New insights into the morphology and sedimentary processes along the western slope of Great Bahama Bank

T. Mulder[1], E. Ducassou[1], G.P. Eberli[2], V. Hanquiez[1], E. Gonthier[1], P. Kindler[3], M. Principaud[1], F. Fournier[4], P. Léonide[4], I. Billeaud[5], B. Marsset[6], J.J.G. Reijmer[7], C. Bondu[1], R. Joussiaume[8], and M. Pakiades[1]
[1]Université Bordeaux 1, UMR 5805 EPOC, 33405 Talence cedex, France
[2]Division of Marine Geology and Geophysics, University of Miami, Miami, Florida 33149, USA
[3]Section of Earth and Environmental Sciences, University of Geneva, 1205 Geneva, Switzerland
[4]Géologie des Systèmes et Réservoirs Carbonatés, Université de Provence, 13331 Marseille Cedex 3, France
[5]Total Centre Scientifique et Technique Jean Féger, 64018 Pau cedex, France
[6]IFREMER, Géosciences Marines, 29280 Plouzané, France
[7]Department of Sedimentology and Marine Geology, Faculty of Earth and Life Sciences (FALW), Vrije Universiteit Amsterdam, Amsterdam, Netherlands
[8]Institut EGID, Université Bordeaux 3, 1, allée F. Daguin, 33607 Pessac Cedex, France

ABSTRACT

New high-quality multibeam and seismic data image the western slope of the Great Bahama Bank and the adjacent floor of the Straits of Florida. The extensive survey reveals several unexpected large- and small-scale morphologies. These include bypass areas, channel-levee-lobe systems, gullied slopes, and products of slope instabilities at various scales, including long slump scars at the lower slope and mass transport complexes that extend ~30 km into the adjacent basin floor. The toe of the slope is irregularly covered with deep-water carbonate mounds. The abundance of the individual morphological features varies from north to south. From 26°00′N to 25°20′N, the slope is dissected by numerous deep canyons that abruptly end southward, where the slope is characterized by a smooth lower portion and small regularly spaced furrows in its upper part. Further south, two long (25–50 km) scars document instability at the lower slope. One of these scars is the source area of a large mass transport complex. In addition to this large-scale feature, several types of gravity-induced sedimentary processes are revealed. Most of the morphologies and inferred processes of this carbonate system are similar to those observed in siliciclastic systems, including mass transport complexes, gravity currents initiated by density cascading, and overspilling channeled turbidity currents. For the first time, a clear asymmetric channel-levee system has been identified along the slope, suggesting similitude in sorting processes between carbonate and siliciclastic systems and enhancing the reservoir-bearing potential of carbonate slopes. Notable differences with siliciclastic systems include: the lack of connection with the shallow and emerged part of the system (i.e., bank top), and the small size of the sedimentary system.

INTRODUCTION

Gravitational transport processes along siliciclastic continental margins have been extensively studied, either for hydrocarbon exploration or for natural hazards. In contrast, sedimentary processes and products occurring on carbonate platform slopes are less well known despite the abundant literature existing on the sedimentation on platform tops. Carbonate-dominated systems (in particular, tropical carbonate systems) differ from their siliciclastic counterparts by the nature of the sediment input: river load for the latter, biogenic productivity and precipitation for the former. In regard to gravitational processes, tropical carbonate factories have several characteristics: (1) They generally lack one point source, but those with steep platform edges often act as a line source (e.g., Mullins et al., 1984); (2) sediment export to the slopes occurs mostly during sea-level highstands when sediment production is at a maximum (Schlager et al., 1994), although it can also occur during lowstands (Lantzsch et al., 2007), and (3) off-bank sediment transport is episodic and controlled by tides, storms, and cascading density currents (Cook and Mullins, 1983; Wilson and Roberts, 1992). In siliciclastic systems, the low buoyancy of silica particles induces a strong segregation between bed-load and suspended-load transport and a sorting of particles. This leads to the formation of extensive deep-sea turbidite systems (Normark, 1970). They result from the stacking of various bed types related to successive gravitational-transport processes. Close to the sediment source, deep canyons and other submarine valleys can incise the continental shelf and slope. Downslope, a channel-levee complex shows a channel filled by coarse-grained gravity-flow deposits and levees resulting from the deposition of spilling turbidity currents interlayered with hemipelagites. In the distal part, which can be located from tens to hundreds of kilometers from the source, sediment settles as thin lobate morphologies with a smooth topography.

The Bahamian archipelago was chosen for this study primarily because of the large amount of existing data, making the Bahamas the most studied carbonate region in the world (Ginsburg, 2001; Bergman et al., 2010, and references therein). The increase in productivity during the present highstand allowed the formation of an accretionary slope prograding westward (Rendle-Bühring and Reijmer, 2002). Consequently, interglacial deposits record more turbidites than glacial deposits (Rendle-Bühring and Reijmer, 2005). The archipelago is located on a passive continental margin, making the tectonic influence less important than sea-level changes and biogenic production with respect to redeposition processes. Finally, it is an isolated carbonate system surrounded by deep seaways that only receive siliciclastic dust carried by winds and surface/bottom currents.

In this paper, we show for the first time a morphologic convergence between channel-levee complexes in a carbonate system and their siliciclastic counterparts. This suggests that the sedimentation models in carbonate systems are more complex than expected and that a carbonate slope could hide unexpected sedimentary rock-forming reservoirs.

SETTING AND METHODS

We focused our study on the western leeward margin of Great Bahama Bank (west and south of the islands of Bimini; Fig. 1A). Carbonate deposition in the Bahamas has occurred since the Cretaceous and perhaps since the Jurassic (Eberli and Ginsburg, 1989). Great Bahama Bank is the largest carbonate platform of the archipelago and results from of the coalescence of several smaller banks (Eberli and Ginsburg, 1987). Since the Miocene, the platform has aggraded ~1500 m of carbonate sediment, and the western margin has prograded 25 km into the Straits of Florida (Eberli and Ginsburg, 1989). In the adjacent Straits of Florida, the Florida Current flows northward with a surface speed ranging from 1.8 to 2 m/s and a velocity on the seafloor of a few decimeters per second (Wang and Mooers, 1997; Fig. 1A). The Florida

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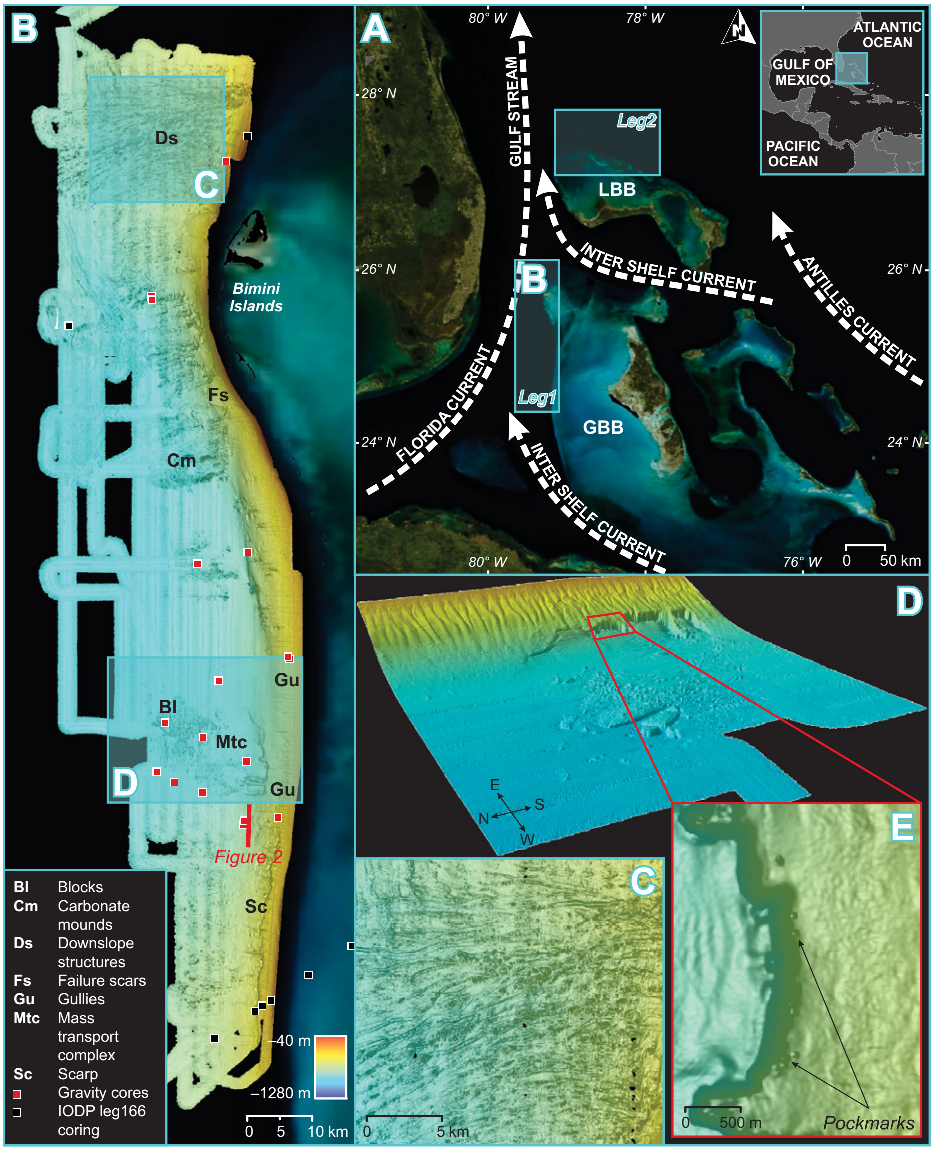

Figure 1. A: Location of two study legs of Carambar cruise, and trajectories of main oceanic currents (white dashed arrows) in western part of Bahamian Archipelago. B: Bathymetric map of carbonate slope located west of Great Bahama Bank (GBB). C: Detail of erosive furrows. D: Three-dimensional view of mass transport complex (MTC). E: Detail of small pockmarks at top of northern scar. IODP—Integrated Ocean Drilling Program.

Current does not fill the entire strait, and deep, opposing undercurrents and coastal countercurrents occur off Florida and the Bahamas. In the study area, near-bottom currents are bidirectional, dominated by semidiurnal (internal) tides, with velocities of up to 0.5 m/s on the lower slopes (Grasmueck et al., 2006). Periodically hurricanes, winter storms, and cold fronts (Wilson and Roberts, 1992) sweep off mostly fine-grained carbonates from Great Bahama Bank (Wilber et al., 1990; Eberli et al., 1997; Swart et al., 2000).

The Carambar cruise was conducted from 31 October to 29 November 2010 on the R/V *Le Suroît* along the slopes of Little and Great Bahama Banks. Its main objective was to better understand the transport of carbonate particles along submarine slopes. Onboard equipment included a Kongsberg EM302 multibeam echosounder (bathymetry and acoustic imagery), an echo subbottom profiler (Chirp frequency modulation), high-resolution multichannel seismic instrumentation, and a Kullenberg corer. Only the first part of the cruise concerned the Great Bahama Bank (Fig. 1A). Data collected during this leg include more than 4750 km^2 of multibeam bathymetry, 1480 km of very high-resolution seismic profiles (penetrating ~1 s two-way traveltime [TWTT]), and 17 gravity cores with a cumulated length of almost 100 m (Fig. 1B). This new data set on carbonate slopes adds to the extensive already-existing data on the carbonate banks, including academic and industrial seismic lines, and the results of Ocean Drilling Program (ODP) Legs 101 (Austin et al., 1988) and 166 (Eberli et al., 1997; Swart et al., 2000) and of the Bahamas Drilling Project (Ginsburg, 2001). This paper presents a short overview of the sedimentary environments identified from multibeam bathymetry with a focus on large-scale failure deposits.

RESULTS AND DISCUSSION

Three distinctive morphological domains have been identified along the slope of Great Bahama Bank: (1) bypass and/or erosion areas; (2) gullied slopes; and (3) slope failures. In addition, cold-water coral mounds are widespread in the toe-of-slope area.

Erosion Features

Bypass and/or erosion areas are mainly located in the northern part of the study area, north and just west of Bimini Islands. In this area, the slope shows a complex network of downslope incisions that are reminiscent of erosive furrows (Fig. 1C). Several-meter-high ridges separate these downslope lineaments. These erosive furrows are perpendicular to the platform margin but start to bend southward in the lower slope, suggesting that these furrows are the result of energetic downslope processes with a strong erosive power. The furrows could result from the erosive action of large lithified blocks avalanching from the bank edge. Similar slope morphology existed in the middle Pliocene on the western margin of Great Bahama Bank (Anselmetti et al., 2000). Like these older buried slope canyons, the modern ones do not connect to the platform top, indicating that they form by headward erosion from the bottom up.

Gullies and Turbidite Complexes

In the southern part of the study area, the smooth middle slope, which has a mean angle of 1.3° between the depths of 400 and 700 m, is incised by gullies (Fig. 1D). The gullies are V-shaped and ~10–20 m deep, ~3 km long, and ~400–700 m wide. They appear at 440 m of water depth and extend down to ~620 m depth. This morphology extends over 100 km from north to south. The gullies extend seaward of a smooth area interpreted as a mud-dominated zone that is a typical facies of the upper and middle slope (Wilber et al., 1990; Malone et al., 2001). The spacing between gullies decreases regularly from 1200 to 400 m from north to south, and it seems to be related to the slope angle (steeper in the north and less steep in the south). In addition, the shape of the gullies varies, being regular and straight in the north and irregular with branches in the south. Their distal fringes reach the eastern side of the Straits of Florida, where they are deflected northward. The disconnection of these gullies from the carbonate bank below a water depth of 440 m and the absence of large-scale failure scars at the

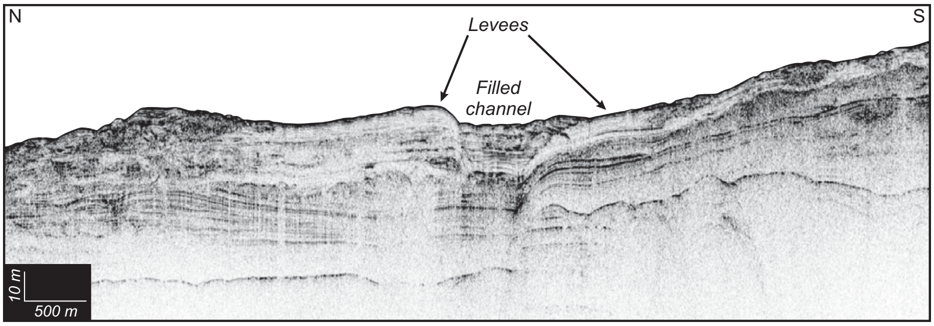

Figure 2. Very high-resolution seismic line showing a filled channel and associated levees.

gully head suggest that they form by the activity of plunging currents that reach the seafloor at ~400 m of water depth. This density-cascading phenomenon has been documented on Bahamian slopes by Wilson and Roberts (1995). This carbonate slope and basin architecture differs from the carbonate slope models described by Playton et al. (2010). Some channels show complete filling by layered sediments associated with mustache-shaped structures interpreted as sedimentary levees, indicating that turbidity currents are active in the gully floors and spill over the sides of the gullies (Fig. 2). Levees are ~20 m thick and 2 km wide. Rough undulating structures interpreted as sediment waves can be seen of the top of the levees, suggesting spillover by channeled turbidity currents. Their elevation from the bottom of the adjacent channel does not exceed 10 m. Such channel-levee complexes are known in small siliciclastic turbidite system and represent an efficient process of sediment differentiation and sorting, even along a short distance. Their discovery for the first time in a carbonate turbidite system suggests a convergence in sorting processes. Particle sorting could improve the reservoir quality of carbonate turbidites. Downslope, some of the gullies widen up and turn into depositional lobes, less than 10 m thick, extending down to ~700 m of water depth. The distal parts of the sedimentary lobes are deflected northward. The complete system, including gullies, channel, and lobes, forms one small carbonate turbidite system or carbonate fan-lobe system with a downslope extent reaching 35 km at the most. Seaward, the gravity processes are not energetic enough, and the entire particle load is pirated by along-bank sweeping currents.

Large Slope Failures and Mass Transport Complexes

Evidence of slope instability is widespread along the slope, starting at ~450–550 m of water depth, and related features are connected to downslope lineaments. Scars from slope failure are typically a kilometer wide and involve a relatively small volume of sediment (range of a few km^3). They typically evolve longitudinally toward a fan-lobe system in which erosional processes dominate over depositional systems. Tongue-shape patches of blind echo-facies are observed locally and could result from debris-flow transport of reworked coarse sediment originating from the bank, or from deep-water coral mounds. The most impressive morphological feature is a large sediment failure and its associated mass transport complex (Weimer, 1989; Fig. 1D). This mass transport complex consists of three failure scarps extending north-south over 9 km. The scar height ranges from 80 to 110 m. Scars extend northward into a deformed area. The northern scar shows small (50 m in diameter) pockmarks on its top (Fig. 1E). Downslope of the scars, the seafloor is a hummocky surface extending westward over 20 km. The width of this area is ~13 km. The surface of the entire deformed area is ~300 km^2. This hummocky seafloor could correspond to an area of partly buried blocks. It ends with large rectangular blocks, which range between 0.8 and 2 km in horizontal dimensions and ~50 m in thickness. The largest of these blocks has a surface of 2 km^2 (volume of ~0.1 km^3). The angular shape of the blocks suggests brittle collapse processes involving already lithified carbonate. Further south and toward the southern end of the study area, the slope shows a 50-m-high scarp at 450 m water depth extending over 35 km. This incipient slope failure is interpreted as a slow deformation area (creeping). No significant sedimentary accumulation occurs at a distance exceeding 20 km from the platform margin.

Cold-Water Coral Mounds

Cold-water corals forming large carbonate mounds dominated by the genus *Lophelia* are widespread in the area (Fig. 1B). They are made of noncemented coral fragments and living organisms in a coarse-grained matrix. They extend from 400 to 800 m of water depth, forming patches and lined-up clusters. Bidirectional sedimentary structures indicate activity of an internal tide at these depths. Their distribution varies along Great Bahama Bank from north to south. North of Bimini, they are very abundant, have a high relief (up to 70 m of elevation above the seafloor), and are aligned along ridges mostly perpendicular to the bank margin. South of Bimini, mounds are less dense and smaller. They are also associated with the mass transport complex, colonizing the large slide blocks (Foubert and Henriet, 2009). Mounds preferentially seem to settle on topographic highs (gully ridges and blocks). These preliminary observations suggest that their size and distribution are not controlled by the activity of the Florida Current (Neumann et al., 1977; Mullins et al., 1981; Paul et al., 2000) but rather by internal tides and slopes. Locally, they control sedimentation processes like sediment accumulation and grain size.

CONCLUSIONS

The Great Bahama Bank shows a strong interplay between various sedimentary processes such as in situ pelagic production, sediment export from the bank, and density cascading that can be related to gully formation at the top of the slope, large-scale slope failure, and turbidite systems forming channel-levee complexes with longitudinal sediment sorting. Similar to processes in siliciclastic systems, carbonate turbidite systems on the slope of western Great Bahama Bank show longitudinal variations in sedimentary processes. Two types of systems coexist along the margin: (1) a gully-related turbidite system that essentially consists of a short depositional fan-lobe initiated along the slope and ending rapidly along the toe of slope, and (2) failure-related turbidite systems that are dominated by erosion and/or bypass processes and mass-transport complexes. The existence of sediment sorting processes suggests that carbonate reservoirs can form on the slope of carbonate banks. Large mass transport complexes are revealed to be major components of the depositional and reservoir architecture of deep-water resedimented carbonates. Due to their large size, mass transport complexes can be tsunamogenic and have to be considered in the assessment of natural hazards. Carbonate mound distribution depends on seafloor morphology and locally impacts on the deposition of surrounding sediment. The along-strike changes in depositional environment, slope morphology, type of sedimentary bodies, and related sedimentary and diagenetic processes suggest that the slopes of tropical carbonate platforms such as Great Bahama Bank cannot be simply described by facies belt models, but instead they require a detailed analysis of the architectural elements and their controlling parameters.

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REFERENCES CITED

Anselmetti, F.S., Eberli, G.P., and Zan-Dong, D., 2000, From the Great Bahama Bank into the Straits of Florida: A margin architecture controlled by sea-level fluctuations and ocean currents: Geological Society of America Bulletin, v. 112, p. 829–844, doi:10.1130/0016-7606(2000)112<829:FTGBBI>2.0.CO;2.

Austin, J.A., Jr., Schlager, W., Comet, P.A., Droxler, A., Eberli, G., Fourcade, E., Freeman-Lynde, R., Fulthorpe, C.S., Harwood, G., Kuhn, G., Lavoie, D., Leckie, M., et al., 1988, Ocean Drilling Program, Scientific Results Volume 101: College Station, Texas, Ocean Drilling Program, 501 p.

Bergman, K.L., Westphal, H., Janson, X., Poiriez, A., and Eberli, G.P., 2010, Controlling parameters on facies geometries of the Bahamas, an isolated carbonate platform environment, *in* Westphal, H., Riegl, B., and Eberli, G.P., eds., Carbonate Depositional Systems: Assessing Dimensions and Controlling Parameters. The Bahamas, Belize and the Persian/Arabian Gulf: Berlin, Springer Verlag, p. 5–80.

Cook, H.E., and Mullins, H.T., 1983, Basin margin environment, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., Carbonate Depositional Environments: American Association of Petroleum Geologists Memoir 33, p. 540–617.

Eberli, G.P., and Ginsburg, R.N., 1987, Segmentation and coalescence of Cenozoic carbonate platforms, northwestern Great Bahama Bank: Geology, v. 15, p. 75–79, doi:10.1130/0091-7613(1987)15<75:SACOCC>2.0.CO;2.

Eberli, G.P., and Ginsburg, R.N., 1989, Cenozoic progradation of north-western Great Bahama Bank, a record of lateral platform growth and sea-level fluctuations, *in* Crevello, P.D., Wilson, J.L., Sarg, J.F., and Read, J.F., eds., Controls on Carbonate Platforms and Basin Development: Society for Economic Paleontology and Mineralogy Special Publication 44, p. 339–351.

Eberli, G.P., Swart, P.K.S., Malone, M., Anselmetti, F.S., Arai, K., Bernet, K.H., Betzler, C., Christensen, B., De Carlo, E.H., Déjardin, P.M., Emman, L., Frank, T.D., and 15 others, 1997, Ocean Drilling Program, Leg 166, Initial Reports Volume 183: College Station, Texas, Ocean Drilling Program, 850 p.

Foubert, A., and Henriet, J.P., 2009, Nature and Significance of the Recent Carbonate Mound Record: The Mound Challenger Code: Springer, Lecture Notes in Earth Sciences, v. 126, 298 p.

Ginsburg, R.N., ed., 2001, Subsurface Geology of a Prograding Carbonate Platform Margin, Great Bahama Bank: Results of the Bahamas Drilling Project: Society for Economic Paleontology and Mineralogy Special Publication 70, 265 p.

Grasmueck, M., Eberli, G.P., Viggiano, D.A., Correa, T., Rathwell, G., and Luo, J., 2006, Autonomous underwater vehicle (AUV) mapping reveals coral mound distribution, morphology, and oceanography in deep water of the Straits of Florida: Geophysical Research Letters, v. 33, p. L23616, doi:10.1029/2006GL027734.

Lantzsch, H., Roth, S., Reijmer, J.J.G., and Kinkel, H., 2007, Sea-level related resedimentation processes on the northern slope of Little Bahama Bank (middle Pleistocene to Holocene): Sedimentology, v. 54, p. 1307–1322, doi:10.1111/j.1365-3091.2007.00882.x.

Malone, M.J., Slowey, N.C., and Henderson, G.M., 2001, Early diagenesis of shallow-water periplatform carbonate sediments, leeward margin, Great Bahama Bank (Ocean Drilling Program Leg 166): Geological Society of America Bulletin, v. 113, p. 881–894, doi:10.1130/0016-7606(2001)113<0881:EDOSWP>2.0.CO;2.

Mullins, H.T., Newton, C.R., Heath, K., and Van Buren, H.M., 1981, Modern deep-water coral mounds north of Little Bahama Bank: Criteria for the recognition of deep-water coral bioherms in the rock record: Journal of Sedimentary Petrology, v. 51, p. 999–1013.

Mullins, H.T., Heath, K.C., van Buren, H.M., and Newton, C.R., 1984, Anatomy of a modern open-ocean carbonate slope: Northern Little Bahama Bank: Sedimentology, v. 31, p. 141–168, doi:10.1111/j.1365-3091.1984.tb01956.x.

Neumann, A.C., Kofoed, J.W., and Keller, G.H., 1977, Lithoherms in Straits of Florida: Geology, v. 5, p. 4–10, doi:10.1130/0091-7613(1977)5<4:LITSOF>2.0.CO;2.

Normark, W.R., 1970, Growth patterns of deep-sea fans: The American Association of Petroleum Geologists Bulletin, v. 54, p. 2170–2195.

Paul, J.H., McLaughlin, M.R., Griffin, D.W., Lipp, E.K., Stokes, R., and Rose, J.B., 2000, Rapid movement of wastewater from on-site disposal systems into surface waters in the lower Florida Keys: Estuaries, v. 23, p. 662–668, doi:10.2307/1352892.

Playton, T.E., Janson, X., and Kerans, C., 2010, Carbonate slopes (Chapter 18), *in* James, N.P., and Dalrymple, R.W., eds., Facies Models 4, GEOtext 6: St. Johns, Newfoundland, Canada, Geological Association of Canada, p. 449–476.

Rendle-Bühring, R.H., and Reijmer, J.J.G., 2002, Quaternary slope development of the western, leeward margin of the Great Bahama Bank: Marine Geology, v. 185, p. 143–164, doi:10.1016/S0025-3227(01)00294-8.

Rendle-Bühring, R.H., and Reijmer, J.J.G., 2005, Controls on grain-size patterns in periplatform carbonates; marginal setting versus glacio-eustasy: Sedimentary Geology, v. 175, p. 99–113, doi:10.1016/j.sedgeo.2004.12.025.

Schlager, W., Reijmer, J.J.G., and Droxler, A., 1994, Highstand shedding of carbonate platforms: Journal of Sedimentary Research, v. B64, p. 270–281.

Swart, P.K., Eberli, G.P., Malone, M.J., and Sarg, J.F., et al., 2000, Proceedings of the Ocean Drilling Program, Scientific Results, Leg 166: College Station, Texas, Ocean Drilling Program, 213 p.

Wang, J., and Mooers, C.N.K., 1997, Three-dimensional perspective of the Florida Current: Transport potential vorticity, and related dynamical properties: Dynamics of Atmospheres and Oceans, v. 27, p. 135–149, doi:10.1016/S0377-0265(97)00004-3.

Weimer, P., 1989, Sequence stratigraphy of the Mississippi Fan (Plio–Pleistocene), Gulf of Mexico: Geo-Marine Letters, v. 9, p. 185–272, doi:10.1007/BF02431072.

Wilber, R.J., Milliman, J.D., and Halley, R.B., 1990, Accumulation of bank-top sediment on the western slope of Great Bahama Bank: Rapid progradation of a carbonate megabank: Geology, v. 18, p. 970–974, doi:10.1130/0091-7613(1990)018<0970:AOBTSO>2.3.CO;2.

Wilson, P.A., and Roberts, H.H., 1992, Carbonate-periplatform sedimentation by density flows: A mechanism for rapid off-bank and vertical transport of shallow-water fines: Geology, v. 20, p. 713–716.

Wilson, P.A., and Roberts, H.H., 1995, Density cascading: Off-shelf transport, evidence and implications, Bahama Banks: Journal of Sedimentary Research, v. A65, p. 45–56.

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