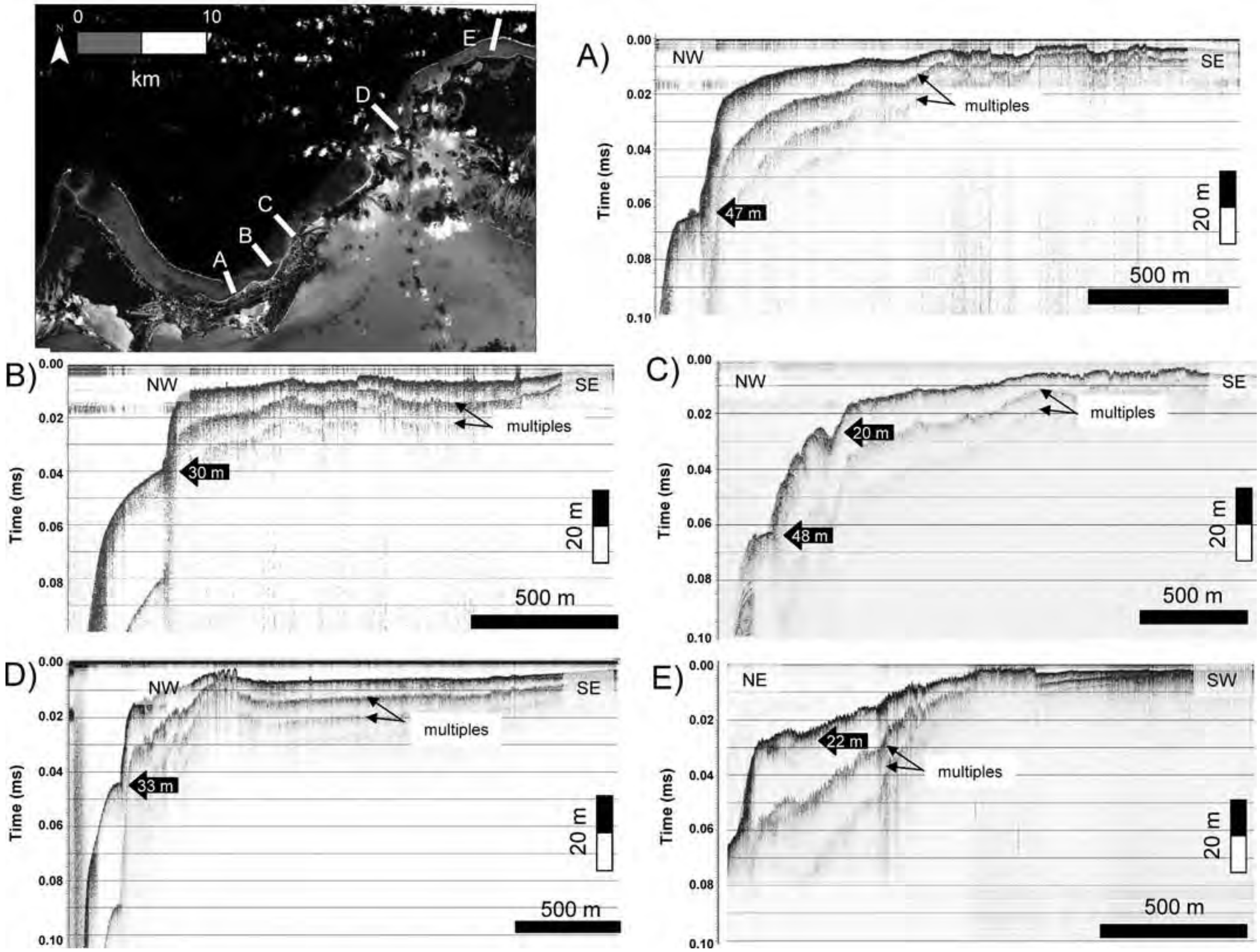

FIG. 2.—Representative Chirp profiles of the shelf margin from in the study area. Vertical lines are in milliseconds (a line every 0.01 millisecond = 7.5 m); note the slightly different horizontal scales. Arrows represent the depths of breaks in slope on the upper slope that could represent terraces. **A)** Line through Sellar's Cut (TC-3), illustrating gradual sloping profile and ledge at ~ 47 m water depth with what appears to be a small reef. **B)** Line running from offshore Club Med (Club Med-15B), illustrating more abrupt drop-off at margin, and a break in slope at ~ 30 m. **C)** Line off Leeward-Going-Through (Club Med-1), including a more rugged margin with a first notch at ~ 20 m, and a second at ~ 48 m. **D)** Line from an area with a shelf-margin reef and a notch at ~ 33 m (Line DCL-3). **E)** Line from northernmost part of the study area (PCL-5) that has a well-defined shelf margin reef, flanked basinward by a gradually sloping surface out to a break in slope at ~ 20 m.

The Caicos platform includes a shallow (mostly < 10 m deep) top, fringed to the north, east, and west by a series of discontinuous Holocene and Pleistocene islands of various sizes (Fig. 1). Although the character of Pleistocene outcrops on the islands has been documented (e.g., Fouke 1984; Waltz 1988; Wanless and Dravis 1989; Guidry et al. 2007), Pleistocene strata in subtidal areas oceanward of the shoreline are not well understood. In the northwestern extreme of the Caicos Platform, the focus of this study, a series of islands lie 2–3 km inboard from the shelf margin.

Methods

Bottom Observation and Sediment Sampling.—Much of the fundamental data for this study are derived from observations in the field by personnel from the University of Miami and ExxonMobil (see acknowledgments), focused on characterizing the seafloor, including water depth, biota, physical or biological sedimentary structures, sediment type, or other notable features. Surficial sediment samples were scooped from the seafloor by hand into a plastic container and capped at depth to avoid loss of fine sediments.

Sediment Analyses—Laboratory.—Upon return to the laboratory, sediment samples were air dried in an oven or freeze-dried and disaggregated. Representative or illustrative samples were analyzed for grain size using a laser particle size analyzer (LS-2000 Coulter counter). Thin sections from a suite of representative sediment samples chosen to capture the range of variability in bottom and sediment types provided the basis for qualitative visual petrographic estimation of the relative abundances of different grains.

Subbottom Chirp Profile Data—Acquisition.—Chirp data were acquired using an Edge-Tech X-Star full-spectrum digital subbottom profiler (500 Hz–12 kHz), mounted on a small (~ 6 m long) catamaran (the "GeoCat"). This state of the art, wideband FM high-resolution subbottom profiler generates cross-sectional images below the seabed using a chirp technique (stepped FM) to minimize multipath and noise effects. The system uses matched filter correlation and waveform-weighted techniques that result in high-resolution profiling with virtually constant resolution with depth. To maintain accurate positioning (with meter-scale accuracy), the GeoCat system was integrated with a survey quality Trimble series 4000. The GeoCat system was guided by navigation and positioning software and remote sensing imagery in the field during data collection.

Acquisition data coverage or quality occasionally were limited in several regards. First, extremely shallow waters (< 1 m) in some areas proved to be not navigable, due to the depth of the Chirp source/receiver and the boat draft, so these areas were avoided in data collection. The most notable inaccessible areas included the crest of the aggraded reef and shallow shoals and shorelines. Second, occasionally, the presence of large waves or strong winds led to challenges in navigation (difficulty in maintaining a constant bearing) or decreased data quality due to the motion of the receiver relative to the bottom. Third, most parts of the back-reef apron did not include well-imaged bedform geometries. This apparent lack of structure could be due to either the coarseness of the sediments, which leads to attenuation, or simply that there were no internal structures other than horizontal bedding. The paucity of well-developed sand waves on the present-day sediment–water interface on reef aprons (due to the coarseness of the sediments) is consistent with these interpretations. In contrast, Chirp data from the tidal deltas and nearshore areas that included surficial sand waves and finer sediments commonly imaged internal bedform geometries, as illustrated below. Finally, the data have not been corrected for changes in the tide, which may result in errors (of up to < 1 m) for some of depth estimates. Because tops from the same trace would be influenced similarly, however, thickness estimates are unaffected.

Subbottom Chirp Profile Data—Interpretation.—The raw subbottom profile data were interpreted using a standard seismic interpretation system. Interpretations of tops were tied to field observations from depth to rock from probing or bottom type (e.g., rocky bottom, sandy bottom, reef) from direct field observation. Lines were interpreted and "loop tied," although the lack of tidal correction led to some variability in estimated depths to tops, as discussed above.

On the Chirp lines, the "top-Holocene" pick is recognized as the first strong reflector, and is a straightforward interpretation, although, in areas of irregular rocky bottom, the reflector is jumpy. This study refers to a "top-Pleistocene" surface, although we have no age data to demonstrate conclusively that the rocky, irregular surface exposed at the seafloor in many areas is indeed the top of the Pleistocene (cf. Shinn et al. 1990). In the numerous areas where this rocky surface was exposed on the seafloor, it was irregular and pitted (see below). The pick was carried away from the locations of sea-floor rocky exposure (e.g., direct observation) via the Chirp data, because it had expression in both amplitude and envelope data. This reflector could be carried from nearshore areas with outcropping Pleistocene or from the seafloor exposures and was laterally continuous across and along the shelf margin, suggesting it was not a local Holocene hardground. In some areas (such as near the shelf-margin reefs), the signal was too attenuated or too near the multiple, precluding confident ties. Such attenuation in reefal settings is an interpretation issue in many carbonate systems (e.g., the seismically transparent reefs in Eberli and Ginsburg 1989; the "lower amplitude, more discontinuous reflectors" of platform rim deposits described in Saller and Vijaya 2002).

The thickness of Holocene sediments was captured by multiplying the sediment isochron by 1500 m/s (roughly the speed of sound in unconsolidated sediment in seawater; Shinn et al. 1990) and dividing by two (to account for the two-way travel time in the raw data). This velocity is a generally accepted as a rough estimate, but velocity can vary with grain size, type, and sorting (e.g., Incze 1998). For our purposes of illustrating general thickness trends from widely spaced lines, this approach is sufficient. All Chirp lines in this report show data in time, although these data are converted to thicknesses in map view.

MARGIN GEOMORPHOLOGY AND SEDIMENTOLOGY

The Caicos platform includes a reef-rimmed margin along much of its northern flank, but there is considerable variability in the area of Providenciales Island (informally known as "Provo"), in the northwestern part of the platform. Here, the margin swings from facing the northeast (near Provo) to the northwest (near Parrot Cay) to the north (near North Caicos) (Fig. 1). Geomorphic characteristics such as types of landforms and orientations on the shelf vary concomitantly with these changes in platform-margin orientation.

At the largest scale, bathymetry of the margin and upper slope changes considerably along the edge of the platform (Fig. 2A–E). In this area, surficial morphology varies. In one area, there is a sharp (~ 8°) drop-off with a narrow ledge at ~ 47 m depth (Fig. 2A). In another area, pronounced initial drop-off (> 15°) and a notch-shelf at ~ 30 m dips off to greater depth (Fig. 2B). Nearby, a gradual oceanward-sloping surface (~ 1.6°) with a sharply steeper (> 15°) drop-off occurs at ~ 22 m depth (Fig. 2E). Interestingly, some terraces (e.g., Fig. 2A) appear to have subtle features that may represent deeper reefs, although these are present on only some lines.

On the platform top, comparable variability is present. Along the northeast-facing margin (Fig. 1, "Provo" margin), the shelf is ~ 2 km wide from island to reef crest. The island of Providenciales is continuous here and is flanked by scattered rocky outcrops and beaches that slope northeastward to a backreef shelf that is up to 5 m deep. Sediments on or immediately adjacent to the shore are well sorted to moderately well-sorted fine sands with peloids, skeletal grains, and a few ooids (Figs. 3, 4A). Just offshore, the shelf includes a mix of sandy patches and areas partly stabilized by seagrass (*Thalassia* and *Syringodium*) (Fig. 5A); blowouts (Patriquin 1975) are common in these areas, as are small patch reefs. Some isolated patch reefs are elongate, with their long axis normal to the shelf margin, whereas others are more circular. Sediments on this 2–5 m deep backreef shelf include moderately to very poorly sorted medium to coarse sands, composed of a mix of foraminiferal, mollusk, coral, unidentified skeletal, and peloidal grains (Figs. 3, 4B). Immediately next to patch reefs, coarse sands and gravels may occur, and some seagrass-covered areas have poorly sorted fine peloidal–skeletal sands.

A sandy reef apron, with relief of up to 2 m in its landward extent, is best developed in the southeastern part of this shelf. This sandy apron includes coarse, reef-derived sediment, isolated corals, and small patch reefs, and it is locally segregated by reefal ridges extending normal to the shelf margin off the main reef crest. Commonly, in areas with a well-developed apron, water depths are up to 1 m deeper than the reef immediately behind the reef crest, and shallow landward (Fig. 1). Sediments on the reef apron generally reflect reefal biota, with common fragments of coral, red and green algae, foraminifera, and mollusks, as well as other skeletal fragments (Figs. 3, 4C). A well-developed reef crest, with an aggraded reef at or near low tide sea level borders this shelf. The reef crest and forereef include a mix of corals (*Acropora*, *Montastrea*, *Diploria*, *Porites*), red algae, and green algae (especially *Halimeda*). The reef is flanked on its oceanward side by a drop-off into deeper water. In these areas of water depths greater than 12 m, moderately well-developed spurs (ridges) and grooves (channels), with trends normal to the shelf margin, start near the reef and widen basinward. Some of the grooves are filled with coarse rippled sands, whereas others have a rocky bottom. No margin-parallel fractures were evident in the areas of first-hand bottom observations.

A noteworthy exception to this general pattern in the northwest occurs near Wheeland Point (Fig. 1). In this area, there is no shelf-edge reef, and the shallow shelf landward of the break in slope is an irregular, rocky bottom with scattered patch reefs. Thin sediments here include heavily bored and micritized skeletal fragments and peloids of coarse sand size.

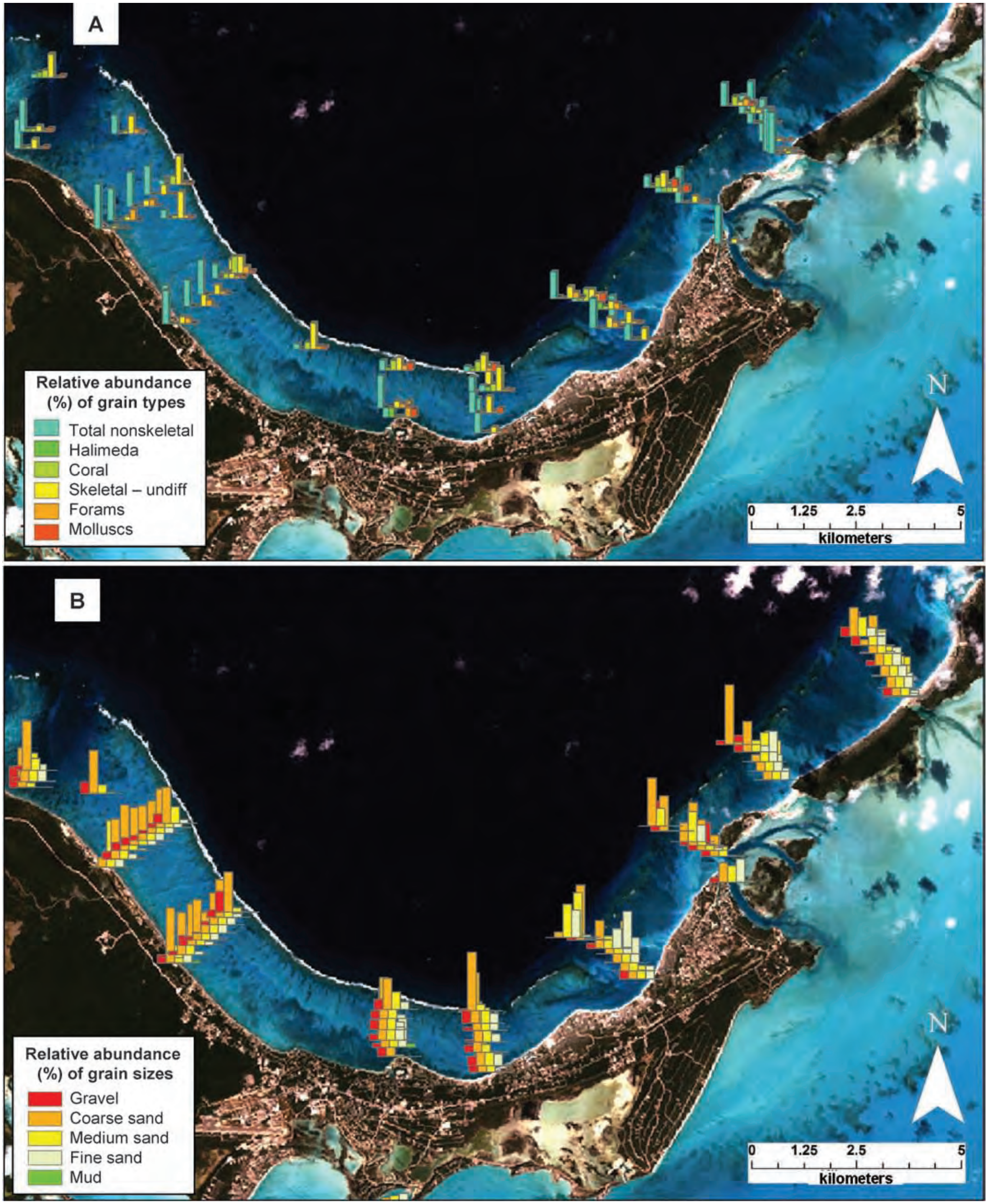

FIG. 3.—Character of sediments, Provo and Leeward margins. **A)** Map illustrating semiquantitative abundance of different types of grains, coded by colors. "Total nonskeletal" includes peloids and ooids. "Skeletal-undiff" represents components identified as skeletal by structure or shape but for which a specific type could not be

In summary, sediments in this area change in type and size across the shelf (Fig. 3). From the shoreline to the reef, the abundance of peloids generally decreases concomitantly with a marked increase in the abundance of skeletal grains (most notably unaltered coral, *Halimeda*, foraminiferid, and mollusk fragments). Sediments gradually fine offshore. The abundance of unaltered skeletal fragments increases markedly near the reef and in areas with a well-developed reef apron.

The northwest-facing shelf margin (generally northward of Leeward-Going-Through, "Leeward" margin) is characterized by different facies patterns, even though the backreef shelf is approximately the same width (Fig. 1). In this area, a series of islands is dissected by five inlets open to the main platform interior. In several instances, sandy ebb tidal deltas extend outward (northwestward) from these inlets. In areas with no tidal deltas, beaches pass offshore to a belt of nearshore sands up to 1 km wide. These nearshore sands include flat and rippled bottoms, but several areas also have well-developed bars with amplitudes up to 1 m, and spacing ~ 100–200 m. Most appear asymmetric, with a gentle slope on the east-northeast and a steeper slope on the west-southwest. Sand bodies are broadest in the areas of tidal inlets but are not limited to these areas. Nearshore tidal delta sediments include peloidal–skeletal fine to medium sands and the nearby beaches are moderately well-sorted medium peloidal–skeletal sands (Figs. 3, 4D, E). Ooids, although present, do not make up more than 20% of sediments in the vast majority of samples.

Outboard of the nearshore sands are areas 1–1.5 km wide with a rocky, irregular bottom that is generally between 5 and 6 m deep (deeper than much of the back-reef shelf of the Provo margin) (Fig. 5B, C). These areas include scattered coral growth, sea fans and whips, and small, thin patches of sediment in lows. Sediments here are moderately to poorly sorted, coarse sand and fine gravel with a dominance of skeletal grains (mollusk, coral, *Halimeda* and foraminiferid fragments) and peloids (including micritized skeletal grains) (Figs. 3, 4).

Near the shelf margin are a series of discontinuous reefs, most of which are slightly deeper (e.g., a boat can cross them) than those on the Provo margin. These reefs are ~ 200 m wide and up to 1 km long along strike, although several reefs, separated by breaks several hundreds of meters wide, may collectively form longer barriers. These reefs lack the continuous elevated crest that characterizes the Provo margin, and well-developed, shallow sand aprons are absent landward of these reefs. Behind the reefs, coarse, poorly sorted sands consist chiefly of micritized skeletal grains and peloids, with unaltered skeletal grains being relatively uncommon except in the immediate proximity of reefs (e.g., Fig. 4F).

Finally, to the north, the margin swings back to an east–west orientation (outboard of North Caicos; "North" margin). This margin, although not a focus of this study, is flanked by a continuous island and includes a shallow, sandy backreef shelf with abundant blowouts and a well-developed continuous reef crest. As such, it is broadly comparable to the Provo margin.

HISTORICAL CHANGES

Geomorphic features are dynamic at various scales. Comparison of historical aerial photos with more recent satellite imagery can facilitate exploring the nature of geomorphic change (e.g., Rankey and Morgan 2002), and provide insight into some of the processes active on these shelves. For this study, we utilize historical aerial photos (from the 1940s) and QuickBird satellite images (2.4 m pixel size) acquired between 2003 and 2006. On these data, features as small as individual mangroves and sand bars can be discerned.

In the ~ 60 years represented by the photos and satellite images, although much of the area appears not to have changed markedly, several areas have detectable changes (Fig. 6). The ebb tidal deltas and nearshore sand bars of the Leeward margin appear to be dynamic regions, and some of the tidal deltas and bars in the northeast migrated generally alongshore to the southwest, at distances of up to several hundreds of meters (Fig. 6A, B). This general trend is consistent with the present-day asymmetry of the bars; they are steeper to the southwest.

The offshore area near Leeward-Going-Through also has changed considerably. One notable area of change is "Donna Cut" (yellow box in Fig. 6C; compare with Fig. 6D), a sandy break between two islands that was breached by Hurricane Donna in 1960 (after the aerial photo). Although the storm created a new cut, the area is now largely infilled, illustrating the ephemeral geomorphic impact of this storm (Saller and Katz 2008). Nonetheless, the beach has still not fully accreted to its pre-Donna location (note the "lip" between the island to the north of Donna Cut and the present-day beach in the satellite image). Similarly, the ebb tidal delta of Leeward-Going-Through has shrunk in size by several hundred square meters, and the ebb channel is oriented more to the northwest than the west (Fig. 6C, red box). However, these modifications are in an area of 2005 dredging (Erikson 2005) and may not reflect changes due to changes in tidal prism (e.g., Reeder 2007).

Contrasting trends in changes are evident in the area offshore of Club Med (Fig. 6E, F) In this area, the reefs have not varied markedly, although changes in texture in the backreef suggest that some previously bare sandy areas are now more stabilized by seagrass. Akin to the other areas, the sand bars to the east of the reef termination appear to have migrated. This area is different, however, in that these bars have migrated up to ~ 200 m to the north-northeast (Fig. 6F), opposite the direction of the other examples. The internal geometries of bars in this area are examined in more detail below.

TOP-PLEISTOCENE SURFACE AND HOLOCENE SEDIMENT ACCUMULATIONS

Chirp subbottom profiles provide a unique means to image the thickness and geometries within Holocene sediments. The differences in geomorphology evident on the remote-sensing data can be further examined by comparing Chirp data from illustrative transects across the shelf.

At the largest scale, transects normal to the shelf break on the Provo margin illustrate a gently (less than 0.1°) northeastward-dipping top-Pleistocene surface apparent on reflection and amplitude data (e.g., Fig. 7). On the northwestern part of the island of Providenciales, Pleistocene rock is locally exposed at the shoreline, and it crops out inland in other areas (Simo et al. 2008). The Chirp data from these nearshore shallow-water survey areas illustrate the top-Pleistocene at depths of ~ 1 m below the sediment–water interface. This surface slopes northeastward, to depths of up to ~ 6 m below the water surface near the present shelf-margin reef (Fig. 8). Field observations and Chirp imaging (e.g., Fig. 9A) of this surface suggests that it is not smooth, but rather can be undulatory and irregular. Above this surface, Holocene sediments are between 1.5 and 3.0 m thick across much of the shelf, although they thin near the shoreline (Fig. 8). The deepest top-Pleistocene surfaces (and thickest sediment accumulations) lie in the area near Sellar's Cut, in the southern part of the study area. Bedrock here appears from the Chirp to be up to 8 m below sea level, consistent with a core collected by Conoco in the 1980s (Morgan 2008). Above solid bedrock at ~ 6 m below the sediment–water interface, this core included an unrecovered interval (2 m; Holocene?) overlain by a thin peat and ~ 4 m of fining-upward skeletal grainstone (Morgan 2008).

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determined (most commonly due to micritization). **B)** Map illustrating the relative abundance of grains of a given size, as coded by the colors in the size-frequency histograms. Note that the coarsest grains are commonly found nearer the reef, there is a paucity of mud, and that grain sizes are generally finer on the Leeward margin (more fine sand and medium sand).

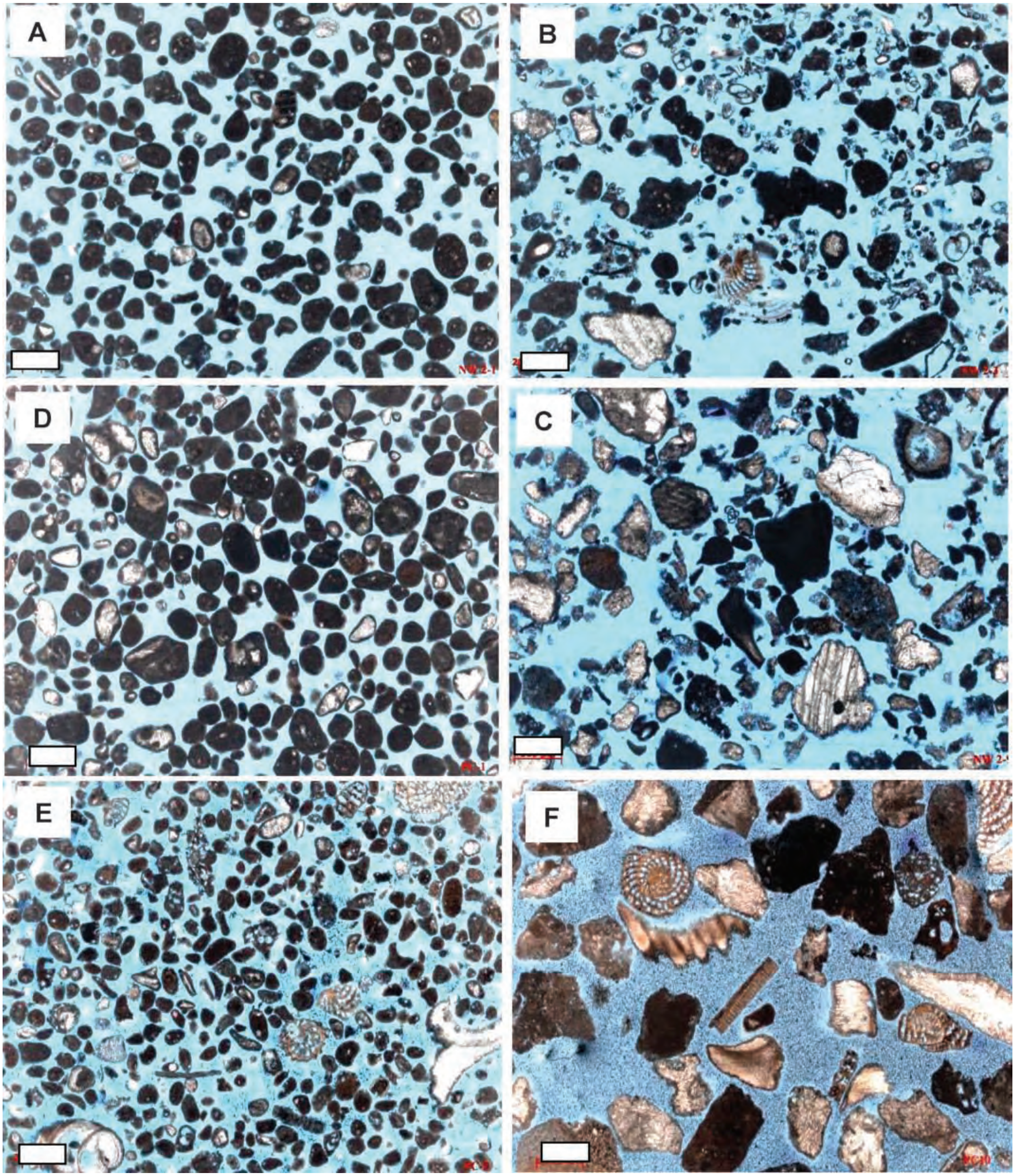

FIG. 4.—Photomicrographs of representative sediment samples. Scale bar on all = 500 µm. A–C are from the Provo margin; D–F are from the Leeward margin. **A)** Well-sorted peloid–skeletal medium sands from nearshore. **B)** Poorly sorted peloidal–skeletal medium sands from the middle shelf. **C)** Moderately to poorly sorted skeletal coarse sands from just behind a reef. Note the micritized coral, red algal, foraminiferal, and mollusk fragments that are less micritized than in the other areas. **D)** Well-sorted peloidal–skeletal medium sands, with some oolitically coated grains from near the beach. **E)** Poorly sorted skeletal–peloidal medium to coarse sands from the deeper part of the shelf. Note that many skeletal grains have micritic rims, and there are some irregularly-shaped grains that are probably micritized skeletal grains. **F)** Moderately to poorly sorted skeletal coarse sands from just behind the reef. Note the less micritized coral, red algal, and mollusk fragments.

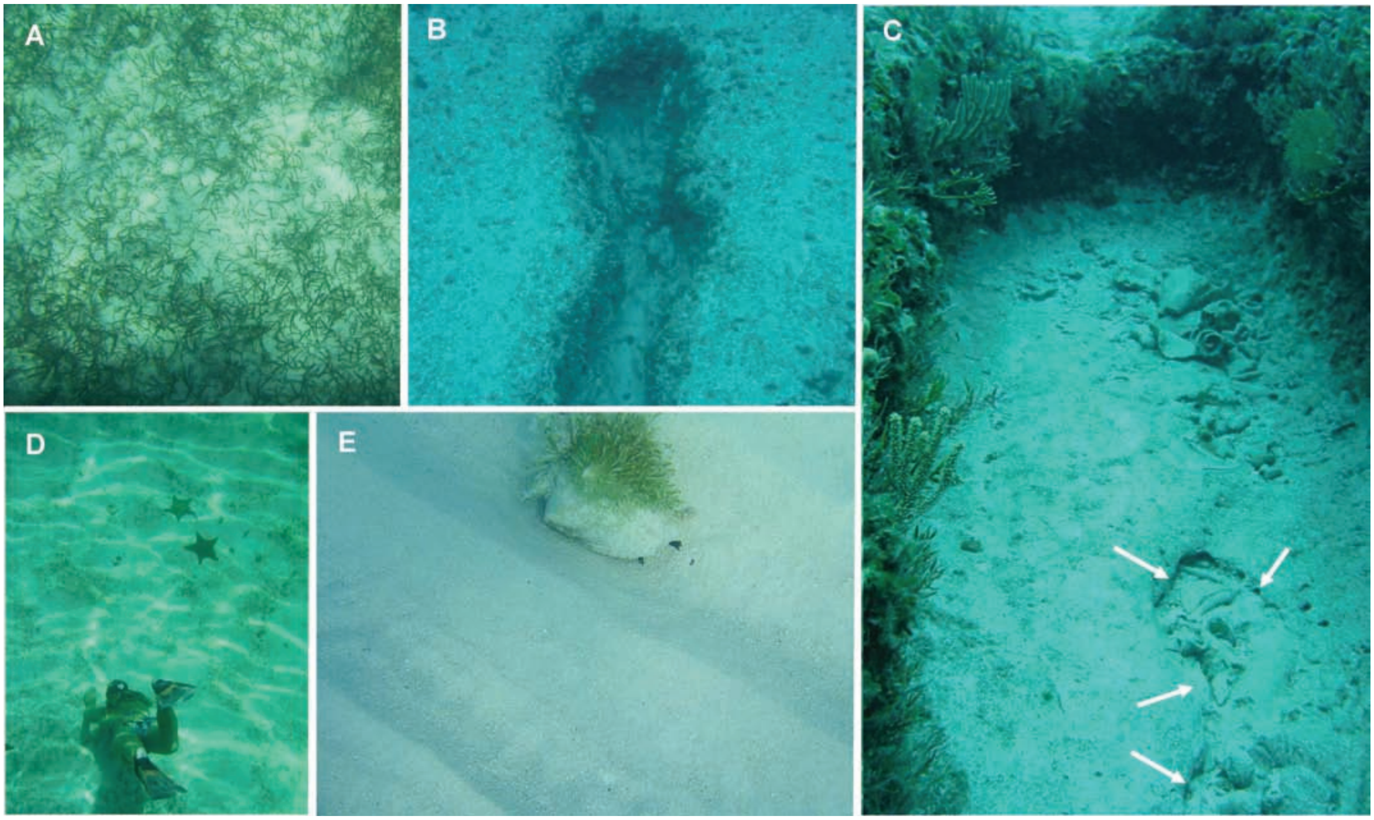

FIG. 5.—Field photos of different bottom types. **A)** Seagrass-covered bottom. **B)** Rocky bottom with irregular trough with vertical sides and abrupt end. Trough was ~ 1 m deep and ~ 2 m wide. **C)** Close-up of the bottom of another irregular pit. This irregular low is ~ 75 cm deep and is partially overgrown on its flanks by hard and soft corals, sea fans, and sea-whips. Note the lag of conch shells, and the irregular pits in the trough (arrowed). **D)** Flat, sandy bottom partly covered with seagrass. Diver for scale. **E)** Symmetric ripples from nearshore. Conch is ~ 20 cm long.

On the Provo margin, prominent surficial geomorphic features include numerous patch reefs and some reef-capped spurs that reach from the shelf-margin reef crest back into the backreef shelf, most commonly normal to the shelf margin. The Chirp data illustrate that some of these patch reefs and spurs appear to have nucleated on the flank of a Pleistocene (?) high (Fig. 9A), others appear to have began in a low (Fig. 9B), and still others appear to have a flat base (Fig. 9C). No persistent trend is readily apparent in the interpreted top-Pleistocene surface beneath these reefs.

At the largest scale, as on the Provo margin, the top-Pleistocene surface on most parts of the Leeward margin slopes gently basinward (to the northwest at gradients of less than 0.1°). In contrast, the sediment thicknesses are considerably more variable here than on the Provo margin, both along and across strike (Fig. 10). As discussed above, on some parts of the backreef shelf, especially those areas with no fully aggraded or continuous shelf margin reef, sediments are thin and discontinuous (e.g., northwestern part of Fig. 10) (cf. Fig. 5B, C). In other areas, especially northeast of Leeward-Going-Through, or on the sandy beaches, sediments thicken considerably, approaching up to 3.5 m thick. The tidal deltas and nearshore sands are discontinuous along strike, however, and on some parts of the shelf, the rocky bottom extends from just offshore almost to the break in slope.

In one illustrative area on the Leeward margin, sediment thicknesses change considerably across short distances. Offshore of Club Med, the seafloor adjacent to shore includes thin rippled peloid–skeletal medium sands that pass into a series of east–west trending bars (Fig. 11A). Field observations suggest that these bars are capped with rippled, moderately well-sorted fine-medium peloidal–skeletal sands. The subbottom profile data illustrate how the bars thicken and thin considerably (from < 1 to 3 m thick) across distances of less than 150 m (e.g., Fig. 11B). Internally, these bars have well-imaged accretionary foresets that, in places, dip northward (e.g., Fig. 11C, D). This orientation is consistent with the trends expected from comparing the historical and satellite imagery (Fig. 6E, F). Outboard of these bars, the shelf is a rocky bottom with clasts and a thin sediment veneer of micritized skeletal–peloidal sands. This rocky bottom slopes north-northwestward to the shelf break with well-defined spur-and-groove features. In this immediate area, there is no shelf-margin reef present, even though there is a continuous aggraded reef crest and sand apron just to the south and west and a less aggraded reefal margin with flanking burrowed sands just to the north.

Summary maps of depth to the top-Pleistocene (Fig. 12A) and Holocene sediment thicknesses (Fig. 12B) interpreted from all lines illustrate the variability along and across this shelf margin. Although on the Leeward backreef shelf and the Provo backreef shelf the top-Pleistocene surface is shallowest near the islands and dips offshore, the thickness of Holocene sediments varies considerably as the margin changes orientation. Even on the Provo margin, sediments thin to the west, in the vicinity of Wheeland Cut, an area in which field observations noted a rocky to reefal bottom with only thin sediment cover.

DISCUSSION

Controls on Patterns of Holocene Sediment Accumulation

Carbonate systems are heterogeneous, and understanding the nature of variability is an important challenge for many stratigraphic applications such as reservoir modeling. For example, as noted by Barnaby and Ward

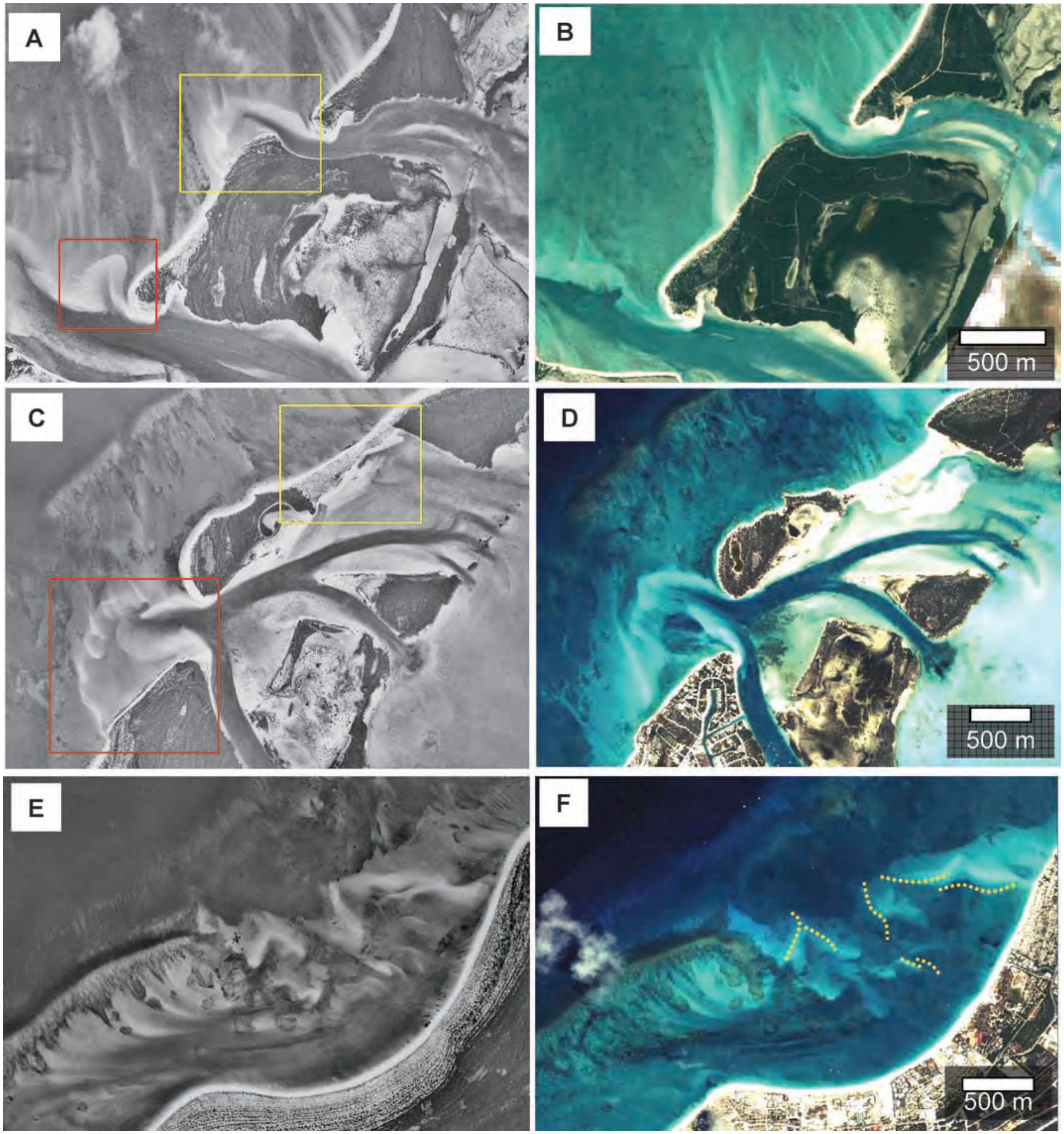

FIG. 6.—Historical changes in the study area. Paired images of aerial photos from World War II era (left, exact date unknown) and remote sensing images from 2003–2004 (right). **A**, **B)** Changes associated with tidal deltas from the northern part of the study area. Note the migration of bar forms in yellow and red boxes. **C**, **D)** Changes in the area of Donna Cut (yellow box) and Leeward-Going-Through (red box). Hurricane Donna (1961) opened an inlet in the area of the yellow box, but this closed relatively quickly. **E**, **F)** Changes associated with the eastern termination of the shelf-margin reef and the Club Med sands. Yellow dashed lines in Part F represent the position of the bar crests in the WW II-era images, and show how these bars have migrated generally to the north and east. Remote-sensing images (B, D, F) are copyright DigitalGlobe.

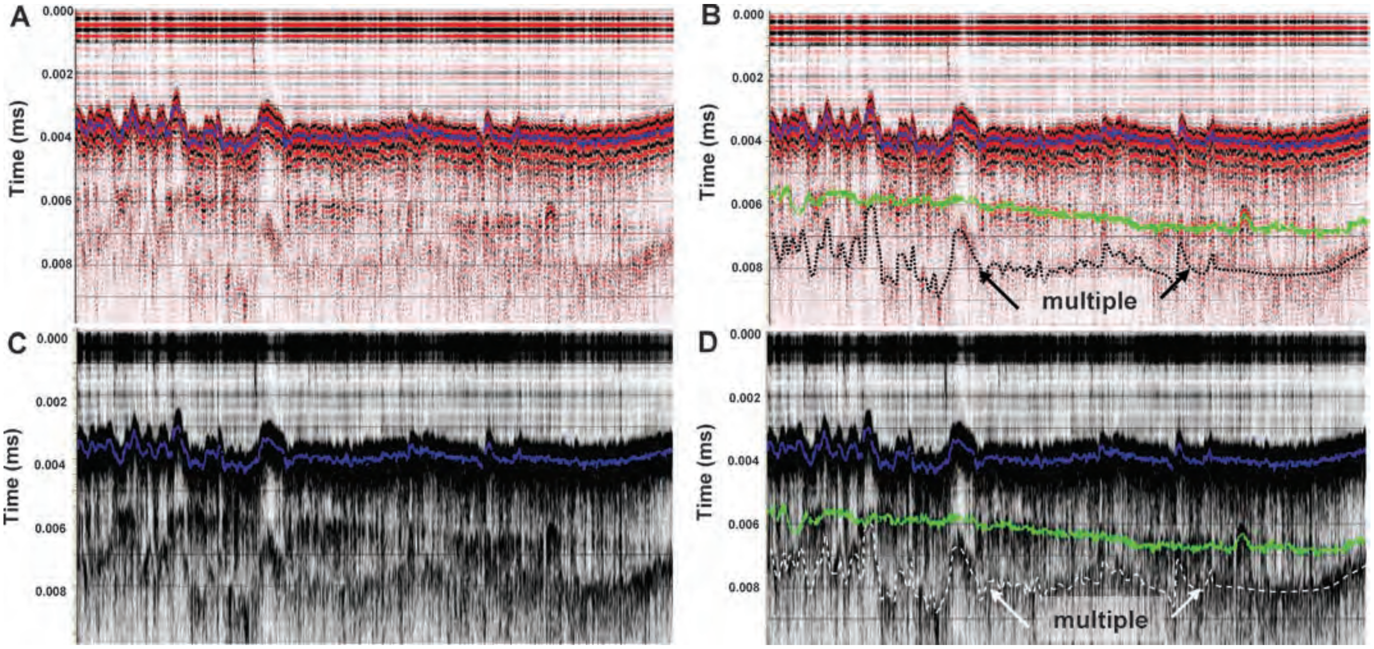

FIG. 7.— Figure illustrating the use of different seismic transforms for interpretation. Upper figures illustrate reflection amplitude data, **A)** uninterpreted, **B)** interpreted. Lower figures show envelope data, **C)** uninterpreted, **D)** interpreted. As with many seismic data sets, interpretation used all possible data sets to assist where reflection strength was diminished. The location of the multiple is indicated by the dashed lines in Parts B and D.

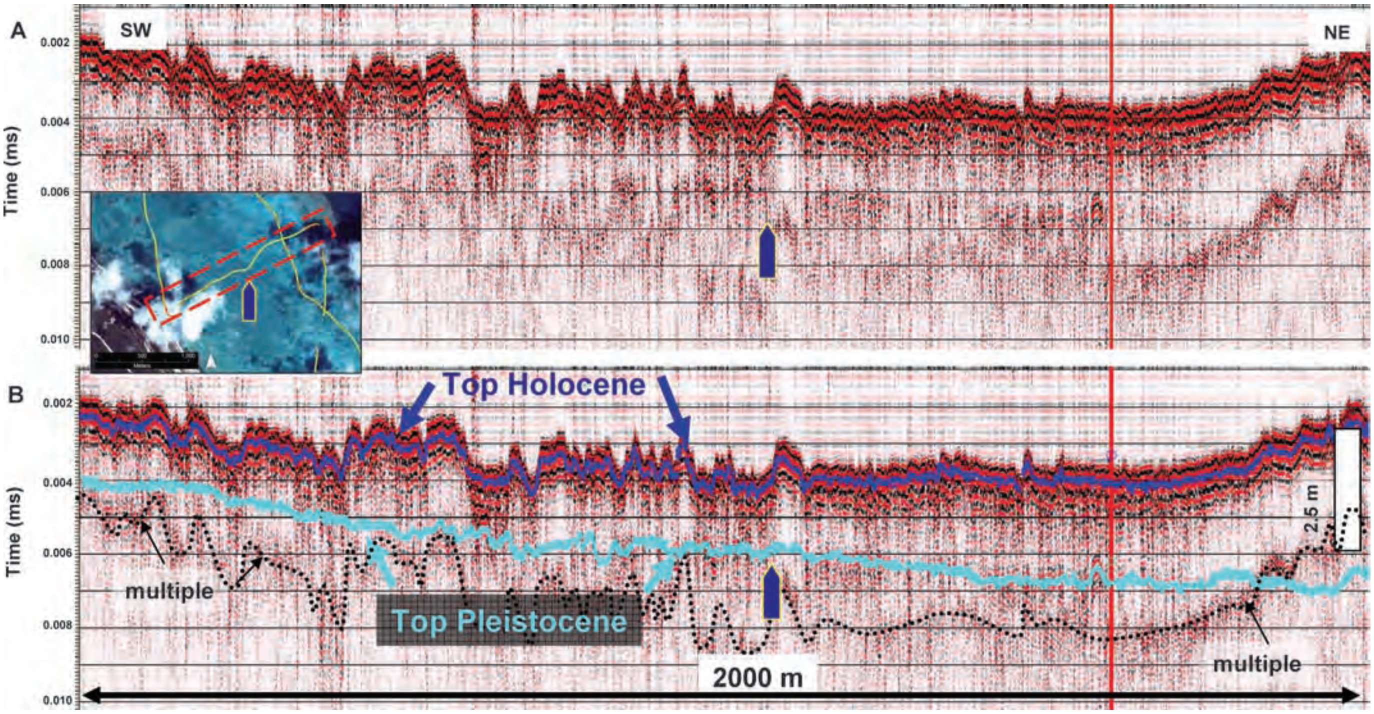

FIG. 8.—Representative Chirp line from the Provo margin, **A)** uninterpreted, **B)** interpreted. Note the oceanward (NE)-sloping top-Pleistocene surface. Inset shows the location of the line, and the location of the blue polygon corresponds with the position of the polygon in Parts A and B. The location of the multiple is indicated by the dashed lines in Parts B and D.

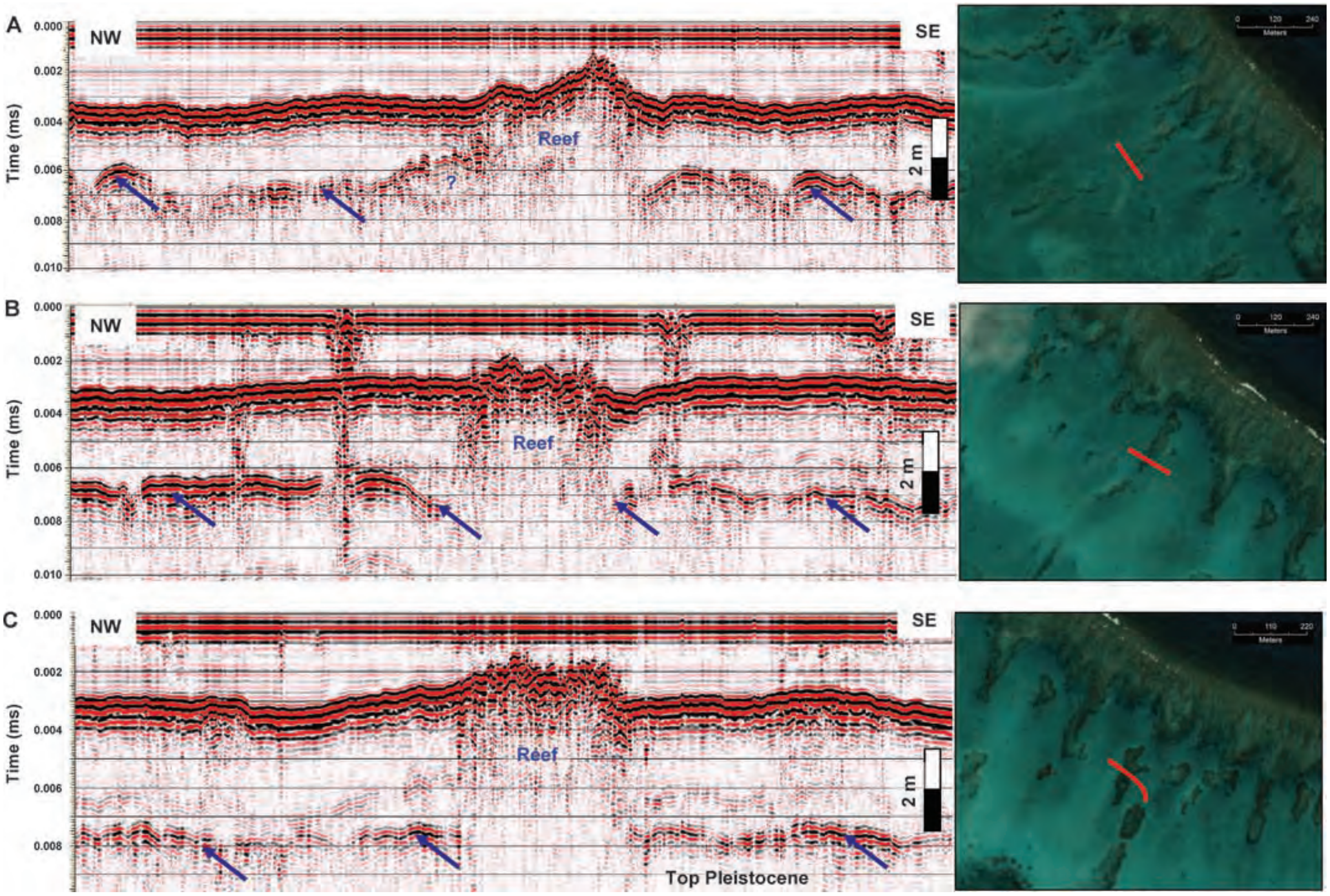

FIG. 9.—Nature of relation between patch reefs and top-Pleistocene surface, illustrated by parts of selected along-strike Chirp lines. **A)** Very irregular top-Pleistocene surface, and possible high (noted with a "?") beneath or just off the flank of the reef. **B)** Planar top-Pleistocene surface, which also appears to dip just below reef. **C)** Planar top-Pleistocene surface which appears to be horizontal beneath a patch reef. Remote-sensing images are copyright DigitalGlobe.

(2007, p. 34), "an understanding of geologic heterogeneity exhibited in outcrop analogs is crucial for geoscientists involved with characterizing and modeling subsurface heterogeneity." In many stratigraphic systems, heterogeneity is a function of the lateral (spatial) and vertical (temporal) extent of different lithotopes. Whereas outcrops, cores, seismic data, or stratigraphic modeling provide the best means to characterize temporal changes in sedimentary systems, it is only in studying extant Holocene sedimentary systems that both the sedimentary processes and the products can be directly observed and related. Thus, in linking spatial variability in processes and products, studies of Holocene systems provide unique opportunities to extend beyond characterization to understanding.

In this study, the bottom observations, analyses of remote-sensing data, and interpretation of subbottom profiles illustrate the considerable heterogeneity across and along strike on this shelf margin. In general terms, along the Provo margin, a continuous reef is flanked by a well-developed reef apron with > 2.5 m of landward-thinning Holocene sediments. In contrast, along the Leeward margin, sands are thickest nearshore and in ebb tidal deltas, and broad parts of the shelf have a rocky bottom with only thin Holocene sediment. The character and distribution of Holocene sediments probably is controlled by several factors, including Pleistocene bedrock configuration (local elevation, presence of highs and islands), prolific sediment production by reefs, and sediment redistribution by waves, tides, and currents.

Subbottom data from both the Leeward and the Provo margins illustrate the same trend on both backreef shelves: bedrock elevation on the shelf is generally 3–5 m below sea level (Fig. 12). Similarly, bedrock is shallowest near the shorelines but it gradually deepens at gradients of less than 0.01° away from the islands. This observation of similar offshore-deepening trends accompanied by different Holocene sediment types and thicknesses suggests that bedrock elevation of the shelf alone does not control the facies changes along this margin. Similarly, there was a lack of consistent evidence that patch reefs nucleated on highs (Fig. 9; cf. Lidz et al. 2003), although in some cases they undoubtedly did. Unfortunately, due to attenuation, most available Chirp data provide only ambiguous information on the elevation of the Pleistocene beneath the Provo shelf margin reefs, so we cannot rule out the presence of a possible precursor high beneath those.

Although in some regards not the dominant control on facies differentiation along the shelf margin, Pleistocene bedrock does play important roles in influencing patterns of sediment accumulation. Specifically, the presence of islands of Pleistocene rock which stand above sea level provide protection for this corner of the platform; currents and waves from across the platform do not sweep over this margin. The islands instead focus the exchange of waters with the bank interior, which in turn influences local hydrodynamics and sediment production on the Leeward margin. For example, the presence of tidal inlets between bedrock-cored cays on the Leeward margin facilitates the development of tidal deltas (cf. Reeder 2007), as it simultaneously inhibits the development of robust shelf margin reefs by providing a conduit for inimical waters from the bank interior (Newell et al. 1959; Neumann and Macintyre 1985). In contrast, the growth of reefs on the Provo margin

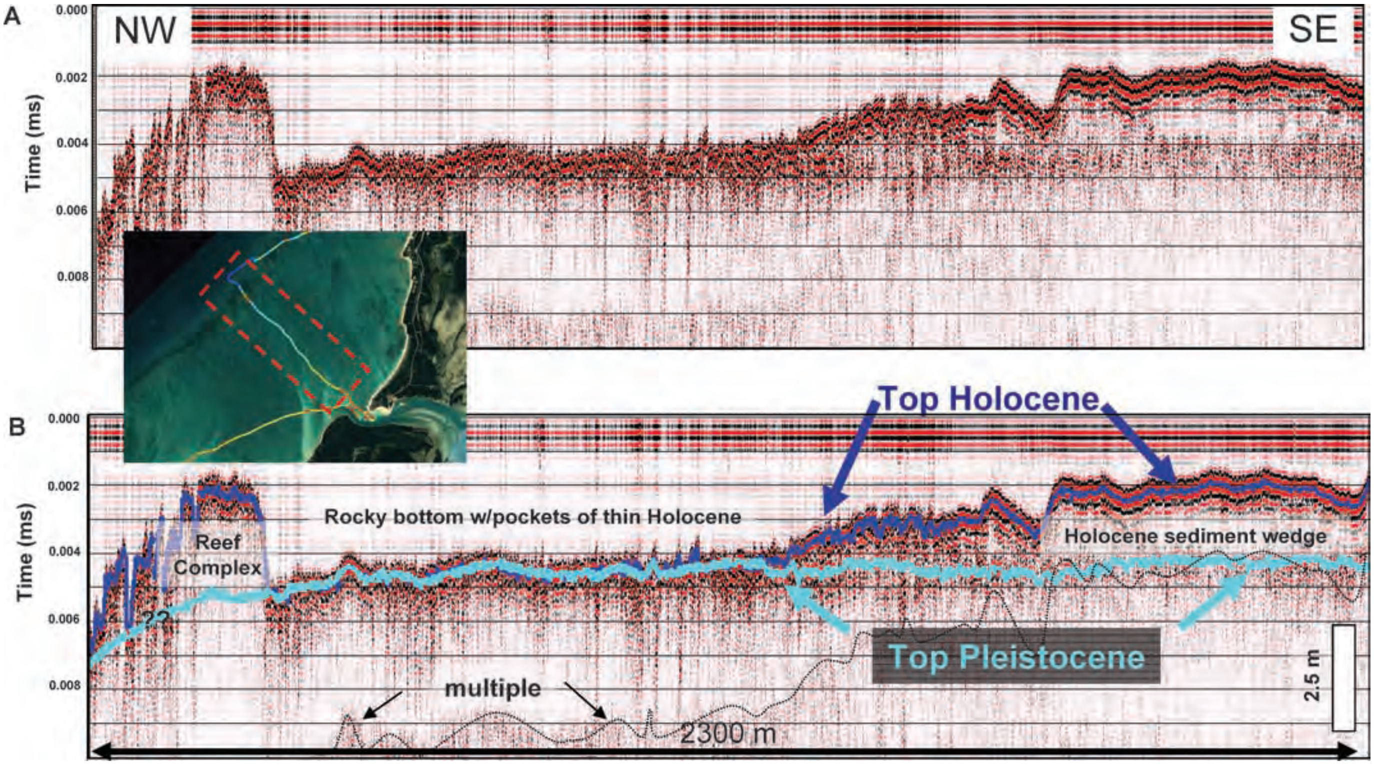

FIG. 10.—Representative Chirp line from the Leeward margin, **A)** uninterpreted, **B)** interpreted. Note the nearshore Holocene sand accumulation, the rocky outer shelf, and the shelf-margin reef complex. The location of the multiple is indicated by the dashed lines in Parts B and D. The reflector beneath the shelf-margin reef is unknown (noted by the "??") due to the attenuated signal. Modified from Rankey et al. (2008).

may be facilitated in part by the shielding presence of the large, continuous island of Providenciales.

Beyond these influences, the lateral changes in Holocene sediment type and thickness also reflect exposure to different physical oceanographic conditions. The dominant winds from this area are from the east, although northerly winds can occur with the passage of strong cold fronts in the winter. The islands provide protection from easterly wind-generated waves on the Leeward and Provo margins, although some smaller wind-generated waves could impact the western part of the Provo margin and the North Caicos margin. Given the limited fetch in the Provo area, however, these waves are smaller than waves generated by northerly winds from strong winter cold fronts or swells coming from the open North Atlantic. As such, this area on the leeward part of the platform is impacted more by waves from the north than those from the east or south.

Parts of the Provo margin face directly into large swells originating in the North Atlantic. Thus, in addition to reflecting the shielding influence of the large island of Providenciales, the growth of well-developed reefs along this margin is probably promoted by the higher wave energy here. Similarly, transport of sediment into backreef areas was probably facilitated by the enhanced wave energy. The fully aggraded shelf-margin reefs on this margin are flanked platformward by a well-developed apron of reef-derived sediments that reaches up to 6 m thick in places.

Unlike the Provo margin, the Leeward margin is oblique to the dominant direction of propagation of large waves. In this area, swells from the north or northeast would be expected to be refracted as they progressively impinged on the shallower platform, creating a southward-directed longshore current in this area. This interpretation is consistent with the asymmetry of the tidal deltas, the geometry of their bedforms, and the observations of historical changes, all of which suggest net southward sediment transport along this part of the margin.

Aside from the impacts of southward-directed longshore transport, the Leeward margin is influenced by tidal currents. Unlike the margins in front of the large islands of Providenciales and North Caicos, smaller cays on the Leeward margin are separated by inlets that provide conduits for exchange of waters with the platform interior. Each of the three major inlet systems (Leeward-Going-Through, Dulles Cut, Stubbs Cut) are associated with ebb tidal deltas. Although it is unclear how much sediment is supplied from the platform interior to the backreef shelf through these inlets, by analogy with siliciclastic examples, these ebb deltas reflect sediment bypass across the inlets (Bruun and Gerritsen 1959; Kraus 2000). Nonetheless, these deltas can appear as a series of almost linear bars, and the sediments include significantly fewer ooids than many other carbonate Bahamian tidal deltas (e.g., Reeder and Rankey 2008), suggesting that perhaps tidal circulation patterns are less pronounced than in examples from farther north in the Bahamas. This interpretation is consistent with qualitative observations suggesting that currents are less pronounced here than in the northern Bahamas (e.g., Reeder and Rankey 2008), and tidal amplitude is lower.

Although we have no direct, quantitative observations of water movement, the geomorphic and sedimentologic patterns suggest that the circulation pattern is perhaps most complicated in the area between Sellar's Cut and Leeward-Going-Through, which forms a transition zone between the Provo and Leeward margins (Fig. 13). Here, some of the east–west oriented bars include foresets that suggest northward transport (Fig. 9, Club Med area), opposite the direction suggested by bar forms farther north on the Leeward margin. In this area, the eastward-directed currents (counter to the prevailing wind direction, illustrating its impotence in these areas) may be driven by the influx of water over the reefs and onto the backreef shelf by waves and tides. Because the waves with greatest energy will propagate onto the shelf, and reefs limit offbank flow over their crest (e.g., Gourlay 1996; Lugo-Fernandez et al. 1998), net on-shelf water movement is probably greater than that directed off-shelf over the reef. Due to the net on-shelf movement of water across the reef, water is forced along depositional strike either to the northwest

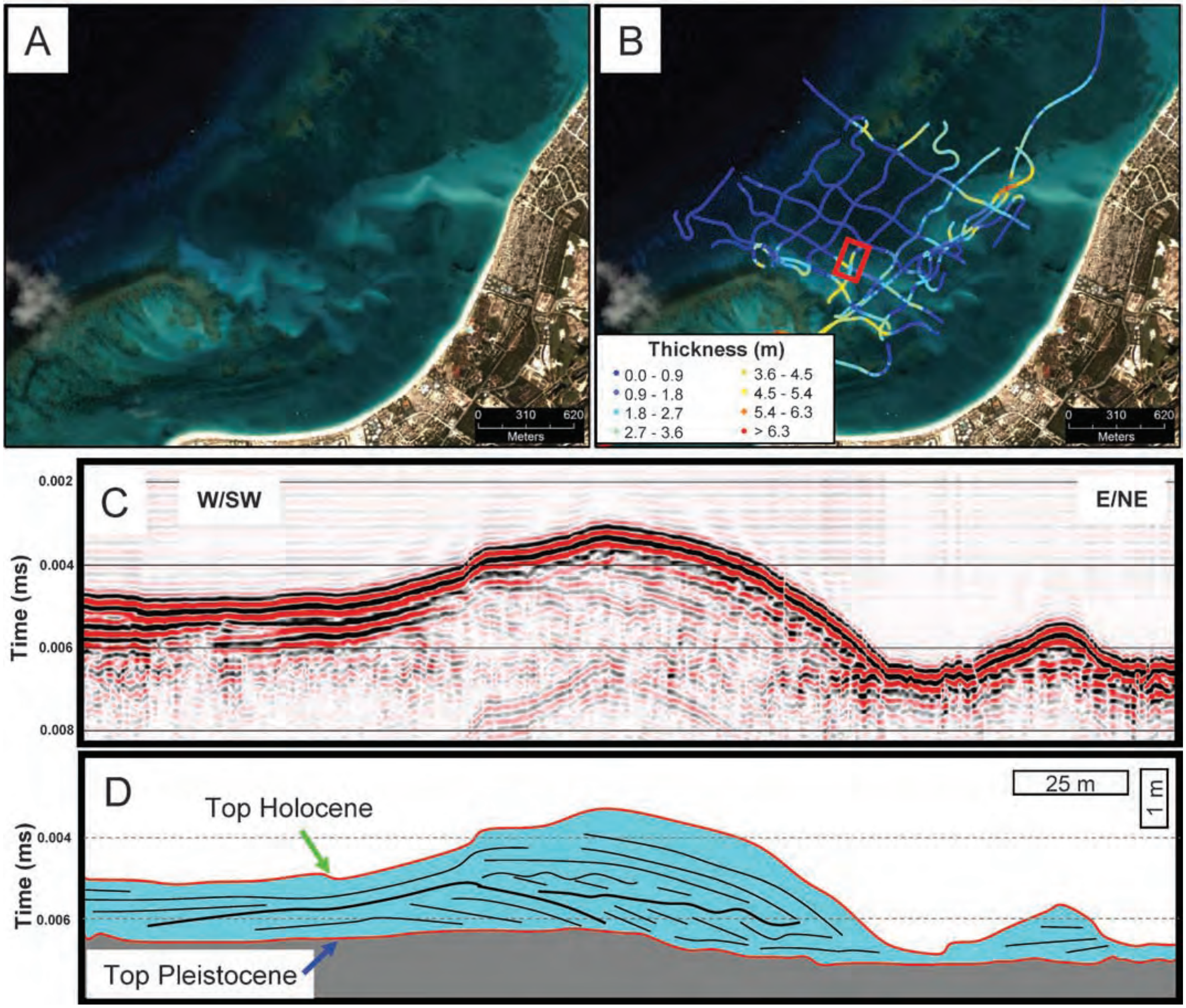

FIG. 11.— Sand-bar geometries in the area of Club Med. **A)** Uninterpreted remote-sensing image. **B)** Interpreted image with interpreted thicknesses of Holocene sediments superimposed. **C)** Uninterpreted Chirp line from the area of the red box in Part B. **D)** Interpretation of Chirp line shown in Part C, illustrating the accretionary foresets dipping to the E-NE. Remote-sensing images are copyright DigitalGlobe.

(Wheeland Cut) or to the Club Med area. In the Club Med area, where southwestward-directed longshore currents are met by eastward-directed currents, convergence in this area could result in a low net flow and accumulation of sediment in the bars (Fig. 11).

Comparison with Bahamian Platforms

The change in orientation of the margin (relative to predominant winds and open Atlantic waves) on Caicos Platform provided the opportunity to evaluate its role on facies patterns. Yet, in this area, another possibly important parameter—presence or continuity of islands—also varied, leading to some possible ambiguity in interpretations. A broader perspective is provided by comparing these areas with other isolated Bahamian platforms, Little Bahama Bank (LBB) and the Crooked–Acklins Platform (CAP), with size and facies patterns broadly comparable with those of Caicos Platform (Fig. 14).

The eastern margin of Little Bahama Bank (Fig. 14A), the northernmost Bahamian platform, does not have a well-developed reefal system, possibly because the shelf is too narrow (especially near the southeastern extent of the platform). Instead, the best developed reefs form a string of fully aggraded, discontinuous reefs in the northern margin of the platform. Although there are breaks in the reef system, occurring near

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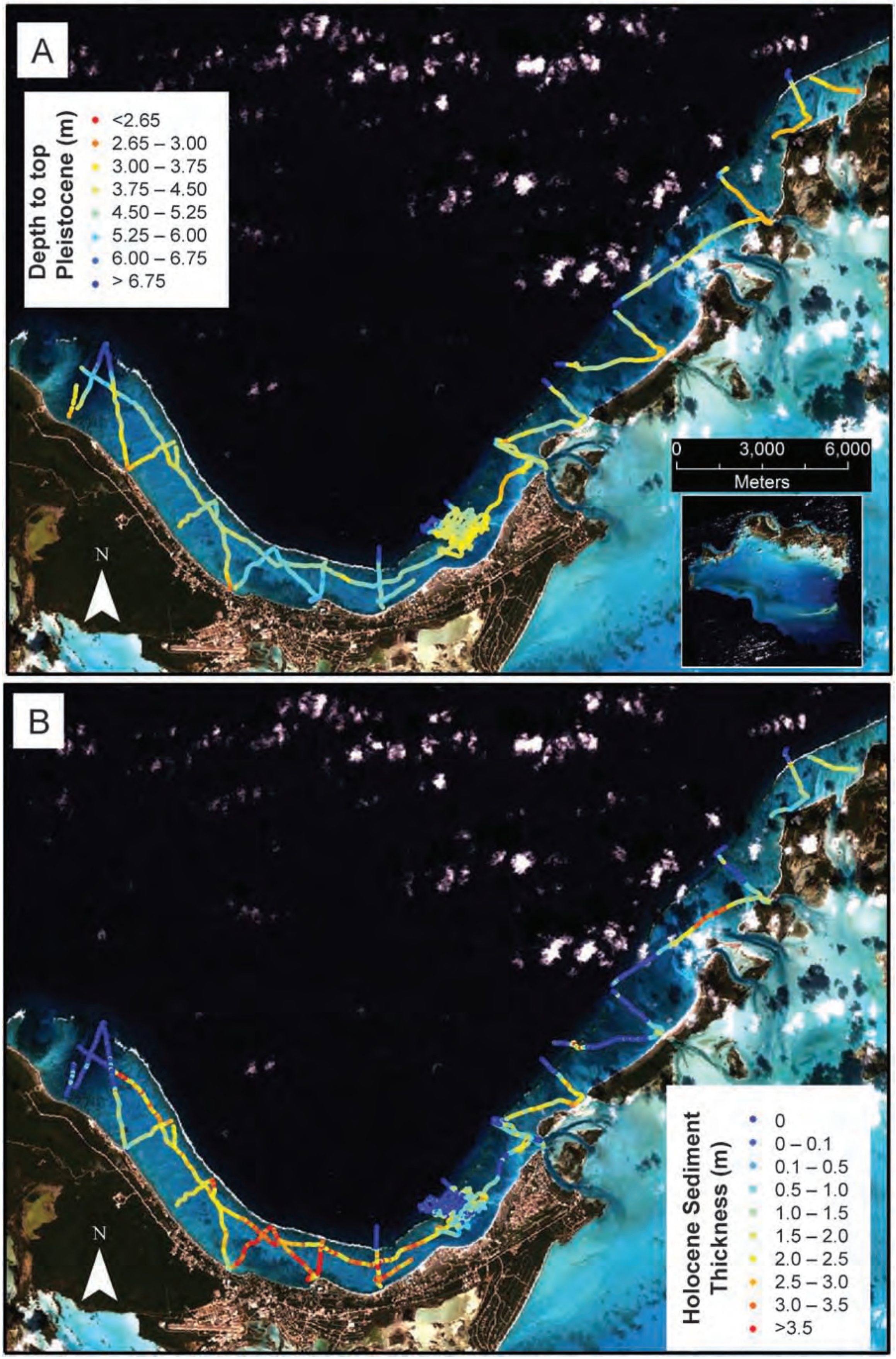
FIG. 12.—Overview maps illustrating: **A)** depth to top-Pleistocene surface (m); **B)** thicknesses of Holocene sediment accumulations. Note that the top-Pleistocene reflector is at comparable depths on both the Provo and Leeward margins, both include similar basinward dips, and both include considerable variability in sediment thicknesses along strike. See text for discussion.


A
Depth to top Pleistocene (m)
<2.65
2.65 – 3.00
3.00 – 3.75
3.75 – 4.50
4.50 – 5.25
5.25 – 6.00
6.00 – 6.75
> 6.75
0
3,000
6,000
Meters
N
B
N
Holocene Sediment Thickness (m)
0
0 – 0.1
0.1 – 0.5
0.5 – 1.0
1.0 – 1.5
1.5 – 2.0
2.0 – 2.5
2.5 – 3.0
3.0 – 3.5
>3.5

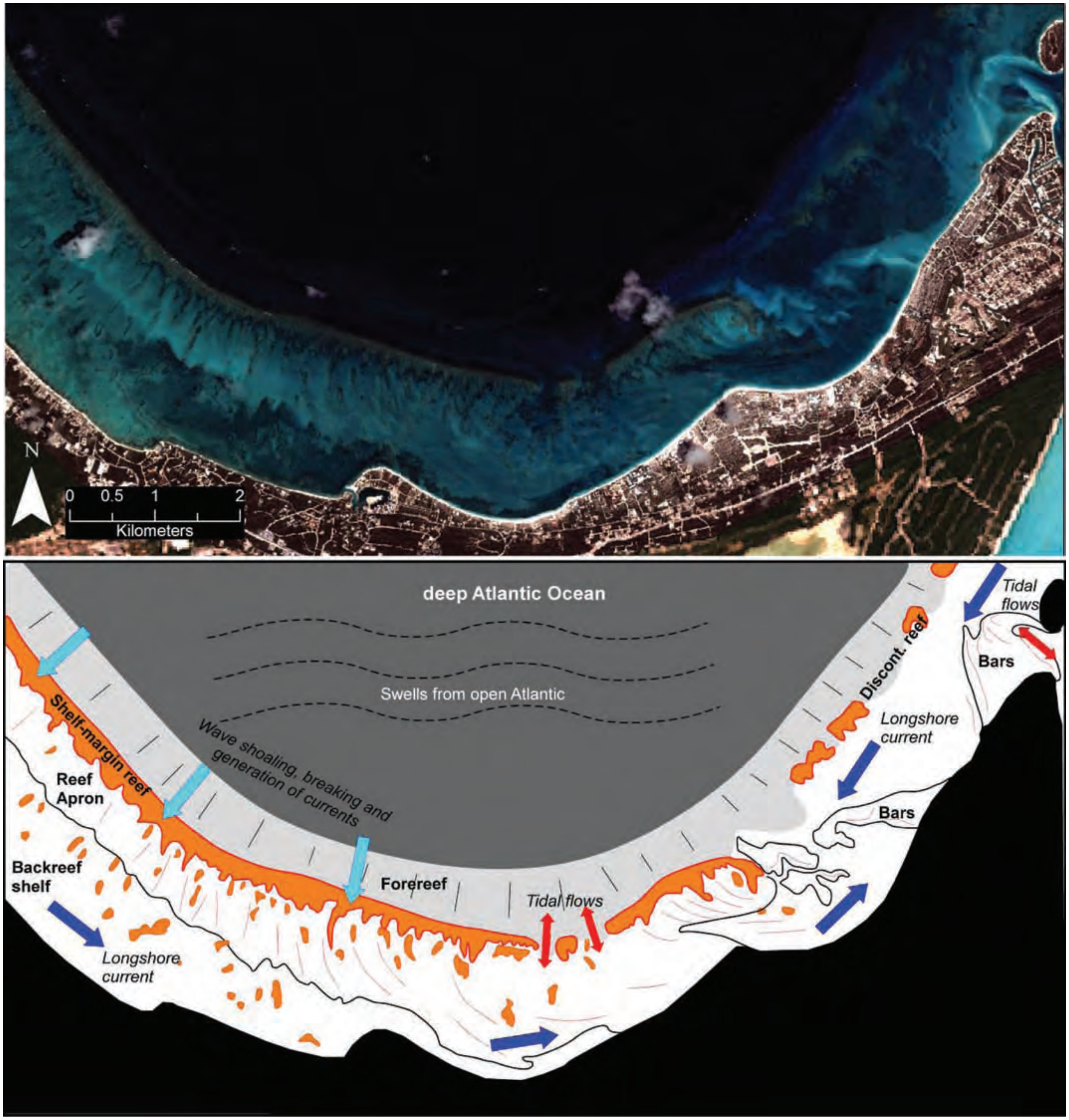


FIG. 13.—Remote-sensing image (upper) and conceptual model (lower) of the sedimentation patterns and current and wave influences in the southern part of the study area. Arrows represent the schematic direction of currents. See text for discussion. Upper image is copyright DigitalGlobe.

wide inlets between the islands, the trend of reefs is continuous along this margin (e.g., Fig. 14B). Therefore, the best-developed reefs on Little Bahama Bank form on the northern flank, akin to those on Caicos Platform.

Several workers (Newell et al. 1959; Neumann and Macintyre 1985; Ginsburg and Shinn 1993) have suggested that reef growth can be inhibited in areas in which there are breaks in islands, such as along the Florida Keys. In the central Keys, seaward movement of Florida Bay water through the passes limited reef growth, whereas reefs are better developed to the north and south, where there is more protection from Bay waters by islands. This situation is mimicked in the Abacos (Fig. 14B), where large inlets commonly face breaks in the reef trend.

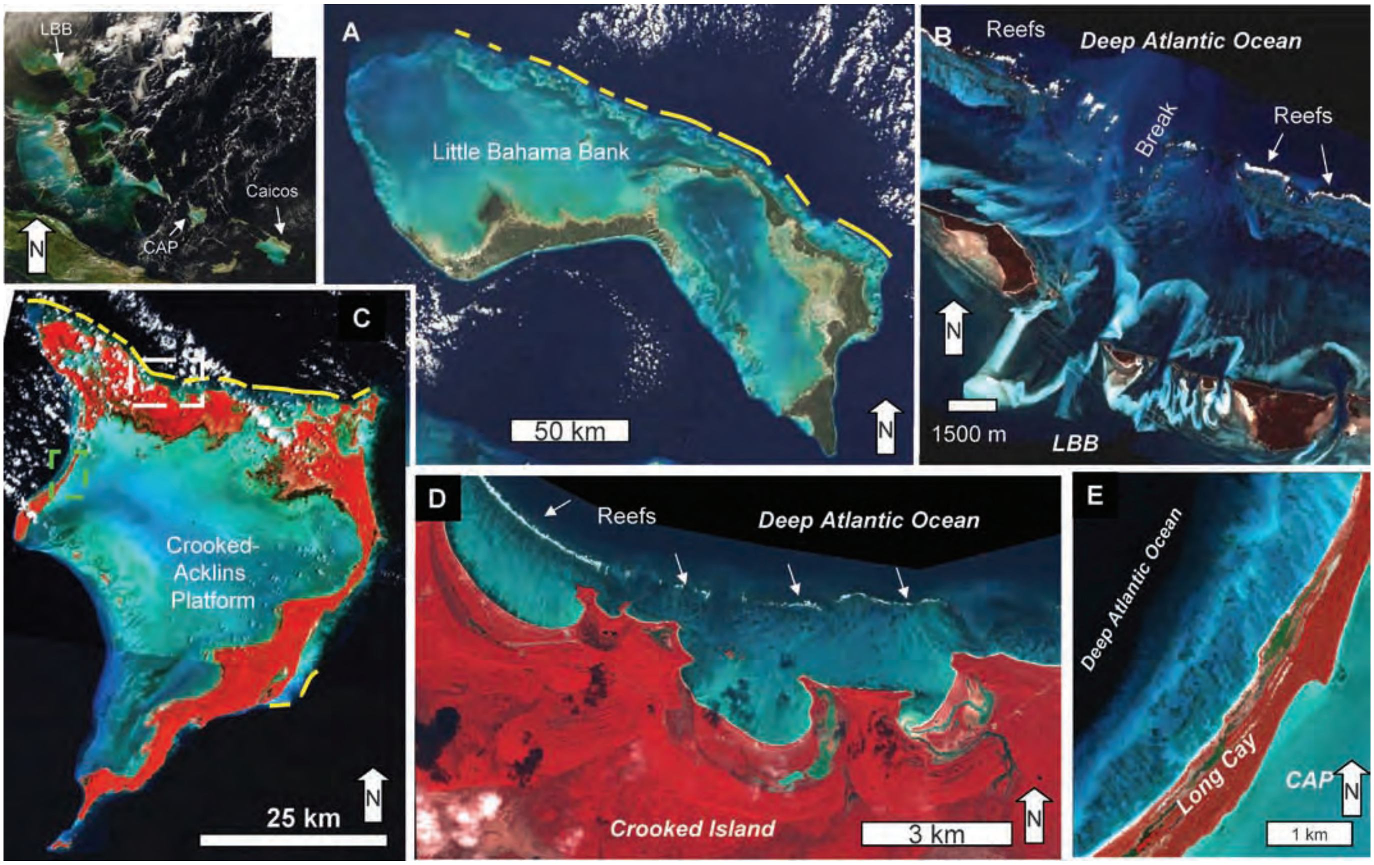


FIG. 14.—Remote-sensing images illustrating facies patterns on Bahamian platforms north of Caicos. Inset map shows the location of Caicos, Little Bahama Bank (LBB), and Crooked–Acklins Platform (CAP) mentioned in the text. **A)** Image of Little Bahama Bank. Yellow lines represent the occurrence of aggraded shelf-margin reefs, and breaks are the general locations of breaks in the reef trend. **B)** Close-up of one part of the system, near Stranger's Cay (white dashed box in Part A). White areas are waves breaking on the reef crest. Note the break in the reef oceanward of the largest inlet between islands. Modified from Reeder and Rankey (2008). **C)** Image of Crooked–Acklins Platform, southern Bahamas. Yellow lines represent the occurrence of aggraded shelf-margin reefs, and breaks are the general locations of breaks in the reef trend. **D)** Close-up of one part of the system (white dashed box in Part C), illustrating the aggraded reef system (white areas are waves breaking on the reef crest). Note the break in the reef oceanward of the continuous Crooked Island. **E)** Close-up of one part of the leeward margin, west of Long Cay (green dashed box in Part C). Note the general paucity of aggraded reefs. Much of the bottom here is irregular and rocky, partly sand-covered, or with low coral growths. (B, D, E are copyright DigitalGlobe).

Analogously, it could be that the inlets between cays on the northwest-facing Caicos margin might provide the means for bank waters to pass over reefs, inhibiting their growth.

Whereas we cannot rule out that bank waters limit reef growth in these areas, it is interesting that on the leeward margin of Crooked–Acklins Platform (Fig. 14C, E), the next large Bahamian platform north of Caicos, facies patterns are very similar to those on the Leeward Caicos margin, even though there is only one inlet system along its 35 km length. In this area, beaches are well developed, an ebb tidal delta is associated with the inlet, and much of the outer shelf is covered with a rocky bottom or thin sediment veneer, landscapes which are all similar to the Leeward shelf on Caicos. Perhaps most importantly, on this western flank of CAP, only smaller reefs that have not aggraded to sea level are present; no continuous barrier reefs akin to the Provo margin on Caicos occur, even though there is only minor flux of bank-interior waters to this margin. This relation is consistent with an interpretation that the presence of the inlets may not be the fundamental driver on facies patterns (especially the discontinuous reefs) on some leeward margins such as the northwest-facing Caicos margin.

On the Crooked–Acklins Platform, the best-developed, most fully aggraded reefs occur on the northern or northeastern margins, facing the open Atlantic waves (Fig. 14D), as on Caicos. In contrast, even though continuous islands block reef-inhibiting bank waters from flowing out across these margins, the eastward-facing (windward) margin has only patchy, non-aggraded reef growths. This observation is consistent with the interpretation that orientation relative to dominant swell is more important than windward-leeward influences or the presence of islands on the large-scale geomorphologic and facies development on platforms in this area.

These results and comparisons suggest that the conceptual model that platform-scale facies patterns are driven primarily by windward–leeward differentiation is overly simplistic. To be clear, these results should *not* be interpreted to suggest that margin orientation relative to the predominant wind direction, the presence of tidal passes, and offbank transport of bank waters have no influence on margin morphology; many studies have clearly illustrated otherwise. Instead, the complexity of these systems simply illustrates that enhanced understanding of fundamental drivers on platform-scale facies heterogeneity will require additional comparative studies in which processes can be systematically isolated and their impacts evaluated.

CONCLUSIONS

Carbonate shelf-margin systems are heterogeneous, and many studies (e.g., Sarg 1988; Eberli and Ginsburg 1989) have illustrated complexities reflected in seismic-scale geometries. At a much finer scale, integration of bottom observations, sediment analyses, remote-sensing data, and subbottom profile data illustrate the considerable spatial variability along the shelf margin of the Holocene sediments of the northwestern Caicos platform. The sedimentology, continuity, and geometry of Holocene shelf-margin reefs, sandy reef aprons, tidal deltas, and nearshore sands vary markedly along strike. The striking changes in Holocene sediments and geomorphology appear to be controlled by relations among several factors, including Pleistocene bedrock configuration (local elevation, presence of highs, and islands and inlets), sediment production, and sediment redistribution by waves, tides, and currents. Comparison of results from this Caicos area with other Bahamian platforms highlights the importance of understanding how oceanographic processes interact with Pleistocene bedrock configuration to influence facies patterns. In all of these examples, facies patterns vary from those which simple windward-differentiated facies models for carbonate platforms might suggest, but they are consistent with an interpretation that deep-water swells from the North Atlantic play a paramount role in shelf-margin facies patterns. These observations and interpretations provide conceptual models for comparable intra-cycle heterogeneity that may be reflected in ancient successions.

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