A PROCESS-RESPONSE MODEL FOR HURRICANE WASHOVERS

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ABSTRACT

The passage of Hurricane Allen over Padre Island in August 1980 presented an excellent opportunity to study the effects and controls of coastal morphology on hurricane deposits. In the Caribbean Sea, Hurricane Allen achieved a central pressure of 899 mb, making it the second strongest Atlantic hurricane ever recorded. Once in the Gulf of Mexico, the storm approached the Texas coast from the east-southeast, building a significant storm surge. Near Brownsville, the storm stalled, spending much of its energy offshore before making landfall early on August 10th near Brazos Santiago Pass at the southern tip of Padre Island.

Surge gauges show that peak recorded storm tides of about 3 m occurred at Port Mansfield, some 35 km north of landfall. Analysis of tide data indicates a time lag of some 14 hours on the rising storm tide between the Gulf and south Laguna Madre. This is due both to the limited tidal exchange across Padre Island and to set-down in the lagoon due to southward-directed cyclonic winds. By contrast, measurements taken in Corpus Christi Bay, some 180 km north of landfall, show that at that point Gulf and bay tides were in phase. The cross-barrier water level differential at South Padre Island (up to 1.5 m) greatly facilitated hurricane breaching of the island.

Oblique and vertical aerial photography show that Padre Island was breached in many places, with about 40 major hurricane channels still open several days after the storm. Surge heights were sufficient to inundate all of South Padre Island except for isolated "dune islands" resulting in broad and often coalescing washover deposits. The more continuous dune ridge on North Padre Island resulted in smaller, discrete washovers. Intensity, distribution, and morphology of washovers are functions of storm tide elevation, its phase relationships, island topography, and lagoonal water depth. The relationship is complex, yet precise enough to permit prediction of the island's response to the impact of a given storm.

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Introduction

Normal, day-to-day physical processes along the northwestern shores of the Gulf of Mexico are relatively low energy. The area is micro-tidal (Hayes, 1979), and the broad, low gradient continental shelf serves to dissipate much of the incident wave energy. In this environment, storm related processes are usually dominant.

The barrier islands of the Texas coast are affected by two types of storms: extratropical cold fronts ("northers") and tropical storms and hurricanes. Both storm types have significant impact on coastal sedimentary environments, but along the Texas coast major effects on the barrier islands of the Gulf shoreline, such as breaching, overwashing, and dune planation are mostly the result of hurricanes.

The last such storm to impact the Texas coast was Hurricane Allen, which made landfall over Padre Island on August 10, 1980 (Figure 1). Oblique and vertical aerial photography showed that the island was breached in many places, and that a variety of washover deposits were laid down. Tide gauge data indicate a time lag of some 14 hours on the rising storm tide between the Gulf of Mexico and the south Laguna Madre. This time lag, or phase difference, set up a cross-barrier water level differential of up to 1.5 m. In this paper, we simulate the currents that could have resulted from storm surge, examine the regional variability in washover types, and discuss the interactions between the storm surge and island morphology.

Hurricanes as Geologic Agents

The importance of hurricanes as geologic agents has been recognized by many workers, and a number of excellent case studies exist in the literature (e.g., Hayes, 1967; Scott and others, 1969; McGowen and others, 1970; Nummedal and others, 1980). A general review of hurricane effects on the Texas coast was presented by McGowen and Scott (1975). Hurricanes are accompanied by torrential rains and high winds, but long term geologic effects are usually the result of the super elevated sea level known as storm surge. Surge height controls the extent of flooding, and permits higher breakers to be brought closer to shore, increasing the incident wave energy.

The sea level variation associated with hurricanes is governed by a number of independent factors, which can be broadly grouped as meteorologic, or those pertaining to a given storm, and geographic, or those relating to the area affected. Meteorologic parameters include the central pressure index (the ratio of pressure in the storm's center to that on its periphery), which causes the bulge-up of water called the "inverse barometer effect", and the frictional stress of the hurricane winds on the water surface, which results in a set-up at the coastline. These factors are functions of a storm's size, intensity, overwater duration, and angle of approach (Simpson and Riehl, 1981).

A given hurricane will produce greatly different surge heights depending upon where it makes landfall, primarily as a result of shoaling of the surge on the continental shelf, and local shoreline configuration. Embayed coastlines will experience a greater surge than open, straight coasts, and broader continental shelves produce greater surges in their corresponding land areas that narrower ones. Figure 2 shows the magnitude of this "shoaling factor" for the Northwestern Gulf of Mexico

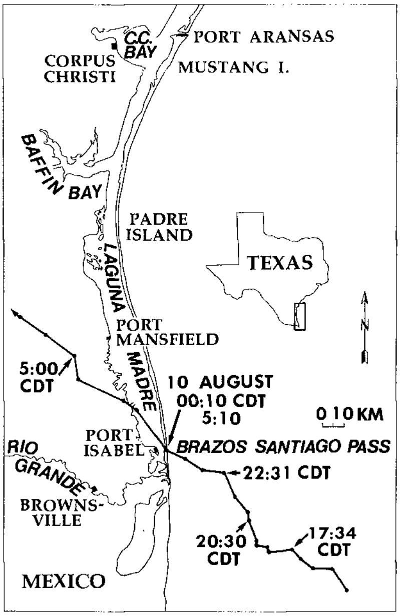

Figure 1. Plan view of Padre-Mustang Barrier Island System along the South Texas coast, northwest Gulf of Mexico. Also shown is the track of Hurricane Allen as it approached landfall (radar data from National Weather Service).

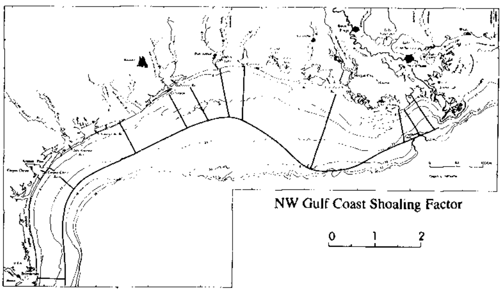

Figure 2. Distribution of the hurricane surge shoaling factor along the northwest coast of the Gulf of Mexico (after Jelesnianski, [1972]).

(Jelesnianski, 1972). From this, it can be seen that a landfalling hurricane will produce a considerably higher surge off the western Louisiana coast than at South Padre Island, Texas.

Superimposed on the storm surge are the effects of astronomical tides and wave set-up. Wave set-up is the nearshore water super elevation produced by the shoaling and breaking of a wave train. These factors combine to produce the actual storm tide (after Coastal Engineering Research Center, 1973). In some areas, wave set-up and/or astronomical tides can be of great significance, but in the northwestern Gulf of Mexico, storm surge is overwhelmingly dominant for large storms. Values given in this paper refer to actual storm tide levels.

Studies of hurricanes on the Gulf coast have led to a general geological effects model for storm impact, separating storm processes and coastal responses in chronological order (Hayes, 1967; McGowen and others, 1970; Nummedal and others, 1980). Storm approach is accompanied by rising waters, waves and wind, which attack the barrier islands, resulting in dune erosion, island breaching, and deposition of washovers on the surge flood. The counterclockwise circulation of the storm (Figure 3) causes the greatest energy to be concentrated in the right front quadrant. Thus, surge heights and storm effects are always greatest north of landfall. As the storm moves onshore, wind shifts produce changes in currents south of the eye, and modification of flood deposits begins. Storm aftermath is marked by the surge ebb, as well as high rains inland.

Storm Tide of Hurricane Allen

Hurricane Allen deviated somewhat from the generalized pattern discussed above. Allen became a hurricane in early August of 1980. While still in the Caribbean Sea, it achieved a central pressure of 899 mb, making it the second strongest Atlantic hurricane on record (an unnamed storm in 1935 attained a central pressure of 892 mb; U.S. Army Corps of Engineers, 1980). Once in the Gulf of Mexico, Allen headed more or less directly for the south Texas coast.

The U.S. Army Corps of Engineers maintains a network of continuously recording tide gauges, as well as surge and crest gauges, along the coast of Texas. Figure 4 shows the distribution of Hurricane Allen's storm tides, as measured by surge and crest gauges, which record peak water levels. Highest open coast storm tide for Allen was slightly less than 3 m at South Padre Island, while the highest bay tides were over 3 m near Corpus Christi. In most plots of this type, the highest storm tides occur in bays or lagoons, where local funneling and wind stress in restricted basins are pronounced (Simpson & Riehl, 1981). Possibly Allen's storm tides may have been higher in the area between South Padre Island and Baffin Bay, but no readings exist for that stretch of coast.

The relatively diffuse nature of Hurricane Allen's surge contrasts sharply with the more peaked asymmetric pattern of the storm tide of Hurricane Carla in 1961 (Figure 4). Carla was a large, intense storm and produced the highest storm tides ever measured on the Texas coast, almost 4 m. The more intense surge felt to the north of landfall is a pattern typical of a direct approach. The diffuse pattern of Allen's surge can be explained in terms of the offshore stallout and subsequent weakening of the storm, as well as the lower data density.

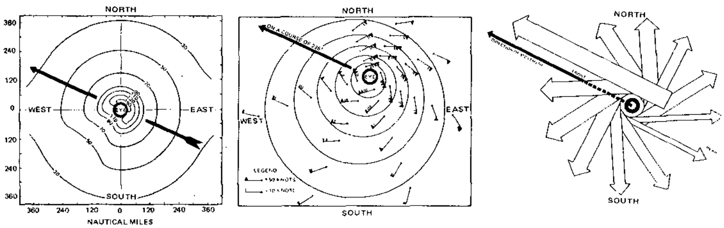

Figure 3. Distribution of pressure, surface winds, and waves within a typical northern hemisphere tropical storm (from Crutcher and Quayle [1974]).

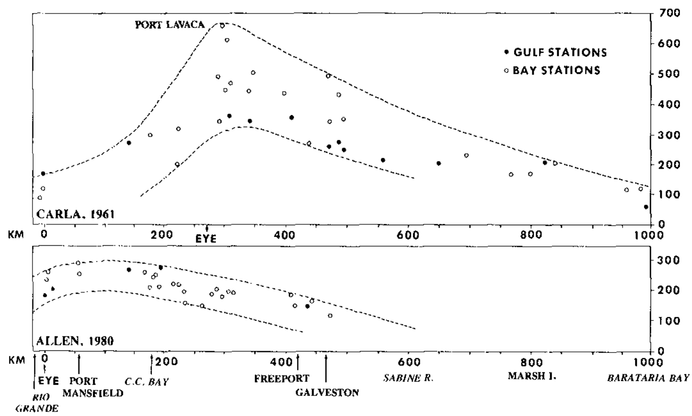

Figure 4. Distribution of observed maximum storm tides along Texas coast for Hurricanes Allen and Carla. Note the peaks occur to the north (or east) of landfall, and that bay tides are much higher than on the open Gulf. Data from Harris (1963) (Carla) and U.S. Army Corps of Engineers (1980) (Allen).

As the storm neared the Texas coast, it stalled offshore for over 24 hours before making landfall (Figure 5). During this time, the storm weakened considerably. Central pressure had risen to 945 mb just before landfall. As a result, the storm surge flood stage was considerably prolonged and diffused.

Early in the morning of August 10, Allen moved onshore just north of Brazos Santiago Pass on South Padre Island, thus spending most of its energy on the least populated stretch of the Texas coast. The major effects of the storm on Padre Island can be understood by a consideration of the regional and local geology.

Regional Geology of the Texas Coast

The southernmost links in the Texas barrier island chain are Mustang and Padre Islands (Figure 1). Taken as a whole, from Aransas Pass in the north of Brazos Santiago Pass in the south, over 200 km of unbroken barrier island faces the Gulf of Mexico. At one time, the two islands were separated by a series of inlets at the southern end of Corpus Christi Bay. Most stable tidal inlets on the Texas coast are located at the southeastern tip of the estuarine basin, where their positions are maintained by north winds during frontal passage. However, deepening of Aransas Pass in the 1920's to accomodate shipping to the Port of Corpus Christi diverted enough of the tidal flow to result in the choking off of the Packery Channel/Corpus Christi Pass inlets (Price and Parker, 1979). Presently, tidal exchange between the Gulf and estuaries in this area occurs only at the northern and southern extremes, and through two shallow artificial cuts, Mansfield Pass in Central Padre Island and Corpus Christi Fish Pass in Mustang Island.

The Padre-Mustang barrier system creates and maintains the extensive Corpus Christi Bay and Laguna Madre estuarine complex. Corpus Christi Bay occupies the valley of the Pleistocene Nueces River, while the linear Laguna Madre lies on a drainage divide. Both are actively infilling with sediment; the process being more apparent in the shallow lagoon, which averages less than one meter in depth and is in fact often emergent in its central reaches. This difference in back barrier basin morphology produces significant variations in hurricane responses.

The Padre-Mustang Barrier system itself displays a north-south morphologic dichotomy. Mustang, North, and Central Padre Islands are relatively broad, high-profile features with continuous foredune ridges of up to 10 m. In the vicinity of Mansfield Pass, island topography changes to a narrow, lower profile with poorly developed, discontinuous foredunes. Morton (1977, 1979 b) showed that regional variations in barrier island types could be correlated with positions relative to deltaic headlands. Near the deltas, thin, transgressive, low profile barriers occur; while within the interdeltaic embayments, thicker, broader, high profile barrier islands are formed (Figure 6). The regional distribution of erosional and stable landforms shown in Figure 7 can be explained by envisioning that wave refraction around deltaic headlands would produce cells of longshore drift convergence in the embayments. Throughout the Holocene, the decreased delivery of coarse sediments has combined with the wave energy concentration at the headlands and compactional subsidence of deltaic deposits to produce headland erosion. Longshore drift convergence concentrated sand in the embayments, producing the accretionary high profile islands. Today, the process has effectively straightened

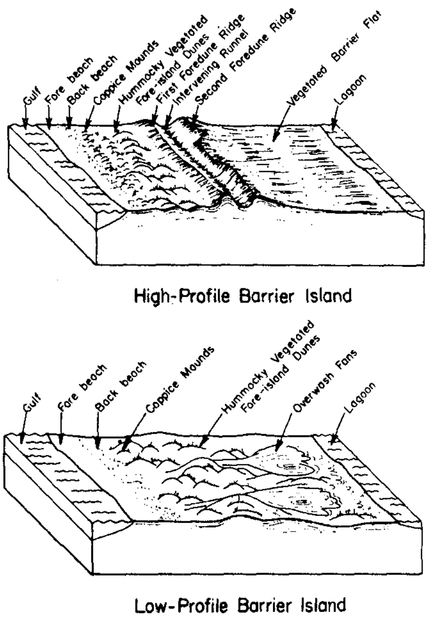

Figure 5. Diagram of high- and low-profile barrier island types. Mustang and North Padre Islands are high profile, while South Padre Island is low-profile, and thus more vulnerable to hurricane washover (from White and others, 1978).

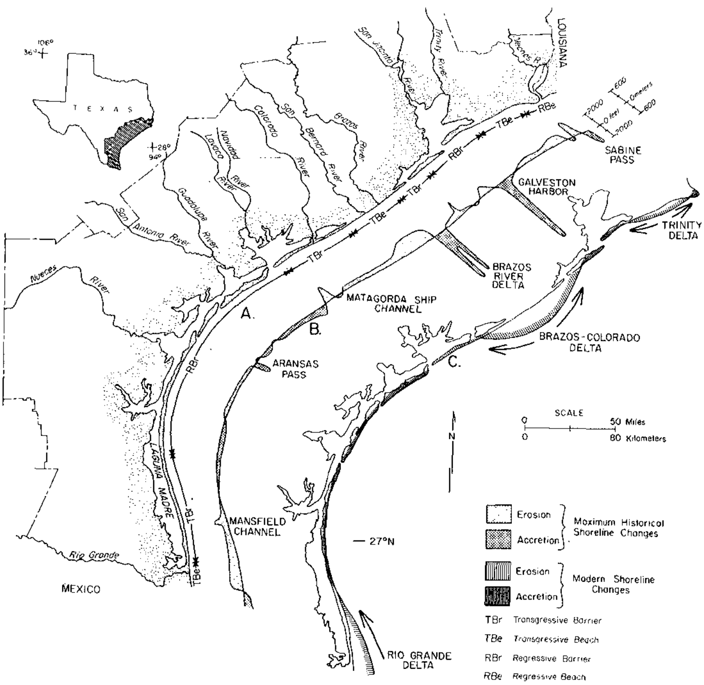

Figure 6. Maps showing (A) morphogenic provinces of the Texas coast, (B) maximum shoreline changes between 1850-83 and 1973-75, and (C) hypothesized late Holocene shoreline showing major promontories and long-shore drift cells. Maximum rates of erosion and low profile barriers occur near deltaic headlands, while accretion and high profile barriers occur in embayments. Longshore drift convergence is now in the area of 27° N. From Morton (1979b).

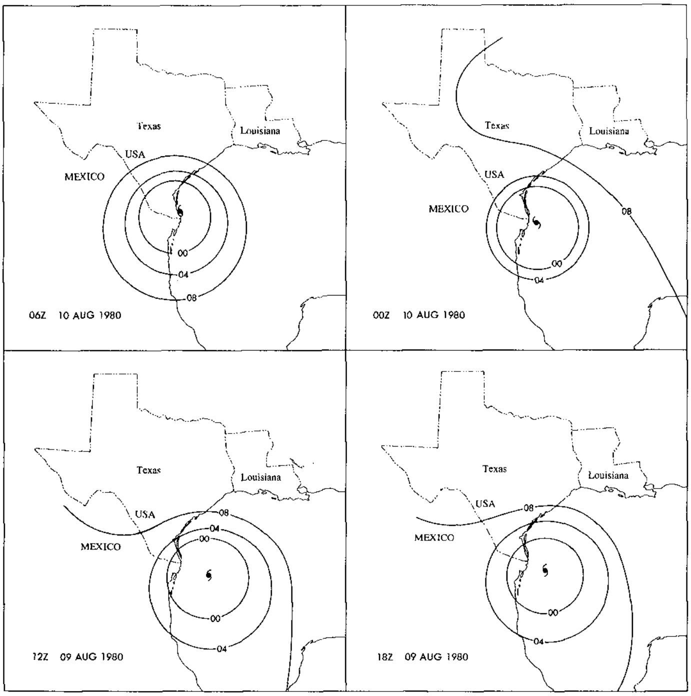

Figure 7. Series of simplified weather maps showing leisurely approach and weakening of Hurricane Allen offshore as it made landfall (data from National Weather Service).

out the Texas Gulf shoreline, and the pattern of drift has changed, converging now on Central Padre Island.

South Padre Island formed on an abandoned lobe of the Holocene Rio Grande Delta (Brown and others, 1980) while Central and North Padre and Mustang Islands formed in the embayment between the Rio Grande and Brazos-Colorado deltas (Brown and others 1976, 1977). South Padre is actively eroding (Morton, 1977) while the remainder of Padre and Mustang Islands are stable, owing to the current longshore drift convergence pattern. This contrast between the island types is well displayed by their response to Hurricane Allen.

Storm Surge Simulations

In the immediate vicinity of landfall, continuous recording tide gauges at Cameron Pier on the Gulf side and Gulf Intracoastal Waterway Marker 75 in Laguna Madre showed marked differences in water level response (Figure 8a). Significant and continuous rise in water levels began on late August 8th on the Gulf side, but lagoonal waters rose some 14 hours later. This time lag, or phase difference in the gulf and lagoon surges, is attributed to the southward directed cyclonic winds of the hurricane piling waters toward the southern outlet at Brazos Santiago Pass. Once Gulf water levels exceeded 1 m, washover of South Padre Island began, causing the lagoonal water levels to begin rising. Peak water in Laguna Madre exceeded 2.5 m before the shift in winds as the hurricane made landfall drove the waters back through hurricane channels.

Similar measurements taken at Brazos Santiago Pass to the south and at Aransas Pass to the north do not display this pattern (Figures 8b, c). There, Gulf and lagoonal surges are in phase. The set-up of water at the south end of Laguna Madre and the passage of surge waters through the inlet at Brazos Santiago combined to produce the in-phase measurements recorded there. Corpus Christi Bay has a considerably different morphology than Laguna Madre, and experienced lesser winds due to its distance from landfall.

The time lag between Gulf and lagoonal surges on the rising storm tide suggests that gravity-driven currents may have been quite strong once breaching of the island occurred. Figure 9 shows simple current velocity simulations derived from the surge level differentials using the Manning equation.

The roughness factor, n, is assumed to be 0.03, the value given by Chow (1959) for sandy streams, and also the average of that measured by Watson and Behrens (1976) during tidal current measurements in the newly dredged Corpus Christi Fish Pass. Barrier width is set at 900 m, we assume that the entire water level differential corresponds to the drop across the barrier, and lagoonal water levels are assumed to be horizontal.

Flow regime 1 simulates the currents for unconfined sheet overwash, with a flow depth of 30 cm. Velocities increase during the rising storm tide, peaking at 55 cm/sec at midnight August 8, and persisting for almost 24 hours. This period should represent the time of most active transfer of Gulf water into Laguna Madre. Due to the lesser elevation differentials, ebb velocities are generally slower, peaking at 46 cm/sec, and shorter lived.

Since a very large number of hurricane channels were cut across

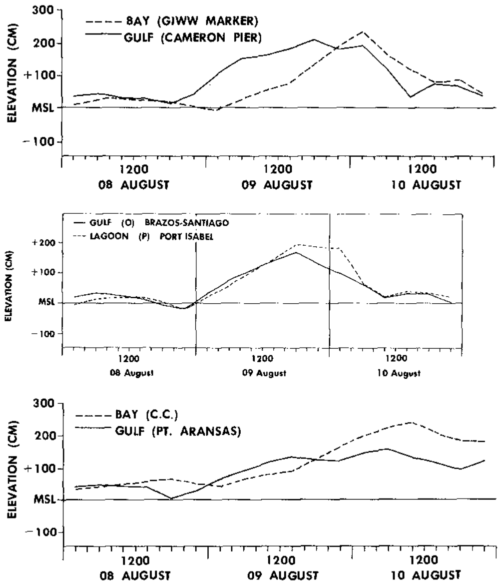

Figure 8. Time series of water surface elevations during impact of Hurricane Allen on south Texas coast, taken from continuous recording tide gauges. A) South Padre Island, B) Brazos Santiago Pass, C) Aransas Pass and Corpus Christi Bay. See Figure 1 for locations.

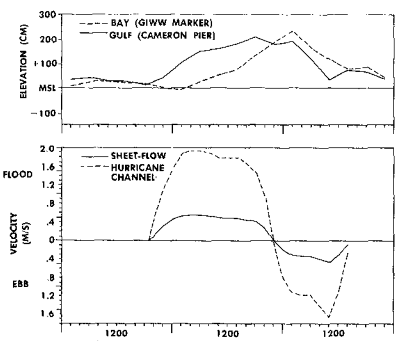

Figure 9. Current velocity simulations for flow across South Padre Island, based on Manning equation. Data from Figure 8A. Flow Regime 1 is for 30-cm deep sheet overwash; Flow Regime 2 refers to 2-m deep hurricane channel.

Padre Island, perhaps a more realistic picture is given by flow regime 2, which corresponds to flow in a confined hurricane channel of 2 m depth. Calculated velocities, as expected, are much higher. During surge flood, a strong lagoonward current of up to 1.92 m/sec persists for almost 24 hours. Maximum simulated ebb velocities reached 1.62 m/sec as surge waters returned to the Gulf.

These simulations represent the simplest case, and refer only to gravity driven currents. More sophisticated techniques should include consideration of wave pump (Bruun and Kjelstrup, 1979) and wind stress. Morton (1979 a) analyzed back barrier bedforms, and estimated wind driven currents in the range of 1.3 to 1.9 m/sec, very similar to those calculated here. The interaction of such intense currents produces the complex patterns of sediment dispersal seen on the back barrier flats.

Greater surge flood currents and the longer duration of the flood versus the ebb cast light on the timing of island breaching. The morphology of hurricane deposits on the back barrier clearly indicates that they are laid down on the surge flood, so it is likely that most of the breaches are initiated on the seaward side of barriers. However, breaches are also known to have occurred from the back side on surge ebb currents as shown by the opening of Pass Drury, Alabama after Hurricane Frederic in 1979 (Nummedal and others, 1980).

Another problem lies in the origin of widespread coarse grained deposits on continental shelves known to occur after major storms. Hayes (1967) suggested that these sediments were deposited by density currents in the ebb surge out of hurricane channels, while Morton (1981) contended that wind induced shoreface bottom return flow (Csanady, 1976; Swift, 1976) was responsible. The morphology of South Padre Island washovers indicate that there was a moderate amount of seaward sediment transport during the storm surge ebb. Current measurements during earlier storms (Forristal and others 1977; Murray, 1970) indicate that seaward shoreface currents peak before or during lamdfall. Therefore, we suggest that both mechanisms provide sediment for the inner shelf graded storm beds.

Washover Channels

The north-south dichotomy of form of the Padre-Mustang system is well illustrated by Figure 10, which shows the location and number of hurricane washover channels cut across the island by Hurricane Allen. Mapping of the channels was done primarily from high altitude photographs taken by NASA ten days after landfall.

Clearly, the vast majority of the breaches occurred along the southern portion of the barriers, due both to the proximity to the point of landfall and the low profile nature of South Padre Island. Surges of over 2 m were experienced all along the barrier system, but foredune height and ridge continuity prevented breaching in the higher profile segments further north.

The abrupt disappearance of washover channels on the northern section of the system is difficult to explain fully, but relates to a gradual transition to a continuous foredune ridge from south to north, and to the resolution of the 10 km sampling interval. Sudden reappearance of major channels at 170 km is due to re-opening of the old tidal inlets that once separated the two islands.

Spacing of the channels presents intriguing problems. Most workers

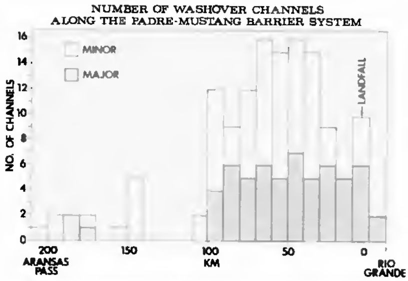

Figure 10. Locations of hurricane channels cut across Padre-Mustang Barrier System by Hurricane Allen. Major channels are those cut below mean sea level, minor channels are less deep.

Figure 11. Vertical aerial photograph showing irregular periodicity of washover channel spacing on Central Padre Island (photo taken 8/20/80).

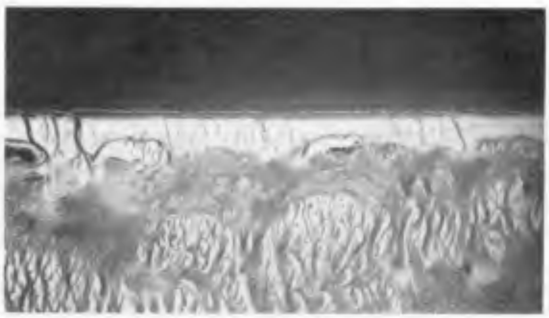

Figure 12. Vertical aerial photograph of washover terrace on South Padre Island, fed by multiple minor and major channels. Note regular channel spacing (photo taken 8/20/80).

attribute locations of washovers to island topography, but there is certain periodicity to the location of the channels within the heavily breached southern area. A series of major washover channels spaced approximately 2.5 km apart begins abruptly at 100 km, coinciding almost exactly with the beginning of the emergent portion of the Laguna Madre. Periodicity also exists in the spacing of minor washover channels in some areas (Figure 12).

This suggests the possibility that some surf zone phenomenon may be enhancing surge levels at regular intervals, and controlling or contributing to location of island breaching, as suggested by Dolan and Hayden (1981). This argument is complicated by the fact that the position of breaches is largely inherited from previous storms. Locations of Hurricane Allen channels coincide with those cut by Hurricane Beulah in 1967. It appears that periodic phenomena are operating, but that pre-existing topography also determines washover location.

Morphology of Washovers

Surge height elevation and barrier geometry not only control the number of hurricane breaches, but also the form of the resulting washover deposit. A variety of washover deposits were laid down by Hurrican Allen. Their type and location can be systematically related to geomorphologic characteristics of the barriers.

Along the higher profile portions of Mustang and Padre Islands, surge heights were insufficient to breach the foredune ridge. Minor discontinuities, such as aeolian blowouts, were attacked and relatively small, discrete interdune fans were deposited (Figure 13). Locally, interdune fans were laid down at two different levels as the storm surge rose, creating a double washover contained within the foredune ridge. Other examples of interdune fans occurred in areas of South Padre with extensive back island fields.

At the other end of the spectrum, washover terraces occurred in areas where the foredune ridge is discontinuous to absent (Figure 12). On south Padre Island, a continuous washover terrace is created by coalescing washover deposits fed by numerous hurricane channels. This contrasts with other examples of such deposits which are generally the result of sheet overwash, such as can be found along other low profile barriers of the Texas and Louisiana coasts (Morton, 1979 a; Boyd and Penland, 1981).

Where the foredunes are extant but discontinuous, channelization of surge resulted in the cutting of major hurricane channels which deposit the washover fan (Figure 14). These washovers are an order of magnitude larger than interdune fans, and are a major features. The form and thickness of the washover fan is determined by the relationship between surge strength and water depth within the back barrier basin. Those deposits laid down by Hurricane Allen have considerable variability in detail, but all are more or less heart shaped owing to flow onto the broad, low gradient back barrier flats of Central and South Padre Islands. Figure 14 approaches the ideal form of such features. Nowhere on Padre Island were any flame shaped washovers (Morton, 1979; Nummedal and others, 1980) seen. These have been reported from the Matagorda Peninsula of Texas (Morton, 1979 a) and Dauphin Island, Alabama (Figure 15; Nummedal and others, 1980). In both of these cases, there was considerable water depths in the back barrier basin at the time of breach-

Figure 13. Oblique aerial photograph of small interdune fan deposited within dune ridge on Mustang Island (photo taken 8/20/80).

Figure 14. Vertical aerial photograph of washover fan fed by major hurricane channel on South Padre Island. Dunes create channelization of flow (photo taken 8/20/80).

ing. As the surge waters crossed the barriers and encountered the deeper water, a hydraulic jump occurred, and the flame shaped washovers were deposited. Lack of these features on South Padre Island is attributed to much different morphology of the back barrier and the shallower Laguna Madre.

The last major washover type was of limited extent due to its specialized nature. The reactivated tidal delta occurred only in the area of juncture between Mustang and Padre Islands, where major breaks in the foredune ridge are located in the choked off tidal inlets (Figure 16). These deposits are the largest washovers laid down by Hurricane Allen, and actually represent modifications of pre-existing flood tidal delta deposits. As such, they would be very difficult to distinguish as washovers in ancient deposits. However, they are illustrative of the fact that interdune fans are not the only type of hurricane deposit that can be expected in high profile barrier islands. Indeed, deposits of this type may be the most significant stratigraphically. Examination of barriers along the Texas coast reveals an extensive series of large, arcuate forms on the back sides of barriers which probably represent washover modified flood tidal deltas (Andrews, 1970). Differences in older and younger deposits no doubt reflect variations through time in island morphology and storm intensity and numbers.

Summary and Conclusions

Hurricane Allen's impact on the south Texas coast confirmed many of the previous concepts of geologic effects of hurricanes on barrier islands. Aerial photography and ground observations revealed that four main types of washover deposits occurred: interdune fans in areas with continuous foredunes, washover terraces in areas with few foredunes, washover fans in areas where the foredune ridge is discontinuous, and reactivated tidal deltas in relict tidal inlets. A number of factors control the form and location of the washovers including storm surge height, barrier island topography and geometry, position relative to storm landfall, and water depth in the back barrier basin. Further analysis may reveal the existence of periodic phenomena interacting with these factors to control washover location. The relationships cannot be easily quantified, but can be easily understood conceptually and applied by coastal planners, engineers, and geologists.

In closing, it is worth mentioning that effects of hurricanes on barrier islands is a subject of increased importance in the years ahead. If there is indeed a secular warming trend caused by inceased CO_2 levels in the atmosphere (Hansen and others, 1981), it can be expected that hurricanes will increase in both number and intensity (Nummedal, 1982). Such increases, coupled with rising sea levels accompanying the global warming and the major population shift to coastal areas, would make the prospect of major hurricane problems in the future a gloomy one indeed.

Figure 15. Vertical aerial photograph of reactivated tidal deltas in Corpus Christi Pass-Packery Channel area between Mustang and Padre Islands (photo taken 8/20/80).

Figure 16. Vertical aerial photograph of flame shaped washovers, Dauphin Island, Alabama, formed during Hurricane Frederic in September, 1979.

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