Journal of Coastal Research | 16 | 4 | 1100–1110 | West Palm Beach, Florida | Fall 2000

Anomalous Response of Beaches to Hurricane Waves in a Low-Energy Environment, Northeast Gulf of Mexico, U. S. A.

Timothy R. Keen† and Gregory W. Stone‡

†Naval Research Laboratory
Oceanography Division
Stennis Space Center,
MS 39529, U.S.A.

‡Coastal Studies Institute
Louisiana State University
Baton Rouge, LA 70803,
U.S.A.

ABSTRACT

KEEN, T.R. and STONE, G.W., 2000. Anomalous response of beaches to hurricane waves in a low-energy environment, northeast Gulf of Mexico, U.S.A. *Journal of Coastal Research,* 16(4), 1100–1110. West Palm Beach (Florida), ISSN 0749-0208.

Submarine sandbars were deposited on the post-storm subaerial beach at Carrabelle Beach, Florida, by Hurricanes Elena and Kate in 1985. These bars contained stratification similar to swash bars and berms, as well as an unusual stratification consisting of interlayered beds and heavy-mineral laminae, which were slightly convex upward. Based on their internal morphology and location above the high-water line, these bars appear to be a relatively unknown type, the stranded bar. Field relationships and grain-size distributions have been examined in order to identify the principal sedimentation mode during deposition. These data support an origin by grain settling from suspension as storm wave energy decreased, but nearshore water levels remained elevated. The sediment pool comprising the bars was progressively sorted during the two hurricanes, which occurred within ten weeks of each other.

ADDITIONAL INDEX WORDS: *Nearshore sand bars, hurricanes, granulometry, Florida.*

INTRODUCTION

The majority of published data pertaining to hurricane impacts on mid-latitude coasts demonstrates that the overwhelming response of beaches to such events is a net sediment loss, caused by the combined effects of the storm surge and wave-generated currents (see reviews in FINKL and PILKEY, 1991; STONE and FINKL, 1995). In this paper, we present evidence indicating an anomalous response of a low-energy beach to two hurricanes, during which large sand bodies emerged in the nearshore. The study site is located along the northeast Gulf of Mexico coast adjacent to Apalachicola Bay, Florida (Figure 1). These findings are considered important in that they shed new light on the morphosedimentary response of beaches to infrequent high-energy events and dispel the notion that such events are unequivocally erosional. In addition, a detailed evaluation of the internal characteristics of these sedimentary bodies is used to evaluate the textural evolution of the sediment entrained by the storm waves.

Conceptual Framework

Perhaps the earliest, most significant contribution to our present understanding of the influence of hurricanes on barrier islands was the work of HAYES (1967). Hayes discussed the morphological response to Hurricanes Carla (1961) and Cindy (1963) along the Texas coast. This particular study shed new light on the redistribution of sediments between the inner shelf, nearshore, and subaerial portions of the coast, indicating the importance of the neritic zone as a source and sink during hurricanes. DOLAN and GODFREY (1973) examined the morphological impacts of Hurricane Ginger, which made landfall on the North Carolina coast in 1971. This and other work (DOLAN, 1972) showed that stabilized dunes along Cape Hatteras experienced extensive dune erosion and recession during Hurricane Ginger, with significant quantities of sediment being transported offshore and alongshore. Natural barriers along the Core Banks responded with a flattening of the beach face, retreat of the berm, deposition on the backshore, and trapping of material by grasses and marshes. The natural barriers thus were able to survive high-magnitude events and recover more rapidly than the stabilized barriers. These findings were re-examined by LEATHERMAN *et al.* (1977) and LEATHERMAN (1979), culminating in a refined model of overwash processes during storms.

Important contributions on the morphological impacts of hurricanes in the Gulf of Mexico include the following: Hurricane Audrey, 1957 (MORGAN *et al.,* 1958); Hurricane Camille, 1969 (WRIGHT *et al.,* 1970); Hurricane Eloise, 1975 (BURDIN, 1975); Hurricane Frederic, 1979 (SCHRAMM *et al.,* 1980; NUMMEDAL *et al.,* 1980; KAHN and ROBERTS 1982; STONE and SALMON, 1988); Hurricanes Juan and Danny, 1985 (PENLAND *et al.,* 1989); Hurricane Gilbert, 1988 (PENLAND *et al.,* 1989; DEBUSSCHERE *et al.,* 1991); Hurricane Andrew, 1992 (STONE *et al.,* 1993; 1997; STONE and FINKL, 1995); Hurricane Opal, 1995 (STONE, 1998; STONE et al., 1996) and Hurricane Georges, 1998 (STONE and WANG, 1999; STONE *et al.,* 1999). Many of these studies support the concept that the

---

99072 received 30 June 1999; accepted in revision 27 January 2000.

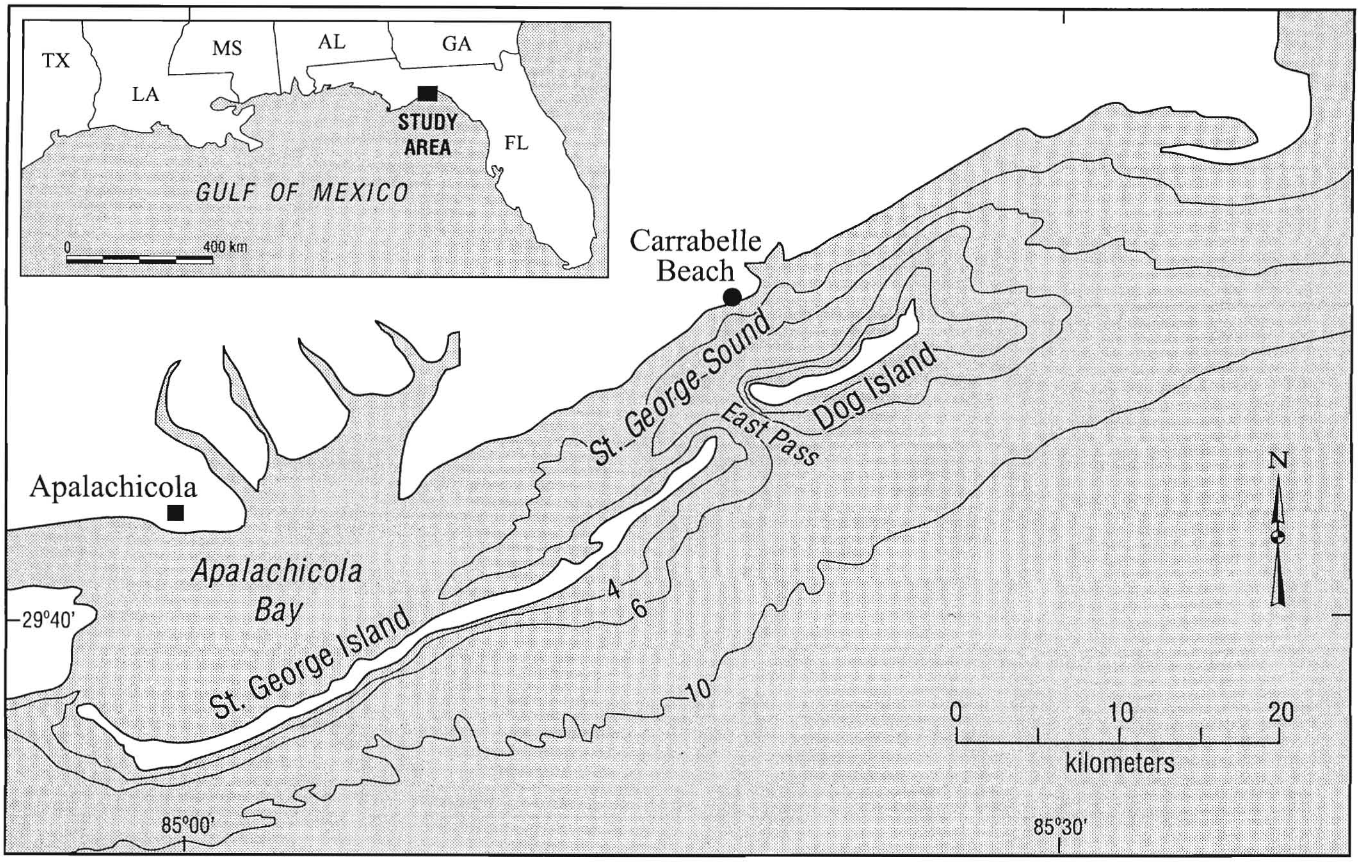


Figure 1. General physiographic setting of Carrabelle Beach (Solid circle) and vicinity, Florida.

elevated water levels and high wave energy during a hurricane cause considerable erosion of the nearshore-beach-dune system. Recent work also reveals attrition along some barriers in the Gulf of Mexico during winter storms (STONE, 1998; STONE and WANG, 1999; STONE *et al.*, 1999).

Although little work has been conducted on the precise spatiotemporal adjustment of barrier islands to hurricanes, it is well established that the post-storm phase is one characterized by deposition (cf. HAYES, 1967; SEXTON and MOSLOW, 1981; THIELER and YOUNG, 1991; SEXTON and HAYES, 1991; DINGLER and REISS, 1995). For example, the formation of depositional sequences such as overwash fans has been well documented (LEATHERMAN *et al.*, 1977; STONE *et al.*, 1996). In some instances this process has resulted in a barrier island conserving mass during catastrophic hurricanes (STONE, 1998; STONE *et al.*, 1996; 1999). Review of the literature indicates the lack of a heuristic model, incorporating both sedimentary processes and transport pathways. Such a model would serve to identify and elucidate the post-storm adjustment of the beach.

Objectives

In 1985, six hurricanes made landfall along the Atlantic and Gulf of Mexico coasts of the United States, two of which struck the northwest coastline of Florida (TANNER, 1986). Hurricane Elena followed a westward track and passed to the south between August 31 and September 2. Hurricane Kate made landfall west of Apalachicola Bay on November 21. During both events, a nearshore bar was deposited by waves at Carrabelle Beach, Florida. The objective of the present paper is to summarize the results of a study of the bars deposited by these two hurricanes, and interpret these data within the framework of sediment dynamics during hurricane conditions. The sedimentary structures of these two bars are evaluated, because it was these same features which led to the introduction of the term, stranded bar, by COLEMAN (1978). From this analysis, some inferences can be made about the processes constructing them. The sediment contained within these bars represents the storm sediment pools and as such, it is used herein to evaluate the textural evolution of the sediment entrained by the storm waves.

BACKGROUND

Study Area

Fieldwork for this investigation was conducted on the public beach at Carrabelle Beach, Florida, situated approximately 100 km southwest of Tallahassee, on the northern flank of

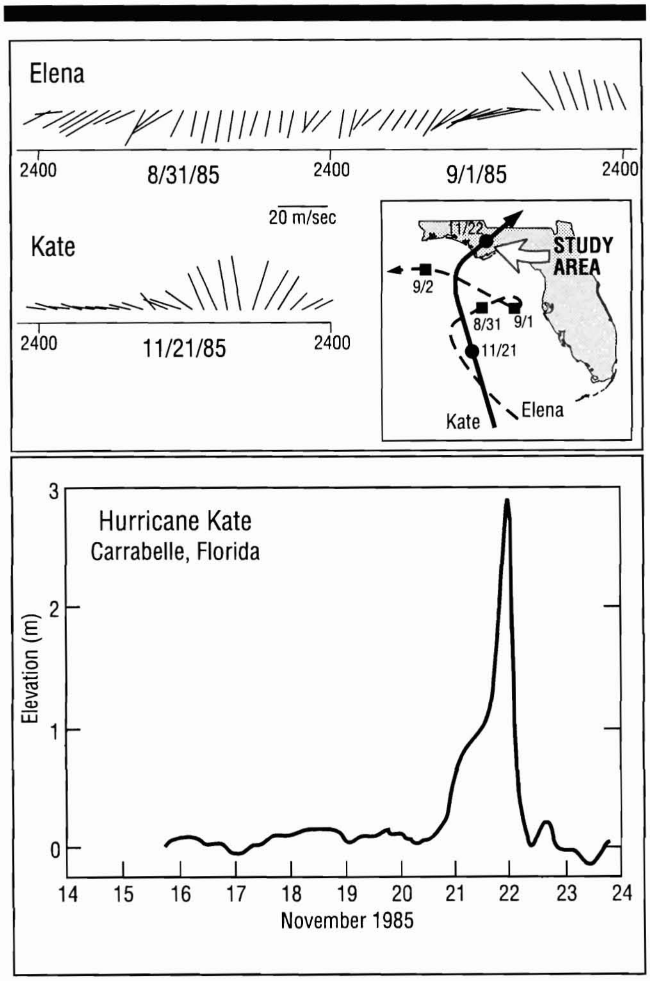


Figure 2. Tracks and wind vectors measured at Apalachicola (solid square in Figure 1) during Hurricane Elena and Hurricane Kate (Upper). Storm surge computed for Carrabelle, Florida, using ADCIRC-2DDI model (Lower) (from Blain, 1997).

St. George Sound (Figure 1). Barrier islands of late Holocene age form the seaward margin of St. George Sound; Dog Island to the east and St. George Island to the west. The landward margin of St. George Sound consists of extensive shoals, transverse bars and pocket beaches. The greatest water depth within the lagoon is less than 7 m and it is characterized by low wave energy, having mean annual breaker heights of 0.1 m or less (Gorsline, 1966). Local physiography, offshore bathymetry, and the location and size of tidal passes, combine to cause the greatest wave effects on landward beaches when the prevailing winds are from the south or southeast (Kofoed and Gorsline, 1963). The littoral transport system is characterized by a complex set of drift cells, which at present are experiencing no net exchange of sediment (Stapor, 1971; 1973; Stone and Stapor, 1996).

Hurricanes Elena and Kate

Hurricane Elena followed an irregular path (Figure 2) and remained south-southeast of the study area from August 31 to September 1. The maximum hourly wind speed recorded at Apalachicola (Figure 2) was 20 m s^{-1}. Hurricane Kate passed directly to the west of Apalachicola Bay and a maximum wind of 23 m s^{-1} was measured. The Gulf side of St. George Island was extensively eroded by Hurricane Elena, as was its Apalachicola Bay shoreline and the landward margin of St. George Sound west of East Pass. During Hurricane Kate, however, significant erosion occurred at Carrabelle Beach and east of Dog Island because these areas were unprotected from the sustained onshore winds that also produced large storm surges. The effects of Hurricane Kate on St. George Island were difficult to judge because of the previous damage caused by Elena, but some erosion and overwash were evident.

Tidal records from Apalachicola Bay were unavailable because of the failure of the tide gauge during both storms. The astronomical tide varied from 0.21 m to 1.1 m above LLWL (lowest low water level) (National Oceanic and Atmospheric Administration, 1985). A reconnaissance of the study area revealed a distinct band of flotsam at the maximum incursion of the strand line, which was used to estimate the total water depth during the storm. The resulting maximum water elevations of 1.5 m above mean water level (MWL) during Hurricane Elena and 3 m during Hurricane Kate included the storm surge superimposed on the astronomical tide. The storm surge during Hurricane Kate has been hindcast using the ADCIRC-2DDI hydrodynamic model (Blain *et al.*, 1994; Blain, 1997). The predicted storm surge at Carrabelle is shown in Figure 2. The maximum surge of 2.8 m is in good agreement with the field estimate, given the uncertainty in the actual storm surge as discussed above.

FIELD METHODS

The stranded bars were deposited with their seaward margins within the mean swash zone (Figure 3). The bar crests were less than 1.5 m above MWL. Figure 3A shows the undisturbed backshore at Carrabelle Beach two weeks after Hurricane Elena made landfall. The scarping at the crest of the bar (Figure 3B) and the lack of storm debris are apparent. The photograph in Figure 3C was taken 18 days after Kate made landfall. This image reveals the effects of the increased storm surge. The Kate bar (Figure 3D) was deposited slightly further above MWL and was eroded very little by post-storm waves. More debris was introduced into the surf zone because of greater flooding. This material was deposited within the bar itself. Both bars exceeded 2.5 km in length. The base of each stranded bar was marked by a seaward-sloping erosional surface that was used as the datum for vertical position and height. The Elena bar's maximum height was 0.6 m at the crest. The Kate bar measured 0.7 m.

To evaluate the sedimentary structures and sediment textures of these two stranded bars, sampling stations were established as shown in Figure 4. Two weeks after hurricane Elena, trenches were excavated across the bar at stations 2 and 4, with pits placed at stations 1, 3 and 5. Two weeks after Hurricane Kate, trenches were placed at stations 0 and 3, and pits were dug at stations 2 and 4. Photomosaics were

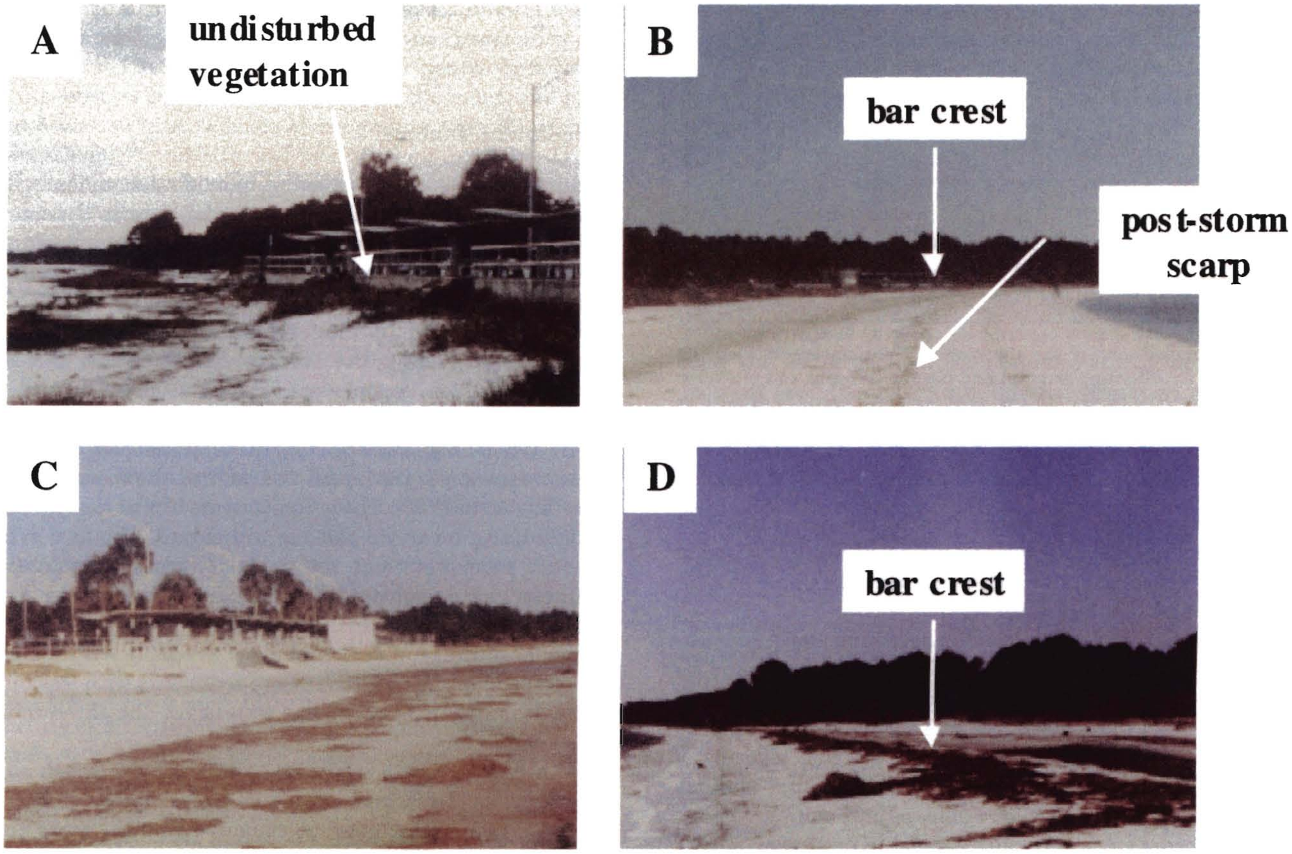


Figure 3. (A) Photograph of the backshore at Carrabelle Beach after Hurricane Elena, showing the lack of erosion at the pavilion. View is to the southwest. (B) Photograph taken on September 14 of the Hurricane Elena bar deposited on September 1, 1985. View is to the northeast. Note the erosional scarp, which was caused by storm waves during frontal passage after the hurricane. (C) Photograph looking to the east of the pavilion in A, showing extensive erosion of backshore area. Note the debris that was deposited in the swale behind the bar. (D) View (looking southwest) of the bar deposited by Hurricane Kate, 21 November 1985.

compiled of the trenches at station 4 after Hurricane Elena and station 3 after Hurricane Kate (Figure 5).

A suite of sediment samples was collected at each station. Laminar samples were collected at the crest of the bar from horizontal layers at intervals of 0.05 m within the more homogeneous sections, and 0.025 m where finer structures were found. Where the lighter-colored beds became less than 0.025 m thick, samples were taken from successive light beds or laminae but heavy mineral laminae were not sampled. Because these samples were taken internally from the bar crest, no post-storm modification of the sediment texture could have occurred. Each sample was separated into size fractions by sieving at 0.25 phi intervals for 30 minutes on a Ro-Tap mechanical shaker after rinsing and drying.

One of the fundamental characteristics of the stranded bars from the Florida study area is the horizontal interlayering of heavy mineral laminae with quartz sand beds (COLEMAN, 1978). STAPOR (1973) reported heavy mineral concentrations of about 62 percent for such layers within Apalachicola Bay, with the common occurrence of ilmenite, staurolite, kyanite, zircon and rutile. The concentration of these minerals within this area is commonly less than one percent (TANNER *et al.,* 1961). The weight-percent heavy minerals for suites E3, K0, K2 and K4 was determined by heavy-liquid separation after the sediment was recombined into two size classes, two-to-three phi ($250\times10^{-6} - 125\times10^{-6}$ m) and greater-than three phi ($< 125\times10^{-6}$ m). Note that the letters "E" and "K" refer to Elena and Kate, respectively.

RESULTS

Internal Geometry

The Elena Bar

The bedding within the Elena bar (Figure 6) was variable both in the vertical dimension and alongshore. The lower part of the bar contained a large quantity of fine-grained material at station 1, making the section appear darker (Figure 6A). The concentration of heavy minerals increases at station 2 (Figure 6B), where the distinctive lamination is evident. A cross-section of the bar at station 3 (Figure 6C) is similar to station 1. Profiles at stations 4 (Figure 6D) and 5 reveal rhythmic, heavy-mineral lamination within the middle part of the bar. The lower section is composed of quartz sand and

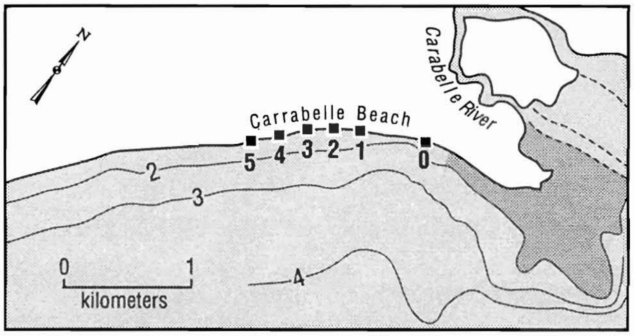


Figure 4. Detailed map of the study area. The numbers indicate the stations used for collecting samples and placing trenches and pits after both hurricanes. The darker stippled area is a shoal partially exposed at low water.

has thicker layering. The upper part of the bar consists of homogeneous quartz sand with no apparent bedding. Eroded debris from the backshore was found within the upper section of the bar at station 5 (Figure 6E).

The Elena bar was evenly bedded perpendicular to the water line (Figure 5A). Individual beds and laminae could be traced more than 1 m. Seaward-dipping cross-bedding was found at the seaward margin of the bar, however, beneath the horizontal lamination. Because the internal layering of the bar was dominantly horizontal and individual laminae and beds did not intersect or truncate one another, it has been described as concentrically bedded (KEEN, 1986; 1987). Thus, the Elena bar is considered to contain the characteristic bedding of the stranded bar as defined by COLEMAN (1978).

The Kate Bar

In contrast to the predominantly concentric bedding and lamination within the Elena bar, bedding within the Kate bar contains both horizontal and cross bedding, as well as erosion surfaces. The bar's internal structure consists of overlapping concentric bedding sets at the eastern end of the study area (Figure 7A). This stratification is similar to hummocky cross-beds (DUKE *et al.,* 1991). The lowest part of the bar is slightly darker because of the presence of fine-grained sediment. Dark laminae are sparse, however. This bedding extends to the top of the bar. This same bedding pattern was found at station 2 (Figure 7B). The most interesting internal structures within the Kate bar were found at station 3 (Figure 5B). The lowermost part of the bar contained landward-dipping cross-bedding, with angles ranging from 8° to 12°. The top of this section is not truncated. Instead, the overlying bedding is horizontal and concentric. The transition from cross-bedding to horizontal lamination is apparent in Figure 7C. Dark laminae, which were found above the cross-bedding, extended for several meters across the bar. These heavy-mineral laminae were offset and disrupted by storm debris within the topmost part of the bar. Heavy minerals were more diffuse within the top as well, which was more homogeneous.

No cross-bedding was found at station 4 (Figure 7D), where the horizontal bedding extended throughout the bar height. This station most resembled the Elena bar. Individual laminae were traced several meters parallel to shore at this end of the study area.

Sediment Texture

Suite data are used instead of individual samples in analyzing the sediment texture. This method reduces the amount of variability displayed in plots of the sediment grain size distribution (granulometric) moments. The results of the grain size analysis for each suite are given in Table 1. The mean and standard deviation represent the average size, and scatter of sizes about the average. The skewness indicates asymmetry about the average. The kurtosis is an index for the peakedness of the size distribution curve.

The typical sediment weight distribution plot consists of three components, the modal swarm, and the coarse and fine tails (TANNER, 1983). These components can be analyzed separately using bivariate plotting techniques. The four granulometric moments treat the modal swarm's granulometric character, as demonstrated for fluvial sediments by FOLK and WARD (1957), in which study they proved useful because of the large range of sediment sizes available within a river bar. In attempting to differentiate sediments with less inherent variability, it is necessary to analyze the three components separately.

Within the Florida study area, only mature beach sands are available. Thus, any distinctive granulometric signatures for these two storms must be sought within the more sensitive tails of the grain size distribution. Kurtosis contains information about the relative size of the modal swarm and the two tails, whereas skewness indicates relative sorting between the tails. FRIEDMAN (1961) found that cross-plots of these two moments were useful in distinguishing sediment of different maturity. Figure 8 is such a plot for the sediment suites from Table 1. The suites from the Kate bar have very low values of skewness (a value of 0 indicates a perfectly symmetrical size distribution) and kurtosis (a Gaussian distribution has a value of 3), indicating that they are close to being normally distributed. They also have less variability than the Elena suites.

Very mature sediments will be normally distributed. The degree of maturity can be further evaluated by considering the weight-percent sediment finer-than or equal-to 4 φ (62.5×10^{-6} m). Immature sediments will contain a greater percentage of silt and clay. As seen in the Tail-of-Fines diagram for these suites (Figure 9), the Kate suites reveal both a smaller percentage of fine sediment, and less variability. Consequently, they would be considered as more mature. The placement of the Elena suites outside the mature beach field suggests that they contained excessive silt and clay and were not uniformly reworked by the storm waves; thus, the higher means of standard deviations.

Systematic trends were found in the vertical distribution of the sample means and standard deviations within the Elena bar. Plotting of the mean and standard deviations of individual samples against their relative height revealed a discontinuity within the Elena suites, with finer grain sizes and smaller standard deviations found within the sand from the upper part of the bar. The variance between and within these two populations of sediment was analyzed using the ANOVA test (HUNTSBERGER and BILLINGSLEY, 1975). The results support this separation for both the mean and standard deviation at confidence levels greater than 99 percent. A weak alongshore pattern of westward fining (Table 1) was discerned for suite means of means ($R^2 = 0.6907$) and means of standard deviations ($R^2 = 0.6177$) for the Elena bar. The samples from the Kate bar contained no evidence for the existence of separate populations for any of the granulometric moments, and no alongshore pattern was apparent.

The average content of heavy minerals for the Elena suite was 2.92 percent for the coarse fraction and 14.3 percent for the fine fraction. The Kate suites averaged 4.04 and 39.1 percent, respectively. Furthermore, the concentration was distributed uniformly within the Elena bar, whereas reversed trends were found within the Kate bar; the percentage decreased with height at station 0, and increased at stations 2 and 4.

DISCUSSION

The stranded bars discussed in this paper appear to have been produced in the same way as that deposited by Hurricane Eloise, as described by COLEMAN (1978). Because of the difficulty of directly observing hydrodynamic processes in the nearshore zone during hurricanes, however, any discussion of the mechanisms responsible for deposition of these stranded bars must be somewhat speculative. Nevertheless, using the field observations, model results, sediment texture data, and general principles of coastal storm flows and sedimentation (*e.g.,* HAYES, 1967; DUKE, 1985; SWIFT *et al.,* 1986; NUMMEDAL and SNEDDEN, 1987), we can shed some light on sediment dynamics during hurricanes at Carrabelle Beach.

Deposition of the Stranded Bars at Carrabelle Beach

Accretion of sediment on the beach during hurricanes is unusual. The recurrence of stranded bars at Carrabelle Beach suggests that the local bathymetry and coastal geometry promote a unique combination of water elevation and storm wave histories in this part of St. George Sound. The internal stratification of the stranded bars is also dependent on the timing of the storm surge and waves. This section will thus discuss the specific timing of waves and elevations at Carrabelle Beach, as they pertain to sedimentation at the study site. Because of the lack of direct observations during the storms, however, this discussion is limited.

A cross-section of the Kate bar just west of the river (Figure 7A) reveals stratification similar to swash bars (ALLEN, 1982). Neither bar contained this bedding to the west. Within the central part of the study area, both bars consisted of thin beds and laminae of quartz and heavy minerals. This concentric stratification was more common at the western end of the study area, which is farthest from the mouth of the Carrabelle River.

The storm wind during Kate (Figure 2) was similar to that during the last part of Elena's passage; the main difference was the slow build-up of onshore winds on November 21. Storm waves generated by the southerly wind would have entered St. George Sound between 1700 and 2400 GMT on November 21. The steady increase in wind caused the storm surge to build slowly after 1200 GMT November 20 (Figure 2) and reach a maximum 36 hours later. Consequently, storm waves would have been significantly diminished at Carrabelle while the storm surge remained high. This scenario would continue until 0600 GMT November 22, by which time the model-predicted water levels had returned to normal.

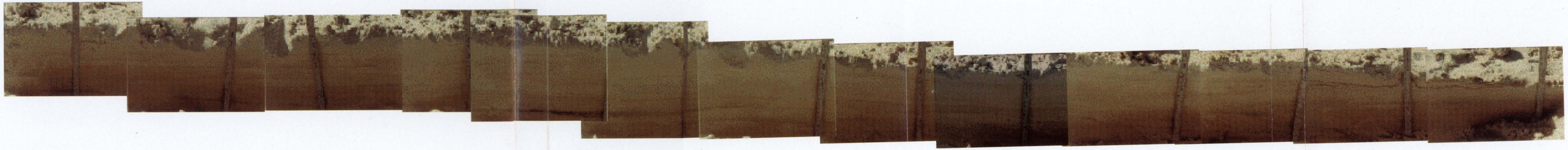
Although there was flotsam within both bars, the quantity was much greater within the Kate bar. This debris intersects the concentric stratification without obliterating the heavy mineral laminae (Figure 7). Since it would have been floating near the water surface, the observed stratigraphic relationship between the debris and laminae would occur only if the debris were deposited simultaneously with the laminae. In many instances, these laminae do not become diffuse as they approach the debris either, implying that flow was not disrupted by the debris, such as would occur if it were in place prior to laminae deposition. The debris seen in Figures 5B, 6E, and 7C does not extend below the horizontally bedded section of the stranded bars. Consequently, the concentric stratification within the Kate bar was produced when the water depth was very shallow and flotsam was being deposited, rather than during the maximum storm surge. Furthermore, this deposition occurred while the storm surge was waning, since the observed quantity of debris would not have been available until after the maximum surge. Deposition of the more complex bar at station 0, and the lower part of the Kate bar elsewhere (such as at station 3), is more problematic.

The cross-beds within the Kate bar at station 3 dipped landward at no more than 12° (Figure 5B). Such low-angle cross-beds result from either a large suspended sediment load, or very deep water relative to the height of the lee slope of the bar (BLATT *et al.,* 1978). The bedload-dominated shallow-water transport occurring during swash bar (or berm) construction produces dip angles near the angle of repose, as seen in accretionary berms (HAYES, 1972). It is reasonable to assume that the suspended load was large during the hurricane. The maximum water depth over the Kate bar could not have been greater than 2 m at the height of the storm. The foresets were tangential at the bottom and the top, indicating that deposition was continuous during bar construction. The uninterrupted deposition at this site is in sharp contrast to the multiple erosion and deposition events recorded at station 0.

Examining the stratification within the Kate bar with respect to the environmental conditions discussed above suggests that the cross-beds were deposited while storm waves were still entering the sound, before 2400 GMT November 21. The wave energy steadily decreased after this and the water level began to drop. The transition to concentric bedding occurred before the storm surge had fallen by more than 1 or 2 m. The shift in depositional mode, from bedload to suspended load, was accompanied by a translation of the surf zone to seaward and a decrease in wave energy. The resulting rapid change in flow and wave conditions permitted deposition of horizontal laminae and flotsam.

The wind (Figure 2) was blowing from the north (offshore) for most of Hurricane Elena, and it shifted rapidly to south-

A) The Elena bar at station 2



B) The Kate bar at station 3

Figure 5. Photomosaics taken from the 1985 stranded bars at Carrabelle Beach, Florida. (A) The Elena bar, at station 2 (See Figure 4 for location). (B) The Kate bar, at station 3. The lagoon is to the right.

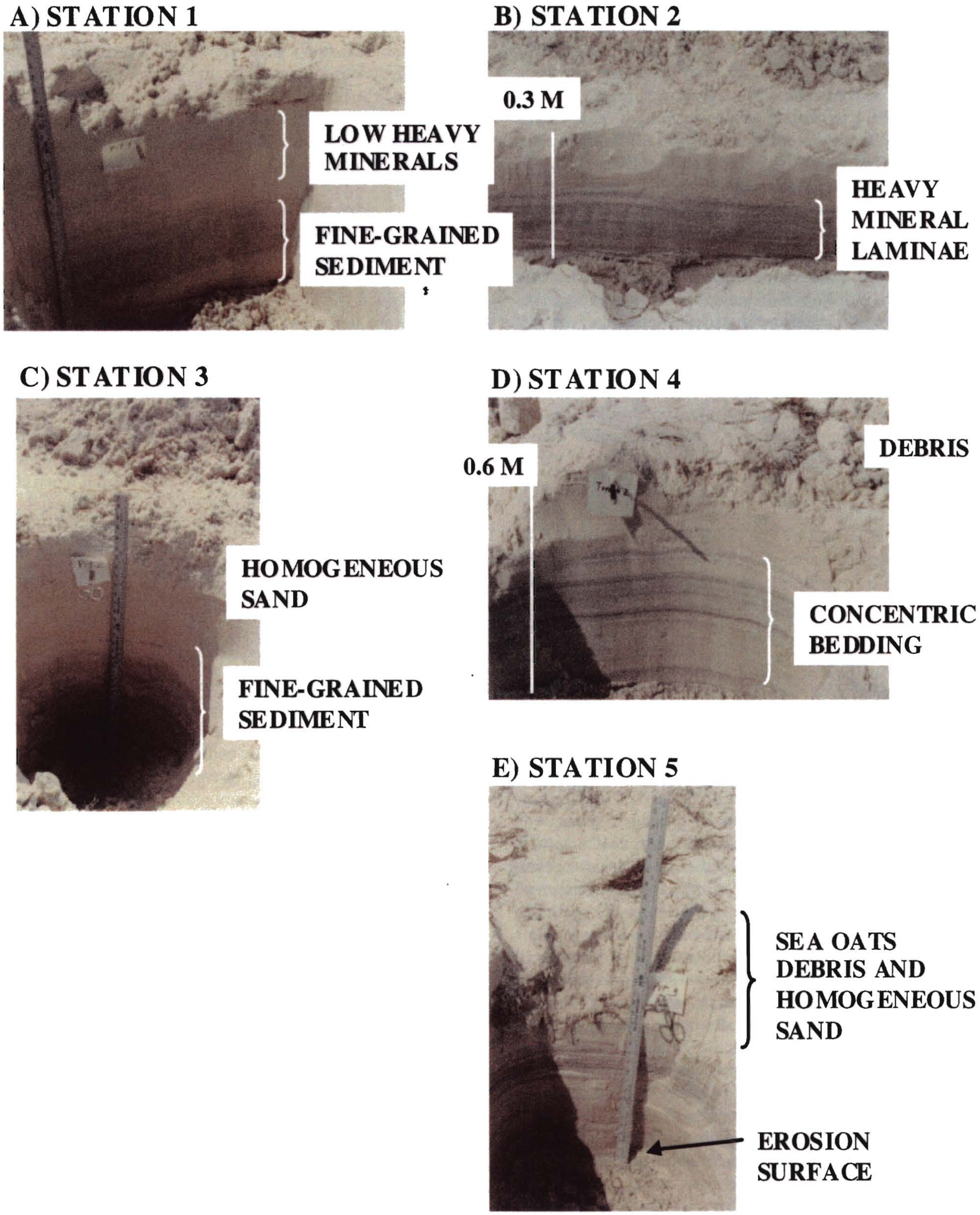


Figure 6. Photographs of pits dug in the Elena stranded bar at (A) station 1, (B) station 2, (C) station 3, (D) station 4, and (E) station 5. See Figure 4 for locations.

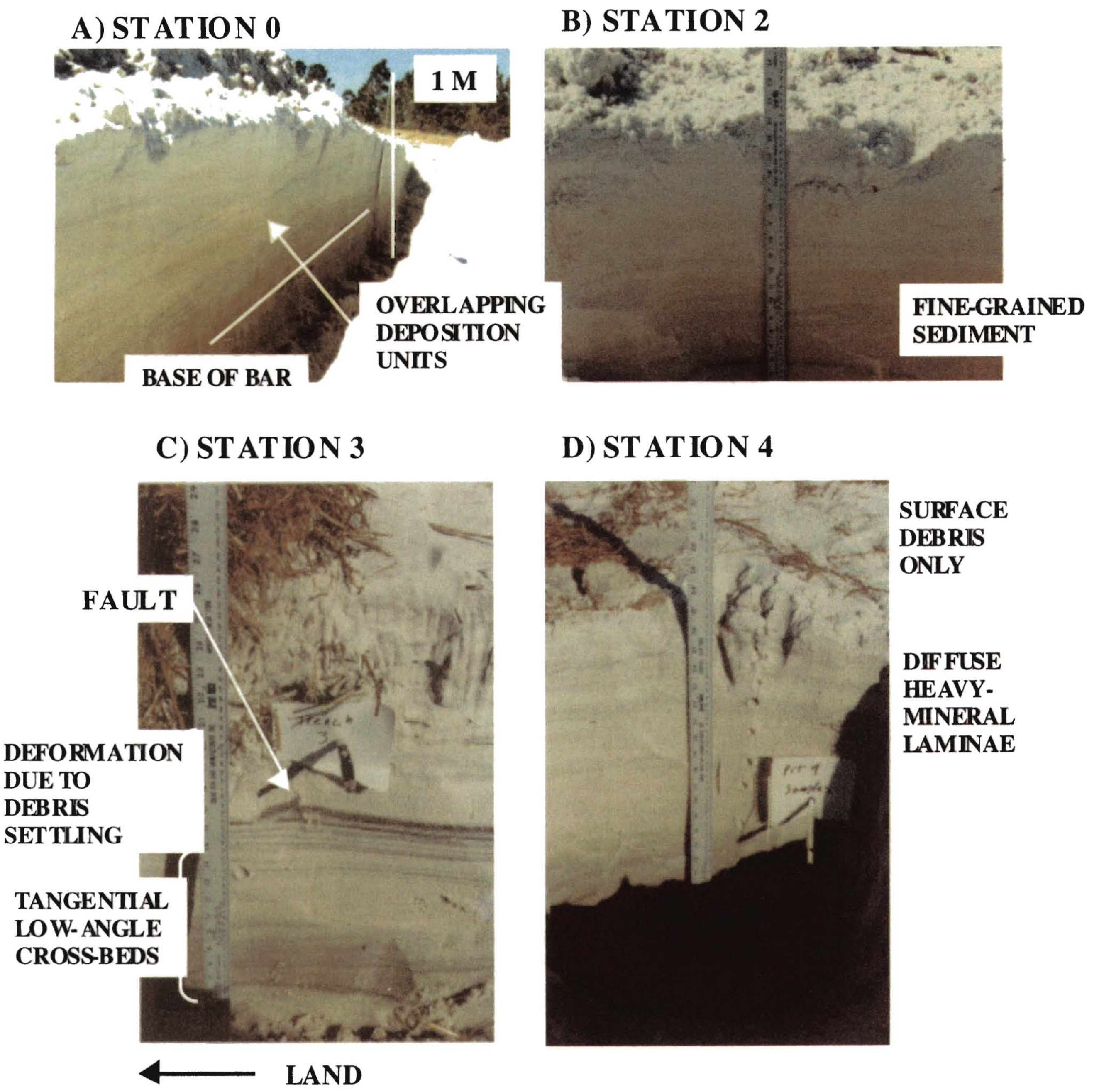


Figure 7. Photographs of pits dug in the Kate stranded bar at (A) station 0, (B) station 2, (C) station 3, and (D) station 4. See Figure 4 for locations.

erly after 1800 GMT September 1. This onshore wind generated storm waves that entered St. George Sound through East Pass. The peak storm surge would have occurred shortly thereafter. Storm waves within the sound would have decreased after 0400 GMT September 2 as the wind died down. There is no evidence of swash bar construction during Hurricane Elena. Thus, it appears that the storm surge of Kate must have exceeded 1.5 m, which was the maximum during Elena, to deposit the cross-beds of the Kate bar. The sustained storm waves within the sound would have been a significant factor as well. Otherwise, the deposition of the Elena bar was probably very similar to concentric deposition within the Kate bar as described above.

Evolution of the Sediment Pool

The sediment within the Kate bar was close to a Gaussian distribution, which commonly results from sediment settling

Table 1. *Statistical moments for the grain size distribution data for sample suites collected at stations indicated in Figure 2. For suite names, E represents Elena suites and K represents Kate suites. Mean and standard deviation are given in phi units (Phi = $-\log_2 D$(mm.)).*

Suite	No. Samples	Mean	Standard Deviation	Skewness	Kurtosis
E1	8	2.126	.373	−.129	3.471
E2	20	2.174	.327	.0128	4.560
E3	10	2.167	.339	.0967	3.746
E4	19	2.259	.300	.0499	5.583
E5	10	2.243	.317	.0229	4.004
K0	9	2.224	.311	.0518	3.292
K2	7	2.188	.301	.0273	3.910
K3	9	2.181	.337	.008	3.779
K4	19	2.264	.325	.049	3.954

through the water column (TANNER, 1983). This depositional mode is in agreement with the stratigraphic relationships between the flotsam and laminae. This greater maturity also suggests greater reworking of the Kate sediment than the Elena sediment.

The Elena sediment had a larger silt and clay component than did the Kate sand pool, which implies that the finer particles were not completely removed from the area before deposition. The Elena sediment contained a statistically significant vertical division within the bar. This temporal trend towards finer and better-sorted sediment implies that the wave energy level was decreasing and the suspended sediment load was not homogeneous, *i.e.*, the sand pool was becoming texturally more mature during deposition of this bar. If the Elena bar was deposited as quickly as the Kate bar appears to have been (less than 6 hours), this implies a very efficient winnowing process.

Sediment texture is not typically uniform across the nearshore zone. The coarsest and poorest-sorted sediment is found at the plunge point. The swash zone contains finer and better-sorted sediment (BRENNINKMEYER, 1978; STAPOR and MAY, 1982; STONE, 1991; STONE *et al.*, 1992). During high-energy events this cross-shore variability should be smeared out, as was found for the open gulf beaches northeast of Carrabelle Beach by RIZK and DEMIRPOLAT (1986). They recognized homogenization events in swash and plunge-point samples collected following Hurricanes Elena and Kate, with textural recovery beginning almost immediately after each storm. This result is supported by the lack of any cross-shore textural trends within the Eloise stranded bar (COLEMAN, 1978). The weak alongshore pattern in the mean and standard deviation for the Elena bar may have been caused by shore-parallel flow during most of that storm.

MAY (1973) proposed that relict heavy minerals may be stored and concentrated within the sediments of the lagoon because of limited exchange with the open ocean. In addition, erosion of the heavy-mineral-rich berms on the beach during storms supplements the lagoon source (STAPOR, 1973). Both of these sediment pools were entrained during the hurricanes at Carrabelle Beach but, because greater backshore erosion occurred during Hurricane Kate, the second process would have predominated. Furthermore, these minerals had already been concentrated within the Elena stranded bar before Hurricane Kate.

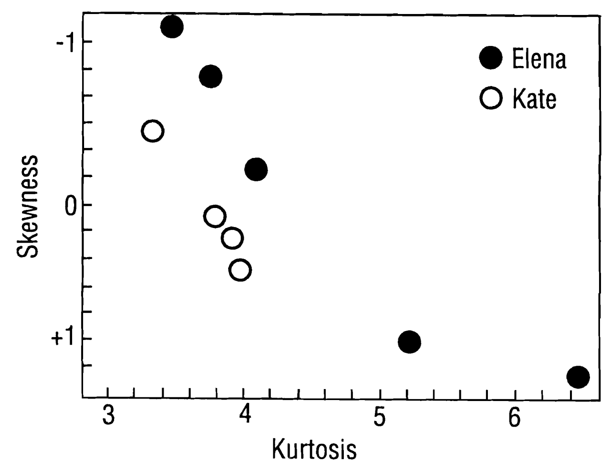


Figure 8. Bivariate plot of skewness-versus-kurtosis for sample suites from both bars. Solid circles are Elena suites and open circles represent Kate suites.

CONCLUSIONS

Evaluation of the sedimentary structures and textures of the 1985 stranded bars from Carrabelle Beach, Florida, suggests that these bars were partly constructed by sediment settling from suspension in very shallow water. An examination of the winds and storm surge during Hurricane Kate (November 1985) indicates that this mode of deposition was possible after the storm waves diminished, but while coastal

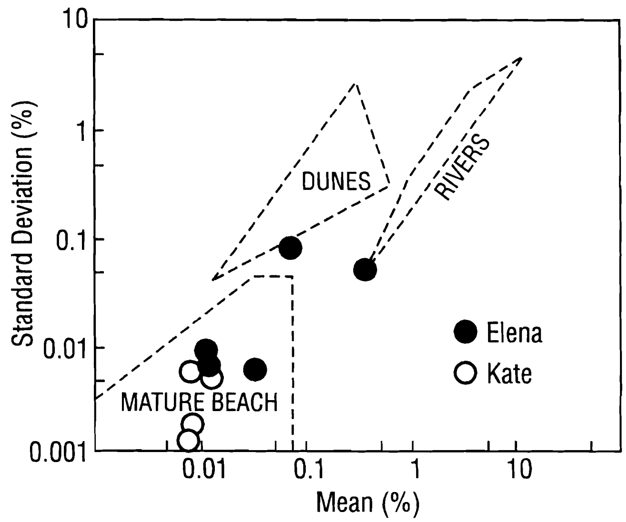


Figure 9. Tail-of-Fines Diagram. The mean of the weight-percent fines for each suite is plotted against the standard deviation of its weight-percent fines. Solid circles are Elena suites and open circles are Kate suites. The divisions on the plot represent observed limits from modern environments.

water levels remained elevated. The sediment dynamics that produce such a localized settling phenomenon are poorly understood.

The data presented here also show that the generally accepted notion of an erosional beach response to hurricanes is not universal. Storm sequences that are deposited as sheets from suspension are common on the inner shelf. Storm sedimentation also consists of localized bars constructed by bedload transport processes within the surf zone or the swash during the relaxation stage of the storm. Observation of storm-related bar formation, however, has been limited to accretionary berms. Bars formed during severe storms have not been observed directly.

ACKNOWLEDGEMENT

The first author was funded by the Office of Naval Research, program element 62435N. Cartographic assistance was provided by Mary Lee Eggard and Clifford Duplechin of Louisiana State University.

LITERATURE CITED

ALLEN, J.R.L., 1982. *Principles of Physical Sedimentology.* Boston: George, Allen, and Unwin, 272 p.

BLAIN, C.A., 1997. Modeling methodologies for the prediction of hurricane storm surge. *In:* SAXENA, N. (ed.), *Recent Advances in Marine Science and Technology,* 96. Honolulu, Hawaii: Pacon International, pp. 177–189.

BLAIN, C.A.; WESTERINK, J.J., and LUETTICH, R.A., JR., 1994. The influence of domain size on the response characteristics of a hurricane storm surge model. *Journal of Geophysical Research,* 99, 18467–18479.

BLATT, H.; MIDDLETON, G., and MURRAY, R., 1978. *Origin of Sedimentary Rocks.* New York: Prentice-Hall, 634p.

BRENNINKMEYER, B.M., 1978. Littoral sedimentation. *In:* FAIRBRIDGE, R.W. and BOURGEOIS, J. (eds.), *The Encyclopedia of Sedimentology.* Stroudsberg, Pennsylvania: Dowden, Hutchinson and Ross, pp. 448–457.

BURDIN, W., 1975. Surge effects from Hurricane Eloise. *Shore and Beach,* April, 2–11.

COLEMAN, C., 1978. The stranded bar: A study of bar formation during storm surges at Carrabelle Beach, Florida. M. S. Thesis, Florida State University, Tallahassee.

DEBUSSCHERE K.; PENLAND, S.; WESTPHAL, K.A.; MCBRIDE, R.A., and REIMER, P. D., 1991. Morphodynamics of the Isles Dernieres barrier shoreline, Louisiana. *Proceedings of the Specialty Conference on Coastal Sediments '91* (American Society of Civil Engineers), pp. 1137–1151.

DINGLER, J. R. and REISS, T.E., 1995. Beach Erosion on Trinity Island, Louisiana Caused by Hurricane Andrew. *In:* STONE, G.W. and FINKL, C.W. (eds.), *Impacts of Hurricane Andrew on the Coastal Zones of Florida and Louisiana; August 22–26, 1992. Journal of Coastal Research,* Special Issue 21, 254–264.

DOLAN, R., 1972. Barrier dune systems around the Outer Banks of North Carolina: A Reappraisal. *Science,* 176, 286–288.

DOLAN, R. and P. GODFREY, 1973. Effects of Hurricane Ginger on the barrier islands of North Carolina. *Geological Society of America,* 84 (4), 1329–1334.

DUKE, W.L., 1985. Hummocky cross-stratification, tropical hurricanes, and intense winter storms. *Sedimentology,* 32, 167–194.

DUKE, W.L.; ARNOTT, R.W.C., and CHEEL, R. J., 1991. Shelf sandstones and hummocky cross-stratification: New insights on a stormy debate. *Geology,* 19, 625–628.

FINKL, C.W. and PILKEY, O. H. (eds.), 1991. *Impacts of Hurricane Hugo: September 10–22, 1989. Journal Coastal Research,* Special Issue 8, 356 p.

FOLK, R.L. and WARD, W.C., 1957. Brazos River bar: A study in the significance of grain size parameters. *Journal of Sedimentary Petrology,* 27, 3–26.

FRIEDMAN, G. M., 1961. Distinction between dune, beach, and river sands from their textural characteristics. *Journal of Sedimentary Petrology,* 31, 514–529.

GORSLINE, D.S., 1966. Dynamic characteristics of west Florida Gulf coast beaches. *Marine Geology,* 4, 187–206.

HAYES, M. O., 1967. Hurricanes as geologic agents: Case studies of Hurricanes Carla, 1961, and Cindy, 1963. *Report of Investigations No. 61,* Bureau of Economic Geology, Texas University.

HAYES, M. O., 1972. Forms of sediment accumulation in the beach zone. *In* MEYERS, R.E. (ed.), *Waves on Beaches and Resulting Sediment Transport.* New York: Academic Press, pp. 297–356.

HUNTSBERGER, D.V. and BILLINGSLEY, P., 1975. *Elements of Statistical Inference* (5th Edition). Boston: Allyn and Bacon, Inc., pp. 243–273.

KAHN, J.H. and ROBERTS, H.H., 1982. Variations in storm response along a micro-tidal transgressive barrier island arc. *Sedimentary Geology,* 33, 129–146.

KEEN, T.R., 1986. The sedimentology of a stranded bar and implications for its origin. *In*: TANNER, W.F. (ed.), *Suite Statistics and Sediment History, Proceedings of the Seventh Symposium on Coastal Sedimentology.* Tallahassee: Florida State University, pp. 167–179.

KEEN, T.R., 1987. The comparative sedimentology of two stranded bars and implications for their origin. M.S. Thesis, Florida State University, Tallahassee.

KOFOED, J.W. and GORSLINE, D.S., 1963. Sedimentary environments in Apalachicola Bay, Florida: *Journal of Sedimentary Petrology,* 33, 205–223.

LEATHERMAN, S.P., 1979. Barrier dune systems: A reassessment. *Sedimentary Geology,* 24, 1–16.

LEATHERMAN, S.P.; WILLIAMS, A.T., and FISHER, J.S., 1977. Overwash sedimentation associated with a large scale Northeaster. *Marine Geology,* 24, 109–121.

MAY, J.P., 1973. Selective transport of heavy minerals by shoaling waves. *Sedimentology,* 20, 203–211.

MORGAN, J.P.; NICHOLS, L.G., and WRIGHT, M., 1958. Morphological effects of Hurricane Audrey on the Louisiana Coast. *Coastal Studies Institute Report 58–3,* Louisiana State University, Baton Rouge.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1985. *Tide tables 1985, High and low water predictions, East Coast of North and South America, including Greenland.*

NUMMEDAL, D. and SNEDDEN, J.W., 1987. Sediment exchange between the shoreface and continental shelf—evidence from the modern Texas coast and the rock record. *Proceedings of the Specialty Conference on Coastal Sediments '87* (American Society of Civil Engineers), pp. 2110–2125.

NUMMEDAL, D.; PENLAND, S.; GERDES, R.; SCHRAMM, W.; KAHN, J., and ROBERTS, H., 1980. Geologic response to hurricane impact on low-profile Gulf coast barriers. *Transactions, Gulf Coast Association of Geologic Societies,* 30, 183–195.

PENLAND, S.P.; SUTER, J.R.; SALLENGER, A.H.; WILLIAMS, S.J.; MCBRIDE, R.A.; WESTPHAL; K.E., REIMER, P.D., and JAFFE, B.E., 1989. Morphodynamic signature of the 1985 Hurricane Impacts on the Northern Gulf of Mexico. *Proc. Sixth Symposium on Coastal and Ocean Management,* Charleston, South Carolina, p. 420–423.

RIZK, F.F. and DEMIRPOLAT, S., 1986. Pre-hurricane vs. post-hurricane beach sand, Franklin County, Florida. *In:* TANNER, W.F. (ed.), *Suite Statistics and Sediment History, Proceedings of the Seventh Symposium on Coastal Sedimentology.* Florida State University, Tallahassee, p.129–142.

SCHRAMM, W.E.; PENLAND, S.; GERDES, R.G., and NUMMEDAL, D., 1980. Effects of Hurricane Frederic on Dauphine Island, Alabama. *Shore and Beach,* 48 (4), 20–25.

SEXTON, W.J. and MOSLOW, T.F., 1981. Effects of Hurricane David, 1979, on the beaches of Seabrook Island, South Carolina. *Northeastern Geology,* 3 (3/4), 297–305.

SEXTON, W.J. and HAYES, M.O., 1991. The Geologic Impact of Hurricane Hugo and Post-Storm Shoreline Recovery along the Undeveloped Beaches of South Carolina, Dewees Island to the Sanatee Delta. *Journal of Coastal Research,* Special Issue No. 8, 275–290.

STAPOR, F.W., JR., 1971. Sediment budgets on a compartmented low-to-moderate energy coast in Northwest Florida. *Marine Geology,* 10, M1–M7.

STAPOR, F.W., JR., 1973. Heavy mineral concentrating processes and density shape size equilibria in the marine and coastal dune sands of the Apalachicola Florida, region. *Journal of Sedimentary Petrology,* 43, 396–407.

STAPOR, F.W. and MAY, J.P., 1982. The cellular nature of littoral drift along the Northeast Florida coast. *Marine Geology,* 51, 217–237.

STONE, G.W., 1991. Differential sediment supply and the cellular nature of longshore sediment transport along coastal Northwest Florida and Southeast Alabama since the late Holocene. Ph.D. Thesis, University of Maryland, College Park.

STONE, G.W., 1998. Hurricane impact and recovery on coastal island geomorphology: Hurricane Opal, October 1995, *NSF Report 9625709.*

STONE, G. W. and SALMON, J. D., 1988. Hurricane-related morphodynamics and implications for hazard mitigation, Perdido Key, Florida, U.S.A. *Journal of Coastal Management,* 16, 245–270.

STONE, G.W. and FINKL, C.W. (eds.)., 1995. Impacts of Hurricane Andrew on the coastal zones of Florida and Louisiana; August 22–26, 1992. *Journal Coastal Research* Special Issue 21.

STONE, G.W. and STAPOR, F.W., 1996. A nearshore sediment transport model for the Northeast Gulf of Mexico Coast. *Journal of Coastal Research,* 12 (3), 786–792.

STONE, G.W. and WANG, P., 1999. The importance of cyclogenesis on the short-term evolution of Gulf coast barriers. *Transactions of the Gulf Coast Association of Geological Societies,* XLIX, 47–487.

STONE, G. W.; STAPOR, F. W.; MAY, J. P., and MORGAN, J. P., 1992. Multiple sediment sources and a cellular, non-integrated, longshore drift system: Northwest Florida and Southeast Alabama coast, U.S.A. *Marine Geology,* 105, 141–154.

STONE, G. W.; GRYMES, J.; STEYER, K.; UNDERWOOD, S.; ROBBINS, K., and MULLER, R. A., 1993. A chronological overview of climatological and hydrological aspects associated with Hurricane Andrew and its morphological effects along the Louisiana Coast, U.S.A. *Shore and Beach,* 61 (2), 2–12.

STONE, G.W.; GRYMES, J.M.; ARMBRUSTER, C.A., and HUH, O.K., 1996. Overview and impacts of Hurricane Opal on the Florida coast. *EOS, Transactions of the American Geophysical Union,* 77, 181–184.

STONE, G.W.; GRYMES, J.W.; DINGLER, J.R., and PEPPER, D.A., 1997. Overview and significance of hurricanes on the Louisiana Coast, U.S.A. *Journal of Coastal Research,* 134 (3), 656–669.

STONE, G.W.; WANG, P.; PEPPER, D.A.; GRYMES, J.W.; ROBERTS, H.H.; ZHANG, X.P.; HSU, S.A., and HUH, O.K., 1999. Researchers begin to unravel the significance of Hurricanes of the northern Gulf of Mexico, *EOS, Transactions of the American Geophysical Union,* 80, 27, 301–305.

SWIFT, D.J.P.; THORNE, J.A., and OERTEL, G.F., 1986. Fluid processes and sea-floor response on a modern storm-dominated shelf: Middle Atlantic shelf of North America. Part II: Response of the shelf floor. *In:* KNIGHT, R.J. and MCLEAN, J.R. (eds.), *Shelf Sands and Sandstone Reservoirs. Canadian Society of Petroleum Geologists Memoir No.* 11, pp. 191–211.

TANNER, W.F., 1983. Hydrodynamic origin of the Gaussian grain size distribution. *In* TANNER, W.F. (ed.), *Nearshore Sedimentology, Proceedings of the Sixth Symposium on Coastal Sedimentology.* Florida State University, Tallahassee, p.12–34.

TANNER, W.F., 1986. Hurricane update. *Coastal Research,* 7 (1), 1–3.

TANNER, W.F.; MULLINS, A., and BATES, J.D., 1961. Possible masked heavy mineral deposit, Florida panhandle. *Economic Geology,* 56, 1079–1087.

THIELER, E.R. and YOUNG, R.S., 1991. Quantitative evaluation of coastal geomorphological changes in South Carolina after Hurricane Hugo. *Journal of Coastal Research,* Special Issue No. 8, 187–200.

WRIGHT, L.D.; SWAYE, FJ., and COLEMAN, J.M., 1970. Effects of Hurricane Camille on the landscape of the Breton-Chandeleur island chain, and the eastern portion of the Lower Mississippi Delta. *Louisiana State University Coastal Studies Bulletin* (Feb. 1970), pp. 13–32.