Tracking hurricane-generated storm surge with washover fan stratigraphy

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ABSTRACT

We use the stratigraphy preserved in a washover fan to reconstruct the timing or emplacement and environmental conditions along the Matagorda Peninsula, Texas, during Hurricane Ike in 2008. Washover fan stratigraphy preserves a topset-foreset break (TFB) that rises 0.42 m in elevation as the fan built landward. We constrain overwash flow depths to 0.1–0.32 m through deposit sedimentology, and tie the rising trajectory of the TFB to rising storm surge water levels measured in the back-barrier bay (0.03 m h^{-1}) as the hurricane approached the coast. This relation allows us to estimate that the fan took 0.52–0.90 days to build, and was finished building before the storm surge peaked. This is 15–25% of the 3.5 days of hurricane-induced storm surge near the site. We show how washover stratigraphy can be used to constrain the timing and amount of sediment redistribution on a coast associated with a hurricane; information that is necessary to test and/or calibrate existing numerical models that predict shoreline change during hurricanes.

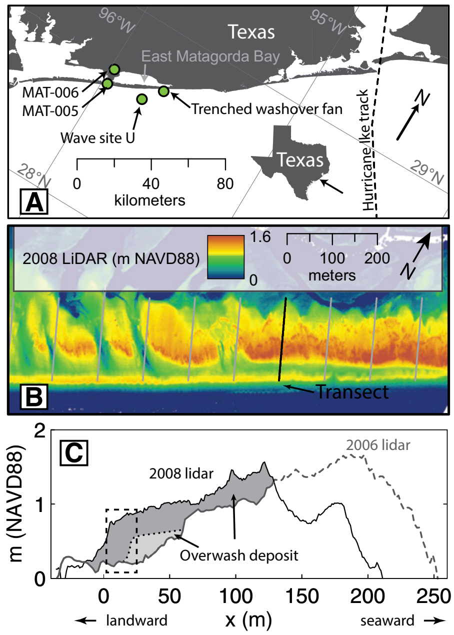

Figure 1. A: Map of the Texas coast, USA, showing the positions of the washover field site, the wave monitoring site U, storm surge sites seaward (MAT-005) and landward (MAT-006) of Matagorda Peninsula, and the hurricane track. (For a large-scale map, see the Data Repository [see footnote 1].) B: Post-storm lidar-based digital elevation model of washover field site in December 2008. The black line indicates the trench location, and the gray lines show some of the transects analyzed to test the regional elevation of the final topset-foreset break (TFB). C: Shore-normal cross section of Matagorda Peninsula at the trench location. Profiles are taken from pre-storm and post-storm lidar. The studied washover deposit from Hurricane Ike is shaded gray; the darker gray is the area interpreted to have been emplaced with a TFB and the lighter gray is the deposit without an observable TFB. Dashed box marks the location of Figure 2A. NAVD88—North American Vertical Datum of 1988.

INTRODUCTION

Overwash, the transport of water and sediment across barrier islands, is extremely difficult to directly measure during hurricanes. The lack of data leaves important questions about coastal evolution unanswered, e.g., under what wave and storm surge conditions did beach erosion or back-barrier deposition occur, and how long did it take? Numerical models have been developed to simulate coastal evolution during hurricanes (Morton, 2002; Donnelly et al., 2006; Plant et al., 2010; Plant and Stockdon, 2012; Lorenzo-Trueba and Ashton, 2014), yet the process of overwash sedimentation remains relatively poorly understood (McCall et al., 2010). Here we show how the internal stratigraphy and sedimentology of a washover deposit can be used to directly estimate change to the coastline during the course of a storm. In particular, we connect washover sedimentation to changing water levels during hurricane surge.

Washover deposits provide a stratigraphic record of landfalling hurricanes (Schwartz, 1982; Wang and Horwitz, 2007; Switzer and Jones, 2008). The resulting stratigraphic models are used to identify ancient storm deposits (Sedgwick and Davis, 2003; Morton et al., 2007) and estimate their intensity (Donnelly et al., 2001, 2004; Woodruff et al., 2008). In the stratigraphic model of a washover fan described by Schwartz (1982), gently dipping planar beds transition abruptly to steeply dipping foreset deposits when overwash deposition enters standing water in a back-barrier bay. The topset-foreset break in slope (TFB) is recognized in many (although not all) washover deposits bordering oceans and lakes.

The trajectory of the TFB has never been systematically studied in washover deposits, yet could provide a record of how the standing water in the back-barrier bay was influenced by storm surge elevation. A basic tenet of river delta stratigraphy (Kim et al., 2006) states that the elevation of an actively building TFB (η) tracks the water level in its receiving basin (ξ). Overwash has a nonzero flow depth (*H*), which is relatively constant over the fan topset (Holland et al., 1991). We propose that on washover fans, η is offset from ξ by flow depth (i.e., $\xi = \eta + H$). We use this relationship to investigate the emplacement history for a washover fan on Matagorda Peninsula, Texas (USA), during 12–13 September 2008 (Fig. 1A). Hurricane Ike produced extensive storm surge and overwash along several hundred kilometers of the Texas coastline (Doran et al., 2009; Sherman et al., 2013). We characterize the internal stratigraphy of the fan using data collected from a shore-perpendicular trench, as well as pre-storm and post-storm digital elevation models (DEMs; Figs. 1 and 2). The trajectory of the TFB is compared to records of storm surge water level measured both seaward and landward of the barrier island (East et al., 2008; Fig. 3A), as well as significant wave height (H_s) and significant wave period (*T*) measured seaward of the barrier by Kennedy et al. (2011; Fig. 3B). Combining the stratigraphy and these records, we show that the washover fan emplacement took 0.52–0.90 days, on the rising limb of storm surge before hurricane landfall.

DATA

Aerial imagery collected after Hurricane Ike (31 December 2008; available on Google Earth) reveals that the eastern 36 km of the Matagorda Peninsula (28.75°N, 95.66°W to 28.59°N, 95.98°W) was worked into series of washover fans, separated by 10 net-erosional channels between 6 m and 33 m wide. A shore-perpendicular trench 88 m long was dug along the axis of one of these washover fans (Fig. 1B). This trench was excavated to the base of the washover deposit marked by the presence of *in situ* grasses bent over in the landward direction.

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GEOLOGY, February 2015; v. 43; no. 2; p. 127–130; Data Repository item 2015051 | doi:10.1130/G36460.1 | Published online 19 December 2014

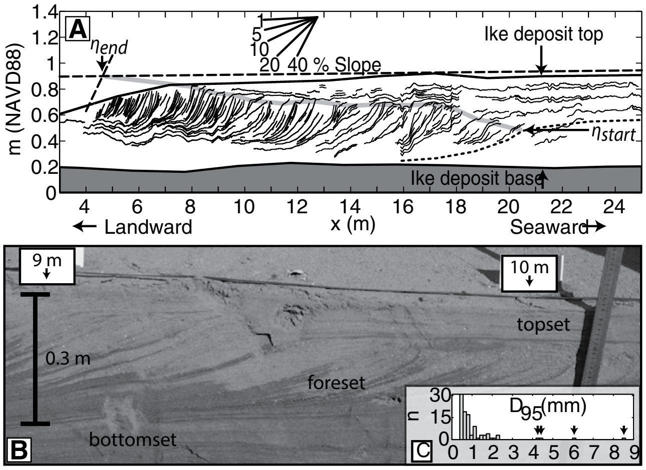

Figure 2. Stratigraphy of the distal washover deposit (dashed box in Fig. 1C). A: Line drawing of washover clinothems observed in the shore-normal trench rectified to NAVD88 (North American Vertical Datum of 1988). Gray line tracks the trajectory of the topset-foreset break (TFB). Elevations for the starting (η_{start}) and ending (η_{end}) TFB locations are marked. Vertical exaggeration = 4.5×. B: Photograph of the washover deposit at x = 9–10 m in Figure 2A showing the shallowly sloping topset, steeply sloping foreset, and shallowly sloping bottomset. C: Histogram of the coarse fraction (D_{95}) of 98 sediment samples. Samples with large D_{95} (marked by arrows) are interpreted to have moved as bedload.

Deposit stratigraphy (Fig. 2) was characterized by sketching and photographing the trench wall, logging detailed stratigraphic sections at 2 m intervals, and collecting 2–4 sediment samples at each section for grain-size analysis.

DEMs derived from airborne lidar surveys were used to estimate the deposit's total cross-sectional area and to rectify the photomosaic of deposit stratigraphy. Surveys from March 2006 (not shown; Texas Water Development Board, 2007) and December 2008 (Fig. 1B; Bureau of Economic Geology, 2009) were taken to represent the pre-hurricane and post-hurricane topography of the peninsula. Using the 2006 DEM as the pre-storm topography is supported by the agreement between deposit thicknesses estimated from differencing the two DEMs and thicknesses measured from the trenched washover fan. Comparison of pre-hurricane and post-hurricane transects derived from the DEMs (Figs. 1B and 1C) reveals that the hurricane built a deposit landward of the berm crest with a local cross-sectional area of 53.8 m^2 (Fig. 1D). This deposit is associated with 106.4 m^2 of material eroded from the beach face, causing 50 m of landward barrier migration.

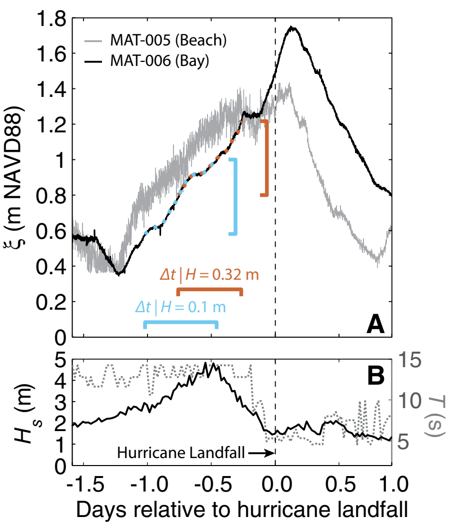

Figure 3. Storm surge and wave time series near the washover field site relative to Hurricane Ike landfall, which occurred at 0210 Central Daylight Time, 13 September 2008 (see Fig. 1A for locations). A: Storm surge elevation (ξ) seaward (MAT-005) and landward (MAT-006) of the Matagorda Peninsula. Vertical brackets show water-surface elevations in the bay associated with deposition of the topset-foreset break (TFB) for the cases where *H* = 0.1 m (blue) and *H* = 0.32 m (brown). Horizontal brackets mark the associated time intervals for deposition. B: Significant wave height (H_s, solid line) and significant wave period (*T*, dotted line) recorded at Site U.

Observed fan stratigraphy conforms to the established facies model for a washover fan building into a bay (Fig. 2; Schwartz, 1982). Sand at the base of the deposit is structureless, ungraded, and up to 0.2 m thick. Above this, the deposit is predominantly planar stratified with laminae oriented subparallel to the deposit top (surface slope = 0.22%). Planar stratification transitions in the landward direction into a set of prograding and aggrading clinoformal surfaces defined by topset, foreset, and bottomset strata (Fig. 2). Many surfaces are traceable from the planar-bedded topset through the foreset and into the bottomset. Notable exceptions are found near the end of the fan (Fig. 2A; 6 m < x < 18 m), where a portion of the TFB has been eroded following its original emplacement.

The ensemble median grain diameter (D_{50}) is 235 μm (n = 98) and is vertically and laterally consistent throughout the deposit. A histogram of the 95th percentile of grain diameter (Fig. 2C) shows that while the bulk of the deposit has a coarse fraction <2 mm in nominal diameter, 4 samples are significantly coarser. These samples are from lenses of shelly material found within and directly above the buried grasses. We interpret the bulk of the planar-stratified deposit to have been built from deposition of suspended sediment. However, the samples with $D_{95} > 2$ mm are interpreted as bedload deposits, because (1) they are restricted to isolated lenses of like-size grains, (2) they are not present in the bulk of the deposit, and (3) organization into discrete patches of very coarse particles is not consistent with suspension deposition. The settling velocities of grains >2 mm from these deposits were measured using a settling column. In addition to these lenses of coarser grains, individual lithic clasts and shell fragments to 100 mm in nominal diameter are found interspersed throughout the deposit, usually well above its base.

The TFB is first recognized as a subtle change in slope of a clinoformal surface at x = 20.5 m, η = 0.48 m NAVD88 (North American Vertical Datum of 1988; dotted line in Figs. 1D and 2A). We name this elevation η_{start}. The strata positioned beneath this clinoform do not show a visible break in slope. Above η_{start}, the TFB climbs through the deposit in the landward direction (Fig. 2). The TFB trajectory climbs at an angle of 8.9° for 18 m < x < 20.5 m, and drops to a climb angle of 4.0° for 7 m < x < 18 m (Fig. 2A). Landward of 7 m, the deposit recording the original TFB has been eroded (Fig. 2A). The missing TFB trajectory (Fig. 2A) is reconstructed by projecting the orientations of preserved topset strata ($\eta = 0.0022\,x + 0.89$) and foreset slopes ($\eta = 0.43\,x - 1.09$). The reconstruction places the final elevation of the TFB at 0.90 m NAVD88 (hereafter called η_{end}). In total, 0.42 m of aggradation was associated with 16 m of fan progradation. Deposits with a well-defined TFB make up 44.6 m^2 of the trench exposure, while stratigraphically lower deposits without a well-defined TFB make up the remaining 9.2 m^2. To check the regional consistency of η_{end}, we measured η_{end} from the post-storm DEM (gray lines in Fig. 1B) on 10 transects parallel to the trench, spaced at 100 m intervals, on either side of the trench (20 total). The mean value of η_{end} was 0.92 m NAVD88, and no trend in elevation and location was found. This confirms that η_{end} is regionally consistent.

Storm surge and wave time series were measured using pressure transducers (East et al., 2008; Kennedy et al., 2011). The rate of storm surge rise and timing of surge peaks varied through the region. Upon analysis of coastline geometry, the size of East Matagorda Bay, and the rate of storm surge rise fan (see the GSA Data Repository[1]), MAT-005 and MAT-006

[1]GSA Data Repository item 2015051, justification for storm surge record selection, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

were selected as faithful records of the storm surge both seaward and landward of the Matagorda Peninsula near the trenched washover.

FORMATIVE CONDITIONS

The storm surge landward of a barrier island (ξ) is related to the elevation of the TFB (η) and flow depth on the fan (H) through $\xi = \eta + H$. To apply this relationship, we first estimate the overwash flow depths during sedimentation (H). Ashida and Bayazit (1973) found that gravel clasts do not move when they protrude above the flowing water's surface. Therefore, we assume that overwash flow was greater than the nominal diameter of the largest clasts in the deposit, setting a lower bound for flow depth ($H \geq 0.1$ m). An upper bound for H was estimated using the interpreted bedload deposits composed of coarse, shelly material. Bagnold (1966) proposed that bedload transport dominates when $w_s/u_* > 1$, where w_s is the settling velocity for a grain and u_* is shear velocity of the flow. A representative value of settling velocity for the smallest bedload grains was taken as the 5th percentile of the settling velocity distributions for particles >2 mm, yielding $w_s = 83$ mm s^{-1}. In order to estimate the greatest possible average flow depth associated with moving a grain with this settling velocity as bedload, we assume that flow was approximately uniform and steady over the washover topset ($\partial U/\partial x = \partial U/\partial t = 0$, where U is down-fan flow velocity and t is time). Our assumption of uniform flow is justified by the smooth upper fan surface and a lack of spatial trends observed in the planar stratified deposits. While surges from individual waves were unsteady, the TFB has a remarkably smooth trajectory with few erosional surfaces that would be preserved if the deposit elevation changed with the rapidly varying flow depth. This suggests that estimates of H should be averaged over many waves, and that steady flow is a reasonable assumption over such a long time scale. The value of u_* can be related to the depth-slope product

$$u_*^2 = gHS, \quad (1)$$

where g is acceleration by gravity (9.81 m s^{-1}) and S is the bed slope. Taking $w_s = u_*$ as the upper estimate for u_* and using the measured bed slope of 0.22% (Fig. 2A), we find $H \leq 0.32$ m.

With H constrained between lower and upper bounds, we can directly relate elevation of the TFB trajectory to the back-barrier storm surge profile (Fig. 3A) to estimate the timing of fan deposition. In the lower bound case ($H = 0.1$ m), the water surface in the bay reached the $\eta_{start} + H$ elevation 1.01 days before landfall (Fig. 3A), marking the beginning of TFB growth. The fan stopped growing after 0.55 days ($\Delta t \mid H = 0.1$ m; "|" reads as "conditional upon"), when the surge reached $\eta_{end} + H$ (Fig. 3A). In this scenario the fan was fully emplaced 0.46 days before hurricane landfall. Assuming that deposit porosity was 35%, an average sediment flux ($q_s \mid H = 0.1$ m) of 6.1×10^{-4} m^2 s^{-1} was required to build the foresetted deposit in this time. In the upper bound case ($H = 0.32$ m), a similar comparison of TFB and surge elevations suggests that deposition lasted 0.42 days ($\Delta t \mid H = 0.32$ m), with an estimated average sediment flux of ($q_s \mid H = 0.32$ m) $= 7.2 \times 10^{-4}$ m^2 s^{-1} (Fig. 3A). In this scenario, the fan deposition finished 0.26 days before hurricane landfall. If H increased from 0.1 to 0.32 m over the course of the storm, fan building would have taken 0.75 days, with $q_s = 4.5 \times 10^{-4}$ m^2 s^{-1}. We argue that H is unlikely to decrease during fan emplacement, because deep standing water on the fan would have caused the TFB to shift to an updip location on the fan and a second prograding trajectory instead of uniformly aggrading the bed.

The estimated timing of washover fan building is concurrent with the greatest significant wave heights (H_s) and periods (T) measured at Site U by Kennedy et al. (2011; Fig. 3), regardless of the assumed H. Peak wave height and period were large during rising storm surge, but retreated to fair-weather magnitudes by the time the hurricane made landfall (Fig. 3B). We take this temporal correlation between significant wave height and estimated fan building times as corroborating evidence that washover deposition occurred prior to hurricane landfall and that storm surge histories are recorded in the TFB trajectories preserved in washover fans.

In estimating an upper bound for flow depth over the fan, we also produced an upper bound estimate for the sediment transporting shear velocity ($u_* \leq 82.7$ mm s^{-1}). Width-averaged sediment flux tied to this shear velocity can be estimated using a modified Meyer-Peter Müller sediment transport equation (Wiberg and Smith, 1989):

$$q_s = \sqrt{\left(\frac{\rho_s}{\rho_f} - 1\right) g D_{50}^3} \times \left[1.6\left(\ln \tau_* + 9.8\right)\right] \times \left[\tau_* - \tau_{*(cr)}\right]^{\frac{3}{2}}, \quad (2)$$

where ρ_s and ρ_f are the densities of sediment (2650 kg m^{-3}) and seawater (1025 kg m^{-3}), $\tau_* = \dfrac{u_*^2}{\left(\dfrac{\rho_s}{\rho_f} - 1\right) g D_{50}}$, and $\tau_{*(cr)} = 0.049$ for D_{50} = 235 μm. These values yield a sediment flux of 3.9×10^{-4} m^2 s^{-1}, which is within a factor of 2 of the values for sediment flux gathered from analysis of TFB climb, and just 13% smaller than the case where H increased from 0.1 to 0.32 m during emplacement. This similarity is taken as further confirmation that the time of fan formation estimated from the TFB trajectory is accurate.

DISCUSSION AND CONCLUSIONS

This study shows that the environmental conditions and timing of washover fan deposition and associated beach erosion can be precisely estimated from stratigraphy and storm surge records. This result is valuable because it demonstrates a methodology for constraining the evolution of shoreline topography associated with hurricane landfall that can be used test and/or calibrate numerical models used to forecast and hindcast coastal change by hurricanes. This study was based on a record assembled from a single carefully selected trench. Future studies using multiple trenches on adjacent fans are expected to improve any characterization of the washover history for a segment of coastline.

Water-surface elevations associated with storm surge seaward of the barrier were ≤1.28 m NAVD88 during the estimated time of fan emplacement (Fig. 3A; MAT-005) and never fully inundated the trenched washover fan, which had a post-storm crest of 1.43 m NAVD88 (Fig. 1C). This means that overwash from wave runup was responsible fan building (Impact level 3 of Sallenger, 2000), making barrier evolution particularly sensitive to wave characteristics. It is interesting that Hope et al. (2013) did not accurately predict the early peak of H_s (Fig. 3B) on the dry (southwest) side of the storm track near the coast. Instead, hindcasts predicted that H_s peaked at landfall on the Matagorda Peninsula. Kennedy et al. (2011) argued that the difference between models and measurements is due to the peak waves being remotely generated rather than generated by local wind shear, as is generally assumed in numerical models (Donnelly et al., 2006; McCall et al., 2010; Plant and Stockdon, 2012). If the modeled wave climate of Hope et al. (2013) was used to force a sediment transport model for the Matagorda Peninsula during Hurricane Ike, sediment transport would have persisted until after hurricane landfall, and fan construction would have been tied to higher surge levels in the bay.

Our analysis lacks a definitive answer to why the first 9.2 m^2 of sand was deposited without a TFB. At present there is no theory for the conditions necessary to initiate foresets on overwash fans. We hypothesize that the basin depth must exceed overwash flow depth H to produce the deceleration and rapid deposition necessary to form a foreset. At the trenched fan, basin depth at the time of foreset development is estimated at 0.3 m (Fig. 1C), or 1–3 times H. Despite this uncertainty, we can apply estimates derived from the deposits displaying a TFB to further understand the total fan emplacement. Applying q_s estimates from the foreset deposit as an upper bound for the non-foresetted deposit suggests that this fraction of the total deposit was emplaced over 0.096–0.15 days at a minimum, making total fan deposition time 0.52–0.90 days, just 15%–25% of the 3.5 days when storm surge affected the coast. Furthermore, the deposit began to build 1.16 days before landfall at the latest, which is shortly after storm surge began to rise along the Matagorda Peninsula (Fig. 3A). Assuming that part of the 106.4 m^2 of sediment eroded from the beach face built the overwash fan, the timing and environmental conditions derived from the fan can also be used to investigate at least 51% of the measured beach erosion.

We conclude that the trajectory of the TFB on a washover fan tracks the water-surface elevation associated with storm surge in the back-barrier bay. Similar analysis can be performed on any fan deposit with a preserved TFB to generate quantitative estimates of environmental conditions for paleotempestology. If the TFB is rising, then the overwash fan was emplaced during rising storm surge leading up to hurricane landfall. Although untested here, we propose that if the trajectory is falling, the overwash fan was at least partially emplaced during falling storm surge, likely after a storm's peak (e.g., Schwartz, 1982, his figure 5C). Furthermore, overwash deposited without a TFB (e.g., Hawkes and Horton, 2012) may also be interpreted as washover that was deposited before flow entered a sufficiently deep body of standing water, providing a potentially useful upper limit on storm surge water levels in the back-barrier bay. The analytical method developed here should prove valuable for testing models of fan development during future storms and improve deduction of environmental conditions during paleohurricanes preserved in the sedimentary record.

ACKNOWLEDGMENTS

We thank members of the 2008 Dynamics of Sediment Transport course at the University of Texas at Austin for trench digging and data processing, and H. Goggin for settling-column analyses. P. Bennett flew Mohrig over the site for initial reconnaissance. A. Kennedy provided the wave datasets. B. Atwater and two anonymous reviewers provided helpful comments on this manuscript. Research was supported by the Jackson School of Geosciences, the National Science Foundation (NSF) National Center for Earth Surface Dynamics (grant EAR-0120914), the Delta Dynamics Laboratory (grant EAR-1135427), and an NSF postdoctoral fellowship to Shaw.

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Manuscript received 14 August 2014
Revised manuscript received 18 November 2014
Manuscript accepted 21 November 2014

Printed in USA