Contrasts within an Outlier-Reef System: Evidence for Differential Quaternary Evolution, South Florida Windward Margin, U.S.A.

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ABSTRACT


Closely spaced, high-resolution, seismic-reflection profiles acquired off the upper Florida Keys (i.e., north) reveal a platform-margin reef-and-trough system grossly similar to, yet quite different from, that previously described off the lower Keys (i.e., south). Profiles and maps generated for both areas show that development was controlled by antecedent Pleistocene topography (presence or absence of an upper-slope bedrock terrace), sediment availability, fluctuating sea level, and coral growth rate and distribution. The north terrace is sediment-covered and exhibits linear, buried, low-relief, seismic features of unknown character and origin. The south terrace is essentially sediment-free and supports multiple, massive, high-relief outlier reefs. Uranium disequilibrium series dates on outlier-reef corals indicate a Pleistocene age (~83–80 ka). A massive Pleistocene reef with both aggradational (north) and progradational (south) aspects forms the modern margin escarpment landward of the terrace. Depending upon interpretation (the north margin-escarpment reef major may not be an outlier reef), the north margin is either more advanced or less advanced than the south margin. During Holocene sea-level rise, Pleistocene bedrock was inundated earlier and faster first to the north (deeper offbank terrace), then to the south (deeper platform surface). Holocene overgrowth is thick (8 m) on the north outer-bank reefs but thin (0.3 m) on the south outlier reefs. Differential evolution resulted from interplay between fluctuating sea level and energy regime established by prevailing east-southeasterly winds and waves along an arcuate (ENE-WSW) platform margin.

ADDITIONAL INDEX WORDS: Florida Keys and reef tract (USA); arcuate paleomargin; antecedent Pleistocene bedrock topography; upper-slope bedrock terrace; stillstand beach-dune ridges; sea-level fluctuations; protective rock-island barriers; Pleistocene and Holocene coral-reef distribution and thickness; effects of energy regime, sediment availability, sedimentary patterns, and water quality on reef vitality; hydrocarbon traps.

INTRODUCTION

In a comprehensive study to map Pleistocene bedrock topography, thickness of overlying Holocene sediments and reefs, and extent and types of modern ecosystems along the Florida reef tract (LIDZ et al., 1996), geophysical data obtained off north Key Largo in the upper Keys verify a markedly different subsurface (bedrock) platform-margin morphology and geometry than what is known off Key West in the lower Keys (Figure 1). The reef tract parallels the arcuate margin for more than 385 km and comprises the seaward part of the new Florida Keys National Marine Sanctuary (FKNMS). The roughly rectangular study area covers ~80 km², measures ~8 km (from north Key Largo offshore to The Elbow reef) by ~10 km (from The Elbow southwest to Molasses Reef), and includes a portion of John Pennekamp Coral Reef State Park and NOAA’s Key Largo National Marine Sanctuary (Figure 2A).

The reef tract fringes a carbonate-bank windward margin. In the Florida-Bahamas region, several models have been proposed for windward margins based on morphologies. HINE and NEUMANN (1977) and HINE and MULLINS (1983) described most Bahamian windward margins as either open (no island or barrier) or protected (island and reef complex at the margin edge). The South Florida morphologies do not strictly fit either model. In a study of Holocene sediment accumulations along the reef tract, ENOS (1977) proposed a model based on shelf morphology: shallow, outer-bank reefs backed by a wide, open lagoon with islands set considerably back from the margin. A new model was recently developed by LIDZ et al. (1991) based on offshore morphology seaward of Sand Key Reef, located ~12 km southwest of Key West (Figure 2B). Their model is distinguished by multiple, discontinuous, fossil, outlier reefs located on an upper-slope terrace and separated from the margin by deep, wide, backreef troughs containing little sediment. The width of the reef-and-trough system varies but attains a maximum of ~2.5 km. This model proposes that the platform progrades—by build-
The general purpose of this paper is to present new seismic data from the upper Keys and to compare them with those obtained in the earlier lower Keys study (Lidz et al., 1991). In the comparison, the general purpose becomes more specific: to examine the striking differences in platform-margin morphologies, to consider problems with their interpretation, and to relate the role of fluctuating sea level to differences in growth and distribution of Quaternary reefs between the areas. One caveat pertains. Given the shortcomings of insufficient evidence other than high-quality seismic records, particularly lack of radiometric control, the approach to morphologic interpretation is to offer alternatives. Within this context, then, the alternatives are intended more to provide ideas for future research in the region than to reach a firm conclusion on which is the more plausible. Nonetheless, in our prelude we also present three previously documented elements (termed PDE) that provide important clues as to which alternative may be the more likely.

**Physiographic Setting**

The Florida Keys and offshore reef tract within the seaward part of the FKNMS consist of four general physiographic provinces. All are Pleistocene bedrock (Figure 3A,B): (1) emergent coral-reef and oolite tidal-bar lithofacies that form the discontinuous chain of islands (keys); (2) a broad, trough-like depression that forms Hawk Channel; (3) a shelf-margin ridge zone fronted by the massive margin-escarpment reef, both underlying modern outer-bank reefs; and (4) an upper-slope terrace. The island chain is divided into three groups: upper, middle, and lower Keys (Figure 1). The upper and middle Keys are lumped by orientation (NE-SW) but separated by differences in tidal-pass width. They form an arc that extends from Soldier Key near Miami to Big Pine Key to the southwest, a distance of 177 km (Hoffmeister, 1974). The middle Keys extend from Lower Matecumbe to Big Pine Key and contain the largest, deepest tidal passes that link the murky waters of Florida Bay and the Gulf of Mexico with the clearer reef-tract waters. The lower Keys are oriented nearly perpendicular (NW-SE) to the arc and extend from Big Pine Key to Boca Grande Key in the Gulf west of Key West, a distance of ~130 km. The reef tract and FKNMS extend another 80 km westward and include the Dry Tortugas.

The difference in orientation between the upper and middle Keys and the lower Keys is due to paleoenvironment, which produced the old shore-parallel coral-reef complex flanked by active, shore-normal, ooid tidal bars at both ends. The reef complex is known as the Key Largo Limestone (Sanford,
1909; the Key Largo unit of the Miami Limestone of Hoffmeister et al., 1967) and accumulated as coalescing patch reefs during the last interglacial at ~125 ka, when sea level was ~7.6 m higher than present (Hoffmeister and Mutter, 1968; Hoffmeister, 1974). The exposed parts of the reef (keys) vary in width (2.6 to 13 km). Reef thickness also varies (18 to >51 m). Its subsurface extent from north to south is unknown. Its extent from east to west includes the area of Miami Beach to the Dry Tortugas (Shinn et al., 1977). Hoffmeister (1974) concluded that the Key Largo Limestone reef rests on an undulating surface and must have been extant for many thousands of years in order to have built a thickness of such magnitude. The lower Keys are composed of the cemented tidal-bar sands that originated as an east-west
mound of unstable ooids and was shaped into northwest-southeast sand bars by strong tidal currents flowing in those directions. Formerly called the Key West Oolite by Sanford (1909), the rock is now considered part of the oolitic Miami Limestone on which the city of Miami is located.

The bedrock depression of Hawk Channel (Figures 2A,B, 3A) lies between the Keys and outer-bank reefs throughout the reef tract. The channel is several meters deeper in the lower Keys than elsewhere (Lidz and Shinn, 1991). Recent core drilling to a depth of 19.8 m below sea level indicates that the bedrock is post-Key Largo Limestone grainstone and lacks corals (Kindinger, 1986; Shinn et al., 1994).

Seaward of Hawk Channel beneath the modern outer-bank reefs, the shallow shelf-margin ridges are composed of multiple, parallel, Pleistocene reefs with a discontinuous cap of Holocene corals. In most cases, Holocene growth was initiated on pre-existing topographic highs, usually the Pleistocene reefs, although a few reefs became established on carbonate sands, muds, and coral rubble (Enos, 1977). At the seaward edge of the shelf-margin ridge zone is the massive reef that forms the margin escarpment. The offbank terrace lies at the base of the escarpment.

Modern reefs are most luxuriant and abundant off Key Largo, least developed and sparse off tidal passes in the middle Keys, and moderately well developed in the immediate area of the lower Keys. Westward, beyond Key West in the Gulf of Mexico where no rock-island barriers exist and north-south tidal currents are strong (Shinn et al., 1990), reefs are also senescent and sparse. According to Marszalek et al. (1977), these trends are related to land barriers and tidal passes, as well as to reef-tract orientation in relation to exposure to cold, wind-driven winter currents.
METHODS

Seismic profiling provided the primary bedrock and sediment-isopach data. More than 100 km of high-resolution seismic-reflection profiles were collected in August 1991 (Figure 2A) using an ORE Geopulse boomer system and a Benthos 20-element hydrophone streamer that provided input to an EPC 1650 recorder. Navigation was recorded at 5-minute intervals using a Magellan Global Positioning System (GPS) receiver and verified with an Apelco DXL 6600 Loran receiver. Because the seismic equipment used to obtain the profiles could not be towed over areas shallower than 3 m, which included many reefs, the seismic data are thus restricted mainly to areas of sediment. Likewise, seismic penetration is often limited by reefal growth and debris, making determination of thickness difficult. In such cases, groundtruthing by diving, probing, and coring was necessary to estimate sediment thickness.

Bedrock-surface and sediment-thickness data points were read from the seismic records at 5-minute intervals. Interpretation was based on the speed of sound in sea water (~1,500 m/s). Thickness of Holocene sediments and reefs was measured on the profiles as the difference between depth from sea level to the seafloor surface and depth to the reflection identified as the Pleistocene bedrock surface. These data were plotted on charts and contoured by hand to construct the bedrock topography and isopach maps at the same scale as an aerial photomosaic used in the modern ecosystem part of the study (LIDZ et al., 1996). Supplementary data were derived from core borings, groundtruthing, and probing. Because the 1991 counterpart lower Keys paper was constrained by length, which limited the use of figures, the interpreted profiles from that study are included here (figures cited later) for comparison of complete data sets.

RESULTS

Comparison of Platform-Margin Morphologies off the Upper and Lower Keys

Antecedent Pleistocene Topography (Depth to Bedrock)

In the study area, depth to bedrock generally ranges from 0 to 25 m but averages 8 to 12 m (Figure 4, Table 1). The Key Largo Limestone extends seaward for several hundred meters as a prominent, ubiquitous, shallow (2-4 m) ledge bordering the seaward side of the linear island of Key Largo. It merges gradually with the gently sloping edge of Hawk Channel, where sediments begin to onlap the rock surface (Figures 5, 6A). Depth from water surface to channel bedrock generally ranges from 2 to 16 m but averages 8 to 10 m. A channel reentrant, marked by the 10-m bedrock contour at Mosquito Bank, occurs landward of White Bank (Figures 4, 6B). At the seaward edge of the shelf-margin ridge zone, depth to bedrock ranges from 20 to 25 m within a relatively narrow and shallow, sediment-filled trough behind a massive fossil reef that forms what we regard as the modern margin escarpment (Figure 3A; others may place the margin farther seaward). The trough is deepest behind The Elbow and branches into a wider, deeper trough at a margin reentrant (pass) just south of the reef (Figures 2A, 5). The reef extension at The Elbow is offset slightly seaward from that at French and Molasses Reefs.

The Pleistocene margin-escarpment reef is the underpinning for the outermost Holocene platform-margin reefs that extend throughout the study area (Figures 2A, 6C, 7A-C, 8). Its dimensions are 28 m high by ~0.5 km wide, roughly the same as those of the primary 57-km-long outlier-reef trend off Sand Key Reef (Figure 2B; LIDZ et al., 1991). The seaward side of the escarpment reef becomes a nearly bare limestone cliff at a depth of about ~15 m. The base of the cliff levels out to form a relatively wide (0.75 km) sediment-covered terrace at depths of ~35, ~40, and ~45 m. The sedimentary seismic facies reveal poorly defined, low-relief (~15 m) features that may represent backfilled reef flats, sand shoals, dune ridges, or incipient proto-outlier reefs (Figures 7B, 8).

The fossil outlier reefs off Sand Key parallel the margin and rise up from a wider (1.75 km) terrace that produces a clearly discernible bedrock reflection at shallow depths of ~30, ~35, and ~40 m (Figure 9). The outlier reefs are discrete morphologic structures consisting, in part, of three parallel rock ridges separated from the margin by deep, wide, intervening troughs. The primary outlier formed at the seaward edge of the terrace, and smaller secondary or “satellite” outliers (Figure 9, trackline 16a-d) developed between it and the margin-escarpment reef. Off Sand Key, the satellite outliers always occur landward of the primary outlier.

A core drilled from the primary outlier (Figure 9, trackline 16a) indicates that Holocene reefs are only 0.3 m thick (SHINN et al., 1992). Uranium disequilibrium series dates of Acropora palmata at a core depth of 0.1 m reveal an age of ~8.2 ka (LUDWIG et al., 1996). Additional cores containing Holocene A. palmata were also recovered by TOSCANO et al. (1995).

The seaward sides of both the massive margin-escarpment reef and outlier reefs are exposed to the Straits of Florida. Off Key Largo, reef orientation is roughly northeast to southwest, whereas orientation of the reefs off Sand Key is roughly east to west. Relative to the backreef troughs in both areas, those to the north are narrower, shallower, and infilled (note obscure acoustic returns in trough sands, Figure 7B), whereas those of the outliers to the south are wider, deeper, and mostly void of sediment. For the most part, the peak of the Key Largo escarpment reef is elevated above the present platform surface by as much as 10 m and thus lies only 6 to 8 m below sea level, whereas the crest of the primary Sand Key outlier reef lies at or below the platform surface and thus is 10 to 15 m below sea level. A similar massive reef fitting the description of an outlier reef, as defined by LIDZ et al. (1991), exists off Carysfort Reef, the next major Holocene platform-margin reef north of The Elbow (SHINN et al., 1989). The Carysfort outlier is also late Pleistocene and is inferred to be contemporaneous with the dated Sand Key outlier.

Holocene Sediment and Reefs (Accumulated Thickness)

The island of Key Largo generally has a veneer of modern soil and caliche (soilstone crust) and supports hardwood forests. Mangrove forests mark the waterline. Sands are thin or
absent along the shallow-water ledge (Figure 5). Most of the submerged part of the shelf seaward of the ledge is covered by mangrove peat, lime muds, carbonate sediments, or coral reefs. Where sediments have not accumulated, the bare Pleistocene limestone usually has a caliche coating and is populated by scattered corals, sponges, and species of the brown alga Sargassum. Sediments generally become thicker in an offshore direction, ranging from 0 to 2 m along the west edge of Hawk Channel, to 2 to 4 m within the channel, and up to 6 m at the east edge. Seaward of the channel within the shelf-margin ridge zone, reefs and sands average 6 to 8 m thick. The thickest sands (18 m) occur within the trough landward of The Elbow. A narrow band of bare or slightly sandy limestone rims the massive margin reef before the gradient steepens into the escarpment.

Off the upper Keys, moderately thick Holocene reefs (~8 m) occur as a discontinuous chain of linear features along the 14-m bedrock contour in the area of Grecian Rocks, located ~1 km landward of the margin-escarpment reef (Figure 4; Shinn, 1980). Off the lower Keys, Holocene reefs are generally thinner (~6 m). North of the study area on Carysfort Reef, Holocene reefs and sediments are ~19 m thick, but there is no Holocene accumulation on the Carysfort outlier (Shinn et al., 1989), and only a veneer (0.3 m) is found on the primary outlier off Sand Key (Shinn et al., 1992).

A Synopsis of Contrasting Morphologies

Within the two areas of study, specifics for major physiographic differences in platform-margin morphologies (Table 1) are summarized here. In general and relative to the lower Keys margin, the north terrace is several meters deeper and lacks outer-terrace outlier reefs; the margin-escarpment reef is on average elevated above the platform surface; and the platform bedrock is shallower. Relative to the upper Keys margin, the south terrace is shallower and is characterized by massive outlier reefs; the outlier reefs and margin-escarpment reef are on average elevated at or below the platform surface; and the platform bedrock is deeper. Thus, during the Pleistocene, the region of the north terrace flooded earlier and faster than that to the south, but during the Holocene, the region of the north platform flooded later and more slowly than that to the south, and it was protected from wave action by offshore rock-island barriers formed by the crest of the margin-escarpment reef. The variations in antecedent Pleistocene bedrock elevation resulted in different environmental conditions along the margin as Holocene sea level rose, and
only some of those conditions were conducive to coral growth. Holocene outer-bank reefs became established earlier to the south than north but grew for a longer period of time to the north than south. These differences were also, in part, the result of platform-margin curvature.

**DISCUSSION**

Before examining the alternative interpretations, we must first consider the fundamental influence of prevailing wind-and-wave energy on the arcuate margin, with regard to sediment transport, accumulation, and to location and development of the massive Pleistocene and lesser Holocene reefs. On the South Florida platform, modern sedimentary patterns provide a key to past patterns (PDE 1, Table 2), in that sediment-transport directions and accumulation during a lowered sea level should have been like those of today.

Investigation of the effects of Hurricane Donna, which impacted the study area in 1960, led Ball et al. (1966) to conclude that storm winds and currents were influenced (but not to the same degree) by the same local and regional topographies that control everyday waves and tides. Thus, in the north part of the reef tract, onshore winds and currents move sediments and reef rubble from the platform-margin edge into the troughs behind the escarpment reefs. In the south part, alongshore processes move sands west and south, parallel to and seaward of the margin. An example of such transport is a distinct, localized lobe of sand >15 m thick that has partially buried a deep outer-bank reef in front of Looe Key Reef (Lidz et al., 1985). In addition, numerous seaward-flowing, tidal "sand aprons" occur in breaks between lower Keys reefs, but only a few such features occur between upper Keys reefs (Lidz et al., 1996). Furthermore, currents within the confines of the "channels" formed by the outlier-reef walls would be strong (Lidz and McNeeill, 1995), tending to remove sediments.

Contour maps of bedrock surfaces and sediment/reef isopachs have been used to reconstruct ancient shorelines off the Keys (Lidz and Shinn, 1991) and to define sediment and reef distribution and thickness (Shinn et al., 1977). Corals and coral reefs have long been known to be proxy indicators of past positions of sea level (cf. Hudson et al., 1976; Lighty, 1977; Fairbanks, 1989, 1990); hence, they provide a long-term record of associated changes in marine environments.
In general, the principal element that determines whether reef growth will keep pace with rising sea level is water quality (Hallow and Schlager, 1986), which has been shown by numerous authors to have deteriorated with rising sea level (Landon, 1975; Lighty, 1977; Porter et al., 1982; Neumann and Macintyre, 1985, among others). Because corals in South Florida recruit preferentially to sediment-free bedrock highs, the primary element that controls their distribution is antecedent topography (Shinn et al., 1977; Shinn et al., 1989). Topographic lows flood first and fill with sediment. Topographic highs flood last, lack a sediment cover due to wave and current action, and thus form a hard substrate suitable for coral recruitment (PDE 2, Table 2). Bedrock contours also constrain those parts of the substrate (highest elevation), now below sea level, that would have been island barriers during periods of lowered sea level. Islands provide protection from high-energy waves and thereby an environment suitable for corals adapted to low-energy conditions. As the islands are submerged, the protected waters in their lee become high-energy surf zones, and the dominant coral species change accordingly, from head corals (Montastraea annularis, Diploria strigosa, Siderastrea radians, S. bournei) to branching (Acropora palmata, A. cervicornis, various Porites spp.) and stinging corals (Millepora complanata, M. alcicornis). Such coral zonations are observed in Holocene cores recovered from Grecian Rocks (Shinn, 1963, 1980) and Looe Key Reef (Lidz et al., 1985) as Acropora palmata replaced Montastraea annularis. Species of Millepora are becoming increasingly abundant on both reefs today. These zonations highlight environmental quality (PDE 3, Table 2) as a critical element in our interpretation.

Pleistocene: Topography, Regional Sedimentation, and Outlier-Reef Distribution

Onset of outlier reef-and-trough development appears to have been dependent upon three non-contemporaneous criteria: (1) presence of an upper-slope bedrock terrace (Figure 3A); (2) later presence of lithified dune ridges on the terrace (Figure 3B); and (3) the energy regime and resulting sedimentation during a post-dune-ridge rapid rise in sea level. Where the bedrock terrace is absent, as, for example, in the pass off Key West (Figure 9, trackline 14), reefs and troughs are absent. Although the terrace has not been sampled, we infer from its variable depths (deeper off Key Largo than off Sand Key, Table 1) that it formed after postulated pre-Pleistocene, westward, platform tilting (Parker and Cooke, 1944; Parker et al., 1955; Kindinger, 1986) and is therefore Pleistocene. The variable depths probably resulted from the undulating pre-Key Largo Limestone topography of Hoffman (1974). Although we do not know whether the terrace is erosional (beachrock) or constructional (cemented sands) in origin, we do know that for corals to have recruited to its surface or to that of any surficial dune ridges, the surfaces had to have been hard (Shinn et al., 1989). Furthermore, given its significant breadth (Table 1), we infer that the terrace likely formed during a rather substantial stillstand. Numerous Pleistocene subaerial-exposure horizons in South Florida (Perrins, 1977) and the Bahamas (Beach and Ginsburg, 1980) indicate that sea-level rises and falls were punctuated.

Common to both the south and north terraces is the linearity of the surface (outlier-reef) and subsurface seismic expressions, respectively, which is consistent with the concept of a dune-ridge origin. A dune-ridge or fringing-reef origin was proposed by Lidz et al. (1991) for the outlier reefs off Sand Key. Although we have no hard evidence for dune-ridge underpinnings beneath the outliers (Figure 3A), and sand dunes do not exist along Keys beaches today, this is not to say that the terrace surface remained bare under conditions of exposure. Indeed, subaerial exposure would invoke seaward transport of platform-derived sediment by freshwater
Figure 6. Continuous high-resolution seismic-reflection profile A-A' (trackline 13) from Key Largo across Hawk Channel and White Bank to French Reef at margin (see Figure 2A for profile location and geographic localities). (A) Area where submerged, bare, bedrock ledge merges with west edge of Hawk Channel. Note thin, muddy, channel sands onlapping ledge (at left) and minor karstic irregularities in bedrock. Also note patch reef on topographic high at left edge of karst depression. (B) Area of Hawk Channel where White Bank sand shoals have accumulated. (C) Area of French Reef showing exposed seaward face of escarpment reef, which extends from The Elbow to Molasses Reef. Note backreef trough infilled with (Pleistocene?) sediments and surficial Holocene reefs.
Figure 7. Portions of high-resolution seismic-reflection profiles across escarpment reef off Key Largo (see Figure 2A for profile locations and geographic localities). (A) Profile B-B' (trackline 91) across The Elbow. Surficial Holocene sediments and reefs cover landward-accreting slope above backreef trough. Note patch reefs on bedrock topographic high at left. (B) Profile C-C' (trackline 28) across The Elbow. Note broad terrace, lack of seismic expression within low-relief terrace features of unknown origin (dune ridges?), and presence of seismic reflections between features, indicating sediment, inferred
runoff and shoreward transport of seafloor sands. Movement of relatively large amounts of both types of sediment load would be expected during respective paleowinter storms and hurricanes.

Carbonate sands move shoreward from the surf zone. For sands to accumulate on the broad terrace above the surf zone, position of a stillstand (? ) sea level would be at or just below the elevation of the seaward edge of the terrace. Coastal dunes are wind-blown features that form along low-lying seashores above high-tide level. In low-latitude carbonate realms, cementation occurs early and rapidly in both marine and non-marine settings (see Milliman, 1974, for discussion). Cemented dunes form dune ridges. Along the exposed terrace off Key Largo, onshore winds would blow sands into transverse dunes that would front the paleomargin cliff (Figure 3B). To the south, alongshore winds would blow sands into streamlined longitudinal dunes along the breadth of the terrace. A modern analogue to a longitudinal-dune hypothesis would have been the extensive, east-west quartz-sand dunes +5 m and higher that existed along the Florida Panhandle Gulf Coast until Hurricane Opal, a Category 3 storm, made landfall on October 4, 1995 (USGS unpub. data). Late Pleistocene analogues, recently sampled and dated by Lock et al. (in press), comprise a series of elevated, shore-parallel ridges as long as 24.5 km located at the seaward edges of deeper terraces (50-125 m) south of the Marquesas Keys. Those authors interpreted the primarily olitic grainstones as representing a subtidal shoal complex (~18.9 ka) and younger (~14.5, 14.0, and 13.8 ka), backstepped, upslope paleoshorelines of eolian-dune or beach origin. The ridges formed during a reduced rate of sea-level rise or a stillstand and were subsequently drowned by rapid pulses of sea-level rise approaching 9 m in <500 yr. These evidences, especially the widespread linearity of the features in our study, are a strong argument for subaerial formation and cementation (Perkins, 1977; Robbin, 1981; Rossinsky et al., 1992) of coastal paleodunes along a pre-existing bedrock terrace. The hard, elevated surfaces would form ideal substrates for coral colonization and initiation of the outlier reef-and-trough system during the next rise in sea level. If our data and inferences to this point are correct, the morphologies imply periods of at least one stillstand (terrace formation), one highstand (Key Largo Limestone formation), and another probable stillstand (?) (sand-dune and dune-ridge formation; Table 3). The third criterion for outlier-reef development, energy regime, becomes apparent in the data interpretations.

The Interpretations

Lacking sufficient information to prove precisely when and why the morphologies developed differentially along the platform margin, we offer two interpretations of the upper Keys data. Each depends on what one defines as an outlier reef (in-situ growth? or merely the presence of terrace morphologies with relief?). Each depends on control by several factors: antecedent topography (the terrace; an exposed, arcuate paleomargin; the dune ridges), energy regime along the paleomargin, and resulting sedimentary geometries. Both assume a constancy in direction of regional energy and sediment transport through time. Unfortunately, no seismic evidence exists to indicate whether the north escarpment reef actually initiated growth on the inner terrace or as a fringing reef on the paleomargin. The terrace reflection cannot be traced beneath the reef as it can, to some degree, under the south outliers (see Lutz et al., 1991).

The first interpretation would regard the north escarpment reef as a fully developed, inner-terrace, outlier reef analogous to the smaller inner-terrace satellite outlier off Sand Key, but with an infilled backreef trough. If this were the case, however, the outer-bank Holocene reefs at The Elbow, French, and Molasses Reefs would have no counterparts on the satellite outlier. Even so, if the north reef is an inner-terrace outlier, it could have begun growth on a transverse dune ridge close to the base of the paleoescarpment, at first accreting laterally to merge with the deeper part of the escarpment, later assuming a more vertical growth style to form the shallow backreef trough. This would place the paleomargin landward of the modern trough (see Figure 8). The intermittent lack of seismic expression on the terrace (Figures 7B, C, 8) would be regarded as indicating backfilled reef flats or sand shoals similar to that at White Bank (Figure 6B). This type of outlier reef-and-trough system would be defined as mature, i.e., the trough has filled and the margin has progressed. Regardless of interpretation, with no high-relief structures fronting the margin, this part of the system has reverted to an aggradational stage (i.e., it can only build upward by coral growth) and would produce the classic margin observed in the geologic record (for examples, see Toomey, 1981).

In this rendering, the upper Keys margin would be more advanced than the lower Keys margin, where the trough behind the analogous satellite outlier reef is not filled and the margin has yet to prograde by its being filled.

The alternative interpretation shifts the emphasis from origin of the north escarpment reef to the unknown features buried on the north terrace. Here, we view them as the dune-ridge underpinnings for outlier reefs that never developed. In this case, (a) the dune underpinnings are analogous to the prominent outliers to the south; (b) the north escarpment reef is not an outlier reef but is equivalent to that along the south margin landward of the outliers; and (c) the escarpment reef along the entire margin initiated growth as fringing reefs on a paleomargin located seaward of the modern backreef trough. The Holocene outer-bank reefs to the north (Molasses, French, The Elbow) now correspond to those to the south (Sand Key Reef, Eastern Dry Rocks, Pelican Shoal; Figure

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Figure 8. Interpreted seismic profiles of platform margin off upper Keys showing escarpment reef-and-trough system. Profiles aligned at what we define as the modern margin (vertical line) in consecutive order from northeast to southwest (see Figure 2A for locations and geographic localities). The alternative interpretations would place the paleomargin (a) landward of the backreef trough if the escarpment reef were an inner-terrace outlier reef, or (b) seaward of the trough if the escarpment reef initiated as fringing reefs. Island of Key Largo to left; Straits of Florida to right. Note (a) broad offbank bedrock terrace at depths between -35 and -45 m and small, buried, unknown features (dune ridges?); (b) infilled backreef trough and lack of seaward outlier reefs, indicating north margin is aggradational; (c) elevation of escarpment reef above platform bedrock surface, indicating presence of a protective rock-island barrier during platform flooding; (d) better resolution of Pleistocene platform bedrock surface than in lower Keys profiles (Figure 9); and (e) poorer resolution of seismic facies in backreef trough, possibly indicating Pleistocene reef-rubble infill. Distance along margin between end profiles is ~10 km. Diamonds indicate profiles used in Figure 14A–D.

2A,B), and the upper Keys margin is defined as less mature than the lower Keys margin, where the outliers are highly developed.

This interpretation raises the questions, why did outer-terrace outlier reefs become highly developed to the south but not to the north, especially when the Pleistocene margin-escarpment reef flourished throughout the reef tract, and how did the escarpment-reef backreef trough to the south become filled? At first, a connection between water depth and rates of coral growth and sea-level rise (Figure 10) might be implied, i.e., greater antecedent-bedrock (terrace) depth to the north appears to correlate with poorer “outlier-reef” devel-
Lower Florida Keys Margin Morphology

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<tr>
<td>10</td>
<td>Pliocene bedrock NW</td>
</tr>
<tr>
<td>11</td>
<td>Escarpment reef NW</td>
</tr>
<tr>
<td>12</td>
<td>Holocene sediment NW</td>
</tr>
<tr>
<td>13</td>
<td>Trough NW</td>
</tr>
<tr>
<td>14</td>
<td>Sand Key Reef NW</td>
</tr>
<tr>
<td>15</td>
<td>Holocene sediment N</td>
</tr>
<tr>
<td>16a</td>
<td>Primary outlier reef</td>
</tr>
<tr>
<td>16b</td>
<td>Double Pleistocene</td>
</tr>
</tbody>
</table>

Figure 9. Interpreted seismic profiles of platform margin (vertical line) off lower Keys showing escarpment reef-and-trough system and multiple offbank outlier reefs. Profiles in consecutive order from east to west (see Figure 2B for locations and geographic localities). Lower Keys to left; Straits of Florida to right. Note pass between outliers off Key West (trackline 14). Dated core obtained from primary outlier off Sand Key Reef (trackline 16a). Note (a) terrace at shallower depths (~30 to ~40 m) than to the north; (b) essentially empty outlier backreef troughs, indicating south margin is progradational; (c) elevation of outlier reefs on average at or below platform bedrock surface, indicating lack of a protective offbank rock-island barrier during platform flooding; and (d) better resolution of onbank and offbank Holocene seismic facies than in upper Keys profiles (Figure 8). Distance along margin between end profiles is ~65 km. Diamonds indicate profiles used in Figure 13A-D. Line 16c not used due to oblique orientation (see Figure 2B), which distorts width of features.

Table 2. Previously determined elements (termed PDE in text) that provide clues critical to interpretation of morphologies at the north margin.

<table>
<thead>
<tr>
<th>Key Elements in Interpretation</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Modern energy and sedimentary patterns mimic past patterns</td>
<td>BALL et al. (1966)</td>
</tr>
<tr>
<td>2. Topographic highs form hard substrates for coral colonization</td>
<td>SHINN et al. (1977), SHINN et al. (1989)</td>
</tr>
</tbody>
</table>

opment. Whereas the north corals might have been less efficient in becoming established in a rapidly rising sea, those on the shallower south terrace might have become established later, thereby being able to keep pace with a slightly less rapid rise. Two critical elements (PDE 1 and 2, Table 2) provide clues to a more subtle but salient connection, however, between location along the margin, rate of rising sea level, and effects of the prevailing-energy regime. Although lacking proof, we offer the following theory for consideration.

Subaerial dune ridges formed along the entire terrace and
were drowned by a rapid pulse of sea-level rise that transported unconsolidated sands along the margin in the directions they are moved today (PDE 1). Off the south margin, sands flowed south and west, between the ridges, allowing corals to recruit to their hard surfaces and initiate outlier-reef formation (PDE 2; Figure 11). Off the north margin, sands moved landward, onto the terrace, burying the ridges too quickly for corals to become established (Figure 12). The amount of in situ growth on the north ridges is probably negligible to none. In this scenario, conditions for offbank coral growth were optimal only along the south terrace strictly because of different sediment-transport directions resulting from different energy patterns impinging on the curved margin. In addition, the thick accumulations and type of coral (predominantly *Montastraea annularis*) in the massive margin-wide escarpment reef attest to ubiquitous warm, quiet, low-nutrient, open-ocean conditions. Therefore, corals should have grown on the north terrace but could not follow the basic plan because there were no hard, sediment-free substrates available for colonization. As the platform

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### Table 3. Relative succession of events along South Florida platform margin indicative of fluctuating sea level. Estimated positions of sea level in meters relative to present (inferred from data in text). Holocene positions based on sea level curve for reef tract (Figure 10).

<table>
<thead>
<tr>
<th>Event</th>
<th>Sea Level (m)</th>
<th>Timing (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ft. Lauderdale reef dies</td>
<td>rising +4°</td>
<td>5.0</td>
</tr>
<tr>
<td>North platform floods</td>
<td>rising +8°</td>
<td>7.0</td>
</tr>
<tr>
<td>South platform floods</td>
<td>rising +12°</td>
<td>8.0</td>
</tr>
<tr>
<td>Outlier-reefs drown</td>
<td>rising +13°</td>
<td>&lt;8.2</td>
</tr>
<tr>
<td>South terrace floods</td>
<td>rising +30°</td>
<td>&gt;9.2</td>
</tr>
<tr>
<td>North terrace floods</td>
<td>rising +35°</td>
<td>&gt;9.2</td>
</tr>
<tr>
<td>Outlier reefs growing</td>
<td>highstand +20°</td>
<td>&gt;83-80</td>
</tr>
<tr>
<td>South outlier reefs originate</td>
<td>rising +25°</td>
<td>&gt;83.0</td>
</tr>
<tr>
<td>North dune ridges buried</td>
<td>rising +30°</td>
<td>&gt;83.0</td>
</tr>
<tr>
<td>Dune ridges form</td>
<td>stillstand +45°</td>
<td>&lt;100.0</td>
</tr>
<tr>
<td>Key Largo Ls. forms</td>
<td>highstand +7.6</td>
<td>125.0</td>
</tr>
<tr>
<td>Terrace forms</td>
<td>stillstand +90-45°</td>
<td>&gt;125.0</td>
</tr>
</tbody>
</table>

---

**Figure 10.** Sea-level curves for Barbados corals (Fairbanks, 1989, 1990) plotted against modified, well-constrained curve for the Florida reef tract based on reef-tract data (solid line, open symbols). Reef-tract curve is used in interpretations in this study. Query indicates lack of reliable reef-tract data older than ~8.2 ka.

**Figure 11.** Proposed model for evolution of lower Keys platform margin sea level fluctuated many times but positions correspond to events shown. (A) Pleistocene stillstands? dune-ridge formation. (B) Colonization of sediment-free paleomargin and dune ridges by Pleistocene corals that keep up with rapid rise in sea level. (C, D) Upward building of margin-escarpment reef and outlier reefs. (E) Death of corals on outliers at ~8.2 ka and later backstepping of Holocene outer-bank reefs with platform-wide flooding.
flooded with continued rise in sea level, the north escarpment-
reef backreef trough became filled by landward transport of the
Pleistocene reef's own rubble, thereby accounting for the poor
seismic resolution within the deeper trough sediments (Figure
7B). The south trough was infilled with less acoustically obscure
(Liu et al., 1991, their Figures 2 and 3) carbonate (versus ree-
fal) sands swept to the southwest from between Hawk Channel
and the margin by alongshore processes.

The primary key, then, to initiation of differential Pleisto-
cene development is an energy regime like that of today act-
ing, during periods of fluctuating sea level, on a readily avail-
able sediment supply on a bedrock terrace that fronted an arcuate margin. From the evidence, we infer that: (1) the
margin-wide escarpment reef originated as contemporaneous
fringing reefs; (2) the north-terrace seismic expressions re-
represent buried dune ridges that probably never harbored sig-
nificant in-situ coral growth; and (3) the north-terrace burial
sediments are non-reefal (i.e., they have seismic resolution;
Figure 7B) and may be primarily Pleistocene. Until all of
these features can be investigated with tools other than seis-
ic profiling, there is no way to know their true origin and
composition, their relation to one another, or which interpre-
tation is correct. However, it is tempting to believe the salient
connection between energy and location along the margin,
and the rapid burial of dune-ridge-like substrates that would
have been suitable for coral colonization of the north terrace.

Life and Death of the Massive Reefs

During the late Pleistocene, the highest sea levels occurred
during substage 5e, when the Key Largo Limestone formed
at ~125 ka (Shackleton and Matthews, 1977). Although
sea level has subsequently fluctuated many times, it has never been as high (Hofmeister, 1974). The Pleistocene parts of the massive reefs are therefore probably cumulative and represent alternating periods of colonization, exposure and cementation, and new colonization. Pleistocene corals eventually formed 28 to 30 m of relief along the margin and in the south outer reefs.

Comparatively speaking, Holocene corals appear not to have fared as well as the Pleistocene corals that built the massive reefs. For unknown reasons, Holocene corals became established more readily and thrived more consistently on edges of shallow lagoon-shelf terraces (Shinn et al., 1989) than on the deeper outer reef. The few Acropora palamata that had colonized the outliers died shortly after ~8.2 ka (Table 3), and a very few, widely scattered colonies of living Montastraea annularis remain (EAS, pers. observ.). It is highly unlikely that poor colonization was related to rate of sea-level rise. Growth rates of both coral species are so great (as much as 4.85 m/ka for M. annularis and twice that rate for A. palamata; Shinn, 1976; Shinn et al., 1977) that they would have kept pace with even a very rapid rise. Differences in Holocene growth occurred within the lagoon-shelf realm as well, with corals faring better to the north than to the south. Three factors inherent to antecedent massive-reef morphology (PDE 3; Table 2), including that of the outliers, may have played a role in the inequalities in Holocene growth: (1) surface elevation relative to that of the platform, (2) location along the margin, and (3) orientation relative to exposure to high-energy and cold, lagoonal, winter-storm waters. Off the lower Keys, the unprotected open-ocean exposure, similar elevation relative to the platform, and parallel orientation relative to prevailing-energy direction made the outliers particularly vulnerable to winter-storm conditions.

Off the upper Keys, however, the influence of higher elevation and different location and orientation relative to land and energy proved positive, in that Holocene corals were less affected by high-energy waves and influx of inimical waters than corals on the lower Keys escarpment and outlier reefs. The age of the oldest Holocene Acropora palamata on the most seaward reef off Ft. Lauderdale is 7 ka (Lighty, 1977). At the time of its growth, position of sea level was at about ~7 m (Figure 10). The massive escarpment reef in the study area and those off Carysfort and Ft. Lauderdale were islands with their seaward sides in the surf zone. Platform topographic highs such as those at Grecian Rocks had not yet flooded. The escarpment reefs were protected from the effects of winter storms by the Key Largo land mass. We believe that Holocene A. palamata thrived on the landward sides of the upper Keys escarpment reefs because bedrock elevation at the seaward edge of the margin was higher than that off the lower Keys. platform flooding occurred more slowly, influx of lagoonal waters was blocked, and the high-energy surf zone remained fairly close to the margin for a longer period of time. Whereas corals on the south outliers died at ~8.2 ka, those on the massive north reefs survived for at least another 3 ky r (the reef off Ft. Lauderdale died at ~5 ka; Lighty, 1977). Demise of the upper Keys Holocene corals is likely a response to flooding of the inner platform with increased tidal exchange of turbid, nutrient-rich waters (PDE 3; Hudson, 1981). Influx of low-salinity waters via runoff from the Everglades would be particularly deleterious to corals in shallow environments. The primary key, then, to differential Holocene reef development is the antecedent dissimilarity in Pleistocene morphology (elevation, location, and orientation) that produced corresponding differences in Holocene environment and reef growth along the margin.

**Holocene: Sea-Level Rise and Margin Morphology**

The first Holocene sea-level curve for South Florida was constructed from 14C dates of subaerially formed terrestrial and/or mangrove peats now submerged in Florida Bay (Scholl, 1964; Scholl et al., 1969). A more recent curve (Figure 1), based on 14C ages of continuous peat sections exposed in tidal passes through the Keys and of peats beneath corals at Alligator Reef (Figure 1; Robbin, 1984), was modified by supplemental 14C ages of cored and excavated corals (Lighty, 1977; Shinn et al., 1977; Shinn, 1980; Shinn et al., 1981; Shinn et al., 1991). The modified curve is preferred for calculating timing and positions of paleoelevations along the reef tract.

Projection of former sea-level positions onto stable-platform contours (Lidz and Shinn, 1991, their Figure 3) shows how margin morphology changed through time. Generalities can be observed as we track rising sea level from paleodepths of ~40 to ~20 m: (1) the area off Sand Key is at first defined by a widely exposed, continuous, broad, high, rock-island ridge, then by three considerably narrower islands of much lower elevation, all formed by the fossil outlier reefs before the outer platform flooded (Figure 13A-D); (2) in contrast, the area off Key Largo is at first defined by a series of low-relief, discontinuous (dune-ridge?) islands with widely flooded, shallow, intervening areas, then by two narrow reef-rock islands at the margin edge (Figure 14A-D); (3) at a paleodepth of ~10 m, the escarpment reef formed a relatively unbroken, margin-wide island barrier off the Keys. All the rock islands probably harbored fringing reefs, and all provided protection from high-energy waves of the Straits of Florida.

Smaller scale changes occurred as the uneven platform surface was inundated and the long protective islands at the margin disappeared (summarized from Lidz and Shinn, 1991). The area of the lower Keys platform flooded earlier and faster than that off the upper Keys, which is opposite the timing and speed of flooding of the terrace. The timing of platform flooding suggests that Holocene outer-bank reef growth began first to the south and is supported by the ages of reefs at Looe Key (6.6 ka) and at Grecian Rocks (6.0 ka). As water flowed throughout Hawk Channel at ~6 ka, fringing reefs backstepped, some by as much as several hundred meters, and increased wave action on the outer bank created conditions more suitable to the moose- and stag horn corals than to the head corals. Extensive, rigorous spurs and grooves developed on windward sides of all outer-bank reefs. With continued flooding of the inner platform, seawater invaded smaller depressions in the Key Largo Limestone that would become the deep tidal passes between the Keys. Larger depressions, now Florida and Biscayne Bays (Figure 1), began to fill at ~4 ka. By ~2 ka, sea level was ~0.5 m lower.
than present. Rodriguez Key (Figure 2A), a peat island surrounded by a mud bank, acquired a cap of branching coral and coralline algae (TURMEL and SWANSON, 1976), and the Florida Keys looked much as they do today. Holocene Acropora palmata and other coral species that once had flourished in the spur-and-groove zones began their decline.

Today, the vigor of modern coral growth continues to decline (DUSTAN and HALAS, 1987; WARD, 1990; PORTER and MEIER, 1992; HALLOCK et al., 1993), and the proliferation of macro-algae and coral diseases that began in the mid-1980s is thought by many (cf. HALLOCK and SCHLAGER, 1986) to be related to sea-level rise, urbanization, agriculture, and resultant deleterious effects of nutrient-rich water. The reefs are further impacted by occasional cold-water temperatures (MAYOR, 1914; ROBERTS et al., 1982) and hurricanes (BALL et al., 1967; PERKINS and EROS, 1968; SHINN, 1976). As in the past, the most diverse and best developed reefs occur in protected locations such as off Key Largo (GINSBURG and

Figure 13. Block diagrams of margin bedrock topography off lower Keys showing morphologies during Holocene sea-level rise. Distance between profiles not to scale (see Figure 2B for geographic locations and scale; profiles from Figure 9). (A) Formation of long, broad, high island ridge on outer terrace with shallow, wide, landward, lagoonal trough. Direction of water flow probably westward. (B) Deepening of lagoon and formation of smaller, marginward, rock-island ridges by satellite outliers. (C) Narrowing of islands. (D) Flooding of Hawk Channel and most of inner platform off lower Keys (see depths to platform bedrock in Table 1). Diagrams at same scale as Figure 14.
Figure 14. Block diagrams of margin bedrock topography off upper Keys showing morphologies during Holocene sea-level rise. Distance between profiles not to scale (see Figure 2A for geographic locations and scale; profiles from Figure 8). (A) Formation of discontinuous series of linear, low-relief islands, possibly dune ridges, with wide, shallow, intervening lagoonal areas. (B) Flooding of terrace islands. (C) Formation of escarpment-reef ( outlier-reef?) islands off Molasses Reef and southwest of The Elbow. Note linear embayment behind The Elbow and forked area of embayment, where margin reentrant, when flooded, would isolate the offset reef (see Figure 5). (D) Narrowing of islands and flooding of outer platform. Most of Hawk Channel and all of inner platform off upper Keys remain dry land (see Table 1 and Figure 4). Diagrams at same scale as Figure 13.
Outlier Reefs in the Geologic Record

To date, no margins characterized by outlier reef-and-trough systems are known from other modern carbonate banks or the geologic record. It is well known that ancient carbonates of all ages worldwide (King, 1948; Rohri and Choquette, 1985; and Dunnih et al., 1988, among others) are extensive hydrocarbon-bearing reservoirs. Given time and sufficient overburden, the outlier reefs off South Florida could form similar discrete, parallel, hydrocarbon-bearing traps within a larger platform-margin complex. They undoubtedly contain numerous calcrete and/or cement seals formed during each fall in Pleistocene sea level. The fact that they form significant structures implies that they probably exist off windward margins elsewhere, as well as throughout the geologic record, but have not been recognized. We suggest that explorationists keep this example in mind when prospecting any ancient platform carbonates.

CONCLUSIONS

High-quality seismic-reflection profiles identify an extensive Quaternary reef-and-trough system along the South Florida windward margin. Depending upon location, the system exhibits contrasting morphologies and has a uniquely opposite, aggradational and progradational potential to build seaward. Differential evolution of the morphologies was controlled by different agents over time. During the Pleistocene, the primary influences were the effects of energy regime and fluctuating sea level on readily available terrace sediments at an arcuate, subaerially exposed margin. During the Holocene, the primary influences were the dissimilarities in the antecedent Pleistocene morphologies that produced, with rising sea level, corresponding, localized contrasts in environment and reef vitality: the thickest Holocene reefs accumulated leeward of bedrock barriers in areas of calm, clear, oceanic waters. The massiveness of this system, particularly that of the outlier reefs, implies that similar systems should exist elsewhere, and perhaps as parallel hydrocarbon traps in the geologic record.

Pending confirmation by acquisition of radiometric data, our preliminary interpretation of terrace morphologies off the upper Florida Keys is based on two key elements: paleoenery and sedimentation patterns similar to those of today, and coral recruitment primarily to elevated, lithified surfaces. We infer that: (1) the acoustically obscure terrace seismic facies represent Pleistocene stillstand beach-dune ridges; (2) the hard ridge surfaces were buried by onshore sediment transport during a rapid pulse of sea-level rise; thus, (3) Pleistocene corals did not duplicate the outlier-reef blueprint of the south, although conditions otherwise were optimal for their growth as exemplified by the margin-wide escarpment reef; and (4) the north part of the margin is less advanced than the south part, where the outlier reefs are highly developed. Future research, perhaps by submersible, might be directed toward sampling the north-terrace (dune?) ridges, the deepest burial sands (Pleistocene?) between the ridges, and possibly the terrace, wherever it is most accessible along the margin, for purposes of dating. Sampling the basal sediments (Pleistocene?) in the north escarpment-reef trough might be accomplished by core drilling.

During the Holocene, the south area of the platform flooded earlier and faster than the north area due to lower elevation and fewer protective rock islands. Holocene reefs are thickest on the north outer bank, thinner on the south outer bank, and very thin on the south offbank outlier reefs. Why corals did not survive on the outliers is not known; they essentially died at ~8.2 ka, whereas those on the north escarpment reefs survived for another 3 kyr until the platform became fully flooded, and cold, turbid, low-salinity lagoonal waters invaded the shallow offshore regime.

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