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Storm deposits in ancient shelf sediments typically form thick sequences of interbedded sand and mud deposited during shoreline regression, whereas modern shelf sediments are generally thin veneers deposited during shoreline transgression. In this paper we present a preliminary comparison between ancient and modern storm beds deposited in these disparate contexts. Hurricane Katrina deposited a storm bed on the Louisiana shelf with a maximum observed thickness of 0.58 m, which thinned to approximately 0.1 m at 200 km west of landfall. This thickness is similar to event beds observed in both ancient and modern sediments. Using data for tropical cyclone landfalls in the Gulf of Mexico, we estimate the return time for a storm of this size to be 40-50 years in this region. This estimated frequency for deposition of storm beds is useful in evaluating ancient storm sequences that were deposited during similar climatic conditions.

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Geological and oceanographic perspectives on event bed formation during Hurricane Katrina

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[1] Storm deposits in ancient shelf sediments typically form thick sequences of interbedded sand and mud deposited during shoreline regression, whereas modern shelf sediments are generally thin veneers deposited during shoreline transgression. In this paper we present a preliminary comparison between ancient and modern storm beds deposited in these disparate contexts. Hurricane Katrina deposited a storm bed on the Louisiana shelf with a maximum observed thickness of 0.58 m, which thinned to approximately 0.1 m at 200 km west of landfall. This thickness is similar to event beds observed in both ancient and modern sediments. Using data for tropical cyclone landfalls in the Gulf of Mexico, we estimate the return time for a storm of this size to be 40–50 years in this region. This estimated frequency for deposition of storm beds is useful in evaluating ancient storm sequences that were deposited during similar climatic conditions.

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1. Introduction

[2] It is difficult to reconcile ancient event beds deposited from single storms on continental shelves with modern storm deposits because the ancient deposits consist of thick aggradational to progradational successions (parasequences) of interbedded sand and mud layers that have undergone the effects of bioturbation and diagenesis, obscuring much of the original character of the sediment. The problem is exacerbated by the lack of thick parasequences on modern shelves [*Hampson and Storms*, 2003]. Modern shelf sediments are typically thin, transgressive successions that overlie a Pleistocene surface eroded during the last glacial maximum at about 20 ka. The thick sand-mud storm sequences observed in the geological record are uncommon in modern environments because of a shortage of sediment supplied to the shelf during the present marine transgression. Basins like the Gulf of Papua, Papua New Guinea, which receive sufficient sediment to develop thick aggradation sequences, are found only near rapidly uplifting source terrains that are not representative of many ancient shelves.

[3] An exception to this rule occurs adjacent to the Mississippi delta where the transgressive systems tract is sufficiently thick and storms are common. A number of storm beds have been preserved there and these allow comparisons to be made with ancient storm sequences. The recognition of specific storm event beds makes it possible to characterize the initial fabric of event beds, estimate their frequency of occurrence, and identify the environmental factors that generate them. Although we expect the stratigraphy of modern and ancient storm-dominated shelves to differ, the characteristics of individual or small packets of event beds should be consistent. Hurricane Katrina made landfall in Mississippi Sound on 29 August 2005, and deposited a regionally extensive bed of sufficient thickness that it can be used to bridge the gap between ancient storm sequences and modern shelves. The purpose of this communication is to describe the Katrina bed, relate its sedimentology to the storm and its flow regime, and to estimate the frequency of storms with a similar magnitude in the stratigraphic record. We specifically address two questions: (1) What is the origin of the sand found within storm beds? (2) What is the frequency with which event beds of sufficient magnitude to be preserved in the geological record are created? We shed light on these questions using oceanographic and geological observations from modern shelves, and in particular the well-studied Hurricane Katrina storm on the Gulf Coast.

2. Geological Background

[4] Storm beds (also called tempestites or event beds) were first recognized in the rock record by their systematic vertical arrangement of facies (Figure 1) and the occurrence of a bedform unique to shelf deposits, now called hummocky cross stratification (HCS). The beds, which are from 0.1 to 2 m thick, have erosive bases and consist of very fine sandstones interbedded with mudstones [*Dott and Bourgeois*, 1982]. They are thought to be deposited from suspension as storm currents wane but waves remain large [*Duke et al.*, 1991].The presence of mudstones and specific ichnofauna suggest deposition on the outer shelf below fair-weather wave base. Storm beds from the inner shelf are commonly less than 0.1 m in thickness [*Driese et al.*, 1991].

[5] The majority of modern storm beds discussed in the literature have been observed in the Gulf of Mexico, probably because of the dominance of tropical cyclones on an otherwise moderately low-energy shelf. It is also easier to identify a sand layer in the heterogeneous and bioturbated sediments that dominate its northern and west-

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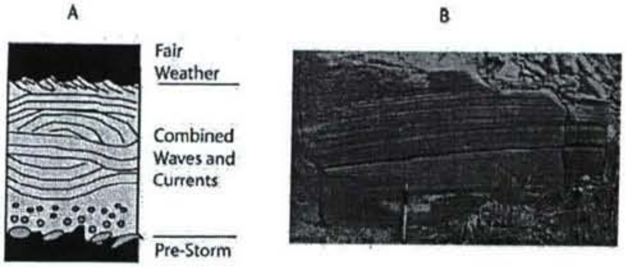

Figure 1. (a) Schematic cross-section through a fining-upward storm bed. The bottom is eroded into finer sediments and may contain a coarse lag deposit. Hummocky cross stratification (HCS) occurs within the middle of the bed and the top is wave rippled and overlain by fine sediment. (b) Example of HCS from the Ferron Sandstone in Utah. The lower part of the bed (behind the pen) contains planar laminae, which indicate a high flow regime during the main depositional event. The upper part contains HCS, which forms as the flow speed decreases but waves remain high (Courtesy of C. L. Summa, Winona State University).

ern margins. Sediment cores collected from the inner shelf of Texas reveal at least 4 m of sand beds up to 0.2 m thick interbedded with bioturbated sand and mud layers [*Morton*, 1981]. *Hayes* [1967] identified an event bed with a maximum thickness greater than 0.09 m, which he proposed was deposited by Hurricane Carla in 1961. The Carla bed, which was found as far as 240 km south of landfall, was mapped by *Snedden et al.* [1988] over an area of 7200 km^2 and into water depths greater than 40 m. *Bentley et al.* [2002] attributed a sandy layer with unique texture, bedding, and radiochemical characteristics within Mississippi Sound and the adjoining inner shelf to Hurricane Camille (1969). In addition, an earlier event layer in these same cores is thought to have been deposited by an unnamed hurricane from 1947 [*Keen et al.*, 2004]. These beds revealed significantly more variability than was observed on the Texas shelf because of the complex coastline within the area, the limited availability of sand, and the increased effects of bioturbation. Storm beds up to 0.2 m thick containing HCS have also been observed in modern shoreface sediments from North Carolina, South Korea, and the North Sea [*Beavers*, 1999; *Yang et al.*, 2006; *Passchier and Kleinhans*, 2005].

3. Event Bed Oceanography

[6] The entrainment of sediment on the shelf and the subsequent creation of an event bed depend on the hydrodynamic regime, which comprises waves, currents, and water levels. Storm waves with peak periods in excess of 10 s and significant wave heights greater than 5 m produce bed stresses large enough to entrain sand on the outer shelf; thus, the critical shear stress for entrainment is exceeded during both extratropical and tropical cyclones. For example, deep-water waves larger than 15 m have been measured during northeasters [*Cardone et al.*, 1996] and a maximum wave of 28 m occurred during Hurricane Ivan [*Wang et al.*, 2005]. Both steady and oscillatory currents near the bed on the outer shelf exceed 1 m s^{-1} during storms when large waves occur, producing substantial sediment transport and bed scour.

[7] Sediment transport during extreme storms consists of transport within and between dynamic zones: (1) the subaerial beach and dunes; (2) the shoreface; (3) the inner shelf; and (4) the outer shelf. Zones (1) and (2) are above fair-weather wave base and sediment is in constant motion within and between them, especially during storms when coastal water levels are elevated. Some of this sediment is transported to the inner shelf during storms [*Wright et al.*, 1994]. Sediment transport has been observed in water depths of 60–80 m during northeasters and hurricanes along the U. S. Atlantic shelf [*Lyne et al.*, 1990; *Dickey et al.*, 1998]. Recent observations in the Gulf of Mexico indicate bottom scour depths greater than 0.3 m on the outer shelf and potential sediment transport to the shelf break [*Teague et al.*, 2006]. Transport path lengths of 40 km have been predicted by a numerical model during Hurricane Andrew in shallower water [*Keen and Glenn*, 2002]. Numerical simulations are consistent with the hypothesis that the bottom stresses and flows during both extratropical and tropical cyclones incrementally move sediment from the beach to the shelf break with successive occurrences of extreme storms [e.g., *Keen and Slingerland*, 1993; *Keen et al.*, 1994], constituting one of the few widespread mechanisms for cross-shelf sediment transport [*Nittrouer and Wright*, 1994].

4. Event Bed Formation During Hurricane Katrina

[8] Bottom samples from the western Louisiana shelf collected in January 2006 reveal a 0.05–0.3 m event bed of mud and coarse silt (Figures 2 and 3), which is probably a combined deposit of Hurricanes Katrina and Rita. Sediment cores collected east of the Mississippi River delta in water depths of approximately 27 m (Sites 1–4 in Figure 4a) have increased gamma densities near the surface (Figure 4b), which are indicative of sandy sediments; these data indicate a 0.1 to 0.58 m silt/sand layer overlying mud. This bed, which comprises a fining-upward sequence consisting of colloidal clays, coarse silt, and shell fragments, is attributed to Katrina because sediment cores from the same locations taken in 1999 (599C3, 599C5, and 599C6 in Figure 4) do not have these characteristics. Note that the pre-Katrina cores from shallower water (599C7–599C9) are coarser at the surface, as is core 599C5, which is proximal to an extensive sand sheet located to the east.

[9] Event bed deposition during Hurricane Katrina is being studied using a system of numerical atmospheric, wave, circulation and sedimentation models as described by

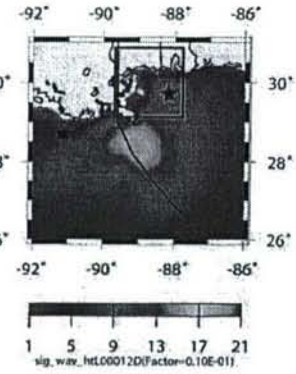

Figure 2. Map of north-central Gulf of Mexico showing the track of Hurricane Katrina and significant wave heights predicted by the numerical wave model at landfall. The maximum wave height is 19 m. The square indicates the approximate location of the cores shown in Figure 3 and the star shows the location of the cores in Figure 4. The sedimentation model grid is outlined by the box.

Keen et al. [2005]. Atmospheric forcing is from the operational COAMPS (Coupled Ocean-Atmosphere Mesoscale Prediction System) model and storm waves are calculated using the SWAN (Simulation WAves Nearshore) wave model. Steady currents and coastal water levels are from the Intra-America Seas implementation of the Navy Coastal Ocean Model (NCOM) [http://www7320.nrlssc.navy.mil/IASNFS_WWW]. Sedimentation is calculated on a 3 km grid using the Littoral Sedimentation and Optics Model (LSOM), which is an extended version of the TRANS98 model used in previous tropical cyclone studies [*Keen and Slingerland*, 1993]. LSOM includes algorithms for entraining and transporting sand and mud mixtures; this study assumes a bed composition of 50% sand everywhere. The sediment in the bed evolves through time as mud is preferentially eroded from the active layer and kept suspended by the storm flow. The simulated event bed (Figure 5) is a relatively uniform layer about 0.09 m thick on the shelf, with a maximum thickness of 0.145 m east of the Chandeleur Islands in a water depth of 16 m. The model also predicts consistent westward transport as indicated by observations during Hurricane Ivan. The thickness of the simulated event bed is greater on the outer shelf than within Mississippi Sound because this study focuses on the shelf and does not accurately reproduce the hydrodynamics within the sound. Both the model results and the core data

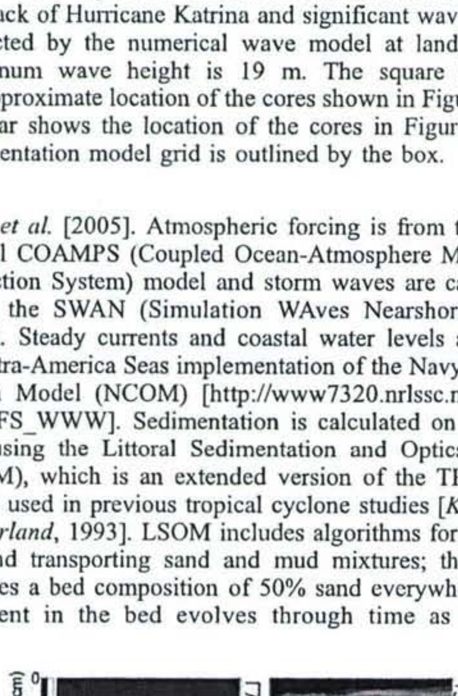

Figure 3. Digital X-radiographs of cores collected in January 2006 on the west Louisiana shelf between the Atchafalaya River and the Chenier Plain. The cores were collected at (left) 29.07° N, 92.46° W in 23 m water depth and (right) 28.94° N, 91.49° W in 14 m water depth prior to the 2006 Mississippi River freshet. The negative images show coarse sediment (high density indicated as silt/sand or s) as light shades, and fine sediment (low density, indicated as clay or c) as dark shades. Event beds are clearly visible with sharp lower boundaries overlying more intensely bioturbated sediment, and more bioturbated upper boundaries. Bed variability probably reflects the varying influences of both Hurricanes Katrina and Rita. The mean bed thickness for 13 cores collected over approximately 5000 km^2 of inner shelf during the cruise is 0.099 m ± 0.041 m.

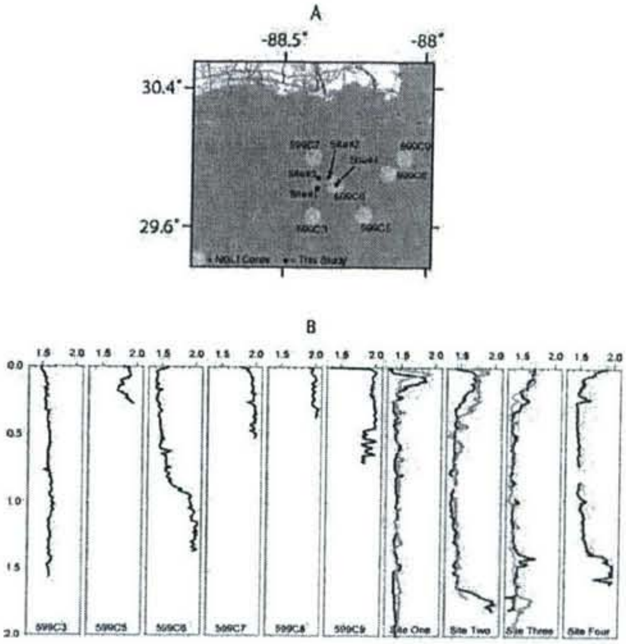

Figure 4. (a) Locations of bottom samples collected before and after Hurricane Katrina. (b) Gamma density (g cm^{-3}) of NGLI (Northern Gulf of Mexico Littoral Initiative) cores and gravity cores from this study are shown together for comparison. Note the low values at the top of NGLI core 599C6 compared to the elevated values in the post-Katrina core from the same location (Site 4). The lighter-colored profiles from sites 1–3 are measurements from repeat cores at the same locations.

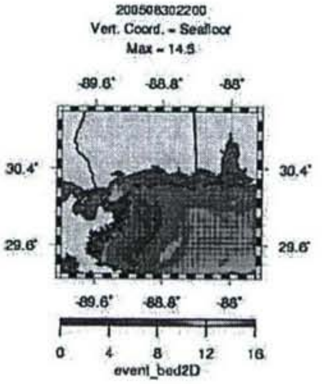

Figure 5. The cumulative thickness of the event bed predicted by LSOM, including both eroded and resuspended sediment.

(Figure 4) indicate spatial variability in the initial bed thickness. Observations of scour, core data, and the model results indicate that the event bed deposited on the Louisiana-Mississippi shelf was produced from in-situ sorting of preexisting bottom sediment as well as transport, which limits the thickness of the event-bed sand layer to available sand within the active seafloor. This sand may have been originally eroded from the shoreface during one of the extreme storms that intermittently transported it across the shelf.

5. Implications for Interpreting Ancient Storm Sequences

[10] The frequency of hurricane landfall is much lower than that of river flood events (typically 2–10 years), and thus the hydrodynamics that would produce a 0.5 m event bed on the outer shelf should be rare. Unlike previous observations, we have for the first time measured an event bed with a known origin that has a thickness of the same order of magnitude as those observed in the geological record. The data from the Katrina bed thus permit estimation of the frequency for deposition of beds like those seen in Figure 1, which supplies a tentative answer to our second geological question about event bed deposition. *Elsner et al.* [2006] estimate a return period of 21 years for this size storm for the entire Gulf coast; however, in order to compare the modern shelf data to the geological data, we must focus on a smaller area. By examining historical track data [http://hurricane.csc.noaa.gov/hurricanes] for Category 4 and 5 hurricanes passing within 100 km of Stennis Space Center, Mississippi, we find three occurrences: (i) an unnamed storm in 1855; (ii) Camille in 1969; and (iii) Katrina. The database spans 1851 to 2005, or 154 years; the small sample size prevents the use of extreme-value models, but we can estimate a return period of 51 years for the Mississippi Bight. For Galveston, Texas, four large hurricanes occurred between 1900 and 1949, giving an estimated return period of 39 years.

[11] The initial thickness is one critical parameter determining whether a storm bed will be preserved in the geological record. Other important factors are subsequent rates of bed reworking (physical and biological) and burial [*Bentley et al.*, 2006]. The continental shelf seafloor is populated with burrowing organisms that constantly rework the upper 0.1–0.12 m of sediment. These infaunal communities are generally very robust and are quickly reestablished after severe storms. Thus, if a storm bed has an initial thickness of less than 0.1 m, its original storm-generated characteristics (basal disconformity, HCS, and graded bedding) will be destroyed by bioturbation. The model results suggest that ~50% of the Mississippi bight shelf was covered by a storm bed with a thickness greater than 0.12 m (Figure 5). Storm beds can also be cannibalized by subsequent storms; thus the amount of sediment deposited between storms must exceed the depth of reworking. Sedimentation rates in Mississippi Sound range from 0.0029–0.0047 m yr^{-1} [*Bentley et al.*, 2002]. The Katrina bed has a good chance of being preserved in the geologic record because this size storm is expected approximately every 50 years, during which time an additional 0.15–0.25 m of sediment would accumulate and bury it.

[12] This result suggests that a bed 0.1–0.5 m thick could be expected approximately every 40 to 50 years within this region. Thinner beds would have a higher frequency because they can be deposited by smaller storms, as well as further from the storm track by larger ones as observed in the Carla bed on the Texas shelf. If we can assume that extreme storm occurrences in the past were similar to those today, this result has significant implications for the interpretation of ancient storm sequences like those seen in Figure 1.

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References

Beavers, R. L. (1999), Storm sedimentation on the surf zone and inner continental shelf, Duck, North Carolina, Ph.D. thesis, Duke Univ., Chapel Hill, N. C.

Bentley, S. J., T. R. Keen, C. A. Blain, and W. C. Vaughan (2002), The origin and preservation of a major hurricane event bed in the northern Gulf of Mexico: Hurricane Camille, 1969, *Mar. Geol.*, *186*, 423–446.

Bentley, S. J., A. Sheremet, and J. M. Jaeger (2006), Event sedimentation, bioturbation, and preserved sedimentary fabric: Field and model comparisons in three contrasting marine settings, *Cont. Shelf Res.*, *26*, 2108–2124, doi:10.1016/j.csr.2006.07.003.

Cardone, V. J., R. E. Jensen, D. T. Resio, V. R. Swail, and A. T. Cox (1996), Evaluation of contemporary ocean wave models in rare extreme events: The "Halloween Storm" of October 1991 and the "Storm of the Century" of March 1993, *J. Atmos. Oceanic Technol.*, *13*, 198–230.

Dickey, T. D., G. C. Chang, Y. C. Agrawal, A. J. Williams, and P. S. Hill (1998), Sediment resuspension in the wakes of Hurricanes Edouard and Hortense, *J. Geophys. Res.*, *25*, 3533–3536.

Dott, R. H., and J. Bourgeois (1982), Hummocky stratification: Significance of its variable bedding sequences, *Geol. Soc. Am. Bull.*, *93*, 663–680.

Driese, S. G., M. W. Fischer, K. A. Easthouse, G. T. Marks, A. R. Gogola, and A. E. Schoner (1991), Model for genesis of shoreface and shelf sandstone sequences, southern Appalachians: Paleoenvironmental reconstruction of an Early Silurian shelf system, *Int. Assoc. Sedimentol. Spec. Publ.*, *14*, 309–338.

Duke, W. L., R. W. C. Arnott, and R. J. Cheel (1991), Shelf sandstones and hummocky cross-stratification: New insights on a stormy debate, *Geology*, *19*, 625–628.

Elsner, J. B., T. H. Jagger, and A. A. Tsonis (2006), Estimated return periods for Hurricane Katrina, *Geophys. Res. Lett.*, *33*, L08704, doi:10.1029/2005GL025452.

Hampson, G. J., and J. E. Storms (2003), Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface-shelf parasequences, *Sedimentology*, *50*, 667–701.

Hayes, M. O. (1967), Hurricanes as geological agents: Case studies of Hurricanes Carla, 1961, and Cindy, 1963, *Rep. Invest.*, *61*, 54 pp., Bur. of Econ. Geol., Austin, Tex.

Keen, T. R., and S. M. Glenn (2002), Predicting bed scour on the continental shelf during Hurricane Andrew, *J. Waterway Port Coastal Ocean Eng.*, *128*, 249–257, doi:10.1061/(ASCE)0733-950X(2002)128:6 (249).

Keen, T. R., and R. L. Slingerland (1993), A numerical study of sediment transport and event bed genesis during Tropical Storm Delia, *J. Geophys. Res.*, *98*, 4775–4791.

Keen, T. R., R. L. Slingerland, and S. M. Glenn (1994), Coastal circulation and sedimentation during severe storms, in *Estuarine and Coastal Modeling III*, pp. 279–293, Am. Soc. Civ. Eng., Reston, Va.

Keen, T. R., S. J. Bentley, W. C. Vaughan, and C. A. Blain (2004), The generation and preservation of multiple hurricane beds in the northern Gulf of Mexico, *Mar. Geol.*, *210*, 79–105.

Keen, T. R., C. Rowley, and J. Dykes (2005), Oceanographic factors and erosion of the Outer Banks during Hurricane Isabel, in *Hurricane Isabel in Perspective*, edited by K. G. Sellner, *Publ. 05-160*, pp. 65–72, Chesapeake Res. Consortium, Edgewater, Md.

Lyne, V. D., B. Butman, and W. D. Grand (1990), Sediment movement along the U.S. east coast continental shelf, I., Estimates of bottom stress using the Grant-Madsen model and near-bottom wave and current measurements, *Cont. Shelf Res.*, *10*, 397–428.

Morton, R. A. (1981), Formation of storm deposits by wind-forced currents in the Gulf of Mexico and the North Sea, in *Holocene Marine*

Sedimentation in the North Sea Basin, edited by S. D. Nio, R. T. E. Shuttenhelm, and T. C. E. van Weering, *Int. Assoc. Sedimentol. Spec. Publ.*, *5*, 385–396.

Nittrouer, C. A., and L. D. Wright (1994), Transport of particles across continental shelves, *Rev. Geophys.*, *32*, 85–113.

Passchier, S., and M. G. Kleinhans (2005), Observations of sand waves, megaripples, and hummocks in the Dutch coastal area and their relation to currents and combined flow conditions, *J. Geophys. Res.*, *110*, F04S15, doi:10.1029/2004JF000215.

Snedden, J. W., D. Nummedal, and A. F. Amos (1988), Storm- and fair-weather combined flow on the central Texas continental shelf, *J. Sediment. Petrol.*, *58*, 580–595.

Teague, W. J., E. Jarosz, T. R. Keen, D. W. Wang, and M. S. Hulbert (2006), Bottom scour observed under Hurricane Ivan, *Geophys. Res. Lett.*, *33*, L07607, doi:10.1029/2005GL025281.

Wang, D. W., D. A. Mitchell, W. J. Teague, E. Jarosz, and M. S. Hulbert (2005), Extreme waves under Hurricane Ivan, *Science*, *309*, 896.

Wright, L. D., J. P. Xu, and O. S. Madsen (1994), Across-shelf benthic transports on the inner shelf of the Middle Atlantic Bight during the "Halloween storm" of 1991, *Mar. Geol.*, *118*, 61–77.

Yang, B. C., R. W. Dalrymple, and S. Chun (2006), The significance of hummocky cross-stratification (HCS) wavelengths: Evidence from an open-coast tidal flat, South Korea, *J. Sediment. Res.*, *76*, 2–8.

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