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Pleistocene Corals of the Florida Keys: Architects of Imposing Reefs—Why?

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ABSTRACT

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Five asymmetrical, discontinuous, stratigraphically successive Pleistocene reef tracts rim the windward platform margin off the Florida Keys. Built of large head corals, the reefs are imposing in relief (~30 m high by 1 km wide), as measured from seismic profiles. Well dated to marine oxygen isotope substages 5c, 5b, and 5a, corals at depth are inferred to date to the Stage 6/5 transition. The size of these reefs attests to late Pleistocene conditions that repeatedly induced vigorous and sustained coral growth. In contrast, the setting today, linked to Florida Bay and the Gulf of Mexico, is generally deemed marginal for reef accretion. Incursion onto the reef tract of waters that contain seasonally inconsistent temperature, salinity, turbidity, and nutrient content impedes coral growth.

Fluctuating sea level and consequent settings controlled deposition. The primary dynamic was position of eustatic zeniths relative to regional topographic elevations. Sea level during the past 150 ka reached a maximum of ~10.6 m higher than at present ~125 ka, which gave rise to an inland coral reef (Key Largo Limestone) and ooid complex (Miami Limestone) during isotope substage 5e. These formations now form the Florida Keys and a bedrock ridge beneath The Quicksands (Gulf of Mexico). High-precision radiometric ages and depths of dated corals indicate subsequent apices remained ~15 to 9 m, respectively, below present sea level. Those peaks provided accommodation space sufficient for vertical reef growth yet exposed a broad landmass landward of the reefs for >100 ka. With time, space, lack of bay waters, and protection from the Gulf of Mexico, corals thrived in clear oceanic waters of the Gulf Stream, the only waters to reach them.

ADDITIONAL INDEX WORDS: *Coral reefs, eustatic apices, Florida Keys, Holocene transgression, Key Largo Limestone, Miami Limestone, outlier reefs, paleoenvironment, Pleistocene topography, sea level fluctuations, windward carbonate margin.*

INTRODUCTION

The platform beneath South Florida and the Florida Keys slopes several meters westward (ENOS and PERKINS, 1977; LIDZ, REICH, and SHINN, 2003). Its southern edge is a windward margin consisting of a shallow (generally <12 m) shelf fronted by an upper-slope terrace 30 to 40 m deep (HOFFMEISTER, 1974; HOFFMEISTER and MULTER, 1968; LIDZ, REICH, and SHINN, 2003; LIDZ *et al.,* 1997a; MULTER *et al.,* 2002). The shelf is informally divided into inner and outer areas (ENOS, 1977) on the basis of margin-parallel bedrock features. Topographically, an erosional nearshore rock ledge (LIDZ *et al.,* 2006; "limestone bedrock" of MARSZALEK, 1977) and a bedrock depression beneath Hawk Channel characterize the inner shelf throughout the keys. Elevated above the channel depression, a narrow, linear, coral ridge-and-swale structure and a wide, discontinuous shelf-edge reef differentiate the outer shelf (LIDZ, REICH, and SHINN, 2003; LIDZ *et al.,* 2006). The Florida Keys chain is set back some 5 to 7 km from the shelf edge, defined in this paper as the contact between the shelf-edge reef and the upper-slope terrace at a water depth of 30 m (Figure 1).

The keys consist of the substage 5e Key Largo Limestone (patch-reef facies) and Miami Limestone (oolite facies) that accumulated ~125 ka when sea level was ~10.6 m higher than today (HALLEY and EVANS, 1983; HOFFMEISTER, 1974; HOFFMEISTER and MULTER, 1968; HOFFMEISTER, STOCKMAN, and MULTER, 1967; SANFORD, 1909; STANLEY, 1966). The submerged shelf extends westward into the Gulf of Mexico as a broad, curved, bedrock promontory dotted with Holocene islands of the Marquesas Keys and the Dry Tortugas. Part of the promontory is a large (~28 by 47 km) rectangular ridge beneath an area of shifting Holocene sands known as The Quicksands (SHINN, LIDZ, and HOLMES, 1990). The Marquesas Keys occupy part of the east end of the ridge. Ridge elevation ranges from 1 to 12 m below present sea level but is typically ~6 to 8 m (LIDZ, REICH, and SHINN, 2003). The age of the ridge bedrock is inferred to be ~125 ka on the basis of its oolitic composition and isolated presence at its northern edge of Pleistocene corals similar to those of the Key Largo Limestone (SHINN, LIDZ, and HOLMES, 1990). Skeletal Holocene corals cap the Pleistocene corals. None of the cored ridge facies has been dated.

Five discontinuous reef tracts rim the shelf edge off the

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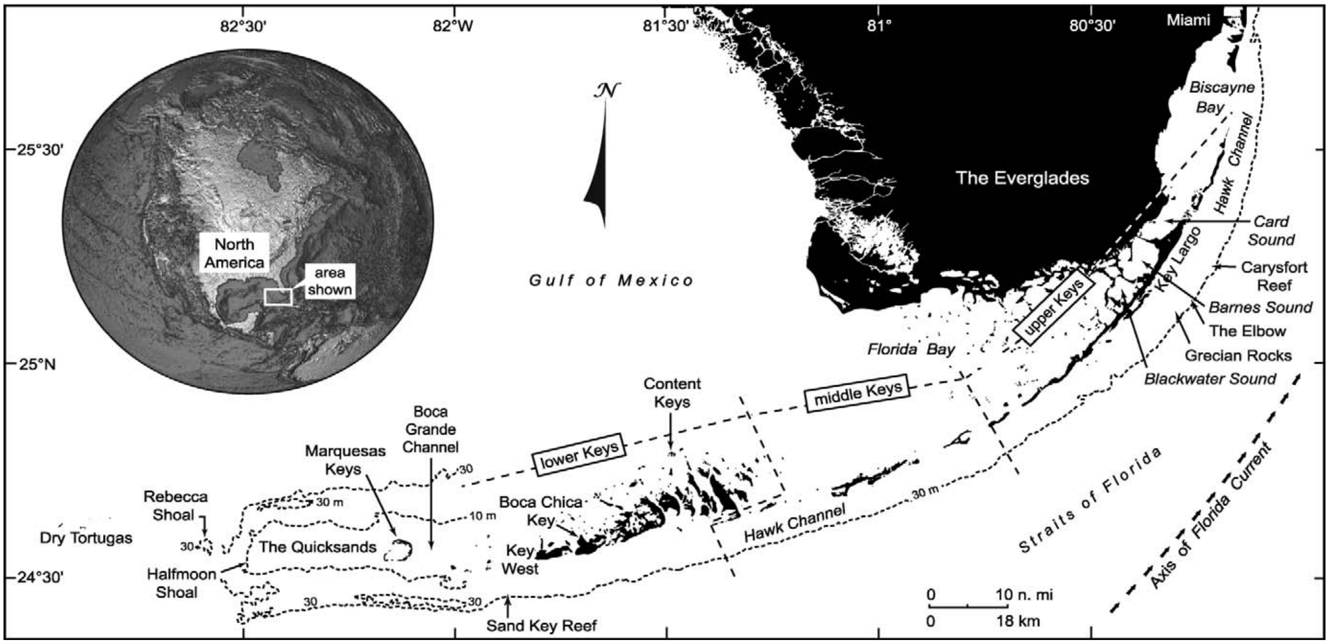

Figure 1. Index map of South Florida and the Florida Keys. Dashed black lines delineate lower, middle, and upper Keys. Dashed dogleg shows that the Key Largo Limestone reef extends south of the eastern part of the lower Keys Miami Limestone oolite. Southeast Reef and Tortugas Bank are located in the Dry Tortugas. Dotted line (30-m depth contour) marks the shelf margin. Contours are in meters.

Florida Keys, forming a broad reef-and-trough structure consisting of the shelf-edge reef and four parallel tracts of outlier reefs on the upper-slope terrace (ENOS and PERKINS, 1977; LIDZ, 2004; LIDZ, REICH, and SHINN, 2003; LIDZ *et al.,* 1991, 1997a). The reefs are well-dated radiometrically to marine isotope substages 5c, 5b, and 5a (LUDWIG *et al.,* 1996; MULTER *et al.,* 2002; TOSCANO, 1996; TOSCANO and LUNDBERG, 1998, 1999) and are inferred to contain corals at depth that would date to the Stage 6/5 transition (LIDZ, 2004; LIDZ, REICH, and SHINN, 2005; LIDZ *et al.,* 2006). Although individually irregular in shape, reflecting differences in coral growth, the largest reefs (keep-up reefs of NEUMANN and MACINTYRE, 1985) are topographically imposing relative to isolated, narrow Holocene accretions. Where present shelf-wide, the five tracts often reach seismic relief of ~30 m, a width of close to 1 km, and are similar in water depth, offshore location, and stratigraphically successive ages. The numerous overall similarities imply that accommodation space was present and conditions favorable for coral growth were consistent during the consecutive times of accrual.

Given accommodation space, a premise often called upon to explain the size of these reefs is time (SHINN *et al.,* 1977). Late Pleistocene corals had thousands of years during each of three successive highstands to build reef framework (LIDZ, 2004; LIDZ, REICH, and SHINN, 2005). Holocene corals also built sizable reefs in the time they had, which, off the Florida Keys, ranged from ~7 to 2 ka (SHINN *et al.,* 1977). Most Holocene reefs cap Pleistocene reefs. The thickest Holocene reef drilled (~17 m) on the Florida reef tract is Southeast Reef in the Dry Tortugas (SHINN *et al.,* 1977). The thickest reefs off the keys (1–2 m) are inshore from the platform margin (SHINN *et al.,* 1989). However, even given substantially more time, at present sea level, Holocene corals would not likely construct a stratigraphic framework section comparable in size and thickness to those (LIDZ, 2004) of the late Pleistocene. Part of the reason is because a relatively stable sea level would confine upward accretion. However, the primary reason relates to significant differences in geomorphic settings caused by inconsistent late Pleistocene and Holocene highstands and in the effects on the respective reefs of resultant ambient conditions. The time span of interest is isotope substage 5e (~125 ka) through today.

This paper is an outcome of a comprehensive synthesis of late Quaternary reef stratigraphy in the Florida Keys (LIDZ, REICH, and SHINN, 2005). The synthesis incorporated as its foundation numerous databases, sources, methodologies, and technologies derived independently for different purposes by others. Through the use of a select combination of those datasets, this article presents evidence for differences in geomorphic settings induced by fluctuating sea level during the late Pleistocene and Holocene. Although the Holocene data have implications for the decline of the modern reef system observed today, it is not the intent here to render judgment on any effect the present transgression might or might not have relative to the decline. The causes of decline are not well understood and are under study by others. However, interpretations of the effect of the Pleistocene settings on reefs of that age are given on the basis of the proxy evidence. Results show that accommodation space and geomorphic settings generated by lower maxima of late Pleistocene sea level provided the stimuli for vibrant reef growth and preservation.

METHODS

Databases relevant to this paper are high-precision radiometric dates on cored late Pleistocene corals, global and local sea-level maxima records, and data from geophysical surveys. Sea-level maxima derived from high-precision dating and depths below present sea level of recovered corals provided coral ages and local apices for highstands during marine isotope substages 5c, 5b, and 5a (LUDWIG *et al.,* 1996; TOSCANO and LUNDBERG, 1998, 1999). The most recent part (last 150 ka) of the generally accepted global $\partial^{18}O$ marine isotope paleotemperature curve (IMBRIE *et al.,* 1984) provided supporting data, as did a local Holocene sea-level curve drawn from ages and depths of mangrove peat and corals (ROBBIN, 1984). High-resolution seismic profiles supplied shelf-wide data for contouring the bedrock surface (LIDZ, REICH, and SHINN, 2003, 2005; LIDZ, ROBBIN, and SHINN, 1985; LIDZ *et al.,* 1991, 1997a, 1997b; SHINN, LIDZ, and HOLMES, 1990). Hydrographic bathymetry on a newly developed National Geophysical Data Center (NGDC) map (DIVINS, 2003) corroborated the approximate paleoshorelines of an emergent South Florida platform as it would have looked during the post-5e episodes of lowered late Pleistocene sea level.

The NGDC contour map is derived from geophysical surveys that acquired onshore topographic elevations and offshore bathymetric elevations and hydrographic sounding densities (PRATSON *et al.,* 1999a, 1999b; SHARMAN *et al.,* 1998; SMITH and WESSEL, 1990; WESSEL and SMITH, 1995). The map is contoured on data points in 3-arc-second grids of areas 1° in latitude by 1° in longitude, in which mean pixel elevation is digitized at 0.1 m. A hill-shaded version of the bathymetry showed areas in which contour data were "smoothed" or bore unusual patterns. Plots of sounding-density grids confirmed that sounding data in those areas were limited. In the map area, bathymetric soundings were lacking altogether from Boca Chica Key to the shelf margin and along the shelf south and west of Key West and across The Quicksands (Figure 1), leading to bathymetric and seismic dataset discrepancies in those areas (LIDZ *et al.,* 2006). These discrepancies pertain to paleoshoreline evidence presented in this paper, particularly at the west end of The Quicksands.

Resolution of the NGDC data (1 pixel = 100 m^2) is not adequate to show the smaller scale (30-m relief) outlier reefs in bathymetric profiles. Thus, the eustatic zeniths for isotope substages 5c, 5b, and 5a are plotted on seismic profiles. Profiles across Carysfort Reef and its outlier, The Elbow (upper Keys), and the Sand Key Reef outliers (lower Keys) are used as examples of shelf-edge stratigraphy relative to peaks of late Pleistocene highstands. These profiles were chosen on the basis of their stratigraphic differences and, in the case of the Carysfort and Sand Key Reef areas, abundant coral age data.

RESULTS AND DISCUSSION

Late Pleistocene Setting

A single large outlier reef occurs seaward of Carysfort Reef off north Key Largo, and four tracts of large outlier reefs occur off Sand Key Reef, located southwest of Key West (named reefs are Holocene accretions; Figure 1). Two core transects across the Carysfort outlier and a single transect across the largest Sand Key outlier enabled reconstruction of paleowater depths and sea levels at those sites. Respective highstand maxima during isotope substages 5c, 5b, and 5a ranged from ~15 to 9 m below present (LUDWIG *et al.,* 1996; TOSCANO and LUNDBERG, 1998, 1999). Although the substage 5e highstand that gave rise to the Florida Keys exceeded that of today by ~10.6 m, the rise and fall of sea level surrounding that highstand would have produced geomorphic settings similar to those of the later substages while the 5e sea was within the same (15–9 m) lower-depths range (Figures 2A and 2B). Corals dating to the Stage 6/5 (substage 5e) transition are inferred to be present near the base of the reefs (LIDZ *et al.,* 2006).

Cored bedrock in contact with Holocene overgrowth off the Florida Keys dates to substage 5a (86–75 ka, Figure 2A) shelf-wide (LIDZ, 2004; LUDWIG *et al.,* 1996; MULTER *et al.,* 2002; TOSCANO, 1996; TOSCANO and LUNDBERG, 1998, 1999). The youngest Pleistocene coral (~77.8 ka) was recovered from the seaward face of Carysfort Reef (MULTER *et al.,* 2002; Figures 2A and 2B). The oldest Holocene coral (~9.6 ka) was recovered from Tortugas Bank in the Dry Tortugas (MALLINSON *et al.,* 2003). Together, their ages bracket a period of ~68.2 ka when little or no marine deposition occurred on the outer Florida shelf (LIDZ, 2004; TOSCANO and LUNDBERG, 1999). However, the interval of prolonged subaerial exposure of the higher-elevation paleoplatform interior was longer (>100 ka) and extended from the time the substage 5e sea abandoned the shelf (~112 ka) to the time the Holocene sea again submerged the area (~8 ka). This time span included two transgressive/regressive cycles during which the sea of substages 5c and 5a breached the outer shelf but not the interior paleoplatform landmass. Substage 5b deposition occurred during regressive conditions (Figure 2A).

Bathymetric contours on the NGDC map approximate paleoshorelines outlining areal extents of the emergent promontory when sea level during those times was at or near its apex: substage 5c at ~15 m, substage 5b at ~12 m (a falling range of 10–14 m), and substage 5a at ~9 m lower than at present (Table 1). Comparison with bedrock surface contours (LIDZ, REICH, and SHINN, 2003, their figure 4A) derived from seismic data shows a similar landmass shape, although the bedrock map indicates dry land at those lowered sea levels extended farther west to include Halfmoon Shoal. Both bathymetric and topographic datasets verify subaerial exposure of the Boca Grande Channel/Quicksands area when sea level was 9 m lower than present and, thus, integrity of the emergent paleoplatform during substage 5a time. In Boca Grande Channel, strong reversing north/south tidal currents between the Gulf of Mexico and Straits of Florida keep the channel scoured to bedrock (SHINN, LIDZ, and HOLMES, 1990), so both datasets show the same channel depth below present sea level (~6–8 m). Elevation of the shallow ridge beneath The Quicksands, typically also 6 to 8 m deep, higher than the substage 5a apex of sea level, supports the inferred bedrock age of ~125 ka, the same age as the emergent Key Largo/Miami Limestone. The emergent Marquesas Keys separate the two areas of like elevation.

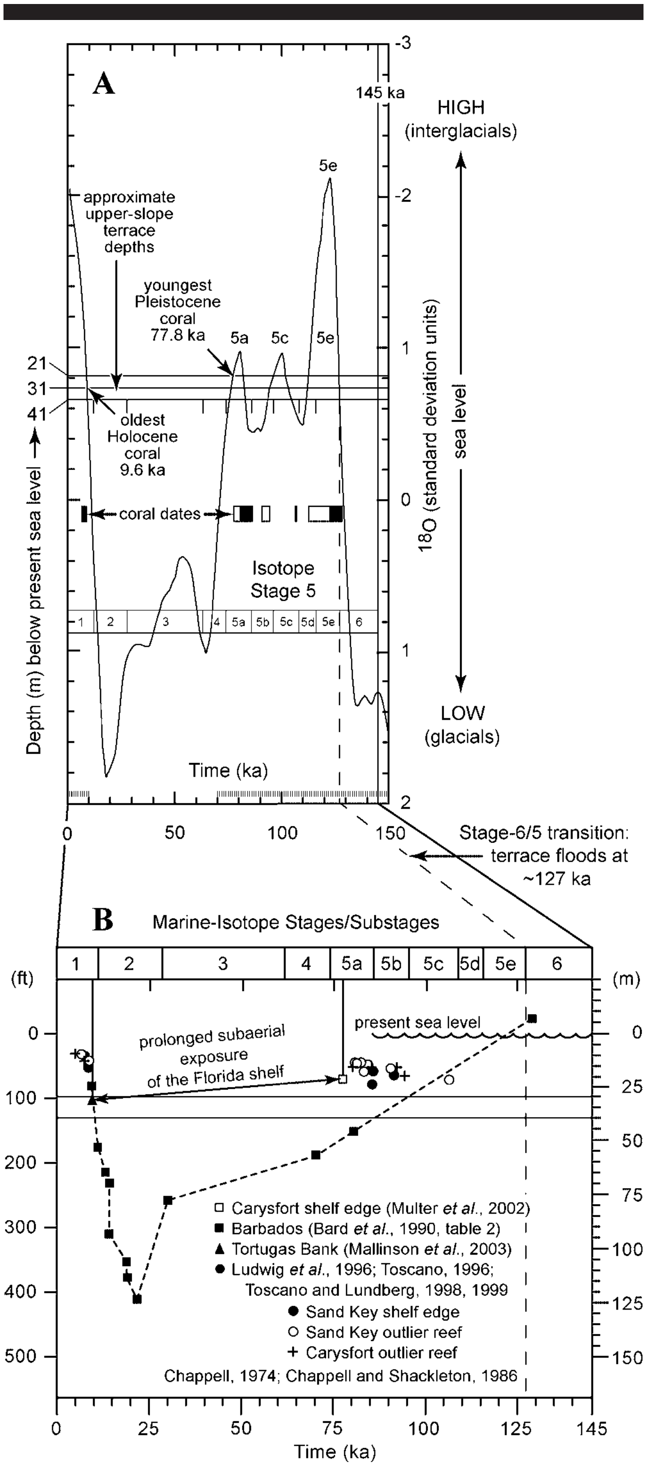

Figure 2. (A) Normalized and smoothed marine $\partial^{18}O$ record for the past 150 ka (from Imbrie *et al.,* 1984) with select data from South Florida added. Modified from Lidz, Reich, and Shinn (2005) to show transgressive (black boxes representing coral dates) and regressive (white boxes) deposition. Shaded bar represents depths (~30–40 m) of present upper-slope terrace beneath the outlier reefs on the basis of actual depths (21 and 31 m) of corals with radiometric ages of 77.8 and 9.6 ka (Mallinson *et al.,* 2003; Multer *et al.,* 2002). Variation in normalized $\partial^{18}O$ mainly reflects changes in sea level from the waxing and waning of continental ice sheets during glacial/interglacial cycles. Approximate durations of substages within Stage 5 are: 5e (127–116 ka), 5d (116–108 ka), 5c (108–96 ka), 5b (96–86 ka), and 5a (86–75 ka). (B) Detailed record of sea-level change during the last glacial/interglacial cycle (modified from Ludwig *et al.,* 1996). Grey curve was derived from dating of tectonically uplifted coral reefs on the Huon Peninsula, New Guinea, and is shown for comparison with coral age data from Barbados (dashed line) and tectonically stable Florida (triangles, circles, and plus signs). All datasets and coral ages point to subaerial exposure of the outer Florida shelf (~68 ka) and the paleoplatform interior (>100 ka) between isotope substage 5a and the Holocene.

Granted, bathymetry and bedrock topography are not the same and do not account for an intervening Holocene sequence. However, considering the regional scale and general thinness of the Holocene section shelf-wide (average ~3–4 m thick [Lidz, Reich, and Shinn, 2003, their figure 4B] relative to deep-sea stratigraphic sections hundreds of meters thick surveyed by the oil and gas industry), both sets of contours are sufficiently correlative to establish firmly that a continuous post-5e landmass remained subaerially exposed until the Holocene. For smoothness of contour lines and shading, the NGDC bathymetry map is used in this paper.

The map shows that when sea level was at the highest (~9 m below present during substage 5a) of its two post-5e peaks, east/west width of the emergent peninsula at the Card Sound latitude was ~160 km (Figure 3). Card, Barnes, and Blackwater Sounds; the Everglades; and Florida Bay were dry land, as was most of the shelf seaward of the upper and middle Keys. The northwest/southeast width at the Content Keys (lower Keys) point of promontory curvature was ~30 km, and the landmass extended another 90 km westward across the Marquesas Keys onto the ridge underlying The Quicksands (Shinn, Lidz, and Holmes, 1990). As noted, bathymetric sounding data are lacking on the ridge, and seismic data point to the entire ridge out to Halfmoon Shoal, an additional 20 km, as having been emergent. Tidal passes across the landmass did not exist to connect colder Gulf of Mexico waters to the shelf-edge reefs during substage 5a time. The only link between Gulf and Atlantic waters then was at the west end of the landmass through an unnamed 20-m-deep channel between Halfmoon and Rebecca Shoals (Figure 1; Lidz, Reich, and Shinn, 2003; Shinn, Lidz, and Holmes, 1990). The west end of the Florida Keys reef tract, which lies south of the ridge beneath The Quicksands, essentially terminates south of Halfmoon Shoal, where the emergent paleoplatform ended (E.A. Shinn, personal communication, 2005).

Three concurrent essentials promoted growth and preservation of post-5e reefs in the keys: protected settings devoid of deleterious coastal, bay, and Gulf of Mexico waters; accommodation space; and time. Successive periods of sea-level zeniths below a consistently emergent platform promontory provided the geomorphic settings. Lack of surf zones of any significant duration precluded widespread establishment of branching corals and favored dominance of head corals. *Montastrea annularis* prevails in the late Pleistocene sequences (Harrison and Coniglio, 1985; Hoffmeister, 1974; Hoffmeister and Multer, 1964, 1968; Toscano and Lundberg, 1999).

Table 1. *Criteria obtained from cored branching (*Acropora palmata*) and head corals (*Colpophyllia natans *and* Montastrea annularis*) used to derive sea-level maxima in the Florida Keys over the last 125 ka.*

Material dated	Dates (ka)	Geologic age	Coral depths (m)†	Thickness in outlier reef (m)	Maximum highstand (m)†	Authors
A. palmata, C. natans	8.9- 6.9	Holocene	-12.3 to -8.9	3.4	0	Toscano and Lundberg, 1998
1 *A. palmata,* 1 *C. natans,* 8 *M. annularis*	84.5- 80.9	5a‡	-24.0 to -12.3	11.7	-9	Ludwig *et al.*, 1996; Toscano and Lundberg, 1999
3 *M. annularis,* 1 *A. palmata*	94.4- 90.6	5b‡	-19.8 to -15.5	4.3	-14 to -10	Toscano and Lundberg, 1999
M. annularis	106.5	5c‡	-21.7	?	-15	Toscano and Lundberg, 1999
M. annularis	128.1-112.4	5e‡	-36.6 to -15.9		~ +10.6	Multer *et al.*, 2002
M. annularis, top of Q5 Unit	~125	5e‡	~ +5.5		~ +10.6	Hoffmeister and Multer, 1968; Perkins, 1977; Halley and Evans, 1983
(highstand)	140		not identified in Florida			Chappell, 1974
Marine Q4 Unit top	mid-Pleistocene		-5.0			Muhs, 2002; Muhs *et al.*, 2004
(highstand)	185		not identified in Florida			Chappell, 1974
(highstand)	220		?			Chappell, 1974
Marine Q3 Unit top	mid-Pleistocene		-8.0			Muhs, 2002; Muhs *et al.*, 2004
Marine Q2 Unit top	>340		-37.5			Multer *et al.*, 2002

Notes: Coral dates and depths of Toscano (1996) and Toscano and Lundberg (1998, 1999) are from the largest Sand Key outlier reef. Coral dates of other authors are from elsewhere in the Florida Keys. Geologic ages assigned to dates are those of the authors cited.

†Depths relative to present sea level. Depths of Q2-Q4 unconformities from Big Pine Key core 56 of Perkins (1977). Elevation for top of Q5 Unit is the highest elevation in the keys (at Windley Key; Stanley, 1966; Lidz and Shinn, 1991).

‡Substages of marine oxygen-isotope Stage 5.

The substage 5a transgression was higher in rise than the 5c transgression/5b regression, which provided corals the new accommodation space necessary to recolonize and increase the size of the reefs (Figures 4A–C). Given space, relatively stable highstand conditions, and sufficient time, carbonate platforms and reefs will build to and just above sea level (TUCKER, 1985). The Florida Keys record shows that, space notwithstanding, not all Pleistocene reefs and sediments reached sea level. A core transect through the outer-shelf coral ridge-and-swale topography of the lower Keys revealed that the cemented Pleistocene sediment–filled swale surface is ~13 m below that of unconsolidated overlying Holocene sediments and the adjacent narrow reef ridge crests (LIDZ, 2004; SHINN *et al.,* 1977). Where the shelf-edge reef is present, seismic profiles depict a Pleistocene backreef trough filled with Holocene sediments (*e.g.,* Figures 4A–C). Depths of dated corals at the Carysfort and Sand Key outlier reefs indicate that reef crests did not build to the highstand apices of substages 5c and 5a (Figures 4A and 4C). The hindering circumstances are not known and are almost certainly responsible for the Pleistocene reefs not being larger than they are. Indeed, if those reefs had filled all accommodation space to a uniform elevation at sea level, the reefs would not have become the discrete topographic controls for distribution of Holocene reefs (SHINN *et al.,* 1977, 1989).

Time, though an essential growth component, was of lesser importance than a protected setting and accommodation space. Judging from the $\partial^{18}O$ and local sea-level curves (Figures 2A and 2B), the hermatypic reefs might have occupied the photosynthetic zone for only around 20 ka during the collective highstand apices, including twice during substage 5e when transgressive and regressive water depths raised and lowered the zone above, then back to, the level at which corals would grow. During the substage 5e transgression, water depth at some point probably became too great for sustained metabolism of the shelf-edge corals. If so, the reefs likely underwent a give-up phase (NEUMANN and MACINTYRE, 1985) until corals could become re-established during the 5e regression. Later corals again colonized the reefs during the substage 5c transgression, at least in the dated Sand Key outlier reef (Table 1; LIDZ, REICH, and SHINN, 2005; LIDZ *et al.,* 2006; TOSCANO and LUNDBERG, 1998). Corals of that age presumably occur elsewhere along the margin where other Pleistocene keep-up reefs are found. During each coral accrual interval, shallow coastal and turbid bay waters were nonexistent, and the reefs were unencumbered by gulf waters.

Corals did not recolonize all reefs, however. Seaward of the Carysfort outlier reef, The Elbow, and elsewhere along the upper Keys terrace, seismic facies indicate presence of four linear low-relief features with irregular surfaces that protrude above Holocene sediments (Figures 4A and 4B; LIDZ *et al.,* 1997a). The jagged seismic surfaces are similar to those of known shelf-edge Holocene reefs (Figure 4A; LIDZ, REICH, and SHINN, 2003). These features are inferred to be immature outlier reefs equivalent to the four outlier tracts off the lower Keys (LIDZ, REICH, and SHINN, 2003). For reasons not known, the features remained give-up reefs, whereas immediately landward, the Pleistocene facies beneath Holocene accretions of Carysfort Reef and on its outlier exhibit the profiles of keep-up reefs. Indeed, corals cored from Pleistocene facies at Carysfort and its outlier date to substage 5a and substages 5b and 5a, respectively (MULTER *et al.,* 2002; TOSCANO and LUNDBERG, 1998). Of interest is that reconciliation of coral ages with the $\partial^{18}O$ curve indicates accretion is both transgressive and regressive (Figure 2A; Table 1). These accrual phases have implications, not addressed in this paper, for rate of rise and fall of late Pleistocene sea level. In turn, the rate, likely inconsistent, could also relate to unfilled accommodation space.

Holocene Setting

Conditions during the early and middle Holocene were similar to those in the late Pleistocene, as shown by bedrock topography (LIDZ and SHINN, 1991; LIDZ, REICH, and SHINN, 2003) and by early head coral colonization such as at Grecian Rocks (Figure 1; SHINN, 1980). Rate of Holocene sea-level rise, at first rapid, had slowed by the time the sea began to cross the Pleistocene reef crests and creep landward (Figure 5). The slowed rate permitted a protracted movement of the surf zone across the crests and the broad low-gradient (PERKINS, 1977) outer-shelf expanse. Coral assemblages responded by changing species and growth habits, even within reefs, and by backstepping (LIDZ, ROBBIN, and SHINN, 1985; SHINN, 1980; TOSCANO and LUNDBERG, 1998). Branching acroporids prevailed, with the staghorn coral *Acropora palmata* being the most prolific species and the dominant Holocene reef framework builder as recently as 30 years ago. Skeletal *A. palmata* now composes linear reef caps and thick seaward-oriented spur-and-groove systems on the Pleistocene reefs (SHINN, 1963). Clearly defined coral zonations are found within outer-shelf reefs, beginning with seaward, deeper-water head corals and migrating landward to oriented then unoriented stands of branching corals. Coral species and orientation were dependent on changing water depth and surf intensity (DUSTAN, 1985; SHINN, 1963, 1980; SHINN *et al.,* 1977, 1989).

In the Florida record, antecedent reefs and beach-dune ridges are well-established outer-shelf nuclei for Holocene corals (MULTER *et al.,* 2002; PERKINS, 1977; SHINN *et al.,* 1977). Isolated Holocene patch reefs are also found on the inner shelf on seaward parts of the nearshore rock ledge, especially off the lower Keys (LIDZ, REICH, and SHINN, 2005; LIDZ *et al.,* 2006; MARSZALEK, 1977).

However, thousands of inner-shelf patch reefs and patch-reef clusters are aligned along the middle of Hawk Channel keys-wide (JAAP, 1997; MARSZALEK, 1977; SHINN *et al.,* 1989). Another outcome of combining select datasets used in the database synthesis (LIDZ, REICH, and SHINN, 2005) was the serendipitous discovery of the underpinnings of the mid-channel patch reefs and thus of a type of nucleus for coral recruitment new to the Florida record. The corals colonized landward edges of two troughs on the seaward side of the bedrock depression beneath the channel (LIDZ *et al.,* 2006). Channel substrate is noncoralline, non–beach dune grainstone/packstone (MULTER *et al.,* 2002; SHINN, REESE, and REICH, 1994). The trough-edge sites were sufficiently deep for head coral growth and were sheltered from surf and landward storm-transported sediment by higher elevation outer-shelf topography (LIDZ *et al.,* 2006).

During the later part of the Holocene, a slowing but nonetheless rising sea level fundamentally transformed the geomorphic setting of the Florida Keys region from that of the previous 100 ka. Spilling through low-elevation areas within the Key Largo/Miami Limestone, the sea filled the shallow (DAVIES, 1980) bedrock depression that became Florida Bay and isolated the chain of Key Largo/Miami Limestone islands. Today, tidal influence is strong, particularly in the middle Keys. Bay and Gulf of Mexico waters flow southward through tidal passes in the keys (SMITH, 1994, 1998) and mix with those of the Gulf Stream and Florida Straits to reach the reefs. These shelf and gulf waters vary seasonally and interannually with respect to temperature, salinity, and turbidity, and with the advent of urbanization, nutrient and chemical pollution, all of which can stress corals (GLYNN, 1984; HALLOCK and SCHLAGER, 1986; ROBERTS *et al.,* 1982). The recently recognized infusion of African dust also imports foreign microbes and chemicals to the ecosystem (GRIFFIN, KELLOGG, and SHINN, 2001; GRIFFIN *et al.,* 2003; SHINN *et al.,* 2000; SMITH *et al.,* 1996; WALSH and STEIDINGER, 2001).

Among adverse components now infiltrating the ecosystem and engulfing the reefs is an assortment of natural—aggravated by human—elements incompatible with coral calcification and accretion. The waters over the reefs are in and of themselves a natural stress (JAMESON, TUPPER, and RIDLEY, 2002), as is clear from the geologic record. When rising sea level began to submerge the once emergent and protective promontory, landmass connectivity was fragmented. Creation of Florida Bay further modified the setting and tied tidally induced coastal, bay, and gulf waters to the reefs. Without reference to any particular effects that Florida Bay waters might or might not have on any particular areas of the reef tract or to types of organisms that might or might not remain vibrant today, it is a simple given that rising sea level has altered physical and hydrologic dynamics on the shelf. Among the natural components that now differ from the late Pleistocene/mid-Holocene highstand settings are water quality, depth, circulation, and resultant character of the reef seascape.

Geologic Significance

Evaluation of reef growth relative to paleolandscapes and past sea levels is a rational approach to assess why some reefs might be larger or exhibit different growth patterns than others in a given region. Not all reefs evolve in the same manner through time or space. In this case, cumulative *in situ* accretion of Pleistocene head corals changed in the Holocene relative to growth sites, habits, and species of corals.

By understanding past controls and reef responses in a re-

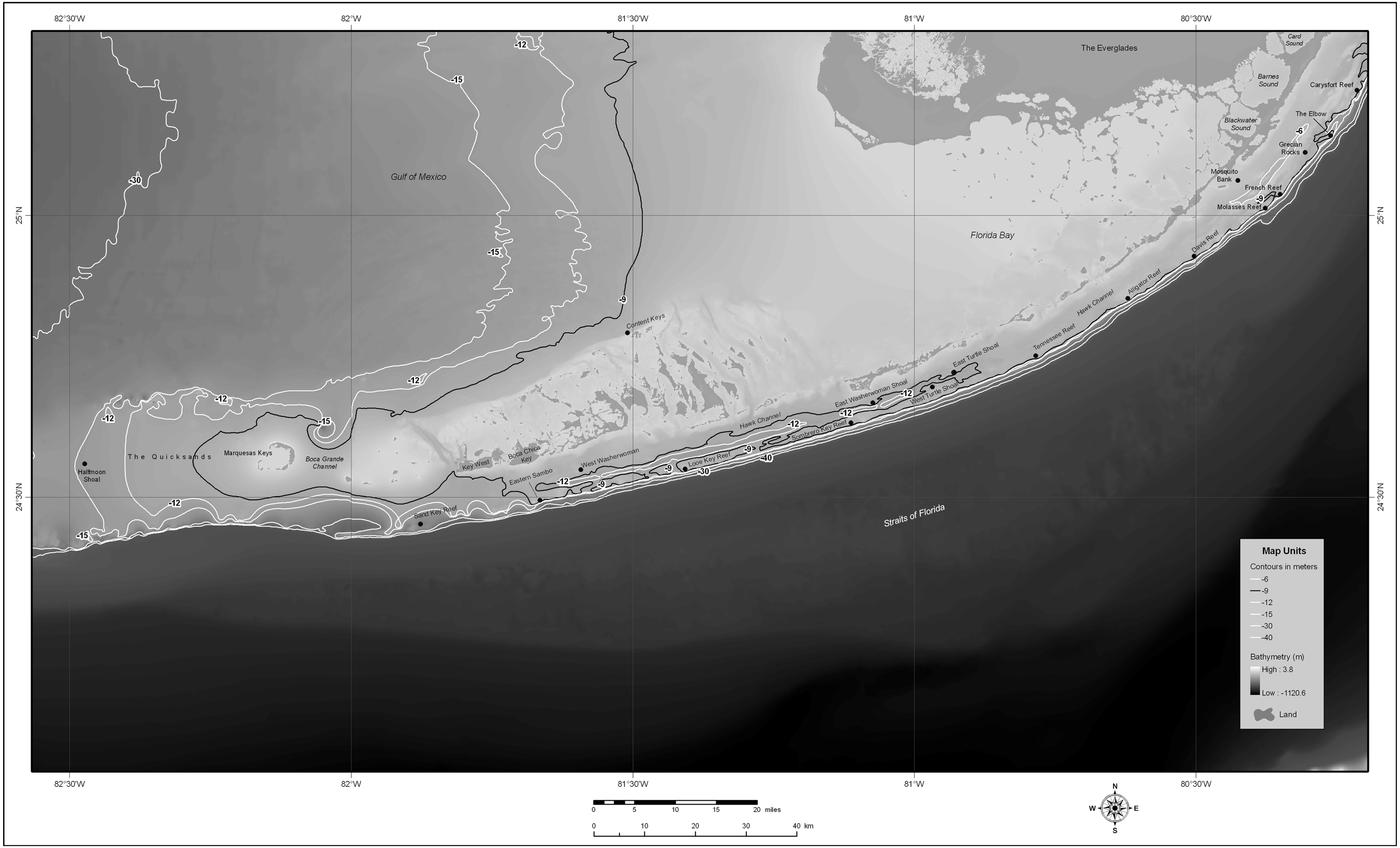

Figure 3. National Geophysical Data Center map shows bathymetric paleoshoreline contours of South Florida at sea levels of ~9, 12, 15, 30, and 40 m below present. Black dots mark major reefs and geographic sites discussed in text. On the basis of bathymetry, the black line (9-m contour) demarcates approximate extent of emergent South Florida paleoplatform at the highest post–substage 5e sea level before the Holocene. The scalloped nature of bathymetry behind the shelf margin west of Eastern Sambo is an artifact because of a lack of sounding datapoints off Boca Chica Key, Key West, and in the area north and west of latitude 24°26′N and longitude 82°W (as illustrated in Lidz *et al.*, 2006, their figure 14). Lack of sounding datapoints west of Key West also affects westward pictured extent of emergent promontory. Seismic data show that the promontory at 9 m below present sea level was likely emergent as far west as Halfmoon Shoal (Lidz, Reich, and Shinn, 2003, their figure 4A). Note two inner-shelf bedrock troughs (white 6-m and black 9-m contours off respective upper and middle/lower Keys) that focused location and alignment of patch reefs in the middle of Hawk Channel (discussed in Lidz *et al.*, 2006).

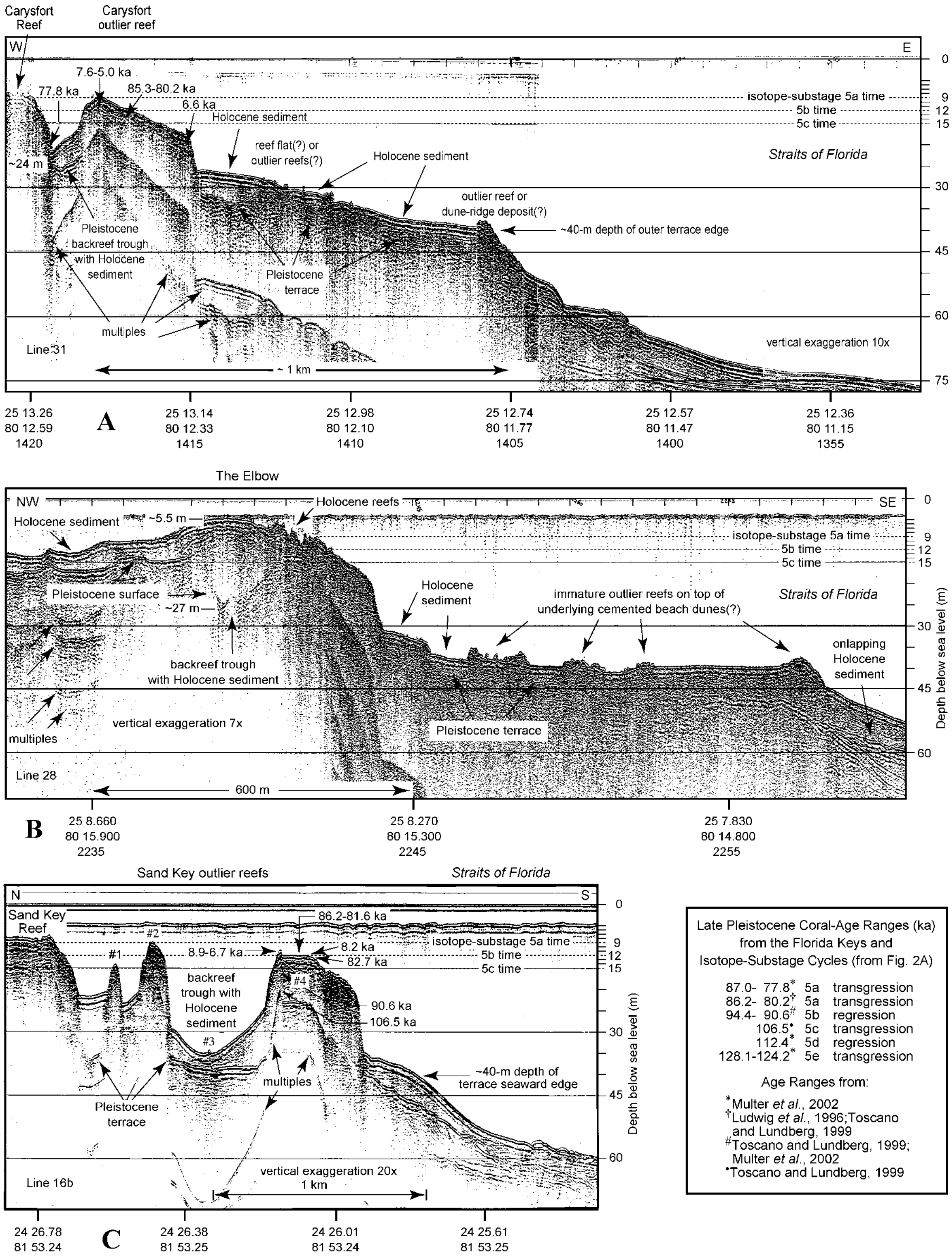

Figure 4. Seismic profiles show stratigraphic variations across the shelf margin. For comparative purposes, the depth scales match. Reef locations are shown in Figure 1. Note peak elevations of sea level during marine isotope substages 5c, 5b, and 5a (dotted lines). Latitude and longitude at bottom of profiles in degrees and decimal minutes are based on GPS coordinates. Hours (military time) below coordinates serve as navigational correlation points along the seismic line. (A) The 24-m-deep backreef trough behind the Carysfort outlier reef has not yet been filled with Holocene sediments. A core sample recovered from the seaward face of Carysfort Reef yielded the youngest Pleistocene age (77.8 ka) so far in the Florida Keys (Multer *et al.,* 2002). (B) Profile across The Elbow shows that the 27-m-deep backreef trough has been filled and overtopped with landward storm-transported Holocene sediments.

gion that harbors modern reefs, deciphering what might be affecting vitality of the present organisms becomes clearer. Anthropogenic influences are now a widely recognized part of the reef decline equation but are of lesser consequence in light of the big-picture evidence found in the late Pleistocene record. The human elements are in addition to the natural stresses induced by changes in geomorphic setting. Clearly, the sole effects of a rising sea level are numerous and substantial—linkage to the reefs of natural water-quality components unsuitable for coral calcification and accretion is but one. The phenomenon is known as reefs being shot in the back by their own lagoon (NEUMANN and MACINTYRE, 1985). The present setting, marginal for reef growth, underscores the significance of the past settings that nurtured the architects of imposing late Pleistocene reefs. The reasons those reefs grew so large are archived in the bedrock elevations, coral ages and depths, and proxy evidence for past eustatic zeniths that, in the Florida Keys, are well preserved. In this shallow-shelf case, one of the key corroborating tools used to decode the events and their effects—bathymetry—is not yet even a part of the rock record.

CONCLUSIONS

An emergent, post–isotope substage 5e platform promontory existed in South Florida for >100 ka during the Pleistocene. The coherent landmass created favorable conditions for offshore reef calcification and accretion by protecting the corals from Gulf of Mexico waters. Shallow coastal and turbid bay waters did not exist. A sea level that fluctuated below the exposed promontory within a highstand range of −15 to 9 m relative to present sea level provided accommodation space during substages 5c, 5b, and 5a. Offshore, head corals dominated and became architects of imposing reefs. Relative to the long landmass duration, collective time of reef accrual was comparatively short, perhaps only about 20 ka. Deposition occurred during both transgressive and regressive conditions, which has implications for rate of rise and fall of late Pleistocene sea level. Not all accommodation space was filled, which might relate to the rate of fluctuation.

Peaks of the late Pleistocene highstands remained below elevation of the ridge beneath The Quicksands. Those positions support the inferred substage 5e ridge age and show that the shallow ridge, like the emergent 5e Florida Keys of the same oolitic and reefal facies, is older than the deeper substage 5a shelf bedrock off the keys.

Late Pleistocene and early/mid-Holocene geomorphic conditions vanished as the Holocene sea moved inland, fragmenting the exposed landmass. A slowed rate of sea-level rise across the shelf induced a slow-moving surf zone, favoring branching corals that once thrived along the outer shelf, even in historic times. Increasing water depth and surf intensity

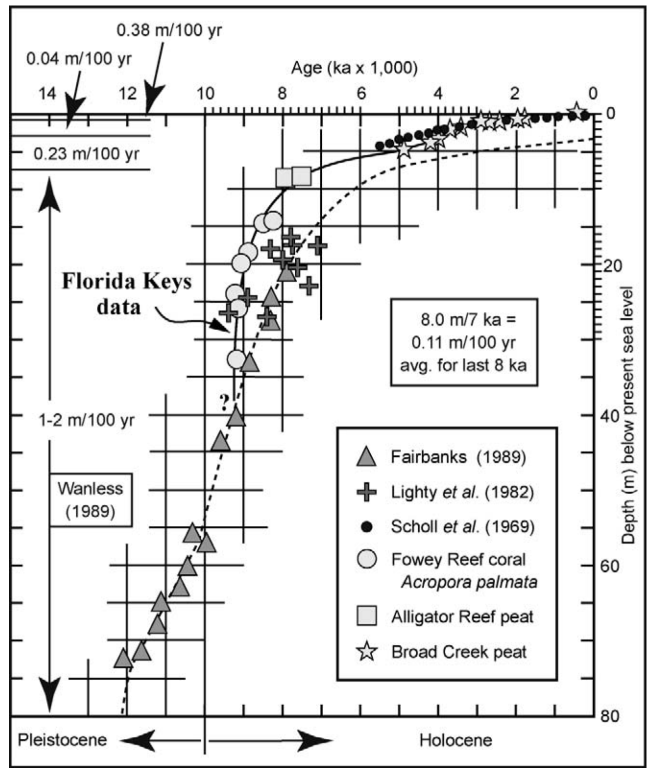

Figure 5. Sea-level curve for the Florida reef tract is well constrained by local proxy data (in conventional ^{14}C ages) as modified (Lidz and Shinn, 1991) from the curve of Robbin (1984). Rates of rise are shown at left. Upper part of rise rates shows actual rise measured by tide gauges at Key West (1932–present).

stimulated changes in Holocene keep-up reefs—in coral species and orientation and in reef structure through backstepping. Notwithstanding the effects of human activities on modern reefs, the geologic record in the Florida Keys over the past 150 ka demonstrates that a changing sea level induced very different late Pleistocene and Holocene geomorphic settings. Within those settings, very different ambient conditions generated very different responses in reef development. The essential factors during the Pleistocene were protected settings, accommodation space, and time. The stratigraphic results are imposing offshore Pleistocene reefs that form distinctive topographic controls for a comparatively thin cap of skeletal Holocene overgrowth.

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Note jagged seismic facies at seaward fill crest, indicating Holocene coral growth. Also note similar facies protruding above Holocene sediments on the upper-slope terrace and an inferred beach-dune ridge at seaward edge of terrace. (C) Profile across margin at Sand Key Reef crossed three tracts of outlier reefs, just missing a fourth tract (labeled #3) visible in aerial photographs (Lidz, Reich, and Shinn, 2003). Although the outliers at Carysfort and Sand Key Reefs show profiles of keep-up reefs, their coral ages indicate the reefs did not grow to peak sea level during the transgressions of isotope substages 5c and 5a. Substage 5b time was regressional.

who provided the map used in Figure 3. Sources of the NGDC bathymetric data include the U.S. National Ocean Service Hydrographic Database, the U.S. Geological Survey (USGS), U.S. Army Corps of Engineers LIDAR, Monterey Bay Area Research Institute, and other academic institutions. Topographic data are from the USGS 3-arc-second digital elevation models and Shuttle Radar Topography data. Volumes 3 through 5 also use bathymetric contours from the International Bathymetric Chart of the Caribbean Sea and the Gulf of Mexico project as input to the gridding process. Volume 3 contains the data for the Florida Keys. The author thanks H. Gray Multer and Eugene A. Shinn for insightful discussions and Pamela Hallock for a highly constructive review of an early version that greatly improved the manuscript. John C. Brock and N. Terence Edgar contributed thoughtful comments and recommendations to the final version. This paper is part of a larger Florida Keys mapping project.

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