4

Coral Reefs, Present and Past, on the West Florida Shelf and Platform Margin

Albert C. Hine, Robert B. Halley, Stanley D. Locker, Bret D. Jarrett,
Walter C. Jaap, David J. Mallinson, Kate T. Ciembronowicz,
Nancy B. Ogden, Brian T. Donahue, and David F. Naar

4.1 Introduction

In spite of the subtle, low-relief contours seen on bathymetric maps of Florida's Gulf of Mexico (west Florida) shelf and slope (Fig. 4.1), this rim-to-ramp carbonate platform has and continues to support a surprisingly wide variety of coral reefs as compared to much better-known morphologically complex areas such the Great Barrier Reef. From the mid-shelf to the upper slope, light-dependent, hermatypic coral reefs have formed as a result of hard substrate availability, ideal oceanographic conditions, and sea-level fluctuations. Indeed, the west Florida slope even supports living light-independent, ahermatypic coral reefs in ~550 m water depth (Newton et al. 1987).

This paper summarizes the geomorphic variability of these different reef types, their geologic setting, and the present coral-reef biological community. The paper is organized along a virtual depth transect by presenting different reef settings and types starting from the shallower mid-shelf or mid-ramp setting, moving to the shelf edge, and then to the deeper upper slope.

4.2 Background

The west Florida shelf/slope is an excellent example of a distally-steepened, carbonate ramp setting, that is fundamentally different than the well-known, rimmed carbonate platforms such as the Bahamas (Ahr 1973; Hine and Mullins 1983; Read 1982, 1985; Mullins et al. 1987, 1988, 1989; Hine 1997). Distally-steepened ramps are accretionary shelves that have a break-in-slope that occurs in deeper water. The only other well-developed carbonate ramps in the modern warm-temperate/tropical ocean are the Campeche Bank located just across the Yucatan Straits from west Florida (Logan et al. 1969) and the south coast of the Persian Gulf (more of a homoclinal ramp where slope gradient is relatively uniform; Purser 1973; Tucker and Wright 1990). A rimmed carbonate platform has a wave or current-dominated shelf margin supporting shallow reefs or sand shoals. The Bahamas, the Great Barrier Reef, the Belize Shelf, and the Florida Keys are examples of rimmed carbonate margins.

The west Florida shelf/slope rests on the Florida Platform, a huge, shallow-water carbonate depositional system that began accumulating sediments in the late Jurassic on top of a mostly crystalline bedrock basement (Klitgord et al. 1984; Sheridan et al. 1988; Poag 1991). The south-southwestern portion of this platform remains to this day a carbonate-dominated province. The southern portion supports reefs along the margin, which define the shelf-slope break. This area is a classic rimmed platform margin (Hine and Neumann 1977; Tucker and Wright 1990). To the west, this reef rim disappears and the Florida Platform becomes an open, non-rimmed margin as the margin curves around to the north. Here, the Florida Platform becomes a classic ramp. The distally-steepened ramp terminates on top of the West Florida Escarpment, a huge erosional, submarine sea-cliff having ~1,800 m of relief (Fig. 4.1).

Prior to the mid-Cretaceous, the western portion of the Florida Platform was dominantly a shallow-water system that supported rudist reefs at the margin.

B.M. Riegl and R.E. Dodge (eds.), *Coral Reefs of the USA*,

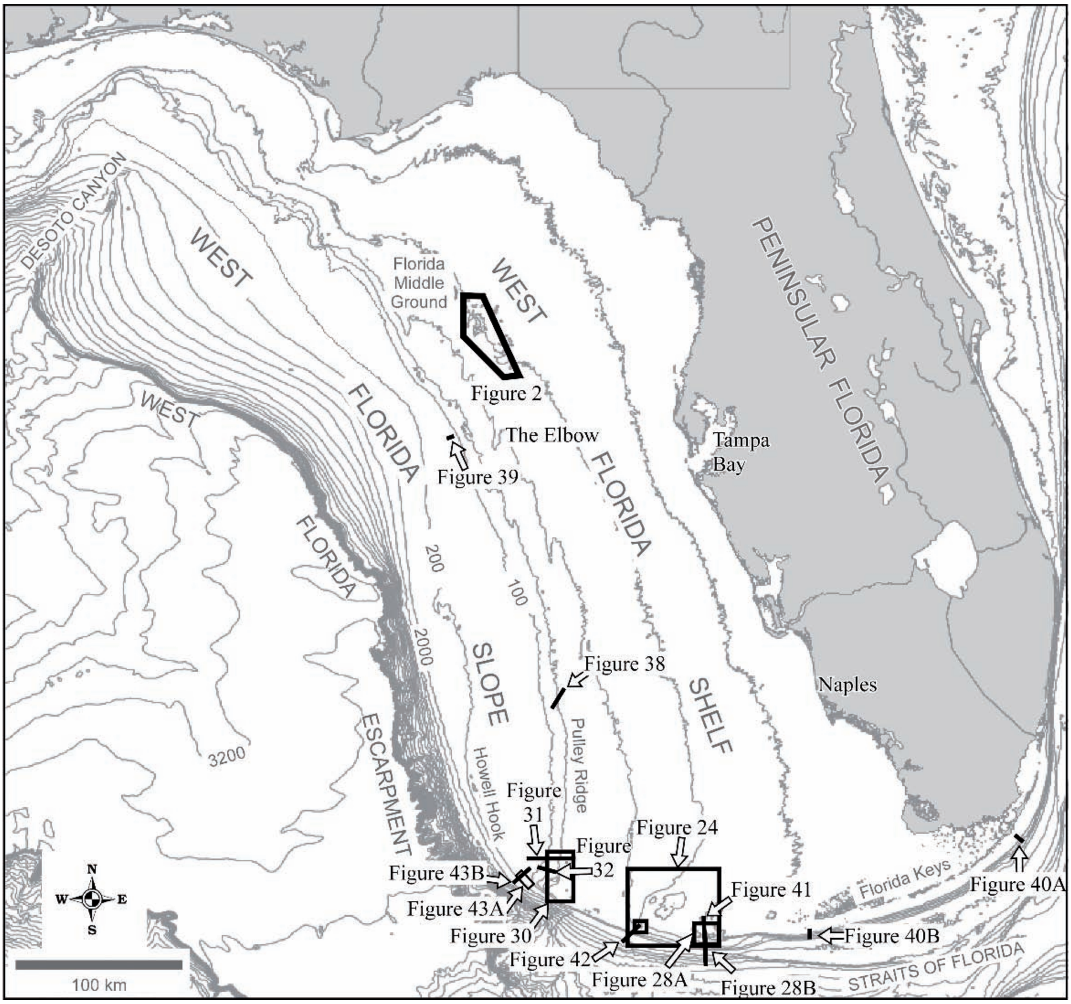

Fig. 4.1. Overall location map of the west Florida platform. Locations of other figures presented in this paper are shown. In the captions, figures are numbered as 4.1–4.43. All depths in meters.

However, most likely due to a succession of oceanic anoxic events (OAEs) coupled with sea-level rise in the mid-Cretaceous, this margin drowned resulting in a widespread and prominent unconformity known as the mid-Cretaceous sequence boundary (Arthur and Schlanger 1979; Corso et al. 1989; Vogt 1989; Buffler 1991). Eventually, the outer portion of the west Florida Platform subsided below the photic zone becoming dominated by pelagic sediments. A foraminifera-pteropod ooze, mixed with silciclastic muds from the Mississippi River plume, is now the predominant sediment beyond ~600 m water depth (Mullins et al. 1987, 1988, 1989). The modern shelf/slope boundary is located roughly at 75 m water depth, and the slope extends down to about 1,800 m water depth where the West Florida Escarpment drops off to ~3,200 m water depth.

The end result of this geologic history is one of the largest continental shelf/slope systems in the world that extends 900 km along the 75 m bathymetric line, passes through 6.5° latitude (700 km), and is up to 250 km wide. The low shelf gradient (0.2 –4 m/km) provides a template over which numerous sea-level driven transgressions and regressions have passed. In addition, its limestone foundation provides unique surficial and subterranean karst features. Finally, the silciclastic influx from the eastern, exposed portion of the platform and from the modern fluvial systems to the north have produced a regional, carbonate-siliciclastic system (Hine 1997; Hine et al. 2003; Hine et al., in press). As a result, the west Florida shelf/slope, situated on top of the Florida Platform, presents pronounced significant depth, substrate, oceanographic, and climatic transitions that convolved to produce and maintain the coral reefs we see today.

4.3 Mid Shelf Reefs

4.3.1 Florida Middle Ground

The Florida Middle Ground (FMG) is a complex cluster of small carbonate banks that supports a diverse benthic environment with variable relief in a mid-to-outer shelf setting. (Figs. 4.1, 4.2). In general, the FMG trends north-northwest, parallel to the platform margin and is ~60 km long by ~15 km wide. Individual banks are approximately 12–15 m in height, and as much as 2–3 km in width. Water depths range from 45 m in surrounding basinal areas to a minimum depth of 24 m on bank-tops (Fig. 4.2). The FMG represents a relict or "give-up" reef (Neumann and Macintyre 1985), with a diverse and complex geomorphology, which is the product of the convoluted interplay of carbonate production, climate and sea-level change, and physical oceanographic processes. This reefal complex is unique, as it occurs in the middle of a carbonate ramp and is the northernmost large reef structure (albeit no longer framework building) in the Gulf of Mexico. Although a number of geologists and biologists have examined this unique reef, many critical questions remain regarding the age of reef growth, the paleoceanographic setting (which was certainly different from today), and the foundation for initial coral recruitment.

The entire west Florida shelf lies within the global "chlorozoan zone" (skeletal sediments dominated by hermatypic corals and calcareous green algae) predicted by Lees (1975) in his model, which is based on sea-surface temperature and salinity. Temperatures in the FMG area range from ~16°C to 30°C and are amenable to reef growth. However, reef growth is likely limited by excess nutrients and the associated increase in bioerosion rates (Hallock and Schlager 1986; Hallock 1988). At present, the northern half of the west Florida shelf is affected by periodic upwelling and seasonal chlorophyll plumes indicating relatively high-nutrient water conditions (Gilbes et al. 1996). These plumes have been recognized each spring using Coastal Zone Color Scanner imagery. Plumes begin north of the FMG area near Apalachicola Bay and migrate south-southeast directly over the FMG. Mechanisms proposed for the origin of the plume include Loop Current interactions with the platform margin producing upwelling and entrainment of high-nutrient water masses from fluvial discharge.

The FMG was initially investigated for its biological significance. The first mapping effort by fathometer was performed by Jordan (1952) and Ludwick and Walton (1957). Gould and Stewart (1956) suggested the FMG relief was related to reef growth, based upon analysis of bottom samples. Brooks (1962) first investigated the area using SCUBA and defined the occurrence of reef communities. Austin and Jones (1974) described the physical oceanographic setting and the relationship to productivity. Grimm and Hopkins (1977) described the occurrence of zooxanthellate corals on the FMG. Geological investigations began in the 1970s with Back (1972), who defined the sediment textures and distributions and related them to carbonate production on the reef banks. Hilde et al. (1981) first performed seismic investigations in the area, and defined three prominent seismic stratigraphic units including a Miocene "basement". More detailed sediment work was performed by Doyle et al. (1980) and Brooks (1981). Even more recent seismic investigations include the work of Brooks and Doyle (1991), and Mallinson et al. (1996, 1999, 2006).

4.3.1.1 Geology

Geophysical data reveal a wide variety of geomorphic and acoustic facies that represent a complex geologic framework of relict Pleistocene limestone mantled with Holocene corals and sediment. Diver and ROV observations reveal highly bioeroded areas with abundant cryptic environments, including arches, overhangs, and shallow caverns. High-relief hardbottoms occur in the northern study area and are characterized by vertical reef growth exhibiting relief of ~12–20 m above the surrounding shelf environment. This general hardbottom morphology includes three varieties: (1) semi-continuous

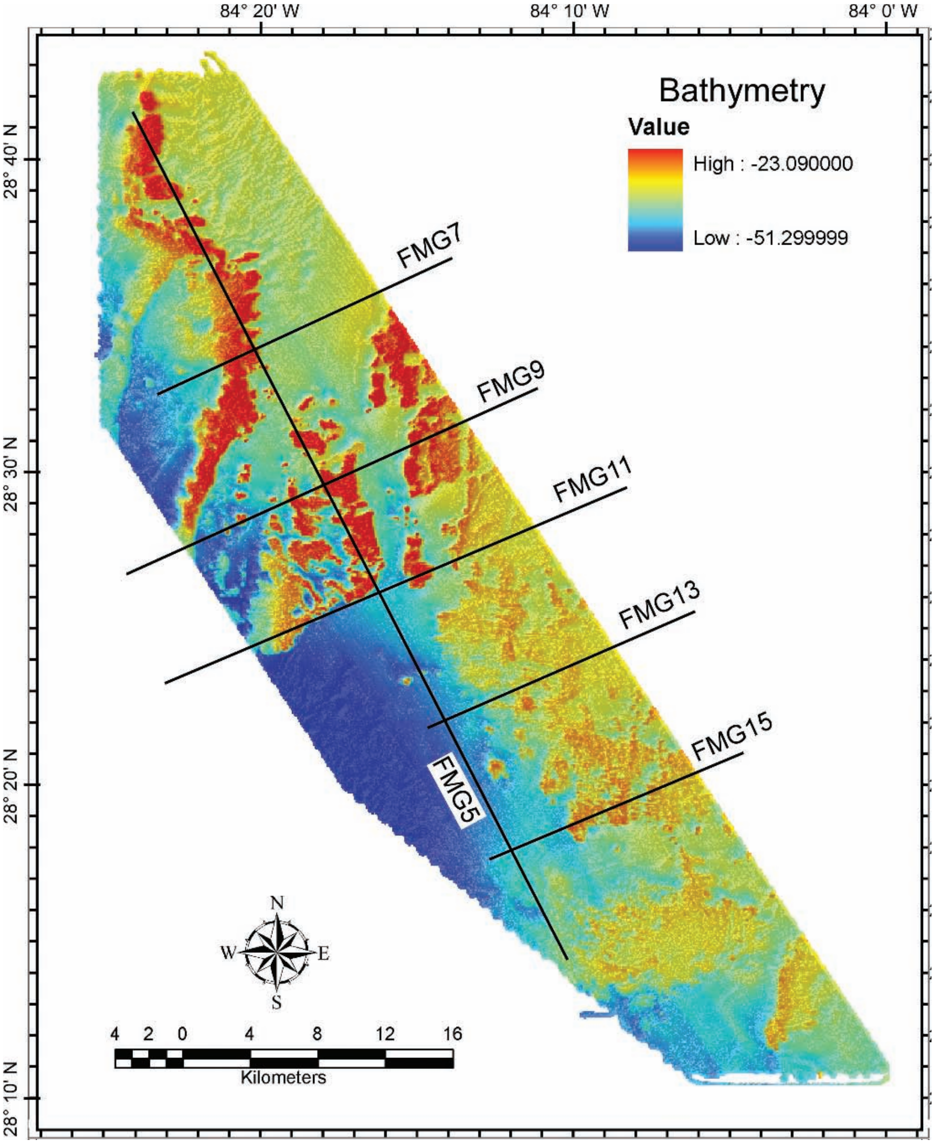

Fig. 4.2. Multibeam bathymetry data reveal a complex geomorphology of small carbonate banks constituting FMG. Location of seismic profiles in Figs. 4.9 and 4.10 are shown

(>8 km) margin-parallel banks 2–3 km in width, (2) isolated flat-topped banks with no particular orientation or maximum dimension, and (3) isolated patch reefs generally <1 km in diameter (Fig. 4.3).

Low-relief hardbottom environments occur in the southern study area and are characterized by relief of ~2–8 m above the surrounding shelf environment. This general hardbottom morphology includes five varieties (Fig. 4.4): (1) undulating/crenulated surfaces exhibiting no discernable patterns, (2) elongate, parallel, overlapping biohermal structures, (3) rounded depressions of unknown origin with central patch reefs ~200 m in diameter, (4) isolated patch reefs, and (5) parallel ridges trending NW–SE.

Soft-bottom environments occur in the surrounding areas and between carbonate banks. Soft-bottom morphologies include: (1) featureless flats, (2) scour depressions surrounding hardbottom environments, (3) scour depressions with active sediment transport, and (4) sand waves

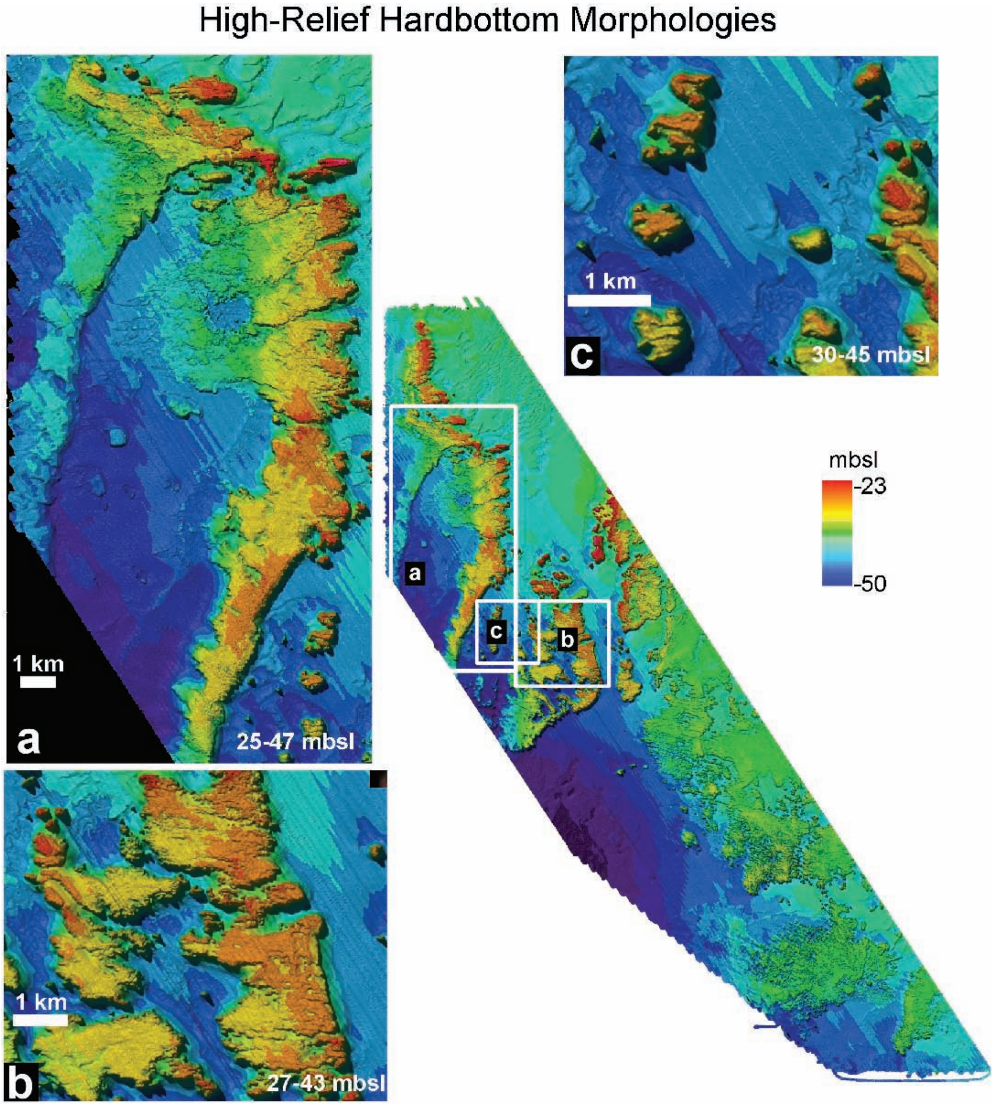

FIG. 4.3. FMG high-relief hardbottoms occur in the northern study area, stand approximately 12–15 m above the surrounding shelf environment, and include three varieties: (**a**) semi-continuous (>8 km) margin-parallel banks 2–3 km in width; (**b**) isolated flat-topped banks with no particular orientation or maximum dimension; (**c**) isolated patch reefs generally < 1 km in diameter

(submarine dunes) ~1–2 m in height and 200 m in spacing (Fig. 4.5).

Bedforms, sediment distribution patterns, and scour patterns indicate an influence of southward-flowing and off-shelf directed currents (Fig. 4.5). Typical bottom scenery is shown in Fig. 4.6. Acoustic backscatter data from side-scan and multibeam sonar data reveal a distinctive contrast between coarse carbonate sediments shed from the reefs, and fine siliciclastic sediments, which are prevalent across much of the surrounding shelf. Low-backscatter areas (light blue in Fig. 4.7) consist of fine quartz and carbonate sand with a median grain size of ~2.5–3.2 phi. High-backscatter areas (dark blue in Fig. 4.7) consist of very coarse carbonate shell material with a median grain size of ~0 phi. Hardbottom /livebottom areas also yield high backscatter and may be distinguished based on texture (Fig. 4.8).

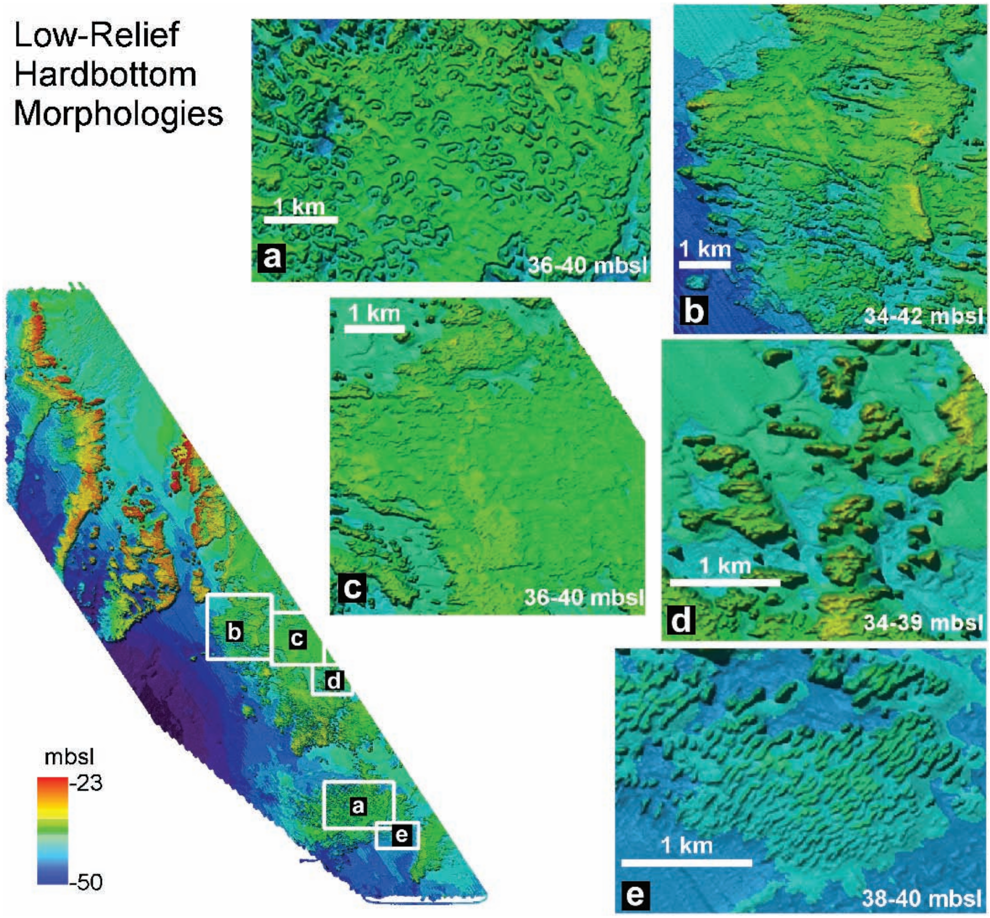

FIG. 4.4. FMG low-relief hardbottom environments occur in the southern study area, stand approximately 2–8 m above the surrounding shelf environment, and include five varieties: (**a**) rounded depressions of unknown origin with central patch reefs, ~200 m in diameter; (**b**) parallel ridges trending NW–SE; (**c**) crenulated surfaces exhibiting no discernable patterns; (**d**) isolated patch reefs; (**e**) elongate, parallel, overlapping biohermal structures

Several high-amplitude, continuous reflections are apparent in seismic data from the FMG (Figs. 4.9, 4.10). The basal reflection occurs at ~65 mbsl (meters below sea level) beneath the western portion of the FMG and rises to ~45 mbsl beneath the eastern portion of the FMG (Fig. 4.10). This surface exhibits up to 4 m of relief and is interpreted to be a karst surface. Based upon previous studies in this region, rocks beneath this surface are likely to be Miocene limestone (Hilde et al. 1981).

Above the karst surface, several seaward-dipping Plio-Pleistocene sequences are recognized. These sequences define a wedge that pinches out beneath the easternmost hardbottoms of the FMG. Sequence boundaries are irregular and indicate dissolution features within a carbonate substrate (Fig. 4.9).

A high-amplitude reflection truncates the Plio-Pleistocene sequences, and separates the dipping sequences from the younger aggradational FMG reefs and surrounding sediments (Figs. 4.9, 4.10). The sediments above this prominent unconformity range in thickness from ~4 to 15 m (under reefs). Soft sediment between reefs is nearly acoustically transparent, whereas the hardbottoms are acoustically opaque. Seismic data are somewhat ambiguous in that a prominent reflection underlies an acoustically transparent bed within the lows between the banks.

The prominent reflection could be interpreted as the Last Glacial Maximum (LGM ~20–18 ka) unconformity, making the FMG very early Holocene. However, there is a faint, discontinuous,

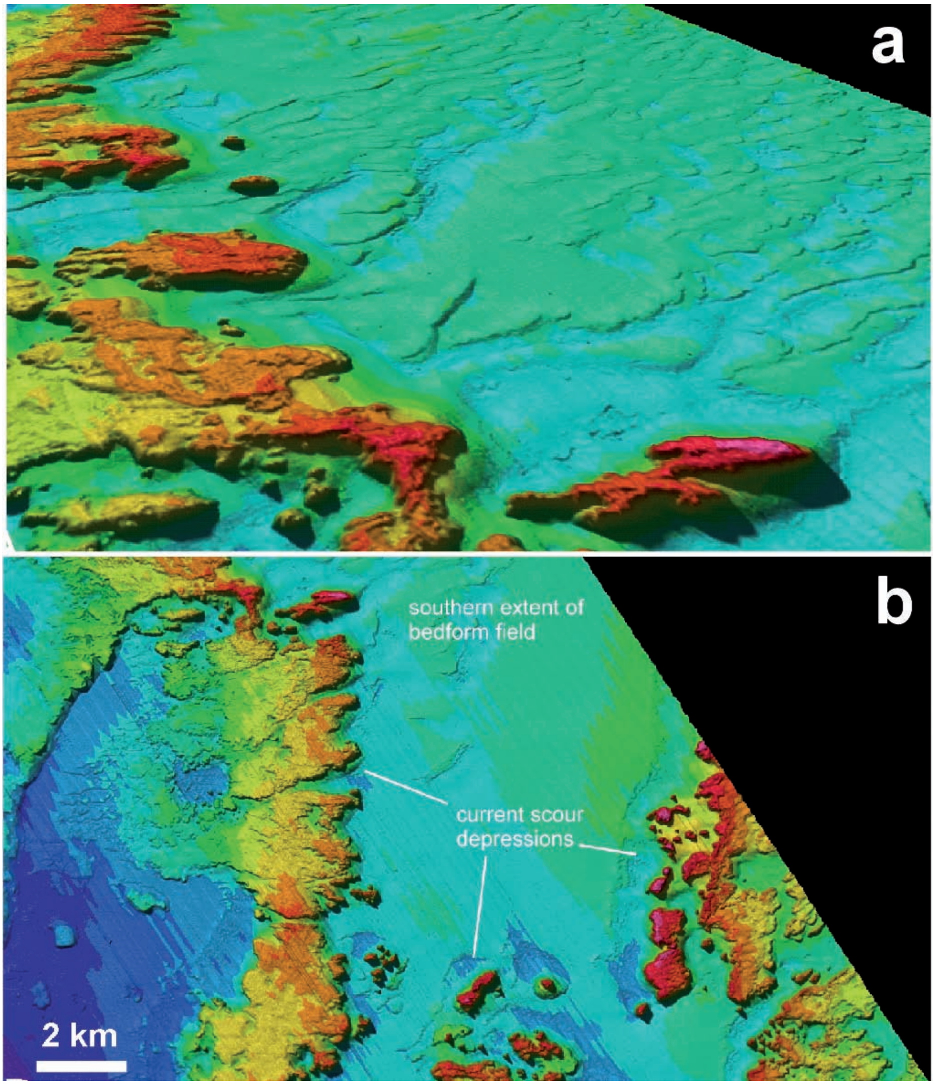

FIG. 4.5. South-flowing shelf currents promote active bedform fields and interact with the bathymetry to yield complex scour patterns surrounding the banks at FMG. (**a**) Bedform field consisting of sand waves of ~1–2 m height and ~500 m spacing (oblique view). (**b**) Current scour depressions surrounding the banks

low-amplitude reflection intermittently observable above the high-amplitude reflection, which has the characteristics of several broad, mound-like structures. One interpretation is that these are lithified, paleoshoreline features upon which the FMG corals were recruited.

Based on the depth, it is possible that the predominance of FMG reef growth occurred rapidly during the early Holocene, well before ~4 ka, when Mississippi River discharge was low due to arid climate conditions over the North American continental interior (Knox 2000; Forman et al. 2001). In this scenario, these reefs would be contemporaneous with the reefs of Tortugas Bank (near the Dry Tortugas). The reefs at Tortugas Bank grew ~8 m in relief from 8.3 to 4.2 ka (Mallinson et al. 2003). Possible enhanced Mississippi River discharge ~4.2 ka may have terminated reef development (Mallinson et al. 2003) as a result of enhanced turbidity, nutrient loading, and decreased salinity. Alternatively, the reef framework may be much older corresponding to Marine Isotope Stage

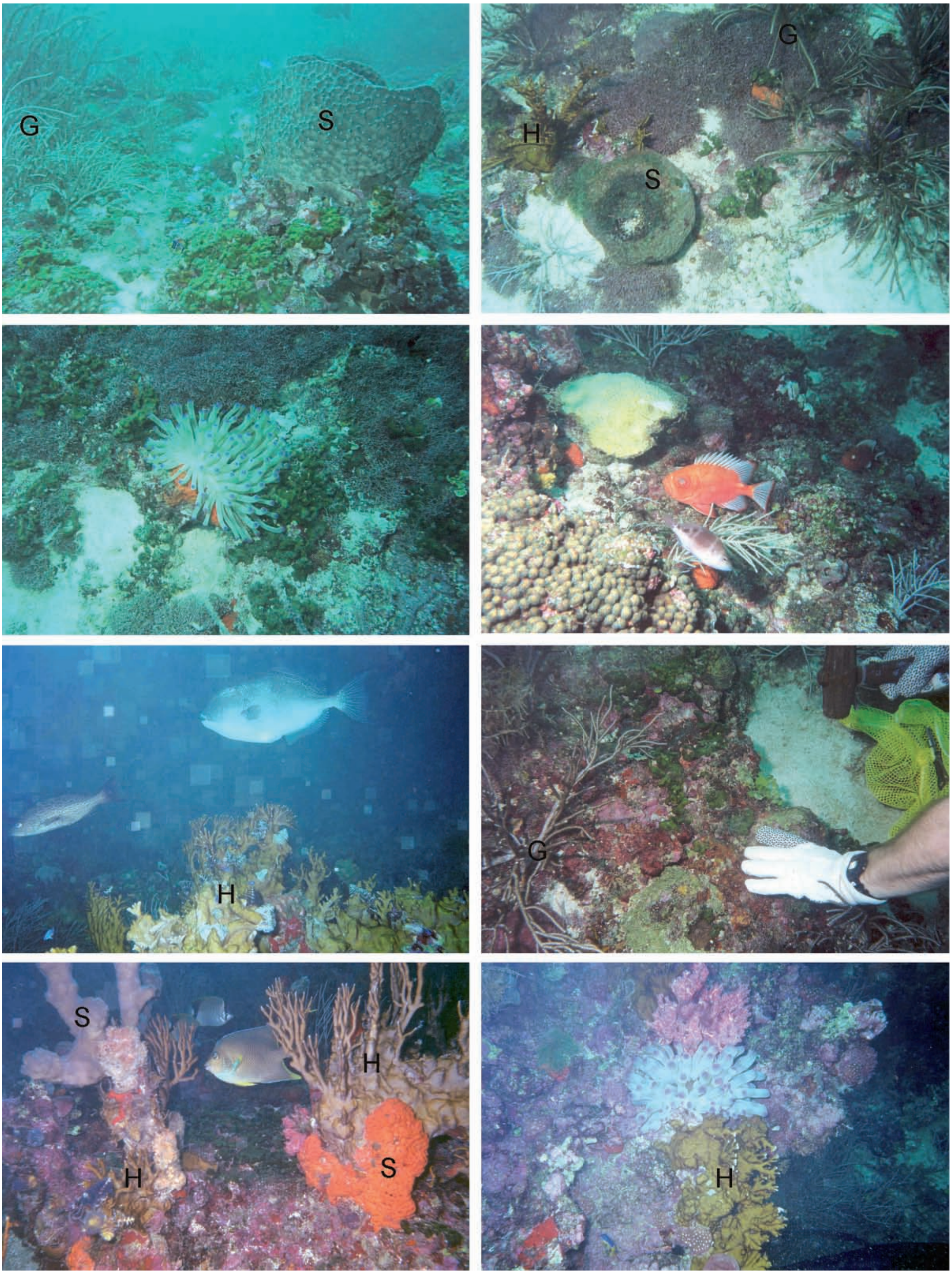

FIG. 4.6. Selected photographs of various dive sites at FMG illustrating the predominance of hydrozoans (H), soft corals (G), and sponges (S)

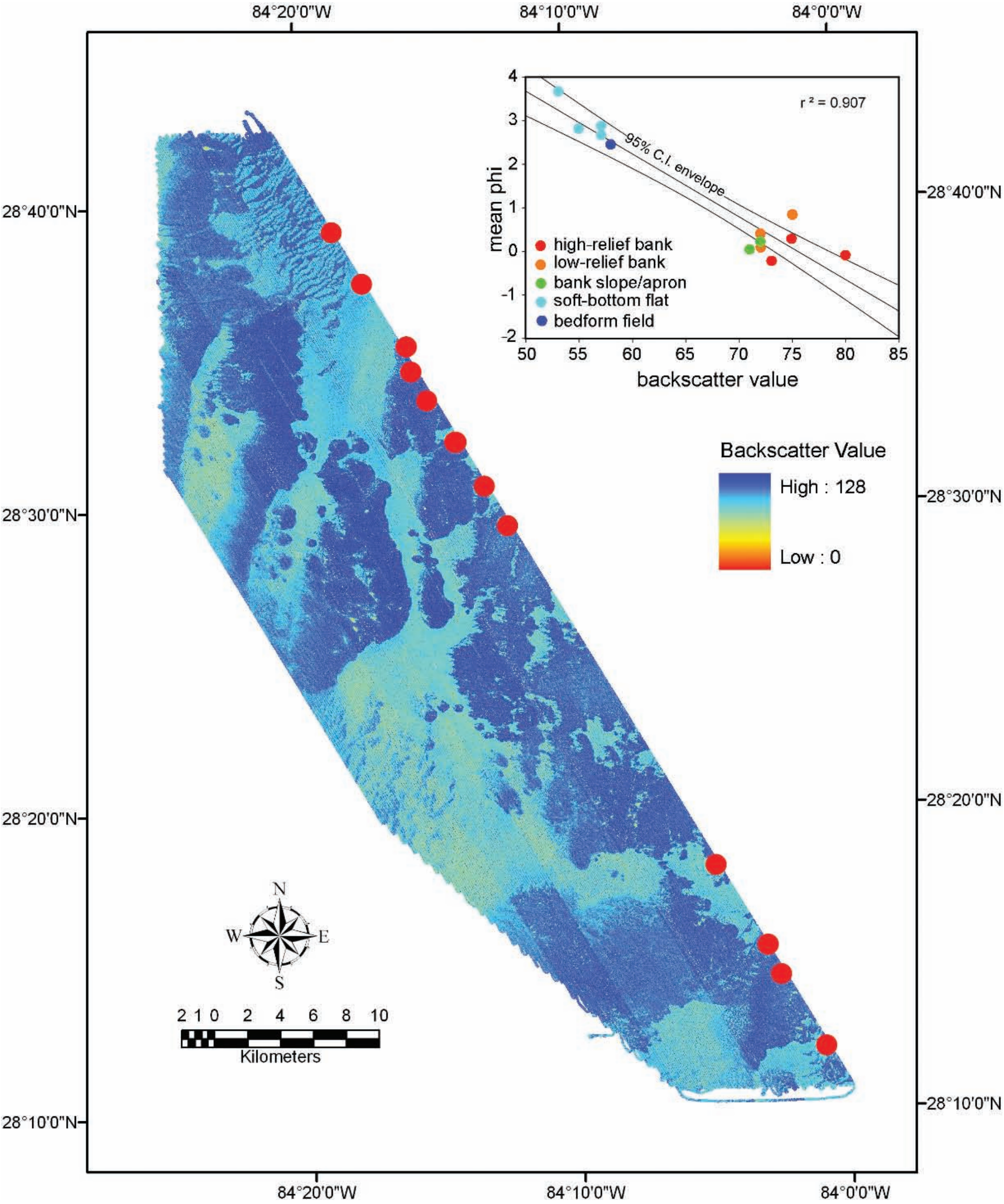

FIG. 4.7. Acoustic backscatter intensity measured with the multibeam system at FMG. Red dots indicate the location of bottom grab samples. A plot of backscatter intensity versus mean phi is shown at upper right. Low backscatter areas (light blue) consist of fine quartz and carbonate sand. High backscatter areas (dark blue) consist of very coarse carbonate shell material. Hardbottom /livebottom areas also yield high backscatter and may be distinguished based on texture

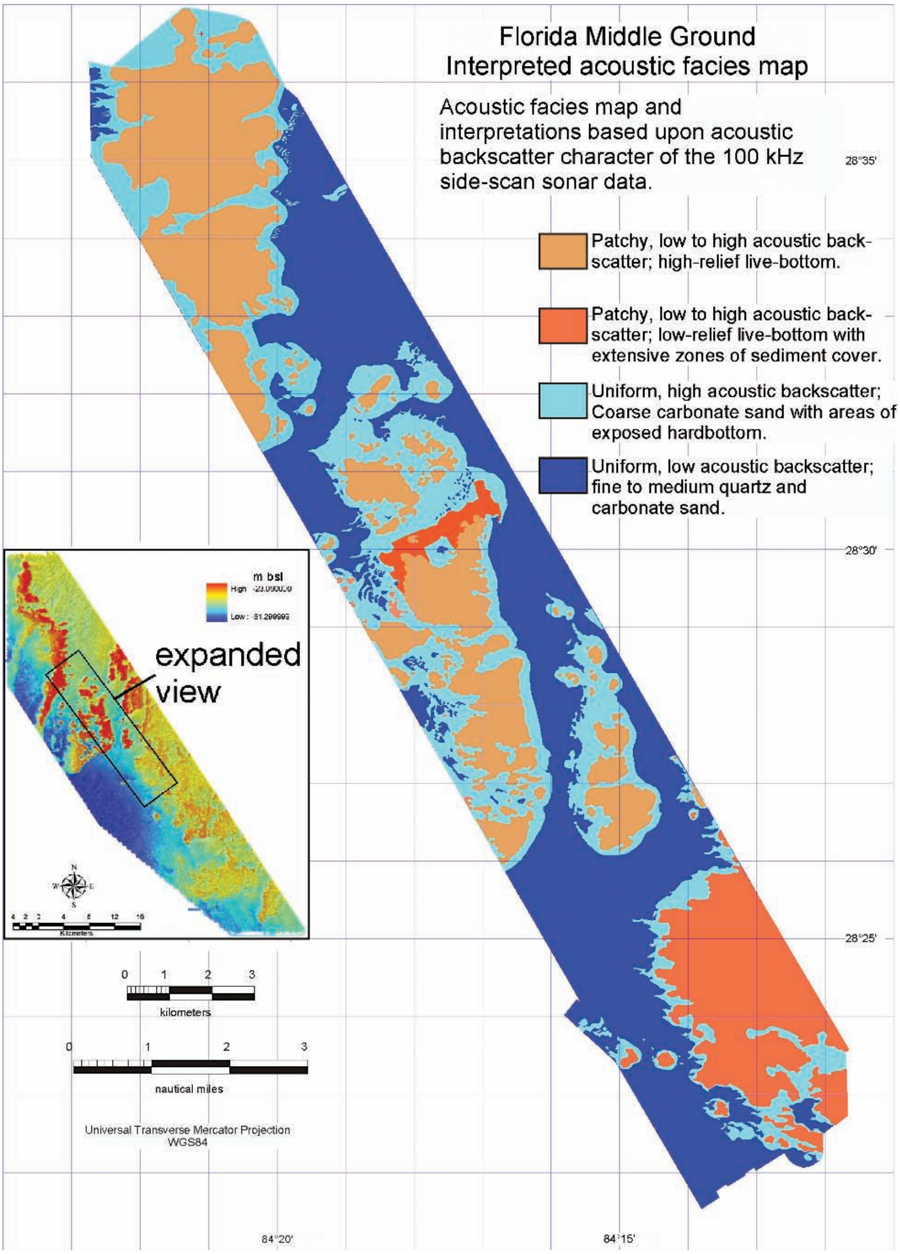

FIG. 4.8. Generalized acoustic facies map based upon backscatter intensity from side-scan sonar data at FMG

(MIS) 5 or 3 (~80 or ~40 ka), and provided recruitment sites for Holocene coral-reef development.

4.3.1.2 Biology

In 1982 a portion of the FMG was designated a Habitat Area of Particular Concern (HAPC) (Mallinson 2000) in the Coral-Coral Reef Fishery Management Plan under the Magnuson Act (Gulf of Mexico and South Atlantic Fishery Management Councils 1982). In spite of its remote location and the HAPC designation, the FMG faces environmental circumstances that reduce the biological richness. Tropical species are unable to tolerate the cool, winter temperatures while temperate organisms are excluded by the warm, summer temperatures.

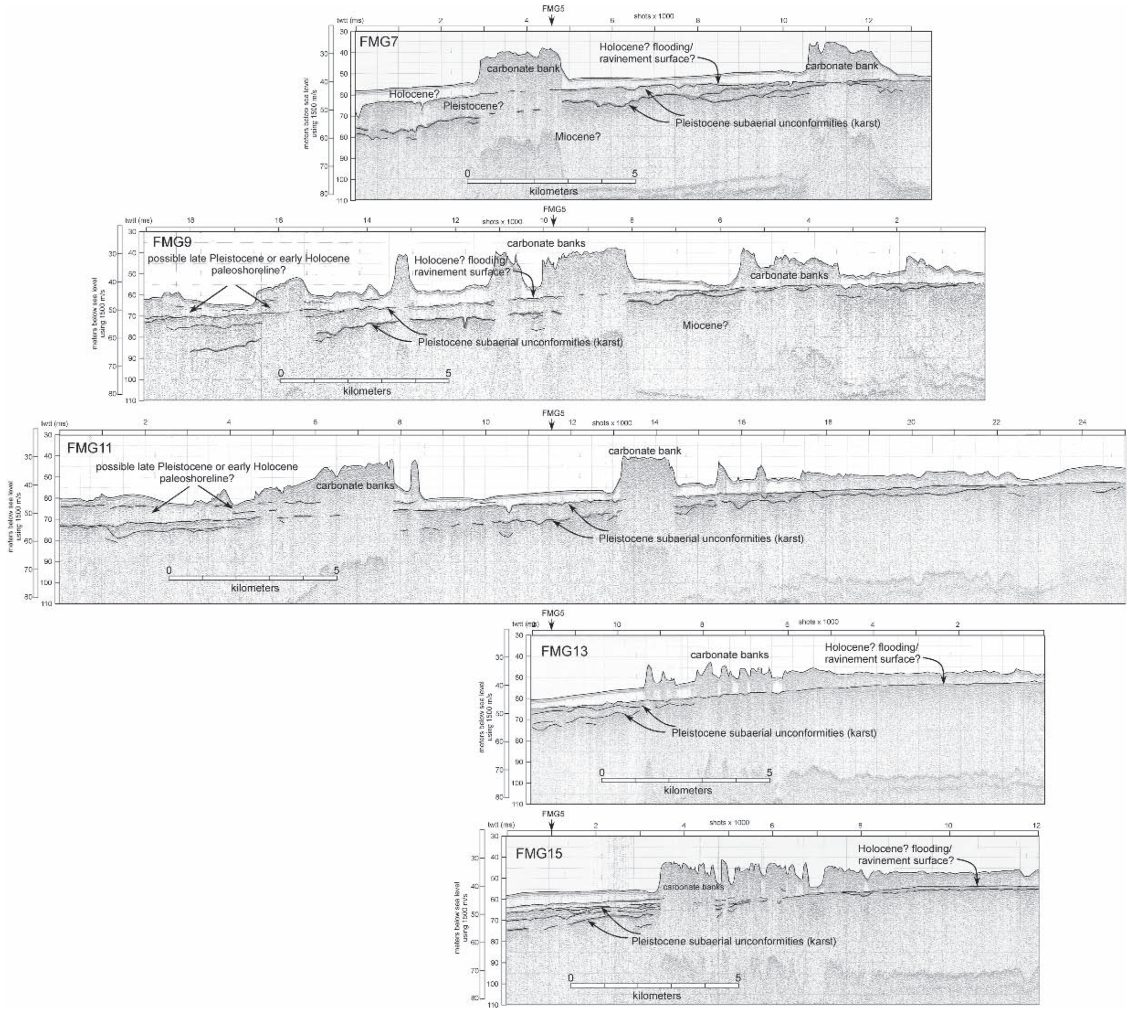

FIG. 4.9. FMG seismic profiles FMG 7, 9, 11, 13, and 15 with interpretations (see Fig. 4.2 for location)

A data buoy near the FMG reports that seawater temperature extreme ranges were 15–33°C from 1994 to 2001. The lowest extreme temperatures occurred in March and the highest in June (Fig. 4.11). Additionally, Mississippi River runoff reaches the FMG on occasion. In May 2003, a plume of Mississippi runoff covered much of the area. This water was cool to cold, reduced in salinity, silt-laden (very turbid), and polluted.

The FMG flora and fauna are eurythermic species. Algae, in particular, exhibit a seasonal pattern (Cheney and Dyer 1974) with the greatest abundance and biomass existing in the late summer and early fall. Late winter and early spring is the period of minimum algal biomass. Common tropical species include *Diadema antillarum* (black, spiny sea urchin), *Spondlus americana* (thorny oyster), *Millepora alcicornis* (fire coral), and *Hermodice carunculata* (fire worm). The area is an enclave of tropical species that co-exist with temperate species. Suspected controlling factors include the complex topographic reef structures providing a diversity of habitat or niches for these plants and animals. Eastern Gulf of Mexico rock-ledge, epibenthic communities are ephemeral due to Red Tides and thermal disturbances (Collard and D'asaro 1973; Godcharles and Jaap 1973; Lyons and Collard 1974; Lyons 1980; Jones et al. 1985). Recruitment of tropical organisms is from local sources as well as propagules that are carried from

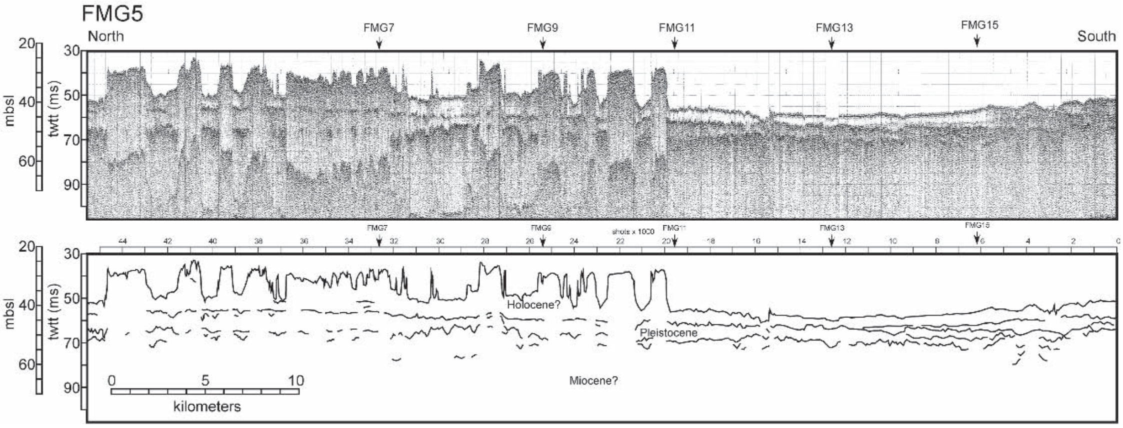

FIG. 4.10. FMG seismic profile FMG5, extending north to south over much of the high-relief hardbottom area (see Fig. 4.2 for the survey location)

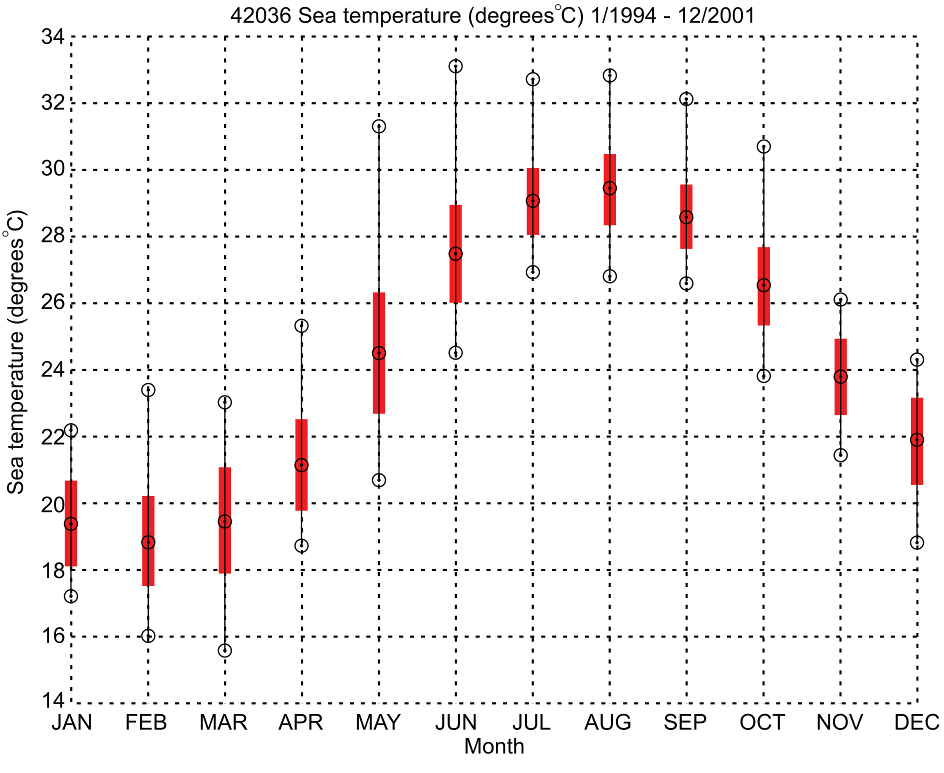

FIG. 4.11. Seawater temperature (C°), oceanographic buoy number 42036 W, 28°30'00"; N, 84°31'00", (NOAA, NDBC ,website; data inclusive 1994–2001near FMG)

the tropics to the FMG by intrusions of the Loop Current (Lee et al. 2002).

Studies in the 1970s documented 103 species of algae, 40 sponge species, 75 mollusk species, 56 decapod crustacean species, 41 polycheate species, 23 echinoderm species (Hopkins et al. 1977) and 170 species of fish (Smith et al. 1975) in the FMG. Most of the massive Caribbean reef-building Scleractinia genera (*Acropora*, *Montastraea*, *Diploria,* and *Colpophyllia)* do not occur at the

FMG (Grimm and Hopkins 1977; Grimm 1978), although it is the northern-most reef in the Gulf of Mexico with significant numbers of zooxanthellate Scleractinia. Grimm and Hopkins (1977) described faunal zones based on octocoral and stony coral (*Milleporina* and *Scleractinia*) distribution and abundance (Table 4.1) and a recent study has confirmed these associations (Coleman et al. 2005). The uppermost levels of the FMG reefs are typically horizontal with some indentations or depressions (depth to 26–28 m) and *Muricea* spp. *Dichocoenia stokesi* and *Porites porites* forma *divaricata* are the characteristic species in this habitat (Figs. 4.12, 4.13).

The slope descends from the horizontal platform to a depth of 30–36 m. Characteristic organisms in this zone include *Madracis decactis* and *Millepora alcicornis* (Figs. 4.14, 4.15). The slope margin is complex with fissures and caves supporting invertebrates, including *Stenorhyinchus seticornis* (arrow crab) and *Diadema antillarum* (Fig. 4.16), the most visible mobile invertebrate animals. The *Millepora alcicornis* occurs in dense clusters at the slope margin, and the ubiquitous purple reef fish (*Chromis scotti*) utilizes *Millepora* colonies as refuge habitat (Fig. 4.15).

Cheney and Dyer (1974) reported a marked seasonal difference in algal species richness and abundance in the FMG. In spring 2003, Rhodophyta were the most diverse and abundant phyla, comprising 62% of the species present, Chlorophyta contributed 20%, and Phaeophyta 17% (Coleman et al. 2005). Algal cover in 2003 was remarkably similar to information reported in Hopkins et al. (1977). He reported 61% of the species present were Rhodophyta, 28% Chlorophyta, and 11%

TABLE 4.1. Faunal zonation, Florida Middle Grounds (Grimm and Hopkins 1977).

Zone depth (m)	Characteristic coral assemblage	Relative position on the reef
26–28	*Muricea-Dichocoenia -Porites*	Horizontal platform
28–30	*Dichocoenia -Madracis*	Margin of the slope and horizontal platform
30–31	*Millepora*	Upper levels of the slope
31–36	*Millepora -Madracis*	Middle and lower levels of the slope

FIG. 4.12. *Muricea* spp., Octocorallia, typical of the upper surfaces of the FMG structures (Photo credit G.P. Schmahl)

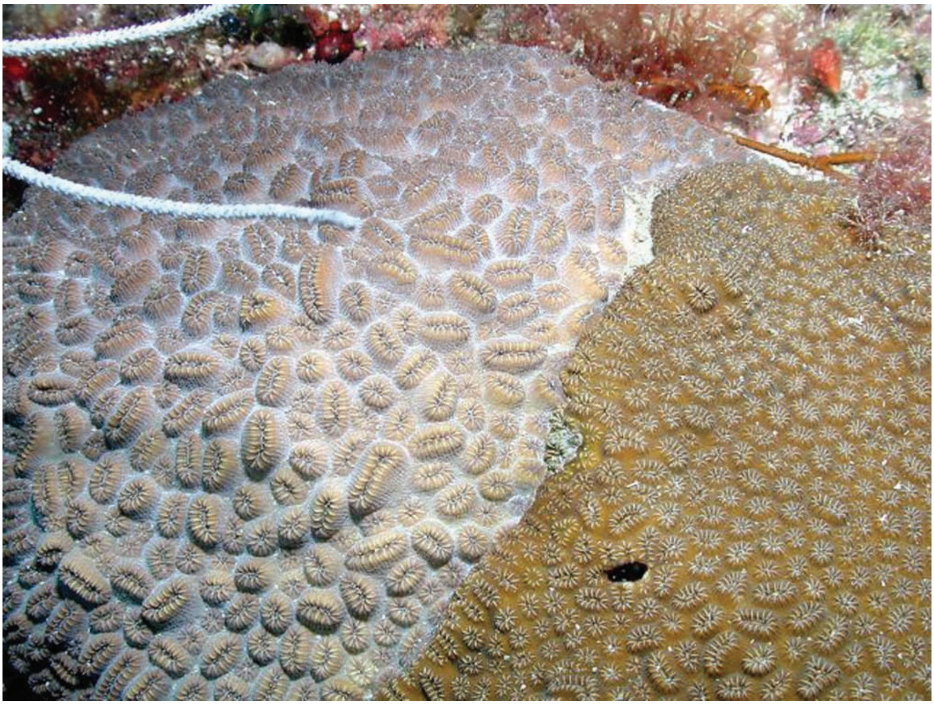

Fig. 4.13. *Dichocoenia stokesi*, Scleractinia, two colonies displaying different pigmentation at FMG. This species often is found in clusters of multiple colonies (Photo credit G.P. Schmahl)

Fig. 4.14. *Madracis decactis*, Scleractinia, FMG (Photo credit G.P. Schmahl)

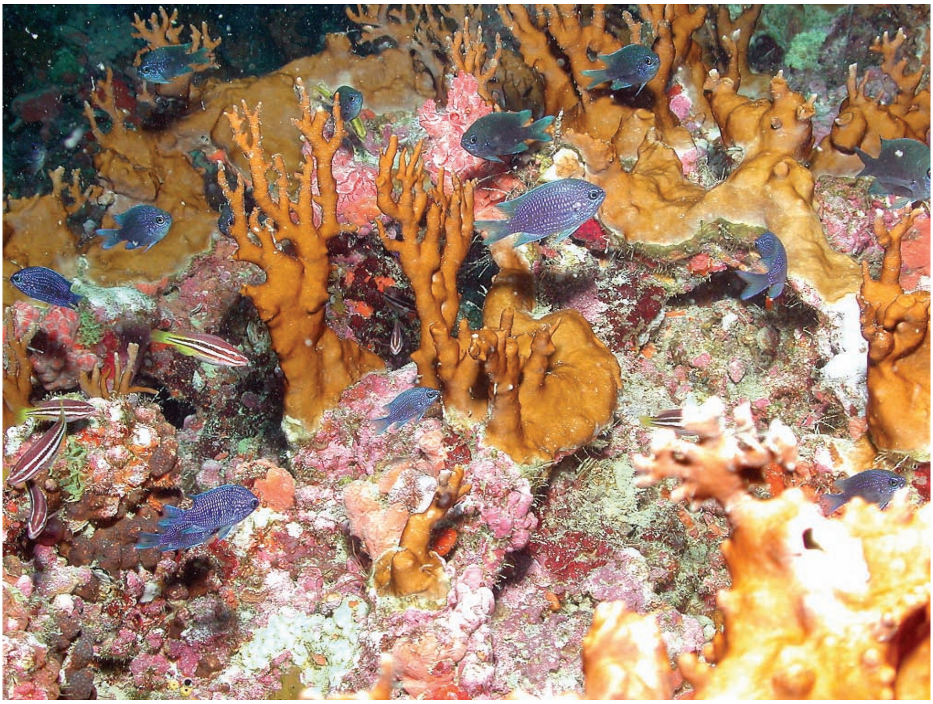

FIG. 4.15. *Millepora alcicornis*, Hydrozoa: Milleporina, with a school of purple reef fish, *Chromis scotti*, The purple reef fish is one of the most abundant fish species in the FMG (Photo credit G.P. Schmahl)

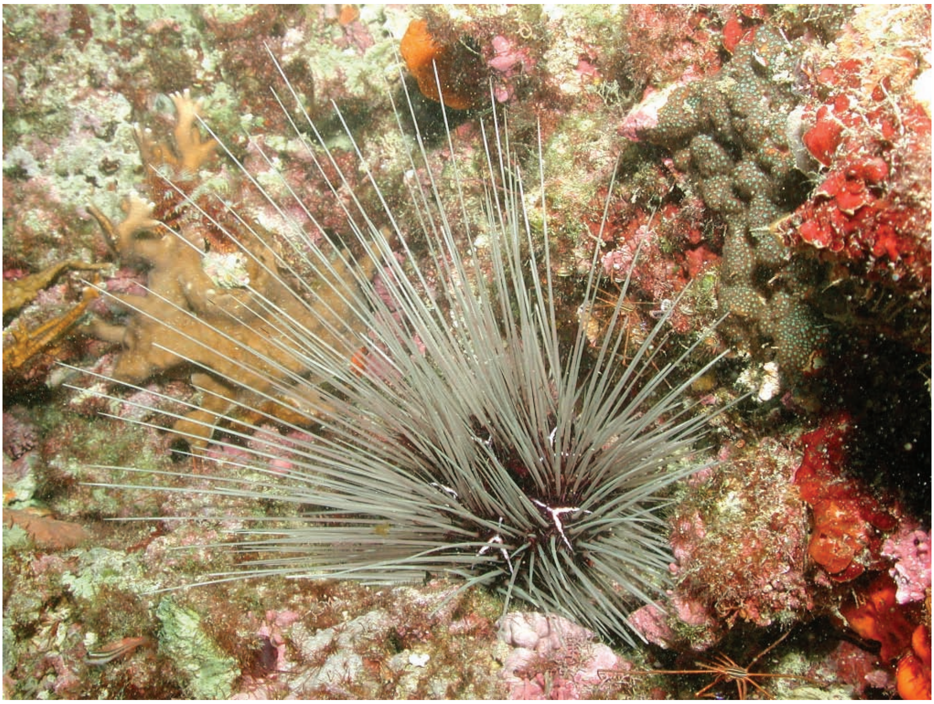

FIG. 4.16. *Diadema antillarum* (long-spine, black sea urchin), and several arrow crabs (*Stenorhyinchus seticornis*) in the back ground at FMG (Photo credit G.P. Schmahl)

were Phaeophyta. He also found that Chlorophyta often dominated in terms of biomass. Gelatinous red algae were the most conspicuous and abundant in late May 2003 (Table 4.2).

Sponges are the second most important component based on percentage cover of the FMG benthic community (Fig. 4.17). In a recent study, 32 sponge species (Table 4.3) were observed at the FMG historical sites (Coleman et al. 2005). *Pseudoceratina crassa*, *Niphates erecta*, *Amphimedon compressa*, and *Cribochalina vasculum* were the most abundant species in quadrat surveys. Sponge density ranged from 9 to12 colonies/m^2 (Table 4.4).

Octocorals are the most ubiquitous epibenthic organism on FMG reef structures, but there are only a few genera and species (Table 4.5, Figs. 4.18, 4.19; Coleman et al. 2005).

Twenty-two species of shallow-water zooxanthellate and azooxanthellate Scleractinia are known to inhabit the FMG (Tables 4.6, 4.7). *Dichocoenia stokesi* and *Meandrina meandrites* only occur in the FMG. They are not found in epibenthic communities between Naples, FL and the FMG. The other species are found throughout the eastern Gulf of Mexico in depths between 10 and 40 m (Jaap et al. 1989; Jaap and Hallock 1990). Both *D. stokesi* and *M. meandrites* are common in the Florida Keys and Dry Tortugas reefs. The FMG Scleractinian community is dissimilar to the Flower Garden Banks, the Florida Keys, and Southeast Florida (Fig. 4.20). The FMG has a greater taxonomic distinctness (Delta plus value; Fig. 4.21) than any of these other locations because the species found in the FMG come from higher-order taxonomic categories (genera, families, suborders) that have fewer species (Warwick and Clarke 2001). For example, the genera *Stephanocenia*, *Meandrina*, and *Dichocoenia* have a single species each. In contrast, the genera *Porites* and *Agaricia* have multiple species.

The FMG is the prime fishing ground in the eastern Gulf of Mexico (Steidinger et al. 1985); groupers are the principal target species (Figs. 4.22, 4.23).

TABLE 4.2. FMG benthic algae at diving stations (Coleman et al. 2005).

Species station	047	247	151	251	GGR	FR	Frequency
Kallymenia westii	XX		XX				0.33
Kallymenia sp.				XX			0.17
Halmenia floridana	XX		XX	XX			0.50
Champia salicornides	XX	XX	XX	XX			0.67
Trichogloea herveyi	XX	XX					0.33
Dictota menstrualis	XX	XX		XX		XX	0.67
Dictyota pulchella			XX				0.17
Sporolithon episporum	XX						0.17
Porlithon pachydermum	XX						0.17
Lithoththamnion reptile				XX			0.17
Lithothamnion sp.	XX						0.17
Gelidium sp.	XX						0.17
Udotea dixonii		XX		XX	XX	XX	0.67
Udotea verticulosa			XX				0.17
Codium coralinanum		XX					0.17
Codium ithmocladum		XX					0.17
Codium intertextum		XX					0.17
Halimeda discoidea		XX					0.17
Halimeda dixonii				XX			0.17
Mesohyllum mesomorphum		XX					0.17
Jania adhaerens		XX					0.17
Lithophyllum congestum		XX					0.17
Botrycladia pyriformis			XX	XX			0.33
Champia parvula				XX			0.17
Chrysymenia enteromorpha			XX	XX		XX	0.50
Chrysymenia sp.						XX	0.17
Colopermenia sinuosa			XX		XX		0.33
Rhiiplia sp.			XX				0.17
Number of taxa	9	11	9	10	2	4	

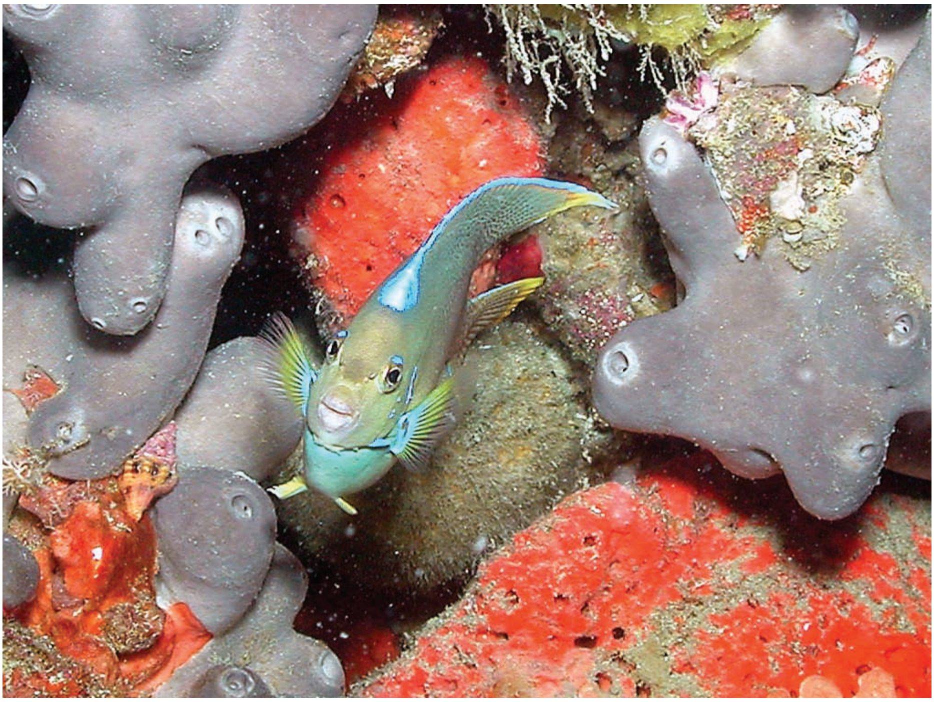

FIG. 4.17. Sponges are a dominant feature of the FMG, seen here (*Erylus formous*, grey; *Agelas clathrodes*, red) with a blue angelfish, *Holocanthus bermudensis* (Photo credit G.P. Schmahl)

TABLE 4.3. Sponge species identified from Florida Middle Grounds surveys, G. Schmahl, 2003 (Coleman et al. 2005).

Phylum Porifera		
Class Demospongiae		
Subclass Homoscleromorpha		
Order Homosclerophorida		
	Family Plakinidae	
		1. *Plakortis angulospiculatus**
Subclass Tetractinomorpha		
Order Spirophorida		
	Family Tetillidae	
		2. *Cinachyra alloclada*
Order Astrophorida		
	Family Geodiidae	
		3. *Erylus formosus*
		4. *Geodia neptuni*
Order Hadromerida		
Family Clionaidae		
		5. *Cliona delitrix**
		6. *Anthosigmella varians*
		7. *Spheciospongia vesparium**
	Family Placospongiidae	
		8. *Placospongia melobesioides*
	Family Spirastrellidae	
		9. *Spirastrella coccinea*
Order Chondrosida		
	Family Chondrillidae	
		10. *Chondrilla nucula*

(continued)

TABLE 4.3. (continued)

Subclass Ceractinomorpha		
Order Agelasida		
	Family Agelasidae	
		11. Agelas clathrodes
Order Poecilosclerida		
	Suborder Microcionina	
‘	Family Microcionidae	
		12. Clathria (Thalysias) juniperina
	Suborder Myxillina	
Family Crambeidae		
		13. *Monanchora unguiferus*
		14. *Monanchora barbadensis*
	Suborder Mycalina	
Family Desmacellidae		
		15. *Neofibularia nolitangere*[*]
	Family Mycalidae	
		16. *Mycale laxissima*
Order Halichondrida		
	Family Axinellidae	
		17. *Axinella corrugata*
		18. *Dragmacidon lunaecharta*
	Family Dictyonellidae	
		19. *Scopalina ruetzleri*
Order Haplosclerida		
	Family Callyspongiidae	
		20. *Callyspongia vaginalis*
		21. *Callyspongia armigera*
		22. *Callyspongia fallax*[*]
	Family Niphatidae	
		23. *Amphimedon compressa*
		24. *Cribrochalina vasculum*
		25. *Niphates erecta*
Order Dictyoceratida		
	Family Ircinidae	
		26. *Ircinia felix*
		27. *Ircinia campana*
		28. *Ircinia strobilina*
	Family Thorectidae	
		29. *Smenospongia aurea*[*]
Order Dendroceratida		
	Family Darwinellidae	
		30. *Aplysilla sulfurea*
Order Halisarcida		
	Family Halisarcidae	
		31. *Halisarca* sp.
Order Verongida		
	Family Aplysinidae	
		32. *Aplysina lacunosa*
		33. *Aplysina cauliformis*[*]
	Family Pseudoceratinidae	
		34. *Pseudoceratina crassa*

Smith et al. (1975) compiled a list of 170 species of fish from the area. In the 2003 study, 95 species were identified (Coleman et al. 2005) with the five most abundant species being *Chromis scotti* (purple reef fish), *Chromis rysura* (yellow reef fish), *Halichoeres bivittatus* (slippery dick), *Scarus iserti* (stripped parrot fish), and *Stegastes variabilis* (coco damselfish). The more abundant commercial food fishes

TABLE 4.4. Quadrat sponge abundance, George Schmahl, 2003 (Coleman et al 2005).

Sponge species	Site 251	Site 247	Site 151	Total	Frequency
Cinachyra alloclata	1	3	7	11	1
Erylus formosus	0	1	2	3	0.67
Geodia neptuni	2	3	0	5	0.67
Anthosigmilla varians	3	1	0	4	0.67
Placospongia melobesioides	2	0	2	4	0.67
Spirastrella coccinea	0	0	1	1	0.33
Agles clathrodes	0	2	2	4	0.67
Clathria (Thalysias) juniperina	0	0	1	1	0.33
Monanchora unguiferus	0	4	2	6	0.67
Monanchora barbadensis	2	0	0	2	0.33
Mycale laxissima	0	0	2	2	0.33
Axinella corrugata	0	0	2	2	0.33
Dragmacidon lunaecharta	1	1	0	2	0.67
Scopalina reutzleri	5	3	2	10	1
Callyspongia vaginalis	4	1	4	9	1
Callyspongia armigera	0	1	0	1	0.33
Niphates erecta	4	10	3	17	1
Amphimedon compressa	8	1	3	12	1
Cribochalina vasculum	6	1	5	12	1
Ircina felix	2	4	0	6	0.67
Ircina campana	1	0	3	4	0.67
Ircina strobilina	2	0	1	3	0.67
Aplysilla sulfurea	1	1	0	2	0.67
Halisarca sp.	0	1	0	1	0.33
Aplysina laculosa	1	0	0	1	0.33
Pseudoceratina crassa	5	10	7	22	1
Gray, encrusting on Geodia	1	1	0	2	0.67
Black ball	1	0	1	2	0.67
Hard, orange	1	4	7	12	1
Orange, ball	1	0	2	3	0.67
Brown, encrusting	1	0	0	1	0.33
Orange, Tethya	0	1	0	1	0.33
Geodia ?	0	0	2	2	0.33
Total					
Species	22	20	21	33	
Colonies	55	54	61	170	
Diversity, H'n, log base e	2.83	2.62	2.85	3.09	
Eveness, J'n	0.94	0.92	0.95	0.88	
No. of 1 m^2 quadrats	5	6	5	16	
Density, colonies m^2	11	9	12.2	10.63	

were *Lutjanus greiseus* (grey snapper), *Mycetoperca phenax* (scamp grouper), and *Epinephelus morio* (red grouper). The area is popular with commercial and recreational fishers. Compared to 30 years ago, there is a marked decline in food fish populations based on visual observations.

Scleractinian corals are a minor component, and the species are hardy, possessing the ability to survive in harsh conditions in contrast to the Florida Keys or the Caribbean. Fish communities are dominated by planktivorous species, such as *Chromis scotti*. In the Florida Keys, reef-fish communities are dominated by *Haemulidae* (grunts), *Scaridae* (parrott fish), and *Pomacentridae* (damsel fish) (Tilmant 1984). While harmful algal blooms, such as Red Tide, are uncommon in the FMG, there are unpublished reports that cold-water upwelling extirpated the benthic flora and fauna in 1977 (T. Hopkins, personal communication 2004). Coleman et al. (2005) reported that the benthic community in the same areas that Hopkins et al. (1977) studied is very similar to the pre-hypothermic disturbance community. The abundant epifaunal elements include the same species of algae,

TABLE 4.5. Octocoral observations, FMG, 2003 (Coleman et al. 2005).

Species site	151	247	251	FR	GGR
Eunicea calculata	XX	XX	XX	XX	
Muricea spp.	XX	XX	XX	XX	XX
Plexaurella spp.		XX	XX		
Pseudoplexaura spp.			XX		
Pseudopterogorgia spp.			XX		XX
Eunicea spp.			XX	XX	XX
Lophogorgia cardinalis				XX	XX
Lophogorgia hebes				XX	XX
Diodigorgia nodinifera				XX	
Pseudoplexaura wagneri				XX	

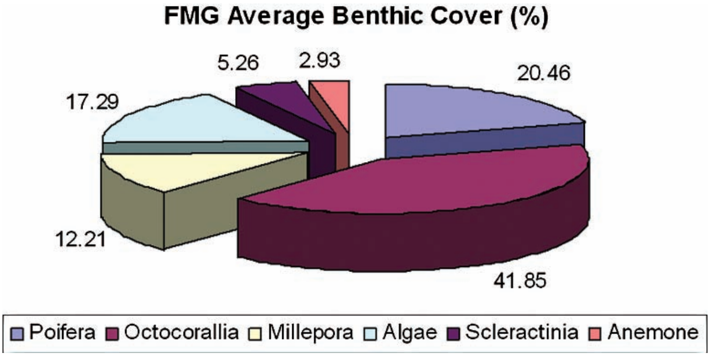

FIG. 4.18. Benthic cover contribution of algae, Porifera, Octocoralia, anemones, Millepora, and Scleractiniia, FMG, 2003, N=7 sampling sites (Coleman et al. 2005)

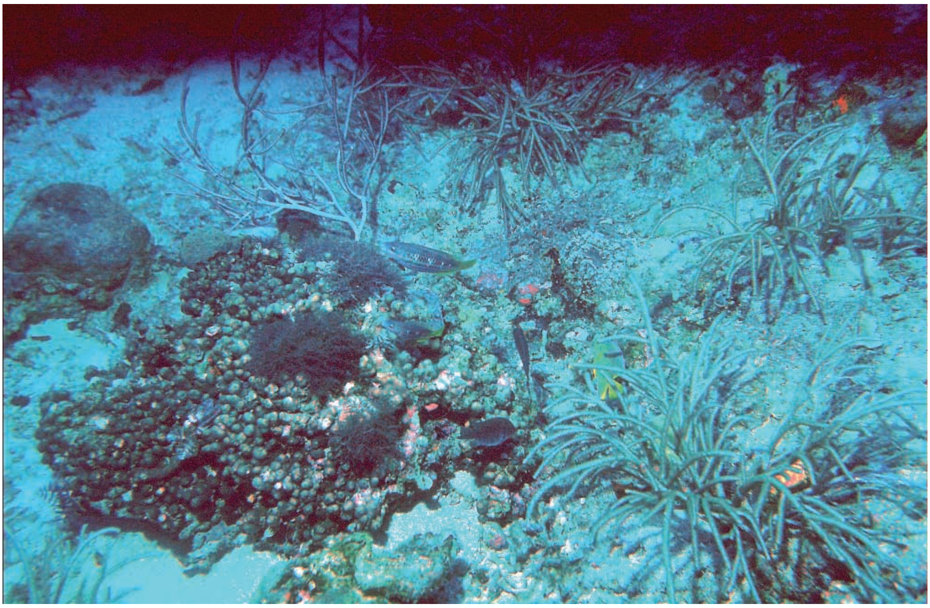

FIG. 4.19. Octocorals and *Madracis decactis*, FMG. (Photo credit T. Hopkins 1976)

TABLE 4.6. Stony corals: milleporina and scleractinia, FMG.

Order Milleporina (Hickson, 1901)		
	Family Milleporidae (Fleming, 1928)	
		1. *Millepora alcicornis* (Linné, 1758)
Order Scleractinia (Bourne, 1900)		
	Family Astrocoeniidae (Koby, 1890)	
		2. *Stephanocenia intersepta* (Lamarck, 1816)
	Family Pocilloporidae (Gray, 1847)	
		3. *Madracis decactis* (Lyman, 1857)
		4. *Madracis pharensis* (Heller, 1868)
	Family Agariciidae (Gray, 1847)	
		5. *Agaricia fragilis* (Dana, 1846)
	Family Siderastreidae (Vaughan and Wells, 1943)	
		6. *Siderastrea radians* (Pallas, 1766)
		7. *Siderastrea siderea* (Ellis and Solander, 1786)
	Family Poritidae (Gray, 1842)	
		8. *Porites porites divaricata* (LeSueur, 1821)
		9. *Porites branneri* (Rathbun, 1888)
	Family Faviidae (Gregory, 1900)	
		10. *Manicina areolata* (Linné, 1758)
		11. *Solenastrea hyades* (Dana, 1846)
	Family Rhizangidae (D'Orbigny, 1851)	
		12. *Astrangia poculata* (Ellis and Solander, 1786)
	Family Oculinidae	
		13. *Oculina diffusa* (Lamarck, 1816)
		14. *Oculina robusta* (Pourtalès, 1871)
	Family Meandrinidae (Gray, 1847)	
		15. *Dichocoenia stokesii* (Milne Edwards and Haime, 1848)
		16. *Meandrina meandrites* (Linné, 1758)
	Family Mussidae (Ortman, 1890)	
		17. *Scolymia lacera* (Pallas, 1766)
		18. *Scolymia cubensis* (Milne Edwards and Haime, 1849)
		19. *Isophyllia sinuosa* (Ellis and Solander, 1786)
	Family Carophylliidae (Vaughan and Wells, 1943)	
		20. *Cladocora arbuscula* (LeSueur, 1821)
		21 *Phyllangia americana* (Milne Edwards and Haime, 1849)
	Family Dendrophylliidae (Gray, 1847)	
		22 *Balanophyllia floridana* (Pourtalès, 1868)

sponges, octocorals, and stony corals (*Millepora* and Scleractinia) that were reported in 1977.

4.4 Small Bank Reefs

Situated along the south Florida margin are three small carbonate banks, Dry Tortugas, Tortugas Bank, and Riley's Hump located ~120 km west of Key West (Figs. 4.1, 4.24–4.28). They have ~40 m of relief, extend ~25 km across, and reside in ~20–30 m water depth. The Dry Tortugas, the largest of the three, does support small sandy cays and shallow living coral reefs (Vaughan 1914; Shinn et al. 1989; Mallinson et al. 1999, 2003). These banks constitute the western extent of the rimmed margin which defines the Florida Keys reef tract. Further to the west, the south Florida margin transitions from a rimmed platform to a carbonate ramp (Jarrett 2003; Jarrett et al. 2005). The morphologic, seismic, and core data all indicate that these banks are reef edifices and have formed by smaller patch

TABLE 4.7. Abundance of stony Corals, FMG, May 2003 (Coleman et al. 2005).

Species site	147	247	151	251	GGR	Total	Frequency
Madracis decactis	9	0	15	14	25	63	0.80
Millepora alcicornis	15	9	13	5	1	43	1
Dichocoenia stokesii	2	1	14	3	0	20	0.80
Scolymia cubensis	0	0	1	6	0	7	0.40
Porites porites divaricata	0	0	3	0	0	3	0.20
Oculina diffusa	0	1	1	0	0	2	0.40
Siderastrea radians	0	0	0	2	0	2	0.20
Porites branneri	0	0	1	1	0	2	0.40
Scolymia lacera	0	0	1	0	0	1	0.20
Madracis pharensis	0	0	0	1	0	1	0.20
Stephanocenia intersepta	0	0	0	0	1	1	0.20
Oculina robusta	0	0	0	0	1	1	0.20
Total							
Number of species	3	3	8	6	4	12	
Number of colonies	26	11	49	32	28	146	
Diversity H’n, log base e	0.88	0.60	1.56	1.49	0.41	1.53	
Eveness, J’n	0.80	0.55	0.75	0.83	0.59	0.61	
No. of 1 m^2 quadrats	9	5	6	8	5	33	
Density, colonies m^2	2.88	2.20	8.17	4.00	5.60	4.42	

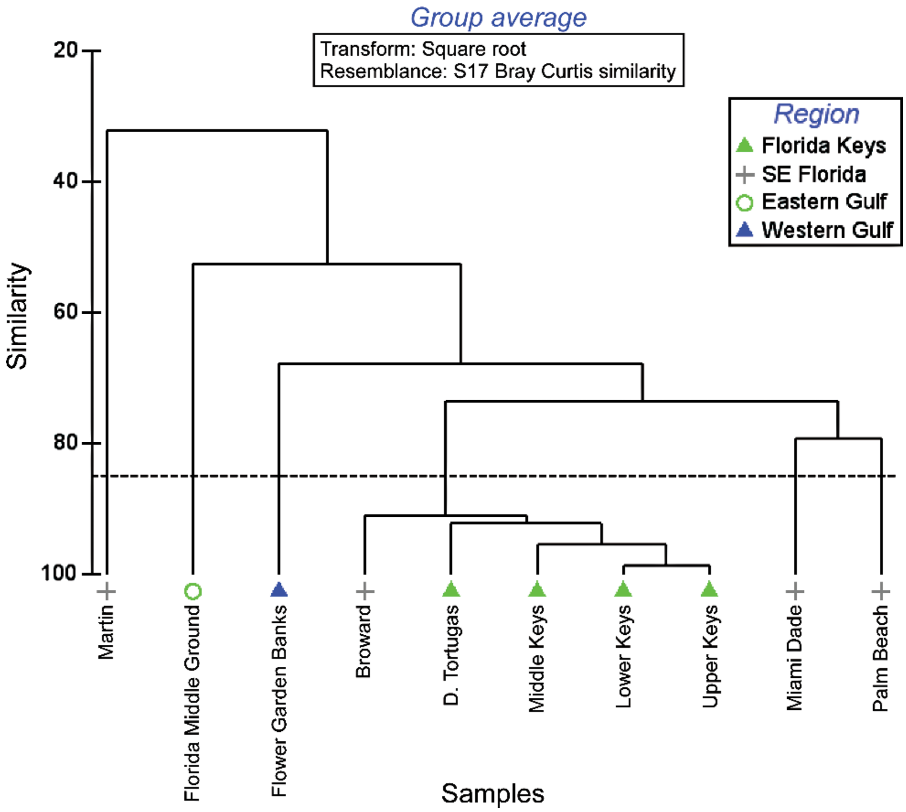

FIG. 4.20. Dendrogram, classification of zooxanthellate Scleractinia, FMG, Florida Keys, Dry Tortugas, Southeast Florida, and the Flower Garden Banks using Bray Curtis Similarity Coefficient and group average sorting to generate the clusters

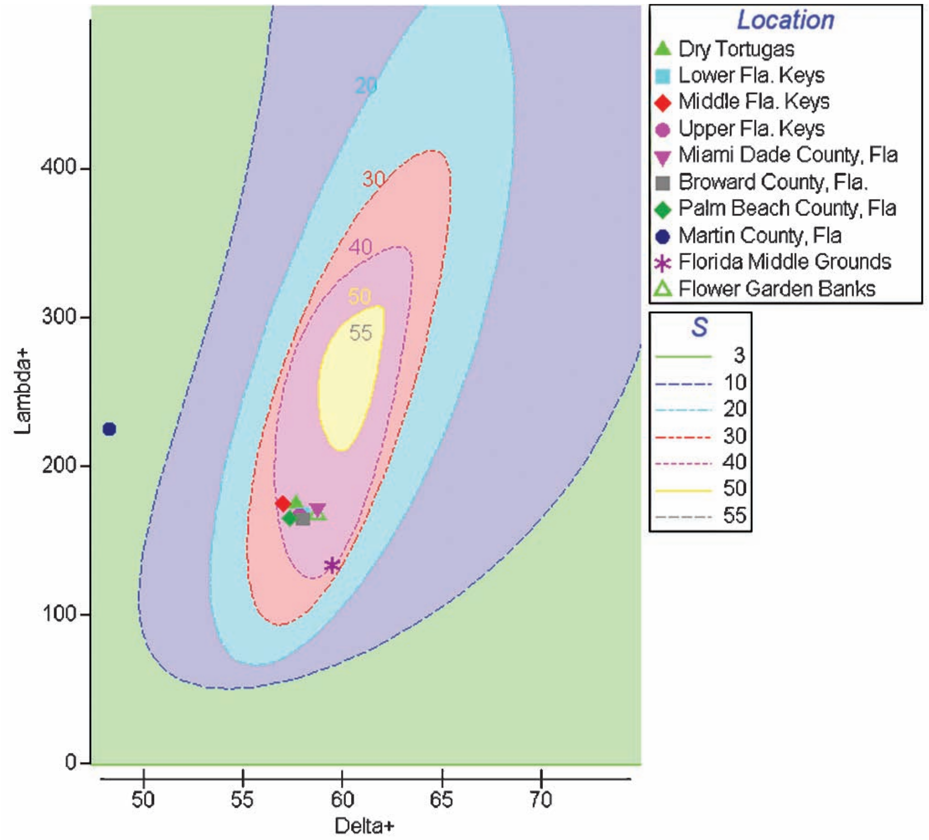

FIG. 4.21. Taxonomic Distinctness (δ +) and Taxonomic Variability (λ +) for the zooxanthellate scleractinia: FMG, Florida Keys, Dry Tortugas, Southeast Florida, and Flower Garden Banks

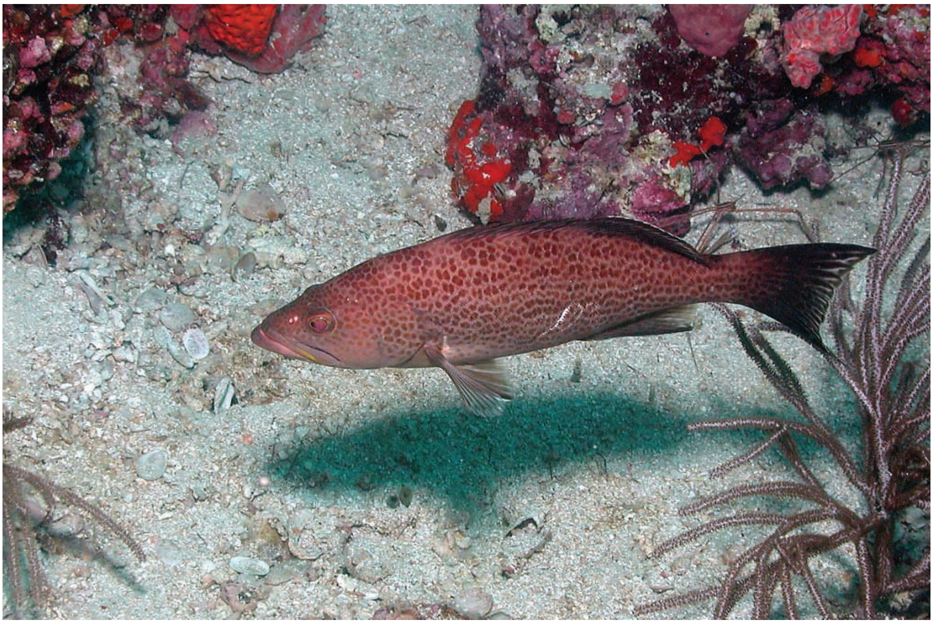

FIG. 4.22. Scamp grouper, *Mycetoperca phenax*, FMG (Photo credit G.P. Schmahl)

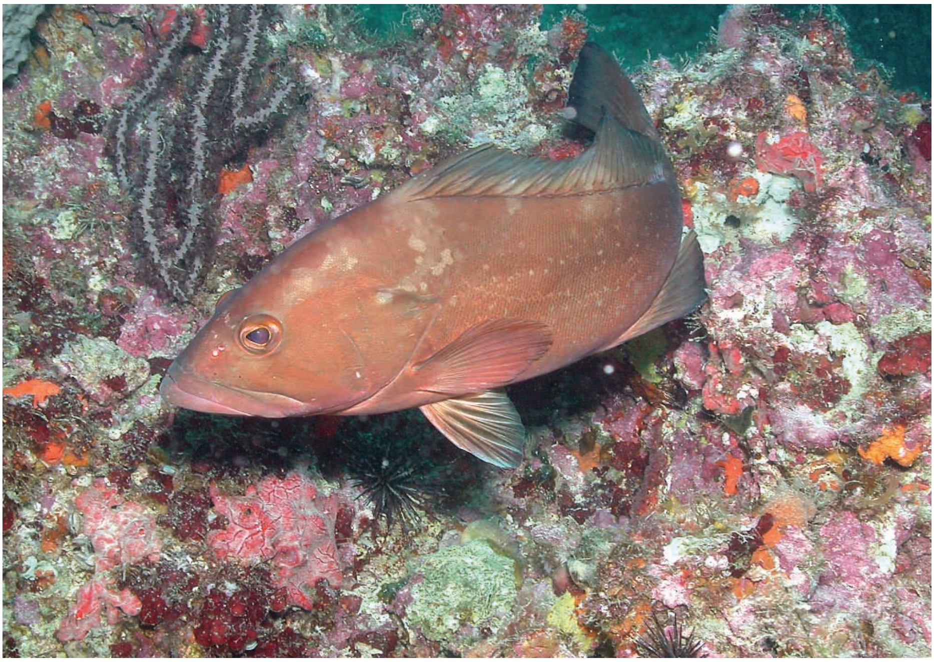

Fig. 4.23. Red grouper, *Epinephelus morio*, FMG (Photo credit G.P. Schmahl)

reefs coalescing and interior basins filling with reef-generated sediment. Radiocarbon age dating further indicates that a ~10 m thick Holocene reef, commencing as early as 9.6 ka, rests unconformably on top of a Pleistocene reef that maybe as much as 20 m in thickness (Fig. 4.25). The 9.6 ka ^{14}C date from Tortugas Bank represents the oldest Holocene date obtained from corals in the Florida Keys.

Mallinson et al. (2003) presented a keep-up, catch-up, give-up scenario (Neumann and MacIntyre 1985) whereby the topographically lower banks were stressed by rapid rates of sea-level rise (Fig. 4.29). As a result, coral-reef growth “steps back” to the next-higher paleo-topographic high. They also proposed that reef-growth demise on Tortugas Bank at 4.2 ka might have been climate-related as a result of decreased salinity, increased nutrients, and increasingly turbid waters emanating from enhanced Mississippi River discharge starting about that time due to a more humid mid-continent climate.

4.5 Reefs and Paleoshorelines

Previous workers have shown that past sea-level stillstands have produced important paleoshorelines along the west Florida shelf (Locker et al. 1996; Jarrett 2003; Jarrett et al. 2005). These shorelines have been preserved because they have been constructed from carbonate sand-sized sediments, which cement rapidly in the shallow marine and freshwater/salt-water groundwater transition. Indeed, bottles and beer cans are seen tightly embedded in newly formed limestone indicating the speed of this process (E.A. Shinn, personal communication 2007). So, when a beach/dune complex is generated during a brief sea-level stillstand, it may be largely preserved during the ensuing sea-level rise as a result of pervasive cementation. This drowned, intact shoreline then becomes a rocky substrate surrounded by finer-grained, uncemented sediments (Locker et al. 1996) and provides a surface upon which a coral reef could form.

4.5.1 The Deep, Light-dependent Reef at Pulley Ridge

4.5.1.1 Geology

Southern Pulley Ridge (Fig. 4.30) presents an ideal example of a coral reef that formed on

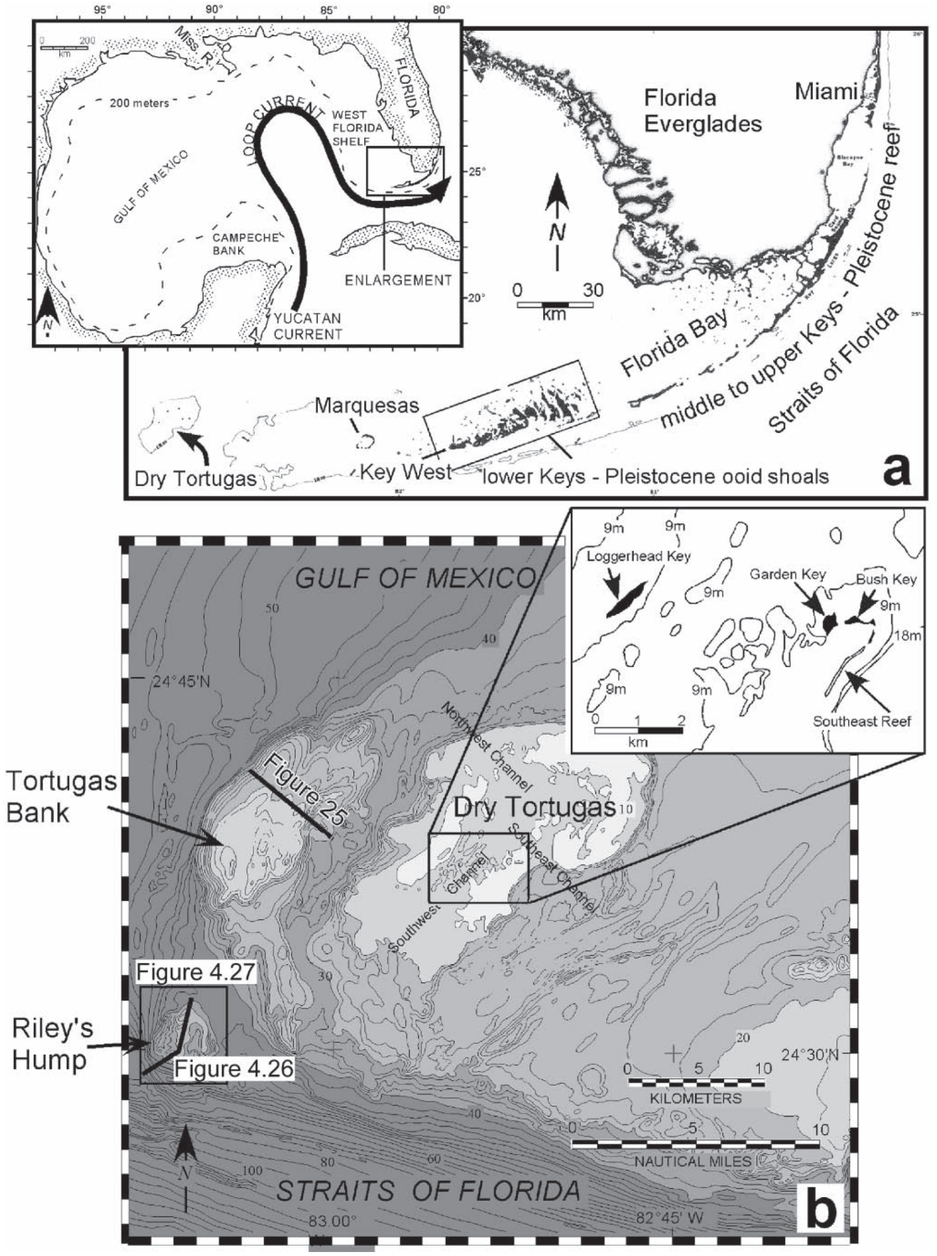

FIG. 4.24. Maps showing the location and generalized bathymetry of the Dry Tortugas, its associated keys, Tortugas Bank, and Riley's Hump. Locations of seismic lines are shown (After Fig. 1 of Mallinson et al. 2003, reproduced by permission of Elsevier)

cemented, coastal carbonate sedimentary deposits (Jarrett 2003; Jarrett et al. 2005). Pulley Ridge is a ~300 km long multiple-ridge complex that lies between 60–90 m water depth and extends N–S along the west Florida outer shelf (Fig. 4.1). Along its southernmost 30 km portion, multibeam bathymetry reveals an intact barrier island featuring multiple beach ridges, recurved spits, closed-off tidal inlets, cat's eye ponds, and a cuspate foreland – all features found on modern barrier

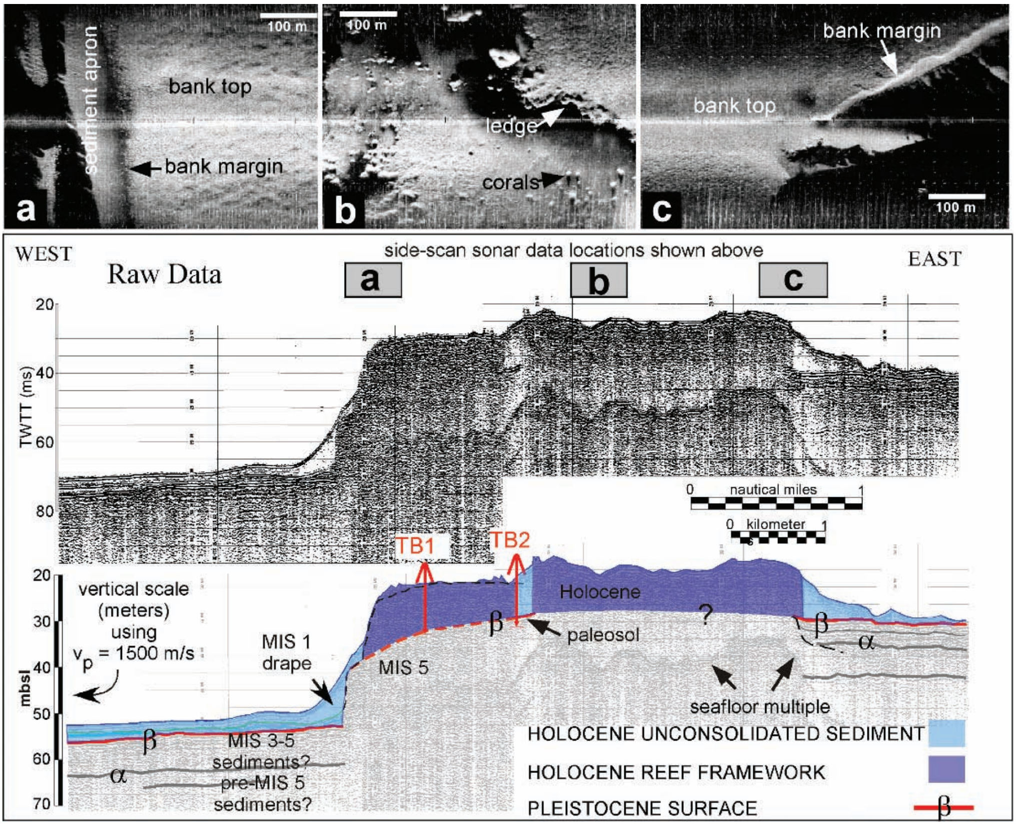

Fig. 4.25. High-resolution seismic profile of Tortugas Bank with interpretation and locations of drill sites TB1 and TB2 and side-scan sonar data (panels a, b, and c). Locations of side-scan data shown in boxes above reef bank. Dark shades of gray in side-scan data represent low back-scatter corresponding to muddy sands. Lighter shades in side-scan data represent high back-scatter corresponding to live-bottom communities, sand, and exposed rock (After Fig 4. of Mallinson et al. 2003; reproduced by permission of Elsevier Ltd.)

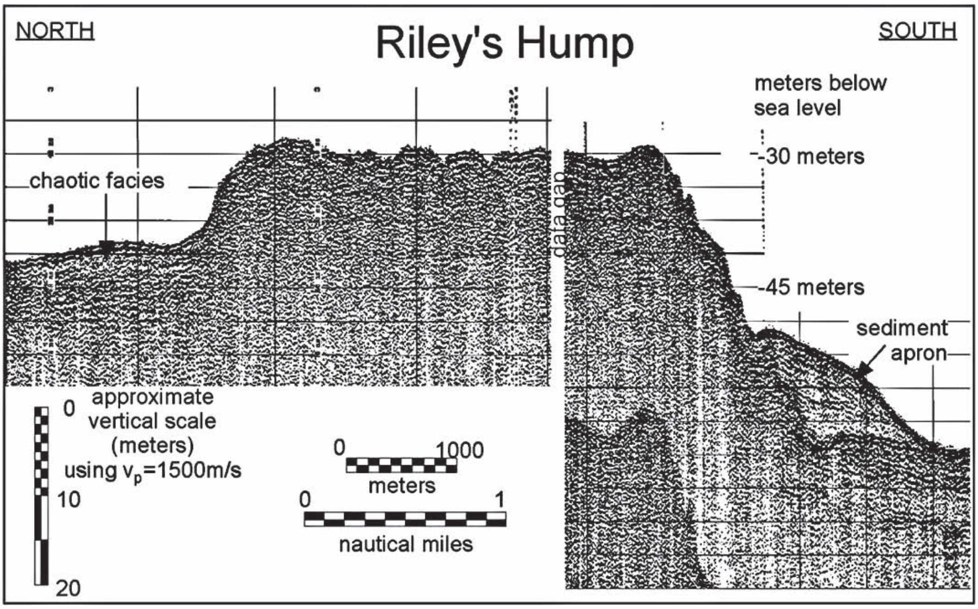

Fig. 4.26. High-resolution seismic profile across Riley's Hump revealing steep reef front and sediment -debris apron at base (After Fig. 6 of Mallinson et al. 2003; reproduced by permission of Elsevier)

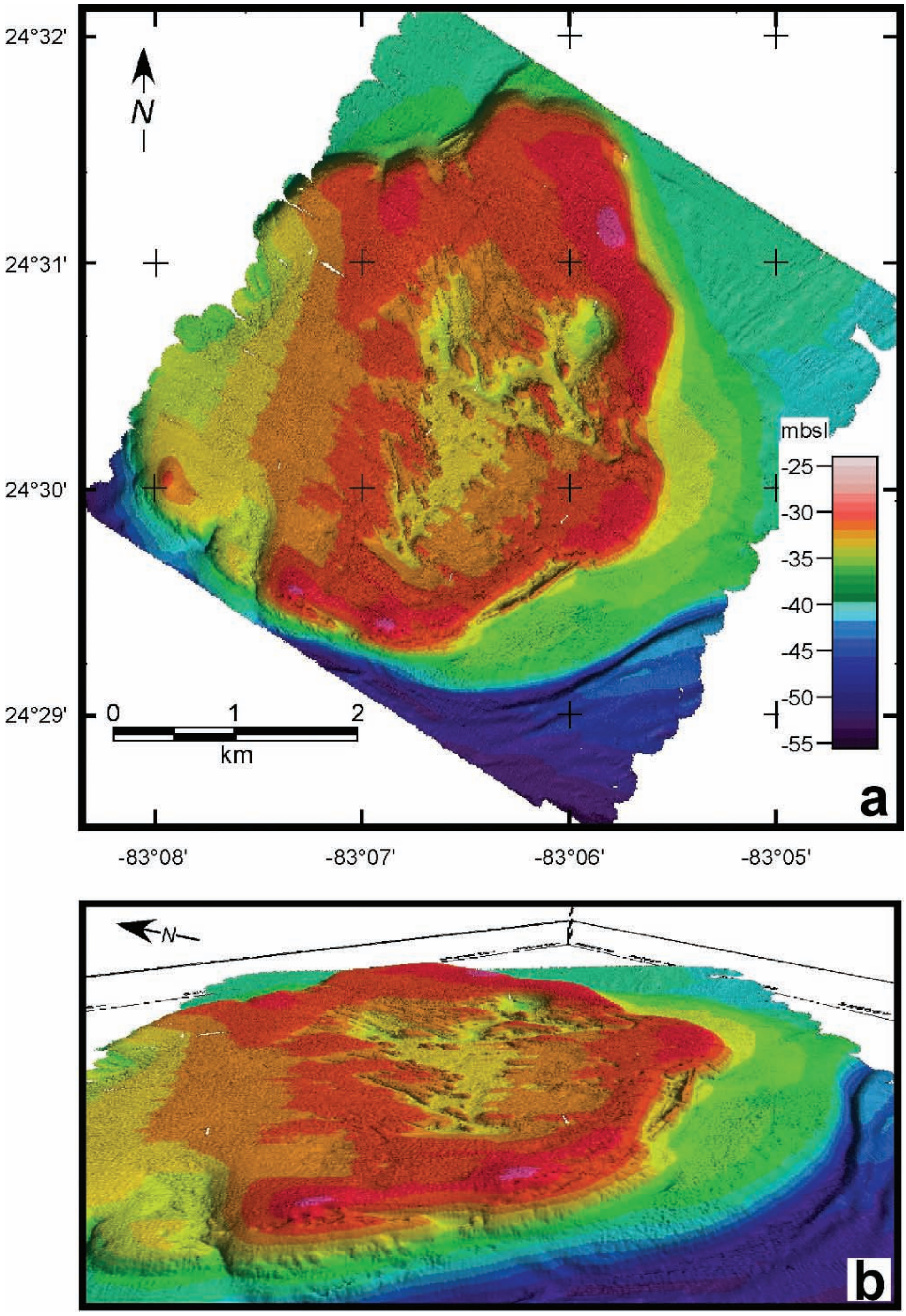

FIG. 4.27. (**a**) Plan view of 300 kHz multibeam bathymetry of Riley's Hump with shading from artificial light source from SE. (**b**) 3D perspective of same data looking towards N55E with 10× vertical exaggeration (after Fig. 7 of Mallinson et al. 2003; reproduced by permission of Elsevier)

islands (Figs. 4.30–4.32). Observations from submersibles and video imagery from ROV-mounted cameras show bedded, rocky outcroppings (Fig. 4.32). These outcroppings are identical to those studied by Locker et al. (1996) at the similar depths located approximately 150 km to the east seaward of the south-facing Florida Keys reef tract just SW of Key West. Rock samples retrieved from this eastern area

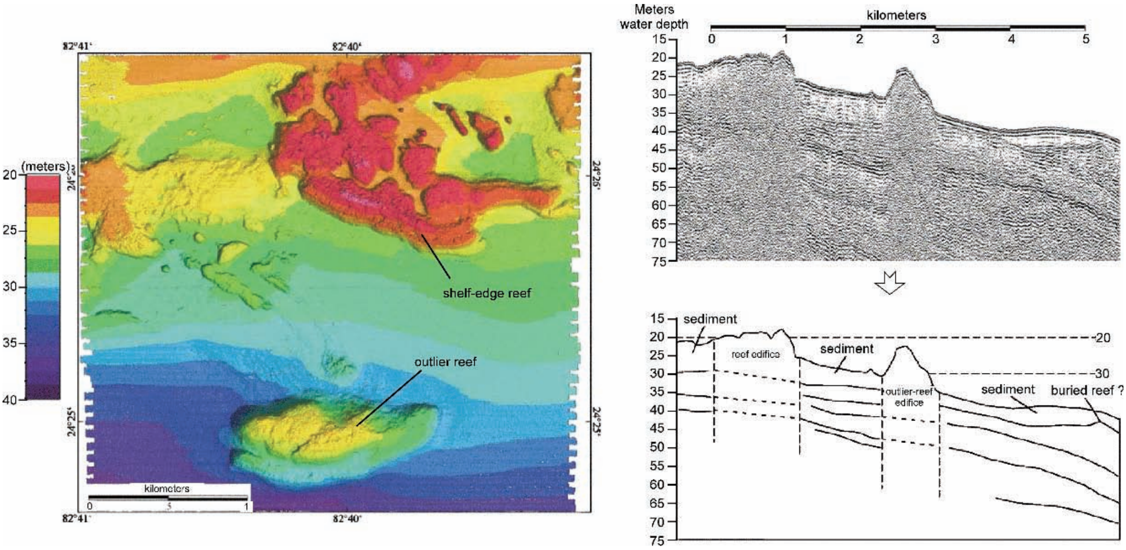

FIG. 4.28. Multibeam and high-resolution seismic images of shelf-edge and outlier reef along southern margin of the Florida Platform. Multibeam image reveals morphologic complexity of this bank reef. Seismic data show sediment bodies in between the shelf-edge reef and the outlier reef. Seaward of the outlier reef is a buried reef

are very-well sorted, finely-laminated oolitic grainstones identical to eolianites seen in the Bahama Islands (Kindler 1992). These rocks were cemented in the fresh groundwater vadose zone based upon cement mineralogy and texture and yield ^{14}C AMS (accelerator mass spectrometer) dates (just dating outer ooid lamellae) ranging from 14.5 to 13.8 ka (Locker et al. 1996). These cements indicate that the marine sediments were ultimately deposited as subaerial, coastal sand dunes formed during multiple, temporary stillstands between Marine Isotopic Stage (MIS) 2 and 1 as the Laurentide Ice Sheet was melting in a non-linear manner. We conclude that the drowned, but intact, barrier-island forming southern Pulley Ridge is a contemporary western extension of these shorelines found off Key West.

At some point after the deposition, cementation, and flooding of the barrier island, when warmer water temperatures due to climatic amelioration and oligotrophic water from the Loop Current intrusions bathed this barrier-island substrate, a coral reef formed (Fig. 4.33a–c) (Jarrett et al. 2005). Since there are no rock cores from Pulley Ridge we do not know when this reef initiation occurred. However, because the underlying barrier-island geomorphology is so easily seen in the multibeam imagery, we conclude that the reef cover is very thin, probably no thicker than 1–2 m. This means that, in geologic terms, this reef is a biostrome (laterally extensive) and not a bioherm (vertical framework constructed) (Jarrett et al. 2005). Additionally, this suggests that the reef is very slow growing (~14 cm/ka over past 14 ka), is relatively young (formed in the past ~6 ka) or a combination of both.

4.5.1.2 *Biology*

The depth of southern Pulley Ridge (~65–70 m) precludes reef characterization by the conventional methods for shallow reefs using SCUBA. Even tech divers using mixed gasses have only 20 min bottom time for sampling and observations. We characterized the seafloor using a combination of towed camera photos and analytical methods used on shallow reefs. More than 1,000 vertical bottom photographs were taken with SeaBOSS, a towed, still-photography and sampling system developed by the USGS (Valentine et al. 2000; Blackwood et al. 2000). The photographs were taken along 14 transects, each a kilometer or longer in length (Fig. 4.30). The scale of Pulley Ridge reef, approximately 5 × 15 km, requires much longer transects (10–100 times) than those used for shallow-water reef surveys. At this

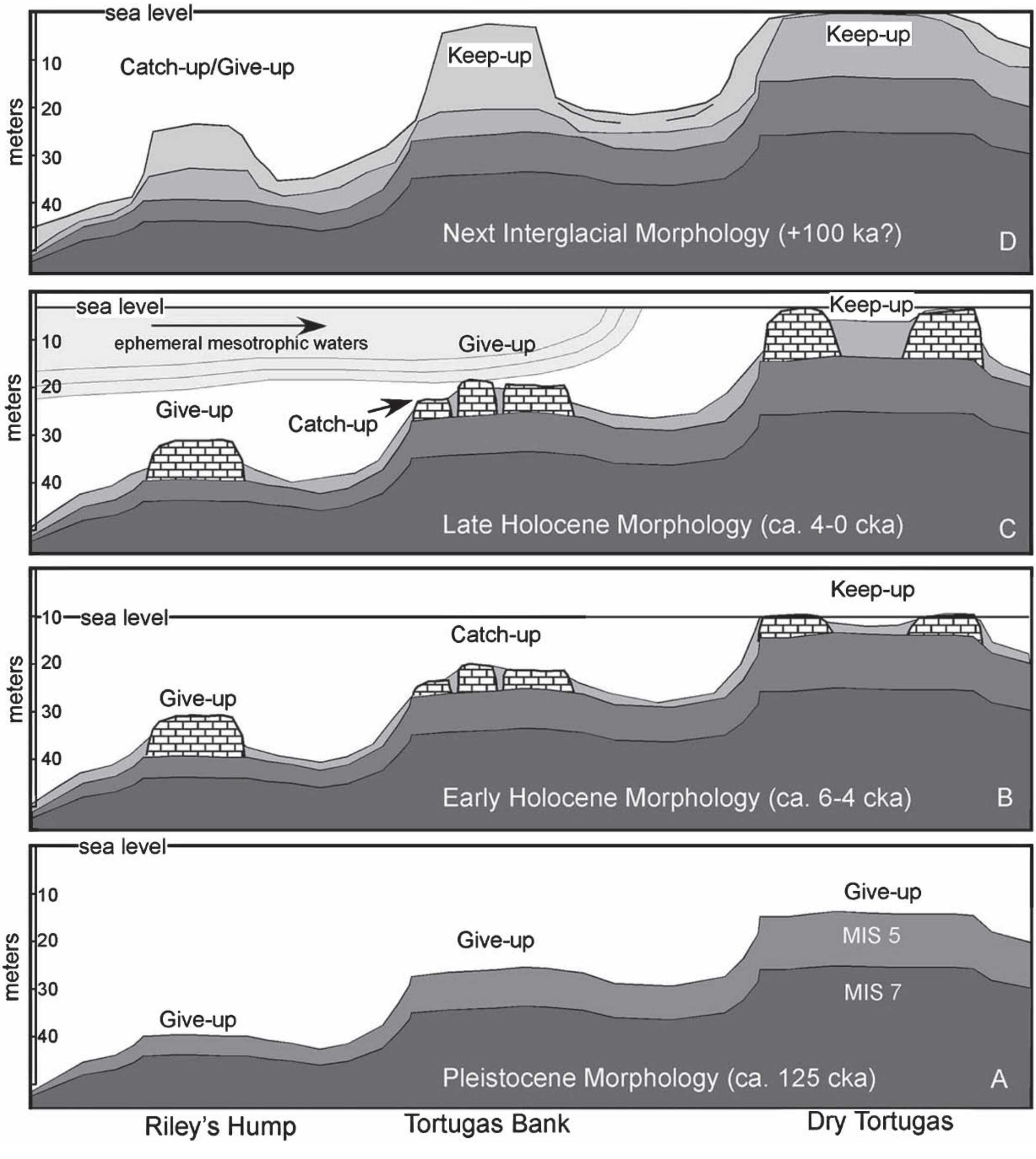

Fig. 4.29. Cross-section of Tortugas Bank, Dry Tortugas, and Riley's Hump with chronostratigraphic framework illustrated. Series of diagrams through time illustrate successive phases of development in response to sea-level changes. Each bank aggrades incrementally during successive sea-level events. Upon drowning of the lower banks (Riley's Hump and Tortugas Bank) corresponding to high rates of sea-level rise, the reef growth back-stepped to an available edifice occurring at an elevation commensurate with slower sea-level rise (Dry Tortugas). Tortugas Bank may have been influenced by the incursion of mesotrophic water from Mississippi River discharge (After Fig. 11 of Mallinson et al. 2003; reproduced by permission of Elsevier)

scale, southern Pulley Ridge is equivalent to a sector of the Florida Keys reefs, and a transect measures a site in the terminology of Murdoch and Aronson (1999). Figures 4.34 and 4.35 illustrate the common stony corals photographed by SeaBOSS. The entire data set is available in Cross et al. (2004, 2005).

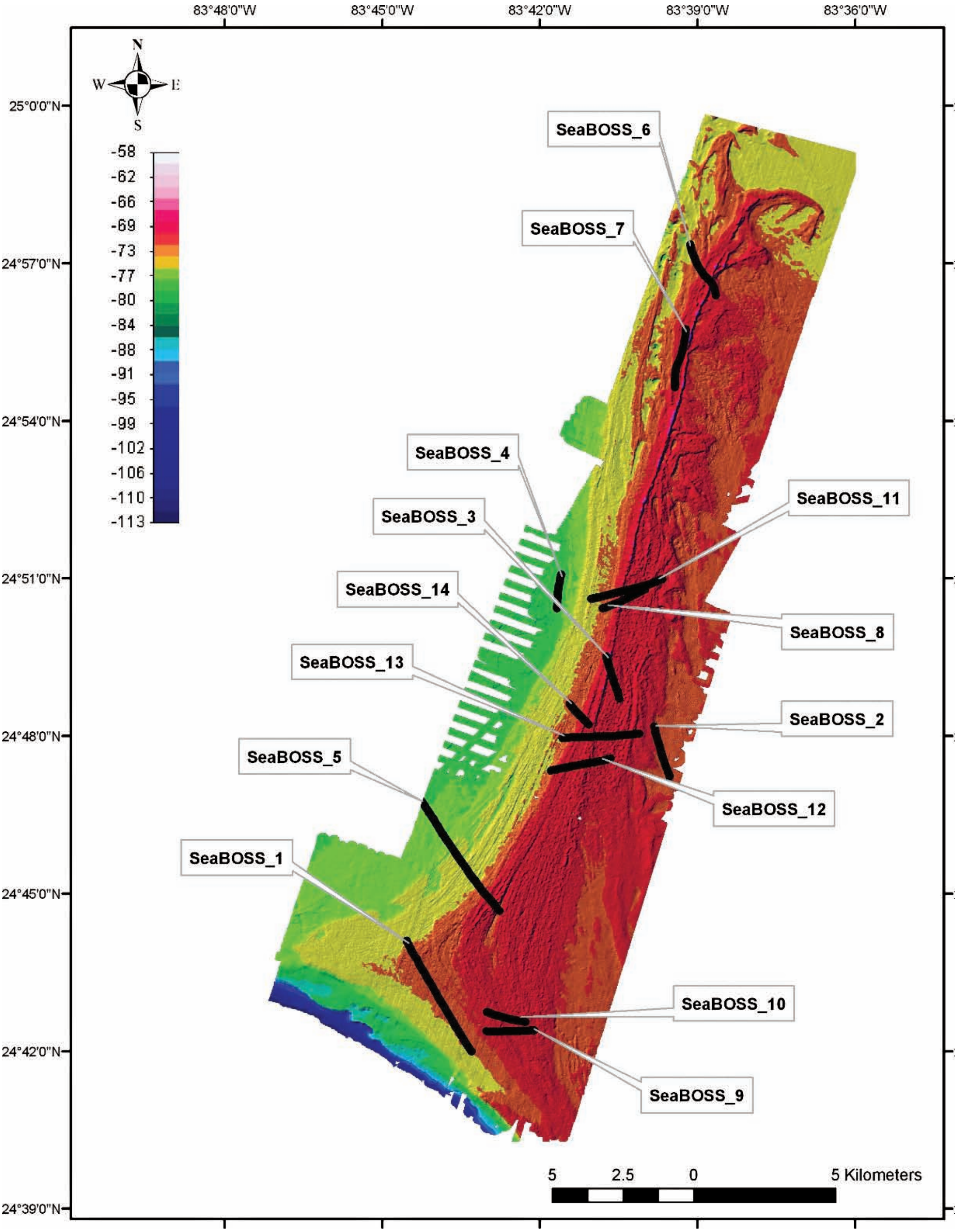

FIG. 4.30. Multibeam image of southern Pulley Ridge clearly showing preserved barrier-island morphology. Location of the 14 SeaBOSS transects on southern Pulley Ridge. Transect lines (black) are superimposed on the seafloor bathymetry (From Jarrett et al. 2005; reproduced by permission of Elsevier)

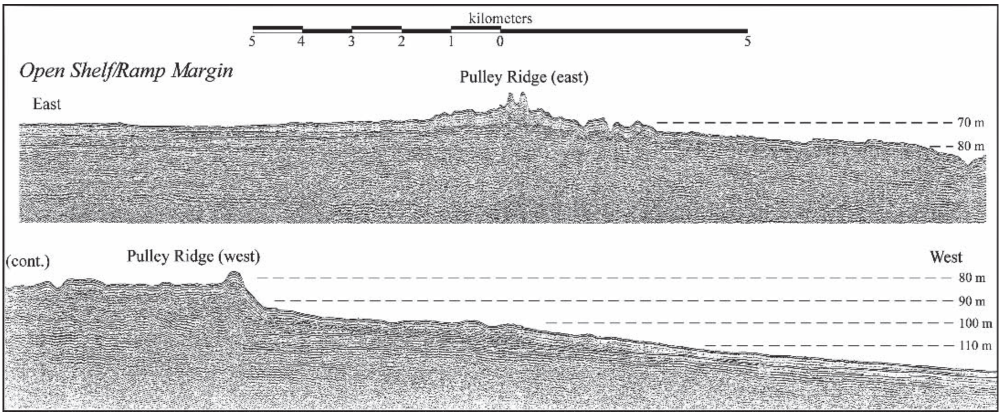

FIG. 4.31. One long E-W seismic line across the two ridges (~−65 m and ~−90 m) that defines Pulley Ridge. The living deep, light-dependent reef covers the ~−65 m deep ridge. Both ridges are paleo-shorelines

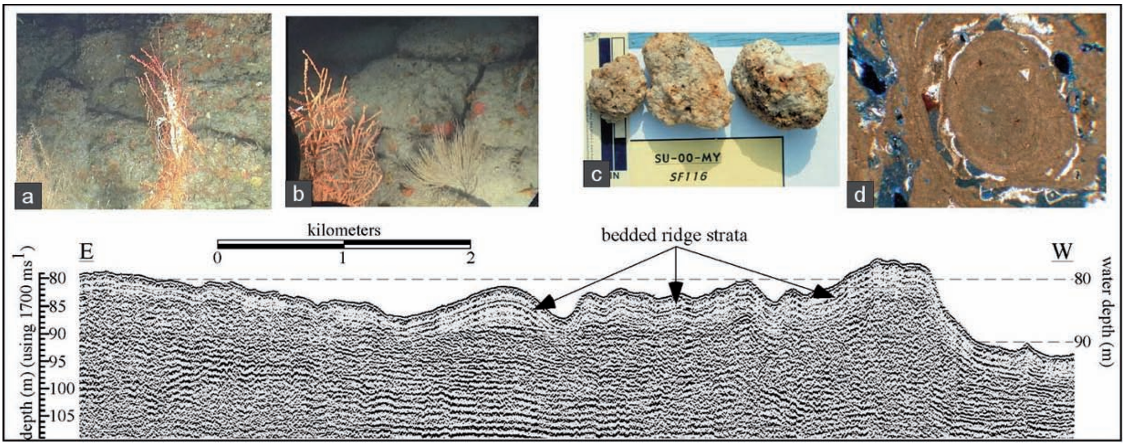

FIG. 4.32. Seismic line across the deeper paleoshoreline at Pulley Ridge. Video images (A, B) illustrate bedded, rectilinear nature of limestone consistent with lithified paleoshoreline facies. This deep ridge is covered with rhodoliths (C) coralline algal nodules. Thin-section photomicrograph (D) confirms rhodolith origin of these nodules (From Fig. 2 of Jarrett et al. 2005; reproduced by permission of Elsevier)

Point-count data were collected in 32 classes and combined into 7 major categories (Fig. 4.36) that account for 87.5% of the observations. Of the remaining 12.5% collectively termed “other”, 5% is macroalgae other than coralline algae or *Anadyomene menziesii* (Tables 4.8, 4.9). Rubble, very coarse gravel, accounts for about 4% of the seafloor, 2% are unknown and 1.5% are identified miscellaneous (octocorals, echinoderms, bryozoans, tunicates, fish, etc.). *Anadyomene menziesii* is in its own category because of the abundance of this otherwise rare alga and because it might be identified as a keystone species for this reef in future studies. Limestone is hardground not covered by previously mentioned organisms. It includes recently dead corals and coralline algae that have lost their color but may be colonized by micro flora and fauna (Fig. 4.35e).

Based on these data, Pulley Ridge reef is a coralline algae-coral dominated reef with these two components comprising 45–56% of the substrate along 11 of the 14 transects. The amount of coralline algae documented here is unusual for a Florida reef, but is typical of reefs in general. Adey (1976) and Adey et al. (1976) found coralline algae to be more abundant

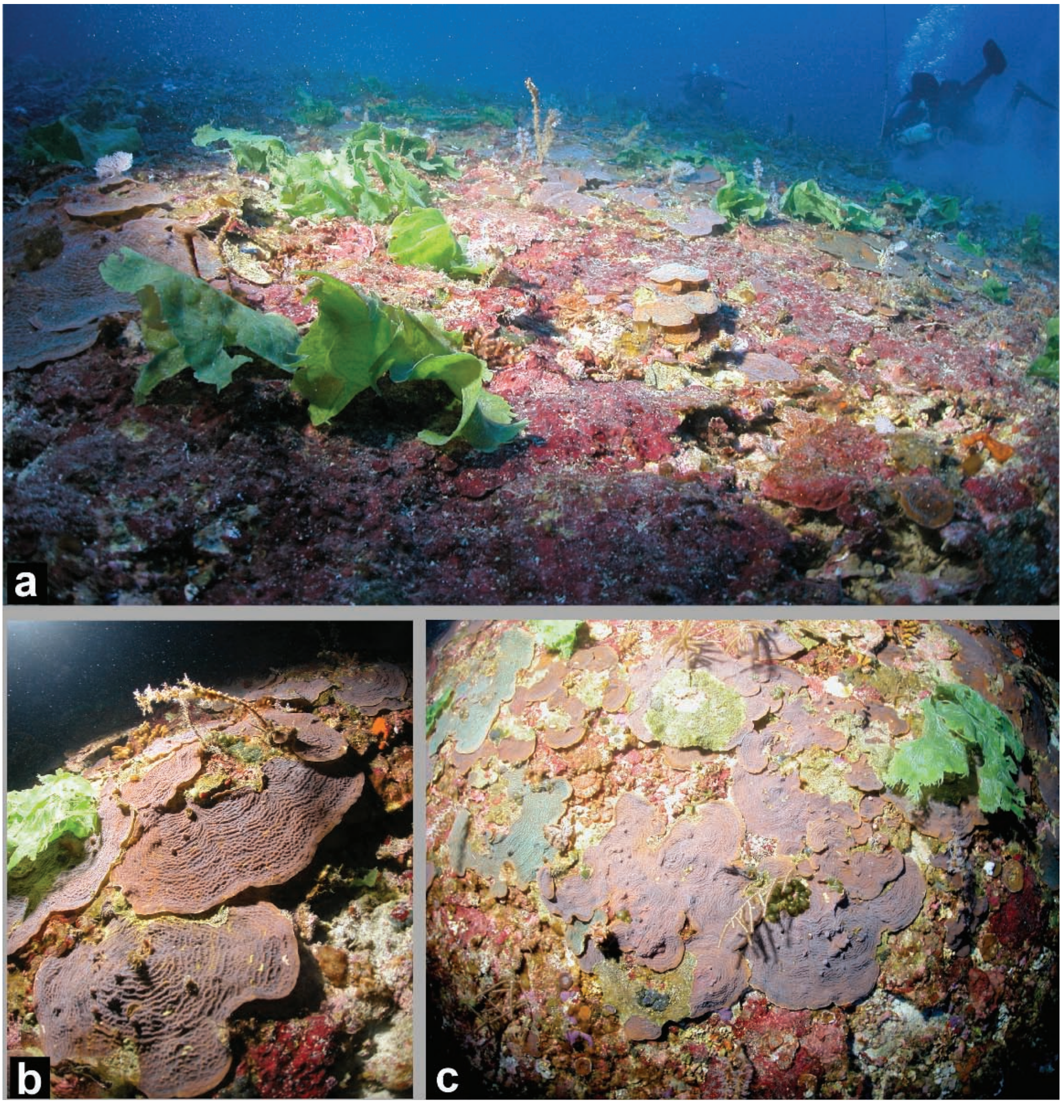

FIG. 4.33. A, B, C Bottom photographs (~65 m depth) taken by Tim Taylor (breathing mixed gas) revealing the coral reef seascape superimposed on top of the cemented barrier island along southern Pulley Ridge.

in the deep fore-reef (30–80 m) of Indo-Pacific reefs than Caribbean reefs. Wray (1977) estimated 20–50% of the mass of modern reef accumulations to be composed of coralline algae. At the depth and low light levels of Pulley Ridge, these algae may be less cryptic than on the shallower Florida Keys reef because there is less light reflected into shaded areas. Adding limestone to the categories of coral and coralline algae provides an estimate of total hardbottom that ranges from 61% to 76% within the 11 transects indicated above. Two of the transects extended off the reef: (1) transect 2 (SeaBoss, Fig. 4.30) on the gravel and sand plain to the east and (2) transect 4 on the sand and gravel plain to the west. Transect 6 is the northern limit for Agaricid corals. Three kilometers north of transect 6, two ROV surveys did not encounter platy corals. This northern portion of the ridge lacks photosynthetic scleractina and many of the large macro algae found further south. The northern ridge supports a heterotrophic octocoral-dominated community that does not contribute to a reefal accumulation like that in the south.

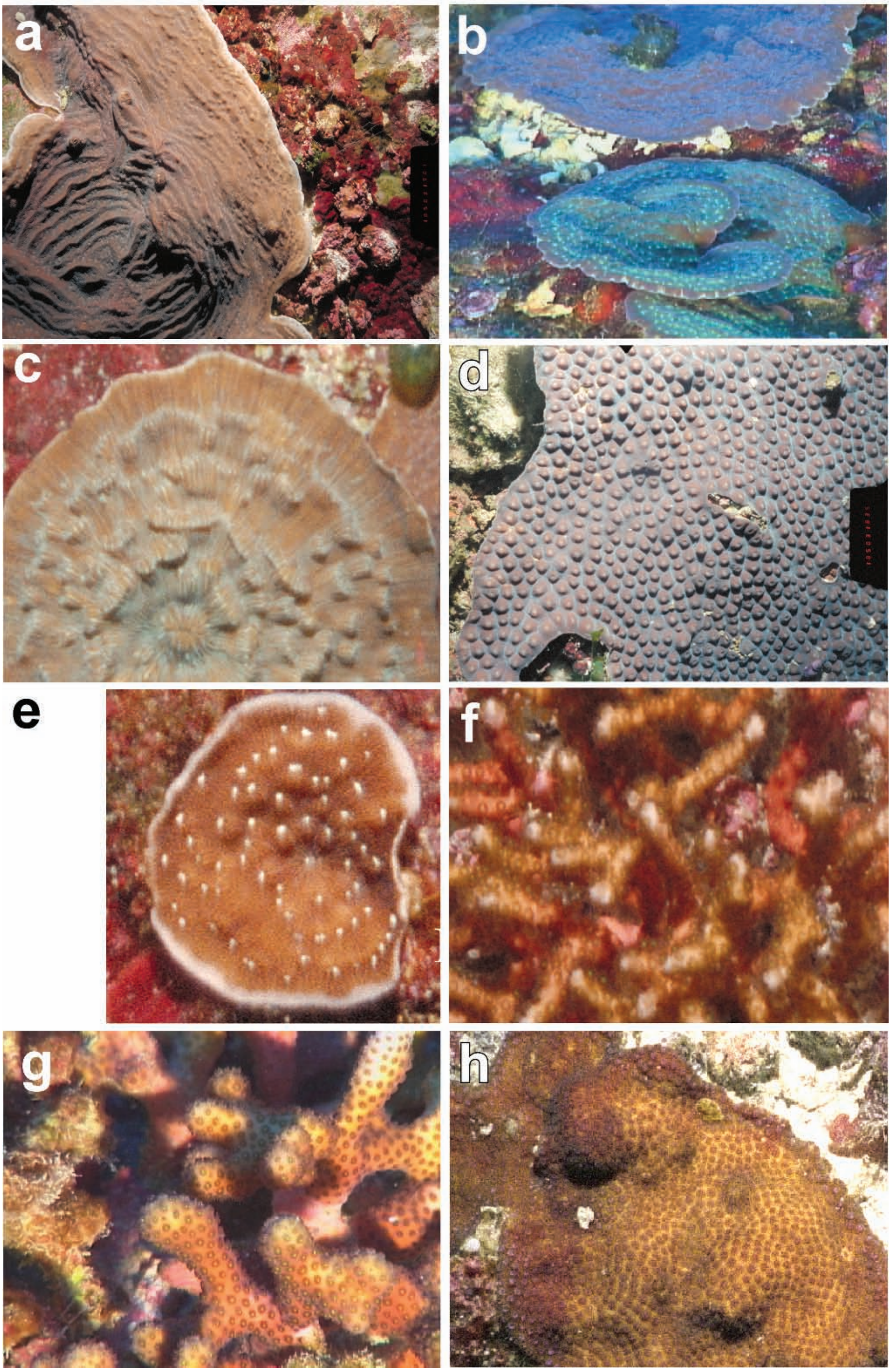

FIG. 4.34. Common stony corals of southern Pulley Ridge. (**a**) *Agaricia undata*; (**b**) *A. lamarki*; (**c**) *Leptoceris cucullata*; (**d**) *Montastraea cavernosa*; (**e**) *A. fragilis*; (**f**) *Oculina sp*. (**g**) *Madracis* sp.; (**h**) *Madracis decactis*

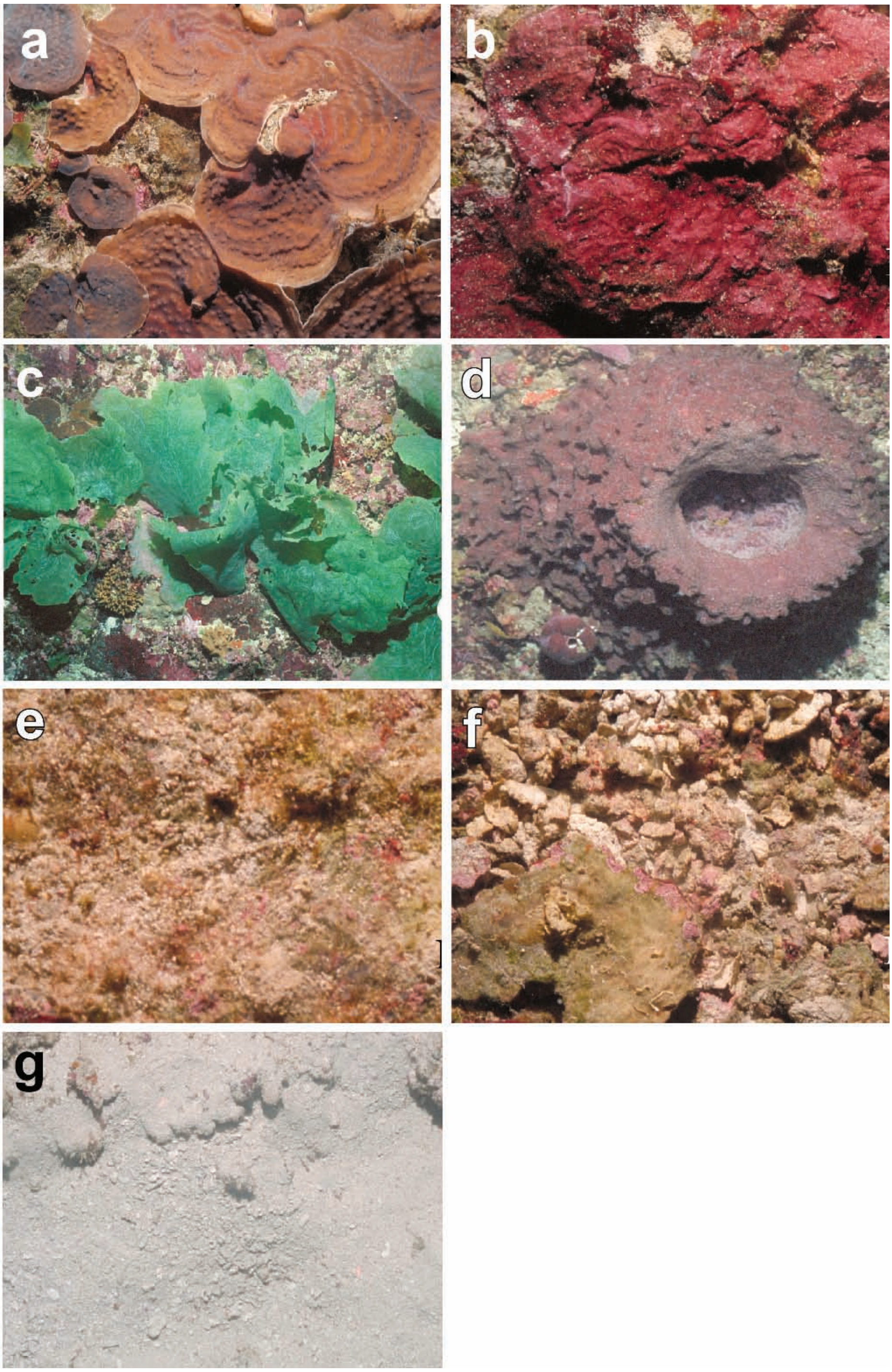

FIG. 4.35. Common benthic cover types of southern Pulley Ridge : (**a**) stony corals, (**b**) coralline algae, (**c**) *Anadyomene menziesii*, (**d**) sponges, (**e**) limestone (with algal turf cover), (**f**) gravel, and (**g**) sand. Bottom types not in these seven types are classified as "other" in Table 4.8

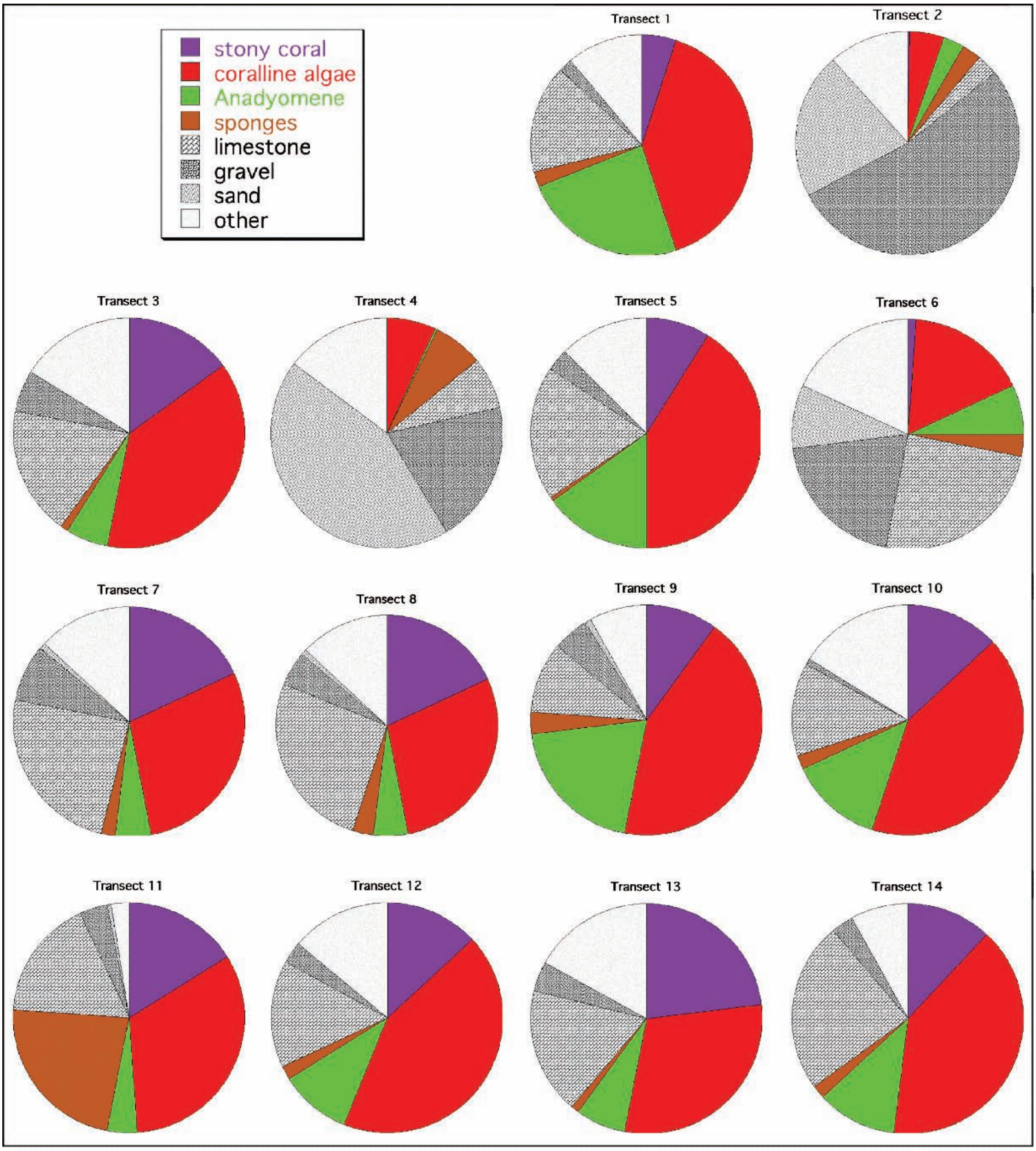

FIG. 4.36. Distribution of benthic cover compiled from 14 SeaBoss transects on Pulley Ridge (see Fig. 4.30): transects 1–7, and transects 8–14

Both coralline algae and the platy Agaricid corals result in foliate framework elements (Fig. 4.37a, b) capable of coating and preserving underlying topography. As mentioned above, the relatively thin coating of reef framework (probably less than a meter) and the platy nature of the framework account, in large part, for barrier-island morphology being so markedly apparent in the present-day bathymetry (Fig. 4.30; Jarrett et al. 2005).

In his now-classic study on the zonation of Jamaican reefs, Goreau (1959) described a reef zonation to depths of about 15 m that became a standard frame of reference for later reef surveys throughout the Caribbean, Florida and the

TABLE 4.8. Percentage distribution of major benthic cover categories at southern Pulley Ridge reef.

Dive #	Stony coral	Coralline algae	Anadyomene menziesii	Sponges	Limestone	Gravel	Sand	Other
1	5	40	24	2	16	2	0	11
2	0.2	5	3	3	3	53	21	11.8
3	15	38	6	1	18	6	0	16
4	0	7	0.3	7	7	20	44	14.7
5	9	41	15	0.5	19	3	0	12.5
6	1	17	7	3	25	20	9	18
7	18	29	5	2	24	8	1	13
8	18	29	5	3	26	5	1	13
9	10	43	20	3	10	5	1	8
10	13	42	13	2	13	1	0	16
11	16	33	4	23	17	4	0.4	2.6
12	13	43	10	2	15	3	0	14
13	23	30	7	1	18	4	0	17
14	12	40	11	2	24	3	0	8

TABLE 4.9. Species list of algae identified from Pulley Ridge (June 2005).

Rhodophyta
- *Antithamnion* sp.
- *Agardhinula browneae* (J. Agardh De Toni, 1897)
- *Cladhymenia lanceifolia* (Taylor, 1942)

Ceramium sp.
Chrysymenia planifrons (Melville)
- *Chrysymenia* new sp.?
- *Dasya bailouviana* (Gmelin) (Montagne, 1841)

Halymenia integra (Howe et Taylor or n.s.?)
- *Halymenia vinacea* (Howe et Taylor, 1931)
- *Herposiphonia* sp.

Hypoglossum anomalum (Wynne et Ballantine, 1986)
- *Ochtodes secundiramea* (Montagne) (Howe, 1920)
- *Peysonnelia conchicola* (Piccone et Grunow)
- *Rhododictyon bermudense* (Taylor)

Phaeophyta
- *Dictyota bartayresiana* Lamouroux (sensu Taylor, 1960)
- *Dictyota cervicornis* Kutzing w/reservations

Lobophora variegata (Lamouroux) Womersley ex E.C. Oliveira – erect and encrusting forms
Chlorophyta
- *Anadyomene menziesii* Harvey
- *Cladophora* ?
- *Codium isthmocladum* Vickers vs Pseudocodium
- *Codium spongiosum* Harvey
- *Halimeda discoidea* Decaisne V. platyloba Boergesen
- *Halimeda gracilis* Harvey
- *Ostreobium* sp.

Ventricaria ventricosa (J. Agardh) (J.L. Olsen et J.A. West)
- *Verdigelas peltata* (D.L. Ballantine et J.N. Norris)

Bahamas. At that time, the deepest part of the fore-reef explored (15–20 m) was characterized by large multi-lobed colonies of *Montastraea annularis*. Deeper diving during the 1960s revealed a different community on the fore-reef slope and deep fore-reef (40–75 m) described by Goreau and Goreau (1973). These zones are characterized by the platy corals *Agaricia undata, A. grahamae* and *A. lamarcki* and *Helioseris* (now *Leptoseris*) *cucullata.* During the 1970s, this zone proved to be widespread in Belize. Using a submersible, James and Ginsburg (1979) identified a zone of platy corals (*A. grahamae*, *A. lamarcki* and *Leptoceris cucullata*) between 40 and 70 m at five dive sites along the Belize barrier reef and Glovers Reef atoll. A very similar zone termed the “algal sponge” zone, is described between 48 and 88 m from Flower Gardens Reef (northwest Gulf of Mexico) by Rezak et al. (1985). They described the zone as being dominated by coralline algal nodules but with colonies of *Helioseris* (*Leptoseris*) cucullata and *Agaricia* and *Madracis* “abundant enough among the algal nodule to be major sediment producers” (Rezak et al. 1985).

It seems likely that the coral community found at southern Pulley Ridge is widespread throughout the Caribbean, Bahamas and Gulf of Mexico and awaits further exploration in a depth range that is not easily accessible by SCUBA, but considered shallow for many submersibles. Pulley Ridge reef might be considered a stand-alone deep fore-reef, detached from any shallower reef zones by the combined effects of antecedent topography and sea-level rise (Jarrett et al. 2005). The deep fore reef, because

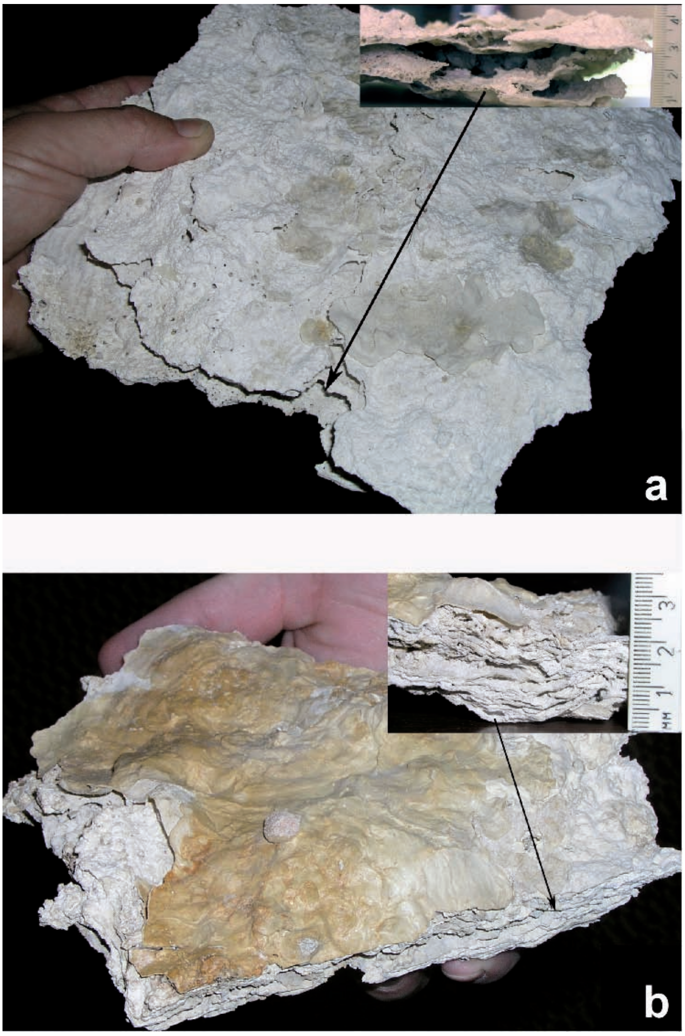

Fig. 4.37. Framework elements of Pulley Ridge reef: (**A**) Agaricid coral plates overgrowing and encrusting one another form a framework with centimeter-scale spaces (inset) that may be wholly or partially filled with sediment in the reef, and (**B**) coralline algae form platy masses of encrusting skeletons with millimeter-scale spaces (inset) partially filled with sediment

of its depth, is not included in reef-monitoring programs and, to the authors' knowledge, has not been re-visited in Jamaica or Belize in 30 years. The apparent health of the Pulley Ridge reef bodes well for this coral zone during decades when shallow reefs of the region have been devastated by disease and coral bleaching. Nevertheless, the coral-reef community covering Pulley Ridge, in ~65 m water, is the deepest, light-dependent coral reef on the US continental shelf known at this point in time (Halley et al. 2004).

Satellite SST and chlorophyll *a* data confirm the influence of the Loop Current on Pulley Ridge deep reef. This oceanographic current separates low-nutrient, outer-shelf waters from cooler, higher-nutrient, interior-shelf waters that are exported seaward across the shallow Florida reef tract. However, we do not understand the complex physical oceanographic interactions of the Loop Current and the west Florida shelf, particularly at the seafloor and how the reef is directly affected by the water column processes (He and Weisberg 2003; Weisberg and He 2003; Weisberg et al. 2005; Law 2003; Jarrett et al. 2005). Even with this very clear, oligotrophic water bathing the deep reef, measurements to date indicate that light at the seafloor is only about 1% of that at the surface.

Finally, the deep reef at southern Pulley Ridge: (1) provides an up-current source of larvae for downstream reefs – a potential refuge for shallow-water species, (2) supports a commercially-viable fishery industry, (3) should eventually provide understanding on how light-dependent corals can grow at such depths, (4) should eventually provide understanding on how this deep reef seems to be absent of disease or other stressors; a new type of natural laboratory, (5) provides clues as to where other similar deep reefs might exist and may not be such an apparent exception, (6) should eventually provide clues concerning timing of coral-reef development in the eastern GOM during the last 15 ka and provide insight to paleoceanographic and paleoclimatic changes, (7) provides an understanding of how the western boundary current (Loop Current component) interacts with the continental shelf and controls benthic communities, and (8) should provide a sanctuary for human study and enjoyment.

4.5.2 Northern Extension of Pulley Ridge

The 30 km long, 5 km wide barrier island forming southern Pulley Ridge seems to be unique. Here-to-fore unpublished side-scan sonar and high-resolution seismic reflection data indicate multiple, less pronounced ridges and paleoshorelines, and in some places a distinct 2–3 m high scarp at ~85 m water depth to the north (Fig. 4.38). This suggests that the modern relief of some ridges may have been produced by erosional processes during sea-level

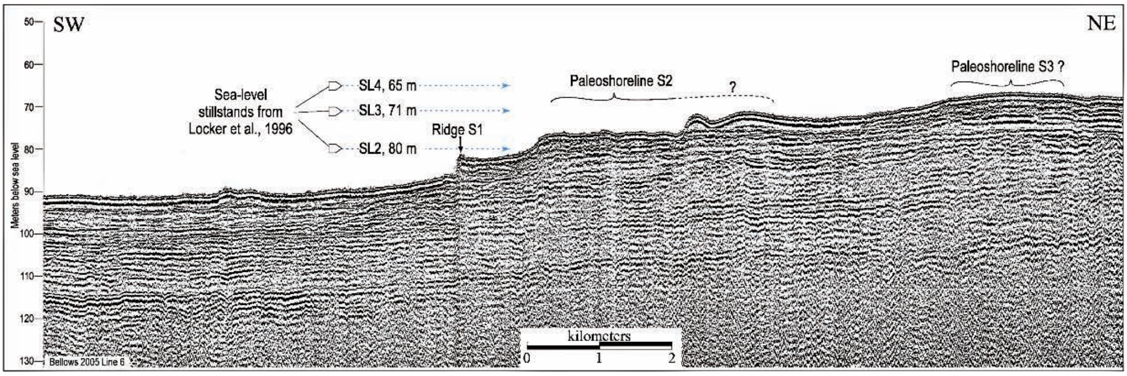

FIG. 4.38. Seismic profile along Pulley Ridge significantly north of the deep reef. Side-scan sonar and high-resolution seismic data reveal morphologies strikingly similar to paleoshoreline and ridge structures identified by Locker et al. (1996) on the south Florida margin facing the Straits of Florida. These alongslope structures are much narrower than the paleo-barrier island of southern Pulley Ridge. Much of this northern shoreline of Pulley Ridge was probably sediment starved and produced minimal coastal sedimentary facies. The depth of sea-level stillstands and structures S1–S3 are identified corresponding to Locker et al. (1996)

rise, or as with the case for ridge S1 in Fig. 4.38, the deeper (>80 m) ridges may reflect late relic Pleistocene reef buildups – yet to be identified. This further suggests that the carbonate sediment production, probably oolitic in nature, was much greater along the extreme SW corner of the Florida Platform than anywhere else. Widely-spaced dredge hauls from the paleoshoreline did not yield any coral-reef material. Additionally, coral reefs have a distinctive seismic facies (chaotic and discontinuous), which was not seen along this paleoshoreline. So, we tentatively conclude that the coral-reef cover is limited to the very southern portion of Pulley Ridge – the area that is influenced by oligotrophic Loop Current intrusions, which are not known to occur further to the north along the west Florida shelf.

4.5.3 Last Glacial Maximum Lowstand Ramp Reefs

Seaward of a prominent shelf ridge called The Elbow (Fig. 4.1) in ~120 m of water is a 1–2 km wide belt of “seismic patch reefs”, that are ~7 m in relief and 50 m across (Fig. 4.39). They are evenly spaced ~200 m apart. In the absence of ground-truthing data, we interpret these to be shallow-water patch reefs that formed when sea-level was lower during the LGM. Instead of an obvious paleoshoreline, this sea-level lowstand resulted in the formation of this belt of isolated mounds (believed to be patch reefs) making it the first feature of its kind found on the west Florida shelf/upper slope. The features are at the same depth as those found on southern Howell Hook (see below) suggesting that they are contemporaries.

4.6 Shelf-edge Reefs

4.6.1 Outlier Reefs

Defining the western extent of the south Florida Platform margin is a primary reef tract that is the extension of the well-known and well-studied main, massive reef tract located seaward of and parallel to the Florida Keys (Fig. 4.1). This nearly continuous shelf-edge reef defines the boundary of the platform top and the upper slope. Lidz et al. (1991, 1997, 2006) and Lidz (2006) have recognized outlier reefs, a reef-and-trough system, that occur along this main reef tract forming what appears to be a double reef edifice separated by a ~30 m deep, 1 km wide basin (Fig. 4.40a, b). In places, this basin has been completely filled with detritus shed from the main reef as well as the outlier reef. These discontinuous outlier reefs extend westward along the south-facing margin of the Florida Platform where they eventually disappear as this margin begins to transition from a rim to a ramp system west of Riley’s Hump (Fig. 4.41).

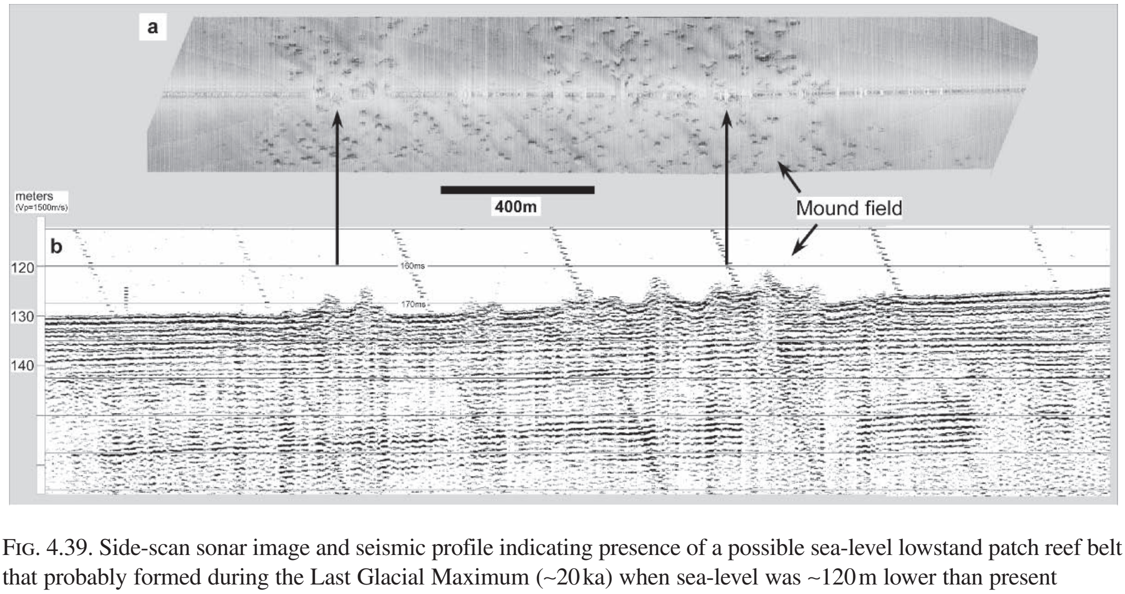

FIG. 4.39. Side-scan sonar image and seismic profile indicating presence of a possible sea-level lowstand patch reef belt that probably formed during the Last Glacial Maximum (~20 ka) when sea-level was ~120 m lower than present

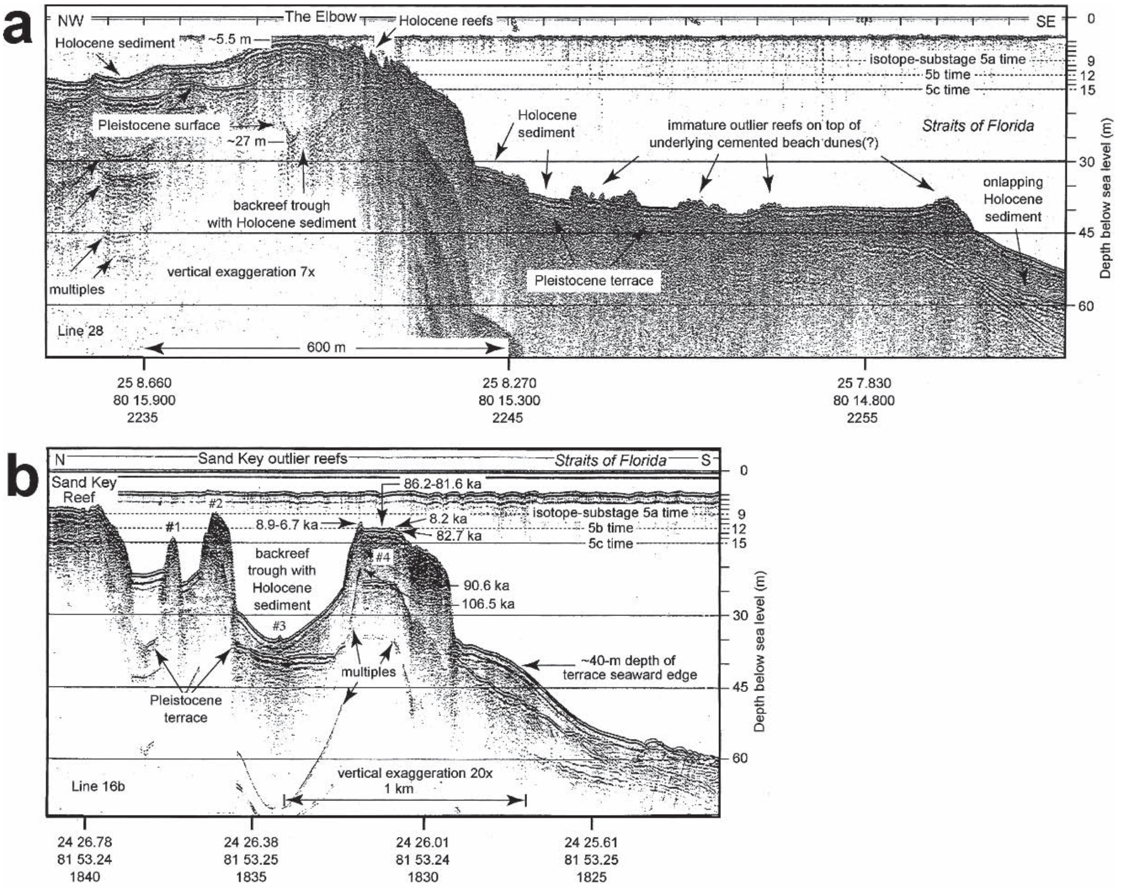

FIG. 4.40. (**a**) Seismic profile across northern Florida Keys reef tract illustrating ~35–40 m deep terrace upon which outlier reefs have been developed. (**b**) Seismic profile across Florida Keys reef tract SW of Key West (near Sand Key) illustrating multiple outlier reefs situated seaward of main reef tract (far left or to north). These late Pleistocene (see ^{14}C dates on figure) outliers have been developed on this 35–40 m deep terrace of unknown origin (Seismic data provided to B. Lidz by A.C. Hine and S.D. Locker; Figures from Lidz et al. 2006; reproduced by permission of Journal of Coastal Research)

These outlier reefs are situated upon a laterally discontinuous upper-slope terrace that lies in ~35 m water depth (Fig. 4.40b). How this terrace was formed and under what sea-level and other environmental conditions are unknown due to the absence of core data. Additionally, its laterally discontinuous nature is enigmatic. It is clearly a constructional feature, not an erosional one. Additionally, all outlier reefs have formed on this terrace. However, there are sections of the margin where the terrace exists but only incipient or no outlier reefs are present. So, the presence of the terrace did not guarantee the growth and development of outliers.

Diamond core drilling into these ~30 m relief outlier reefs indicate that they support a thin Holocene veneer of *A. palmata* that began ~9 ka and essentially ceased ~5 ka. A poorly preserved paleo-subaerial exposure horizon generally exists at ~16–12 mbsl. Below this unconformity lies a dominantly *M. annularis* reef whose TIMS U-Th dates range from 80.9 to 106.5 ka (MIS 5c, b, and a) with most between 80.9 and 85 ka (Toscano 1996). The longest core extends to 21.29 mbsl and is 10 m in length. No cores reached the terrace upon which the outlier reefs rest. So, MIS 5c, b, and a must have been a period of extensive shelf-margin reef building seaward of the Florida Keys and westward along the south Florida margin from ~12 to ~24 m below present sea level.

4.7 Upper Slope Reefs

4.7.1 Miller's Ledge

Located seaward of Riley's Hump along the upper slope is a 30 m high prominent escarpment called Miller's Ledge (Figs. 4.1, 4.42). From high-resolution seismic reflection data, this appears to be the seaward scarp of a reef that now lies in ~80 m water depth. Although this water depth is technically at shelf depth, it lies seaward of the reef-dominated rimmed margin of the Florida Platform. So, from a morphological viewpoint, it lies along the very upper slope. It probably is contemporary with the deeper component constituting Pulley Ridge (~90 m). It has not yet become buried by sediments being shed from the shallower reefs lying to the north, although that may yet become its fate. This escarpment may be the result of submarine erosion by strong, slope-parallel flows associated with the Loop Current.

4.7.2 Howell Hook

Extending along the upper slope of the SW margin of the Florida Platform in ~120–160 m water depth is a discontinuous ridge consisting of a series of "seismic reefs". This is the southernmost component of Howell Hook – a prominent bathymetric feature that runs ~300 km along the west Florida upper slope roughly parallel to Pulley Ridge, which lies in shallower water (60–90 m; Fig. 4.1). Earlier work by Holmes (1985) revealed that Howell Hook is encrusted with coralline algae where dredged.

Bathymetric maps and multibeam data clearly show this lack of linearity (Fig. 4.43a). Additionally, seismic reflection data reveal that rather than a single ridge line, there are multiple, stair-stepped ridges that occur along this upper slope (Fig. 4.43b). The acoustically chaotic seismic facies strongly suggest that these features were coral reefs. Figure 4.43b shows a 10 m high escarpment at ~125–135 m water depth, which could be an erosional feature probably formed during the sea-level lowstand occurring during the LGM. However, seaward of this scarp are three mound-like structures reaching 140, 155, and 185 m. The

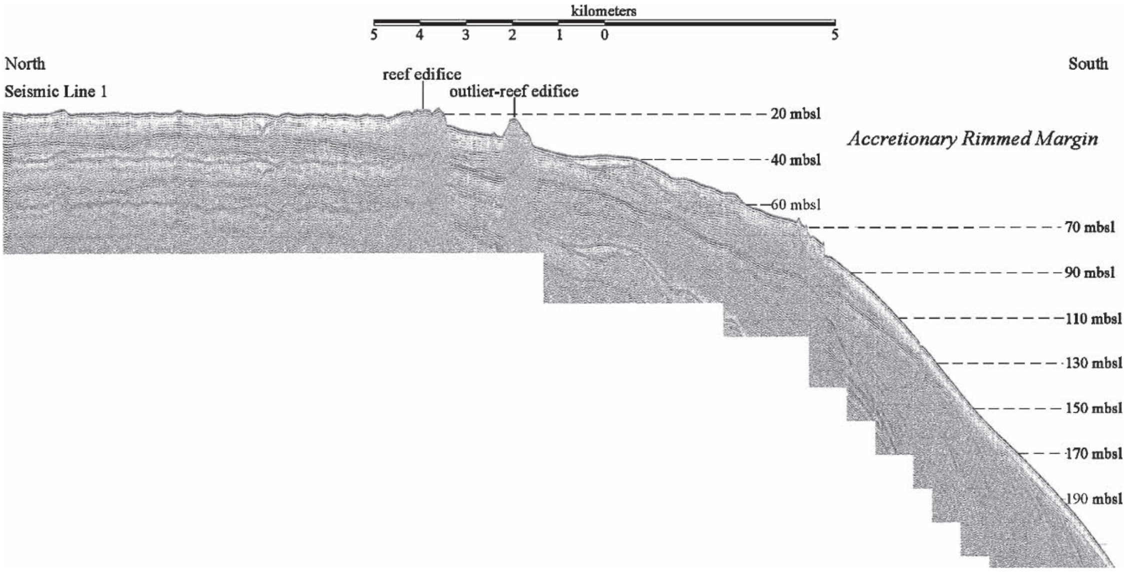

Fig. 4.41. High-resolution seismic line N–S across southern margin of Florida Platform illustrating reef and outlier reef structures. This is near the western-most extent of the Florida Keys reef tract and the end of the rimmed type of platform margin. Note buried reef at ~–40 m depth. Also, note paleoshoreline feature at ~–70 m

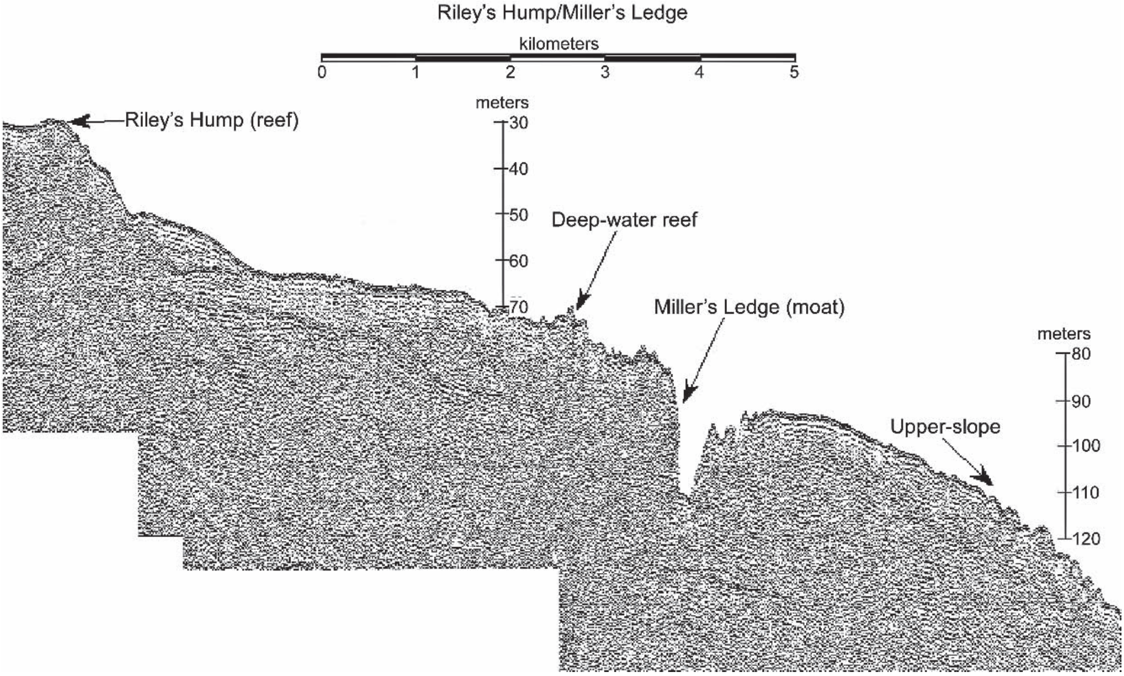

FIG. 4.42. Seismic profile across Miller's Ledge on the upper slope which is a reefal structure located at approximately the same depth (~90 m) as the deeper ridge associated with Pulley Ridge.

mound reaching 140 m is enigmatic as the basin behind it was filled by layered strata and the seaward side has been eroded perhaps by biological activity stimulated by currents associated with the Loop Current. Increased water flow may enhance bio-erosion activity (A.C. Neumann, personal communication 1975). In fact, this entire upper slope appears to have been significantly influenced by Loop Current erosion as the seismic stratigraphy reveals multiple, buried erosional surfaces.

To date there have been no ROV deployments, dredging, or drilling of these features. As a result, we simply do not know what type of reefs these features constitute. So, they remain a mystery, but based on their depth, may have been formed some 20 ka indicating that environmental conditions were appropriate for coral-reef growth at that time.

4.8 Discussion and Summary

The morphologic diversity of coral reefs, present and past, on the south, south-west and west Florida platform results from the interplay of antecedent topography, substrate type, sea-level fluctuations and water circulation. The broad nature of a ramp allows for extensive, lateral movement of the shoreline during sea-level cycles thus allowing for a diverse distribution of shorelines and shallow-water coral reefs. Where margins are steep, reefs become laterally compressed and vertically stacked. The rim-to-ramp transition along the south margin of the Florida platform adds to this complexity.

The small circular reef banks (Dry Tortugas, Tortugas Bank, and Riley's Hump, Florida Middle Ground) seem anomalous as compared to expected reef linearity imposed by laterally extensive shelf margins and paleoshorelines. Along the south Florida margin, perhaps the reef banks were originally sited on cemented, tide-dominated sand shoals that comprise the southern Florida Keys? In the Florida Middle Ground area, perhaps karst pinnacles provided the original antecedent topography on which these numerous small reef banks became established? Additionally, all reefs seem

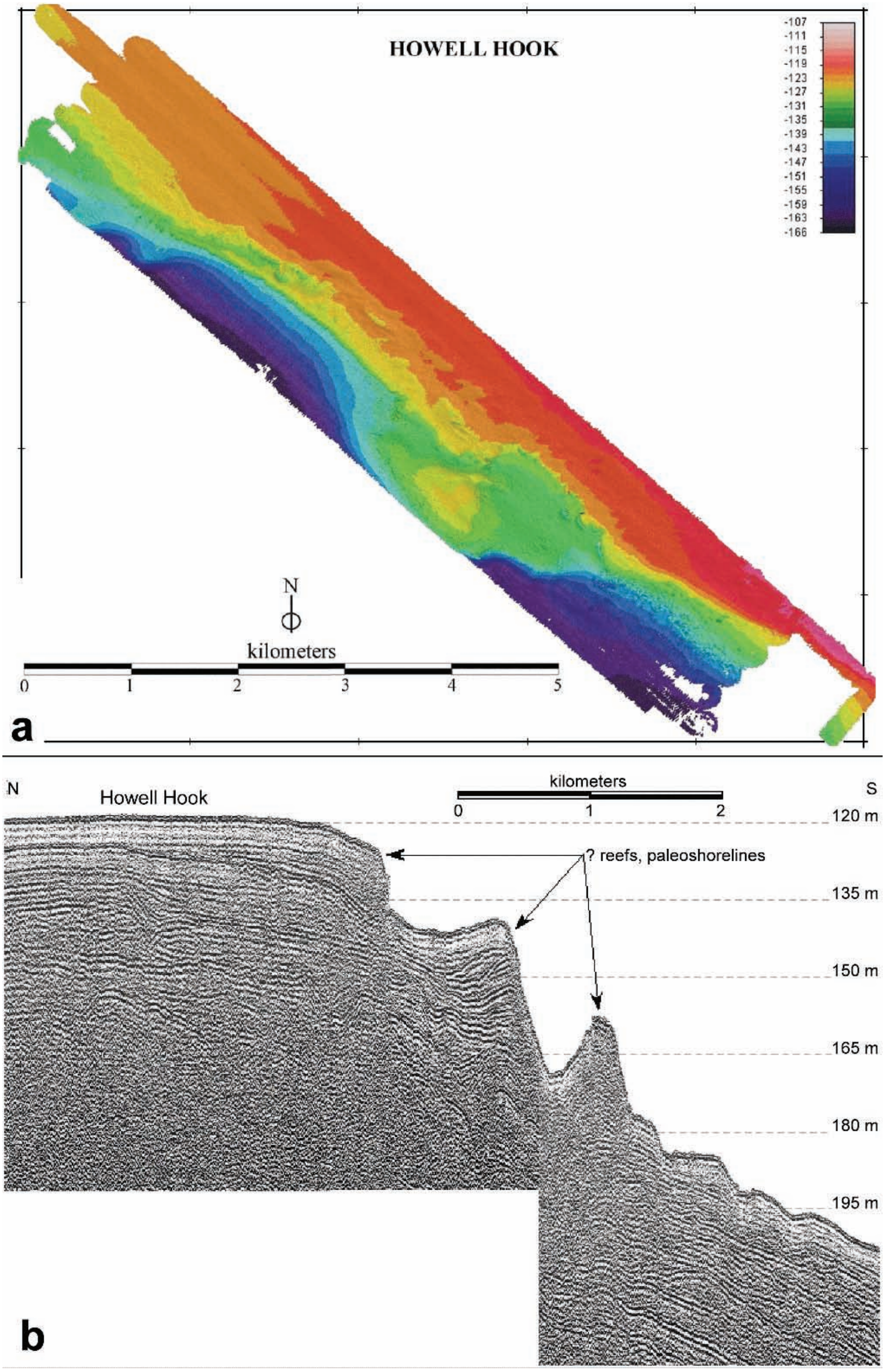

FIG. 4.43. (**a**) Multibeam data of SW margin of Florida Platform revealing multiple ridges and large mound structure that may be a sea-level lowstand reef. This is the southern extension of Howell Hook. (**b**) Seismic profile across this area revealing multiple "seismic reefs", one of which appears to have been significantly eroded. These are the deepest "seismic reefs" along the entire south, southwest, and west Florida margin

to be dominated by aggradation, backstepping, or drowning rather than progradation suggesting that rapid sea-level changes have been critically important in their development.

Sea-level fluctuations result not only in depth changes but also significant changes in shelf/adjacent deepwater circulation, water temperature, water quality as well as concomitant changes in continental/marine interaction. Healthy coral-reef development occurs when ideal conditions for substrate availability, water quality, and stable or slowly rising sea-level simultaneously converge. The diversity of reefs dispersed on the Florida platform indicate that such convergence is not simultaneous nor ubiquitous.

Acknowledgments For the south Florida and SW Florida margin work (outlier reefs, Dry Tortugas area, Pulley Ridge, Howell Hook) we thank Drs. A.C. Neumann, Sylvia Earle, Pamela Hallock, David Twichell, and Chuanmin Hu for their expertise. We thank Beau Suthard, David Palandro and many other graduate students and research associates (Chris Reich, Don Hickey) for their assistance at sea and in the laboratory. We thank the US Geological Survey, the National Oceanographic and Atmospheric Administration – National Underwater Research Center (particularly Mr. Lance Horn), Office of Naval Research, the Naval Oceanographic Office, the Florida Institute of Oceanography, the Harte Institute, the National Fish and Wildlife Foundation, and the Sustainable Seas Expedition for financial support. We thank Ben Haskell of the Florida Keys National Marine Sanctuary. We thank the crews of the Florida Institute of Oceanography's research vessels; *R/V Suncoaster* and *R/V Bellows*. We also thank the crew of the *M/V Spree*. We thank Mr. Tim Taylor of the *R/V Tiburon*, Inc. for use of the underwater photos of Pulley Ridge taken by divers. We thank G.P. Schmahl for photos taken in the FMG area.

For the Florida Middle Ground work, we are grateful for a 2003 cruise – the findings from which are provided in a report with appendices, including an album of photographs (Coleman et al. 2005). We thank all of the participants: Felicia Coleman, Mike Dardeau, George Dennis, Tom Hopkins, George Schmahl, Chris Koenig, Sherry Reed, Carl Beaver, Lance Horn, Selena Kupfner, Mike Callahan, Matt Lybolt, Anne McCarthy, and Jim Kidney for their persistence under difficult circumstances. We thank the Gulf of Mexico Fishery Management Council for funding support for the expedition. Tom Hopkins, Mike Dardeau, Paul Johnson, and others from the 1970s MAFLA expeditions provided photographs and unpublished data from their work. Tom Hopkins and Mike Dardeau confirmed the station locations using the ROV video which was a great help in locating the Hopkins et al. (1977) sampling stations.

References

Adey WH (1976) Crustose coralline algae as microenvironmental indicators for the Tertiary, in Gray J, Boucot AJ (eds) Historical Biogeography. Plate Tectonics, and the Changing Environment, Oregon State University Press, Corvallis, OR, pp 459–464

Adey WH, Adey PJ, Burke R, Kaufman L (1976) Holocene reef systems of eastern Martinique, French West Indies. Atoll Res Bull 211:1–40

Ahr WM (1973) The carbonate ramp : an alternative to the shelf model. Gulf Coast Assoc of Geol Soc 23:221–225

Arthur MA, Schlanger SO (1979) Cretaceous "oceanic anoxic events" as causal factors in reef-reservoired oil fields. Geol Soc Am Bull 69:870–885

Austin H, Jones J (1974) Seasonal variation of physical oceanographic parameters on the Florida Middle Ground and their relation to zooplankton biomass on the West Florida Shelf. Florida Scientist 37:16–32

Back RM (1972) Recent Depositional Environment of the Florida Middle Ground. Florida State University, Tallahassee, FL, 237 pp

Blackwood D, Parolski K, Valentine P (2000) Seabed observation and sampling system. U.S. Geological Survey Fact Sheet FS-142–00 (http://woodshole.er.usgs.gov/operations/sfmapping/seaboss.htm)

Brooks HK (1962) Observations on the Florida Middle Ground (abstract). Geol Soc Am Spec Publ 68:65–66

Brooks GR (1981) Recent Carbonate Sediments of the Florida Middle Ground Reef System; Northeastern Gulf of Mexico. University of South Florida, St. Petersburg, FL, 137 pp

Brooks GR, Doyle LJ (1991) Geologic development and depositional history of the Florida Middle Ground: a mid-shelf, temperate-zone reef system in the northeastern Gulf of Mexico, in Osborne RH (ed) From Shoreline to Abyss – Shepard Commemorative Volume:189–203

Buffler RT (1991) Seismic stratigraphy of the deep Gulf of Mexico and adjacent margins, in Salvador A (ed)

The Gulf of Mexico basin: the geology of North America, Geol Soc Am:353–387

Cheney DP, Dyer JP, III (1974) Deep-water benthic algae of the Florida Middle Ground. Mar Biol 27:185–190

Coleman C, Dennis G, Jaap WC, Schmahl GP, Koenig C, Reed S, Beaver CR (2005) Status and trends of the Florida Middle Ground. Technical Report of Gulf of Mexico Fisheries Management Council, Tampa, FL, 135 pp

Collard SB, D'asaro CN (1973) Benthic invertebrates of the eastern Gulf of Mexico., in Jones JI, Ring RE, Rinkel MO, Smith RE (eds) A summary of knowledge of the eastern Gulf of Mexico, Coordinated by the State Univ Sys Florida Inst Oceanogr, St. Petersburg, FL IIIG1–IIIG28

Corso W, Austin JA, Buffler RT (1989) The early Cretaceous platform off northwest Florida: controls on morphologic development of carbonate margins. Mar Geol 86:1–14

Cross VA, Blackwood DS, Halley RB, Twichell DC (2004) Bottom photographs from the Pulley Ridge deep coral reef. DVD-ROM US Geological Survey Open-file Report 2004–1228

Cross VA, Twichell DC, Halley RB, Ciembronowicz KT, Jarrett BD, Hammar-Klose ES, Hine AC, Locker SD, Naar DF (2005) GIS Compilation of data collected from the Pulley Ridge deep coral reef region. DVD-ROM US Geological Survey Open-file Report 2005–1089

Doyle LJ, Steinmetz JC, Brooks GR, Parker DM (1980) Gulf of Mexico topographic features study, Florida Middle Ground. Final Report, BLM, New Orleans, LA (BLM Contract AA5512-CT8–35)

Forman SL, Oglesby R, Webb RS (2001) Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links. Global Planet Change 29:1–29

Gilbes F, Tomas C, Walsh J, Muller-Karger F (1996) An episodic chlorophyll plume on the West Florida Shelf. Cont Shelf Res 16:1201–1224

Godcharles MF, Jaap WC (1973) Fauna and flora in hydraulic clam dredge collections from Florida west and southeast coasts. Fla Dep Nat Resour Mar Res Lab Spec Sci Rep 40:89

Goreau TF (1959) The ecology of Jamaican reefs. I. Species composition and zonation. Ecology 40:67–90.

Goreau TF, Goreau NI (1973) The ecology of Jamaican coral reefs. II. Geomorphology, zonation, and sedimentary phases. Bull Mar Sci 23:399–464

Gould HR, Stewart RH (1956) Continental terrace sediments in the northeastern Gulf of Mexico., in Finding ancient shorelines, SEPM Spec Publ 3:2–19

Grimm D, Hopkins T (1977) Preliminary characterization of the octocorallian and scleractinian diversity at the Florida Middle Ground. Proc 3rd Int Coral Reef Symp, Miami, 1:135–141

Grimm DE (1978) The occurrence of the Octocorallia (Colenterata: Anthozoa) on the Florida Middle Ground. M.S. thesis, University of Alabama, 85 pp

Gulf of Mexico and South Atlantic Fishery Management Councils (1982) Fishery Management Plan Final Environmental Impact Statement for Coral and Coral Reefs. Gulf of Mexico Fishery Management Council, Tampa, FL, 178 pp

Halley RB, Hine AC, Jarrett BD, Twichell DC, Naar DF, and Dennis GD (2004) Pulley Ridge : The US's Deepest Hermatypic Coral Reef. Geological Society of America Annual Meeting, Denver, CO, Abstracts with Programs, 302 pp

Hallock P (1988) The role of nutrient availability in bioerosion: consequences to carbonate buildups. Palaeogeogr Palaeoclim Palaeoecol 63:275–291

Hallock P, Schlager W (1986) Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 1:389–398

He R, Weisberg RH (2003) A Loop Current intrusion case study on the West Florida shelf. J Phys Oceanogr 33:465–477

Hilde WC, Sharman G, Waris W, Lee CS, Feely M, Meyer M (1981) Mapping and Sub-bottom Profiling, Texas A&M University, College Station, TX.

Hine AC (1997) Structural and paleoceanographic evolution of the margins of the Florida Platform, in Randazzo AF, Jones DS (eds) The Geology of Florida, University Press of Florida:169–194

Hine AC, Mullins HT (1983) Modern carbonate shelf-slope breaks. Soc Econ Paleontol Mineral Spec Publ 33:169–188

Hine AC, Neumann AC (1977) Shallow carbonate bank margin growth and structure, Little Bahama Bank. Bull Am Assoc Petrol Geol 61:376–406

Hine AC, Brooks GR, Davis Jr. RA, Duncan DS, Locker SD, Twichell DC, Gelfenbaum G (2003) The west-central Florida inner shelf and coastal system; a geologic conceptual overview and introduction to the special issue. Mar Geol 200:1–17

Hine AC, Buthard B, Locker SD, Cunningham KJ, Duncan DS, Evans M, Morton RA (in press) Karst subbasins and their relationship to Florida transport of Tertiary siliciclastics, in Swart PK, Eberli, GP McKenzie J (eds) Perspectives in Sedimentary Geology: A Tribute to the Career of Robert Nathan Ginsburg, IAS Special Publication, Sedimentology, v.41

Holmes CW (1985) Accretion of the south Florida platform, late Quaternary development. AAPG Bull 69:149–160

Hopkins TS, Blizzard DR, Brawley SA, Earle SA, Grimm DE, Gilbert DK, Johnson PG, Livingston EH, Lutz CH, Shaw JK, Shaw BB (1977) A preliminary characterization of the biotic components of composite strip transects on the Florida Middle Ground, northeastern Gulf of Mexico. Proc 3rd Int Coral Reef Symp 1:31–37

Jaap WC, Hallock P (1990) Coral reefs, in Myers RL, Ewell JJ (eds) Ecosytems of Florida. University of Central Florida Press, Orlando, FL, pp 574–616

Jaap WC, Lyons WG, Dustan P, Halas JC (1989) Stony coral (Scleractinia and Milleporina) community structure at Bird Key Reef, Ft. Jefferson National Monument, Dry Tortugas, Florida. Fla Mar Res Publ 46:1–31

James NP, Ginsburg RN (1979) The Seaward Margin of Belize Barrier and Atoll Reefs. Special Publication 3, International Association of Sedimentology, Blackwell, Oxford, 191 pp

Jarrett BD (2003) Late Quaternary carbonate sediments and facies distribution patterns across a ramp to rim transition: a new conceptual model for the southwest Florida platform. Ph.D. dissertation, College of Marine Science, University of South Florida, 135 pp

Jarrett BD, Hine AC, Halley RB, Naar DF, Locker SD, Neumann AC, Twichell D, Hu C, Donahue BT, Jaap WC, Palandro D, Ciembronowicz K (2005) Strange bedfellows – a deep hermatypic coral reef superimposed on a drowned barrier island; southern Pulley Ridge, SW Florida platform margin. Mar Geol 214:295–307

Jones AC, Berkeley SA, Bohnsack JA, Bortone SA, Camp DK, Darcy GH, Davis JC, Haddad KD, Hedgepth MY, Irby EW, Jaap Jr. WC, Kennedy FS, Lyons Jr. WG, Nakamura EL, Perkins TH, Reed JK, Steidinger KA, Tilmant JT, Williams RO (1985) Ocean habitat and fishery resources of Florida., in Seaman Jr., W (ed) Florida Aquatic Habitat and Fishery Resources. Florida Chapter American Fisheries Society, Kissimmee, Fl, pp 437–542

Jordan GF (1952) Reef formation in the Gulf of Mexico off Apalachicola Bay, Florida. Geol Soc Am Bull 63:741–744

Kindler P (1992) Coastal response to the Holocene transgression in the Bahamas : episodic sedimentation vs continuous sea-level rise. Sediment Geol 80: 319–329

Klitgord KD, Popenoe P, Schouten H (1984) Florida: a Jurassic transform plate boundary. J Geophys Res 89:7753–7772

Knox JC (2000) Sensitivity of modern and Holocene floods to climate change. Quat Sci Re 19:439–458

Law J (2003) Deep ocean effects on outer continental shelf flow: a descriptive study in the Loop Current, Florida Current, and Gulf Stream systems. M.S. thesis, University of South Florida, St. Petersburg, FL, 102 pp

Lee TN, Williams E, Johns E, Wilson D, Smith NP (2002) Transport processes linking south Florida coastal ecosystems, in Porter J, Porter K (eds) The Everglades, Florida Bay, and Coral Reefs of the Florida Keys : An Ecosystem Sourcebook, CRC, Boca Raton, FL, pp 309–342

Lees A (1975) Possible influence of salinity and temperature on modern shelf carbonate sedimentation. Mar Geol 19:159–198

Lidz BH (2006) Pleistocene corals of the Florida Keys: architects of imposing reefs – why? J Coastal Res 22:750–759

Lidz BH, Hine AC, Shinn EA, Kindinger JL (1991) Multiple outer-reef tracts along the south Florida bank margin: outlier reefs, a new windward model. Geology 19:115–118

Lidz BH, Shinn EA, Hine AC, Locker SD (1997) Contrasts within an outlier-reef system: evidence for differential quaternary evolution, south Florida windward margin, USA. J Coastal Res 13:711–731

Lidz BH, Reich CD, Peterson RL, Shinn EA (2006) New maps, new information: coral reefs on the Florida Keys. J Coastal Res 22:260–282

Logan BW, Harding JL, Ahr WM, Williams JD, Snead RG (1969) Late Quaternary carbonate sediments of Yucatan Shelf, Mexico. Am Assoc Petrol Geol Mem 11:5–128

Locker SD, Hine AC, Tedesco LP, Shinn EA (1996) Magnitude and timing of episodic sea-level rise during the last deglaciation. Geology 24:827–830

Ludwick JC, Walton WR (1957) Shelf-edge calcareous prominences in the northeastern Gulf of Mexico. Am Assoc Petrol Geol Bull 41:2054–2101

Lyons WG (1980) Molluscan communities of the west Florida shelf. Bull Am Malac Union 1979:37–40

Lyons WG, Collard S (1974) Benthic invertebrate communities of the eastern Gulf of Mexico., in Smith RE (ed) Proceedings of Marine Environmental Implications of Offshore Drilling in the Eastern Gulf of Mexico, State University System of Florida Institute of Oceanography, St. Petersburg, FL, pp 157–165

Mallinson D (2000) A Biological and Geological Survey of the Florida Middle Ground – HAPC: Assessing Seafloor Impacts of Fishing-related Activities, National Marine Fisheries Service, St. Petersburg

Mallinson D, Hine AC, Muller PH (1999) Structure and origin of relict reefs on the West Florida Margin. Eos transactions, American Geophysics Union Fall Meeting

Mallinson D, Hine A, Hallock P, Locker S, Shinn E, Naar D, Donahue B, Weaver D (2003) Development of small carbonate banks on the south Florida Platform margin: response to sea level and climate change. Mar Geol 199:45–63

Mallinson DJ, Hine AC, Locker SD (1996) Paleocirculation and paleoclimatic implications of the Florida Middle Ground reefs. Geological Society of America Abstracts with Programs 1996 National Meeting, Denver, CO

Mallinson DJ, Donahue B, Naar DF, Hine AC, Locker SD (2006) Pleistocene and Holocene geologic controls on the Florida Middle Ground relict reef complex; a diverse seafloor environment on the west Florida shelf, AGU Ocean Science Meeting OS261–04

Murdoch TJT, Aronson RB (1999) Scale-dependent spatial variability of coral assemblages along the Florida Reef tract. Coral Reefs 18:341–351

Mullins HT, Gardulski AF, Wise SW, Applegate J (1987) Middle Miocene oceanographic event in eastern Gulf of Mexico: implications for seismic stratigraphic succession and Loop Current/Gulf Stream circulation. Geol Soc Am Bull 98:702–713

Mullins HT, Gardulski AF, Hinchey EJ, Hine AC (1988) The modern carbonate ramp slope of central west Florida: J Sediment Petrol 58:273–290

Mullins HT, Gardulski AF, Hine AC, Melillo AJ, Wise SW, Applegate J (1989) Three-dimensional sedimentary framework of the carbonate ramp slope of central west Florida: a sequential stratigraphic perspective. Geol Soc Am Bull 100:514–533

Newton CR, Mullins HT, Gardulski AF, Hine AC, Dix GR (1987) Coral mounds on the west Florida slope: unanswered questions regarding the development of deep-water banks. Palaios 2:356–367.

Neumann AC, MacIntyre I (1985) Reef response to sea level rise: keep-up, catch-up, or give-up. Proc 5th Int Coral Reef Congr, Tahiti 2:105–110

Poag W (1991) Rise and demise of the Bahama – Grand Banks gigaplatform, northern margin of the Jurassic proto-Atlantic seaway. Mar Geol 102:63–150

Purser BH (1973) The Persian Gulf: Holocene Carbonate Sedimentation and Diagenesis in a Shallow Epicontinental Sea. Berlin, Springer, 471 pp

Read JF (1982) Carbonate platforms of passive (extensional) continental margins: types, characteristics, and evolution. Tectonophysics 81:195–212

Read JF (1985) Carbonate platform facies models. Am Assoc Petrol Geol Bull 64:1575–1612

Rezak R, Bright TJ, McGrail DW (1985) Reefs and Banks of the Northwestern Gulf of Mexico, Wiley, New York, 259 pp

Sheridan RE, Mullins HT, Austin Jr. JA, Ball MM, Ladd JW (1988) Geology and geophysics of the Bahamas., in Sheridan RE, Grow JA (eds) The geology of North America, V. I-2, The Atlantic continental margin, U.S. Geol Soc Am :329–364

Shinn EA, Lidz BH, Kindinger JL, Hudson JH, Halley RB (1989) Reefs of Florida and the Dry Tortugas. American Geophysics Union Field Guide T176, p 53

Smith GB, Austin HM, Bertone SA, Hasting RW, Ogren LH (1975) Fishes of the Florida Middle Ground with comments on ecological zoogeography. Fla Mar Res Publ 9:14

Steidinger KA, Tilmant JT, Williams RO (1985) Ocean habitat and fishery resources of Florida., in Seaman Jr., W (ed) Florida Aquatic Habitat and Fishery Resources. Florida Chapter American Fisheries Society, Kissimmee, Fl, a: pp 437–542

Tilmant JT (1984) Reef fish., in Jaap WC (ed) The Ecology of the South Florida Coral Reefs: A Community Profile, US Fish and Wildlife Service FWS/OBS-82/08:52–62

Toscano MA (1996) Late Quaternary stratigraphy, sea-level history, and paleoclimatology of the southeast Florida outer continental shelf: unpublished Ph.D. dissertation, College of Marine Science, University of South Florida, 280 pp

Tucker ME, Wright VP (1990) Carbonate Sedimentology, Blackwell, p 482

Valentine P, Blackwood D, Parolski K (2000) Seabed observation and sampling system. U.S. Geological Survey Fact Sheet FS-142–00 http://woodshole.er.usgs.gov/operations/sfmapping/seaboss.htm)

Vaughan TW (1914) A contribution to the geologic history of the Florida plateau, in papers from the Tortugas Laboratory, v. IV. Carnegie Inst Wash Spec Publ 133:99–185

Vogt PR (1989) Volcanogenic upwelling of anoxic, nutrient-rich water: a possible factor in carbonate bank/reef demise and benthic faunal extinctions? Geol Soc Am Bull 101:1225–1245

Warwick RM, Clarke KR (2001) Practical measurers of marine biodiversity based on relatedness of species. Oceanog Mar Biol Ann Rev 39:207–231

Weisberg RH, He R (2003) Local and deep-ocean forcing contributions to anomalous water properties on the West Florida Shelf. J Geophys Res 108:C6, 15, doi:10.1029/2002JC001407

Weisberg RH, He R, Liu Y, Virmani JR (2005) West Florida shelf circulation on synoptic, seasonal, and inter-annual time scales, in Sturges W, Lugo-Fernandez, A (eds) Circulation in the Gulf of Mexico. Amer Geophys Union Monogr Ser 161:325–347

Wray JL (1977) Calcareous Algae, Amsterdam, Elsevier, 185 pp