BUREAU OF ECONOMIC GEOLOGY
The University of Texas
Austin, Texas 78712

Peter T. Flawn, Director

Report of Investigations—No. 61

Hurricanes as Geological Agents: Case Studies of Hurricanes Carla, 1961, and Cindy, 1963

By

Miles O. Hayes

August 1967
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Miles O. Hayes[1]

ABSTRACT

Tropical storms, which cross the Texas coastline with a frequency of 0.67 storms per year, play a major role in nearshore sedimentation on the south Texas coast. Greatest geological effects of these storms are produced by wind-driven waves and by storm surges.

The comparison of a part of the near-shore environmental complex of a segment of the south Texas coast before and after hurricane *Carla,* 1961, shows the effects of the storm. The bottom of the inner neritic zone was both a contributor and a receiver of hurricane deposits. As the storm moved landward, it picked up mollusc shells, rock fragments, coral blocks, and other materials from depths as great as 50 to 80 feet and deposited them on the barrier island. After the storm passed inland, strong currents spilled out of the numerous hurricane channels cut into the island by the storm-surge flood. These currents deposited a thin layer (0.5 to 1.5 inches) of sand over what was previously sandy mud bottom out to depths of 60 feet and a graded layer of fine sand, silt, and clay (a *turbidite*) farther out on the shelf. The storm removed a belt of foredunes 20 to 50 yards wide from the seaward side of Padre Island and left the foredune ridge with wave-cut cliffs up to 10 feet high. The formation of a broad, flat *hurricane beach* drastically altered the beach profile. The landward side of the barrier island (Wind-tidal flats) received much washover material containing surf zone and beach molluscs. The storm also submerged high-level mud flats along the landward side of Laguna Madre and covered them with a fresh layer of mud. A much milder storm (*Cindy*) passed through the area in September 1963, and a small swash bar was deposited over the seaward edge of the pre-existing *hurricane beach.*

Some important stratigraphic implications of these observations include: (a) Hurricanes can mix environment-sensitive faunas from a variety of environments into a single sedimentary deposit; (b) hurricanes can play a primary role in sediment transport in nearshore environments; (c) hurricanes displace sedimentary processes such that sediment textures and structures normally related to a particular process (e.g., fluvial channel flow) may occur in alien areas; and (d) a great deal of energy is expended sporadically in nearshore environments rather than in a uniform, constant manner.

INTRODUCTION

On September 7, 1961, hurricane *Carla,* one of the largest North Atlantic hurricanes of the century, passed through the Yucatan Channel and entered the Gulf of Mexico. The storm eventually crossed the coastline near Port O'Connor, Texas, on the afternoon of September 11. Inasmuch as the Writer had begun a study of the Recent sediments in the vicinity of central Padre Island, Texas, the occurrence of the hurricane presented a unique opportunity to evaluate catastrophic storms as geological agents.

During the two years following hurricane *Carla,* the study area (fig. 1) was revisited numerous times, the offshore area

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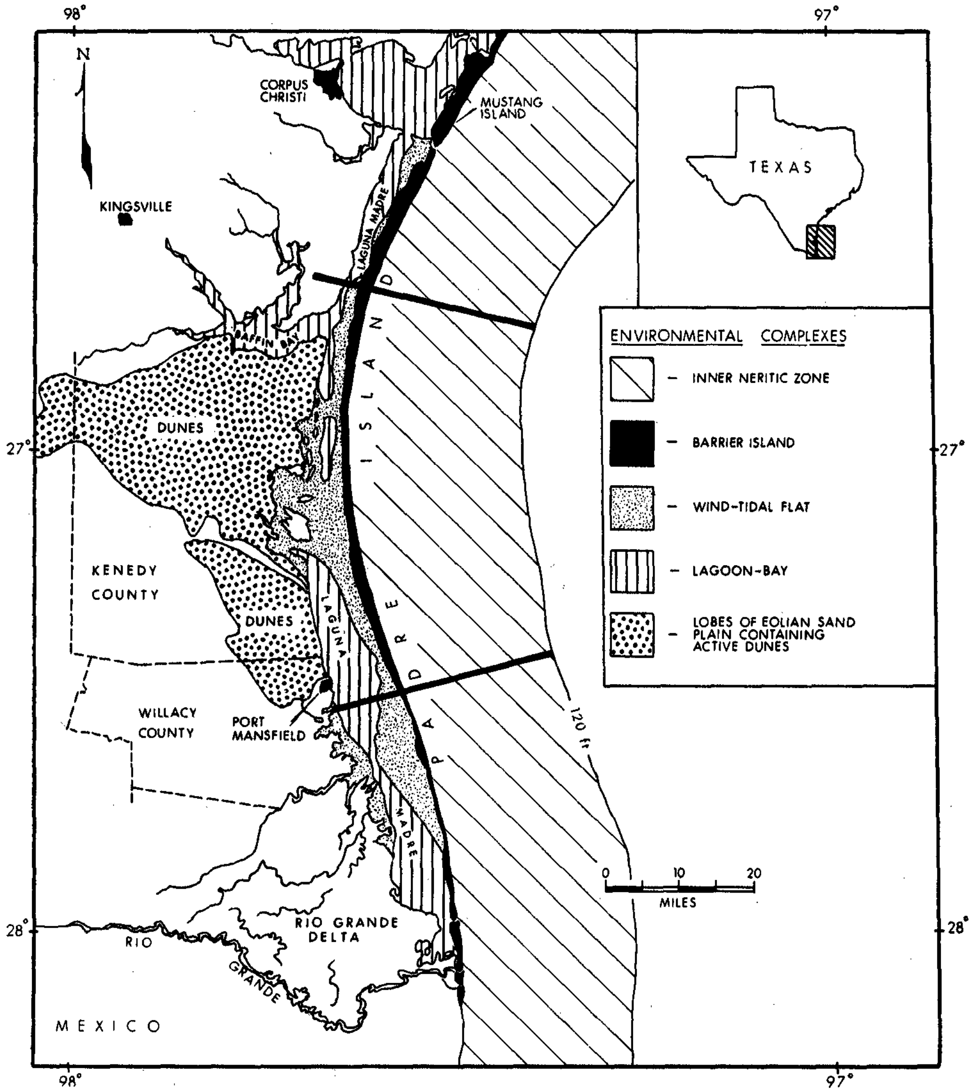

FIG. 1. Index map of major nearshore sedimentary environmental complexes of the South Texas coast. Major complexes include inner neritic zone (0 to 120-foot depth), barrier island complex, wind-tidal flats, lagoon-bay complex, and sand lobes of eolian sand plain containing active dune fields. Detailed study was limited to area bounded by heavy lines.

was completely resampled, and observations were made during all seasons of the year. In September of 1963, hurricane *Cindy,* a relatively mild storm, passed through the area and its geological effects were also recorded.

Observations of the effects of these two storms are presented in this report to emphasize the fact that catastrophic storms play a very important role in nearshore sedimentary processes, and that they leave an indelible record in the sediments. It is hoped that evidence presented here may lead to recognition of storm deposits in the rock record.

This report is based on a Ph.D. dissertation in the Department of Geology of The University of Texas under supervision of Professor Robert L. Folk. A. J. Scott, E. F. McBride, and W. A. Price made many helpful criticisms throughout the study. The field assistance of Reece Brown, laboratory assistance of Clyde Seewald, and photographic work of David Hagar are gratefully acknowledged. Field work was conducted under the sponsorship of the Institute of Marine Science in Port Aransas, Texas. Financial support for various phases of the work was provided by the American Association of Petroleum Geologists (grant-in-aid of research), Pan American Petroleum Foundation (fellowship), and Sun Oil Company (field support).

Tropical cyclones.—Technically, a hurricane is "a storm of tropical origin with a cyclonic wind circulation (counter-clockwise in the Northern Hemisphere) of seventy-four mph or higher" (⩾ 12 on Beaufort scale) (Dunn and Miller, 1960, p. 9). The hurricane is the North Atlantic member of the tropical cyclone family that includes the typhoon of the western North Pacific, the cyclone of the northern Indian Ocean, and the willy-willy of Australia (Tannehill, 1956). Tropical cyclones are the most powerful and destructive of all storms (Dunn and Miller, 1960; Tannehill, 1956). Tornadoes have higher wind velocities (central axis velocities may attain 400–500 mph), but tropical cyclones are also intense (winds may reach 150–200 mph) and cover a much larger area. At one stage, hurricane *Carla's* circulation enveloped the entire Gulf of Mexico and fringe effects were felt by all Gulf Coast states (Cooperman and Sumner, 1962).

Tropical cyclones occur in the North Atlantic, the area of concern in this report, with a frequency of approximately 7.5 per year and occur most often during the months of August, September, and October. The season of maximum occurrence of tropical cyclones corresponds roughly to the time when the ITC (intertropical convergence zone, or equatorial trough) has its maximum divergence from the equator.

Inasmuch as tropical cyclones originate above a restricted portion of the earth's surface, any evidence of these storms found in ancient sediments could possibly be used for paleo-latitude interpretations. In order to get quantitative information on the latitudes that tropical cyclones frequent, U. S. Weather Bureau records for the North Atlantic (1900–1963) and U. S. Navy records for the western North Pacific (1958–1962) were consulted. The data were treated two ways. One method was to count every storm that occurred within 5-degree latitude intervals (during the years stipulated). This was done by visual inspection of hurricane (or typhoon) tracks on the maps in the U. S. Weather Bureau Summaries. Thus, a single storm was often counted several times, but it was counted only once for each 5-degree interval. These results are given in table 1 and

TABLE 1.—*Tropical cyclone occurrence and land crossings (by latitude) for North Atlantic and western North Pacific.*

	North Atlantic (1900—1963)			Western North Pacific (1958—1962)		
	Hurricane passed through	Hurricane crossed major land mass*		Typhoon passed through	Typhoon crossed major land mass*	
Latitude	(% of total)	No.	Percent	(% of total)	No.	Percent
5–10° N.	0.0	0	0.0	3.7	1	1.2
10–15° N.	4.6	5	2.3	11.1	10	12.2
15–20° N.	13.4	35	15.8	20.9	6	7.3
20–25° N.	18.6	47	21.2	22.7	23	28.1
25–30° N.	23.9	70	31.5	17.0	10	12.2
30–35° N.	17.3	48	21.6	12.0	15	18.3
35–40° N.	11.9	6	2.7	7.6	12	14.6
40–45° N.	8.1	8	3.6	3.9	5	6.1
45–50° N.	1.7	2	0.9	0.8	0	....
50–55° N.	0.3	1	0.5	....	0	....
55–60° N.	0.1	0	....	....	0	....
Total	....	222	....	....	82	....

* Same storm may be counted more than once.

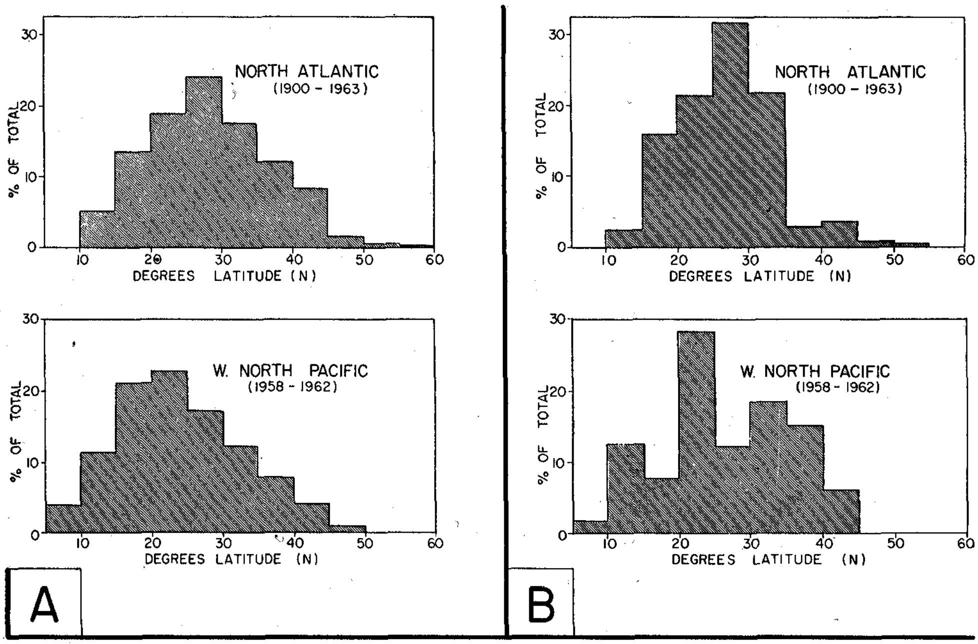

FIG. 2. A. Occurrence of tropical cyclones (by latitude) in the North Atlantic for the period of 1900–1963 and in the western North Pacific for the period of 1958–1962. The North Atlantic median is 28° N. and the western North Pacific median is 23° N.

B. Latitudes in which tropical cyclones (hurricanes and typhoons) crossed major land masses in the North Atlantic during 1900–1963 (upper) and the western North Pacific during 1958–1962 (lower). The upper diagrams for both A and B are based on annual summaries of North Atlantic tropical cyclone activity by Cry, Haggard, and White (1959), Cry (1960, 1961), and Dunn and staff (1964). The lower diagrams are based on annual summaries of the western North Pacific tropical cyclone activity by the U. S. Navy (1958, 1959, 1960, 1961, 1962).

in the histograms in figure 2A. Twentieth-century North Atlantic hurricanes (fig. 2A) occurred in latitudes extending from 10° to 55° N., with a median value of 28° N. The histogram of figure 2A (lower) indicates that western North Pacific typhoons occurred in lower latitudes than North Atlantic hurricanes; however, this is partly, if not entirely, due to the fact that the tropical storm stage was not distinguished from the typhoon stage on the Pacific weather maps. Western North Pacific typhoons (1958–1962) occurred from 5° to 50° N., with a median value of 23° N. Another method of treating the latitude data was to plot the localities (by latitude) where hurricanes and typhoons crossed major land masses.[2] These results are given in table 1 and figure 2B. North Atlantic hurricanes scored 222 hits on major land areas during this century, and the latitudinal distribution of these localities (fig. 2B, upper) is very similar to the latitudinal distribution of all hurricanes (fig. 2A, upper). Western North Pacific typhoons struck major land areas 82 times during the period of 1958–1962. The distribution of these areas (fig. 2B, lower) is not uniform throughout, however, because of the unequal land-mass distribution in the western North Pacific. For example, the low number of hits in the 25°–30° interval is due to the absence of any major land mass in the area except the north-south-trending China shoreline, which provides a small target for the northward-traveling typhoons. In summary, the distribution of tropical cyclones in the Northern Hemis-

[2] Major North Atlantic land areas included in the tabulation were North America, Central America, Cuba, and Hispaniola. Western North Pacific land areas counted included southeast Asia, Formosa, Philippines, and Japan.

phere is such that land areas lying between 20°–30° N. will be struck most frequently. Limits of occurrence lie between approximately 10° N. and 45° N. Therefore, if the occurrence of tropical storms can be recognized in the rock record and other substantiating climatic evidence is present, inferences can be made about paleo-latitudes. This conclusion will probably be received with some skepticism by residents of Ireland, whose shores were visited by hurricane *Debbie* in 1961 (winds > 100 mph), and by residents of New England, where two severe hurricanes (*Edna* and *Hazel*) occurred in 1954. However, of the 10 hurricanes that passed inland north of 40° during this century, six occurred since 1950. Thus, the past fifteen years has been an unusually severe period for hurricane activity in the higher latitudes.

A thorough discussion of the origin and meteorological aspects of tropical cyclones is beyond the scope of this report. An introduction to this topic, which has been the subject of many recent papers and texts, may be obtained by consulting the following references: Palmén (1948), Riehl (1954, 1963), Thuronyi (1956), Nupen and Rigby (1956), Tannehill (1956), Dunn and Miller (1960), Kasahara (1961), Yanai (1961), La Seur (1962), and Landers (1962). However, those aspects of tropical cyclones and associated phenomena that produce greatest geological effects in nearshore sedimentary environments—storm surges, waves, and currents—are briefly discussed, focusing attention primarily on North Atlantic hurricanes.

Storm surge.—Not only is the *storm surge,*[3] or storm tide, the "primary cause of death and property damage in a hurricane" (Freeman, Baer, and Jung, 1957, p. 12), but it is also the characteristic of hurricanes most responsible for making them important geological agents. The rise in water level brought about by hurricanes inundates vast areas of low-lying coastal regions, producing widespread erosion and deposition of nearshore sediments.

The two most important factors in the generation of storm surges are the stress of wind on the sea surface (sometimes called wind set-up) and reduction of atmospheric pressure, or inverted barometer effect. Winds of North Atlantic hurricanes have frequently reached velocities of 100 to 135 mph and a few have attained 200 mph (Dunn and Miller, 1960). The width of the path of a single storm may sometimes extend 200 to 300 miles. These factors, combined with the fact that a storm may last for several days, give hurricanes the ability to pile up tremendous quantities of water against the coastline. Several other factors, such as shoreline configuration and shape and slope of continental shelf, may also tend to accentuate, or modify, the storm surge. Thorough discussions of the storm surge can be found in the following references: Pore (1961), Harris (1958, 1963), Freeman, Baer, and Jung (1957), Dunn and Miller (1960), Wilson (1960), and Bretschneider (1963).

Data on maximum storm surges in the Gulf of Mexico were compiled by Conner, Kraft, and Harris (1957) for the period of 1893–1950. They found that during that period storm surges of ten hurricanes had a maximum height of 10 feet or more on the *open coast,* with a maximum tide of 14.8 feet occurring at Matagorda, Texas, during the 1942 hurricane. Tides are usually higher in the bays than on the open coast, and 15 feet was exceeded during several storms. The maximum tide recorded on the Gulf Coast (to the writer's knowledge) was the 22-foot maximum that occurred in the bay at Port Lavaca, Texas, during hurricane *Carla,* 1961.

Waves.—Probably the most spectacular geological effect of hurricanes is the erosion produced by breaking waves. A cubic yard of water weighs about three-fourths of a ton, and a breaking wave may move forward at speeds up to 50–60 mph (Dunn and Miller, 1960). Their erosive effects are greatly increased when they ride the crest of a large storm surge, because much

[3] The *storm surge* is "the rise or fall of the sea level caused by a meteorological disturbance" (Pore, 1961, p. 151). As used here, it refers to the hurricane surge, or "a rapid rise in the water produced by hurricane winds and falling barometric pressure," and other factors (Dunn and Miller, 1960, p. 207).

greater land areas are exposed to erosion. Some hurricane waves attain tremendous heights. "Forty to forty-five foot waves were reported by Coast Guard stations in New England during hurricanes *Carol* and *Edna* of 1954" (Pore, 1957, p. 385).

A study of deep water hurricane waves in the Gulf of Mexico was carried out by Wilson (1957). Using data for selected hurricanes from the 1900–1949 period (hindcast technique), he determined frequencies of occurrence of hurricane waves of specific significant heights for several deep water stations. Expected frequencies for a deep water (100 fathoms) station off Brownsville, Texas (closest station to study area) are as follows:

SIGNIFICANT WAVE HEIGHT (FEET)	APPROXIMATE EXPECTED FREQUENCY
10	once in 2 years
20	once in 5 years
30	once in 20 years
40	once in 50 years

Another type of hurricane wave, called *Raz de marée* by the French (Dunn and Miller, 1960), is sometimes associated with tropical cyclones. These waves, which are similar to *tsunamis* in that the wave is very large and is attended by a sudden water level rise, have nearly always accompanied the most severely destructive storms, such as, for example, the tropical cyclone in 1876 that produced a wave that drowned more than 100,000 people in Backergunge, India (Tannehill, 1956; Dunn and Miller, 1960).

Currents.—Sea conditions during hurricanes prohibit taking oceanographic measurements from a surface ship, so ocean currents generated by hurricanes are very poorly known. Some indirect evidence indicates that the strong winds associated with hurricanes set up appreciable currents. Tannehill (1956, p. 34) described the effects of currents generated by the Texas hurricane of 1915 as follows:

> . . . the current set up by the storm carried Trinity Shoals gas and whistling buoy nearly ten miles to the westward. This buoy weighed 21,000 pounds, and was anchored in 42 feet of water with a 6,500 pound sinker and 252 feet of anchor chain weighing 3,250 pounds.

Meteorological and oceanographic measurements were carried out by Japanese research vessels in neighboring vicinities of North Pacific typhoons in 1949 (Masuzawa, 1950). Changes in oceanographic conditions (discontinuous from surface to 200-m. depth) were caused by inflow of different water masses resulting from variation in the current systems accompanying the typhoons.

Breaking waves, especially those breaking obliquely to the shoreline, probably generate strong longshore currents during hurricanes. Timbers and pilings from Bob Hall fishing pier on northern Padre Island, Texas, which was completely destroyed by hurricane *Carla,* were found for many miles south along the beach after the storm.

Strong currents flow in hurricane channels cut into Texas coast barrier islands during the high-water stage of the hurricane surge. These currents are discussed in more detail in the section on hurricane effects on barrier islands (pp. 31–42).

Hurricane activity on Texas coast.—An analysis of the U. S. Weather Bureau annual summaries of North Atlantic tropical cyclone activity (summaries by Cry, Haggard, and White, 1959; Cry, 1960, 1961; Sumner, 1959; and Dunn and staff 1964) shows that the Texas coast has been host to 42 tropical cyclones during this century (1900–1963), an average of 0.67 per year. Fourteen of these were in the tropical storm[4] stage and 28 were in the hurricane stage at the time they crossed the coastline. Points of entry of these storms on the Texas coast are shown in figure 3B, which demonstrates that very little of the Texas coastline has escaped passage of the eye of at least one tropical cyclone during this century. Furthermore, it is probable that any given locality on the Texas coast was affected in some way by each of the 28 storms classified as hurricanes and was strongly affected by at least one-half of them. A histogram summarizing the number of tropical cyclones that passed

[4] Tropical storms are tropical dirturbances with closed isobars that have wind velocities of 38 mph or more (Dunn and Miller, 1960). If the winds exceed 74 mph, the tropical storm becomes a hurricane.

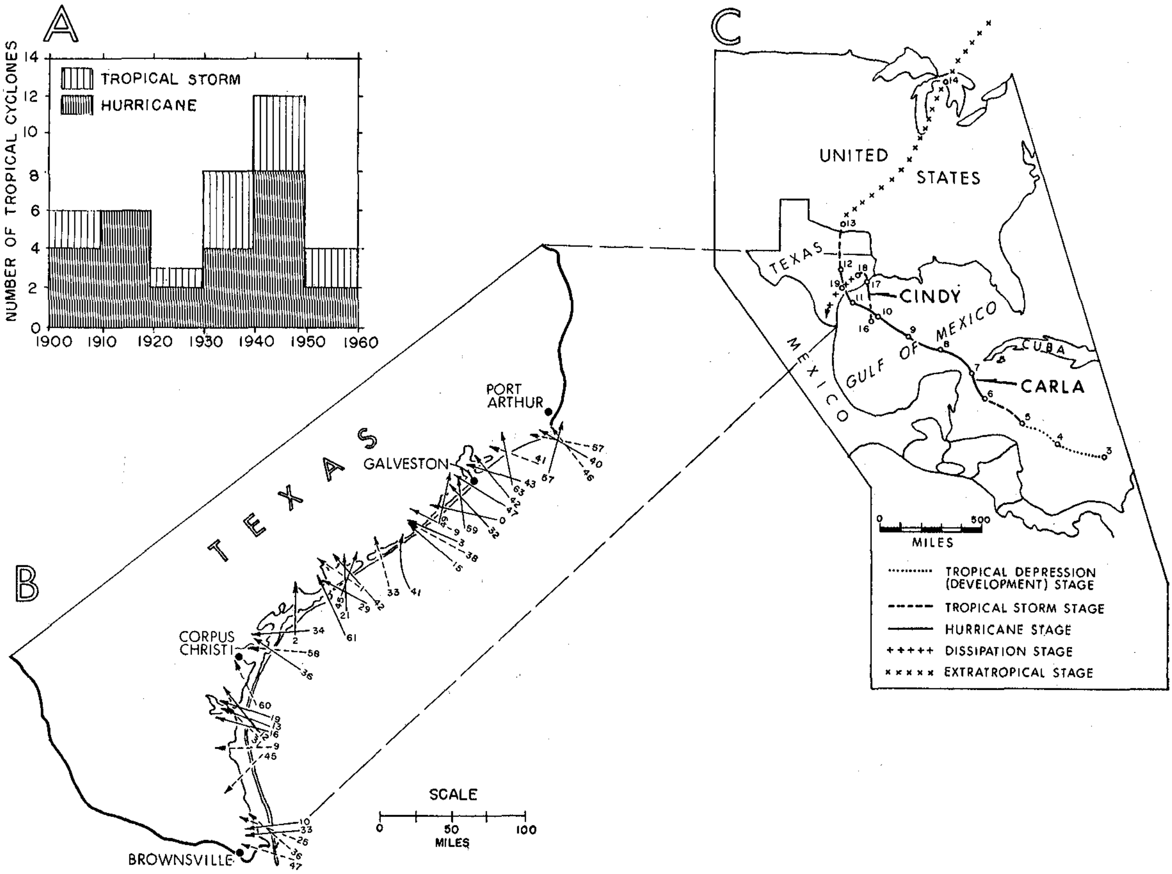

FIG. 3. A. Histogram summarizing tropical cyclone activity (by decade) on the Texas coast for the period 1900–1963. Based on number of storm centers crossing the Texas coastline during that period (data of diagram B).

B. Location of points of entry on the Texas coast of tropical cyclone centers for the period 1900–1963. Tropical storms (winds > 39 mph and < 74 mph) are shown as dashed arrows, and hurricanes (winds > 74 mph) are indicated by solid arrows. Numbers indicate year (during this century) the storms occurred.

C. Location of paths of hurricane *Carla,* September 3–16, 1961, and hurricane *Cindy,* September 16–19, 1963. Open circles indicate position of storm center at 7:00 a.m. E.S.T. of date shown. (Based on data of U.S. Weather Bureau.)

inland in Texas during each decade of this century is given in figure 3A. The maximum number crossing the Texas coast during any one decade was 12 (1940–1949). Tropical cyclones struck the Texas coast most frequently during late summer, having the following monthly frequencies:

MONTH	NUMBER OF TROPICAL CYCLONES	PERCENT OF TOTAL
June	10	24
July	7	17
August	11	26
September	11	26
October	3	7

Hurricane Carla, 1961.—According to the New Orleans Hurricane Center (U. S. Weather Bureau), this storm was one of the largest, most intense, and most destructive hurricanes to strike the U. S. Gulf Coast. The vivid memory of the devastating death and destruction inflicted by hurricane *Audrey* in 1957 greatly facilitated evacuation of coastal residents. Over 300,000 people were evacuated, perhaps the largest mass evacuation in the Nation's history. This evacuation kept *Carla's* death toll at a relatively low 46, half of which were due to floods and tornadoes. This discussion of hurricane *Carla* draws heavily on information presented by Cooperman and Sumner (1961, 1962), Dunn and staff (1962), Cry (1961), U. S. Weather Bureau (1961), Rosendal (1961), and Harris (1963).

Location of the path followed by hurricane *Carla* in early September 1961 is shown in figure 3C. *Carla* formed on September 3 in the western Caribbean and began moving slowly northwestward, attaining hurricane-force winds on September 6. On September 7 it moved through the Yucatan Channel, strafing western Cuba and the Yucatan Peninsula with fierce gales. The storm turned again northwestward, and during the period of September 8–10, moved slowly across the Gulf of Mexico at the rate of approximately 9 mph, maintaining central winds estimated at 150 mph. It finally crossed over the Port O'Connor—Port Lavaca, Texas, area early in the afternoon of September 11. The storm's lowest central pressure (931 mb) was measured by reconnaissance aircraft just before it passed inland.

The unusually large size of this storm is illustrated in figure 4. When the hurricane center crossed the coastline, hurricane-force winds (> 75 mph) encompassed the area from a few miles north of Brownsville to east of Port Arthur into Louisiana, a distance of over 300 miles. The 150-mph velocity-contour enclosed approximately 100 miles of coastline. Maximum winds of over 175 mph (est.) occurred near the point where the storm center passed inland.

Coastal flooding due to *Carla's* storm surge appears to have been the most extensive on record in Texas (Harris, 1963).

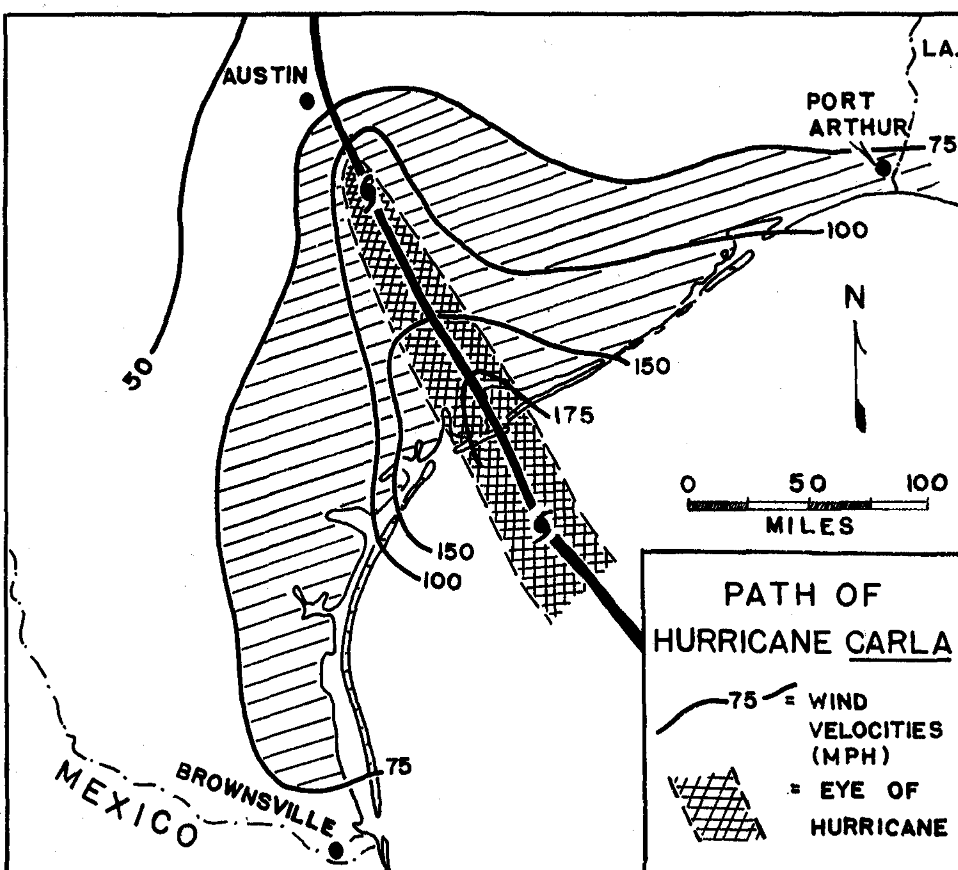

FIG. 4. Path of hurricane *Carla*, 1961, across Texas. Contours of velocities (mph) of winds associated with the storm are also shown. (After Cooperman and Sumner, 1961.)

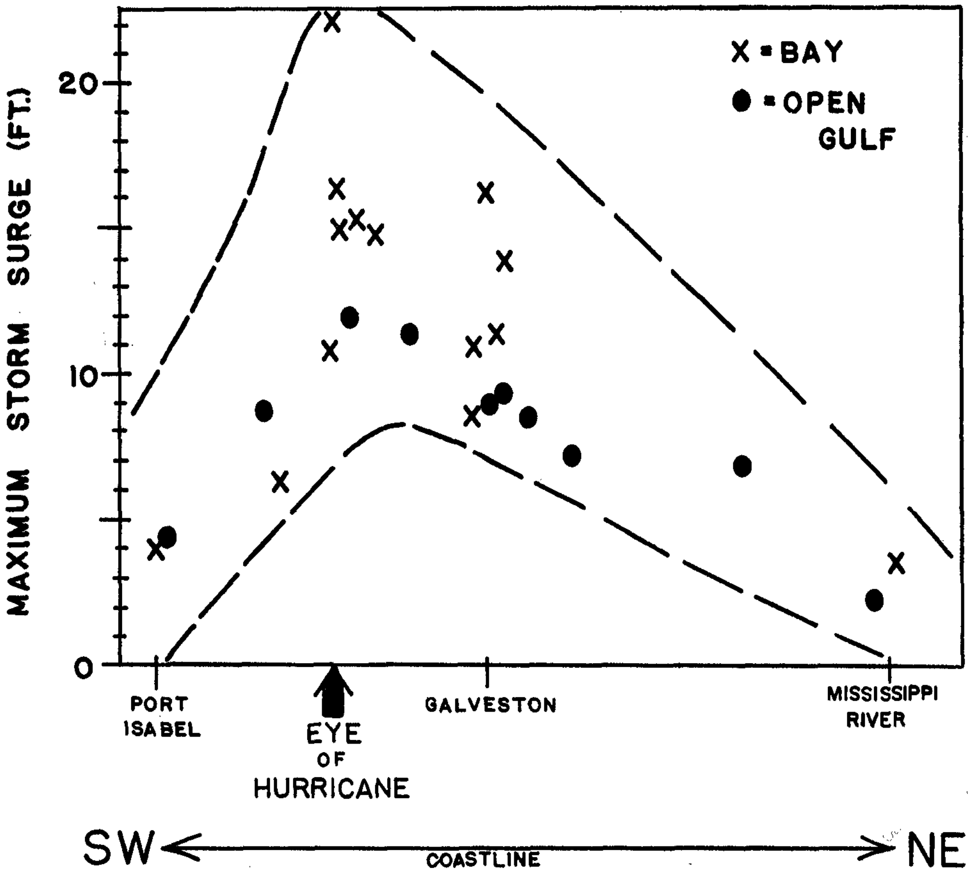

FIG. 5. Maximum storm surge occurring during hurricane *Carla,* 1961, at 14 bay and 10 open Gulf localities along the northwest Gulf of Mexico (tide stations approximately located). Based on tide data collected by the U. S. Army Corps of Engineers, Galveston and New Orleans Districts, and presented by Cooperman and Sumner (1961) and Harris (1963).

This was due partly to the very slow movement of the storm, as well as to its size. Figure 5 gives maximum tide data for 14 bay and 10 open Gulf localities along the northwest Gulf of Mexico. Tides of 4 feet were registered at Port Isabel, Texas, just north of the Mexican border, and tides of 2 to 3 feet were recorded near the mouth of the Mississippi River. Tides greater than 10 feet occurred at many localities between the point where the eye passed inland (Port O'Connor) and Galveston (fig. 5). Tides were usually higher in the bays than on the open Gulf, with one bay locality near Port Lavaca having a maximum of 22.0 feet.

In summary, hurricane *Carla* is a good example of an exceptionally large and intense hurricane with an extremely high storm surge. Its effects will be compared with those of a much milder storm, hurricane *Cindy,* 1963.

Hurricane Cindy, 1963.—The path of this small storm is also given in figure 3C. It was the only tropical cyclone occurring in the Gulf of Mexico in 1963 and the first since *Carla,* 1961. It originated on September 16 in the northern Gulf and passed inland midway between Galveston and Port Arthur, Texas, on September 17. Highest winds were around 80 mph, barely putting it in the hurricane category. Inasmuch as it was a small storm and developed near the coast, extremely high tides were not produced by the storm surge. "Tides ranged from 3 to 5 ft. (mean sea level) along the upper Texas and western Louisiana coast" (Dunn and staff, 1964, p. 132). However, *Cindy* did produce heavy rains, drenching some areas with as much as 15 to 20 inches.

Mode of presentation.—The remainder of this report presents the effects of these two hurricanes, *Carla* and *Cindy,* on the study area (fig. 1) in chronological sequence. The first discussion concentrates on the events that took place while *Carla's* storm surge was on the rise (storm-surge flood), and the second discussion concentrates on events taking place while the storm surge was falling (storm-surge ebb). Next is a discussion of the two-year period following *Carla* (hurricane aftermath) during which the environments were readjusting to normal conditions. The effects of the mild storm, *Cindy,* are then enumerated, and, finally, a summary of storm effects on the south Texas coast and their stratigraphic implications are presented.

STORM-SURGE FLOOD

This discussion of storm-surge flood effects pertains mostly to the detailed study area in the vicinity of central Padre Island (fig. 1). Storm-surge data of Harris (1963) indicate that the storm-surge tides in this area during hurricane *Carla* were between 5 and 10 feet. Maximum tides were near 5 feet at Port Isabel and near 10 feet at Port Aransas; however, no tides were recorded within the detailed study area. The format for discussion of this section is to treat individually the major environmental complexes affected—inner neritic zone, barrier island complex, and wind-tidal flats.

Inner neritic zone (0–120-foot depth).—Presumably, the greatest effect of the storm-surge flood on the inner neritic zone is erosion and transportation of bottom materials by the strong currents and enormous waves that accompany hurricanes. Curray (1960, fig. 6, pp. 232–233) determined the probable frequency of fine sand movement by significant waves on the continental shelf of the Gulf of Mexico, using hindcast wave statistics of Wilson (1957) and correlative bottom velocities determined by Lamb's (1945) equation for horizontal component of orbital velocity. He used a velocity of 35 cm/sec. (after Sundborg, 1956) as the "approximate mean velocity at 1 meter above the bottom which is required to pick up and move fine quartz sand" (p. 233). He concluded that "sediments on the edge of the shelf are stirred by the surge of waves of a hurricane approximately once every five years, and on most of the rest of the shelf more frequently than once every two years" (p. 233). He speculated on probable frequency of bottom sediment agitation by waves for different depth ranges within the inner neritic zone (portion of shelf covered in this study) as follows:

APPROXIMATE DEPTH (FEET)	PROBABLE FREQUENCY
0– 60	500 hours/year[5]
60– 90	1 time in 1½ years
90–120	1 time in 1½ to 2 years

Calculations of the same nature by W. Armstrong Price[6] (1962, personal communication) indicate that a maximum bottom current velocity of 5.2 ft./sec. can be expected off Texas (in 300 feet of water) "one time per century during one day" (based on occurrence of 50-foot waves with maximum period of 18 sec.). Waves producing bottom velocities of 0.84 ft./sec. (based on 10-foot waves) occur several days a year. Price said further that the effectiveness of these bottom velocities for sediment transport would be increased approximately three times due to the oscillatory motion of the waves. Both of these estimates agree that, within the span of a few years, bottom sediments of the inner neritic zone undergo considerable agitation due to hurricane waves. Transportation of these sediments depends on whether the waves are accompanied by directional currents.

Curray (1960) utilized hurricane waves to explain the occurrence of "homogenously mixed polymodal sediments" on the continental shelf of the Gulf of Mexico. This sediment type is very common in the study area (for example, coarse Pleistocene dune sand is homogeneously mixed with silt and clay; Hayes, 1965) and is commonly found in ancient sediments (Lloyd Pray, 1964, personal communication). Hurricane waves may well be the cause, but the importance of burrowing organisms should not be underestimated.

Unfortunately, the writer has no way of determining the amount of bottom transport and sediment-mixing that took place in the inner neritic zone of the study area as a result of the storm-surge flood of hurricane *Carla*. No difference could be seen in cores taken before and after *Carla* in regard to homogeneity except for the

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[5] Frequency for the 0–60-foot zone is based on hindcast wave statistics for normal wave conditions (after Bretschneider and Gaul, 1956a, b, and c). Others are based on hurricane wave statistics of Wilson (1957).

[6] Based on calculations of R. O. Reid, physical oceanographer at Texas A&M University.

FIG. 6. Beach zone of northern Mustang Island, Texas on September 15, 1961, four days after hurricane *Carla* struck the Texas coast. Note broad, flat nature of beach. Dashed line represents approximate location of foredunes before storm, with forward edge marking the pre-*Carla* beach-dune contact. Dunes were eroded back to wave-cut cliff (approximately 50 yards), exhuming the fence row, which had been buried in dune sand before *Carla*. Surface of beach is littered with molluscs and other fauna from surf zone and deeper.

presence of a graded bed in the top few centimeters of 40 of the 62 post-*Carla* cores (result of storm-surge ebb; *see* discussion below). All mud cores, collected both before and after *Carla,* were composed predominantly of homogeneously mixed fine sand, silt, and clay. An indirect method to study inner-shelf sediment transport is to determine depths of origin of invertebrate fauna and other materials washed up on the beach. This was done and results are discussed where surge-flood effects on the beach are presented (p. 21).

In conclusion, the major effects of the storm-surge flood on the inner neritic zone during hurricane *Carla* were probably

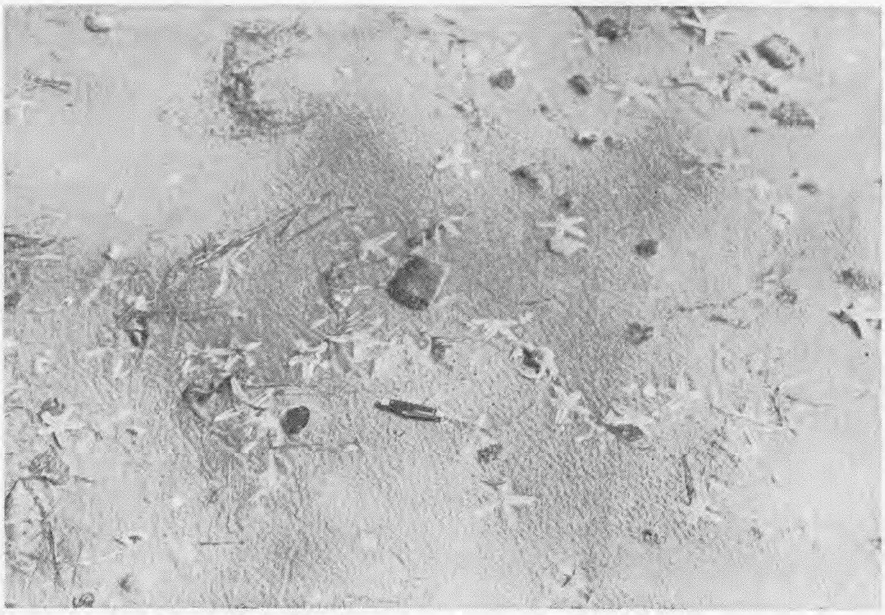


FIG. 7. Death assemblage of offshore fauna on beach of northern Mustang Island (same locality and date as fig. 6). Starfish were concentrated at this spot, but generally molluscs (*Atrina, Dinocardium,* etc.) were the most abundant types. (Photograph by Walter L. Siler.)

erosion and transportation and mixing of bottom materials by wave and current action; however, little supporting evidence can be offered. The effects of the storm-surge *ebb* on the inner neritic zone are much more clearly defined than the effects of storm-surge flood and are presented in detail under that heading.

Barrier island complex.—The most spectacular and most easily recognizable effects of hurricane *Carla* were visible on the barrier islands, in particular on their seaward sides. During *Carla* a tremendous amount of wave erosion took place on the seaward sides of Padre and Mustang Islands (fig. 6). Foredune ridges on Mustang Island were eroded back 50 to 100 yards, and more in some places, and were left with wave-cut cliffs as much as 10 to 15 feet high.

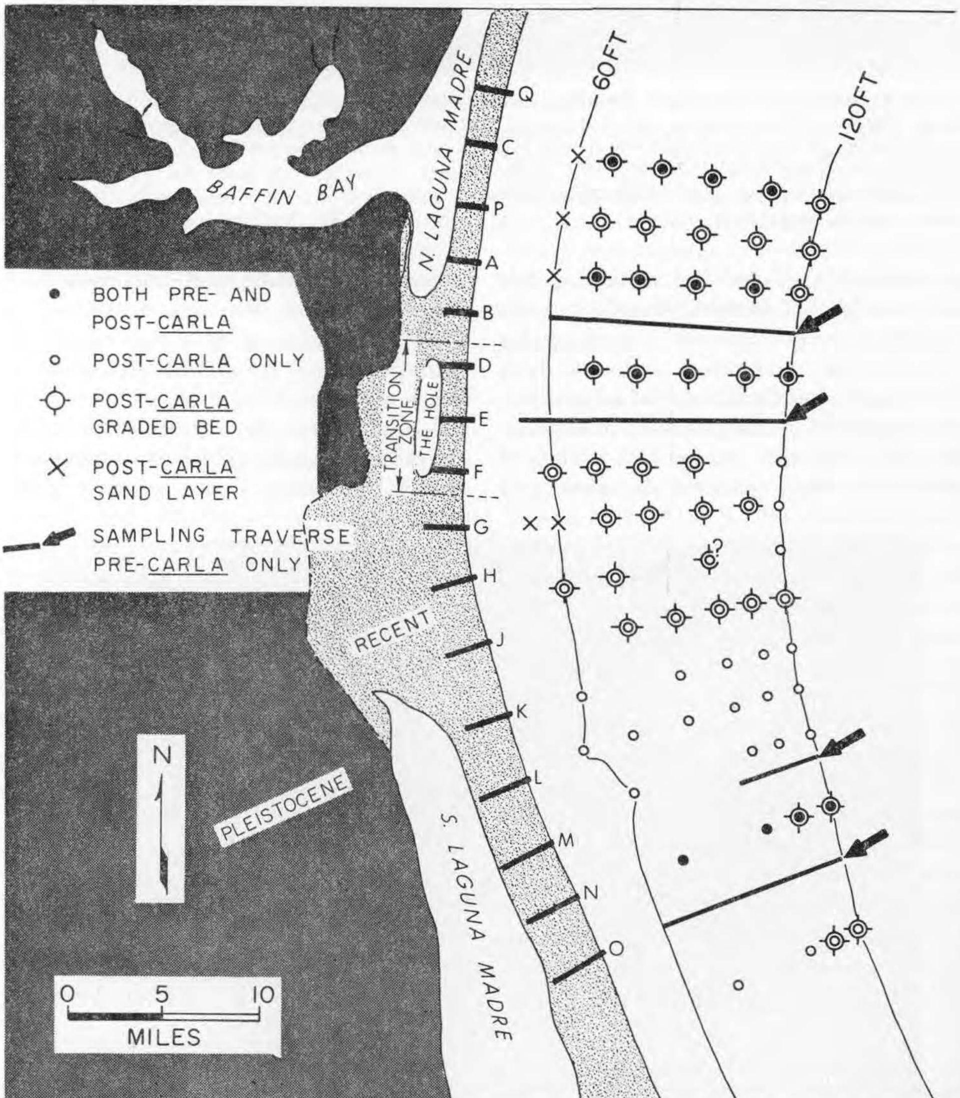


FIG. 8. Index map. Locations of the 16 central Padre Island study traverses are given by letter. Also given are the locations of cores collected in inner neritic zone. No locations for grab samples are given except for those marked by X, which had a surface layer of sand (over mud) deposited by hurricane *Carla*. Locations of cores lost in the storm are not indicated.

Not only were the barrier islands severely eroded by waves, but they also received a wide variety of material from the Gulf, such as, for example, myriads of invertebrate remains (fig. 7). Sea-going vessels were tossed about like toys and locally left half-buried on the beaches. Within the study area, Bob Hall fishing pier (on northern Padre Island) was demolished by the storm.

Due to the complexity of the barrier islands on the south Texas coast, they are subdivided for discussion into two parts, *beach zone* and *barrier proper*. The *beach zone* is the area facing the open Gulf and the *barrier proper* is the remainder of the barrier island landward of the foredune ridge. This discussion is concerned primarily with central Padre Island, but reference is also made to Mustang Island.

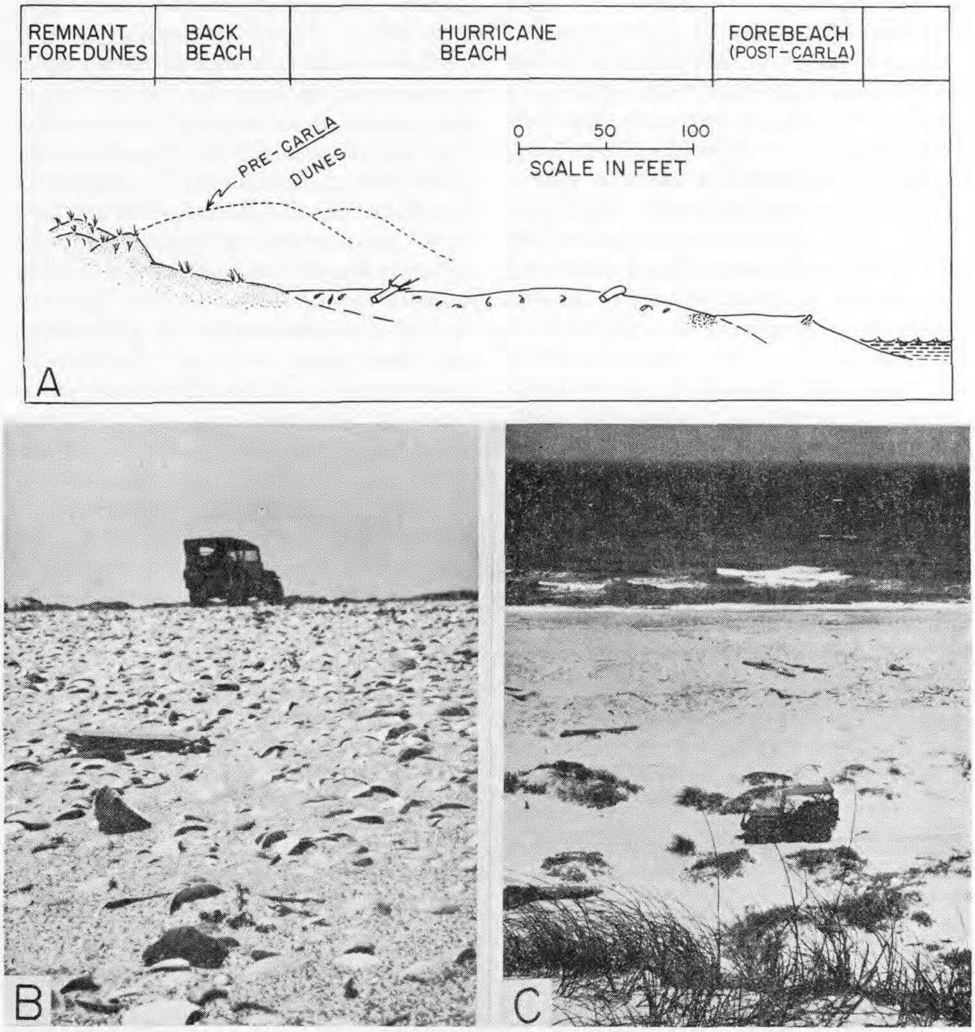


FIG. 9. Beach zone.

A. Typical beach zone profile for central Padre Island during spring of 1963.

B. Crab's-eye view of hurricane beach. Large, heavy mollusc shells, especially *Mercenaria mercenaria campechiensis*, are scattered over surface. Photograph taken April 11, 1963 at traverse L (fig. 8).

C. View from top of remnant foredune ridge looking east across beach zone. Jeep sits in back-beach area surrounded by vegetation clumps, all of which are remnants of pre-*Carla* foredunes that extended approximately 25 yards east of jeep. Hurricane-beach surface is littered with large logs. Photograph taken on April 6, 1963 near traverse E (fig. 8).

The beach zone was not studied systematically before hurricane *Carla*, although it was visited a number of times. In the spring of 1963, a systematic study of central Padre Island was begun and storm effects on the beach zone were studied in detail. Sixteen traverses across the island, located approximately 3.5 miles apart, were studied and samples were collected from each subdivision of the beach zone and the barrier proper (positions of traverses indicated on fig. 8).

On the basis of this study, a typical beach profile was constructed (fig. 9A). The beach zone was split into three subdivisions: (1) back-beach (zone where foredunes were planed off by wave action), (2) hurricane beach (swash zone during Car/a), and (3) forebeach (post-*Carla* accumulation of normal beach deposits). This profile was typical of most of the area during the spring and summer of 1963. The three major subdivisions were present throughout the area, but they varied considerably in width, as the following width data based on the 16 study traverses indicate:

SUBDIVISION	WIDTH RANGE IN FEET	COMMENTS
back-beach	87–1320	widest in vicinity of breaches and washovers
hurricane beach	108– 246	widest in vicinity of breaches and washovers
forebeach	45– 105	....

In general, the back-beach averaged approximately 100 feet in width, the hurricane beach approximately 200 feet, and the forebeach approximately 75 feet. Photographs (figs. 9 and 10) of the different subdivisions of the beach zone include a general view of the beach zone from the top of the foredune ridge (fig. 9C), the sharp contact between forebeach and hurricane beach (fig. 10), and the shell-littered surface of the hurricane beach (fig. 9B).

There are some exceptions to the typical profile given in figure 9A. Within a large area of the beach zone in the vicinity of the Port Mansfield jetties (southern edge of detailed study area) the foredunes were completely planed off. and a low hurricane beach ridge was the only topographic high between the surf and the back side of the island (back-island dune fields). This area is treated at length under the discussion of the storm-surge ebb (pp. 31–33). The beach profile was also different in the vicinity of washover and hurricane channels. As is shown later (p. 49), the normal beach profile was altered somewhat by hurricane *Cindy* in September of 1963.

The effects of the storm-surge flood on each subdivision of the beach zone of central Padre Island is now considered. The foredunes were attacked strongly by waves and were eroded back an average of 100 feet, forming the back-beach subdivision of the beach zone (fig. 9A). A

FIG. 10. Forebeach area. Automobile tracks cross over hump onto hurricane beach (left). Forebeach is very flat and broad at this point. Photograph taken on April 6, 1963 in vicinity of traverse J (fig. 8).

thin veneer of shell was deposited over the back-beach surface in some places. The forebeach zone is independent of the storm-surge flood, because it is a post-*Carla* phenomenon. Probably the most significant beach zone subdivision, geologically, is the hurricane beach; therefore, it is treated more thoroughly than the other parts.

Hurricane beach sediments represent a large body of sediment deposited solely as the result of the hurricane. It is difficult to determine whether most of these sediments were deposited during the storm-surge flood or during the storm-surge ebb; they are discussed under this heading because the sediments, most of which came from offshore, were eroded and moved towards the beach during the storm-surge flood. Sediments of the hurricane beach are quite distinct from sediments of the two environments lying in juxtaposition with it, the post-*Carla* forebeach (normal beach deposits) and the back-beach (eroded dune sand).

In order to study the internal structure of the hurricane beach, a few large trenches were dug in the vicinity of traverse G (fig. 8) in April 1964 by Alan J. Scott, Peter B. Andrews, Walter L. Siler, and the writer. Internal structures of the hurricane beach at one of these localities are illustrated in figure 11. The internal structure consists mostly of horizontal laminations of terrigenous sand and shell fragments. In general, these structures are similar to normal beach deposits, except for dip. The dip of forebeach beds averages 5° to 8° in this area (*see* fig. 11E). Extensive seasonal studies of beach gradients were not included in this study. However, Blankenship (1953) stated (on the basis of numerous beach profiles) that there is a characteristic flat-slope beach, or *storm beach,* and a characteristic steeper beach, or *normal beach,* on this coast. Unit F (fig. 11A), which has coarse shell scattered randomly through a matrix of fine material, is typical of the hurricane beach. The hurricane beach sediments generally contain more and coarser shell material than forebeach deposits in the central Padre Island area, but the forebeach deposits are pure shell in some areas.

A distinctive feature of the hurricane beach is the presence of a coarse shell pavement on its surface (figs. 9B and 11C), which forms primarily as the result of wind deflation (fig. 11D). Deflation of the fine material probably resulted in considerable thinning of the original hurricane beach deposit, if the ratio of coarse shell to fine material in the sections investigated (figs. 8 and 11) is typical of the whole area. The writer has seen new, active foredunes (mostly barchans) 15 to 20 feet high on the lee side of the broad hurricane beach areas. They were especially conspicuous in the spring and summer of 1962, the first full season of exposure of the hurricane beach deposits to the strong, prevailing southeasterly winds. This type of shell pavement could be deceiving if encountered in a consolidated ancient rock, in that its origin is the result of the work of two geological agents, hurricane waves and prevailing wind.

Another stratigraphically significant feature of the hurricane beach is the wide assortment of materials included in the sediments, some of which are illustrated in figure 12. Coral blocks (fig. 12B), sandstone fragments (fig. 12C), caliche blocks (fig. 12E), Pleistocene fossils (fig. 12D), and a variety of invertebrates (fig. 12A) were found in hurricane beach sediments. The source of the coral blocks, which are numerous on central Padre Island, is a puzzle. Kornicker and Squires (1962) postulated that they float in from the carbonate provinces to the south (e.g., Campeche Bank). An alternate hypothesis is that they were transported to the beach during hurricanes from the "coral head" areas offshore from central Padre Island that were described by Mattison (1948). Sandstone and caliche blocks were also numerous on the hurricane beach, especially between beach traverses O and L (fig. 8). These probably were eroded from an offshore area of fingerlike ridges in 35 to 80 feet of water. These ridges are thought to be Pleistocene to early Recent calichified sediments of the eolian sand

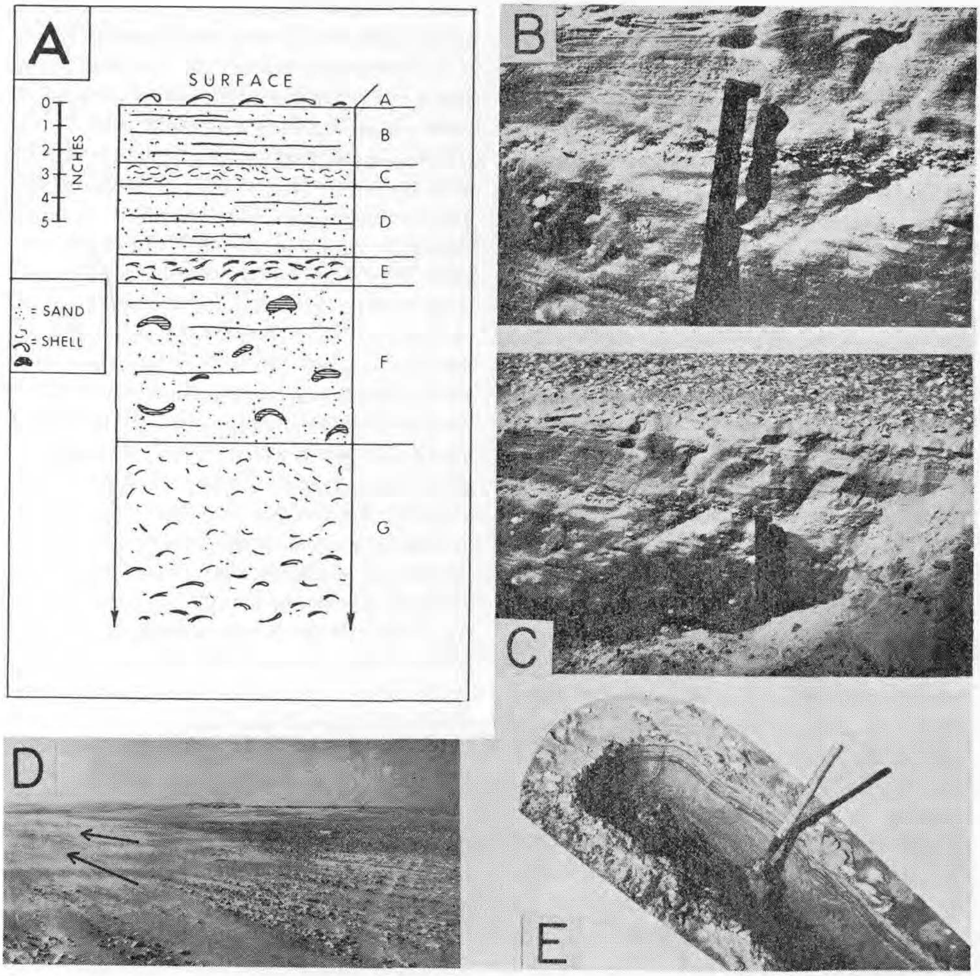


FIG. 11. Internal structure of hurricane beach.

A. Vertical section in trench dug in hurricane beach near traverse G (fig. 8) on April 18, 1964. Individual units of section are described below:

(A) Surface shell pavement; rounded, frosted heavy mollusc shells with mean diameter of 1.5 inches; fine-grained shell hash trapped between coarse shells.

(B) Well-laminated sand; individual laminae average 0.05 inch thick; 80 percent terrigenous sand and 20 percent shell hash (estimated) ; a few fine-grained shell hash placers.

(C) Fine shell hash zone; well laminated; mean diameter of hash = 0.08–0.10 inch; shell fragments highly polished and rounded; 60 percent terrigenous sand and 40 percent shell hash (estimated).

(D) Same as (B).

(E) Medium-grained shell hash zone; mean diameter.= 0.5 inch, maximum diameter = 1.5 inches; hash highly abraded; 70 percent shell, 30 percent sand (estimated).

(F) Sand (80 percent) ; faintly to well laminated; large shells and shell fragments (up to 1.5 inches in diameter) scattered throughout like raisins in a pudding.

(G) Graded unit; fine-grained shell hash (60–65 percent shell; mean diameter = 0.1 inch) at top grading to medium-grained shell hash (85–90 percent shell; mean diameter = 0.5–0.8 inch) at bottom; all shell hash is highly rounded and polished.

B. Photograph of hurricane beach section described in diagram A.

C. Same trench as one shown in diagrams A and B from a distance. Note shell pavement on surface of hurricane beach.

plain (Hayes, 1965). No large rock fragments were dredged from this area, but some grab samples contained small (1 mm) calcareous sandstone fragments. Thus, Holocene and pre-Holocene sediments are mixed on the hurricane beach.

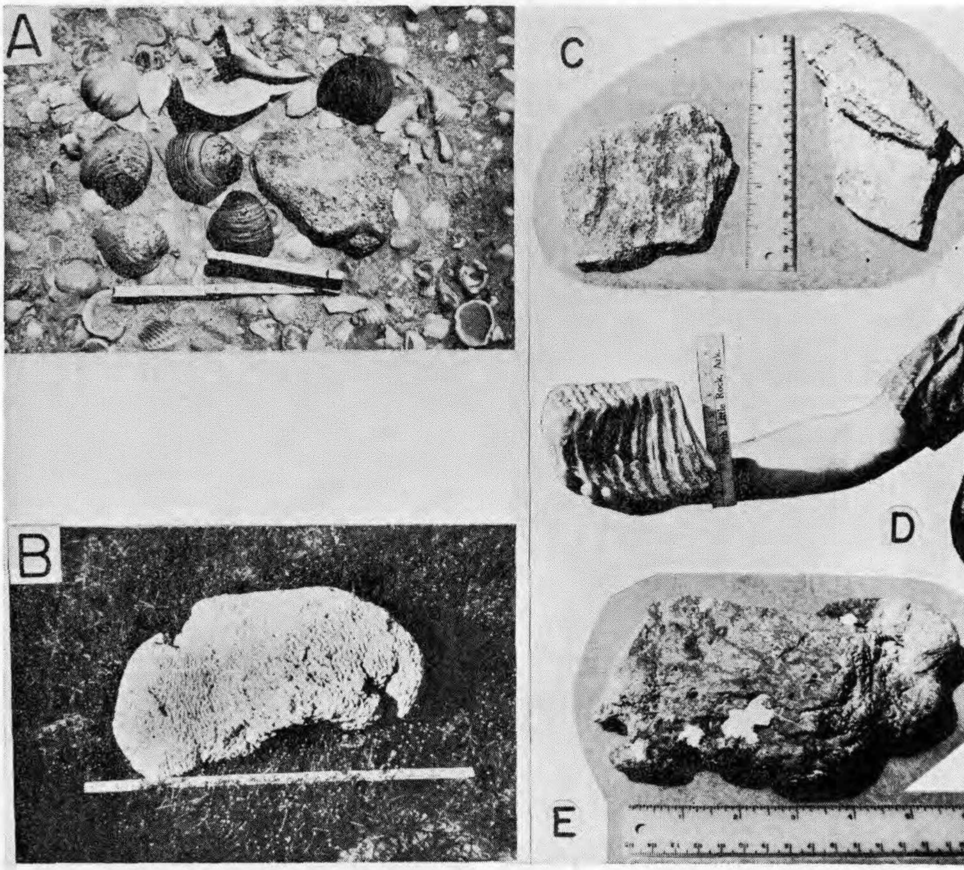


FIG. 12. Hurricane beach deposits

A. Assortment of coarse, heavy shells and rock fragment (lower right) collected from hurricane beach at traverse L (fig. 8) on April 11, 1963. Background is hurricane beach surface. Dominant pelecypod is *Mercenaria mercenaria campechiensis*.

B. Large coral block collected from hurricane beach near traverse 0 (fig. 8) on September 12, 1961 (the day after hurricane *Carla* crossed the coast) by Mr. Vallie "Fuzzy" Cole, Jr., of Port Mansfield, Texas.

C. Calcareous sandstone specimens collected from hurricane beach in vicinity of Port Mansfield jetties.

D. Pleistocene elephant tooth washed up on Padre Island beach.

E. Caliche block collected from hurricane beach near Port Mansfield jetties.

FIG. 11 (Continued)

D. Shell pavement in process of formation. Sand and fine-grained shell hash are being blown back to foredunes, leaving behind a deflation pavement of coarse shell. Arrows indicate direction (N.40° W.) of sediment transport by southeasterly winds. Numerous large, barren foredunes (mostly barchans) are forming at left (leeward of hurricane beach) as a result of this deflation. Photograph taken near southern end of Padre Island on June 5, 1962.

E. Typical internal structure of normal forebeach deposit (post-*Carla*) presented for comparison with hurricane beach structure. Laminae, composed predominantly of terrigenous sand and containing distinct concentrations of heavy minerals, dip 5°–6° seaward. Photograph taken near traverse O (fig. 8) in November 1962.

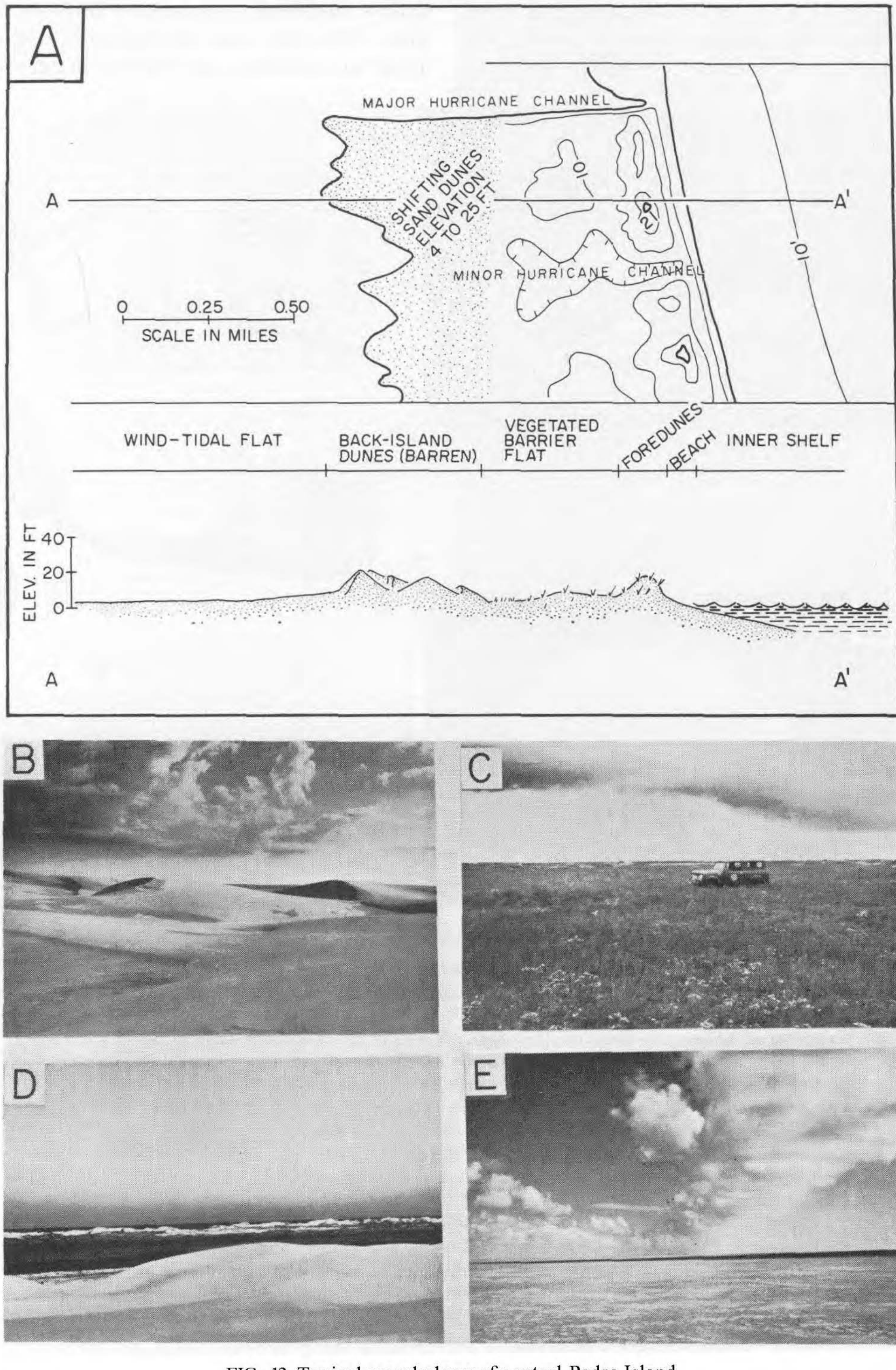


FIG. 13. Typical morphology of central Padre Island.

A. Topographic map and profile of a representative portion of central Padre Island. Morphological subdivisions include beach zone, foredunes, vegetated barrier flat, back-island dunes, and wind-tidal

There is also a great deal of mixing of faunal assemblages (based on depositional environment). At most localities, there were representatives from four of Parker's (1960) macro-invertebrate faunal assemblages present in the hurricane beach sediments. Listed below are the assemblages and the species that were common on the hurricane beach.

FAUNAL ASSEMBLAGE (after Parker, 1960)	MOST COMMON SPECIES ON HURRICANE BEACH
1. Surf zone	*Donax variabilis*
2. Inner shelf (2–12 fathoms)	*Atrina serrata*
	Dinocardium robustum
	Dosinia discus
	Mellita sp.
	Mercenaria mercenaria campechiensis
	Petrolicola pholadiformis
	Spisula solidensis raveneli
	Tellina tayloriana
3. Intermediate shelf (12–35 fathoms)	*Murex fulvescens*
	Strombus alatus
4. Calcareous bank assemblage	*Arca transversa*
	Echinochama cornuta

Specimens from the inner shelf and surf zone are more common than those from the other assemblages, but all are well represented. Hurricane beach fauna occur in all stages of preservation. Some specimens are articulated and unabraded, but the majority are disarticulated and abraded to some degree.

In conclusion, hurricane beach deposits in ancient sediments would present many interpretative problems. Fossils of different ages and of many environmental assemblages (four on Padre Island hurricane beaches) could be mixed. Nor would fossil preservation be always useful for identifying displaced fauna; starfish and crabs were well preserved on the Mustang Island hurricane beach (fig. 7).

The remainder of the barrier complex, the barrier proper, is now considered. Figure 13 includes a topographic map and profile of a representative portion of central Padre Island and photographs illustrating each major subdivision of the barrier proper. The typical morphology of the island, as presented in figure 13, consists of the following subdivisions: beach zone, foredunes (or foredune ridge), barrier flat, and back-island dunes. *Wind-tidal flats*[7] adjoin the western (landward) side of the island. This barrier morphology is unique for the Texas coast, differing markedly from Galveston Island (described by Bernard, Major, and Parrot, 1959, and by Bernard, LeBlanc, and Major, 1962) and St. Joseph Island (described by Shepard and Moore, 1955). The unique features are the presence of extensive back-island dune fields and absence of abundant, well-developed beach ridges. Both of these factors are probably due to the dryness of the climate of Padre Island (which prohibits stabilization by vegetation) in comparison to the more humid islands to the north.

Wave erosion during the storm-surge flood on the seaward face of the *foredune ridge* has been discussed in connection

[7] Broad, vegetationless flats (bordering lagoons and bays) that are covered at irregular intervals by bay or lagoonal waters under influence of wind-generated tides. They are especially abundant on the landward side of central Padre Island (*see* fig. 1). Term is modified from Price's (1958) term, "wind-tide accumulation flats," for the same feature.

flats. Two types of hurricane channels are shown—major (upper; eroded below sea level during hurricanes) and minor (lower; breach through foredune ridge at higher level than mean sea level). This profile is not typical of the area south of traverse M (fig. 8), where foredune ridge and barrier flat areas are considerably different, nor is it typical of the area opposite *The Hole* (fig. 8) that includes traverses D, E, and F, where back-island dunes and abundant hurricane channels are absent. (Generalized from U.S. Geological Survey topographic maps.)

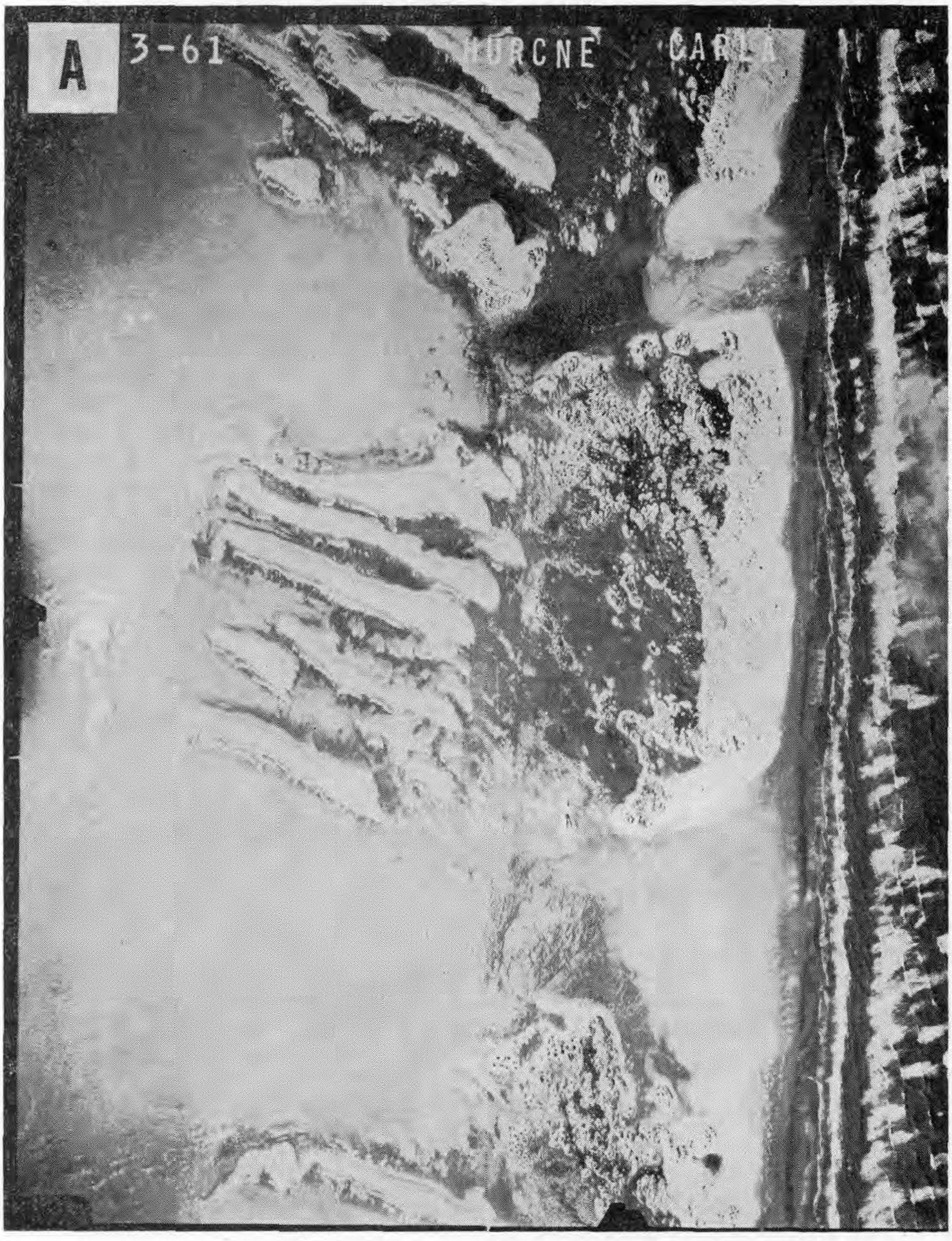
B. Active barchan dunes (estimated at 35–40 feet high) in back-island dune field on traverse 0 (fig. 8) (September 18, 1963). Looking north-northeast.

C. Vegetated barrier flat, looking south from traverse C (fig. 8) (September 20, 1963).

D. View from top of barren back-island dune, looking southeast across vegetated barrier flat and foredunes. Gulf is barely visible in background. Photograph taken near traverse Q (fig. 8) on August 5, 1962.

E. Wind-tidal flat in vicinity of traverse F (fig. 8), looking north (August 1963).

with the formation of the back-beach portion of the beach zone. In places, the storm-surge flood not only eroded the foredune ridge but also breached it. Foredune ridge breaches were generally of three types—*major* hurricane channels, *minor* hurricane channels, and total destruction of the foredune ridge for long distances (1 mile or more). Some breaches are eroded below mean sea level and maintain an open connection with the Gulf for several weeks after the storm. This type of breach is here defined as a *major hurricane channel.* The term hurricane channel is used to emphasize the importance of hurricanes in the formation of the channels. However, such features have also been called *overwash channels* (W. Armstrong Price, 1965, per-



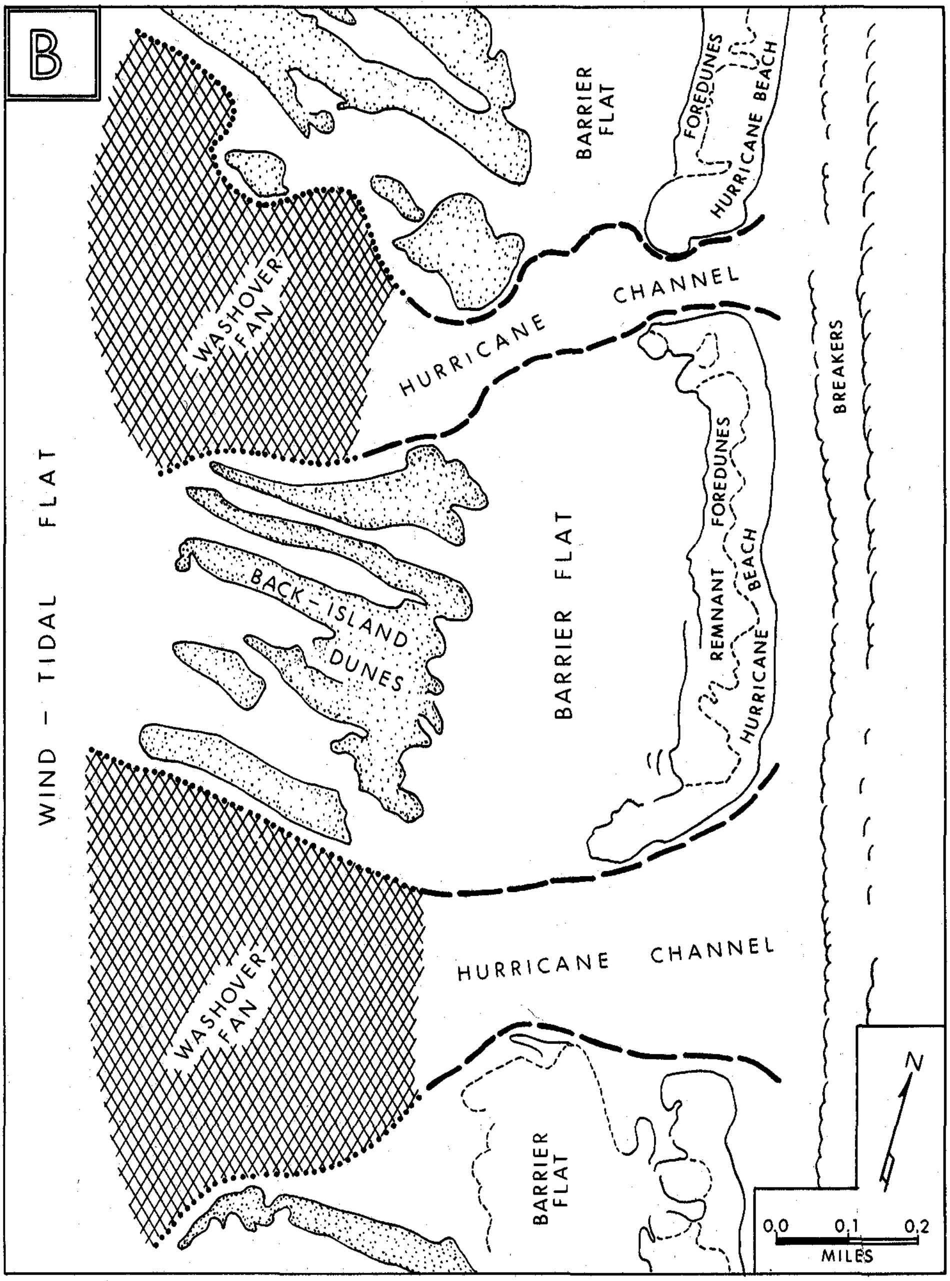


FIG. 14. Hurricane channels and washover fans.

A. Aerial photograph of a portion of Padre Island located 2.25–3.5 miles south of traverse O (fig. 8) (Port Mansfield jetties) illustrating the profound effect of hurricane *Carla,* 1961, on the island morphology. Photograph was taken on October 3, 1961, three weeks after *Carla* crossed the Texas coast. (Photograph courtesy of U.S. Army Corps of Engineers, Galveston District.)

B. Tracing of photograph A. Two large hurricane channels and washover fans are shown. Note hurricane beach, remnant foredunes, barrier flat, and back-island dunes (compare with figs. 9 and 13). Also note long, east-west-trending sief dunes in back-island dune fields.

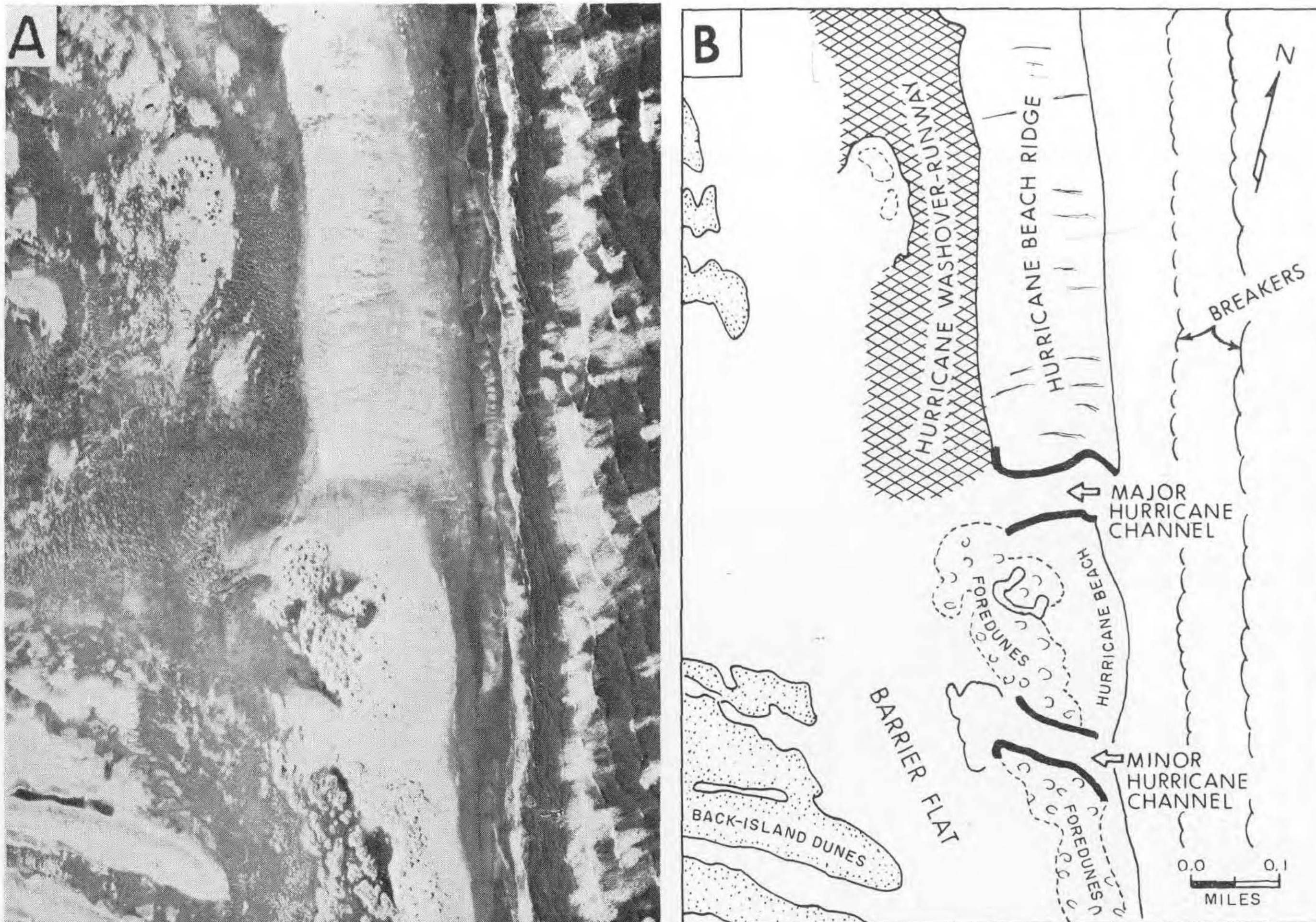


FIG. 15. Storm-surge flood vs. foredune ridge.

Aerial photograph of a portion of Padre Island located 2.5 miles south of traverse O (fig. 8) that was taken on October 3, 1961, three weeks after hurricane *Carla* crossed coastline. (Photograph courtesy U. S. Army Corps of Engineers, Galveston District.)

Photograph (A) and tracing (B) illustrate three results of the hurricane-surge upon the foredune ridge:

1. Foredune ridge breached and small channel cut through it but not eroded to mean sea level. (*minor hurricane channel*; see bottom of diagrams)
2. Foredune ridge breached and deep channed cut through it below mean sea level. (*major hurricane channel*; see center of diagrams)
3. Foredune ridge completely breached and planed off, becoming site of deposition of hurricane beach ridge. Trough-shaped *hurricane washover-runway* develops behind hurricane beach ridge to provide for escape of overwash waters. (see top half of diagrams)

sonal communication). The major hurricane channels usually leave a persistent cut through the foredune ridge that is reopened during every major storm, with only the beach zone being healed between storms. Two of these channels on central Padre Island are illustrated in figure 14, which shows their appearance three weeks after hurricane *Carla* crossed the Texas coast. Another type of breach is a high-level hurricane channel cut through the foredune ridge during the high-water stage of the storm but not eroded below mean sea level. These channels are termed *minor hurricane channels,* because they are usually short-lived and easily healed. In the third type, the foredune ridge is completely breached for a long distance. This area then becomes the site of deposition of a hurricane beach ridge, which is a bar formed beneath the flood waters by wave breakers. A troughlike depression (herein designated *hurricane washover-runway*) is formed just back of the new hurricane beach ridge, presumably much like a longshore trough is cut behind a longshore bar in the normal nearshore breaker zone. This wave-cutting process, plus scour by escaping waters, erodes into the former *barrier flat,* producing a shallow trough in what was formerly a level plain. The washover-runway only occurs where the foredune ridge is completely planed off. It was very well developed near the southern edge of the detailed study area (traverses M, N, O, fig. 8) after *Carla.* All three breach types are depicted for a single stretch of Padre Island beach in figure 15.

Another important morphologic subdivision of the barrier proper is the *barrier flat* (figs. 13A, C, D, 14, and 15). The surface of this area is generally flat, but in some localities blowout dune fields, which adjoin the foredune ridge, project out on the flat. Frequent flooding by hurricane-surge waters helps maintain the flat topography.

The remaining morphological feature of the barrier proper, the *back-island dunes* (figs. 13A, B and 14), can also be closely linked to hurricane activity. These unique dune fields locally cover broad areas and individual dunes are as much as 40 to 50 feet high. Predominant dune types are sief dunes (fig. 14), barchans (symmetrical and asymmetrical; *see* fig. 13B), and small longitudinal dunes. Boker (1953, p. 57) made the following comment concerning the source of the back-island dune sand:

> High-water levels associated with hurricanes wash large quantities of sand from the beach and foredune complex to the non-vegetated areas on the western side of the island. This process results in rapid accumulation of dune building sand in those areas where maximum development of dunes on Padre Island occurs.

Blankenship (1953) made a similar statement.

Three lines of evidence lead the writer to agree with Boker's and Blankenship's contention that back-island dune sediments are derived primarily from hurricane washover materials:

1. Textural properties of foredune and back-island dune sediments are very similar. A scatterplot of skewness versus kurtosis (the most environment-sensitive grain size parameters, according to Mason and Folk, 1958) for 28 foredune and 24 back-island dune samples is given in figure 16. No textural distinction is apparent between the sediments of the two dune types. A plot of graphic mean (M_Z) versus graphic standard deviation (σ_Φ) gave similar results. This indicates that their sediments were probably not subject to radically different transport distances. This supports hurricane washover material as the source for back-island dune sand, because distance of transport would be greatly reduced if the source were washover material rather than the beach zone, which is in some places more than a mile away. However, the use of grain size parameters for diagnosis in this area is very tenuous because of the mixing of grain size modes (discussed elsewhere; Hayes, 1964, 1965). Boker (1953) found no differences in the sphericity (Riley's method) of the sediments of the two dune types.

2. The writer saw hurricane washover material being blown into back-island dune fields at several localities after hurricane *Carla.*

3. The most convincing evidence is the

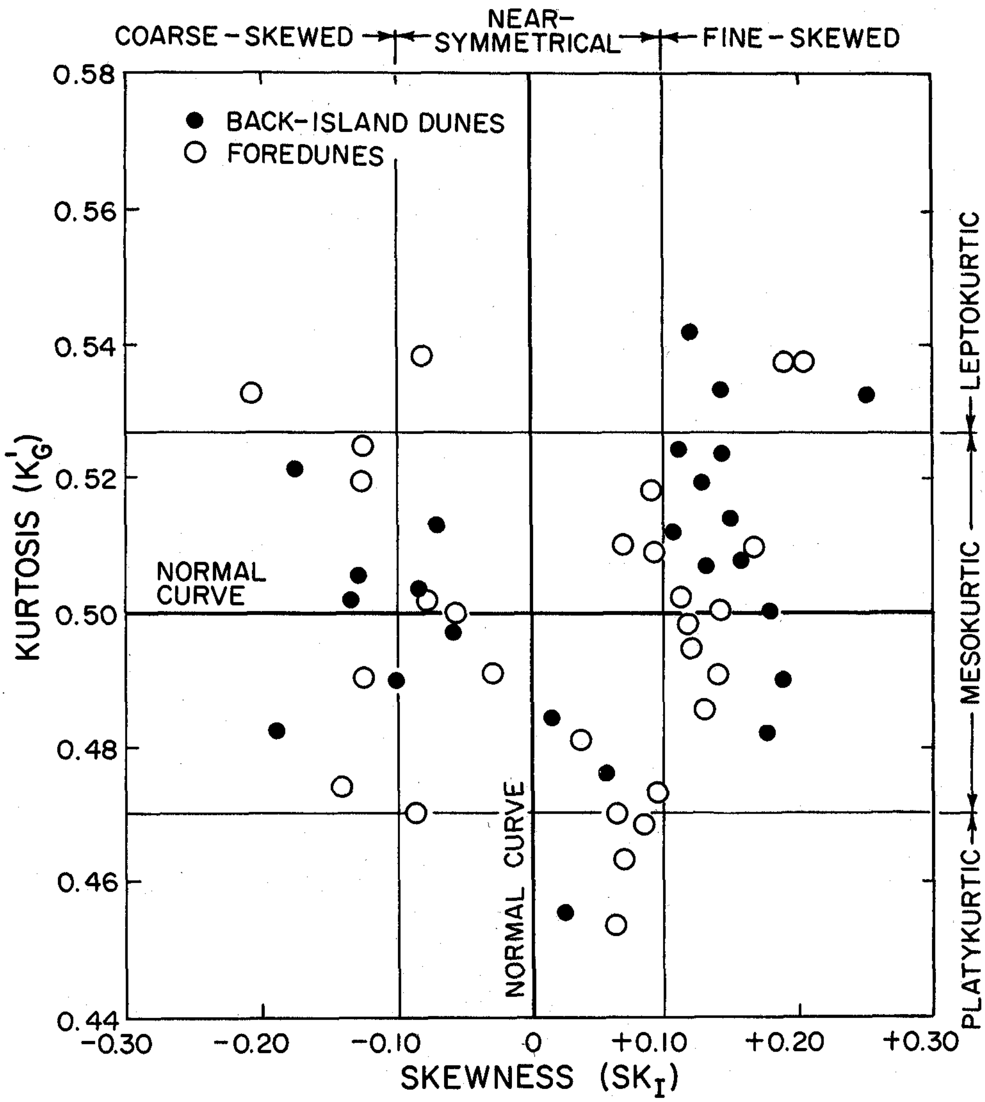


FIG. 16. Scatterplot of graphic skewness (SK_I) and transformed graphic kurtosis (K'_G) for 24 back-island dune samples and 28 foredune samples from central Padre Island. No distinction between the two environments is apparent. Statistical parameters are graphical measures of Folk and Ward (1957).

fact that hurricane channels and back-Island dunes occur together, and that where one is absent, the other is absent also. Well-developed back-island dunes are absent from a 10-mile strip of central Padre Island (traverses D-F, fig. 8; lat. 27° N.), where the foredune ridge is very high and very well developed with only a few hurricane channels. This area lies opposite *The Hole* (fig. 8). It is oriented exactly north-south and is the center of convergence of the two petrologic provinces contributing sediments to the area, northern rivers (Brazos, Colorado, Nueces, etc.) and the Rio Grande (Van Andel and Poole, 1960; Hayes, 1964, 1965). It will be referred to as the *transition zone* because of the sudden change of sediment type within its boundaries. The morphology of this area, sans back-island dunes

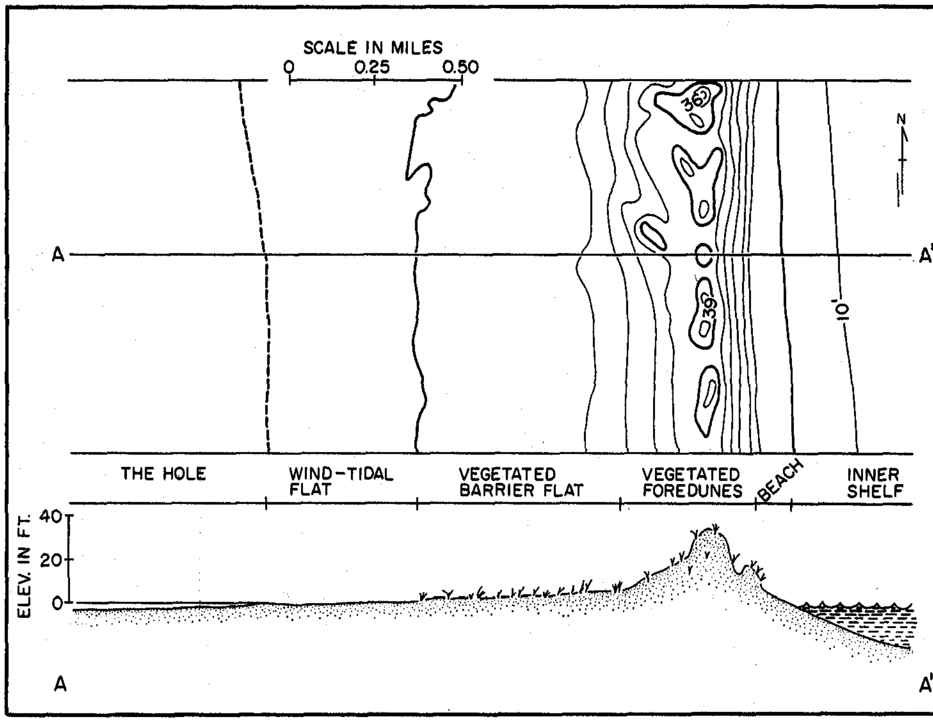


FIG. 17. Topographic map and profile of typical portion of transition zone, central Padre Island (near lat. 27° N.). Compare this morphology with that of rest of island portrayed in figure 13. Major difference is absence of hurricane channels and back-island dune fields. Foredunes are exceptionally high and vegetation is very well developed. (Generalized from U. S. Geological Survey topographic maps.)

and hurricane channels, is illustrated in figure 17. The presence of the lagoonal depression (*The Hole*)[8] in the midst of an otherwise completely infilled lagoon clearly indicates the important contribution hurricane washovers make to lagoonal infilling in this area. They do this either directly, as washover fans, or indirectly, by providing to back-island dunes sand which is eventually blown onto the wind-tidal flats. Thus, the evidence indicates that back-island dunes receive much of their sediment from materials laid down during the storm-surge flood of hurricanes.

If the storm is a large one, such as *Carla,* the back-island dunes may also be subject to some erosion during the storm-surge flood. Study of aerial photographs taken three weeks after *Carla* revealed extensive erosion of the back-island dunes in the southern part of the study area. Back-island dune erosion was probably greater in this area than elsewhere, because the foredune ridge was destroyed and the back-island dunes were exposed directly to the open Gulf. Ponds still occupied numerous scour pits in the dunes at the time the photographs were taken. A thin (½-inch) mud layer was deposited in these ponds, and it was encountered at several localities during the sampling program. This layer, which is presumably composed of mud eroded from the continental shelf, is still another of the many curious stratigraphic complexities brought about by hurricanes.

Wind-tidal flats.—Storm-surge floods play an important role in sedimentation on the wind-tidal flats. For this discussion, it is necessary to distinguish wind-tidal flats bordering the barrier island from those bordering the mainland, because of the

[8] The topography of this area was described in detail by Fisk (1959).

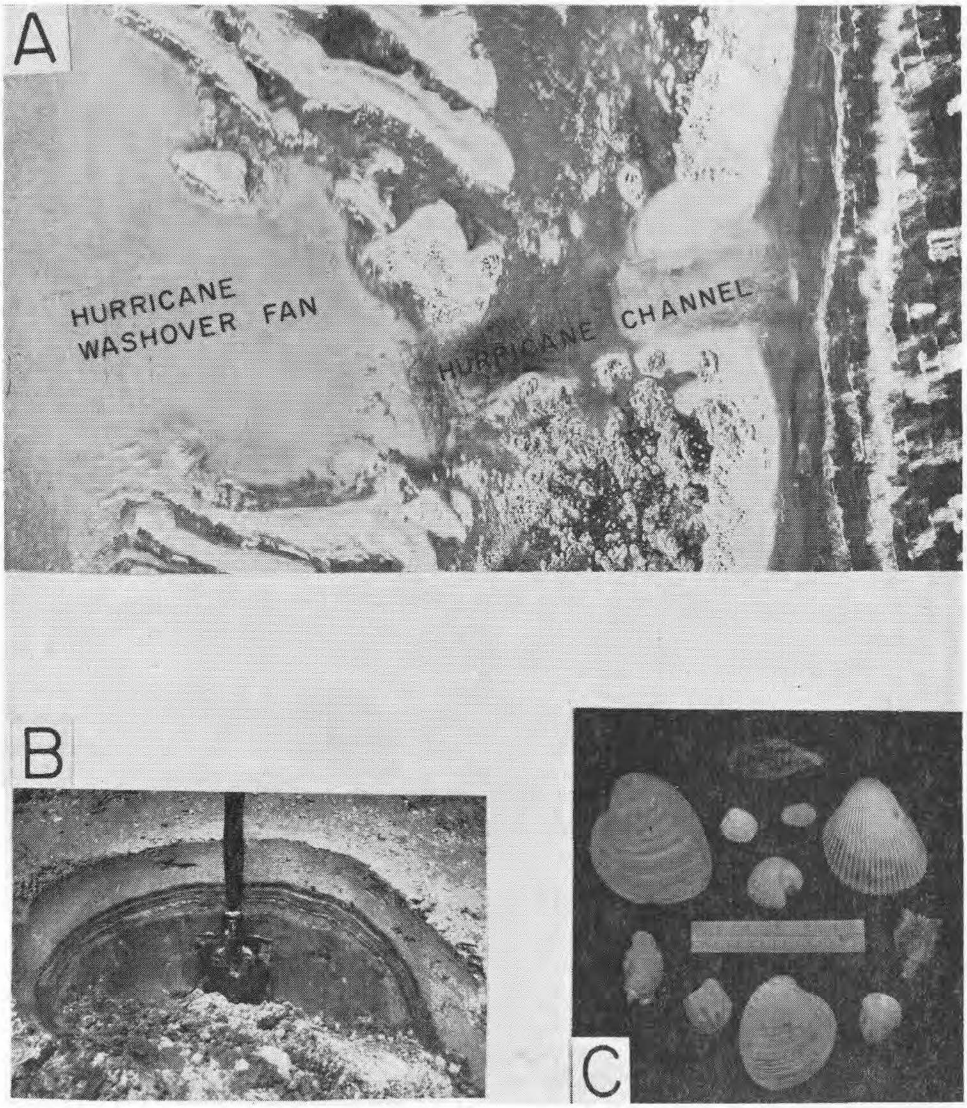


FIG. 18. Hurricane washover fan deposits.

A. Aerial photograph of hurricane washover fan and hurricane channel on central Padre Island. 3.5 miles south of traverse O (fig. 8). Photograph was taken three weeks after hurricane *Carla* crossed the Texas coast. This demonstrates how offshore and beach sediments were spread over wind-tidal flats by hurricane *Carla.* (Photograph courtesy of U. S. Army Corps of Engineers, Galveston District.)

B. Trench dug in hurricane washover material on wind-tidal flat. Three and one-half inches of washover material overlies 2.5 inches of typical algal mat (wind-tidal flat) sediment. Surface is littered with Gulf macro-invertebrates from the surf zone and other environments. *Donax variabilis* is the most common species. This spot is located on traverse P (fig. 8), 1½ miles from Gulf beach. (April 12, 1963)

C. Assortment of shells collected from wind-tidal flat surface on traverse O (fig. 8), approximately 2.5 miles from Gulf beach, that were deposited by storm-surge flood of hurricane *Carla.*

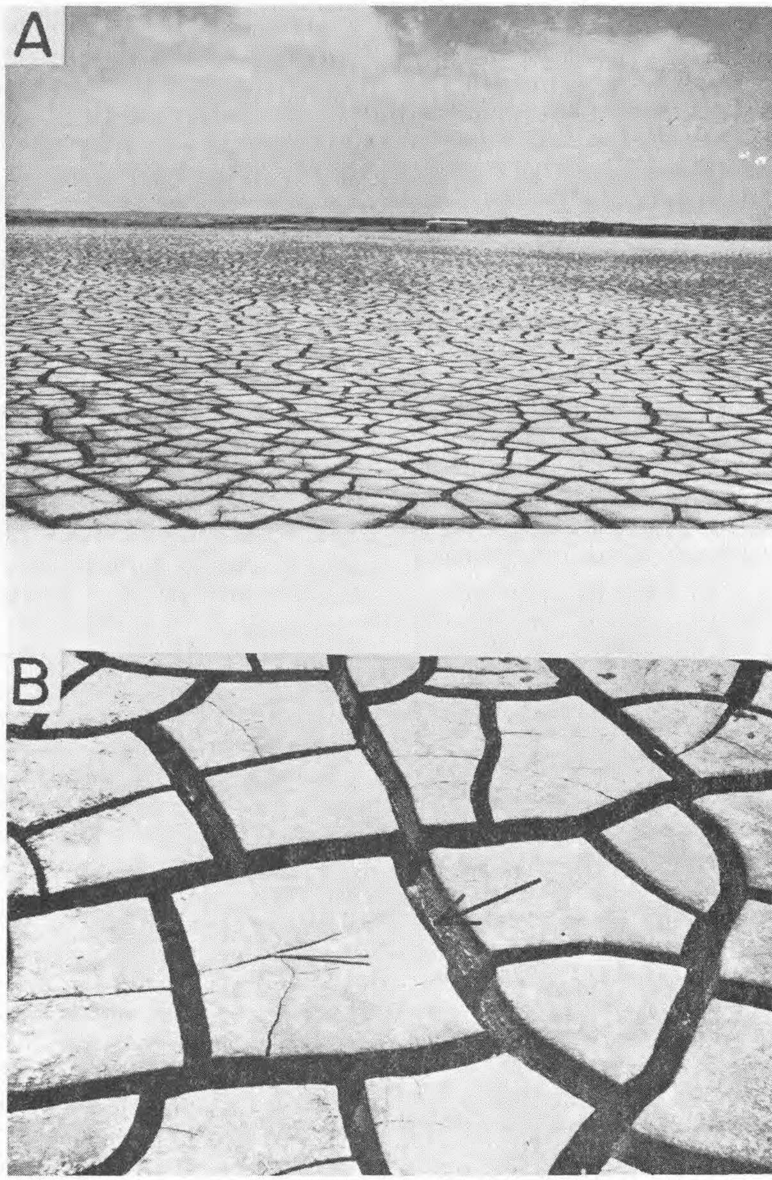


FIG. 19. Hurricane *Carla* mud layer.

A. Mainland wind-tidal flat 1 mile south of Port Mansfield, Texas. These flats were flooded by hurricane *Carla* in September 1961 and covered with a fresh layer of mud (3 to 4 inches thick at this locality). Large desiccation cracks were forming at the time this photograph was taken (May 22, 1962).

B. Close-up of mud-cracked surface of flat (pencil for scale). Arrow points to buried layer of grass that was growing on flat before *Carla* flood tide.

different nature of surge-flood sediments deposited on these two types of flats.

Sediments of the *barrier* wind-tidal flats are composed typically of laminated thin clay seams, deposited during normal *high* wind tides, and blue-green algal mats. This sediment is interlayered with pure sand that is blown across the flats from back-island dune fields during normal *low* wind tides. During storm-surge flood, water rushing through the hurricane channels deposits washover fans over these sediments. Such washover fans were common after hurricane *Carla* (figs. 14 and 18A). A pit dug into the wind-tidal flat surface on traverse P is shown in figure 18B. In this section, a 3.5-inch layer of washover sand and shell overlies typical algal mat sediments. The washover material contains abundant offshore and beach macro-invertebrates. In places these displaced organisms were carried as far as 2.5 miles inland from the beach, and they were found on the flats at many localities within the study area (see fig. 18C).

Mainland wind-tidal flat sediments also contain algal mats but lack the windblown sand fraction, because the lagoon lies on the windward side of the flats. Therefore, mainland wind-tidal flat sediments have a high mud content. These flats were flooded by the storm surge of hurricane *Carla* and covered with a new mud layer 3 to 4 inches thick; much of this mud was probably derived from the lagoon floor. In the Port Mansfield area, grass grows on these flats between infrequent floods, resulting in alternations of grass mats and surge-flood-deposited mud layers. Photographs of these flats and of the hurricane *Carla* mud layer are given in figure 19.

Lagoon-bay complex.—No comments are made about hurricane effects on this environmental complex because it was not studied before hurricane *Carla*. Thus, it would be very difficult to relate any aspect of the sediments to a particular storm.

STORM-SURGE EBB

As soon as a hurricane passes inland, storm-surge waters begin to subside. Sometimes the ebb of the surge tide is very **rapid and strong currents are generated.** Two subdivisions of the study area were affected greatly by the storm-surge ebb of hurricane *Carla,* the hurricane washover-runway (part of barrier complex) and the inner neritic zone.

Hurricane washover-runway.—This segment of the barrier island has already been mentioned several times. It is a trough-like depression on the landward side of the hurricane beach ridge in areas where the foredune ridge was leveled by the storm. An aerial photograph and a physiographic diagram of an area with a well-developed washover runway (1 mile north of Port Mansfield jetties) are given in figure 20. Several trenches were dug in the runway at this locality, and detailed study of the internal sedimentary structures produced some of the most significant findings of the whole study.[9]

The story of hurricane washover-runway sedimentation is presented diagrammatically in figure 21, a north-south-oriented vertical section of runway surface sediments. The bulk of the surface sediments of the washover-runway (in that area) comprise a single unit, called the hurricane *Carla* sedimentation unit, that was deposited during the storm-surge ebb of hurricane *Carla.* Although it does not conform exactly to Otto's (1938) definition of a sedimentation unit, it is a distinct sediment unit deposited within a very short time interval, and it should be distinguished from other sediments in the area that are deposited under normal conditions. The lower part of the unit is made up of festoon cross-beds formed by the migration of megaripples (illustrated in figs. 20 and 21). In the trenches investigated, cross-beds dip south and trend parallel with the beach, because ebb waters in the runway trough were apparently forced to flow parallel with the beach ridge until reaching an outlet to the Gulf. Although the cross-beds dip south in the area investigated (fig. 20), it is probable that dip direction depends on direction to nearest outlet for surge waters. The nearest outlet for the storm-surge ebb at the study locality was the Port Mansfield channel (based on aerial photograph evidence; *see* fig. 22). The large-scale cross-beds at the base of the hurricane *Carla* sedimentation unit are overlain by increasingly smaller-scale cross-beds up the section, indicating a decrease in depositional current velocity as the surge subsided. The top of the unit is a pure clay layer that was deposited in ponds left by the storm surge. These ponds were still in evidence three weeks after *Carla* (*see* aerial photograph in fig. 20). The hurricane *Carla* sedimentation unit is overlain by a thin layer of windblown sand and underlain by a pure clay layer that was most likely deposited by an earlier hurricane (possibly hurricane *Audrey,* 1957). Thus, the major portion of the surface sediments of the hurricane washover-runway were deposited during one catastrophic event.

These results unveil three facets of washover-runways that apply to studies of ancient sediments:

(1) The sequence of sedimentary structures present in the washover-runway (festoon cross-bedding and so forth) are very similar to those produced in fluvial channels, according to Harms and Fahnestock (1964) and others. These structures are present in sediments laid down on a barrier island between the beach zone and barren, active back-island dune fields (*see* fig. 20). Thus, it is the process, rather than the strict environmental category, that determines the distribution of these sedimentary structures.

[9] This work was carried out in cooperation with Alan J. Scott, Peter B. Andrews, and Walter L. Siler, whose comments and suggestions are greatly appreciated, not to mention their "spade" work.

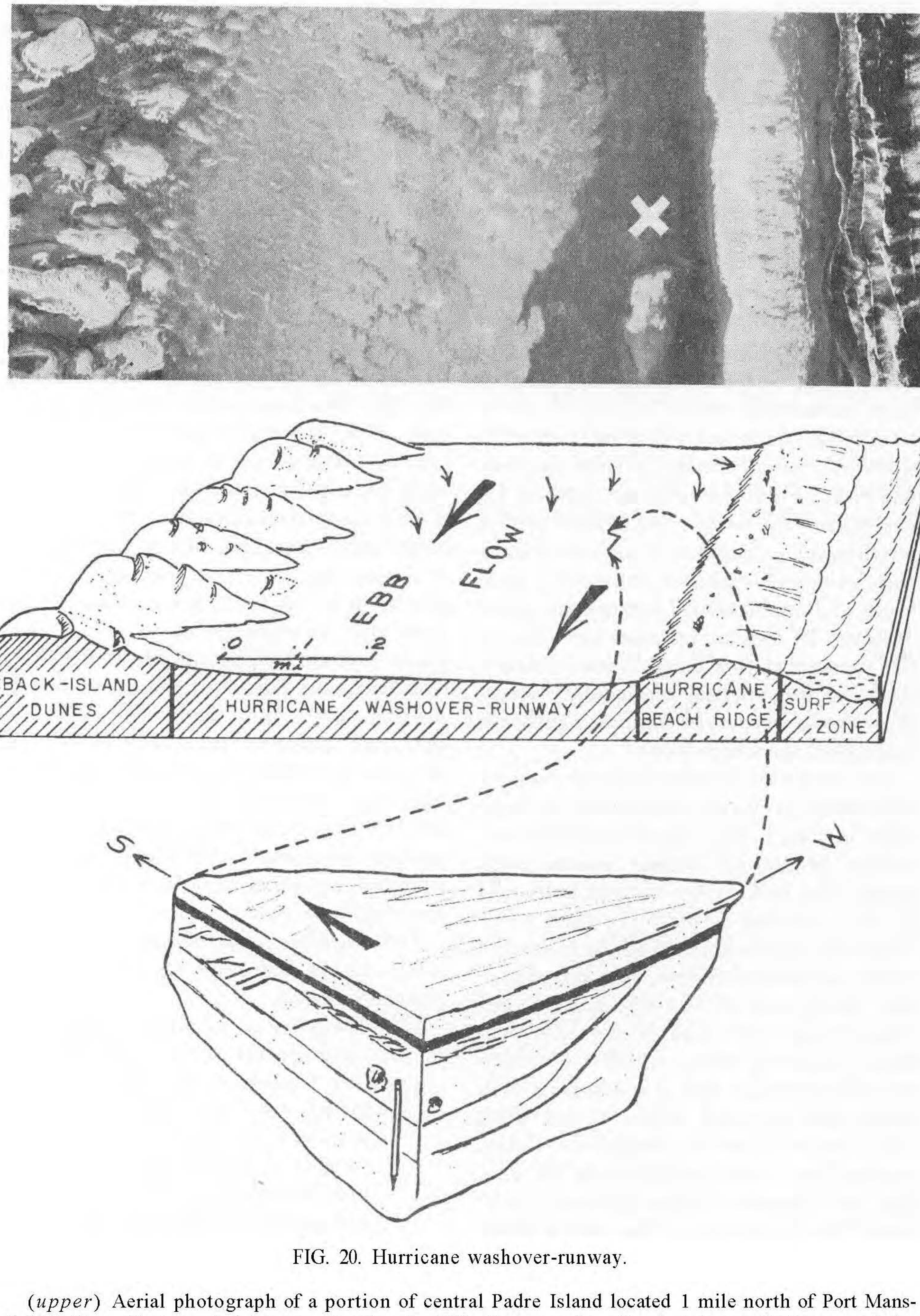


FIG. 20. Hurricane washover-runway.

(*upper*) Aerial photograph of a portion of central Padre Island located 1 mile north of Port Mansfield jetties. Photograph taken on October 3, 1961, three weeks after hurricane *Carla* crossed the Texas coast. Foredune ridge was leveled and hurricane beach ridge deposited (light vertical band on right side of photograph). Hurricane washover-runway occupies area behind (left of) beach ridge. Water was standing in portion of runway at time photograph was taken (dark area left of beach ridge). Back-island dunes are visible at far left.

(*middle*) Physiographic diagram of hurricane washover-runway and neighboring environments in same general area as upper photograph. Arrows mark flow direction of currents during storm-surge

(2) The cross-beds dip parallel with the beach. Therefore, paleocurrent directions based on cross-beds of similar ancient sediments would be oriented parallel with the coastline, or regional depositional strike, rather than perpendicular to it.

(3) The *erosional unconformity* between units E and F (fig. 21) represents a time interval of at least four years (assuming unit E was deposited by hurricane *Audrey,* 1957), and possibly more. Most sediments in the section, units C-E, were deposited within a few hours,[10] and the overlying clay layer (unit B) within a few days. Therefore, in regard to the relation of time to sediment thickness, most of the section was deposited within a very short time interval.

Inner neritic zone.—The fact that part of the inner neritic zone of the detailed study area had been sampled before hurricane *Carla* presented an excellent opportunity to study storm effects on the bottom sediments of this zone. Therefore, the area was completely resampled in the spring and summer of 1962. Sampling traverses (both before and after *Carla*) were located 3 nautical miles apart and samples were taken at 2-fathom intervals from depths of 12 to 120 feet. Cores ranging from 6 inches to 2 feet in length were collected with a Phleger corer, and grab samples (restricted to pure sand areas) were collected with a modified Peterson grab sampler. Although about 60 of the pre-*Carla* samples were lost in the storm, 36 grab samples and 42 cores were retained. A total of 66 grab samples and 62 cores were collected during post-*Carla* sampling. Location of the pre- and post-*Carla* cores is given in figure 8. Grab samples were located in shallow water portions of the same traverses.

A major change brought about by the hurricane was the deposition of a thin sand layer across the normal mud bottom of the inner shelf in 48- to 60-foot depths (fig. 23). This post-*Carla* sand layer was only observed in grab samples because the corer would not work in sand. The sand layer overlay homogeneous mud at each station where it was encountered (these stations are located by X in fig. 8). The exact thickness of the sand layer in the grab samples was difficult to determine, but it appeared to range between 0.5 and 1.0 inch and possibly is considerably thicker. Grain size curves for pre- and post-*Carla* samples, which were collected at the 60-foot depth station on traverse C (fig. 8), are given in figure 24A. These curves illustrate the relatively pure composition of the post-*Carla* sand layer (83% sand) as opposed to the pre-*Carla* mud (20% sand; 42% silt; 38% clay). The homogeneous mud underlying the sand layer of the post-*Carla* grab sample (CC-60) was also analyzed for grain size and found to be similar to the pre-*Carla* mud curve in figure 24A, except for having a higher silt content and less sand. This decrease in sand content is not understood but is probably related to wave action during the storm-surge flood. The pre-*Carla* mud sample (C-60), which has a

[10] It is difficult to be precise about this because no tide records are available for the study area itself, and local topography and other focal factors influence ebb rates. Nevertheless, on the basis of tide records for other areas, it is assumed that it took 10 to 15 hours, or possibly even less, for storm-surge waters to drop below the level of the washover-runway after *Carla* crossed the coast.

ebb of hurricane *Carla* as determined by cross-bedding in washover-runway sediments and other evidence.

(*lower*) Sketch from photograph of L-shaped trench in hurricane washover-runway at spot marked by X in photograph and located by dashed lines and arrows in middle diagram (trench dug on April 19, 1964). The festoon cross-bedding indicates a southward flow-direction of depositional currents of storm-surge ebb of hurricane *Carla.* Dark layer near top of section is clay layer deposited after *Carla* in pond shown in photograph. Clay layer is overlain by a thin deposit of windblown sand. Cavities in trench face near pencil represent former positions of clay blebs eroded from underlying clay layer, which was deposited by an earlier hurricane.

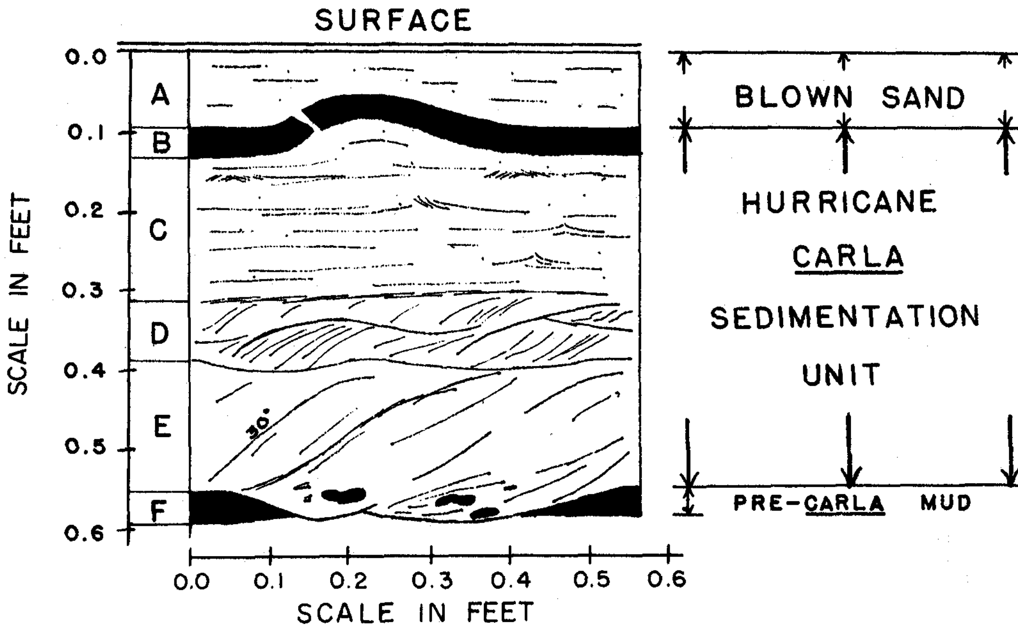


FIG. 21. Vertical section of hurricane washover-runway sediments in a north-south-oriented trench located 1 mile north of Port Mansfield jetties (April 19, 1964). Description and interpretation of each unit (top to bottom) follow:

Description	*Interpretation*
A. Pure sand (mode = 0.2 mm); structureless; 1% shell hash.	Windblown sand from hurricane beach ridge.
B. Pure clay; distinct contacts; sometimes fractured and slightly offset; sand layer one grain thick near bottom.	Pond deposit from hurricane *Carla*, 1961, storm-surge waters (*see* aerial photograph in fig. 20). Fracturing is due to desiccation of mud. layer after pond dried up. (this was observed in the field). Thin sand layer was probably windblown.
C. Semi-continuous pure sand laminae; small ripple (symmetrical) and micro-cross-bedding.	Last sand deposited by flowing waters of storm-surge ebb. Laminations and symmetrical ripples caused by wind waves in shallow pond left by flood waters.
D. Pure sand; small-scale cross-bedding dipping to left (toward south); formed by intermediate-sized asymmetrical ripples.	Higher current velocities than (C). Deposited during storm-surge ebb.
E. Festoon cross-bedding; high-angle cross-beds dipping 29°–30° toward south; some shell hash near base; clay blebs (maximum diameter = 1 inch) also abundant near base.	Maximum depositional current velocity during storm-surge ebb. Underlying clay eroded and incorporated into sand. High-angle cross-beds of migrating megaripples indicate southward flow direction toward Port Mansfield jetties.
F. Pure clay; same as (B).	Same origin as (B) but deposited by an earlier hurricane.

Thus, units (B) through (E) comprise a single unit deposited during the ebb flow of the hurricane *Carla* storm surge. A gradual decrease in depositional current velocity from bottom to top is indicated by large-scale cross-bedding and coarse sediments at base (unit E), by smaller-scale cross-bedding in center (units C and D), and by fine clay sediments at top (unit B).

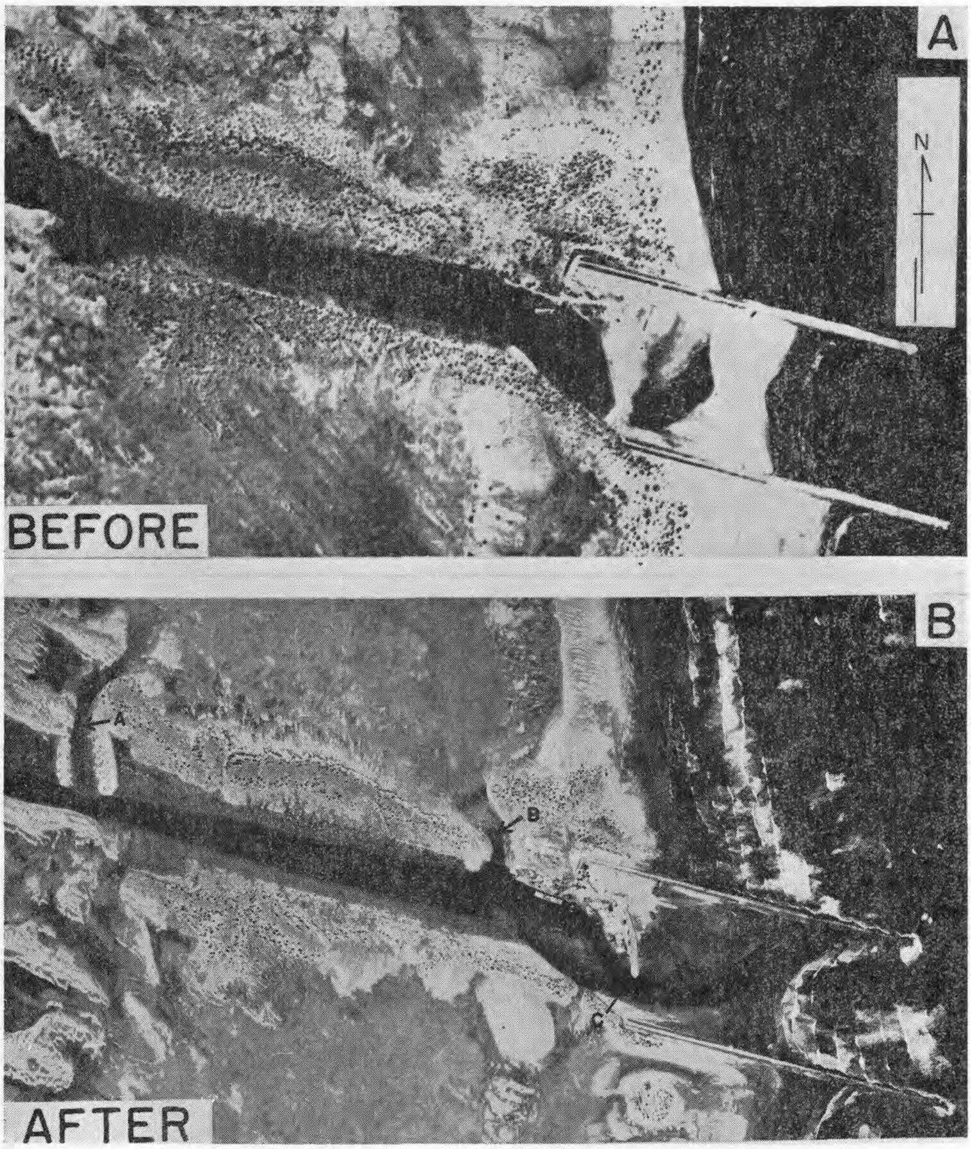


FIG. 22. Effects of hurricane *Carla* on Port Mansfield jetties area.

A. Before *Carla*. Aerial photograph of Port Mansfield jetties, Padre Island, Texas, taken in July 1961.

B. After *Carla*. Appearance of area three weeks after hurricane *Carla* crossed the Texas coast (October 3. 1961). Arrow (a) points to channel cut through back-island dunes, and arrow (b) points to channel cut through spoil heaps. Both channels were cut by washover-runway waters spilling into main channel during ebb of storm surge. Arrow (c) points to remnant of roadway across channel-fill (see above) which was washed out by ebb waters. (Photographs courtesy of U. S. Army Corps of Engineers, Galveston District.)

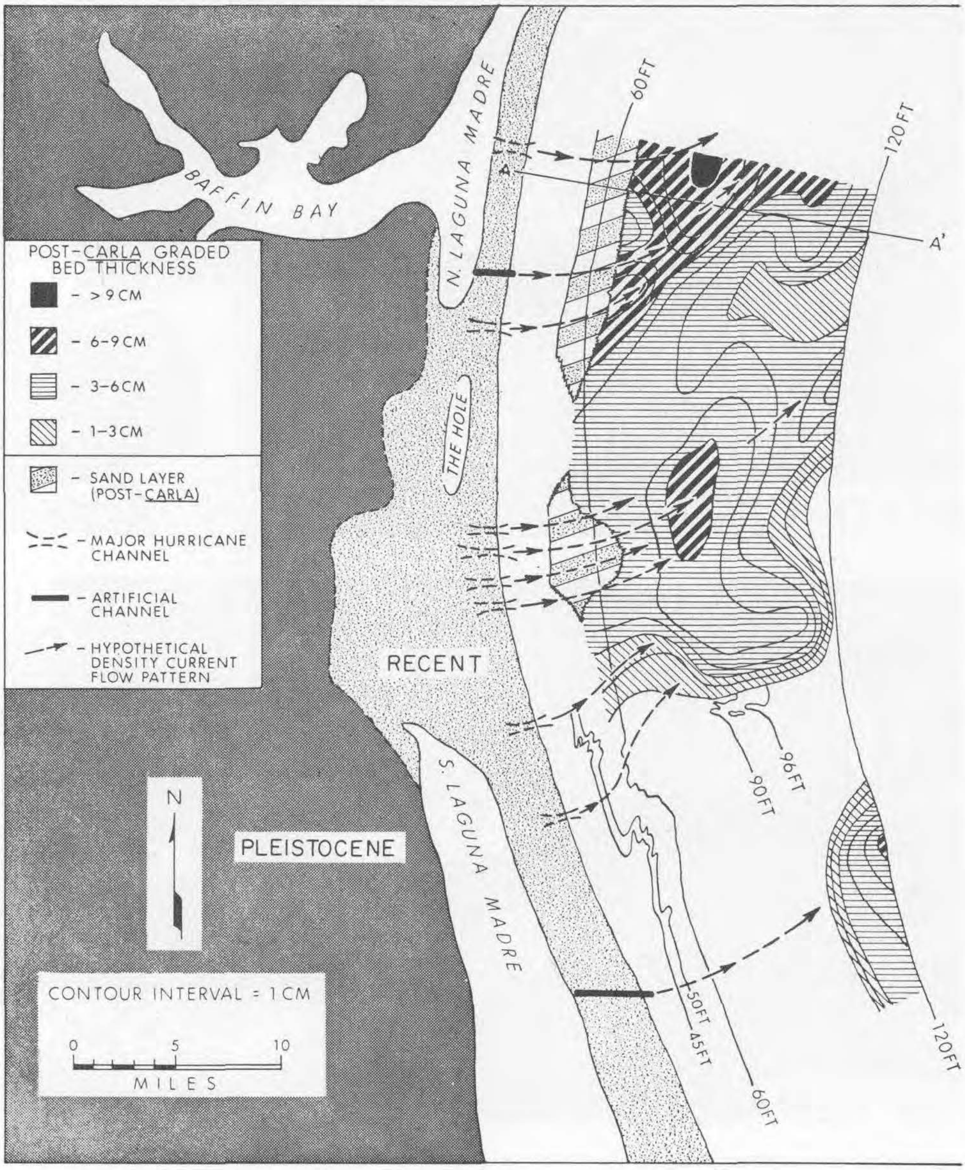


FIG. 23. Sediments deposited in inner neritic zone off central Padre Island during and after hurricane *Carla*. Distribution of sand layer deposited over nearshore mud (48 to 60 feet) during storm is shown. Map includes isopachs (contour interval = 1 cm) for graded beds deposited over mud bottom of the inner neritic zone (60 to 120 feet) during storm (probably during storm-surge ebb). Data points for isopachs are post-*Carla* sampling localities (fig. 8). Note correlation between distribution of graded bed and sand layer and location of major hurricane and artificial channels. This and other evidence implies a density current origin for the post-*Carla* sand layer and graded bed rather than an origin due to bottom wave action (*see* text). Submerged sand ridges are indicated by the 45- and 50-foot depth contours in the southern part of the area. Some outer pinnacles are indicated by the 90- to 96-foot depth contours.

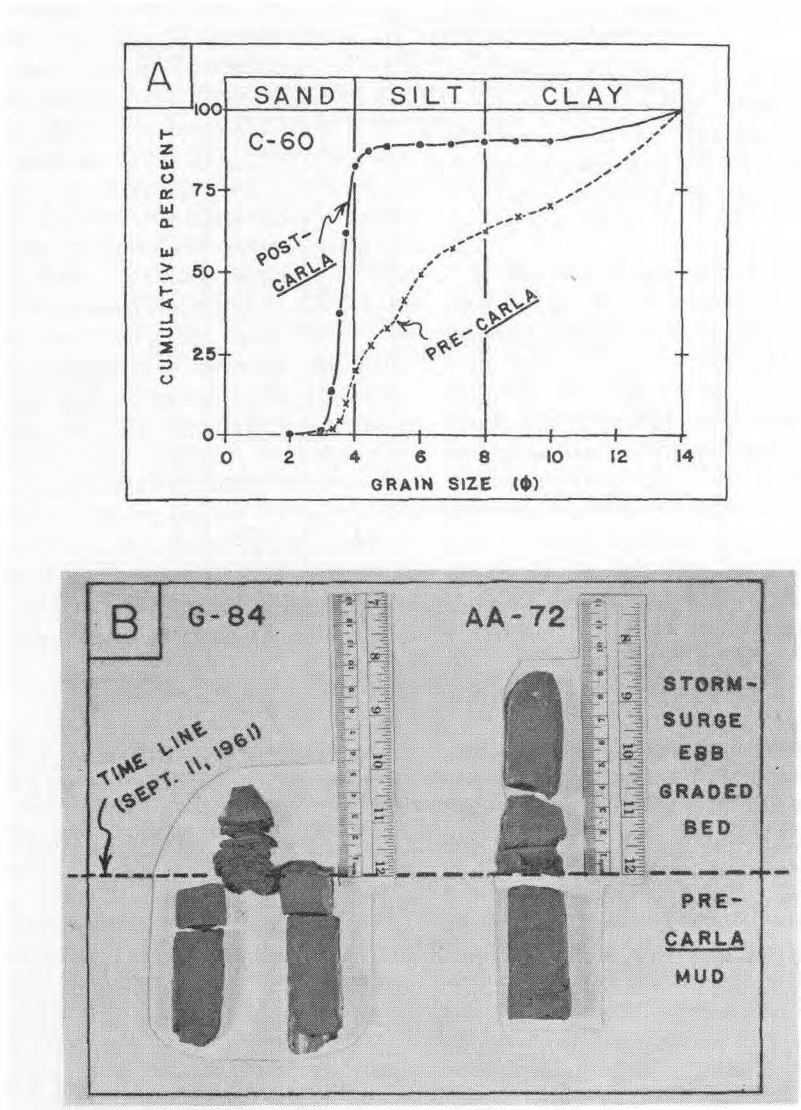


FIG. 24. Hurricane *Carla* sand layer and graded bed.

A. Cumulative grain size distribution curves for surface samples collected on traverse C (fig. 8) at 60-foot depth both before (July 27, 1961) and after (June 27, 1962) hurricane *Carla*. The post-*Carla* deposit was a relatively clean sand layer (0.5 to 1 inch thick) overlying the homogeneous pre-*Carla* mud.

B. Graded beds of fine sand, silt, and clay deposited during storm-surge ebb of hurricane *Carla* at 84-foot depth on traverse G (G-84) and at 72-foot depth on traverse A (AA-72) (fig. 8). Dashed line represents time line (September 11, 1961; date of hurricane) separating sediments deposited before the hurricane (homogeneous mud) from those deposited as result of storm (graded bed). Note laminations in coarse material at base of graded bed in core G-84.

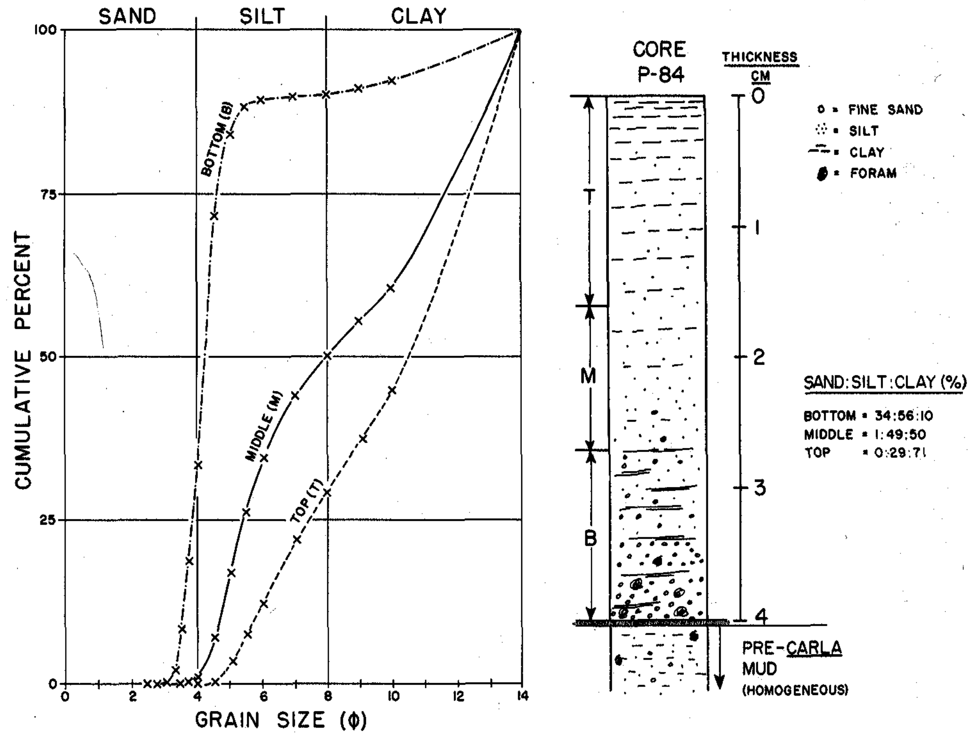


FIG. 25. Cumulative grain size distribution curves for three vertical segments (bottom, B; middle, M; top, T) of a post-*Carla* graded bed, which overlies normal pre-*Carla* homogeneous mud at depth of 84 feet on traverse P (fig. 8). Foraminifera are concentrated near base of bed (*see* sketch at right). Segment B (bottom) contains 34 percent sand and 10 percent clay, segment M (middle) contains 1 percent sand and 50 percent clay, and segment T (top) contains no sand and 71 percent clay.

homogeneous structure, is typical of all mud deposited in the inner neritic zone. Table 2 includes sand-silt-clay percentages for 6 mud samples on traverse C (fig. 8) (based on pipette analyses). Similar results were obtained for 11 inner-shelf mud samples from other traverses.

Detailed descriptions of cores collected before and after *Carla* were made by hand lens and binocular microscopic inspection of the cores and petrographic examination of 34 thin sections. This inspection revealed a remarkable feature in the post-*Carla* cores. The tops of these cores from the deeper portions of the inner neritic zone (seaward of the post-*Carla* sand layer) are composed of a graded bed of very fine sand, silt, and clay. The contact between the bottom of the graded bed and the underlying mud, which in most places

TABLE 2.—*Bottom samples on traverse C* (fig. 8).

Sample No.*	Percent sand	Percent silt	Percent clay	Description
CC-60A	83	8	10	post-*Carla* sand layer
CC-60B	4	55	41	pre-*Carla* mud (?); underlying post-*Carla* sand layer
C-60	20	42	38	pre-*Carla* homogeneous mud
C-72	13	36	51	pre-*Carla* homogeneous mud
C-84	20	38	42	pre-*Carla* homogeneous mud
C-108	10	38	52	pre-*Carla* homogeneous mud

* Letters designate traverse and numbers designate water depth (in feet).

is a homogeneous mixture of fine sand, silt, and clay (*see* table 2), is very sharp. The maximum measured thickness of the graded bed is 9 cm (approximately 3.5 inches) and the average thickness is between 4.5 and 5.0 cm. This graded bed was not observed in any pre-*Carla* core but is present in 39 of the 62 post-*Carla* cores. Locations of post-*Carla* cores topped by graded beds are shown in figure 8. The post-*Carla* graded bed is widely distributed and is a considerable contribution (in terms of thickness of sediment deposited) to the bottom sediments on the area (isopach map, fig. 23). The grading of the beds was easily recognizable in the cores (fig. 24B). Figure 25 gives grain size curves for the bottom, middle, and top portions of the graded bed (P-84). It is distinctly graded, having the following proportions of sand, silt, and clay (by percent) in each of the three segments of the graded bed:

	BOTTOM	MIDDLE	TOP
clay	10	50	71
silt	56	49	29
sand	34	1	0

Analysis of another sample of the graded bed (G-84; fig. 24B) gave similar results. In some cores, the coarse fraction of the graded bed was laminated (fig. 24B). The small caliber of the core barrel (1.5 inches) prevents study of the base of the graded bed for sole marks. A notable difference between the mud portion (top of the graded bed) and normal inner-shelf mud, in addition to grain size, is the absence of foraminifera in the top of the graded bed. Foraminifera are concentrated near the base of the graded bed, in the coarse silt—fine sand zone, and most are abraded, whereas in the normal deposits they are scattered randomly throughout the sediment. This is a result of the rapid rate of sedimentation of the graded bed as contrasted with the slow rate of normal deposition.

Figures 23, 24, and 25 describe two changes in inner-shelf bottom sediments (sand layer and graded bed) brought about the hurricane, the origin of which presents an intriguing problem. Two origins seem feasible:

(1) Result of agitation and resettling of bottom materials by waves.
(2) Deposition by sediment-laden currents generated by the rapid ebb of the storm-surge tide through channels in the island.

If the first hypothesis is correct, the distribution and thickness of post-*Carla* deposits should show a close correlation with water depth, inasmuch as bottom agitation due to waves decreases with depth and is spread out evenly over the bottom in areas of equal depth. Therefore, thickness of the post-*Carla* layers should decrease gradually with increasing depth and the beds should be of uniform thickness in the same water depths throughout the area. Inspection of the graded bed isopach map (fig. 23) shows that this is not the situation, hence hypothesis (1) is rejected.

If the existence of strong currents flowing seaward through hurricane channels during the storm-surge ebb could be established, this would be an excellent mechanism for spreading the post-*Carla* deposits across the inner shelf, and it would offer strong support to hypothesis (2). Observations made by T. W. Bailey (State Highway Department division engineer) during an airplane flight along Padre Island, two days after the hurricane of September 4, 1933, revealed more than 40 passes through the island from which lagoonal waters were pouring into the Gulf. The water was then at about 4.5 feet msl (Reese, 1938, p. 7). Another example of the force of the storm-surge ebb is illustrated in figure 22, which documents the changes that took place in the vicinity of the Port Mansfield jetties during hurricane *Carla*. The artificial channel, which was closed by sediments before the storm, was reopened and spoil heaps and dunes were bisected by two large cuts on its north side. The outrush of the waters during the storm-surge ebb must have been extremely strong in this area (*see* fig. 22).

Major hurricane channels in the central

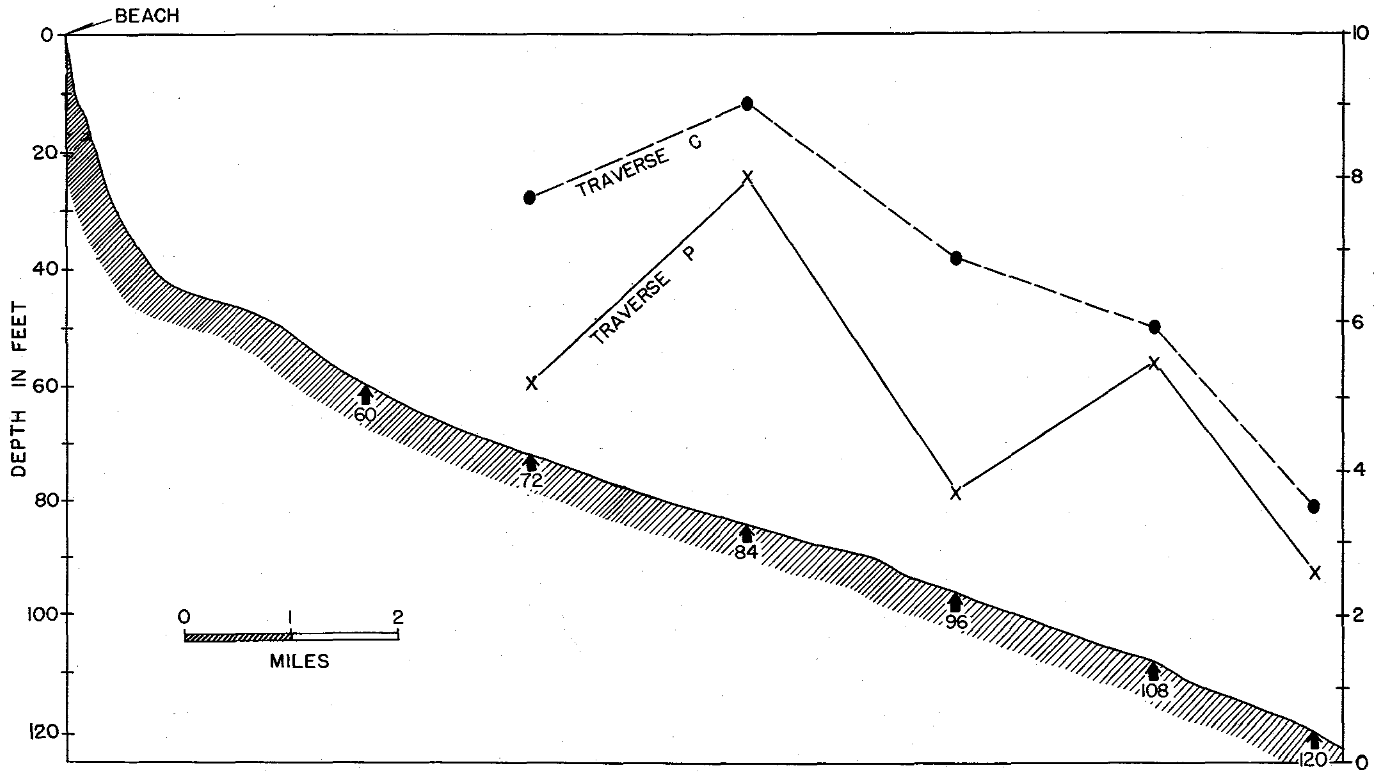


Fig. 26. Inner neritic zone bottom profile along line A-A′ (in fig. 23). Arrows along profile indicate sampling localities for traverse C (1.5 nautical miles north of profile line) and traverse P (1.5 nautical miles south of profile line) (fig. 8). Thickness of post-*Carla* graded bed is plotted at sampling depth for these two traverses (C and P; graded bed thickness scale on right). (Based on detailed U. S. Coast & Geodetic Survey soundings, 6396 and 6403.)

Padre Island area are located on the map in figure 23. Some locations are somewhat uncertain because complete post-*Carla* aerial photograph coverage of the area was not available, and some channel locations are based on U. S. Geological Survey topographic maps and field observations. The channels most accurately located are the four clustered south of *The Hole* (fig. 23), which still retain remnant ponds in some parts of their channels at the time of this writing (1965). The excellent correlation of distribution and thickness of the post-*Carla* sediments with channel locations demonstrated in figure 23 indicates that the channels were points of origin of sediment-laden currents that deposited the post-*Carla* beds. This correlation is particularly strong for the channels south of *The Hole,* off which a well-developed sand sheet and a thick graded bed were deposited. This evidence strongly supports hypothesis (2).

A density-current mechanism of sediment transport away from the channel outlets is also favored for the following reasons:

(1) Turbidity currents have long been considered capable of depositing graded beds. Furthermore, the graded bed is laminated in places, which indicates transport by current action.

(2) The thickness of the graded bed is greatest where the sea floor slope is least; hence, it is inferred that the graded-bed thickness is controlled by bottom topography. Figure 26 gives the inner neritic zone bottom profile along line A-A′ in figure 23. The bottom profile of this area is made up of a series of terraces. Although these terraces, which occur throughout the area, are not prominent in figure 26, they were easily recognized on the fathometer trace when they were passed over in the ship. The thickness of the graded bed along traverse C (1.5 nautical miles north of profile) and traverse P (1.5 nautical miles south of profile) is plotted in figure 26. In general, the bed thins away from shore, but anomalous thicknesses reflect bottom topography. Thickest deposits occur at a depth of 84 feet, near the outer edge of a broad terrace. The relatively thin samples collected at 96 feet occur just east of a prominent terrace break, and the relatively thick samples from 108 feet occur near the outer edge of another terrace. This relationship holds true for other parts of the study area (other than that illustrated in fig. 26). Thickness of the graded bed apparently was controlled by velocity of the density current as it moved across the shelf, in that thickest deposits occur where the current lost velocity as it moved across flat terraces, and thinnest deposits occur where the current gained velocity as it crossed over “steep” terrace breaks (*see* fig. 26).

(3) The graded bed is missing from the seaward side of the submerged ridges and pinnacles in the southern part of the area (traverses L, M, and N, fig. 8). The ridge locations are indicated in figure 23 by 45- and 50-foot depth contours, and the outer pinnacles by 90- and 96-foot depth contours. The nearshore ridges, which are oriented NNE-SSW, apparently diverted the seaward-flowing density currents to the north, where considerable sediment was accumulated (traverse J, figs. 8 and 23).

Hypothetical density-current flow-patterns away from the channel mouths are drawn on the isopach map in figure 23. Graded-bed thickness distribution patterns (fig. 23) indicate that these currents probably were deflected slightly to the north.

A distinction should be made between a turbidity current (energy source due to density difference) and a storm-surge current (energy due to hydraulic head). Apparently the currents under discussion were initiated by the storm-surge effect and the primary energy source for their generation was hydraulic head. Once these currents passed through the inlets, however, they probably became typical density currents and were propelled along the bottom as a result of their higher density. The high density of the water mass making up this current is thought to have resulted primarily from the concentration of shallow water and bay sediments within the mass and secondarily to the unusually high salinity[11] of the bay water that was undoubtedly incorporated into the flow. When the graded bed sediments were deposited, the current was a turbidity current in the classical sense and the graded bed can be properly referred to as a *turbidite.* Thus, the catastrophic storm is demonstrated to be a mechanism whereby turbidites are deposited in shallow-water areas. It seems likely that this mechanism could be extended to deeper-water areas as well.

[11] Thirty-two randomly distributed water samples collected from Laguna Madre in the summer of 1962 had an average salinity of 39.8‰ with a maximum value of 59.0‰. The average salinity for 14 Baffin Bay samples was 55.8‰.

HURRICANE AFTERMATH

This section is devoted to the period between the time hurricane *Carla* crossed the Texas coast in September 1961 and the advent of hurricane *Cindy* in September 1963. Considerable time was spent in the central Padre Island area during that interval and there were many opportunities to observe aftermath effects of hurricane *Carla.* Three of the most geologically significant events occurring during that interval are (1) accumulation of sargassum weed on the beach in the spring of 1962, (2) healing of hurricane channels, and (3) aftermath effects on foredune cross-bedding.

Sargassum accumulation.—In early May of 1962 large masses of seaweed were washed up on the Texas beaches. This accumulation is pictured near its peak in figure 27 (A, B). The seaweed accumulations were very widespread, occurring from Miami, Florida, to the Mexican border. After a few weeks, the rate of accumulation declined and the deposit was either abraded away by waves or was buried by beach sand. The appearance of a buried sargassum layer is shown in figure 27C. The principal constituents of this deposit were *Sargassum natans* and *S. fluitans,* the species of brown algae that populate the Sargasso Sea in the southwestern North Atlantic. These weeds float near the surface with the support of numerous gas-filled, berry-like bladders (Marshall, 1954).

This seemingly trivial event has important geological implications. This was the greatest accumulation for several years, and some biologists attributed the accumulation to hurricane *Carla* (details given in Hayes, 1965). If this is the cause, then the weed accumulation, if preserved, would make an excellent time horizon marking the occurrence of the storm. That such accumulations can be preserved in the rock record is suggested by the buried layer in figure 27C. Furthermore, strand-line accumulations of marine vegetation have been observed in Tertiary sediments of Central Texas (A. J. Scott, 1964, personal communication).

The pelagic weeds bring to the beach a rich assemblage of open ocean fauna (fish, crabs, snails, bryozoa, shrimp, anemones, etc.). Most of these would not be fossilized, but those that were would make excellent time markers for a particular storm if properly recognized, and a puzzling stratigraphic problem if not.

Healing of hurricane channels.—Probably the major morphological change in the central Padre Island area brought about by hurricane *Carla* was the opening of numerous hurricane channels through the island; however, these channels were surprisingly short-lived. Within a few weeks the mouths of all channels had been closed to the Gulf by longshore drift. Figure 28A is a view of a channel-mouth bar deposited by longshore drift across the mouth of the second major channel south of *The Hole* (*see* fig. 23). This is the largest and most nearly permanent channel in the central Padre Island area.

The channels present an interesting stratigraphic contrast, because their sediments are distinctly different from normal forebeach and hurricane beach deposits. Even the channel-mouth bar sediments are different in that they usually have a higher sand content than normal beach deposits. Eolian sand is an important contributor to the portions of channels back of channel-mouth bars, and it overlies organic-rich pond deposits (mostly sand) in some areas. The distinction between channel and hurricane beach deposits is illustrated in figure 28B, which shows fine, cross-bedded (eolian) channel-fill deposits lying in juxtaposition with coarse shell laminae of the hurricane beach. Figure 28C shows channel-fill deposits (fine sand) overlying channel-floor sediments (coarse shell). Some writers have stated that some of these channels become filled with mud; however, no mud was observed in the

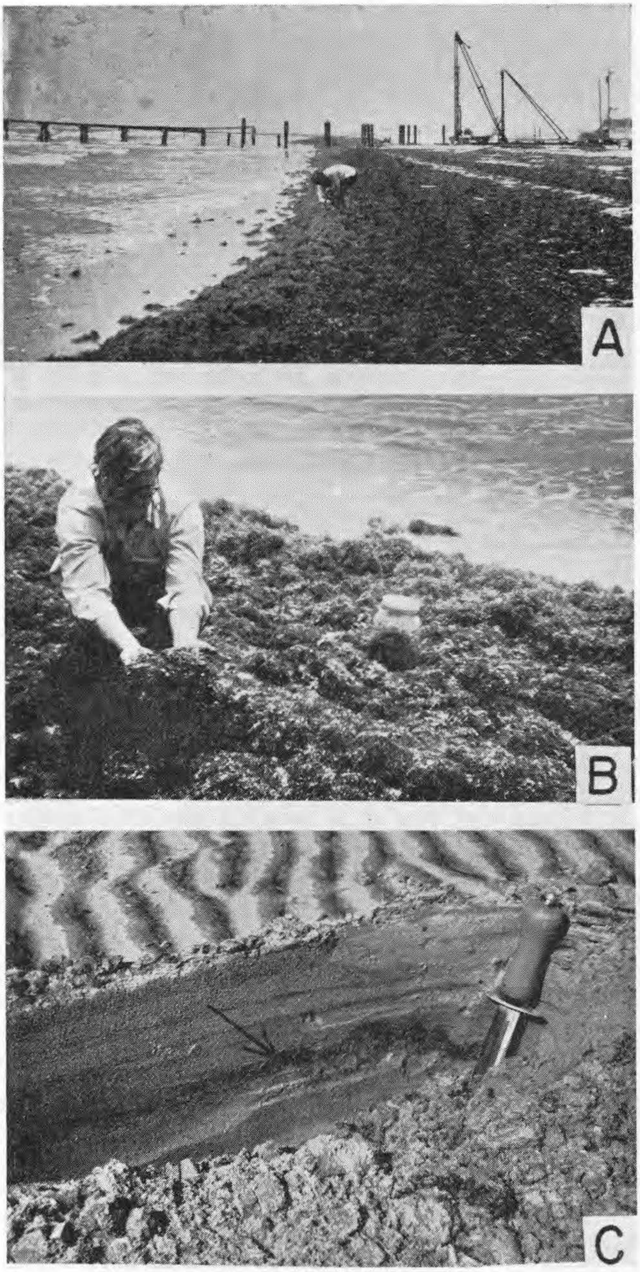


Fig. 27. Sargassum landfall.

A. Accumulation of seaweed (*Sargassum natans* and *S. fluitans*) on beach of northern Mustang Island in spring of 1962 (photograph taken May 11, 1962). The zone of weed accumulation ranged from 40 to 75 feet wide and averaged about 1 foot deep. Caldwell fishing pier, which was badly damaged by hurricane *Carla,* is under repair in background.

B. Close-up of weed at same locality and on same data as (A). Black, decaying organic matter underlies fresh weed.

C. Buried sargassum accumulation (arrow) in forebeach sediments of Padre Island near Port Mansfield jetties. Photograph taken on November 4, 1962.

channels of central Padre Island, possibly because mud is scarce in the surrounding environments (dunes, wind-tidal flats, and sandy lagoon). The possibility that mud fillings do occur in some channels cannot be ruled out, however, because this problem was not studied in detail. The distinctive differences between channel deposits and normal beach deposits, plus the usual cut-and-fill channel relationships (*see* fig. 28B), should make hurricane channel deposits easily recognizable in the rock record.

Hurricane effects on foredune cross-bedding.—The nature of foredune cross-bedding on Mustang Island. Texas, was

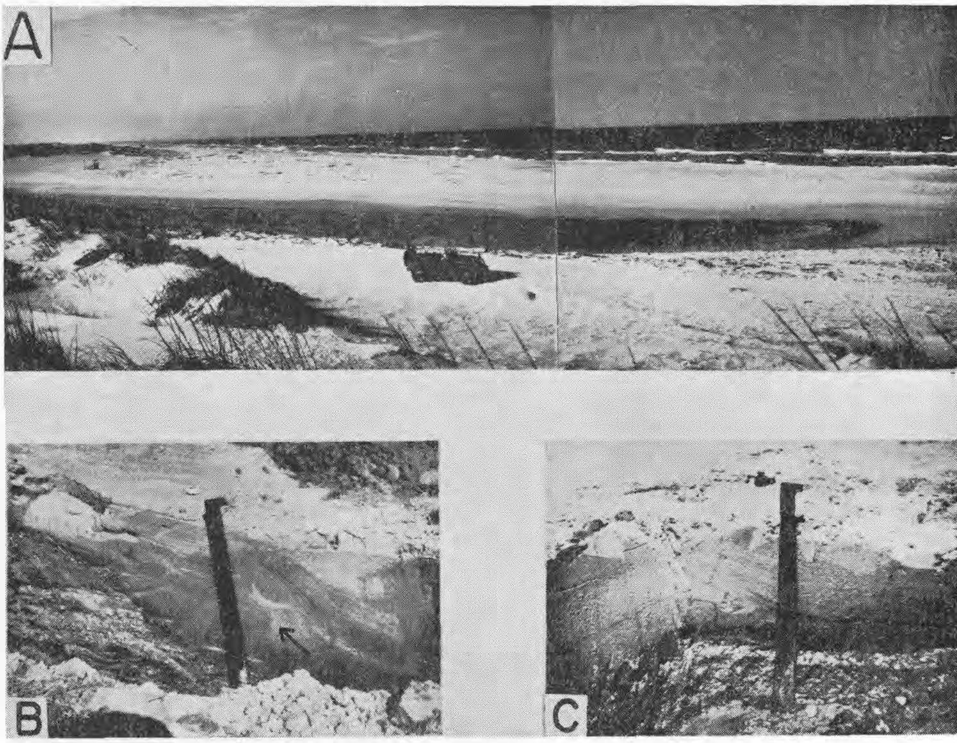


FIG. 23. Healing of hurricane channels.

A. View of central Padre Island hurricane channel (second south of *The Hole*, fig. 23), looking north-northeast on April 10, 1962. Mouth of channel is closed off by longshore drift.

B. Trench cut in side of same channel (upper left, photograph A) on April 19, 1964. Horizontal, shell-bearing sediment of hurricane beach is exposed at left and is considerably coarser than channel-fill sediment (sand and fine shell hash). Note steepness of channel side and high-angle dip of heavy mineral laminae (eolian) 6 inches to right of machete. Faint vertical notch in channel-fill sediments (arrow) probably represents small cliff cut by waves of channel pond.

C. Pit dug in major hurricane channel exposing channel-fill sediments (first major channel south of *The Hole*, fig. 23). Top of section (light color) is composed of eolian sand and fine shell hash which was blown into channel from hurricane beach. Faint high-angle cross-beds, dipping 31° south, are visible to left of machete. This eolian sand is underlain by a black, organic-rich pond deposit (mostly sand). Pond deposit is underlain by a shell pavement believed to have been deposited while the channel currents were active.

presented in an earlier paper (McBride and Hayes, 1963), which was based on a study of cross-beds exposed in wave-cut cliffs left by hurricane *Carla*. Since that time additional observations on the formation of cross-bedding on both Mustang and Padre Islands have been made. These observations indicate that two characteristics of the foredune cross-bedding on these islands can be related to hurricane activity: (1) bimodal cross-bed dip direction (fig. 29A, B) and (2) steep, seaward-dipping cross-beds.

The discovery of the bimodal cross-bed dip azimuth pattern was very puzzling. The two modes dip north and west, directions that diverge approximately 45° from what would normally be expected for the south Texas coast, which has a strong southeast-prevailing wind component (*see* fig. 29A). The hypothesis was finally formulated that a unique dune shape (asymmetrical pyramidal dunes), which has the requisite geometrical qualifications (*see* McBride and Hayes, 1963, fig. 5), was responsible for the bimodal pattern. This

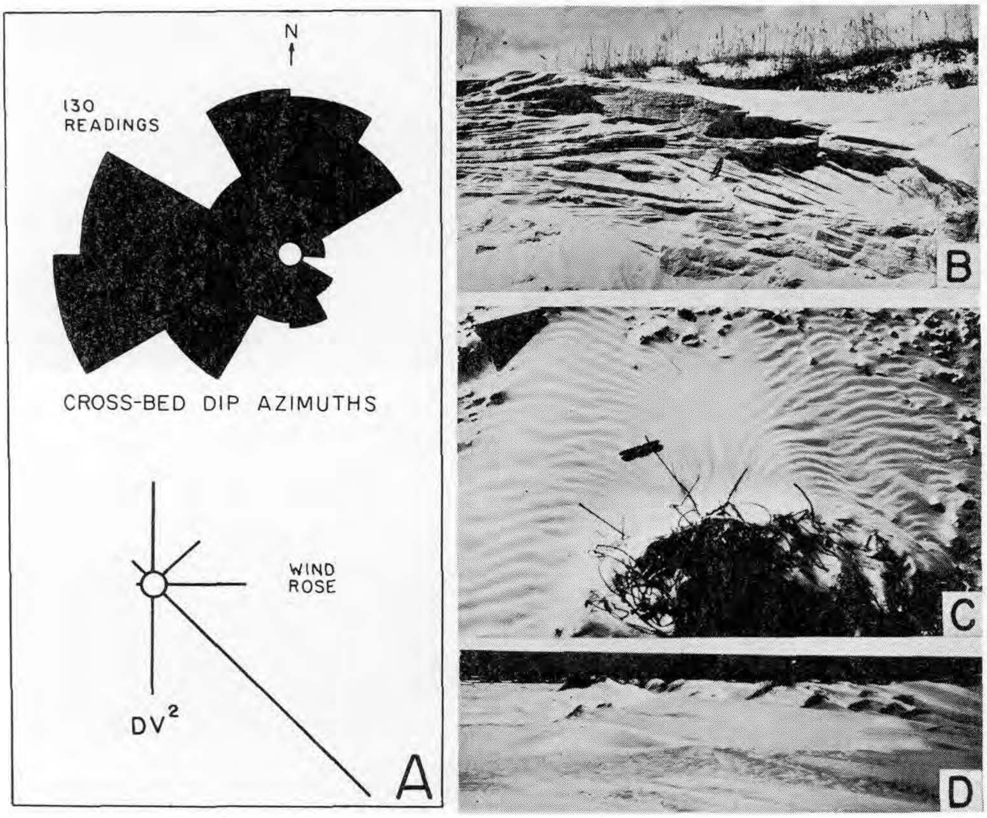


FIG. 29. Bimodal foredune cross-bedding.

A. (*upper*) Cross-bed dip azimuth histogram for 130 readings of foredune cross-bedding on Mustang Island, Texas. Pattern is bimodal; one mode dips north and one dips west (after McBride and Hayes, 1963).

(*lower*) Wind rose for Corpus Christi, Texas weather station based on duration times velocity squared (after Price, 1933, fig. 9).

Note that the two cross-bed dip modes diverge about 45° from prevailing wind direction.

B. Cross-bedding in seaward-facing cliff (cut by waves during hurricane *Carla*) of foredune on Mustang Island, Texas. The two major cross-bed sets exposed in the cliff dip in the direction of two primary modes of histogram in diagram A. (Photograph taken on September 14, 1961.)

C. Sand accumulation behind small vegetation clump on hurricane beach near southern end of Padre Island. Left and right sides of photograph are oriented N. 40° W., parallel to wind direction the day the photograph was taken (June 5, 1962). This photograph illustrates the principle of wind-shadow dune formation. This dune type is responsible for bimodality of foredune cross-bedding of Mustang Island (*see* text).

D. Abundant pyramidal, wind-shadow dunes behind vegetation clumps on Padre Island (remnants of foredune ridge left by hurricane *Carla,* 1961).

dune shape was recognized on topographic maps. McBride and Hayes further stated (p. 549) that these dunes "may be an intermediate step in the transformation of barchans to longitudinal dunes during the movement of sand inland." Observations of the foredune area during the aftermath period call for a revision of these ideas. The geometric dune shape is still thought to be correct, but the mechanism of formation is quite different for most pyramidal dunes, although the one postulated does happen occasionally.

Although a few of the steep seaward-dipping beds were observed in the original study, no origin for them was postulated.

Aftermath observations have apparently solved this problem as well.

The following sequence of events, with hurricanes as the primary cause, is thought to bring about the formation of these two distinctive features of the foredune cross-bedding on south Texas barrier islands.

Step I. Initial foredune formation on lee side of beach ridge, probably predominantly in form of active barchans, but wind-shadow dunes may also be common.

Step II. Vegetation of foredune ridge.

Step III. *Hurricane.* Foredune ridge attacked by hurricane waves. Ridge cut up into isolated vegetation clumps in some areas. Wave-cut cliffs abundant.

Step IV. *Hurricane aftermath.*

A. As soon as normal winds begin to blow again, sand begins to accumulate downwind of the isolated vegetation clumps and remnant foredunes (fig. 29C). The wind-shadow dunes formed behind these foredune remnants are asymmetrical pyramids, with two active slip faces in the wind-shadow area, one dipping north and one dipping west (under prevailing southeasterly wind conditions). The occurrence of this dune type, then, is apparently the solution to the bimodality problem. On every trip to the study area, the writer was amazed at the large number of these dunes. The abundance of this dune type along the stretch of beach shown in figure 29D is an example. These wind-shadow dunes change shape and orientation with the wind, but the prevailing southeasterlies move the most sand in the foredune area and are responsible for the observed bimodal dip directions.

B. Not only is sand blown around the vegetation clumps to form wind-shadow dunes, but it also is blown against the face of the wave-cut cliffs. Some of the sand slides back down the cliff face as a talus slope, and this talus forms the steep seaward-dipping beds. Eventually barchans migrate up the gradually reduced slope and inundate the area formerly occupied by the wave-cut cliff. This mechanism of formation of the seaward-dipping beds was observed many times. Only a few seaward-dipping beds were rioted in readings after *Carla* (*see* McBride and Hayes, 1963); the foredune ridge was cut back an exceptional distance during *Carla,* and many of the seaward-dipping beds probably were destroyed. The discovery of similar beds (steep, seaward-dipping) in an old beach ridge on Sapelo Island, Georgia, by Land (1964) emphasizes the importance of these beds in the recognition of ancient foredune cross-bedding. Land did not discuss the origin of the seaward-dipping beds.

Step V. The above steps are repeated many times. Evidence for this is given in figure 6, which shows a fence row that was exhumed by hurricane *Carla.* The fence row was built during the aftermath of some earlier storm, before the foredunes had reclaimed the back-beach area.

HURRICANE CINDY, 1963

The importance of hurricane *Cindy* has possibly been somewhat overemphasized in the earlier part of this report. Actually, as far as could be ascertained, the only major effect of the storm on the study area was the deposition of a swash bar over the contact between the hurricane beach (*Carla*) and the forebeach zone. The bar averaged about 50 feet wide and 2 to 4 feet high and covered approximately the seaward one-fourth of the hurricane beach.[12]

Details on the origin of swash bars were presented by King and Williams (1949) and King (1959). A major requirement for their formation is the occurrence of flat waves [based on wave steepness = H (height)/L(length); higher waves will build higher bars]. This requirement was met on the south Texas coast on September 16. 1963, when *Cindy* was active in the Gulf and at its nearest point to the study area (*see* fig. 3C), in that the storm was sending high (est. 8 to 10 feet), long-period waves to the beach. On that day, Charles Ellis and John Rodgers (of Sinclair Research, Inc.) and the writer observed the swash bar in formation on northern Mustang Island. The hurricane-*Cindy* bar is illustrated in figure 30.

The importance of this mild storm is that it formed sedimentary structures and deposited sediment assemblages not found under normal conditions on the barrier beaches of south Texas. For example, King and Williams (1949, p. 70) pointed out that there are two major types of beach bars, "one type being found on non-tidal beaches and the other on beaches with a considerable tidal range." They defined two correlative beach types, *ridge* and *runnel beaches* (large tidal range) and *barred beaches* (non-tidal). The Texas coast is of the barred beach type, that is, the predominant bar types are submerged break-point bars. Ridge and runnel beaches are composed essentially of a series of swash bars between mean high tide and mean low tide. In describing ridge and runnel beaches, King and Williams (1949, pp. 76–77) said:

> It was observed that the upper parts of the steep slopes of the ridges facing the sea were of smooth sand, whereas the runnels and landward facing sides of the ridges were rippled.

This is a perfect description of the hurricane-*Cindy* swash bar. Structures of a ridge and runnel beach on the German coast were described by Reineck (1964). Two of the diagnostic features he presented were festoon cross-bedding (perpendicular to beach) in the runnel and normal low-angle cross-bedding in the ridges. The writer observed similar features on the ridge and runnel beach of Jekyll Island, Georgia, in March 1964 but had seen nothing resembling these on the Texas coast before hurricane *Cindy*.

In summary, the distinctive characteristics of the beach-zone sediments of hurricane *Cindy* were:

(1) Fine, well-sorted texture. Swash bar was nowhere composed of coarse, poorly sorted material like the hurricane *Carla* beach (*see* fig. 11). Five *Cindy* bar samples were sieved, and all were similar to normal forebeach sediments.

(2) Bar structures. The swash bar had typical low-angle beach cross-bedding (fig. 30D), but dips were somewhat greater than normal forebeach beds. King and Williams (1949, p. 81) found that in wave-tank experiments the swash-zone slope is made very much steeper by the formation of a swash bar.

(3) Runnel structures. Large ripples (asymmetrical and rhomboidal; *see* fig. 30C) were present in runnel, oriented perpendicular to beach.

Swash bars are not destroyed when the water level drops, so the *Cindy* swash bar was stranded on the middle beach. Subse-

[12] This was the first time this part of the beach had been transgressed since hurricane *Carla*, which demonstrates the appropriateness of the term *hurricane beach*.

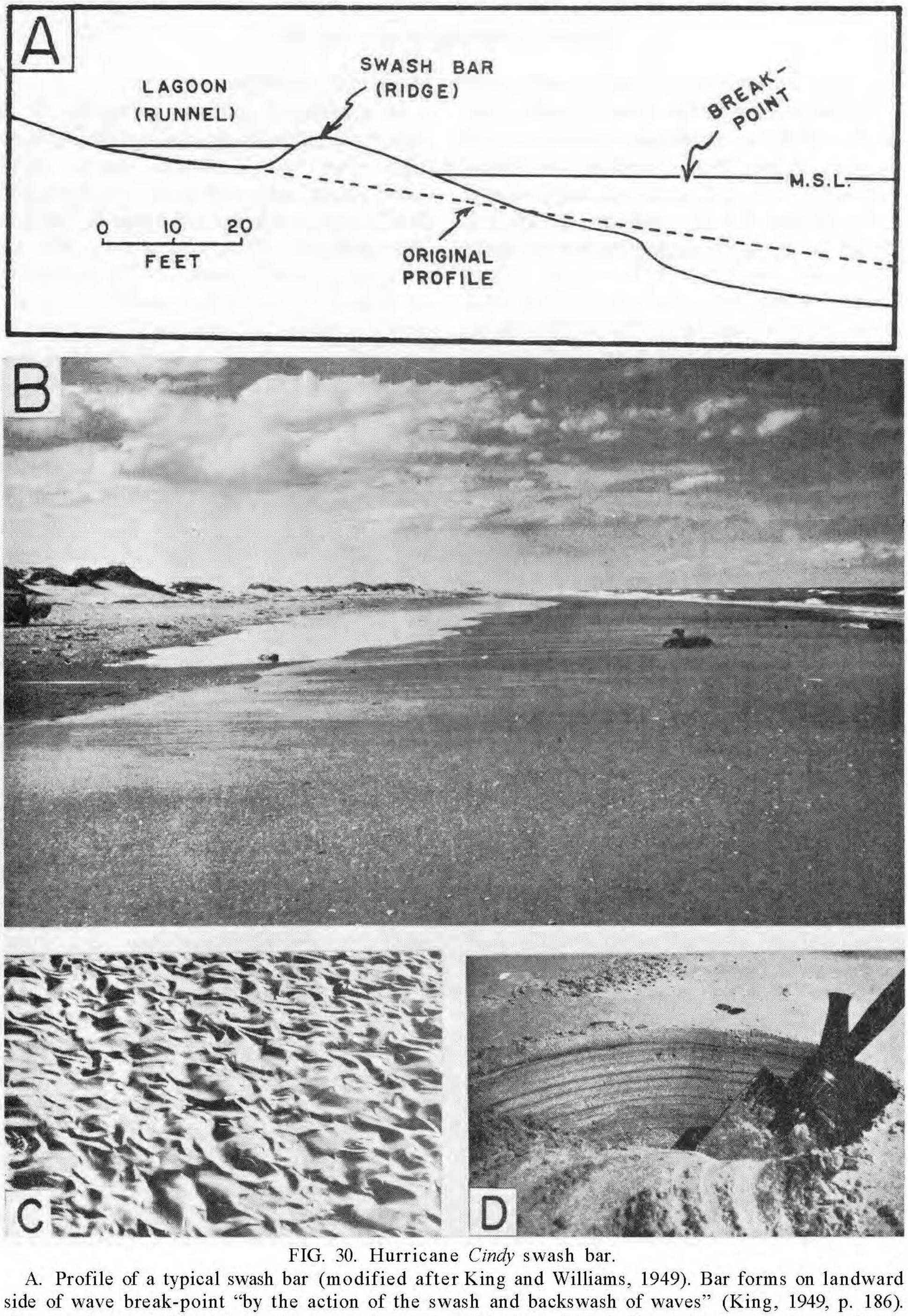


FIG. 30. Hurricane *Cindy* swash bar.

A. Profile of a typical swash bar (modified after King and Williams, 1949). Bar forms on landward side of wave break-point "by the action of the swash and backswash of waves" (King, 1949, p. 186). This mechanism of bar formation was observed on Mustang Island, Texas during hurricane *Cindy.*

B. Hurricane *Cindy* swash bar and lagoon (after 2–3-foot tide had receded) on Padre Island beach near traverse M (fig. 8) (looking north). Photograph was taken on September 17, 1963, the day *Cindy* crossed the Texas coast (far to the north).

C. Rippled surface of runnel floor at same locality (left center, photograph B). Ripples formed as result of currents (flowing parallel with beach) that were generated by excessive run-up of high waves.

D. Internal structure of *Cindy* swash bar, which is composed of relatively steeply dipping pure sand laminae. Photograph was taken at traverse O (fig. 8) on September 18, 1963 (surf at left). Compare with hurricane *Carla* beach structures (fig. 11).

quently, normal wind waves, rain, and wind flattened out the beach profile, and in April 1964 no evidence of the bar could be seen on the beach surface. Therefore, sediments and structures of mild storms are probably not as abundant in the rock record as those of major storms or those of normal conditions.

In studies of ancient sediments, it is important to be able to distinguish between high- and low-tidal-range coasts. Mild storm swash bars, such as the one deposited by hurricane *Cindy,* make the distinction more difficult.

SUMMARY

The following effects of hurricane *Carla* on the major nearshore environmental complexes of the south Texas coast were observed during the 2½-year period beginning on September 13, 1961 and ending in May, 1964.

Inner neritic zone.—As the storm moved landward, various bottom materials (rock fragments, macro-invertebrates, coral blocks, etc.) from depths as great as 50 to 80 feet were transported to the beach and scattered over the barrier island complex and wind-tidal flats. After the storm passed inland and the storm surge began to recede, strong currents spilled out of the numerous hurricane channels that were cut through the barrier island during the storm-surge flood. These currents, which presumably evolved into density currents, spread a pure sand layer (0.5 to 1.0 inch thick) over formerly homogenous mud bottom in depths of 48 to 60 feet and spread a graded bed, or *turbidite* (up to 9.0 cm thick), of fine sand, silt, and clay farther out on the shelf.

Beach zone.—The morphology of the beach zone was drastically altered by the formation of a hurricane beach ridge and by extensive flattening and broadening of the beach profile by foredune erosion. Hurricane beach deposits consist of horizontal laminations of coarse shell and sand. Commonly as many as four of Parker's (1960) environmental faunal assemblages were mixed together in hurricane beach sediments. Deflation of fine shell hash and terrigenous sand from the hurricane beach produced a surface pavement of coarse, thick mollusc shells. In May of 1962, accumulations of seaweed (*Sargassum sp.*; thought to be a result of storm activity) were drifted up on the post-*Carla* forebeach and later buried in the beach sand, thus marking the occurrence of the storm.

Foredune ridge.—The foredunes were eroded an average of 100 feet on central Padre Island. The foredune ridge was breached at many localities and completely leveled along some stretches of the beach. The nature of the cross-bedding in the dunes was strongly affected by this storm, in that during the aftermath period bimodally-dipping beds (north and west) formed in wind-shadow dunes behind vegetation clumps left by the hurricane, and steep, seaward-dipping beds were formed in front of wave-cut cliffs.

Barrier flat and back-island dunes.—The barrier flat was the scene of much erosion and deposition as waters spilled through the foredune ridge. Another increment of sediment, composed of a sand zone containing abundant festoon cross-bedding (deposited by the rapidly flowing storm-surge ebb waters) and a thin clay layer (deposited in remnant ponds), was added to the barrier flat in some places. Abundant washover material was deposited on the mainland side of the barrier flat, refurbishing the back-island dunes. Back-island dunes were eroded in places and a thin mud layer was deposited in the scour pits.

Wind-tidal flats.—Barrier wind-tidal flats received much washover material in the form of extensive washover fans spreading out from the hurricane channels. Coarse Gulf and beach macro-invertebrates, some of which were displaced as much as 2.5 miles, were numerous in the washover material. Mainland wind-tidal flats were covered with a fresh layer of mud (3 to 4 inches thick).

In September of 1963, hurricane *Cindy* deposited a swash bar (average 50 feet wide) across the contact between the old (*Carla*) hurricane beach and the post-*Carla* forebeach. Large ripples, oriented perpendicular to the beach, were formed in the runnel behind the bar.

STRATIGRAPHIC IMPLICATIONS

The stated purpose of this report was to present evidence that would assist in recognition of catastrophic storm effects in the sedimentary rock record. It is hoped that comparison of features described herein with similar features in ancient sediments will aid in this task. There are, however, certain stratigraphic implications in these findings that have greater significance than merely defining storm deposits. Some of these are:

(1) Of major importance is the extent of mixing of environment-sensitive faunas. Many artificially constructed faunal assemblages for ancient sediments deposited in the nearshore zone (area where environment transitions are most sharp and most numerous) may be made up of individual species that lived in several different environments. Hence, it is recommended that extreme caution be employed in the reconstruction of paleo-environments based on faunal assemblages, especially if the outcrop area is limited and surrounding sediments and faunal assemblages cannot be studied in detail.

(2) The importance of catastrophic storms as sediment movers cannot be overemphasized. This is apparent from the role that hurricanes play in the infilling of Laguna Madre (washover fans and back-island dune sand derived from washover material). During sediment transport by a storm, several environments may be by-passed. For example, surf zone sediments by-pass the beach zone, foredune ridge, barrier flat, and back-island dune fields on their way to the wind-tidal flats (as washover fans).

(3) One of the most striking stratigraphic effects of hurricanes is the displacement of *sedimentary processes.* For example, the hurricane washover-runway on Padre Island assumed many of the characteristics of a river channel during the storm-surge ebb of hurricane *Carla.* The reconstructive ability of the paleogeographer and paleoecologist depends on how well he can conjure up a mental image of an environment and its associated sedimentary processes and apply this image to an outcrop of ancient sediments. The introduction of alien sedimentary processes into an area by catastrophic storms taxes the imagination even more, because these infrequent visitations of exceptionally effective processes must be pictured against a background of all the *normal* processes that are at work in the area. Even environments that are essentially dormant, such as parts of the inner continental shelf and bay centers, are hosts to very active processes during storms (e.g., wave action and density currents on the inner continental shelf).

(4) Observations made in this study indicate that most energy is expended in present-day nearshore-marine environments, not in a uniform, constant manner but rather in sporadic bursts, or spurts, as a series of minor *catastrophes.* Examples of these repeating energy bursts are hurricanes, “northers,” turbidity currents, and many others. This brings to mind the concept on which quantum mechanics is based, the quantum theory. This hypothesis accounts for the stability of the atom and other phenomena on the premise that in radiation the energy of electrons is discharged not continuously but in discrete amounts, or *quanta.* This is also apparently the way most energy is expended in nearshore sedimentary environments, that is, within short time intervals that are separated by long periods of relative calm.

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