ELSEVIER

Marine Geology 214 (2005) 295–307

MARINE GEOLOGY

INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

# Strange bedfellows—a deep-water hermatypic coral reef superimposed on a drowned barrier island; southern Pulley Ridge, SW Florida platform margin

B.D. Jarrett[a,*], A.C. Hine[a], R.B. Halley[b], D.F. Naar[a], S.D. Locker[a], A.C. Neumann[c], D. Twichell[d], C. Hu[a], B.T. Donahue[a], W.C. Jaap[e], D. Palandro[a], K. Ciembronowicz[b]

[a]*College of Marine Science, University of South Florida, 140 Seventh Avenue South, St. Petersburg, FL 33701, USA*
[b]*U.S. Geological Survey, Florida Integrated Science Center, Center for Coastal and Watershed Studies, St. Petersburg, FL 33701, USA*
[c]*Department of Marine Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA*
[d]*U.S. Geological Survey, Woods Hole Field Center, Woods Hole, MA 02543, USA*
[e]*Florida Marine Research Institute, St. Petersburg, FL 33701, USA*

Received 21 May 2004; received in revised form 4 November 2004; accepted 4 November 2004

## Abstract

The southeastern component of a subtle ridge feature extending over 200 km along the western ramped margin of the south Florida platform, known as Pulley Ridge, is composed largely of a non-reefal, coastal marine deposit. Modern biostromal reef growth caps southern Pulley Ridge (SPR), making it the deepest hermatypic reef known in American waters. Subsurface ridge strata are layered, lithified, and display a barrier island geomorphology. The deep-water reef community is dominated by platy scleractinian corals, leafy green algae, and coralline algae. Up to 60% live coral cover is observed in 60–75 m of water, although only 1–2% of surface light is available to the reef community. Vertical reef accumulation is thin and did not accompany initial ridge submergence during the most recent sea-level rise. The delayed onset of reef growth likely resulted from several factors influencing Gulf waters during early stages of the last deglaciation (~14 kyr B.P.) including; cold, low-salinity waters derived from discrete meltwater pulses, high-frequency sea-level fluctuations, and the absence of modern oceanic circulation patterns. Currently, reef growth is supported by the Loop Current, the prevailing western boundary current that impinges upon the southwest Florida platform, providing warm, clear, low-nutrient waters to SPR. The rare discovery of a preserved non-reefal lowstand shoreline capped by rich hermatypic deep-reef growth on a tectonically stable continental shelf is significant for both accurate identification of late Quaternary

---

* Corresponding author. Tel.: +1 727 553 1183; fax: +1 727 553 1189.

*E-mail addresses:* bjarrett@marine.usf.edu (B.D. Jarrett), hine@marine.usf.edu (A.C. Hine), rhalley@usgs.gov (R.B. Halley), naar@marine.usf.edu (D.F. Naar), stan@marine.usf.edu (S.D. Locker), aneumann@email.unc.edu (A.C. Neumann), dtwichell@usgs.gov (D. Twichell), hu@carbon.marine.usf.edu (C. Hu), briand@marine.usf.edu (B.T. Donahue), Walt.Jaap@fwc.state.fl.us (W.C. Jaap), palandro@marine.usf.edu (D. Palandro), kciembro@usgs.gov (K. Ciembronowicz).

doi:10.1016/j.margeo.2004.11.012

sea-level position and in better constraining controls on the depth limits of hermatypic reefs and their capacity for adaptation to extremely low light levels.

*Keywords:* Biostrome; Hermatypic reef; Barrier island; Paleoshoreline; sea-level change

## 1. Introduction

An anomalously deep and healthy hermatypic coral reef extends ~32 km N–S along the outer margin of the southwest Florida platform in 60–75 m of water (Fig. 1A). Displaying maximum local relief up to 10 m, this reef-capped ridge (SPR) forms the southeastern component of a more extensive, ~200-km-long rocky ridge system called Pulley Ridge (Fig. 1B). Pulley Ridge is located seaward of SPR and crests between 80 and 90 m below sea-level (Fig. 1B). Unlike SPR, the southern portion of this deeper-water ridge system supports a benthic cover consisting primarily of coralline algae (Fig. 2D,E).

Holmes (1985) identified four post-Miocene reef complexes on the southwest Florida platform, including a 10-km-wide zone of reef-like structures and patchy hardgrounds within the geographic confines described herein as SPR (Fig. 1A). Additionally, live corals associated with coralline algal pavements have been described from SPR in a series of U.S. government reports (e.g., Environmental Science and Engineering, et al., 1987); however, no follow-up research was conducted.

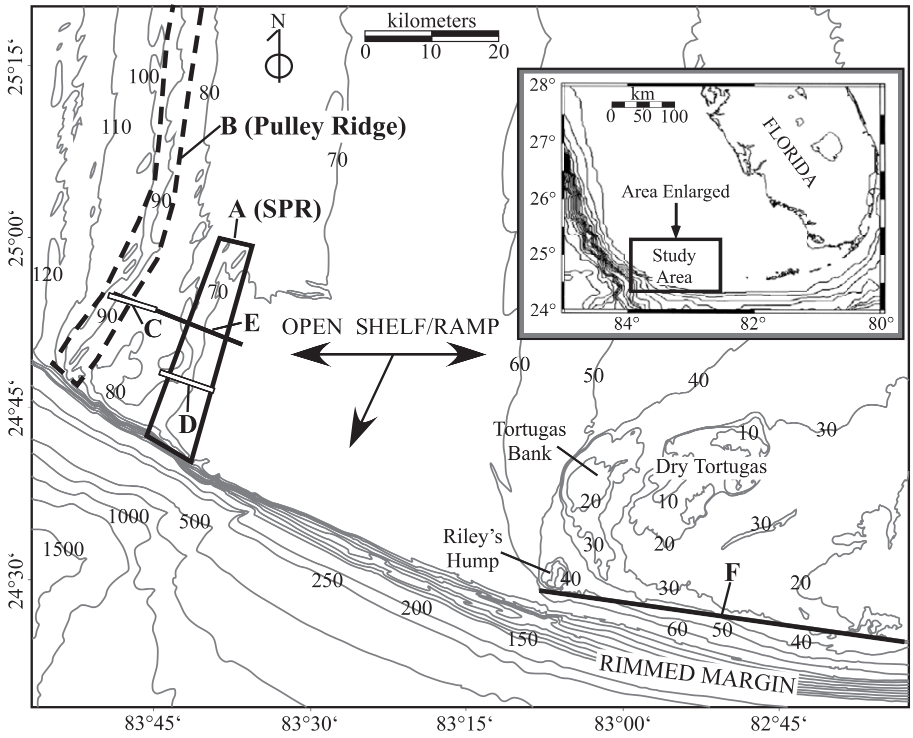

Fig. 1. Location map of southwest Florida margin (contours in meters). A: Boxed area marks location of SPR and 300-kHz multibeam bathymetry coverage. B: Dashed area outlines the southern portion of Pulley Ridge, a feature that extends over 200 km N–S. C and D: Locations of seismic reflection profiles displayed in Figs. 2 and 3, respectively. E and F: Locations of satellite data time-series transects used for comparison of surface waters influencing deep (SPR) (E) and shallow (south of Dry Tortugas) (F) reef environments (results shown in Fig. 5).

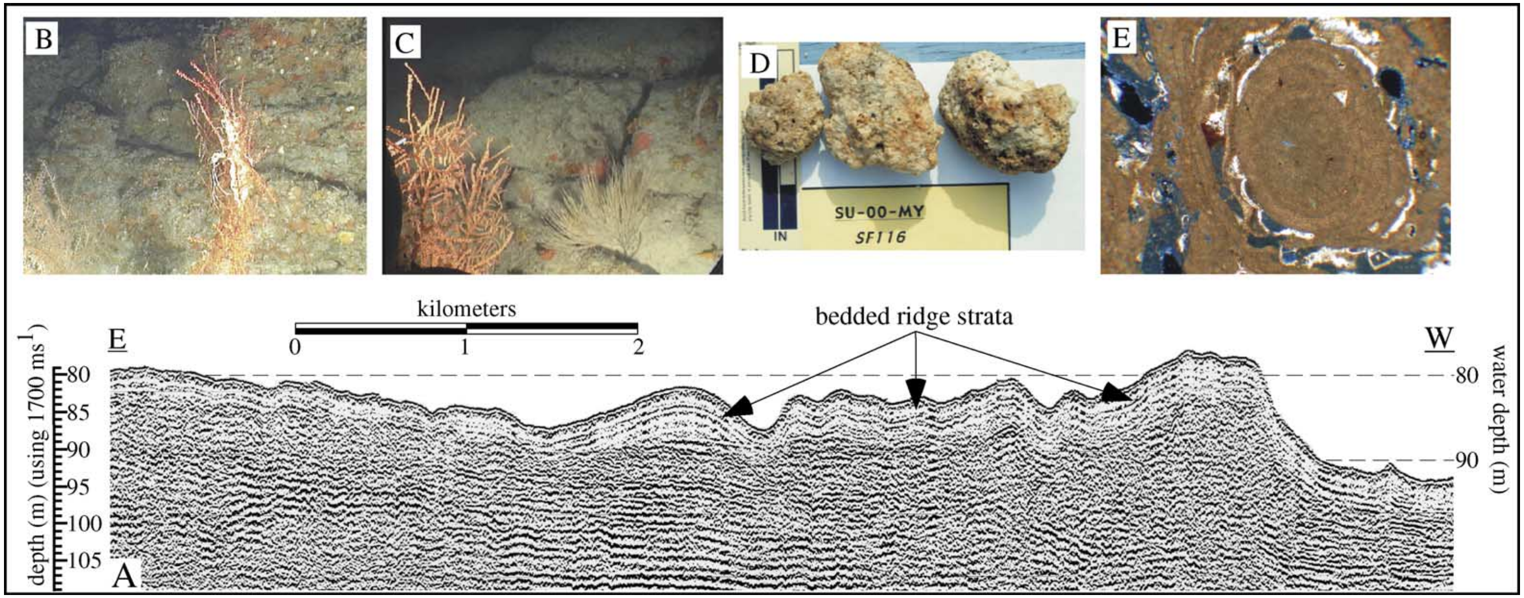

Fig. 2. Features of the seaward component of SPR in 80 to 90 m of water. A: Seismic reflection line shows irregular topography and internal acoustic facies, which are characterized by layered stratal surfaces (non-reefal). B and C: Video imagery of ridge outcrops reveal tabular, bedded deposits and rectilinear jointing consistent with a coastal marine origin (i.e., beach, eolian, beachrock). D: Coralline algal nodules (rhodoliths) commonly produce vast cobble fields atop the deep-water ridge (rhodolith facies). E: Thin-section photomicrograph of rhodolith facies reveals coralline algal boundstone (field of view=2.4 mm).

While previous work has documented the presence of live reef at SPR, the nature of the ridge substrate, the extent of coral cover and associated benthic community (both carbonate and non-carbonate-producing), the surrounding sedimentary facies, and the controls on the existence of this enigmatic coral reef had not been determined. Therefore, the purpose of this study was to investigate the subsurface depositional history of the ridge, its surface geomorphology, the modern distribution of organisms and sediments, and surrounding water-column characteristics to determine the late Quaternary development of an outer-ramp carbonate ridge complex that is believed to support the deepest hermatypic coral reef in American waters. Additionally, surface waters and dominant benthic biota are compared from reef environments across the south Florida platform to explain the paradox between healthy deep reefs at SPR and declining shallow reefs on the well-studied Florida Keys reef tract (e.g., Dustan and Halas, 1987; Porter and Meier, 1992; Lidz and Hallock, 2000).

## 2. Methods

High-resolution single-channel digital seismic reflection data (Huntec Boomer/Elics Delph Seismic) (~256 trackline km) and multibeam bathymetric mosaics (300-kHz Kongsberg Simrad EM 3000) were used to map and interpret the geological origin of SPR. Multibeam depths were corrected for daily tidal variations (He and Weisberg, 2002) and a TSS brand POS/MV 320-V2 position and orientation system and Sea Bird CTD were used for roll, pitch, heave, and sound velocity profile compensation. Additionally, 100-kHz side-scan sonar data were collected (Edgetech DF-1000/Triton Elics ISIS) and mosaicked (XSONAR, WHIPS, PCI) to augment multibeam imagery.

Twenty-eight video transects were made between 1999 and 2003 using ROV (*Phantom S2*) and manned submersible (*DeepWorker*) technologies as well as the USGS Seabed Observation and Sampling System (*SEABOSS*), providing still camera and sampling capabilities. The majority of video imagery was collected within SPR; however, *DeepWorker* transects were also conducted across portions of the deeper-water ridge located seaward of SPR. CTD casts with an attached light transmissometer allowed for interpretation of vertical water-column structure and light penetration.

Five dredge samples, supplemented by material collected from *Phantom S2*, *DeepWorker*, and *SEABOSS* allowed for sedimentary and biological analyses of surficial sediments within the study area.

Satellite data were used to determine surface characteristics of waters bathing SPR reefs as well as to compare with waters influencing shallow-water reef environments south of the Dry Tortugas (Fig. 1E,F). Sea surface temperature (SST) from 1994, 1997, and 1999 along with ocean color (chlorophyll *a* proxy) data from 1997 and 1999 were collected by the Advanced Very High Resolution Radiometer (AVHRR) sensors and the Sea-Viewing Wide Field-of-View (SeaWiFS) sensor, respectively. Data were recovered using the High-Resolution Picture Transmission (HRPT) antenna located at the University of South Florida in St. Petersburg, Florida.

## 3. Results

### 3.1. The antecedent substrate—a drowned, lithified barrier island

A lush biological cover over the majority of SPR masks underlying rocks and prohibits clear determination of the antecedent depositional environment from video observations. However, the seaward component of SPR (Fig. 1B), in 80–90 m of water, is less biologically encrusted due to increased water depths. Here, video from rock outcrops clearly reveal a non-reefal origin for the ridge edifice. Horizontal layered bedding patterns are apparent both in outcrop and in seismic reflection profiles (Fig. 2A,B,C). Further, these tabular rocks often display rectilinear jointing, consistent with beachrock formation (Fig. 2C).

Using submersible video imagery, Locker et al. (1996) described similar bedding patterns and obtained rock samples from four lithified paleoshorelines on the south Florida margin southwest of the Marquesas Keys (~140 km east–southeast of SPR). The paleoshorelines formed from brief sea-level stillstands during the last deglaciation ($^{14}$C AMS dates of 14.5 to 13.8 kyr B.P.) (Locker et al., 1996). These oolitic-grainstone shorelines crest between 60 and 94 m below sea level, as

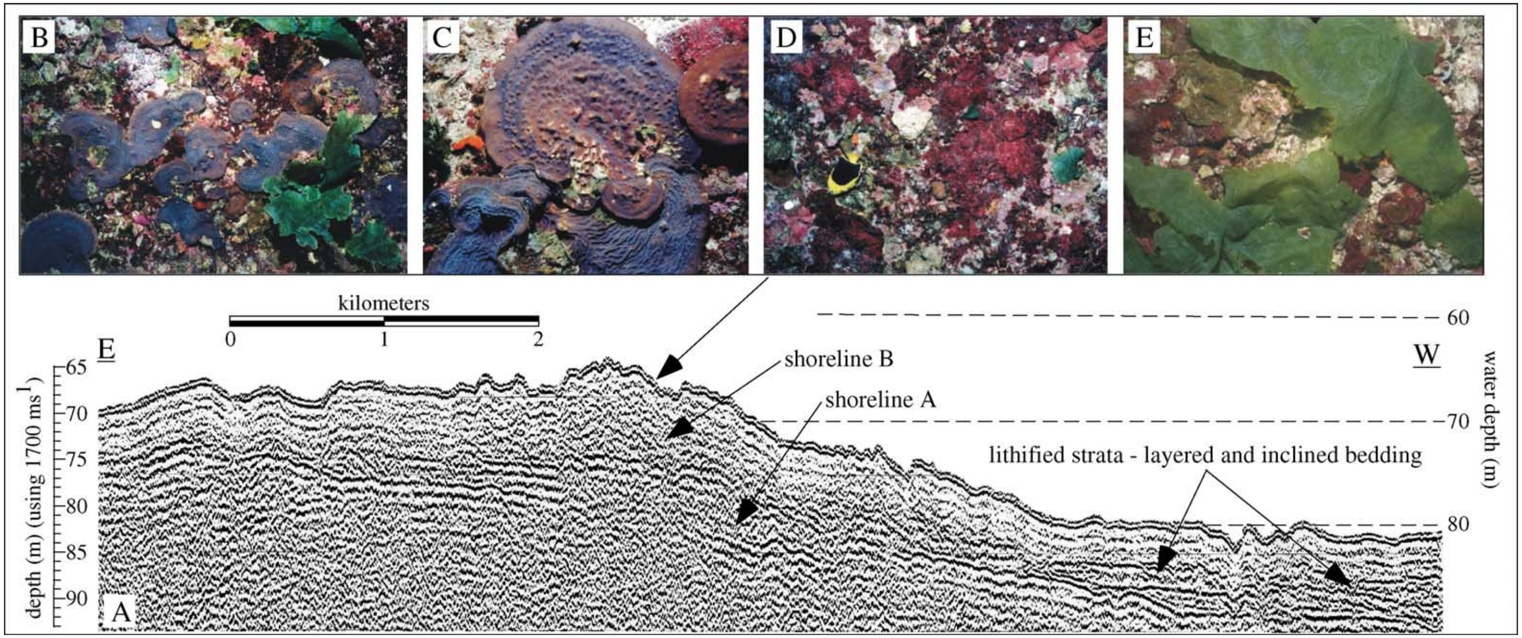

Fig. 3. Geological and biological components of SPR. A: Seismic reflection line shows subtle relief and an irregular surface. Acoustic facies are layered, coherent, and two phases of shoreline development (extending ~30 km N–S) are recognized from the subsurface. No evidence of vertically extensive reef growth is seen from seismic data. B, C, D, and E: Imagery of biostromal hermatypic reef community capping SPR. Plate corals of the Family Agariciidae (B, C), encrusting coralline algae (B, D), and the non-calcareous leafy green algae *A. menziesii* (B, E) are the most abundant sessile epifauna.

does the ridge complex at SPR. Most likely, both sets of ridges are contemporaneous even though not physically contiguous. Like paleoshorelines southwest of the Marquesas Keys, the SPR ridge complex is lithified. This is affirmed directly from rock outcrops (Fig. 2B,C) and indirectly from high-amplitude bedded reflectors visible in seismic reflection profiles (Figs. 2A and 3A), and indicates that carbonate sediments constituting these paleoshorelines were subject to rapid sub-aerial and submarine cementation, allowing them to resist erosion during ensuing sea-level rise (e.g., Locker et al., 1996). Regardless of whether these two ridge systems from the south Florida platform are contemporaneous, direct observations of the 80–90-m-deep ridge seaward of SPR show no indications of reefal accretion (other than capping), and the interpretations from exposed outcrops therein are consistent with known, drowned paleoshorelines (e.g., beach or dune facies).

From seismic reflection profiles across SPR and its seaward component, the dominant internal acoustic facies consist of layered, continuous, clearly traceable parallel to subparallel stratal surfaces consistent with a barrier island depositional setting (Figs. 2A and 3A). In places, high-amplitude reflectors are inclined (Fig. 3A), indicative of a subtidal beach or eolian setting, and acoustically chaotic seismic facies typical of reefs such as are found on the south Florida margin (Mallinson et al., 2003) are not seen.

Further, two episodes of paleoshoreline development are mapped from the subsurface of SPR (Fig. 3A), whose physical dimensions, depth of formation, and acoustic signatures are strikingly similar to the oolitic paleoshorelines described by Locker et al. (1996). The combined maximum vertical accumulation of SPR paleoshoreline sequences is ~15 m, with an estimated 1–2 m of surficial reef growth. In summary, seismic data reveal no evidence for extensive, pre-modern reef development from the subsurface of SPR.

Finally, multibeam bathymetry data at SPR display convincing evidence for a barrier island origin (Fig. 4A). A drumstick morphology, multiple prograding beach ridges, recurved spits, relict inlets and tidal channels, and a well-developed cuspate promontory (cape), all classic barrier island features, are evident in the multibeam imagery (Fig. 4A). Although longer than most modern drumstick barrier islands, the geomorphological features readily apparent from multibeam data correlate well with modern barrier islands such as those along the U.S. Southeast Embayment (coastlines of South Carolina and Georgia) (e.g., Hayes, 1994) (Fig. 4B).

### *3.2. Benthic community*

Currently, a healthy deep-water biostrome colonizes SPR, giving the seafloor a strikingly flat but shingled appearance in ROV imagery (Jarrett et al., 2000) (Fig. 3B,C). The most common scleractinian corals are members of the Family Agariciidae. Tan-brown colonies of *Agaricia lamarcki* and *Agaricia fragilis* are most abundant, along with *Leptoseris cucullata*, whose deeply pigmented blue-purple plates overlap in a shingle-like pattern (Fig. 3B,C). Individual plates are as much as 50 cm in diameter and account for up to 60% live coral cover at some localities (Halley et al., 2003). Less abundant but commonly encountered stony corals include *Madracis formosa*, *Madracis pharensis*, and *Madracis decactis*, forming low buildups of densely packed colonies. Additional stony corals displaying high inter-site variability include *Montastrea cavernosa* (in platy habit), *Porites divaricata*, *Scolymia cubensis*, and *Oculina tenella*. Corals appear healthy at SPR, with no evidence of either coral bleaching or disease (Fig. 3B,C) and are found to water depths of 75 m.

Coralline algae approximate stony coral in abundance. Dredge samples and video observations from shallower portions of the ridge (<70 m) reveal coralline algae primarily in the form of individual layered crusts and thin encrustations on *Agaricia* sp. coral (Fig. 3B,D). Deeper portions of SPR (>70 m) and its seaward component support coralline algal nodules (rhodoliths) (Fig. 2D,E), which produce vast cobble-zone fields. Rhodoliths, common in south Florida, are found on the Florida Keys outer-shelf (Prager and Ginsburg, 1989) and on the upper-slope of the non-reef-rimmed margin connecting the Florida Keys with SPR (Jarrett, 2003).

Other abundant contributors to the benthic epifauna are the non-calcareous green algae *Anadyomene menziesii* (Fig. 3B,E). These dark-green fan-shaped algae cover many hectares at densities of tens of individuals per square meter (Halley et al., 2003). Less abundant macroalgae include *Halimeda tuna*,

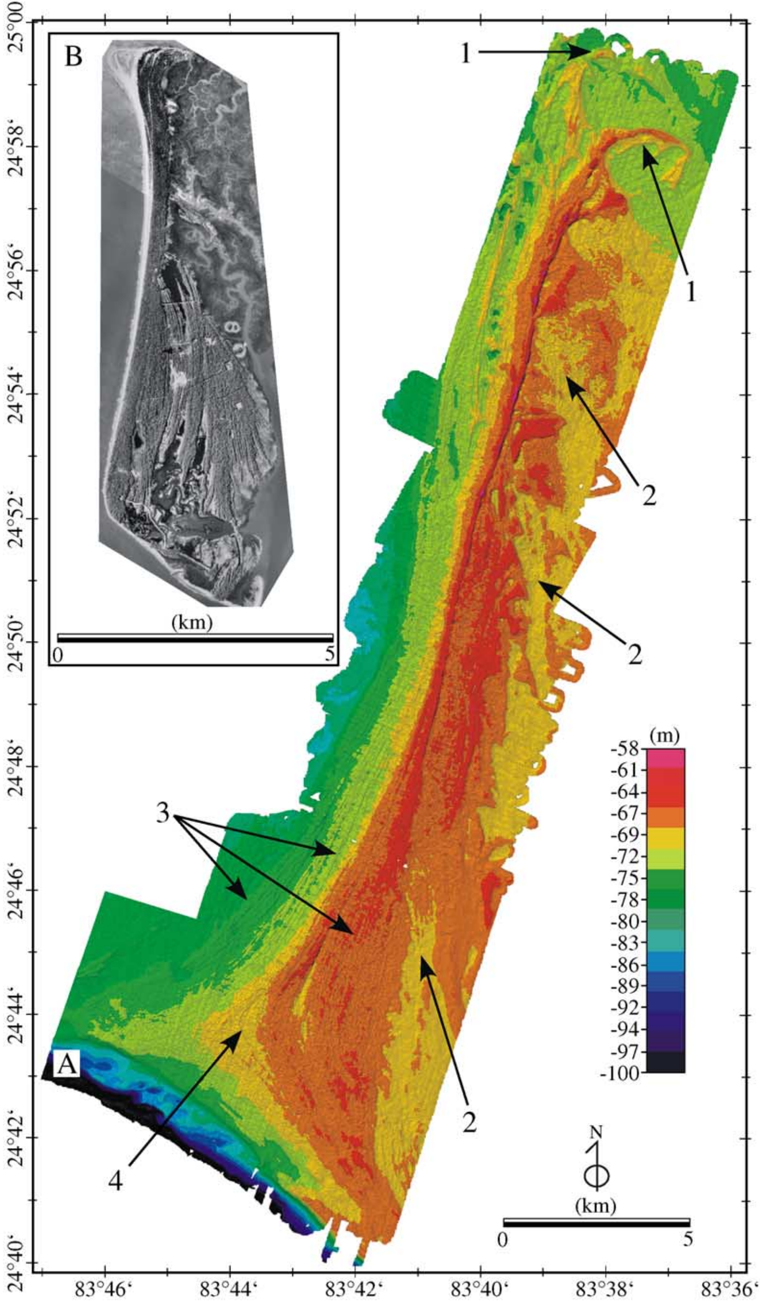

Fig. 4. A: Multibeam bathymetry data from SPR display characteristics common to barrier islands including; 1: recurved spits, 2: tidal inlets and channels, 3: prograding beach ridges, and 4: cuspate promontory and drumstick shape. B: Aerial photo of modern drumstick barrier (Bull Island) from the coastline of South Carolina shows similar geomorphology as SPR. Bull Island photo oriented SE (top) and NW (bottom).

*Dictyota divaricata*, *Lobophora variegata*, *Ventricaria ventricosa*, *Verdigelas peltata*, and *Kallymenia* sp. Finally, interspersed within this reef environment are sponges (solitary and encrusting), zooxanthellate and azooxanthellate octocorals, antipatharians, and patches of carbonate sediment.

### *3.3. Ocean circulation and other key environmental parameters*

Such moderate to high benthic productivity at depths of 60–75 m is highly unusual in the Gulf of Mexico. Environmental factors other than available substrate are believed important in sustaining this coral reef.

The Loop Current dominates circulation in the eastern Gulf of Mexico and has played a significant role as a major boundary current in controlling deposition on the outer ramp of west Florida since the mid-Miocene (Mullins et al., 1987). The current enters the Gulf of Mexico through the Yucatan Channel, flows northward, curves clockwise creating a wide loop, and then heads southward where it exits the Gulf through the Florida Straits and becomes part of the Gulf Stream (Nowlin and McLellan, 1967; Hofmann and Worley, 1986). Near-surface velocities are on the order of 100 cm $s^{-1}$ (Chew, 1974) and have been reported as high as 150 cm $s^{-1}$ (at 300 m) in the Yucatan channel (Nowlin and McLellan, 1967). Recent physical oceanographic studies reveal complex interactions between the Loop Current and circulation on the Florida platform (e.g., Weisberg and He, 2003).

Away from Loop Current influence, shallow-water coral reef environments located south of the Dry Tortugas along the westernmost south Florida reef tract (Fig. 1F) are declining. Here, on low-relief octocoral-dominated reefs in 10–30 m of water, corals are commonly diseased or heavily epiphytized, water clarity is moderate to poor containing abundant particulate matter, reefs are severely bioeroded, and filamentous/branching brown algae are pervasive (Jarrett et al., 1999).

Satellite imagery of SST and chlorophyll *a* data confirm the influence of Loop Current waters as a significant oceanographic boundary separating warm, low-nutrient, outer-shelf waters from cooler, higher-nutrient, interior-shelf waters (Fig. 5A,B). SST gradients are sharply defined during winter–spring and become more diffuse during summer–fall as temperatures warm uniformly across the southeastern Gulf. SPR reefs are situated on the eastern boundary of this warm low-nutrient water mass (Fig. 5A,B), whereas reefs located south of the Dry Tortugas are subject to seasonal temperature–nutrient–turbidity fluctuations from interior-shelf waters that flow unimpeded over the western south Florida shelf (Fig. 5A,B).

Excessive nutrients are one of the greatest threats to coral reefs, favoring heterotrophic suspension feeding organisms and benthic plants over phototrophic animal–plant symbionts (e.g., Hallock and Schlager, 1986). Annual time-series transects of chlorophyll *a* values underscore a significant surface-water nutrient difference between the two aforementioned reef environments. For 1999, chlorophyll *a* values at SPR typically ranged between 0.1 and 0.2 mg/m$^3$ and did not exceed 0.3 mg/m$^3$ (Fig. 5C). In contrast, waters impacting reefs south of the Dry Tortugas over the same time period were between 0.25 and 0.4 mg/m$^3$ for eight months of the year (Fig. 5C). For comparison, Hallock et al. (1988) defined a chlorophyll *a* gradient between healthy reefs on the north coast of Jamaica (<0.1 mg/m$^3$) and algal-sponge-dominated benthic communities on several drowning platforms southwest of Jamaica (0.1–0.2 mg/m$^3$).

At both SPR and south of the Dry Tortugas, surface water cholorophyll *a* values indicate an intermediate nutrient flux (0.1–1.0 mg/m$^3$) (i.e., mesotrophic conditions; Mutti and Hallock, 2003), an environment likely to favor algal-sponge-dominated benthic communities. However, a persistently lower nutrient flux at SPR (Fig. 5C), combined with associated high water clarity allows for hermatypic coral dominance despite mesotrophic conditions. In contrast, surface water chlorophyll *a* values south of the Dry Tortugas are significantly higher (0.25–0.4 mg/m$^3$) than those bathing reefs of the Nicaraguan Rise and support a similar algal-sponge biota.

For shallow reefs south of the Dry Tortugas, no significant rock island barriers (such as the subaerially exposed islands of the Florida Keys to the east) are present bankward of the reef tract to prevent the transfer of sediment-laden, nutrient-rich waters derived from shallow coastal environments and Florida Bay. This results in algal-overgrown, “give-up” reefs (Neumann and Macintyre, 1985) and poor water quality across this reef tract, despite water depths conducive for reef construction (Jarrett et al., 1999; Mallinson et al., 2003).

In contrast, Loop Current waters sustain and promote deep-water reef productivity at SPR. Satellite data show that persistent nutrient and temperature

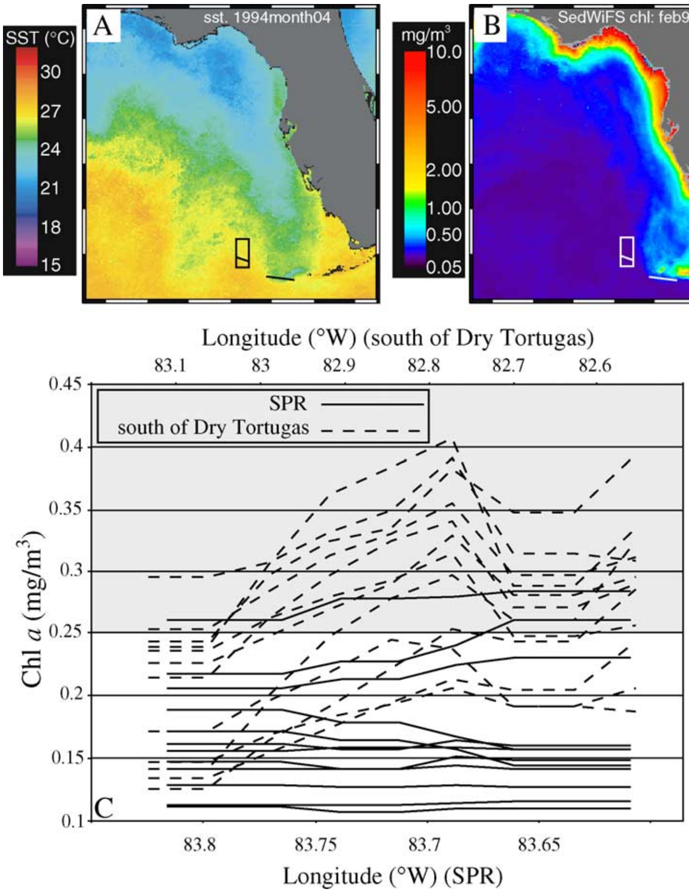

Fig. 5. A and B: Monthly composites of SST (A) for April 1994 and chlorophyll *a* (B) for February 1999 in the eastern Gulf of Mexico. Boxed areas outline location of SPR, and line segments mark spatial coverage of time-series transects. SPR is situated on the eastern boundary of Loop Current influence, thereby receiving warmer, lower nutrient surface waters than occurs on the shelf to the east. C: Comparison of chlorophyll *a* values (monthly composites for 1999) along time-series transects. SPR values are significantly lower (<0.2 mg/m$^3$ for 9 months) than within waters influencing reefs south of the Dry Tortugas. Along with temperature and nutrient characteristics conducive for reef development, the Loop Current also provides high water clarity to the southwestern margin, thus further promoting reef productivity.

gradients cross the southwest Florida platform due to the semi-fixed, Loop Current/shelfal water-mass boundary, resulting in warm, low-nutrient surface waters at the study area (Fig. 5A,B). Hydrographic data support these findings of persistent advection of Loop Current waters onto the shelf of the southwest Florida platform. Law (2003) used satellite altimetry, SST, and ocean color to investigate the extent to which deep ocean boundary currents (Loop Current, Florida Current, Gulf Stream) force flow onto the continental shelf. Results from a nine-year record revealed that the region seaward of the southwestern Florida shelf was the only area where a deep-ocean boundary current was observed to force flow consistently on and off the outer- to mid-shelf region (Law, 2003). From video, water clarity is pristine at SPR, supporting the conclusions of Calder and Haddad (1979) that Loop Current water transparency is comparable to that of the Sargasso Sea. These combined influences along with suitable substrate provided by the drowned lithified barrier island are believed to result in the proliferation of deep-water reefs at SPR.

Amazingly, the largely photosynthetic reef community at SPR is thriving on only 1–2% (5–30 microEinsteins/m$^2$/s) of available surface light (PAR) and about 5% of the light typically available to shallow-water reefs (500–1000 microEinsteins/m$^2$/s) (Halley et al., 2003). The variety and extent of photosynthetic organisms between 60 and 75 m of water and their adaptive ability to flourish in such low-light conditions is extraordinary. While studies on coral reefs around Jamaica and Bahamas report hermatypic coral reef communities in comparable water depths (70 m) (e.g., Goreau and Wells, 1967; Jaap and Olson, 2000), SPR is believed to be the deepest hermatypic reef of its kind in American waters (Halley et al., 2003).

## 4. Discussion

### 4.1. Preservation of the Pulley Ridge paleoshoreline complex

Significant sea-level lowstands, such as the Last Glacial Maximum (LGM), most likely produced abundant coastal and shallow-marine deposits worldwide. However, their discovery has been rare due to the erosive effects of post-depositional sea-level rise, burial, and the logistical difficulties involved in locating and identifying such deposits. Preservation potential is especially low for coastal siliciclastic environments, where cementation does not accompany or shortly follow deposition. In contrast, carbonate sediments may be rapidly cemented due to their propensity toward early diagenesis (e.g., Bathurst, 1975; Tucker and Wright, 1990). Thus, rapid cementation allows for significantly higher preservation potential of lowstand carbonate coastal deposits (Fig. 6A). Where found, such lowstand deposits, whether reefal or coastal, have proven invaluable in accurately marking past sea-level positions, estimating rates of sea-level rise, and in calibration of proxy eustatic sea-level curves (e.g., Fairbanks, 1989; Fletcher and Sherman, 1995; Locker et al., 1996). The extensive paleoshoreline complex at SPR is located on a classic, distally inclined carbonate ramp (Ahr, 1973; Read, 1985; Mullins et al., 1988a,b) (Fig. 1). The broad, open, mildly dipping ramp slope has provided an ideal template for extensive lowstand paleoshoreline development. Such carbonate ramps provide excellent sites to record minor sea-level changes, because shorelines can easily migrate significant distances in response.

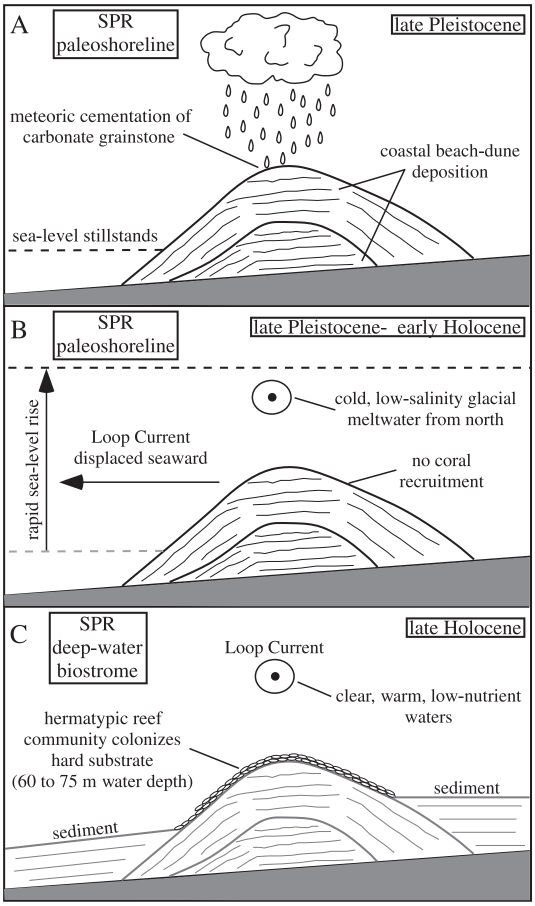

Fig. 6. Conceptual illustration of the proposed processes and timing of events in the evolution of SPR. A: During the late Pleistocene sea-level rise following the LGM, periodic sea-level stillstand events allowed for accumulation of carbonate strandline deposits in a coastal depositional setting. Meteoric waters rapidly lithified the sub-aerial grainstone. B: A rapid late Pleistocene sea-level rise protected the SPR paleoshoreline from erosion due to wave action. Additionally, glacial meltwater pulses and the seaward displacement of the Loop Current during the late Pleistocene to early Holocene prohibited coral reef development at SPR. C: Responding to late Holocene Loop Current circulation patterns, a deep-water hermatypic biostrome capped the lithified paleoshoreline deposit as a thin veneer, and zooxanthellate stony corals are presently found to 75 m water depth.

With reefs currently capping SPR, it is fair to question as to how the modern seafloor maintains a barrier island geomorphology (i.e., Fig. 4). First, modern reef growth is biostromal, conforming to the bathymetric contours of the underlying paleoshoreline, thereby not obscuring the antecedent geomorphology of the strandline deposit. Second, the capping reef facies is estimated no more than 1–2 m in thickness from seismic data. Had extensive vertical reef growth occurred after submergence of SPR, it is probable that the bathymetric detail of the paleoshoreline would be obscured from view using surficial sonar techniques.

### *4.2. Delayed onset of SPR reef growth after submergence*

The time of reef initiation at SPR is unclear. Holmes (1985) reported a mid-Holocene age for coralline algae radiocarbon-dated from SPR. Of five coral samples radiocarbon-dated for this study, all contained bomb carbon (post-1950). As stated, the reef facies is probably no more than 1–2 m thick. So, why did thick shallow-water reefs not grow immediately following shoreline drowning when water depths were more conducive to hermatypic reef growth?

By careful dating of paleoshorelines on the south Florida margin, Locker et al. (1996) showed definitive physical evidence for centennial-scale, episodic and rapid sea-level fluctuations during the last deglaciation. These data are supported by additional shoreline studies (e.g., Carter et al., 1986; Sager et al., 1992; Fletcher and Sherman, 1995) as well as by studies of ice-sheet dynamics and ice cores (e.g., Anderson and Thomas, 1991; MacAyeal, 1993; Bond and Lotti, 1995). Specifically correlated to the timing of south Florida shelf paleoshorelines dated between 15 and 13 kyr B.P. (Locker et al., 1996) are stable-isotope records of meltwater pulses off the Scotian margin (Keigwin and Jones, 1995) and iceberg discharges/ice-rafting subevents in the North Atlantic (Bond and Lotti, 1995; Grousset et al., 1993).

These records indicate that high-frequency sea-level and climate changes occurred during early stages of the Pleistocene–Holocene transition. Furthermore, several deglacial meltwater pulses are recognized from the Gulf of Mexico. Leventer et al. (1982) report two major discharge events of meltwater into the Gulf of Mexico lasting between 16.5 and 11.6 kyr B.P. Flower et al. (2004) resolve similar discharge events with peak meltwater influx from 14.5 to 13 kyr B.P. Such pulses of cold, low-salinity water and accompanying rapid sea-level rises could have retarded shallow-water reef growth upon submergence of the barrier island forming SPR (Fig. 6B). Finally, during initial ridge submergence, with substantially lowered sea-level position, it is probable that Loop Current circulation patterns were displaced seaward, thus not influencing this portion of the platform as in the modern (Fig. 6B). Therefore, it is understandable why coral reefs, which require strict environmental conditions and stable sea-level for maximum productivity, did not appear until the late Holocene, when more amenable conditions returned, even in the face of increased water depth (Fig. 6C).

## 5. Conclusions

A healthy deep-water biostrome caps a drowned late Quaternary barrier island as a thin veneer on the southwest margin of the Florida Platform. The finding is significant because: (1) drowned barrier island shorelines are rarely preserved; however, rapid cementation on a ramped carbonate outer-shelf allowed for preservation of SPR and further provided hard substrate for later coral reef growth; (2) the depths (60–75 m) at which photosynthetic-dependent reef biota are found at SPR makes this biostromal reef community one of the deepest of its type as a result of interaction with reef-sustaining Loop Current waters; and (3) the abundance of hermatypic organisms and the adaptive ability of the reef community at SPR to survive on exceedingly low light levels are comparatively rare adaptations of corals and their associated organisms to attenuated light conditions at depth.

## Acknowledgements

We thank the U.S. Geological Survey Coastal and Marine Geology Program, the NOAA National Undersea Research Center (UNCW-NURC), the Office of Naval Research (DOD-DURIP), and the Florida Institute of Oceanography (FIO) for support of this research. We gratefully acknowledge the skilled crews and scientific participants from cruises aboard the R/V *Suncoaster*, R/V *Bellows*, and M/V *Spree* between 1999 and 2003. Additional thanks are extended to the Sustainable Seas Expeditions (SSE) of 2000 and 2001, led by Dr. Sylvia Earle. Helpful discussions and direction were provided by Pamela Hallock and Frank Muller-Karger. Finally, special thanks to Beau Suthard for exceptional support on cruises and with technical assistance.

## References

Ahr, W.M., 1973. The carbonate ramp: an alternative to the shelf model. Trans.-Gulf Coast Assoc. Geol. Soc. 23, 221–225.

Anderson, J.B., Thomas, M.A., 1991. Marine ice-sheet decoupling as a mechanism for rapid, episodic sea-level change: the record of such events and their influence on sedimentation. Sediment. Geol. 70, 87–104.

Bathurst, R.G.C., 1975. Carbonate sediments and their diagenesis, second ed. Elsevier, New York. 658 pp. Chapter 8.

Bond, G., Lotti, R., 1995. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. Science 267, 1005–1010.

Calder, K.L., Haddad, K.D., 1979. Transmissometry on the eastern Gulf shelves. MAFLA Survey 1976–1978: Mississippi, Alabama, Florida outer continental shelf Baseline Environmental Survey 1977/1978, IIB. Bureau of Land Management, Washington, DC, pp. 931–989.

Carter, R.M., Carter, L., Johnson, D.P., 1986. Submergent shorelines in the SW Pacific: evidence for an episodic post-glacial transgression. Sedimentology 33, 629–649.

Chew, F.C., 1974. The turning process in meandering currents: a case study. J. Phys. Oceanogr. 4, 27–57.

Dustan, P., Halas, J.C., 1987. Changes in the reef-coral community of Carysfort Reef, Key Largo, Florida: 1974 to 1982. Coral Reefs 6, 91–106.

Environmental Science and Engineering, LGL Ecological Research Associates, Continental Shelf Associates, 1987. Southwest Florida Shelf Ecosystems Study Data Synthesis Report, Submitted under Contract No. 14-12-0001-30276 to the Minerals Management Service, New Orleans, LA, 3 vol.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642.

Fletcher, C.H., Sherman, C.E., 1995. Submerged shorelines on O'ahu, Hawaii: archive of episodic transgression during the deglaciation? In: Finkl, C.W. (Ed.), Holocene cycles: climate, sea levels, and sedimentation, J. Coast. Res. Spec. Issue vol. 17, pp. 141–152.

Flower, B.P., Hastings, D.W., Hill, H.W., Quinn, T.M., 2004. Phasing of deglacial warming and Laurentide Ice Sheet meltwater in the Gulf of Mexico. Geology 32, 597–600.

Goreau, T.F., Wells, J.W., 1967. The shallow-water Scleractinia of Jamaica: revised list of species and their vertical distribution range. Bull. Mar. Sci. 17, 442–453.

Grousset, F.E., Labeyrie, L., Sinko, J.A., Cremer, M., Bond, G., Duprat, J., Cortijo, E., Huon, S., 1993. Patterns of ice-rafted detritus in the glacial North Atlantic (40–55°N). Paleoceanography 8, 175–192.

Halley, R.B., Garrison, V.E., Ciembronowicz, K.T., Edwards, R., Jaap, W.C., Mead, G., Earle, S., Hine, A.C., Jarrett, B.D., Locker, S.D., Naar, D.F., Donahue, B., Dennis, G.D., Twichell, D.C., 2003. Pulley Ridge—the US deepest coral reef? Joint conference on the science and restoration of the Greater Everglades and Florida Bay ecosystem from Kissimmee to the Keys, GEER program and abstracts, Palm Harbor, FL, pp. 238–240.

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

Hallock, P., Hine, A.C., Vargo, G.A., Elrod, J.A., Jaap, W.C., 1988. Platforms of the Nicaraguan rise: examples of the sensitivity of carbonate sedimentation to excess trophic resources. Geology 16, 1104–1107.

Hayes, M.O., 1994. The Georgia Bight barrier system. In: Davis, R.A. (Ed.), Geology of Holocene barrier island systems. Springer-Verlag, Berlin, pp. 233–304.

He, R., Weisberg, R.H., 2002. Tides on the west Florida shelf. J. Phys. Oceanogr. 32, 3455–3473.

Hofmann, E.E., Worley, S.J., 1986. An investigation of the circulation of the Gulf of Mexico. J. Geophys. Res. 91, 14221–14236.

Holmes, C.W., 1985. Accretion of the south Florida platform, late Quaternary development. Am. Assoc. Pet. Geol. Bull. 69, 149–160.

Jaap, W.C., Olson, D., 2000. Scleractinia coral diversity and community structure: Lucaya, Grand Bahama, Bahamas. Proc. 20th AAUS Diving for sci. symp. St. Petersburg, FL, pp. 67–69.

Jarrett, B.D., 2003. Late Quaternary carbonate sediments and facies distribution patterns across a ramp to rim transition: a new conceptual model for the southwest Florida platform. PhD dissertation, University of South Florida, St. Petersburg, FL.

Jarrett, B.D., Hine, A.C., Neumann, A.C., Naar, D.F., 1999. "Give-up" late Quaternary reefs west of the Florida Keys (abs.). EOS Trans.-Am. Geophys. Union 80, F498 (Fall Meeting Suppl. Abstract).

Jarrett, B.D., Hine, A.C., Neumann, A.C., Naar, D.F., Locker, S.D., Mallinson, D.J., Jaap, W.C., 2000. Deep biostromes at Pulley Ridge; southwest Florida carbonate platform (abs.). EOS Trans.-Am. Geophys. Union 81, F737 (Fall Meeting Suppl. Abstract).

Keigwin, L.D., Jones, G.A., 1995. The marine record of deglaciation from the continental margin off Nova Scotia. Paleoceanography 10, 973–985.

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

Leventer, A., Williams, D.F., Kennett, J.P., 1982. Dynamics of the Laurentide ice sheet during the last deglaciation: evidence from the Gulf of Mexico. Earth Planet. Sci. Lett. 59, 11–17.

Lidz, B.H., Hallock, P., 2000. Sedimentary petrology of a declining reef ecosystem, Florida reef tract (U.S.A.). J. Coast. Res. 16, 675–697.

Locker, S.D., Hine, A.C., Tedesco, L.P., Shinn, E.A., 1996. Magnitude and timing of episodic sea-level rise during the last deglaciation. Geology 24, 827–830.

MacAyeal, D.R., 1993. Binge/purge oscillations of the Laurentian ice sheet as a cause of the North Atlantic's Heinrich events. Paleoceanography 8, 775–784.

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.

Mullins, H.T., Gardulski, A.F., Wise, S.W., 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. Amer. Bull. 98, 702–713.

Mullins, H.T., Gardulski, A.F., Hinchey, E.J., Hine, A.C., 1988a. The modern carbonate ramp slope of central west Florida. J. Sediment. Petrol. 58, 273–290.

Mullins, H.T., Gardulski, A.F., Hine, A.C., Melillo, A.J., Wise, S.W., Applegate, J., 1988b. Three-dimensional sedimentary framework of the carbonate ramp slope of central west Florida: a sequential seismic stratigraphic perspective. Geol. Soc. Amer. Bull. 100, 514–533.

Mutti, M., Hallock, P., 2003. Carbonate systems along nutrient and temperature gradients: some sedimentological and geochemical constraints. Int. J. Earth Sci. 92, 465–475.

Neumann, A.C., Macintyre, I., 1985. Reef response to sea-level rise: keep-up, catch-up, or give-up. Proc. 5th Int. Coral Reef Congress, Tahiti vol. 3, pp. 105–110.

Nowlin, W.D., McLellan, H.J., 1967. A characterization of the Gulf of Mexico waters in winter. J. Mar. Res. 25, 29–59.

Porter, J.W., Meier, O.W., 1992. Quantification of loss and change in Floridian reef coral populations. Am. Zool. 32, 625–640.

Prager, E.J., Ginsburg, R.N., 1989. Carbonate nodule growth on Florida's outer shelf and its implications for fossil interpretations. PALAIOS 4, 310–317.

Read, J.F., 1985. Carbonate platform facies models. Am. Assoc. Pet. Geol. Bull. 69, 1–21.

Sager, W.W., Schroeder, W.W., Laswell, J.S., Davis, K.S., Rezak, R., Gittings, S.R., 1992. Mississippi–Alabama outer continental shelf topographic features formed during the late Pleistocene–Holocene transgression. Geo Mar. Lett. 12, 41–48.

Tucker, M.E., Wright, V.P., 1990. Carbonate sedimentology. first ed. Blackwell, Oxford. 482 pp. Chap. 7.

Weisberg, R.H., He, R., 2003. Local and deep-ocean forcing contributions to anomalous water properties on the West Florida Shelf. J. Geophys. Res. 108, 15-1–15-16.