

Sand and mud deposited by Hurricane Katrina on Deer Island,
Biloxi Bay, Mississippi

Annaliese A. Eipert

Committee Members:

Brian F. Atwater
Joanne Bourgeois
Liujuan (Rachel) Tang

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Department of Earth and Space Sciences

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ABSTRACT

Hurricane Katrina overwash berms on both sides of Deer Island, Mississippi, include sub-horizontally layered, landward dipping cross-bedded, and visually structureless units. Thickness of Katrina sand varies along two parallel profiles from 30-90 cm landward of Gulf of Mexico beach dunes, 0-10 cm for 90-140 m across the island, and 30-60 cm on the Biloxi Bay back beach. In Gulfside deposits, vertical samples of sub-horizontally layered and visually structureless lower units vary more in skewness than mean grain size, whereas cross-dipping and structureless upper units vary more in grain size than in skewness. This shift in grain size properties probably represents the addition of a new sediment source that occurred with changing wind directions at landfall. In Bayside deposits, sub-units vary widely in both skewness and mean grain size.

In the thickest Gulfside Katrina deposit, a normally graded mud layer marks a prominent structural transition between underlying sub-horizontal layering and overlying steeply dipping cross-beds. Unlike the bedload deposition of the sandy units, the mud layer settled from suspension during low bottom velocity conditions that occurred while the island was still overtopped by storm surge. Wave heights near Deer Island reached their maxima while storm surge was still low, 10 hours before Katrina’s landfall. At peak

surge, bottom effects of waves were dispersed through 6-8 m of water that covered Deer Island. Using cnoidal wave theory and approximations of Deer Island surge and wave conditions from meteorological observations and models, we find that minimum bottom velocities occurred during landfall when storm surge was at its peak. Conversely, flow depths that were shallow relative to wave heights, during initial overtopping of the island and later as the storm surge retreated, created high bottom velocities amenable to bedload transport. In a seeming paradox, extreme water levels during Katrina's peak intensity created relative quiescence below the surface, which allowed mud to settle out of suspension. This unique mud layer demonstrates that storms are able to create mid-event conditions amenable to the settling of fine particles, a capability previously attributed only to tsunamis.

AUTHOR'S STATEMENT

I prepared this report both for a non-thesis M.S. degree from the Department of Earth and Space Sciences, University of Washington and for publication in the Journal of Coastal Research. The "we" in this report includes Bretwood Higman, Bre MacInnes, and Beth Martin, with whom I did the field work at Deer Island and on behalf of whom I made grain-size analyses, assembled weather and wave data, drafted the illustrations, and wrote the text.

INTRODUCTION

Geologic records of storms can provide extended histories of storm recurrence. Most of these records consist of overwash deposits (ANDRADE *et al.*, 2004; BRIDGES, 1976; BUYNEVICH *et al.*, 2004; DONNELLY *et al.*, 2004; HILL *et al.*, 2004, and SEDGWICK and DAVIS, 2003). Overwash, a common response to hurricanes and winter storms around the world that has been especially well documented on the U.S. Gulf and Atlantic coasts (DONNELLY *et al.*, 2006), overtops a beach crest without immediately returning to its seaward source (DONNELLY *et al.*, 2006; LEATHERMAN, 1977). The water builds fans on the landward side of a beach crest if it slows enough to drop sediment that it carries mainly as bedload (LEATHERMAN, 1977; SCHWARTZ, 1975; WANG and HORWITZ, 2006). Because of this deposition, overwash commonly rivals wind as the major process in maintaining barrier islands (ANDREWS, 1970; HAYES, 1967; LEATHERMAN, 1977; MOLLER and ANTHONY, 2003).

The central U.S. Gulf Coast has seen the landfall of 45 hurricanes since 1722, recently including Hurricanes Camille (1969), Frederic (1979), Elena (1985), Georges (1998), Lily (2002), and Ivan (2004), and Katrina (2005). Hurricane Camille followed a similar path to Katrina's, but despite stronger winds at landfall, Camille's smaller maximum wind radius created a lesser storm surge and inflicted more localized damage (GRAUMANN *et al.*, 2005). Other notable hurricanes that affected this area include Elena (JACOBSON and REES, 2006), and Ivan, which made landfall farther east on Alabama's Gulf coast. Ivan preceded Katrina by only a year, and caused damage in 17 states (GRAUMANN *et al.*, 2005).

Hurricane Katrina attained Category 5, the highest on the Saffir-Simpson scale. In Louisiana and Mississippi, hurricane-force winds at landfall extended 161 km, and gusts of up to 204 km/h were measured. Atmospheric pressure fell as low as 902 mb, the fourth lowest storm pressure on record to that date. The combination of wind, low

pressure, and the Gulf's bathymetry drove the sea ashore in a storm surge as high as 9 m in western Mississippi. In Biloxi, Katrina's surge surpassed that of Camille by 1-3 m or more (GRAUMANN *et al.*, 2005). Hurricane Katrina killed 1833 people, displaced over a quarter of a million people, and was to date the costliest natural disaster in United States history. In Waveland, Mississippi, where Katrina made her final landfall on the morning of 29 August, 80% of residences were destroyed (GRAUMANN *et al.*, 2005).

Offshore, Katrina created enormous waves. Those recorded at NOAA Buoy 42040, 80 km east of the mouth of the Mississippi River, include a "significant wave height," defined as the average trough-to-crest amplitude of the highest third of the waves, of 16.91 m. This significant wave height matches the highest recorded in 30 years of National Buoy Data Center (NDBC) operation (NATIONAL DATA BUOY CENTER STAFF, 2006). Maximum wave heights are typically 1.9 times the significant wave height (WORLD METEOROLOGICAL ORGANIZATION STAFF, 1998), which implies that Katrina's maximum wave heights were in excess of 30 m.

This paper explores potential links between a Katrina overwash deposit and the hurricane's surge and waves. New observations consist of the architecture and internal structure of an overwash deposit on Deer Island, Mississippi. This deposit contains a puzzling mud layer that, in a seeming paradox, may represent the time of peak storm surge.

DEER ISLAND

Narrow, 6-km-long Deer Island spans the entrance to Biloxi Bay (Fig. 1). Remains of Gulfport Formation Pleistocene beach ridges crop out in the island's northwest part, which is high enough to support pine forests. The Gulfport dips southeastward beneath the muddy and sandy deposits of Holocene marshes (Fig. 2; OTVOS, 1985; SCHMID and OTVOS, 2003; SLOAN and SCHMID, 2003).

An offshore chain of five barrier islands several kilometers to the south (Fig. 1) offers enough protection from offshore waves to make local winds the dominant factor in controlling Deer Island's wave climate. Significant wave heights near Deer Island are typically on the order of 0.5 m (RANKIN *et al.*, 2005). Both prevailing local winds and an alongshore current come from the southeast, but peak ebb tidal currents come from the northwest (RANKIN *et al.*, 2005). Mean tidal range is ~0.5 m (CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES, 1979).

Deer Island has lost nearly 50% of its area through erosion since first mapped by the U.S. Coast Survey in 1851 (Fig. 2; OTVOS, 2005). The rate of island loss per kilometer of exposed shoreline quadrupled from an average of 405 m³/km/y during the period from 1851 and 1997, to 1618 m³/km/y during the period between 1997 and 2004 (OTVOS, 2005). Storm surge is the dominant factor controlling beach shape (RANKIN *et al.*, 2005). Deer Island has been estimated to lose approximately 30,600 m³ of sediment, half of that sand, every year (RANKIN *et al.*, 2005). Erosion by hurricanes includes a western breach that Hurricane Camille initiated in 1969 and Hurricane Elena enlarged in 1985 (Fig. 3; JACOBSON AND REES, 2006).

Though recently without human inhabitants, Deer Island has a long history of human use. Choctaw Indians lived there for millennia, European settlers arrived in 1717, and an amusement park was built in 1915 (SCHMID AND OTVOS, 2003). Hurricane Camille destroyed the island's structures in 1969 and redevelopment plans ended in 2002 when

Mississippi named Deer Island a Marine Protected Area. Having some of the few remaining natural sand beaches in the area (SCHMID and OTVOS, 2003), Deer Island is now a designated Coastal Preserve administered by the Mississippi Department of Marine Resources (MISSISSIPPI DEPARTMENT OF MARINE RESOURCES, 2007; SLOAN and SCHMID, 2003).

METHODS

Meteorological records and observations of Hurricane Katrina were compiled with field observations of overwash deposits to reconstruct the timing of depositional events on Deer Island. Because key tide gauges failed mid-storm (CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES, 2005), we reconstructed storm surge heights with the aid of models (LOUISIANA STATE UNIVERSITY, 2005), government-sponsored maximum water height observations (FEDERAL EMERGENCY MANAGEMENT AGENCY, 2006a; 2006b; GRAUMANN *et al.*, 2005), and our own high-water observations based on debris stranded in trees..

The closest estimation of Deer Island wave heights is based on NDBC buoy 42007, located approximately 30 km away from Deer Island in 14 m water depth (Fig. 1). This buoy became unmoored as waves intensified, but it continued to record throughout the storm. Because wave patterns from this buoy matched well with those from nearby buoys, we considered this data credible enough to take into account. Waves likely decreased upon crossing the outer chain of barrier islands (Fig. 1), so Buoy 42007 wave conditions are regarded as maxima for Deer Island. Destruction of the National Data Buoy Center facility, near Waveland, at 1500 UTC on 29 August marks the end of all buoy records for Hurricane Katrina (KRASSOVSKI *et al.*, 2005).

We visited Deer Island from 10-14 October 2005, a month and a half after Hurricane Katrina and two weeks after Hurricane Rita. Wracklines indicated that Rita did not completely overtop Deer Island, and the two storms' deposits were distinguishable in most cases based on deposit size, location, elevation, and relative stratigraphic position. Observations of the architecture and internal structure of Katrina deposits were made around the island. We took measurements of 243 flow direction indicators from various locations including ripples on the surface of Katrina deposits, flattened palms, and large windblown pine trees. Symmetrical ripples or those with ambiguous flow directions were ignored.

We surveyed two topographical profiles across the northwest portion of the island, with a closing error of 0.8 cm. Waterline elevations were related to tidal datum Mean Lower Low Water (MLLW) through interpolation between Gulfport and Pascagoula tide gauges (Fig. 1; CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES, 2005). We photographed, sketched, peeled, and described stratigraphy on both sides of the island, in two Gulfside trenches and in one Bayside trench.

We also conducted detailed grain size analysis to look for trends that may not have been visible in the field due to the deposits' composition of well-sorted, fine sand composed almost entirely of quartz. Each pit was sampled at centimeter or sub-centimeter vertical intervals. In the lab, sand was run through a settling column, and empirical equations (FERGUSON and CHURCH, 2004) were used to convert settling velocities into grain size distributions for each sample depth. Grain size trends and

distributions were computed for each sub-unit in the logarithmic phi scale, using the computer code of HIGMAN (2007). We then compared vertical variations between mean grain size, standard deviation, and skewness, a measure of a distribution's asymmetry about its mean (cf. MCLAREN AND BOWLES, 1985).

STORM WATER LEVELS

The eye of Hurricane Katrina made landfall at Waveland, 50 km west of Biloxi, which puts Deer Island within Katrina's radius of hurricane-force winds (Fig. 1). Moreover, by being located in Katrina's front right quadrant, Deer Island was overrun by the highest part of the storm surge (EMMANUEL, 2005). No tide gauges within this quadrant survived the peak of the storm. However, storm surge models (LOUISIANA STATE UNIVERSITY, 2005), high water marks inside inundated buildings (FEDERAL EMERGENCY MANAGEMENT AGENCY, 2006a; 2006b, and GRAUMANN *et al.*, 2005), and a Biloxi River gauge (US GEOLOGICAL SURVEY, 2005) indicate that at least 8 m surges flooded nearby Biloxi.

On the north side of Deer Island we found hurricane debris as high as 8.8 m above MLLW (Fig. 4). In addition to storm surge, maximum water elevations would have included the effects of bathymetry: *wave setup*, a superelevation of mean water level, and *swash*, fluctuations about this mean (U.S. ARMY CORPS OF ENGINEERS, 2006).

Several studies, most on the Atlantic and Pacific coasts, have attempted empirically to determine the amount of runup, which includes the effects of both wave setup and swash. WANG *et al.* (2006) found for their Hurricane Ivan study sites along the northwestern Florida barrier island coasts, that of various models, those that incorporated local beach slope tended to over predict runup levels. However, the simple linear model of GUZA and THORNTON (1980, 1981, 1982) of $R = 0.17H_0$, where R = runup and H_0 is offshore significant wave height, matched well. If we apply this model to conditions at Deer Island during peak storm surge, we find that $R = 0.44$ m, a small but significant addition. Wind setup and fluctuating tides would have made additional contributions to total flow depth.

DEER ISLAND OVERWASH DEPOSITS

Katrina overwash deposits 30-90 cm thick form berms on both sides of Deer Island (Fig. 5). Past an abrupt taper of the Gulfside deposits (Fig. 6) Katrina sand thicknesses fluctuate between 0 and 10 cm. Maximum inland thicknesses occur on either side of the topographic high of a road crossing the profiles, and in scour pits along the forest profile. Down-beach dipping cross-beds in Bayside pits show that overwash sand was deposited by cross-island flow, rather than as a result of inundation from Biloxi Bay (Fig. 7; cf. WANG and HORWITZ, 2006).

Because no pre-storm profiles were conducted at our study site, we are not able to measure the net topographic change that Hurricane Katrina caused. Due to the frequency of Gulf of Mexico storms and the susceptibility of Deer Island coastlines to those storms, it is likely that pre-Katrina dunes were similar to those observed during our survey. WANG *et al.* (2006) found that for their Florida coast field sites, foreshore slopes generally recovered to their pre-storm morphologies within 30 days after Hurricane Ivan. The Deer Island survey was conducted only two weeks after Hurricane Rita, and it is possible that foreshore slopes had not completely recovered by the time of our fieldwork.

Gulfside deposits

The Gulfside trench along the marsh profile, KAT 1 (Fig. 6), contains units of sub-horizontal and cross-dipping lamination, as well as a mud layer that separates them. The lowermost sub-unit of KAT 1, Unit 1a, preserves growth-position grasses that were living prior to their recent rapid burial. Such an event can only be attributable to Katrina (Fig. 6). Unit 1a is visually structureless except for traces of faint, sub-horizontal planar lamination. It is erosively overlain by a thin, normally graded mud layer, Unit 1b, which is topped by sets of steeply landward-dipping cross-beds, Unit 1c. The upper unit is capped by several sub-horizontal laminae, which are truncated at the top. Several other truncations are apparent throughout the upper unit. Mean grain size throughout KAT 1 varies in a series of normal and inverse trends, patterns which are both common in overwash deposits (Fig. 8a; LEATHERMAN and WILLIAMS, 1983; SCHWARTZ, 1975; SCHWARTZ, 1982; WANG and HORWITZ, 2003).

KAT 2, the Gulfside pit along the forest profile, also shows a pronounced change in structure midway through the deposit. Complex sub-horizontal layers within the lower portion, Unit 2a, are overlain abruptly by 1.5 cm of plant debris and sand, Unit 2b, and topped by a visually structureless unit, Unit 2c. Mean grain size again displays both normal and inverse trends (Fig. 8b).

Comparison of mean grain size and skewness distributions for samples taken vertically throughout the Gulfside deposits suggests that the changes in structure are mirrored by changes in grain size properties. In the case of KAT 1, the mud layer marks this transition. Below the KAT 1 mud layer, structureless sand of Unit 1a is distributed in a nearly bell-shaped, or non-skewed, grain size curve. Above the mud layer, the cross-bedded sand of Unit 1c displays a fine mode with a coarse tail, or negative skewness (Fig. 8a). Unit 1a sub-sample skewnesses range from -2 to 2, in contrast to Unit 1c sub-samples for which skewnesses are close to 0. Conversely, Unit 1c sub-samples show more variation in mean grain size, between 2 and 1.6 phi, than Unit 1a sub-samples, concentrated on the fine end of the spectrum between 2 and 1.9 phi (Fig. 8a).

KAT 2 grain size properties show a similar pattern to those of KAT 1. In KAT 2 the transition occurs in Unit 2b, an organic-rich sand layer. While Unit 2a sub-samples have relatively fine mean grain sizes, from 2.1 to 1.9 phi, mean grain sizes of Unit 2c sub-samples vary more widely, from 2.1 to 1.7 phi. Skewness of the lower Unit 2a ranges from -2 and 2, more varied than the lower KAT 1 unit but less varied than Unit 2c, which has a range of -2 to 5. The sub-horizontally layered sandy and organic KAT 2 section, Unit 2b, shares both the low skewness of Unit 2c and the fine grain size of Unit 2a. Grain size properties of the sub-horizontally layered lower section of KAT 2, Units 2a and 2b, roughly correspond to that of the nearly structureless Unit 1a, while the upper structureless part of KAT 2, Unit 2c, shares similar grain size properties with the cross-bedded Unit 1c.

Bayside deposits

KAT 8, the Bayside pit along the marsh profile (Fig. 1), contains several distinct sub-units that are each clearly discernable by color and texture. Normal and inverse grading trends are both present (Fig. 8c). Overall, KAT 8 sediments show a wide range of variation in mean grain size and skewness, and visual transitions between sub-units are mirrored by their grain size properties. Though no mud is present in KAT 8, we did observe 10-20 cm long mud flasers buried by 0-10 cm of sand in many locations along

the Biloxi Bay beach. The mud was filling in the troughs of sandy ripples, some generated by down-beach flow, and some that lacked an obvious flow orientation.

Flow direction indicators

Flow direction measurements indicate that while the entire island was subjected to inundation from the Gulf of Mexico, drainage of those floodwaters occurred mainly over the lower elevation southeastern part of the island (Fig. 9). Large fallen pine trees were assumed to be windblown, and their predominate north-northwest fall directions were plotted separately from other flow indicators (Fig. 9a). Well-preserved ripples on the surface of Hurricane Katrina sand (Fig. 9b and c) probably represent the last flows of water during the storm. Flattened palms, small bent pine trees, and other flow direction recorders show little evidence of seaward flow west of the profiles (Fig. 9d).

INTERPRETATION

Katrina vs. Rita

Since Hurricane Rita followed only two weeks after Katrina, separating the effects of the two storms was essential to our analysis. Rita did leave overwash deposits on Deer Island, but did not overtop the island completely, and most of the time wracklines marked the inland extent of flow (Fig. 10a and b). Where Rita wracklines were present, we are confident in our distinction between deposits of the two storms, since maximum Rita deposit heights are typically well below wrackline elevations (MORTON, 2002).

It is tempting to ascribe the mud layer in KAT 1 to the drainage of Katrina floodwaters, and attribute the sandy cross-bedded unit above the mud layer to Rita in spite of the wrackline we observed below this elevation (Fig. 6). However, even if we ignore the wrackline and consider the possibility that Rita waves were able to overtop lower elevation beach dunes, it is unlikely that deposition of a 40 cm thick cross-bedded unit could result from swash overtopping a nearly dry surface (cf. SCHWARTZ, 1975). Additionally, both 1a and 1c end at the same landward extent, and both display “bathtub rings” as a result of the marsh being drained down from the top of the deposit (Fig. 6). The filling of such a bathtub cannot be attributed to Rita’s wave action alone.

Additional identification of Rita deposits comes from precipitation observations. Locals reported to us that it had rained since Hurricane Katrina but not since Hurricane Rita. National Weather Service precipitation observations confirm this (NATIONAL WEATHER SERVICE, 2005). Presence of raindrops on deposits of both hurricanes, and lack of raindrops on post drainage Rita surfaces indicates that the last precipitation to fall on Deer Island was during Hurricane Rita, but before rain and overwash had drained from behind Rita deposits (Fig. 10c and d).

Overwash structure

Deer Island overwash deposits include two distinct depositional structures that are common to many overwash deposits. Horizontal to sub-horizontal, parallel to sub-parallel laminae are present in the lower part of KAT 2, and to some extent in lower units of KAT 1 and KAT 8 (cf. HAYES, 1967; LEATHERMAN, 1977; LEATHERMAN and WILLIAMS, 1983; NELSON and LECLAIR, 2006; SCHWARTZ, 1975; SEDGWICK and DAVIS, 2003; WANG *et al.*, 2006, and WANG and HORWITZ, 2006). Such lamination is usually attributed to upper plane bed deposition from swash overwash onto a wetted subaerial surface (Fig. 11; SCHWARTZ, 1975). These types of flows often have near-supercritical flow, with Froude numbers ranging from 0.6 to 1.1.

Steeply dipping cross-beds, like those apparent in upper units of KAT 1 and KAT 8, are another common element of overwash deposits (SCHWARTZ, 1975; SCHWARTZ, 1982; SEDGWICK and DAVIS, 2003; NELSON and LECLAIR, 2006; WANG and HORWITZ, 2003). They have been interpreted by SCHWARTZ (1975) and others as a result of bedload overwash deposition into a subaqueous environment, such is the case when ponds or standing water fill the area landward of breached or overtopped dunes (Fig. 11).

The sharp taper of Gulfside overwash deposits, on the marsh profile in particular, is likely attributable to the rapid loss of flow energy the overwash would have suffered upon encountering dense vegetation. Typically, overwash penetration distance is inversely related to marsh extent for a given area (MORTON and SALLENGER, 2003).

Early deposition

In the Deer Island vicinity, peak wave heights preceded maximum storm surge by about 10 hours (Fig. 12). Some dune erosion would have occurred as high energy waves began breaking on the beach and dune face (Fig. 13a). The marsh profile beach crest was overtopped by waves during this time and sediments scoured from the nearshore, beach, and dune face, were deposited on the back side of the dune (cf. MORTON, 2002) as they began to build Unit 1a.

The near lack of visible structure in the lower unit of KAT 1 (Unit 1a) is puzzling since most overwash deposition occurs as bedload. However, faint traces of sub-horizontal layering are apparent. While complete deposition from suspension is rare in overwash deposits, combined bedload and suspended load transport is common. LEATHERMAN (1977) measured 16% suspended material in “large” overwash pulses with flow depths of 0.3 m. He posited that a higher percentage of suspended load might be present in flows deeper than 0.3 m. WANG and HORWITZ (2006) observed that between their study sites, more sand was deposited from suspension in areas that were densely vegetated. A relatively high concentration of suspended sand, resulting from large wave pulses encountering densely growing grasses, may explain the partial lack of structure in Unit 1a.

The Gulfside forest profile deposit, KAT 2, is higher than KAT 1 and would not have been overtopped by high waves alone. However, a rising storm surge would have given breaking waves the boost they needed to overtop the KAT 2 dune (Fig. 13b). The lowest sub-horizontal layering of KAT 2 typifies the upper plane bed deposition of subaerial overwash deposits. The obvious layering in Unit 2a, compared to the subtler structure present in Unit 1a, is perhaps the result of smaller pulses of water and sand carried by lower energy waves, or of deposition over a smoother surface with less interference from vegetation.

Peak storm deposition

Interpreting Unit 1b, the thin, normally graded mud layer overlying Unit 1a, was the crux of Deer Island Hurricane Katrina deposits. Normal grading of the mud indicates that it was deposited from suspension. Since we are confident that Units 1a and 1c were both deposited by Katrina, we must explain how a period of mid-storm “quiescence” was created, which allowed mud to settle between two periods of primarily bedload deposition.

Calculations using cnoidal wave theory reveal that the lowest bottom velocities during Hurricane Katrina’s passage over Deer Island occurred during peak storm surge

(Fig. 12). Waves had weakened from those that initially overtopped the KAT 1 dune, and were now being dispersed through a 6-8 m water column. Their effect on the ground surface of Deer Island would have decreased as surge height increased. Paradoxically, it seems that low energy conditions needed to deposit mud from suspension were met when Katrina's storm surge was highest, around the time of landfall (Fig. 13c).

Possible sources for the mud include offshore waters surrounding Deer Island, and the proximal marsh. Fines in Biloxi Bay come from drainage of the Biloxi and Tchoutacabouffa Rivers, and from erosion of Deer Island itself (RANKIN *et al.*, 2005). Mud may also have been derived from the marsh directly southeast of the KAT 1 deposit (Fig. 6), which would explain the lack of mud in KAT 2. Mid-deposit organic-rich sands in Unit 2b may indicate the occurrence of a parallel sequence of events in KAT 2, where no mud was included in the suspended load.

Late-stage deposition

Assuming that deposition of the KAT 1 mud layer and KAT 2 organics occurred at peak surge, the landward-dipping cross-bedded Unit 1c and structureless Unit 2c must both have been deposited by a retreating storm surge. Once the storm water level was low enough that incoming waves were once again breaking over the topographical high of the beach dune, bedload deposition resumed (Fig. 13d). The entire island was still covered with water, which explains the steeply dipping foresets of Unit 1c, typical of subaqueous overwash deposition. KAT 2 was overtopped only briefly after landfall (Fig. 13e), which explains the thinness of Unit 2c compared to Unit 1c. The structureless Unit 2c may probably represents suspension settling that occurred as the last water drained from this area.

After breaking waves dropped their initial sediment load, little sand was deposited across the interior of the island until flow reached the far beach. Bedload deposition on the Biloxi Bay side of the island was probably initiated when cross-island flow encountered resistance from elevated storm water levels in Biloxi Bay. Sediment sources of these backbay deposits would have varied according to local geology and sand availability. Bayside overwash sand sources include deposits from previous storms, Holocene muddy sands, and Pleistocene Gulfport sands.

Lower Katrina boundaries are ambiguous on the far side of the forest profile at KAT 8. The contact of the lowermost sand unit, Unit 8a, obviously scours the sub-surface sandy soil, but this erosion could have been the result of Katrina or of a previous storm (Fig. 7). Down-beach dipping cross-beds in Units 8d and 8e must have been the result of cross-island flow. Preservation of structure in these upper units also indicates that they have had little time to be reworked, and are most likely the result of Hurricane Katrina. Downbeach soft-sediment shear from above, possibly from the flow that deposited Unit 8f, appears to be responsible for the deformation in Unit 8e. However, we were not able to identify Rita wracklines at this location, and it is possible that the upper unit is not the result of cross-island flow, but is instead Biloxi Bay beach sand deposited in the up-beach direction by Rita.

While all sand samples are nearly 100% quartz, the varying degrees of brownish tints in KAT 8 sub-units are the result of partial staining by mildly decaying organic matter (cf. WANG *et al.*, 2006). Part of the lower Gulfport Formation, which cores Deer Island, is impregnated with humate, an amorphous organic material (OTVOS, 1991). The source of the tan and brown colors in KAT 8 could be from recent organic staining, or

from humate-stained excavated Gulfport Pleistocene sands. It is unclear how many events are represented by these distinct units.

Mud flasers in the Biloxi Bay beach were likely formed as Hurricane Katrina waters drained, and therefore are not temporally correlated with the KAT 1 mud layer. These mud flasers are analogous to those observed by RICHARDSON AND BRIGGS (2005) in shallow sandy shelves in the Gulf of Mexico, where Hurricane Ivan backwash mud settled onto rippled sands and was later covered with sand by subsequent tropical storms. Deer Island flasers filled in the troughs of Katrina ripples as floodwaters drained. Most flasers were found at low elevations and were covered with sand that was laid down by Hurricane Rita.

Grain size trends

Shifts in mean grain size and skewness patterns probably reflect changing sediment sources. Early sedimentation in Gulfside deposits occurred as waves lapped up on the beach face and dune, and scoured, then re-deposited this material. After flow had crossed the entire island, however, additional sand sources would have been encountered and potentially scoured. Pleistocene and Holocene sands from lower elevations to the southeast, beach sands from the Gulf or Bay sides, and old storm deposits are potential sources for KAT 8 deposits. Geological recycling of Deer Island's limited sand by storms and wind, however, creates homogeneity and complicates identification of sand sources.

Overwash sediment source is partially the function of hurricane location, which is variable over time. While southeasterly winds generated southeasterly waves at Deer Island for most of Katrina's approach, wind direction changed at landfall. As the eye of the storm passed Deer Island, wind and waves would have rapidly shifted to a more southerly, then southwesterly source (Fig. 1a). Storm waves are a combination of short-period wind waves and long-period swell, and the two types would respond differently to changes in the storm's location. Swell is developed over the course of a storm and would be slower to respond than wind waves. Changing winds at landfall would thus trigger a change in wave quality (cf. ALLISON *et al.*, 2005), and the incorporation of additional sediment by wind waves now approaching from the southwest.

The temporal increase in mean grain size variation, decrease in skewness variation, and the general coarsening throughout each Gulfside deposit, probably reflects the addition of a new sediment source when winds shifted at landfall. It is difficult to account for parallel grain size trends by changes in flow processes alone, given that structural changes also reflect changing flow properties. While grain size properties between the two deposits progress similarly from bottom to top, the structures within them argue that water depths and bottom velocities were different for each of the two profiles. At any given time, bottom velocities at KAT 1 and KAT 2 would have been different, but wave direction was always the same for both. After Katrina's landfall, which is marked by mud in KAT 1 and organics in KAT 2, winds shifted from the southwest to the southeast, and waves began scouring sand grains from a more westerly source.

DISCUSSION

Implications for distinguishing tsunami and storm deposits

Hurricanes and tsunamis are two prevalent coastal hazards that can both deposit sand sheets as a record of their passage. Detailed studies of modern storm and tsunami sand sheets can help us understand the processes that deposited them, as well as our capabilities and limitations for recognizing such deposits in the field.

When considered as generation mechanisms for coastal flooding, tsunamis and storms are fundamentally different. Tsunamis are made up of several waves with wavelengths of hundreds of kilometers, are disturbance-generated and propagate out from a specific location (BROWN *et al.*, 2000). Storms are meteorological phenomena composed of wind-generated waves stacked onto a wind- and pressure-generated storm surge. They can affect a single area for days or weeks, move rapidly or slowly, grow or shrink in size, intensify or weaken (EMMANUEL, 2005). Despite their disparities, tsunami and storm deposits often share strong resemblances and casual identification of the two types of sand sheets can be difficult (cf. DAWSON AND SHI, 2000; FOSTER *et al.*, 1991; NANAYAMA *et al.*, 2000; SWITZER *et al.*, 2005).

Nevertheless, the ability to distinguish between tsunami and storm deposits is desirable. Understanding the relative hazards of tsunamis and storms is especially important in areas where tectonic hazards are poorly understood, or where the historical record is short. Additionally, far-field and aseismic tsunamis are a risk for even tectonically passive coastlines.

Several researchers have used the dissimilar natures of tsunamis and storms as a basis for direct comparison of specific examples of the two types of deposits (GOFF *et al.*, 2004; MORTON *et al.*, in press; NANAYAMA *et al.*, 2000; TUTTLE *et al.*, 2004). Each of these studies established valuable frameworks for distinguishing between tsunami and storm deposits. However, it is difficult to uniformly apply these deposit observations to every coastline and every event. Size, energy, duration, and location of the generating mechanism interact with local bathymetry, topography, and vegetation, to determine the initial sediment transport potential. Sediment type and availability further influence the resulting deposit.

Inclusion of mud laminae is not a valid diagnostic criterion for identifying tsunami deposits, as was proposed by MORTON *et al.* (in press). Deposition from suspension is common in tsunamis, and MORTON *et al.* argue that the length of time between subsequent tsunami waves is sufficient to allow mud to settle out, whereas this is not the case during storms. The researchers do present an example from Hurricane Isabel on the United States Atlantic coast, of a mat of organic debris that settled out of suspension mid-storm. Perhaps if a mud source was nearby, mud may have replaced or accompanied the organic mat, as we claim was the case for KAT 2. The Deer Island deposits provide a counter-example to the claim that mid-storm mud layers do not occur.

Tsunamis have the potential for more extensive erosion than do storms. On Deer Island, preservation of growth position grasses indicates that burial was rapid and that early flows over vegetated areas were depositional rather than erosional on the lee side of the beach dune. Typically, erosion associated with overwash occurs on the beach face, foredune, around obstacles, and localized in channels. Storm erosion creates scarps and provides sediments for inland deposits or offshore transport (cf. DONNELLY *et al.*,

2004; MORTON, 2002; MORTON and SALLENGER, 2003; MORTON *et al.*, 2000; OTVOS, 2004; SALLENGER, 2000; WANG *et al.*, 2006). Tsunamis, however, are capable of eroding broad zones inland of the beach (cf. CISTERNAS *et al.*, 2005; GOFF *et al.*, 2003; LIU *et al.*, 2005; HINDSON AND ANDRADE, 1999; MORTON *et al.*, in press; SHI *et al.*, 1995; TUTTLE *et al.*, 2004). In cases where extensive inland erosion underlies event deposits, tsunamis should be favored over storms as the responsible candidate.

In modern settings, thick overwash deposits laid down parallel to the line of breaking waves during a hurricane are easily contrasted with extensive, sheet-like tsunami deposits. During the hours or days of a storm, each wave has the potential to scour and deposit new material. Thick overwash deposits are the result of successive storm waves that break and drop their sediment loads in similar locations in response to obstructions, marshes, and vegetation. In contrast, while a tsunami bore will also lose energy and deposit sediment into a marsh, additional energy is still being supplied by the tail end of the encroaching 100 km wave. In this manner, tsunamis have the potential to deposit relatively more extensive and regular deposits than do storms. However, the original geometry of tsunami and storm deposits may not be entirely preserved in the geologic record.

Geologic record of previous storms on Deer Island

Potential candidates for past storms were observed on Deer Island in the form of buried sand sheets separated by organic debris. Examples of past event deposits were noted along the north side of Deer Island, both in the interior (Fig. 15), and potentially on the Biloxi Bay beach in lower units of KAT 8 (Fig. 7). Possible transporters of these sand sheets include Hurricanes Camille (1969), Elena (1985), Lily (2002), and Ivan (2004).

No buried sand layers were discovered below modern Deer Island marsh deposits. Considering that even sand laid down by Hurricane Katrina penetrated only a few meters into the marsh, a lack of sand here does not mean that previous storms did not build overwash deposits on Deer Island. The thickest overwash deposits, which probably have more preservation potential than thin deposits (cf. WANG and HORWITZ, 2006), are located just landward of beach berms. Since Deer Island's shoreline is rapidly retreating towards the interior of the island, older overwash deposits may be buried or reworked by impinging beaches. Deer Island is eroding at variable rates, and relatively stable parts of the island may have better overwash preservation potentials than rapidly eroding areas.

CONCLUSIONS

A storm surge of 8-9 m at Deer Island during Hurricane Katrina's landfall allowed for dispersal of enough wave energy throughout the water column that bottom velocities were reduced and mud was allowed to settle out of suspension. The relationship between storm water depths and wave heights not only controls the structure of overwash deposits, but determines whether deposition occurs from bedload or suspended load. Thick overwash deposits underlying and overlying an observed mud layer must have been the result of Hurricane Katrina, and therefore preclude any pre- or post-storm explanations for mud layer deposition. The Deer Island KAT 1 deposit also provides a counter example to a proposal that storms are not able to leave mid-deposit mud layers (MORTON *et al.*, in press).

Grain size distribution and skewness trends differ spatially between deposits on opposite sides of the island as well as temporally throughout Gulfside deposits, and probably represent a changing sediment source. In two Gulfside pits, sand populations in structureless and sub-horizontally bedded lower overwash units exhibit narrow ranges of mean grain size and wide ranges of skewness. Conversely, sub-samples within cross-bedded and structureless upper units display wide ranges of mean grain size, and narrower ranges of skewness. This abrupt transition probably reflects the addition of new sediment when wind wave directions shifted during Katrina's landfall. In Bayside pits, where overwash was deposited from across the island, mean grain size and skewness vary greatly between sub-units in a seemingly unorganized progression. Grain size and skewness variations seem to be compounded in overwash deposits on the far side of the island where more potential sediment sources exist.

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REFERENCES

- ALLISON, M.A.; SHEREMET, A.; GOÑI, M.A., and STONE, G.W., 2005. Storm layer deposition on the Mississippi-Atchafalaya subaqueous delta generated by Hurricane Lili in 2002. *Continental Shelf Research*, 25, 2213-2232.
- ANDRADE, C.; FREITAS, M.C.; MORENO, J., and CRAVEIRO, S.C., 2004. Stratigraphical evidence of Late Holocene barrier breaching and extreme storms in lagoonal sediments of Ria Formosa, Algarve, Portugal. *Marine Geology*, 210, 339-362.
- ANDREWS, P.B., 1970. Facies and genesis of a hurricane washover fan, St. Joseph Island, Central Texas Coast. *Report of Investigation No. 67, Bureau of Economic Geology*, University of Texas Austin, Austin, TX.
- BRIDGES, P.H., 1976. Lower Silurian Transgressive Barrier Islands, Southwest Wales. *Sedimentology*, 23, 347-362.
- BROWN, E.; COLLING, A.; PARK, D.; PHILLIPS, J.; ROTHERY, D., and WRIGHT, J., 2000. *Waves, Tides, and Shallow-water Processes, 2nd ed.* Burlington, Massachusetts: Butterworth-Heinemann, 228p.
- BUYNEVICH, I.V.; FITZGERALD, D.M., and VAN HETEREN, S., 2002. Sedimentary records of intense storms in Holocene barrier sequences, Maine, USA. *Marine Geology*, 210, 135-148.
- CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES, 2005. *Historic water level observations, 874-5557 Gulfport Harbor, MS, and 8741533 Pascagoula NOAA Lab.* Available at: <http://tidesandcurrents.noaa.gov>.
- CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES, 1979. *Historic water level data for 874-3812 Deer Island, Biloxi Bay, MS.*
- CISTERNAS, M.; ATWATER, B.F.; TORREJÓN, F.; SAWAI, Y.; MACHUCA, G.; LAGOS, M.; EIPERT, A.; YOULTON, C.; SALGADO, I.; KAMATAKI, T.; SHISHIKURA, M.; RAJENDRAN, C.P.; MALIK, J.K.; RIZA, Y., and HUSNI, M., 2005. Predecessors of the giant 1960 Chile earthquake. *Nature*, 437, 404-407.

- DAWSON, A. and SHI, S., 2000. Tsunami deposits. *Pure Applied Geophysics*, 157, 875-897.
- DONNELLY, J.P.; BUTLER, J.; ROLL, S.; WENGREN, M., and WEBB, T., III., 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey. *Marine Geology*, 210, 107-121.
- DONNELLY, C.; KRAUS, N., and LARSON, M., 2006. State of Knowledge on Measurement and Modeling of Coastal Overwash. *Journal of Coastal Research*, 22(4), 965-991.
- EMMANUEL, K., 2005. *Divine Wind: The History and Science of Hurricanes*. New York, New York: Oxford University Press, 285p.
- FEDERAL EMERGENCY MANAGEMENT AGENCY STAFF, 2006. *MS-I25 Hurricane Katrina surge inundation and advisory base elevation map, Harrison County, MS*. Washington, D.C.: Federal Emergency Management Agency, 1 sheet.
- FEDERAL EMERGENCY MANAGEMENT AGENCY STAFF, 2006. *MS-I26 Hurricane Katrina surge inundation and advisory base elevation map, Harrison and Jackson Counties, MS*. Washington, D.C.: Federal Emergency Management Agency, 1 sheet.
- FERGUSON, R.I., and CHURCH, M.A., 2004. A simple universal equation for grain size settling velocity. *Journal of Sedimentary Research*, 74(6), 933-937.
- FOSTER, I.D.; ALBON, A.J.; BARDELL, K.M.; FLETCHER, J.L.; JARDINE, T.C.; MOTHERS, R.J.; PRITCHARD, M.A., and TRUNER, S.E., 1991. High energy coastal sedimentary deposits; an evaluation of depositional processes in southwest England. *Earth Surface Processes and Landforms*, 16, 341-356.
- GOFF, J.; MCFADGEN, B.G., and CHAGUÉ-GOFF, C., 2004. Sedimentary Differences between the 2002 Easter storm and the 15th century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine Geology*, 204(1-2), 235-250.
- GRAUMANN, A.; HOUSTON, T.; LAWREMORE, J.; LEVINSON, D.; LOTT, M.; MCCOWN, S.; STEPHENS, S., and WUERTZ, D., 2005. Hurricane Katrina, A Climatological Perspective. Asheville, North Carolina: National Oceanic and Atmospheric Administration Climatic Data Center, *Technical Report 2005-01*, 27p.
- GUZA, R.T., and THORNTON, E.B., 1980. Local and shoaled comparisons of sea surface elevations, pressures, and velocities. *Journal of Geophysical Research*, 85(C3), 1524-1530.
- GUZA, R.T., and THORNTON, E.B., 1910. Swash oscillations on a natural beach. *Journal of Geophysical Research*, 87(C1), 483-491.
- GUZA, R.T., and THORNTON, E.B., 1982. Wave set-up on a natural beach. *Journal of Geophysical Research*, 86(C5), 4133-4137.
- HAYES, M.O., 1967. Hurricanes as geological agents, south Texas coast. *American Association Petroleum Geologist Bulletin*, 51, 937-942.
- HIGMAN, B., 2007. *ViscoSands version 4.17*. Available at: Network for Earthquake Engineering Simulation, <http://www.nees.org>.
- HILL, H.W.; KELLEY, J.T.; BELKNAP, D.F., and DICKSON, S.M., 2004. The effects of storms and storm-generated currents on sand beaches in Southern Maine, USA. *Marine Geology*, 210, 149-168.
- HINDSON, R.A., and ANDRADE, C., 1999. Sedimentation and hydrodynamic processes associated with the tsunami generated by the 1755 Lisbon earthquake. *Quaternary International*, 56, 27-38.
- JACOBSON, J., and REES, S.I., 2006. *Environmental assessment for restoration of Deer Island, Harrison County, Mississippi, Grand Bayou Marsh, southern shoreline restoration, and the western breach, a restoration project: Draft*. Mobile, Alabama: U.S. Army Corps of Engineers, 35p.
- KNAPP, R.D.; RHOME, J.R., and BROWN, D.P., 2005. *Tropical Cyclone Report: Hurricane Katrina, 23-30 August 2005*. Miami, Florida: National Hurricane Center, 42p.
- KRASSOVSKI, M.; THOMSON, R., and RABINOVICH, A., 2005. *Coastal sea level response to Hurricane Katrina*. Sidney, B.C., Canada: Institute of Ocean Sciences and University of Victoria, 6p.
- LEATHERMAN, S.P., 1977. Overwash Hydraulics and Sediment Transport. *Coastal Sediments '77*, 135-149.
- LEATHERMAN, S.P., and WILLIAMS, A.T., 1983. Vertical Sedimentation Units in a Barrier Island Washover Fan. *Earth Surface Processes and Landforms*, 8, 141-150.
- LIU, P.L.-F.; LYNETT, P.; FERNANDO, H.; JAFFE, B.; FRITZ, H.; HIGMAN, B.; MORTON, R.; GOFF, J., and SYNOLAKIS, C., 2005. Observations by the international tsunami team in Sri Lanka. *Science*, 308, 1595.
- LOUISIANA STATE UNIVERSITY, 2005. *Experimental ADCIRC Storm Surge Model Hurricane Katrina Hindcast*. Available at: <http://hurricane.lsu.edu/floodprediction>

- MCLAREN, P., and BOWLES, D., 1985. The effects of sediment transport on grain-size distributions. *Journal of Sedimentary Petrology*, 55(4), 457-470.
- MISSISSIPPI DEPARTMENT OF MARINE RESOURCES, 2007. *Mississippi Department of Marine Resources* [Web Page], accessed Feb 21, 2007. Available at: <http://www.dmr.state.ms.us/Coastal-Ecology/GEMS/Deer-Island.htm>.
- MOLLER, I., and ANTHONY, D., 2003. GPR study of sedimentary structures within a transgressive coastal barrier along the Danish North Sea coast. In: Bristow, C.S., and Jol, H.M., Eds., *Ground-Penetrating Radar in Sediments*. Geological Society of London Special Publication, 211, 55-67.
- MORTON, R.A., 2002. Factors Controlling Storm Impacts on Coastal Barriers and Beaches- A Preliminary Basis for Near Real-Time Forecasting. *Journal of Coastal Research*, 18(3), 486-501.
- MORTON, R.A., and SALLENGER, A.H., Jr., 2003. Morphological Impacts of Extreme Storms on Sandy Beaches and Barriers. *Journal of Coastal Research*, 19(3), 560-573.
- MORTON, R.A.; GONZALEZ, J.L.; LOPEZ, G.I., and CORREA, I.D., 2000. Frequent non-storm washover of barrier islands, Pacific coast of Columbia. *Journal of Coastal Research*, 16(1), 82-87.
- MORTON, R.A.; GELFENBAUM, G., and JAFFE, B.E., in press. Physical Criteria for Distinguishing Tsunami and Storm Deposits Using Modern Examples. *Sedimentary Geology Special Issue on Tsunami Deposits*.
- NANAYAMA, F.; SHIGENO, K.; SATAKE, K.; SHIMOKAWA, K.; KOITABASHI, S.; MIYASAKA, S., and ISHII M., 2000. Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. *Sedimentary Geology*, 135, 255-264.
- NATIONAL DATA BUOY CENTER STAFF, 2006. *Reports from the National Data Buoy Center's Stations in the Gulf of Mexico During the Passage of Hurricane Katrina 27-30 August 2005*. Stennis Space Center, Mississippi, National Data Buoy Center. Available at: <http://www.ndbc.noaa.gov/hurricanes/2005/katrina>.
- NATIONAL GEODETIC SURVEY, 2005. *NOAA Images 24332310 and 24332330*. Hurricane Katrina Images. Available at: <http://ngs.woc.noaa.gov/katrina>.
- NATIONAL WEATHER SERVICE, 2005. *Precipitation Analysis*. Available at: http://www.srh.noaa.gov/rfcshare/precip_analysis_new.php
- NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 2005. *GOES 12 Hurricane Katrina satellite image 1745 UTC 28 August 2005*.
- NELSON, S.A., and LECLAIR, S.F., 2006. Katrina's unique splay deposits in a New Orleans neighborhood. *GSA Today*, 16(9), 4-10.
- OFFICE OF COAST SURVEY, 1851. *T-Sheet 324*, Harrison County. Mississippi Office of Geology, 2 sheets.
- OTVOS, E.G., 1985. *Guidebook, Coastal Evolution- Louisiana to Northwest Florida*. American Association of Petroleum Geologists Annual Meeting. New Orleans, Louisiana: The New Orleans Geological Society, 91p.
- OTVOS, E.G., 1991. Northeastern Gulf Coast Quaternary. In: Morrison, R.B., ed., *Quaternary Nonglacial Geology: Conterminous U.S.* Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-2.
- OTVOS, E.G., 2004. Beach Aggradation Following Hurricane Landfall: Impact Comparisons from Two Contrasting Hurricanes; Northern Gulf of Mexico. *Journal of Coastal Research*, 20(1), 326-339.
- OTVOS, E.G., 2005. A Severely Endangered Recreational Island, Mississippi Gulf Coast: Potential Solutions to Erosion Problems. *Final Report for Mississippi Dept of Marine Resources*, 59p.
- RANKIN, K.L.; SCHMID, K., and GAFFNEY, D.A., 2005. *Deer Island: Erosion Analysis and Solution Planning Report*. Franklin, Tennessee: Beach Restoration, Inc., prepared for Mississippi Department of Marine Resources, 36p.
- RICHARDSON, M.D., and BRIGGS, K.B., 2005. Development of Flaser and Lenticular Bedding in Response to Tropical Cyclones [abs]. *American Geophysical Union*, abstract #OS33A-03.
- SALLENGER, A.H., Jr., 2000. Storm Impact Scale for Barrier Islands. *Journal of Coastal Research*, 16(3), 890-895.
- SCHMID, K., and OTVOS, E.G., 2003. Deer Island, Coastal Mississippi- a geological and historical story [abs]. *Journal of the Mississippi Academy of Sciences*, 48(1), p. 45. Presentation available at: geology.deq.state.ms.us/coastal/NOAA_DATA/Publications/Presentations/Harrison/MAS_DeerIsland_Geology_Pres.pdf

- SCHWARTZ, R.K., 1975. Nature and Genesis of Some Storm Washover Deposits. *Technical Memorandum 61*. Ft. Belvoir, Virginia: U.S. Army Corps of Engineers, Coastal Engineering Research Center, 99p.
- SCHWARTZ, R.K., 1982. Bedform and stratification characteristics of some modern small-scale washover sand bodies. *Sedimentology*, 29, 835-849.
- SEDGWICK, P.E., and DAVIS, R.A., Jr., 2003. Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. *Marine Geology*, 200, 31-48.
- SHI, S.; DAWSON, A.G., and SMITH, D.E., 1995. Coastal sedimentation associated with the December 12, 1992 tsunami in Flores, Indonesia. In: Satake, K., and Imamura, K. (ed.), *Recent Tsunami, Pure and Applied Geophysics*, 144, 526-536.
- SLOAN, S.D., and SCHMID, K., 2003. Deer Island, Evolution and morphology [abs]. *Mississippi Academy of Sciences*, 48(1), p 45.
- SWITZER, A.D.; PUCILLO, K.; HAREDY, R. A.; JONES, B. G., and BRYANT, E. A., 2005. Sea Level, Storm, or Tsunami: Enigmatic Sand Sheet Deposits in a Sheltered Coastal Embayment from Southeastern New South Wales, Australia. *Journal of Coastal Research*, 21(4), 655-663.
- TUTTLE, M.P.; RUFFMAN, A.; ANDERSON, T., and JETER H., 2004. Distinguishing Tsunami from Storm Deposits in Eastern North America: The 1929 Grand Banks Tsunami versus the 1991 Halloween Storm. *Seismological Research Letters*, 75(1), 117-131.
- US ARMY CORPS OF ENGINEERS, 2006. EM 1110-2-1100 Part II. *Coastal Engineering Manual*. Available at: <http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=ARTICLES;104>.
- US GEOLOGICAL SURVEY, 2005. *USGS 02481000 Biloxi River at Wortham, MS*. USGS Water data for the nation. Available at: <http://waterdata.usgs.gov/nwis>.
- WANG, P., and HORWITZ, M.H., 2006. Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. *Sedimentology*, online early articles, 1-20.
- WANG, P.; KIRBY, J.H.; HABER, J.D.; HORWITZ, M.H.; KNORR, P.O., and KROCK, J.R., 2006. Morphological and Sedimentological Impacts of Hurricane Ivan and Immediate Poststorm Beach Recovery along the Northwestern Florida Barrier-Island Coasts. *Journal of Coastal Research*, 22(6), 1382-1402.
- WORLD METEOROLOGICAL ORGANIZATION STAFF, 1998. Geneva. *Guide to Wave Analysis and Forecasting, WMO No-702, 2nd Edition*. Geneva, Switzerland: World Meteorological Organization, p10.

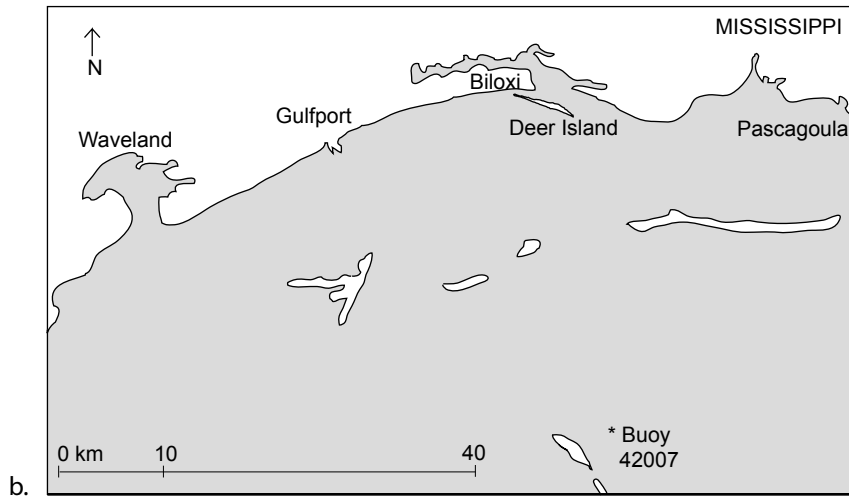
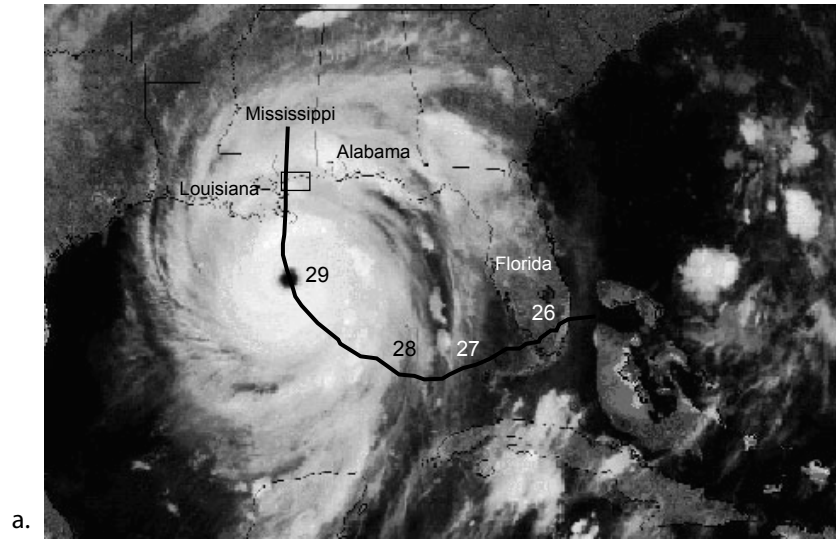
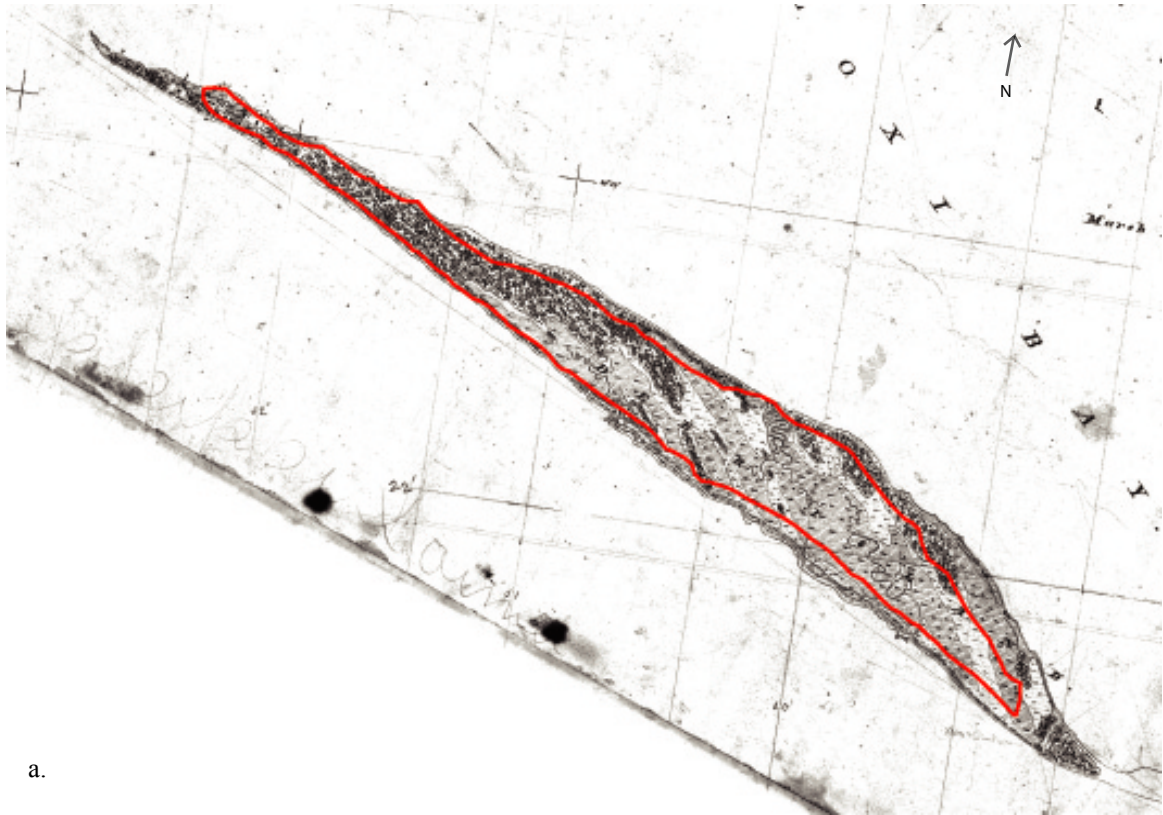
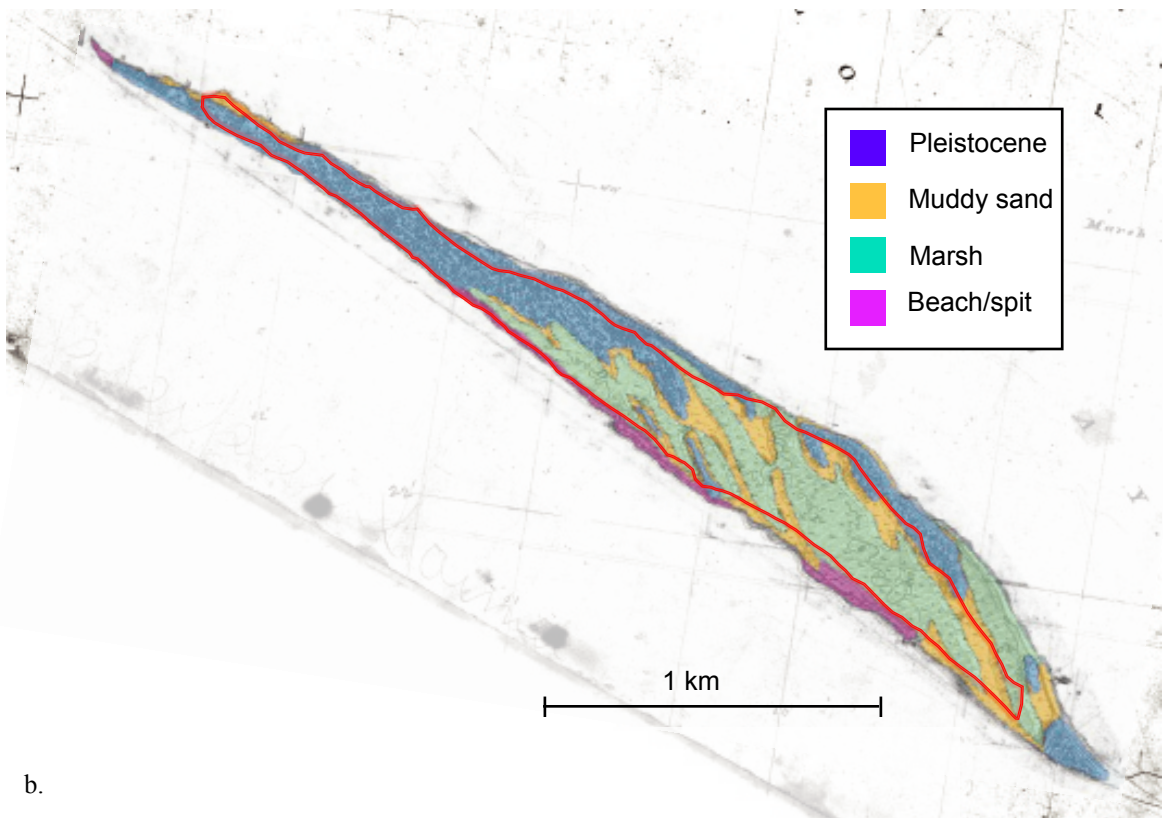


Fig. 1. a) NOAA GOES 12 satellite image (2005) of Hurricane Katrina just before final landfall. Track of Katrina is superimposed in black with location of the eye represented by dates in August, 2005. b) Western Gulf of Mexico region. Deer Island and Biloxi are partially protected by a chain of outer barrier islands. NDBC buoy 42007 is also shown in its approximate moored location at 14 m water depth.



a.



b.

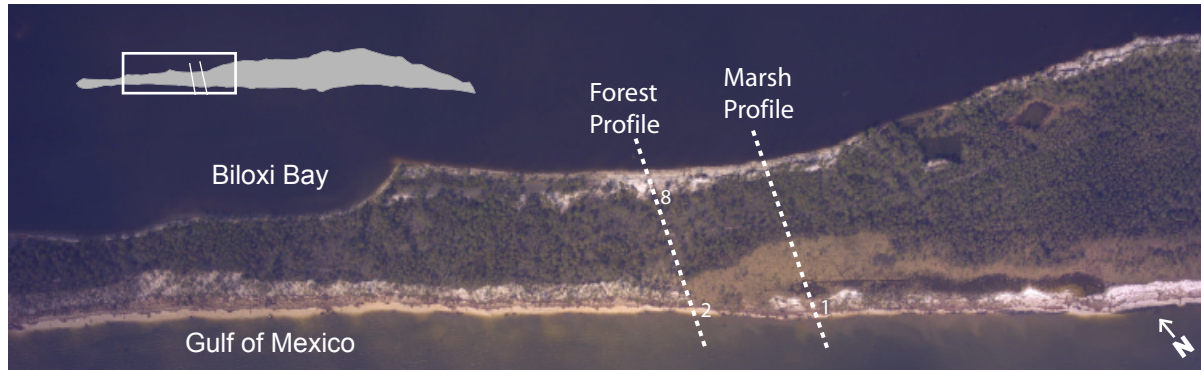
Fig. 2. a) 1851 Office of Coast Survey T-sheet of Deer Island with today's Deer Island outlined in red. b) 1851 surface geology types as interpreted by Coastal Restoration Solutions (RANKIN et al., 2005). Deer Island's shoreline character today is much a result of pre-existing surface geology.



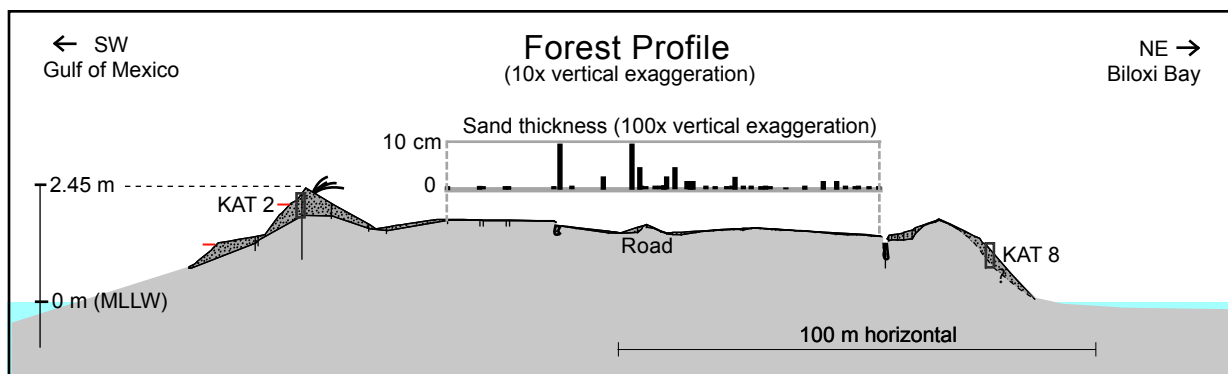
Fig. 3. NOAA air photo from August 31 (NATIONAL GEODETIC SURVEY, 2005), two days after Hurricane Katrina's landfall, showing a breach that cut off the former western tip of Deer Island. This breach was first created by Hurricane Camille in 1969, was further widened by Hurricane Elena in 1985, and exacerbated by Hurricane Katrina in 2005.



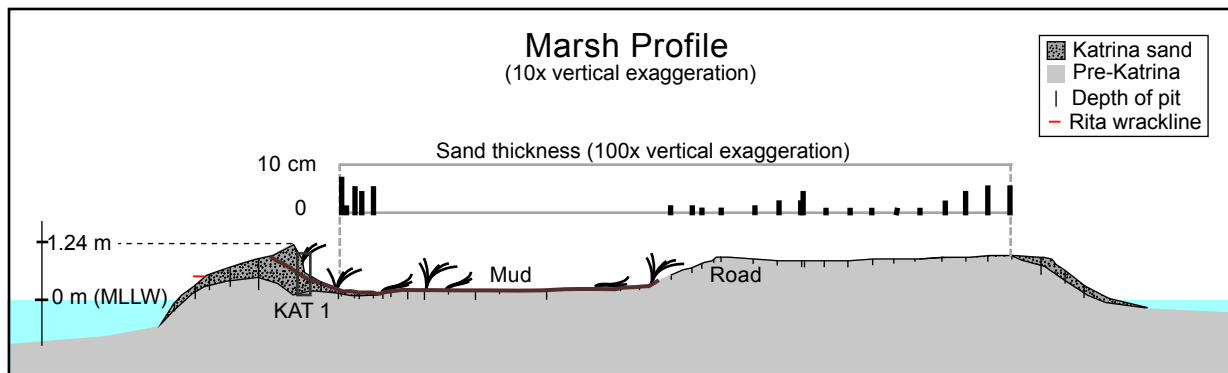
Fig. 4. A stranded tree trunk indicates that Hurricane Katrina water levels reached 8.83 m above MLLW on Deer Island. Photo is taken towards the north with Hurricane Katrina-damaged Biloxi in the background.



a.



b.



c.

Fig. 5. a) Deer Island map and aerial photo (NATIONAL GEODETIC SURVEY, 2005) of field site from August 31, 2005, two days after Hurricane Katrina's landfall in Waveland. Numbers represent "KAT" sample sites used for grain size analysis. b) and c) Deer Island topographic profiles and Hurricane Katrina deposits. Thin (<10 cm) deposits are magnified at 100x vertical exaggeration. Thick Bayside sand bodies were deposited by cross-island flow directed towards Biloxi Bay. Locations of along-profile KAT sample sites in thick Gulfside and Bayside deposits and Hurricane Rita wracklines are noted on profiles. Boxes indicate approximate areas of detailed description of KAT 1 and KAT 8 in Figs. 6, 7, and 8, and of KAT 2 in Fig. 8. In b) dashed line under KAT 8 represents ambiguity of the Katrina deposit's lower limit.

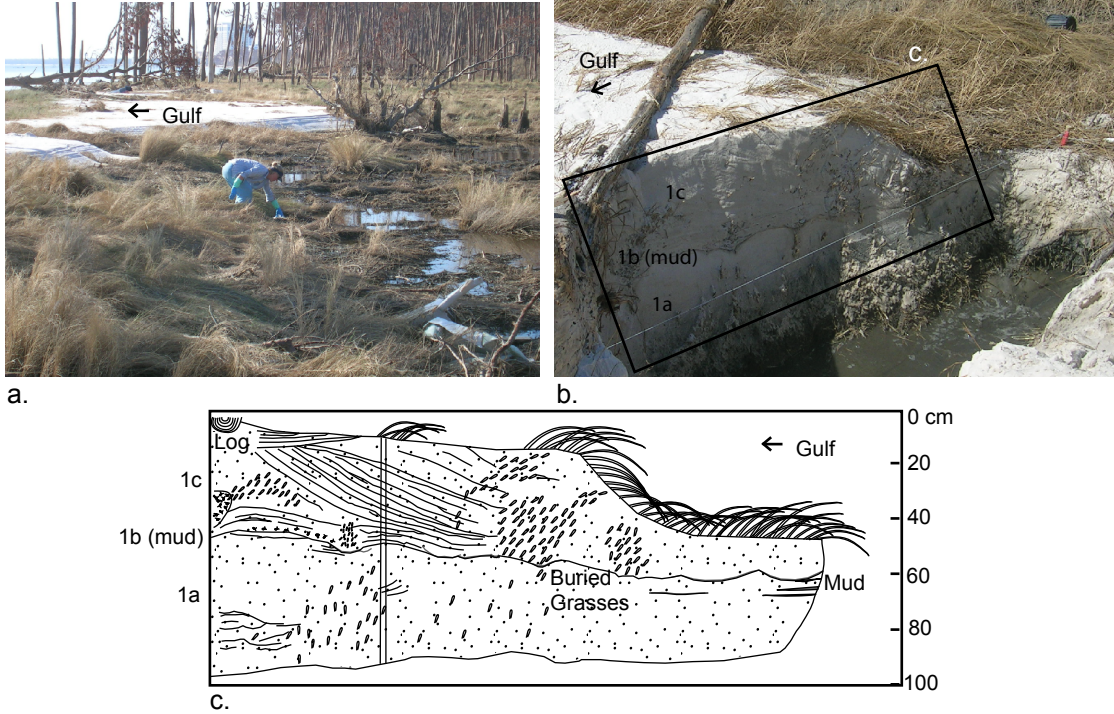


Fig. 6. Gulfside deposits. a) South end of Marsh profile looking towards forest profile. b) and c) Overview of KAT 1 sample site. Note mud layer dividing the deposit, and differences in structure between top and bottom halves of the deposit. Unit 1a shows traces of sub-horizontal laminae; Unit 1c shows truncated, steeply dipping foresets, and faint, truncated planar lamination in the top left corner.

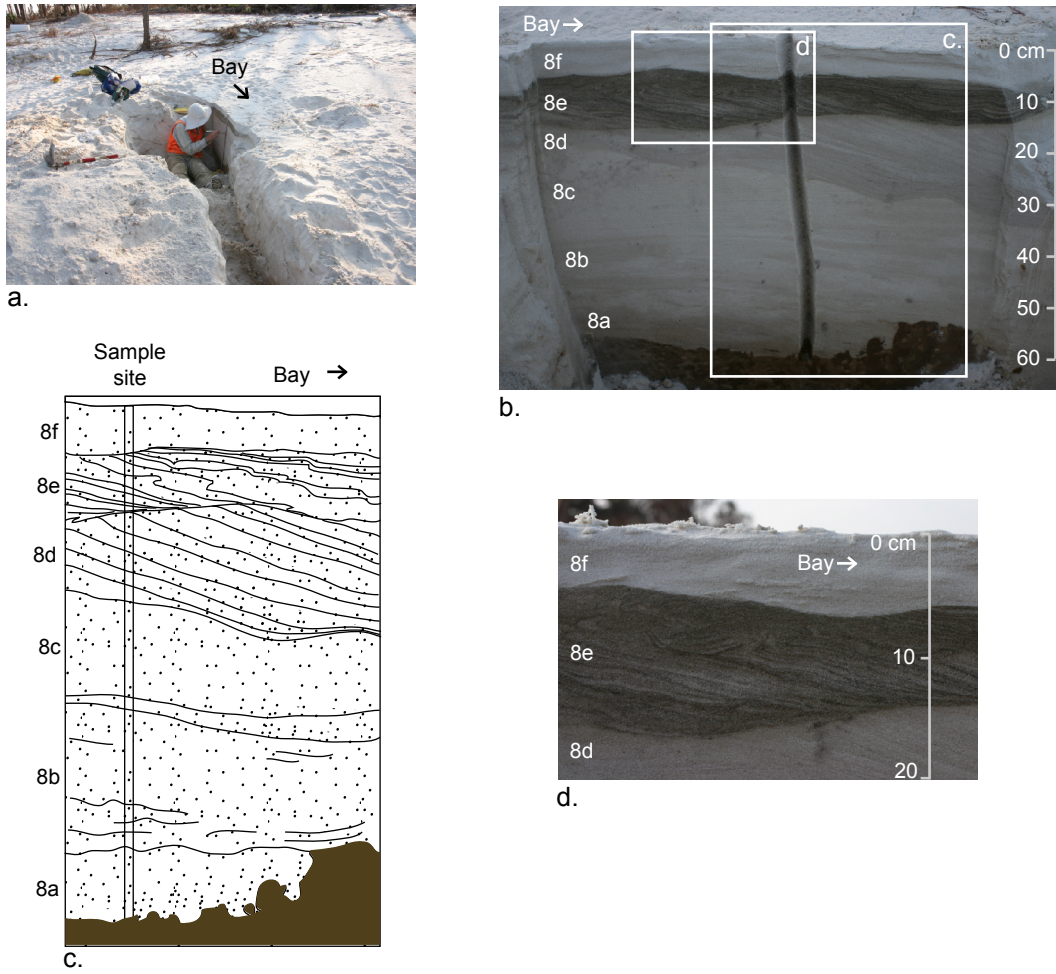


Fig. 7. Bayside deposits. a) KAT 8 trench overview, looking south onto Deer Island from beach. b) Overview of KAT 8 trench and sampling site. c) Sketch of KAT 8 structure. d) Closeup of upper layers before they were sampled. Note foresets dipping towards the bay, and evidence of downbeach shearing in top section of 8e.

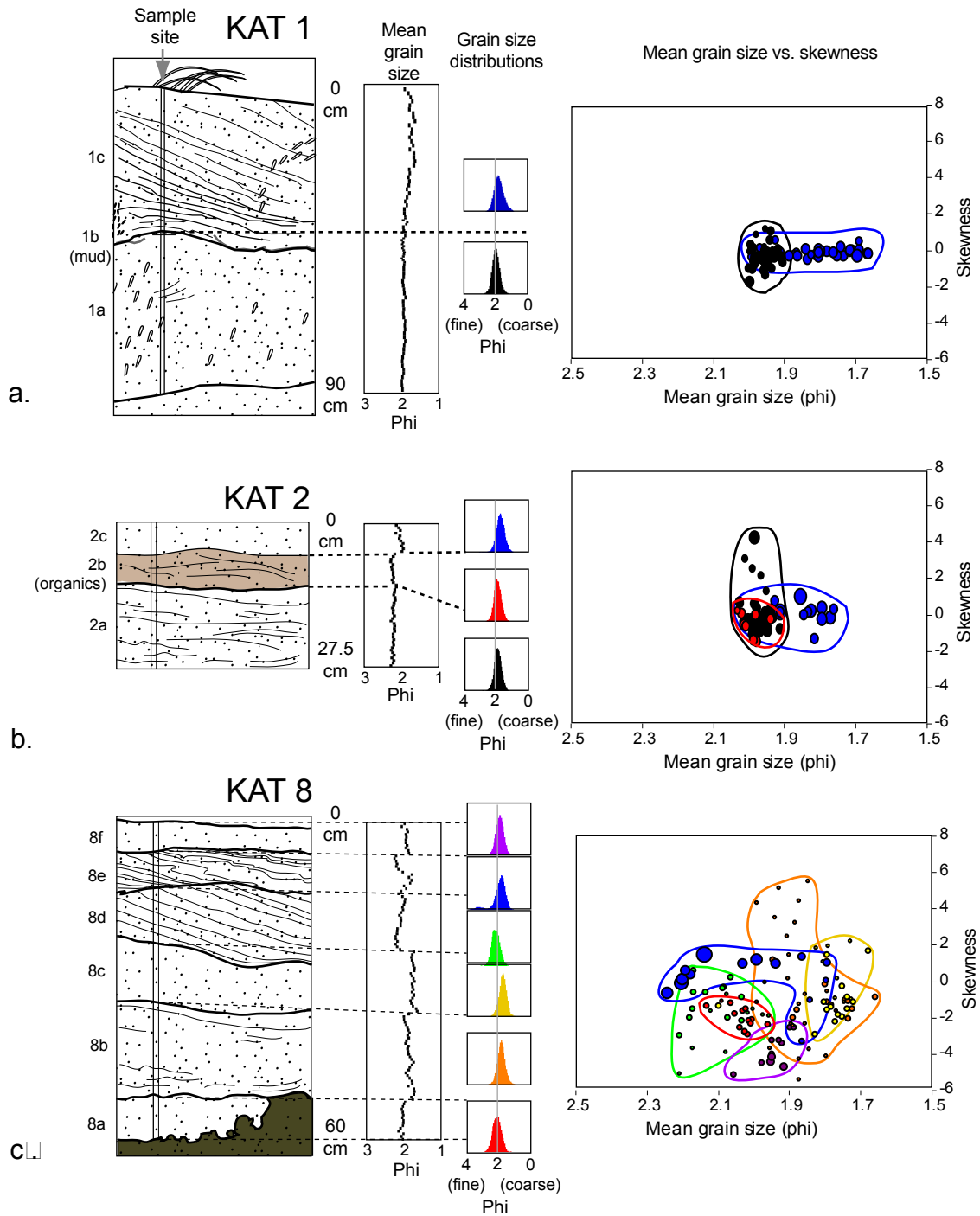


Fig 8. Results of grain size analysis for KAT sample sets 1, 8, and 2. Mean grain size plots show variation of mean grain size with depth; normal and inverse grading trends are apparent at each location. Grain size distributions are divided into segments based on obvious differences in structure that were observed in the field, or on transitions apparent in grain size analysis. Mean grain size vs. skewness are also plotted with respect to these sub-units. Bubbles represent individual samples and are scaled by width to reflect standard deviation. In a) and b), the two Gulfside overwash deposits, note that lower units show narrow distributions of mean grain sizes and wide distributions of skewnesses. Conversely, upper units have wider mean grain size distributions and narrower skewness distributions. c) KAT 8 varies greatly in mean grain size and skewness, but with no obvious trend between sub-units.

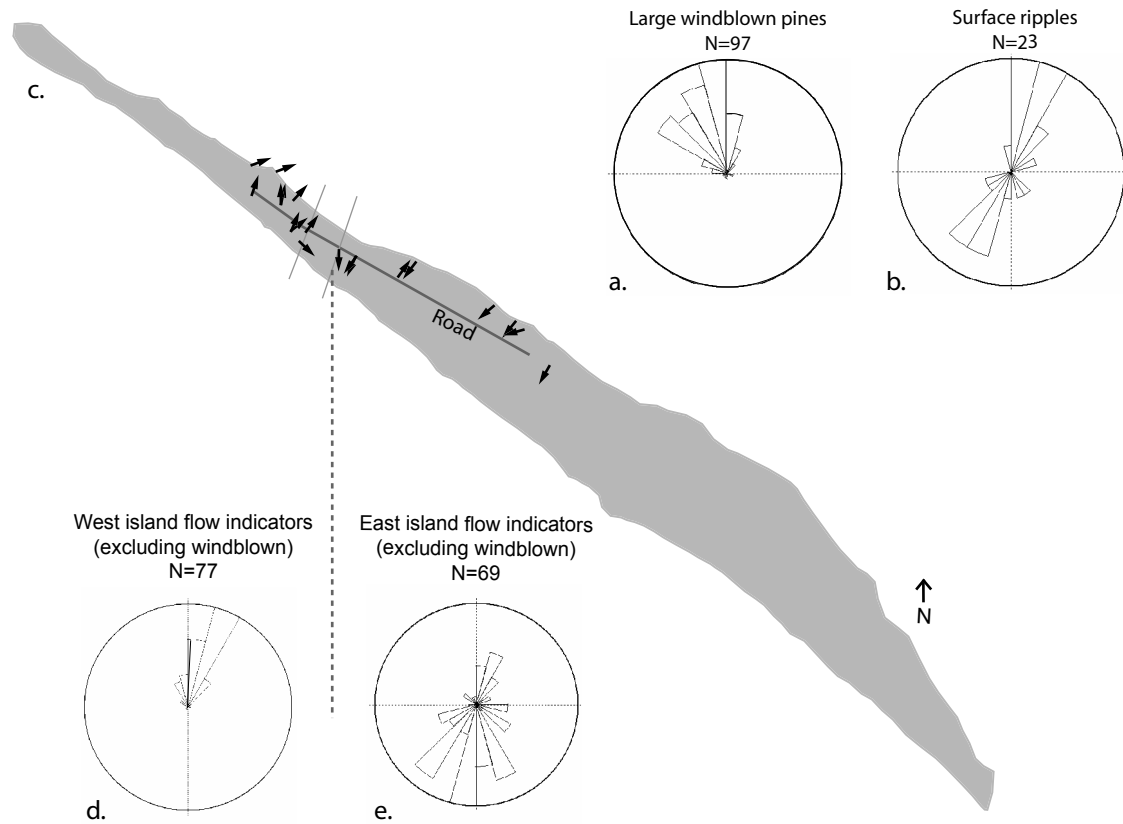


Fig. 9. a) Fall directions of large windblown pine trees show that southeasterly winds were responsible for downing these trees. b) Ripples on the surface of Hurricane Katrina deposits likely represent the last flows over Deer Island after flooding. These ripples indicate both ebb and flood directions. c) Map of Deer Island with measured surface ripple flow directions. Ripple measurements were taken at point of origination for each arrow; some duplicates are not displayed. When divided by location, ripples and other flow indicators including flattened palms and small pine trees show that flooding of the western part of the island was mostly from the south (d), whereas ripples and other indicators show evidence of both flood and ebb currents on the lower elevation central and eastern parts of the island (e).



a)



b)



c)



d)

Fig. 10. a) Hurricane Rita wrackline, south (Gulf of Mexico) side of Deer Island. b) Hurricane Rita wrackline, north (Biloxi Bay) side of Deer Island. Large pieces of stranded debris indicates that this wrackline was not the result of high tides. c) Close-up of Hurricane Rita deposit in a. Note rain drop impressions that fell during Hurricane Rita, and lack of impressions after post-storm drainage. d) Hurricane Katrina deposit from south side of island, near KAT 1. These raindrop impressions were formed after drainage of standing water from behind this deposit was complete. Raccoon tracks and 10 cm colored bands on shovel for scale.

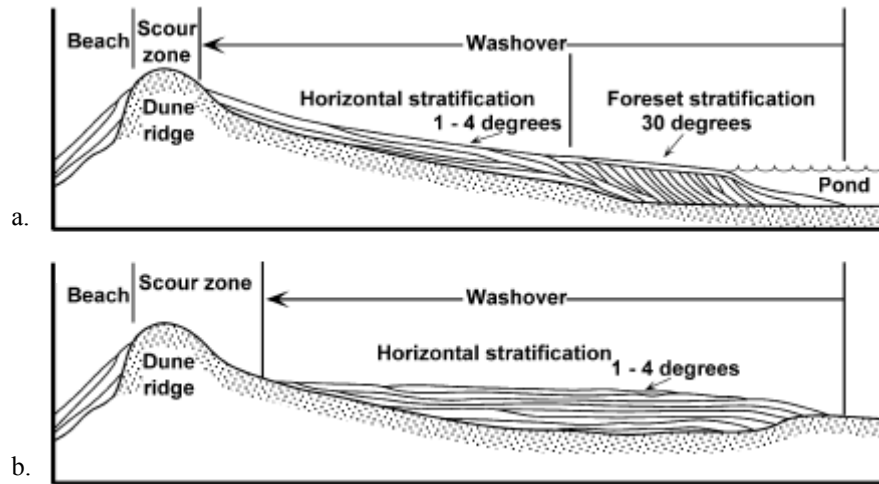


Fig. 11. Generalized washover fan stratigraphy. a) Angle of repose landward-dipping foresets are deposited as a microdelta when overwash encounters standing water. b) Horizontal to gently dipping lamination results when overwash is subaerial rather than subaqueous (from SCHWARTZ, 1975).

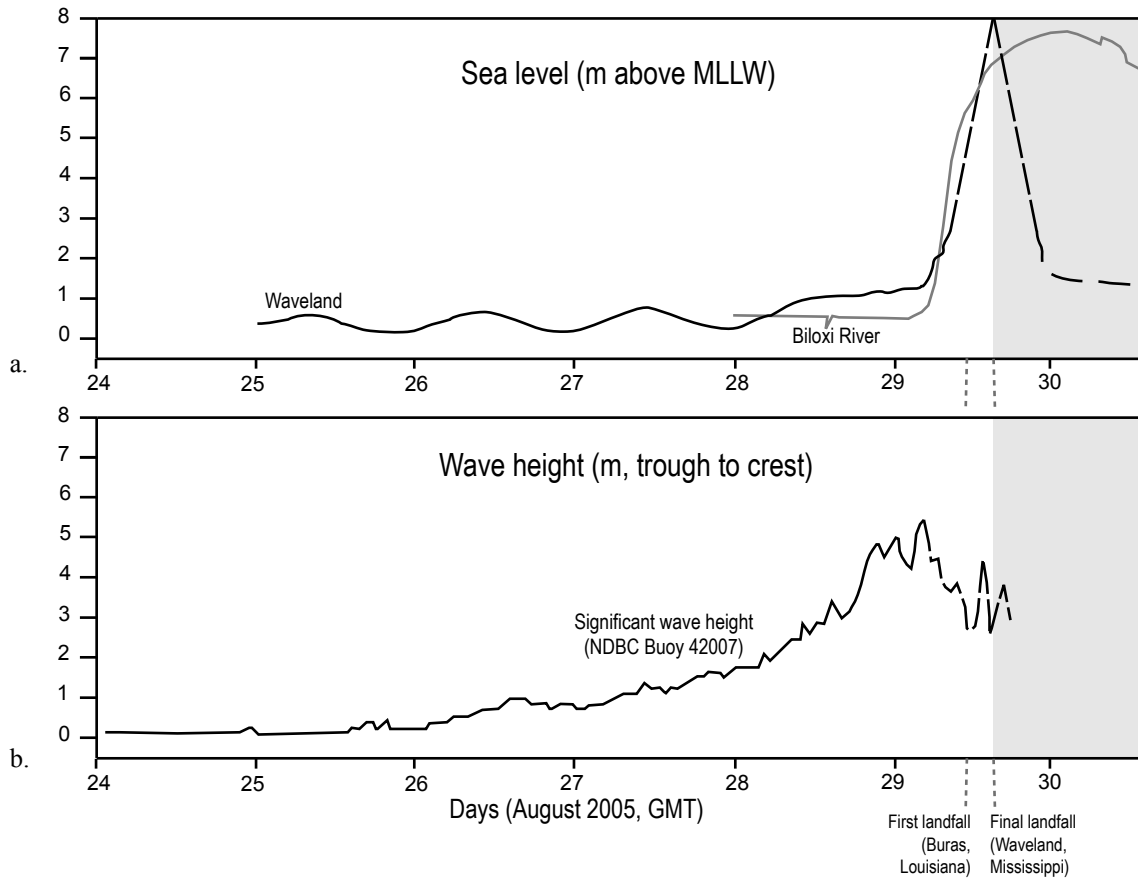


Fig. 12. Relative timing of changing storm surge and wave conditions near Deer Island leading up to and during Hurricane Katrina. Time after landfall is shaded. a) Black line shows sea level as recorded at Waveland tide gauge (NATIONAL DATA BUOY CENTER STAFF, 2006). Gray line shows Biloxi River mouth surge (U.S. GEOLOGICAL SURVEY, 2005). After Waveland tide gauges were damaged, storm surge is extrapolated (dashed line) based on LSU model (LOUISIANA STATE UNIVERSITY, 2005) and the assumption that peak surge occurred at time of landfall. b) Wave measurements from NDBC Buoy 42007 probably represent maxima that Deer Island would have experienced for any approximate time. Significant wave heights are calculated as the average of the highest one third of waves, and are probably about half the value of maximum wave heights. Wave data are dashed after Buoy 42007 broke free from its mooring and went adrift.

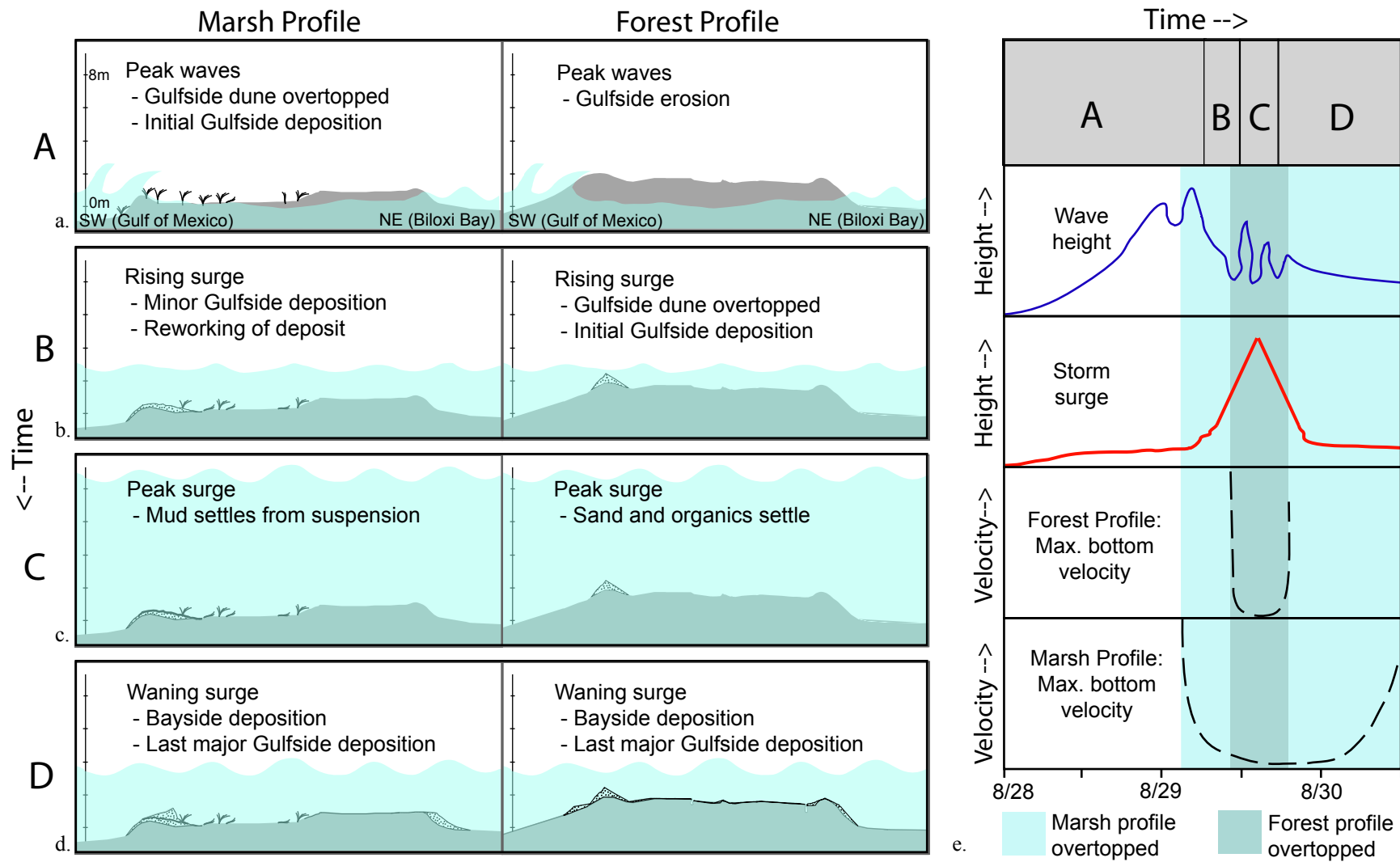
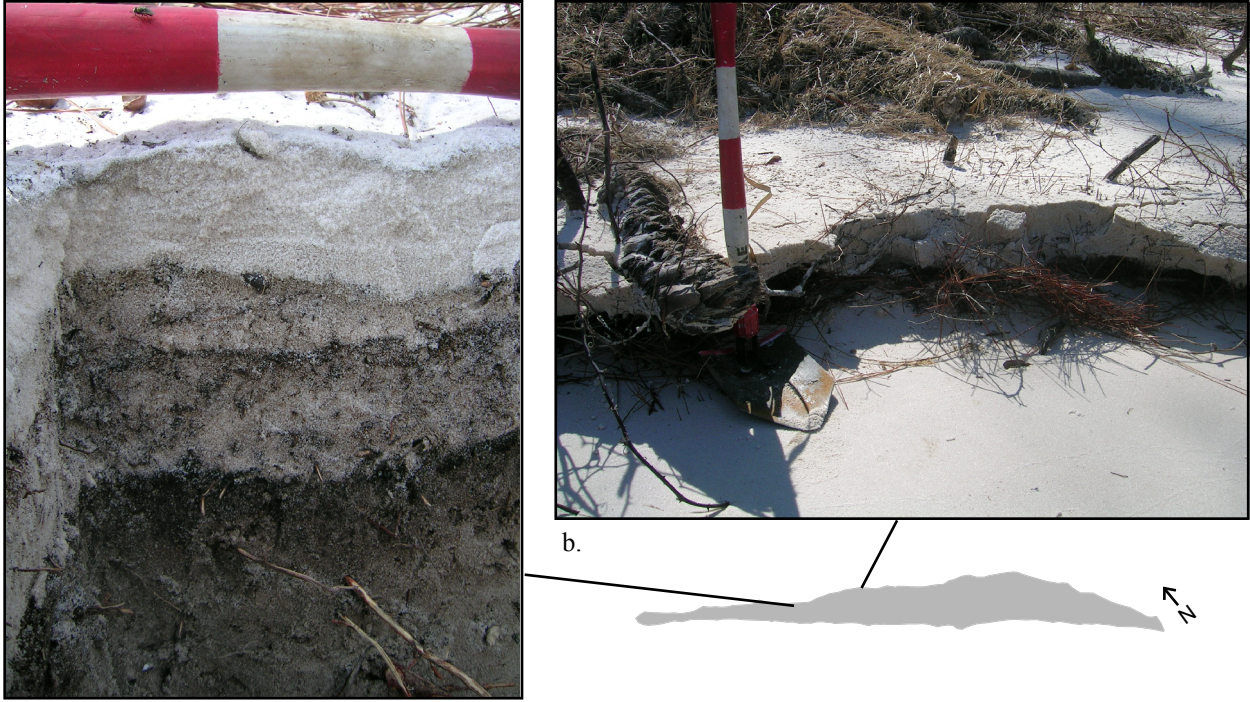


Figure 13. a-d) Interpretation of discrete depositional periods throughout storm for each profile, based on water and wave heights and calculated bottom velocities. e) Relative timing of factors that would affect deposition as Hurricane Katrina progressed towards Deer Island. Wave heights are based on Buoy 42007. Storm surge is an extrapolation of Waveland tide gauge records based on models and post-storm observations of maximum water height. Maximum bottom velocities are estimated from wave and surge components according to maximum post-storm beach dune heights for each profile. Note occurrence of peak wave heights several hours before maximum storm surge.



a.

Fig. 14. a) Three sand bodies separated by organic detritus. Each sand layer represents a potential historical storm event. Scattered pine needles on the surface of the uppermost deposit, from Hurricane Katrina, will decompose into the next organic lamina. b) A modern-day analog. Hurricane Rita or Katrina sand covers a blanket of pine needles that sits atop the previous sand unit. Colored bands on shovel handle are 10 cm. Black fly is approximately 6 mm.