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Late Pleistocene Bays and Reefs: Ancestors to the Modern Caribbean Coast, Yucatán Península, México

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ABSTRACT

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Low-lying indentations along the modern Caribbean coast of the Yucatán Peninsula host shallow bays with classic crescent-shaped, white-sand beaches. These indentations have previously been explained as products of Holocene dissolution of Pleistocene limestones within a brackish coastal mixing zone. This paper demonstrates that the lows confining the modern bays were formed by sedimentary processes 122,000 ± 2000 YBP, during the late Pleistocene. A 50 km stretch of the Caribbean coast between Tankah and Playa del Carmen, here called the high coast, is characterized by rocky headlands that are underlain by fossilized coral reefs of late Pleistocene age and lows between headlands occupied by modern bays. Study of landforms using aerial photographs together with field examination of late Pleistocene calcarenite exposed in quarries has led to recognition of a series of arcuate Pleistocene beaches with large attached spits that developed during a period of falling sea level that followed the oxygen isotope substage 5e sea-level highstand. Pleistocene beaches and associated triangular spits form a series of cuspate arcs, each precisely aligned with one of the modern bays and each triangular spit aligned with the center of a modern headland. This exact and repeated coincidence of substage 5e bays with modern bays and beaches indicates that low areas occupied by modern bays lie within the lowest portions of late Pleistocene bays that were drained during the Wisconsin glacial and reflooded in their lowest parts during the post-Wisconsin rise of sea level in the Holocene.

ADDITIONAL INDEX WORDS: *Holocene, coastal morphology, mixing zone, karst, high coast.*

INTRODUCTION

Pleistocene rocks on the Yucatán Peninsula of México crop out along a well-preserved coastal belt, 1 to 10 km wide, that surrounds the entire peninsula (Weidie, 1985). Late Pleistocene beach ridges ("strand-plain" of Ward, 1985) and a contemporaneous reef facies ("barrier-reef limestone" of Ward, 1985) border the Caribbean high coast and were first mapped during the 1970s by W.C. Ward and his students. Their results were published in a series of guidebooks, the last of which appeared in 1985 (Ward, Weidie, and Back, 1985), and, together with its predecessors, this remains the only regional description of Pleistocene geology on the Caribbean coast of México. This paper introduces some refinements to that pioneering work.

What is here called the Caribbean "high coast" of the Yucatán Peninsula of México refers to 50 km of coastline between Tankah and Playa del Carmen that follows the east base of a ridge, 10 km wide and 20 m high, that stands as an outlier east of similar elevations farther west (Figure 1). The shore of the high coast is characterized by white, crescent-shaped, beaches separated by headlands composed of Pleistocene reef rock (Shaw, 1996). Headlands are absent both to the north and south of the high coast. In places where high, rocky areas are found apart from the high coast, they are of a fundamentally different character, consisting of indurated Pleistocene dunes that formed during the fall of sea level at the end of the last interglacial (Kelley *et al.*, 2004; Ward, 1985). North of the high coast, dunes near Cancun underlie the offshore islands of Isla Contoy and Isla Mujeres or are connected to the mainland by tombolos, as at Isla Cancun. South of the high coast, waves break against a shore lined by indurated late Pleistocene dunes similar to those offshore from Cancun. The ancient Maya city of Tulum (Tulum Ruins) sits atop the highest of these indurated dunes. The southern dunes start 5 km north of the Tulum Ruins and continue southward for 18 km (Kelley *et al.*, 2004; Ward, 1985). Figure 2 is a reproduction of the regional map by Ward and Brady (1979), which also appears in the 1985 guidebook (p. 62) and shows the distribution of Pleistocene sedimentary environments. The high coast is not recognized on this map as something different in character from surrounding coastal areas.

Measurements in the field, discussed herein, indicate that the late Pleistocene beach on the high coast near Akumal reaches a maximum elevation of 8 m within 1.5 km from the modern shore. Shorelines both to the south and north of the high coast are close to sea level. The 8 m contour near Tulum lies 8 km inland. Similarly, the 8 m contour west of Cancun lies 20 km inland from the Caribbean coast (Figure 1). Flooded mangroves cover a wide area that more or less corresponds to the band of Holocene carbonate sediments shown by the pattern of inclined ruling on Figure 2. Mangrove stands extend to the shore, where, in most places, they are overlain by sandy beach that might be only 1–2 m wide, south of Punta Maroma, or tens of meters wide, as at Cancun and at Puerto Morelos (see Figure 1 for locations).

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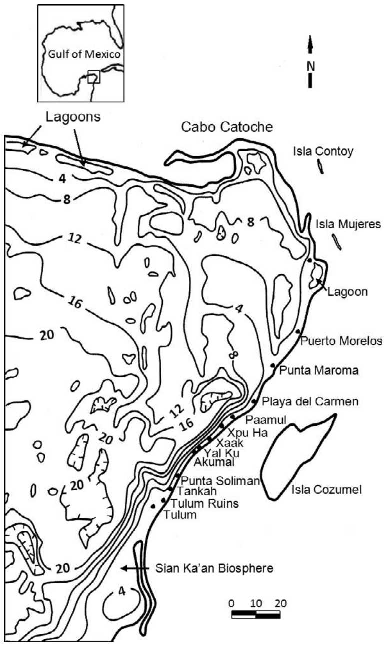

Figure 1. Topographic map of the northeastern Yucatán Peninsula. Regional topography is shown at a contour interval of 4 m, along with localities mentioned in the text. The area of this study covers 50 km of unique rocky coast between Tankah and Playa del Carmen, here called the "high coast." Interpretive details for the high coast are based on topographic and stratigraphic data developed near the pueblo of Akumal.

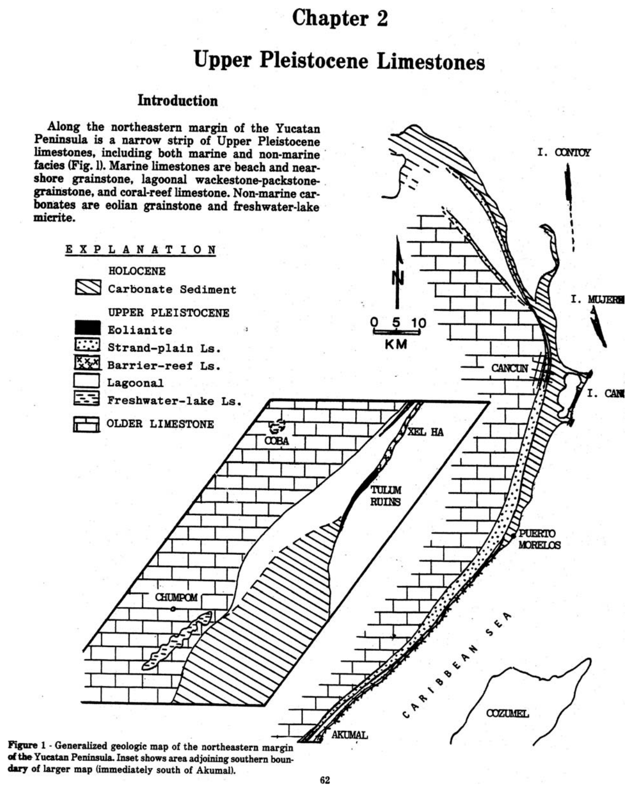

Figure 2. "Generalized" geologic map of the northeastern margin of the Yucatán Peninsula. (from Figure 1 of Ward 1985, p. 62).

South of the high coast, the line of Pleistocene dunes mentioned here terminates a few kilometers north of where the modern beach east of the Tulum Pueblo separates from the mainland (Figure 1) to form a barrier bar between the extensive Holocene wetlands of the Sian Ka'an Biosphere Reserve and the open Caribbean. The high coast stands between these low areas of coastal mangrove. Its unique development of bays and headlands is the subject of this investigation.

METHODS

Series of cuspate landforms that are attached to the strand-plain calcarenites mapped by Ward and Brady (1979) were first recognized on aerial photographs. Two of these cusps on the high coast near Akumal were surveyed at a scale of 1:4000 (Figure 3) between the Pleistocene beach ridge (strand-plain of Ward) and the coast in order to define details of topographic features on the aerial photographs (Figure 4). The quarry shown on Figure 3 was the collection site for rock samples used by Szabo *et al*. (1978) for uranium series dating. Study of landforms, field examination of spit sediments exposed in the quarry, and examination of fossilized late Pleistocene reefs exposed in the modern headlands reveal a well-preserved Pleistocene coastal depositional system and morphology. The Pleistocene morphology has been modified by dissolution along a coast-parallel zone of karst collapse where modern groundwater mixes with seawater (Back, Hanshaw, and Pyle, 1976; Back *et al*., 1979; Beddows, 2004, p. 10–12).

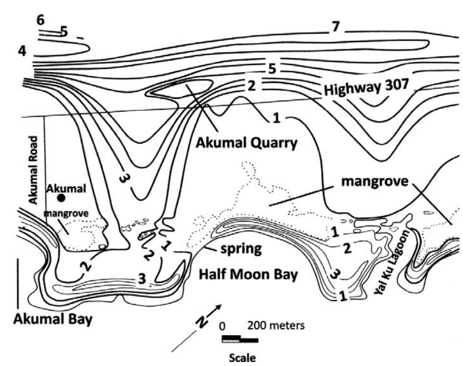

Figure 3. Topographic map of the area between Akumal Bay and Yal Ku Lagoon. The 8-m-high ridge at the top of the map is the crest of the late Pleistocene beach ridge (strand-plain of Ward, 1985). Triangular spits centered behind each headland are composed of calcarenite deposited during the fall of sea level after the oxygen isotope substage 5e highstand. A zone of irregular topography that conspicuously disrupts the coastward point of the large spit behind the Akumal headland reflects a linear collapse zone, 200 m wide, that crosses the entire map left to right and that can be traced across the entire high coast. The karst zone is where brackish groundwater flows to the surface. Numerous dissolution features lie within the karst zone, including Yal Ku Lagoon.

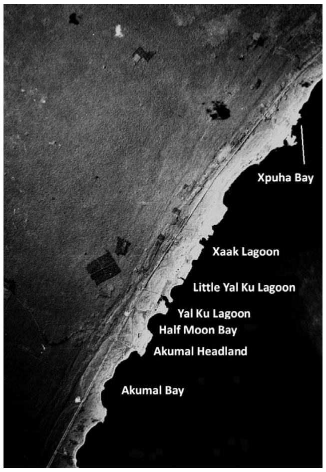

Figure 4. Aerial photograph showing the regional extent of beaches and triangular spits similar to those studied at Akumal. The two white dots are quarries in spits that bracket Akumal Bay. The north quarry is the site of photographs in Figures 7 and 8. The spit separating Akumal Bay and Half Moon Bay is crossed by Highway 307. A 200-m-wide zone of karst collapse behind the coast, visible in the topography on Figure 3, shows as a series of lagoons and sinkholes. The gray band at Yal Ku Lagoon is part of the collapse zone occupied by mangrove. The collapse zone marks where fresh groundwater from inland mixes with seawater and discharges to the surface.

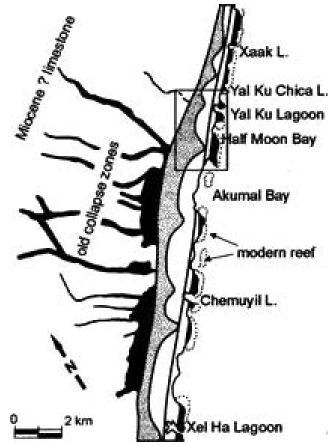

Figure 5. Map showing interpretations of topographic features on Figure 4. Pleistocene beaches (stipple), limestones on the Pleistocene bay floor (white), and headland reefs (black on coast) are delineated. Dotted lines offshore show modern reef crests. Black areas inland from the Pleistocene beach indicate old collapse zones in possible Miocene rocks (Lopez Ramos, 1975). A line behind the modern headlands is the west edge of the collapse zone where brackish water emerges at the surface. This line is marked in the field by a low scarp that ranges in height between 0.5 and 2 m, depending on the local topography. The spit at Xaak is blunted where it meets the collapse zone and makes a 2 m scarp. Rectangle shows area of Figure 3.

RESULTS

Mapping for this study has revealed a consistent geographic pattern between the distribution of late Pleistocene marine environments and similar Holocene environments. A case in point is found on the seaward edge of the Pleistocene reef that forms the headland at Akumal, which presently is host to modern coral growth upon the submerged skeletons of their ancestors (Jordán-Dahlgren, 1993; Ward, 1985). At Akumal, small elkhorn corals (*Acropora palmata*) grow in 1 m of water that floods the essentially flat floor of a wave-cut notch in the Pleistocene reef rock. The notch extends seaward for about 3 m before dropping steeply to a depth of –10 m. The surface of the steep outer slope displays classic ridge and groove topography with meter-deep grooves oriented straight down the slope. Sparse elkhorn coral growth covers the wave-cut notch and the tops of the narrow ridges. Water from breaking waves returns down the grooves. Ward (1985) reports that a core drilled to 12 m total depth on the headland at Akumal penetrated Pleistocene coral throughout (Ward, 1985, p. 63, 67).

Observations at the south and north ends of the Akumal headland show that, while the shoreline turns sharply landward into Akumal Bay and Half Moon Bay, respectively, living corals that follow the fronts of the headlands continue without deflection across the bays, and at Akumal, they have built spectacular submarine growths, 10 m high, that protect the bays from the open sea. Scuba exploration along the reef wall in front of Akumal Bay revealed huge cannon-shaped growths of elkhorn coral that rise to the surface, where they form a broad reef crest over which waves perpetually break in a continuous white line. It is not known if this modern barrier has been built on an older Pleistocene reef in the same position. Seaward of the reef crest, between depths of –10 m to –30 m, modern, coast-parallel, patch reefs are separated by areas of sandy bottom. These occupy a zone that extends 0.8 km seaward where the bottom drops steeply from –30 to –160 m, as indicated by unpublished sonar data collected by Dr. Andrew Fischer, then with the Monterey Bay Research Institute (MBARI), and his students. The complex of reef and sand bordering the Yucatán Peninsula is part of the Mesoamerican Barrier Reef, which, at 1000 km long between the north end of the peninsula at Cabo Catouche and the Bay of Honduras, is the second largest barrier reef in the world (Jordán-Dahlgren, 1993).

Pleistocene and Modern Bays

Figure 3, surveyed in 1994 with the help of student interns at Centro Ecológico Akumal, shows landforms in the area between Akumal Bay and Yal Ku Lagoon. Low, swampy ground below 1 m in elevation lies immediately inland from the modern beaches and is underlain by Pleistocene strata consisting of fine-grained clastic limestone that preserves a fossil fauna of whole clams, snails, and scattered coral debris, especially staghorn coral. These low coastal areas, like that inland from Half Moon Bay, extend up to 750 m inland from the modern beach to the base of the Pleistocene beach ridge at the 2 m contour on Figure 3. The Pleistocene deposits and fauna are similar to those in the modern bays.

Pleistocene Beaches, Spits, and Reefs

Figure 3 captures previously unrecognized triangular spits attached to the Pleistocene beach and positioned behind each of the modern headlands. The top of the large spit behind the

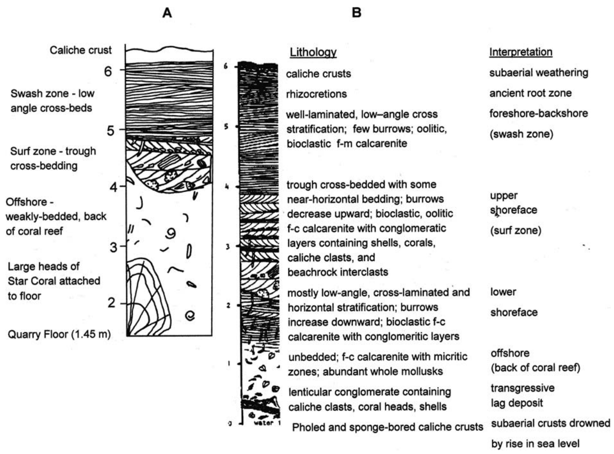

Figure 6. Contrasts between the "diagrammatic" stratigraphic column of Ward and Brady (1979) and strata exposed in the Akumal quarry. (A) This column depicts strata exposed in the east wall of the Akumal quarry and relates them to strata recognized by Ward and Brady (1979). The foreshore sediments in column B are mostly absent in the Akumal quarry, as might be expected due to its protected position behind the Pleistocene reef in the Akumal headland. Significant stratigraphic details are noted in the photograph of the east wall in Figure 7, which may be compared directly with Figure 6A. (B) "Generalized" section meant to represent the entire "beach-ridge plain" of Ward (1985) and Ward and Brady (1979). A scour surface at the top of Ward and Brady's "lower shoreface" might be represented at Akumal by what appears to be a scoured surface above the thick "offshore" deposits shown on Figure 6A and on Figure 7.

Figure 7. Photograph showing detail of the east quarry wall at Akumal. A large coral head (*Montastraea annularis*) is attached at the quarry floor and presumably grew in clear water prior to being smothered by sediment. Annual growth bands record 150 years of growth. A second *Montastraea* head may be seen immediately left in front of the person's head. Nearby fossils include large, whole conch, clams, and snails. Photo: Kristin Kelley, Mississippi State University.

Akumal headland reaches an elevation of 5 m where crossed by Highway 307 (Figure 3), in agreement with published estimates of the late Pleistocene rise in sea level based on isotopic studies (Szabo *et al*., 1978) and the estimate of Blanchon *et al*. (2009). Figure 3 shows the mapped topography uncluttered by interpretive patterns, which are presented later.

The aerial photograph in Figure 4 shows a repeating pattern of Pleistocene spits along 18 km of coast, each attached to the Pleistocene beach ridge and positioned behind a Pleistocene reef. The cusps between spits, like those shown in detail in Figure 3, bracket the lows occupied by modern bays. Figure 4 presents the terrain without interpretive patterns or lines. Figure 5 highlights features recognized on Figure 4 and indicates the Pleistocene sedimentary environments associated with each landform. The triangular spits are positioned close to the centers of each headland and separate the Pleistocene bays. Together, these Pleistocene landforms and associated strata define a series of bays inland from each of the modern bays on the high coast.

The Pleistocene beach ridges between spits rise steeply in elevation from 2 m at their base to 8 m, or more (Figure 3). The attached spits show flat tops at 5 m, except close to the higher beach ridge, where they may reach 6 m. West of Highway 307, the quarry exposes the internal sedimentary sequence of the spit.

Figure 6 compares the "generalized" stratigraphic section of Ward and Brady (1979) with a similar column measured in the Akumal quarry. Figure 6A shows strata exposed on the east quarry wall close to Highway 307. Figure 7 is a photograph of the same east wall. The patterns used in Figure 6A follow those used on Figure 6B by Ward and Brady (1979) and Ward (1985, p. 66) for their "beach-ridge plain" mapped on Figure 2. Ward and Brady's section closely matches the internal sedimentary sequence and related marine environments observed in the Akumal quarry with one important exception—the thick foreshore deposits representing high energy in the surf zone shown in Figure 6B are largely absent from the spit at Akumal, as might be expected in the protected environment behind the Pleistocene reefs.

The east wall of the quarry exposes a thickened offshore facies, about 2.5 m thick, that is overlain by a cross-bedded "upper-shore" sequence consisting of the swash zone and foreshore of Ward and Brady (1979) that is more than 2 m thick above a scoured base (Figures 6A, 6B, and 7). The scour zone could signal the beginning of sea-level regression and the deposition of beach sand across the spit.

At its base, the offshore facies encloses several large heads of *Montastraea annularis* up to 1.5 m in diameter. These are attached to the quarry floor in growth position (Figures 6 and 7). Annual growth bands (Dodge *et al*., 1993) that are 1 cm thick indicate 150 years of growth before an influx of sediment buried them. Figure 8 shows a long view of the east wall and the adjacent quarry floor. At the top of Figure 8, the N-sloping surface of the spit may be seen as it descends into the Pleistocene low associated with Half Moon Bay. At the far end of Figure 8, the cut of the wall is at right angles to the slope, giving the apparent flat contact between a thinned section of quiet-water deposits and the cap of cross-bedded beach at top.

Ward (1985) suggested that the quarry floor at Akumal, at 1.75 m above sea level on the west and sloping gently to 1.45 m near the east wall, might belong to an older Pleistocene

Figure 8. Photograph showing a broad view of the east wall in the Akumal quarry. At the top, cross-bedded "foreshore" (beach) deposits of the swash zone, 1 m to 1.5 m thick, overlie fine-grained "back-reef" sediments that contain unbroken fossils. The N-sloping upper surface of the quarry wall is the spit surface where it descends northward toward the Pleistocene bay floor behind modern Half Moon Bay (see Figure 3). The high-energy "surf zone" facies shown in Figure 6B is absent. Note person near the center for scale. Location of Figure 7 is directly to the person's left. Photo: Kristin Kelley, Mississippi State University.

interglacial. An alternative interpretation might be based on similar altitudes and fossils in the nearby floor of the Pleistocene Half Moon Bay, also at an elevation of less than 2 m (Figure 3), suggesting that the spits could have spread over earlier Pleistocene deposits that preceded the rapid rise in sea level associated with oxygen isotope substage 5e (Blanchon *et al*., 2009; O'Leary *et al*., 2013). This interpretation would explain the lack of a sponge-bored surface at Akumal like that shown at the bottom of the column on Figure 6B.

Reefs that lived contemporaneously with the Pleistocene bay-floor/spit fauna form the modern headlands, where massive accumulations of staghorn coral (*Acropora cervicornus*), star coral (*Montastraea annularis*), and brain coral (*Diploria strigosa*) are found along with scattered elkhorn corals (*Acropora palmata*). The latter dominate the fauna on the reef crest and the area immediately seaward of the crest. These Pleistocene coral communities are exposed in the headlands and are especially well exposed along transcoastal channels like at Yal Ku, Xel Ha, and other coastal lagoons shown on Figure 1.

Coastal Mixing Zone

A 200-m-wide zone of karst collapse is associated with the coastal mixing zone, where calcium carbonate–saturated groundwater from inland mixes with seawater, also saturated with calcium carbonate. Mixing of the two waters leads to an increase in the solubility of calcium carbonate in the brackish zone relative to its solubility in either the freshwater or seawater (Back, Hanshaw, and Pyle, 1976; Back *et al*., 1979). Zero salinity is found in wells and small sinkholes near Highway 307 and inland.

The karst zone lies parallel to the coast immediately behind the line of headlands and crosses the nearshore areas of the modern bays. This zone appears on Figure 3 as a 200-m-wide zone of irregular topography that disrupts the smooth contours of the large spit behind the Akumal headland. Further, the area occupied by mangrove inland of Half Moon Bay on Figure 3 outlines a low area within the Pleistocene bay that also is disrupted by the karst zone and, therefore, must predate dissolution associated with the modern coastal mixing zone.

On a regional scale, the aerial photograph in Figure 4 shows the collapse zone between Xel Ha and Xaak Lagoon as a continuous feature crossing bays as well as headlands (Figures 4 and 5). The karst zone can be recognized along the entire 50 km of the high coast.

The karst zone is connected to the sea at intervals by channels dissolved across Pleistocene headlands, which often are connected to *caletas* behind the headlands. Examples of the channels are numerous and can be seen on Figure 4 at Xaak, Yal Ku Chica, and Yal Ku Lagoon. Figure 5 extends a bit farther south and includes *caletas* at Chemuyil and Xel Ha. All these features have been dissolved across headlands.

DISCUSSION

The prevailing idea for the origin of the bays and *caletas* on the Caribbean coast was proposed by W. Back, B.B. Hanshaw, and T.E. Pyle (1976) and expanded by Back *et al*. (1979) to account for karst relationships they studied at Xel Ha Lagoon. Their idea was that modern bays started with *caletas*, which they interpreted as recent features dissolved from Pleistocene reef and back-reef sediment by brackish water rising to the surface in the coastal mixing zone (Back, Hanshaw, and Pyle, 1976). This interpretation is in agreement with observations reported here from Yal Ku Lagoon, as is the post-Pleistocene timing of the process.

To account for the modern bays, however, Back and his coworkers took their theory a step further and proposed that large bays, like Akumal Bay and Half Moon Bay, were due to widening of early *caletas* until adjacent *caletas* merged. This hypothesis would mean that the lows occupied by modern bays are modern features, the locations of which are controlled by dissolution after modern sea level had been reached.

Figures 3, 4, and 5 imply the opposite, *i.e*. that the bay morphology was developed during the last interglacial. Having established herein that the Pleistocene bays were formed during substage 5e, and that the modern karst zone postdates the late Pleistocene spits and other Pleistocene deposits, it follows that the Holocene collapse zone would cross preexisting topographic highs and lows. Scattered subsea springs in the modern bays discharge brackish water from the mixing zone beneath, but the expansion of *caletas* to form bays is both unnecessary and unsupported by modern examples of such a process in progress.

CONCLUSIONS

Sequences of cuspate beaches composed of a beach ridge and attached triangular spits of carbonate sand are prominent features of the Pleistocene high coast. Topographic relationships on Figures 3, 4, and 5 demonstrate that the Pleistocene

cusps are centered behind each of the modern bays. Each triangular spit between bays is located behind the center of each headland, where accumulation of sand was protected behind late Pleistocene reefs as sea level dropped following the late Pleistocene substage 5e highstand. Approximately 100,000 years later, as the Holocene sea reached its modern level following the Wisconsin glaciation, the lowest parts of the late Pleistocene bays were again flooded, while adjacent Pleistocene reef masses remained above sea level. With the sea at close to modern level, brackish water outflow within the coastal mixing zone dissolved a more or less linear, coast-parallel, collapse zone across all preexisting coastal topography, including beneath the modern bays, but history, not karst processes, controlled their positions.

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