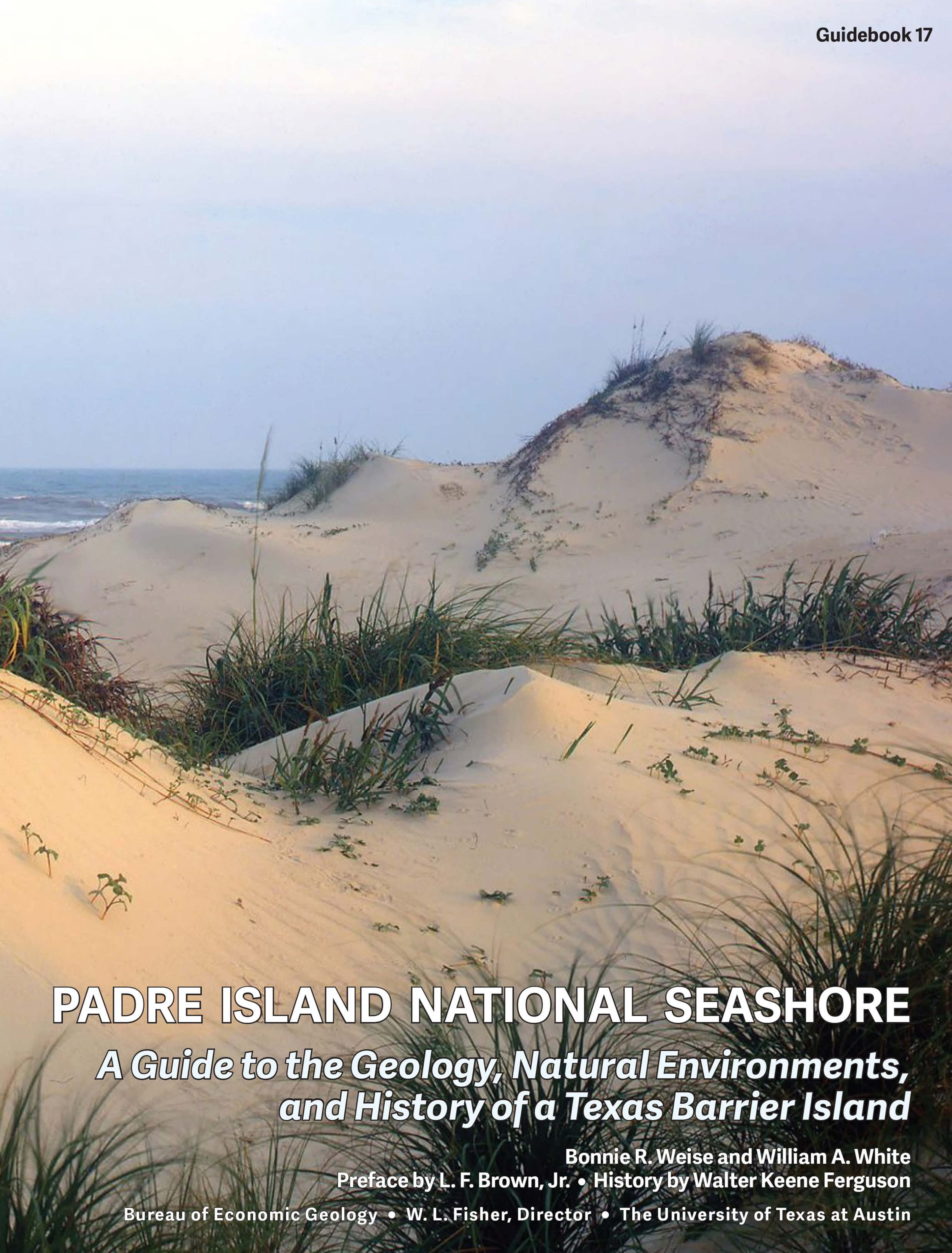
Guidebook 17



PADRE ISLAND NATIONAL SEASHORE

A Guide to the Geology, Natural Environments, and History of a Texas Barrier Island

Bonnie R. Weise and William A. White
Preface by L. F. Brown, Jr. • History by Walter Keene Ferguson

Bureau of Economic Geology • W. L. Fisher, Director • The University of Texas at Austin

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A Guide to the Geology, Natural Environments, and History of a Texas Barrier Island

BONNIE R. WEISE
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1980
Second Printing, August 1991
Third Printing, April 2016

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ISSN: 03634132
ISBN: 978-1-970007-04-6

BUREAU OF ECONOMIC GEOLOGY • W. L. FISHER, DIRECTOR • THE UNIVERSITY OF TEXAS AT AUSTIN • AUSTIN, TEXAS 78713

Cover: View of the surf zone from sand dunes that have been partly stabilized by driftwood and sea oats (*Uniola paniculata*), Padre Island National Seashore. Photo by William A. White.

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PREFACE

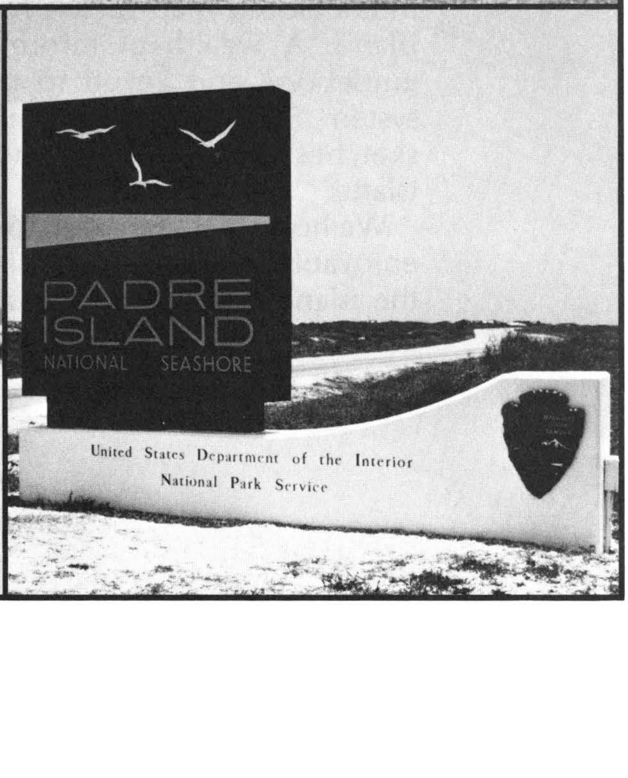
For the past decade, geologists at the Bureau of Economic Geology, The University of Texas at Austin, have prepared many kinds of maps of the Texas Coastal Zone. The *Environmental Geologic Atlas of the Texas Coastal Zone,* a seven-volume series, includes environmental geologic maps as well as other maps depicting special features of the region such as land use, mineral and energy resources, and natural processes. A special atlas, *Natural Hazards of the Texas Coastal Zone,* illustrates the occurrence and significance of such hazards as hurricane tidal flooding, coastal erosion, and land subsidence. Another atlas, *Sediment Distribution, Bathymetry, Faults, and Salt Diapirs on the Submerged Lands of Texas,* presents a view of Texas lands beneath bays, lagoons, and the inner continental shelf. These and other published maps of the Texas Coastal Zone provide a comprehensive picture of the natural environments and man-made features of this remarkable coastal region.

More and more Texans and out-of-state visitors are becoming interested in the Coastal Zone and its recreational attributes, economic potential, and environmental sensitivity. Consequently, our coastal geologists have prepared a nontechnical guide to a fascinating part of our Coastal Zone — Padre Island National Seashore. We hope that this guidebook and map will acquaint the casual seashore visitor with our most primitive Texas barrier island. For more serious amateur naturalists, the guidebook and map provide an introduction to the many natural environments and active processes that compose this South Texas barrier island.

The guidebook is designed to complement the accompanying multicolored map of the natural and man-made features of the island. A wealth of information has been summarized in the guidebook and keyed to the map using a coordinate location system. Similarly, many ground-level and aerial photographs and sketches explain the past history and current character of Padre Island.

We hope that the guide to Padre Island will make your visit more enjoyable. Perhaps your visit will give you a fuller appreciation of the island's natural setting and its sensitivity to natural processes and man's modification.

L. F. Brown, Jr.
Associate Director
Bureau of Economic Geology
The University of Texas at Austin
September 1980


PADRE
ISLAND
NATIONAL SEASHORE
United States Department of the Interior
National Park Service

INTRODUCTION

Stretching 113 miles under the South Texas sun is the longest barrier island in the United States. This is Padre Island—where shipwrecked Spaniards were once pursued and massacred by fierce Karankawa Indians; where Pat Dunn's vaqueros herded thousands of cattle in preparation for trips to the market; and where now almost a million visitors every year spread out along the miles of sandy and shelly beaches to enjoy the untamed beauty of Padre Island National Seashore.

To those experiencing the serenity and solitude of Padre's primitive stretches, the island may seem forever unchanging. But geologically, Padre is actually a dynamic system of environments that change almost continuously. The face of Padre is shaped by the day-to-day action of the wind, currents, waves, and tides. Even more important, large storms, especially hurricanes, produce dramatic changes on the island. Padre Island can be thought of as a natural laboratory where complex interaction of the wind, land, and sea produces unique features and environments that can be examined and questioned by all who visit the National Seashore.

PURPOSE AND SCOPE OF THE GUIDE

The Guidebook

This guide to Padre Island National Seashore describes and explains island and lagoon environments, the active processes that constantly change the face of Padre, and natural records left by those processes. A road log for a short field trip directs readers to these environments and effects of the active processes. The guide also presents summaries of the geologic origin and history of Padre, as well as the history of human use of the island and interaction with the natural environments.

Because this book is designed for an audience with a wide range of interests, education, and experience, the text should prove useful and interesting to geologists and students as well as to the casual island observer. Although this guide is essentially nontechnical, it is necessary to include some terms that are probably unfamiliar to many readers. These terms are explained on first use within the text and also in a glossary at the end of this guidebook.

The Geology and Natural Environments Map

A colored map of the National Seashore (pl. I, in pocket) illustrates the present geologic and man-made environments of the island and lagoon. Natural environments were mapped on the basis of origin, landforms, vegetation, and active processes. Several special features ensure that the map can be read easily by geologists and nongeologists alike. To aid those unfamiliar with reading maps, a detailed explanation of the map and its use is presented in a later section (see p. 10-12).

Padre is a barrier island with rapidly changing environments. Despite inevitable natural changes on the island, the Geology and Natural Environments Map will remain a useful record from which to monitor future changes. The map can also serve as an illustration, or model, of those environmental relationships that do not change and that can be observed repeatedly on Padre and on similar barrier islands.

GENERAL SETTING

Location

Padre Island is one of the southernmost links in the chain of barrier islands and peninsulas along the curving Texas coastline (fig. 1). Broken only by a man-made channel, Mansfield Channel, this island extends southward from Corpus Christi almost to Mexico. Padre Island is separated by Brazos Santiago Pass from Brazos Island, which lies at the southern end of the chain. Corpus Christi Pass, a natural pass to the north, once separated Padre Island from Mustang Island but is now filled so that the two islands are joined.

Although an attractive site for resorts, most of Padre has remained undeveloped. In 1962, the United States Congress passed legislation establishing Padre Island National Seashore; this 80-mile segment of Padre Island will preserve the natural qualities of this pristine island (fig. 1).

Physiography and General Geology

PADRE ISLAND

Geologically, Padre Island is very young; its oldest deposits are only several thousand years old. Waves and currents in the Gulf of Mexico piled sand into a barrier island separated from the Texas mainland by a lagoon, Laguna Madre. Most of Padre Island is less than 20 feet above mean sea level. However, the island's highest points, along the fore-island dune ridge, reach up to 50 feet above sea level. Nearest equivalent elevations are about 25 miles inland.

Prevailing southeasterly winds from the Gulf of Mexico heap beach sand into high foredunes. In some places, the onshore wind may blow loose sand from the foredunes and beach across the flats beyond. Active sand dunes march across the island, smothering vegetation in their paths and leaving barren sandflats in their wakes. In other places, vegetation

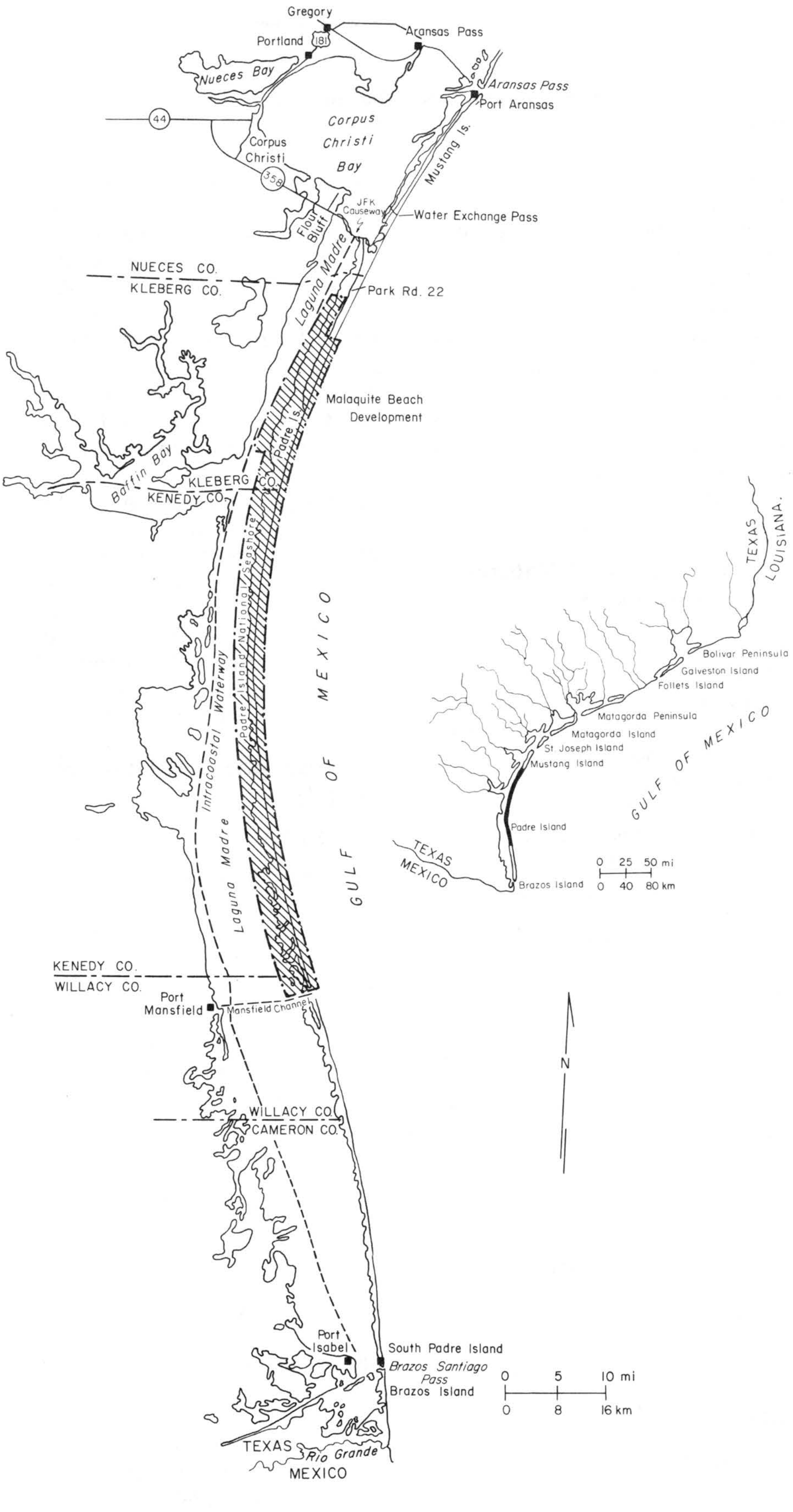


Figure 1. Index and location maps for Padre Island and the surrounding area.

may win a battle of its own and stabilize the blowing sand by binding it with roots and vines. Slower daily movements of the sand and stabilizing effects of vegetation are interrupted occasionally by the brutal force of hurricane winds, waves, and tides. During storms, beaches are eroded, vegetation is ripped up, dunes are flattened, and channels are scoured across the island.

These natural processes at work on Padre have produced a predictable pattern of environments across the island, which, within the National Seashore, varies in width from about 1,000 yards to about 2.5 miles. A common sequence of environments from the Gulf to Laguna Madre includes the sand and shell beach; a stable ridge of fore-island dunes; vegetated flats with scattered, stabilized, grass-covered dunes; the barren, shifting sands of back-island dune fields; and the featureless plains of wind-tidal flats (fig. 2).

Not only do environments change across the island, but also considerable variation occurs within each environment along the length of the island. For example, the beach changes from a gently sloping sand beach on north Padre, to the steeper Little Shell and Big Shell Beaches on central Padre, to the mixed sand and shell beaches on south Padre. The fore-island dune ridge is highest and most continuous adjacent to the shell beaches. However, in the southern parts of the Seashore, the ridge is absent or present only as short segments of low foredune ridges because of (1) higher shoreline erosion rates, which reduce the amount of sediment available for dune construction, and (2) a drier climate and consequently much less vegetation to bind the sand. Without the protective natural barricade provided by the dune ridge, the southern parts of the island are much more susceptible

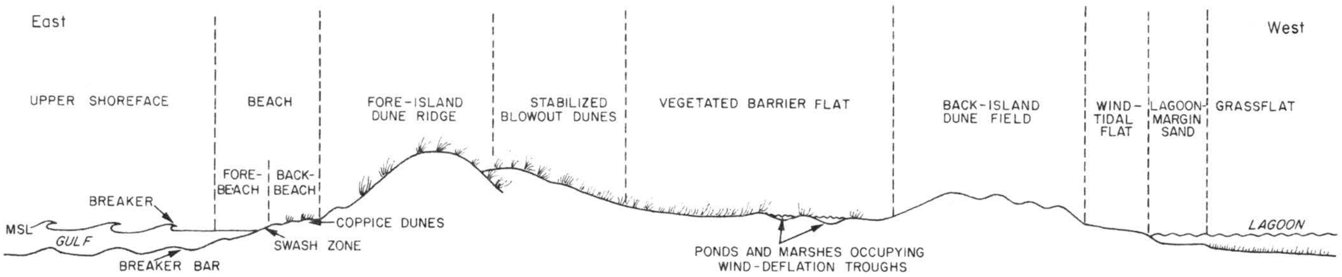


Figure 2. Generalized cross section of north Padre Island environments, from the Gulf shoreline to Laguna Madre (modified from McGowen and others, 1977).

to breaching during the fury of hurricanes. Therefore, storm washover channels are much more prominent on the southern part of Padre Island.

LAGUNA MADRE

Laguna Madre, separating Padre Island from the Texas mainland, is locked in by the barrier island. Consequently, circulation of seawater in and out of the lagoon is highly restricted. The combination of a high rate of evaporation under the hot Texas sun and little mixing with either fresh water or normal seawater has made Laguna Madre extremely salty.

The maximum width of the lagoon is approximately 10 miles. In many places, however, lagoon width fluctuates considerably with the height of wind-generated tides. The lagoon is widest during highest wind tides, which produce maximum flooding of the vast tidal flats.

Like the island environments, the environments of Laguna Madre vary considerably. Within the National Seashore, the northern part of the lagoon is occupied largely by grassflats having an average water depth of about 3 feet. These grassflats are environments of very high biologic activity, serving as spawning grounds for a number of fish, clams, and snails.

The shallowest parts of the lagoon lie in the central part of the National Seashore. These areas are known as *Middle Ground* and the *Land-Cut Area*, where the Intracoastal Waterway was dredged through the rarely flooded wind-tidal flats (pl. I). The Hole, which lies between Middle Ground and the Land-Cut Area, is not really much of a hole; its average depths are only 1 to 2 feet. This "hole" is occupied mostly by flats supporting shoalgrass and algae. The deepest parts of the lagoon are south of the Land-Cut Area, where the muddy sand bottoms lie at depths as great as 8 feet (pl. I).

Two small natural islands in Laguna Madre are unique environments within the National Seashore. North and South Bird Islands (pl. I), each a series of sand berms or ridges, have become important bird rookeries. Some of the man-made spoil islands along the Intracoastal Waterway are also nesting grounds for a variety of birds.

Climate

The climate of Padre Island is subtropical and semiarid — in other words, generally hot and dry. Summers are long and hot, and winters are relatively short and mild. Spring and fall are merely transitional periods.

PRECIPITATION AND EVAPORATION

Average annual rainfall ranges from approximately 29 inches at the northern end of the island to approximately 26 inches at the southern end (fig. 3). Evaporation rates increase southward along the island. The combination of lower annual rainfall and higher evaporation rates for south Padre results in a drier climate and a different set of environments from those on north Padre.

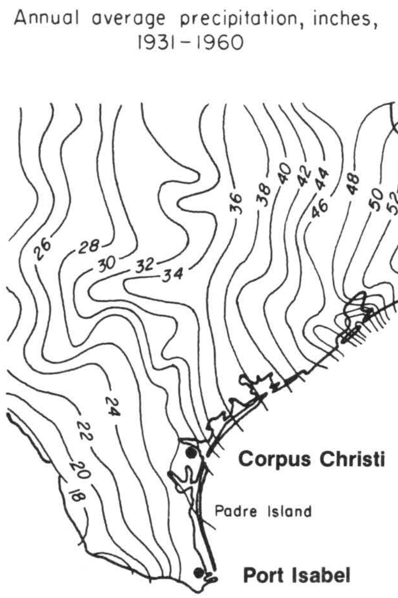
TEMPERATURE

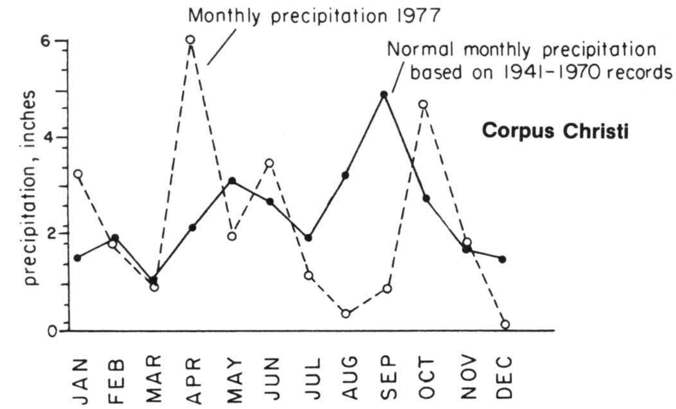
The higher rate of evaporation in the south results from higher mean annual temperature (fig. 4). Average temperatures range from approximately 72°F in the north to approximately 74°F in the south. Temperatures on the island are moderated by tropical maritime air coming off the Gulf of Mexico. Although temperatures on the nearby Texas mainland commonly exceed 100°F during the summer, island temperatures are rarely above 95°F. At Corpus Christi, on the mainland near the northern end of the island, the temperature falls to freezing or below about 10 times a year (Dahl and others, 1974). Freezing temperatures, however, are less frequent southward and are rare on Padre Island.

WINDS

The prevailing winds (winds that blow across Padre most frequently) are southeasterlies (fig. 5). Winds are mostly from the southeast in the summer months, or from about May through September. However, during the winter, from December through February, wind direction fluctuates between northerly and southeasterly, as a series of "northers," or cold polar fronts, pass through the coastal area.

Direction is not the only important aspect of the wind that influences island and lagoon





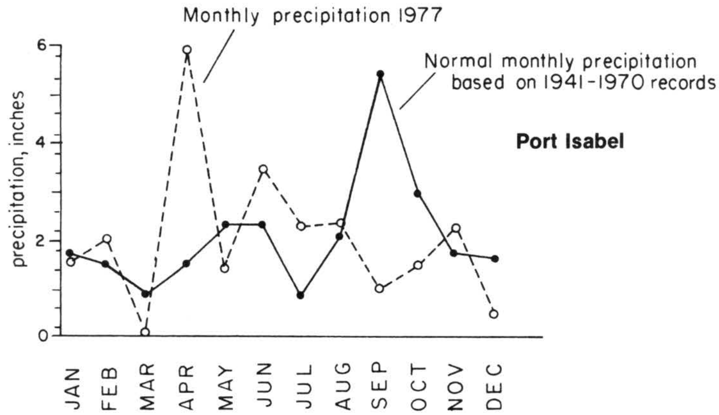
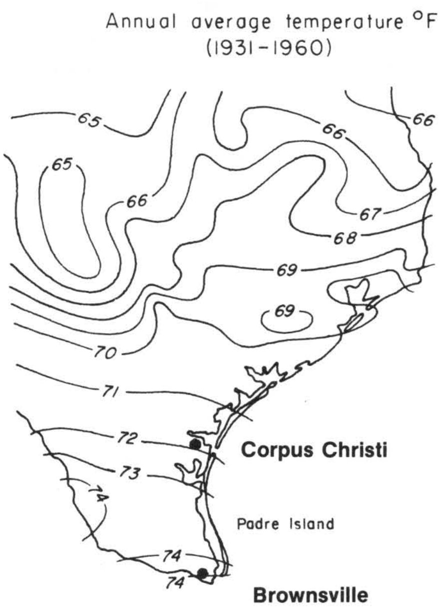


Figure 3. Annual average precipitation along Texas coast and monthly precipitation data for Corpus Christi and Port Isabel, Texas. Note that annual average precipitation decreases down the coast (southward). Curves showing normal monthly precipitation exhibit peaks in May and September, but variations from these normal levels may occur during any year as indicated by the 1977 monthly precipitation curves. (Data on annual average precipitation from Carr, 1967; data on monthly precipitation compiled from records of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service.)



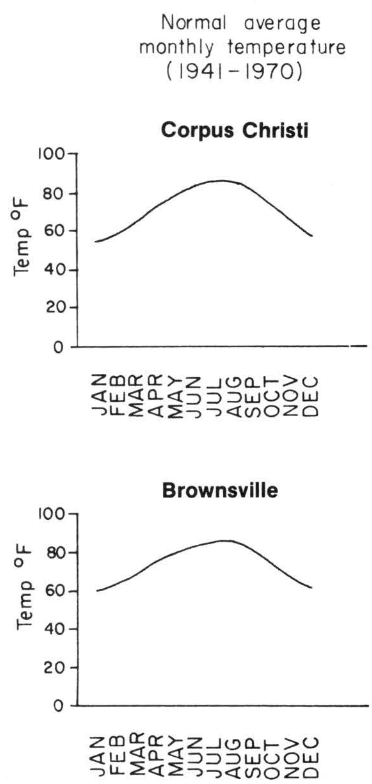


Figure 4. Annual average temperatures along Texas coast and average monthly temperatures for Corpus Christi and Brownsville, Texas. Note that annual average temperature increases down the coast (southward). (Annual average temperature from Carr, 1967; average monthly temperature compiled from records of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service.)

environments. The ability of the wind to transport sand and generate currents, waves, and tides depends on the velocity and duration of the wind. Dominant winds, capable of transporting sand, are from the north to north-northeast and from the south-southeast to southeast. Winds sweeping across Padre reach velocities high enough to transport sand about 85 percent of the time (Dahl and others, 1974).

Hurricanes and Tropical Storms

The average climatic conditions previously described are punctuated by fierce tropical storms and hurricanes. Tropical storms become hurricanes when the wind velocity exceeds 74 miles per hour. Wind velocities in the most intense hurricanes may exceed 200 miles per hour. The cyclonic wind circulation of these storms, which may be hundreds of miles in diameter, has a counterclockwise motion in the Northern Hemisphere. The storms are characterized by very low barometric pressure, with the lowest pressure in the central calm region, or eye, of the storm. Hurricanes may deposit tens of inches of rain and commonly spawn tornadoes, contributing to their destructiveness (see table 1, p. 39).

Tropical cyclones (tropical storms and hurricanes) strike the Texas coast at an average rate of 0.67 storms per year (Hayes, 1965). In other words, two storms strike the coast every three years. Most hurricanes hitting the Texas coast originate in the Caribbean Sea or Gulf of Mexico. The hurricane season actually begins in late spring, but the prime time for tropical cyclone development is late summer and early fall, or from August through October. One of the largest and most destructive recorded storms to strike the Gulf Coast was Hurricane Carla, which formed in the Caribbean in early September, 1961. Although the eye of Carla struck the central section of the Texas coast in the Port O'Connor area, hurricane winds affected almost the entire Texas coast and part of Louisiana. Maximum wind velocity in the storm was estimated to be about 175 miles per hour (Hayes, 1967).

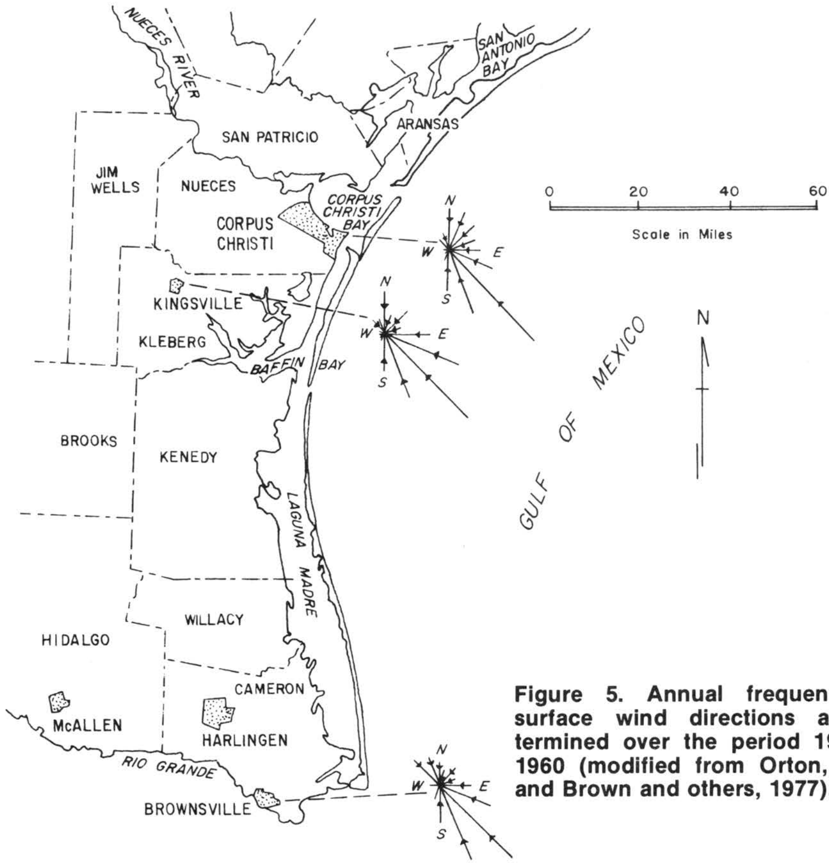


Figure 5. Annual frequency of surface wind directions as determined over the period 1951 to 1960 (modified from Orton, 1964, and Brown and others, 1977).

The destruction caused by hurricanes can be tremendous. On the open sea not even the largest vessels are safe. Once these storms strike land, they may move hundreds of miles inland before finally dissipating. Within the United States alone, hurricanes have caused millions of dollars' worth of property damage and have taken thousands of lives. The high winds are not the only direct, damaging forces of the storms; many times the storm tides, huge waves, strong currents, and heavy rainfall accompanying hurricanes have even greater impact. A section of this guide describes hurricanes and their effects on Padre Island (see p. 38).

ESTABLISHMENT AND MANAGEMENT OF PADRE ISLAND NATIONAL SEASHORE

Creation of a National Seashore

In 1954, the U.S. National Park Service surveyed the 3,700 miles of U.S. coastline and discovered that only 6.5 percent of the coastline was reserved for public recreation. The Park Service recommended that national parks be created in three coastal areas: (1) Point Reyes, California, (2) Cape Cod, Massachusetts, and (3) Padre Island, Texas. Legislative action, however, was necessary to acquire lands for the national parks, or *seashores,* as they were later named. Senator Ralph Yarborough introduced the first Padre Island bill to the U.S. Congress in 1958. After several years of hearings, Congress, on September 28, 1962, passed the law establishing Padre Island National Seashore.

The enabling legislation, Public Law 87-712, stated the purpose of Padre Island National Seashore: "to save and preserve, for purposes of public recreation, benefit, and inspiration, a portion of the diminishing seashore of the United States that remains undeveloped. . . ." Indeed, Padre Island is the largest stretch of undeveloped ocean beach in the United States.

The legislative act of 1962 authorized no more than $5 million for purchase of land for the newly created National Seashore. Subsequent legislation in 1968 and 1969, however, provided more money for land acquisition. The Federal Government has spent almost $16 million for land within Padre Island National Seashore.

The 1962 legislation also set the boundaries of the Seashore. Except for an extension of the Seashore south of Mansfield Channel, these boundaries are shown on the Geology and Natural Environments Map (pl. I). South of Mansfield Channel, the National Seashore includes only 2 small pieces of land totaling 18 acres, plus 11.5 miles of beach donated by the State of Texas. However, a proposed boundary change for southern Padre Island National Seashore is described in the National Park Service Master Plan (1973). This will provide space for recreational facilities on the south side of Mansfield Channel. The Park Service will exchange its land south of Mansfield Channel for land adjacent to the channel. The section of beach donated by the State and lying south of the channel will be returned to the State.

U.S. National Park Service and Seashore Management

Padre Island National Seashore is administered by the U.S. National Park Service, U.S. Department of the Interior. Park Service headquarters are located in Corpus Christi on South Padre Island Drive, the main access route to the Seashore.

Management objectives outlined by the National Park Service in its Master Plan for the Seashore (1973) are (1) to serve the visitor, (2) to preserve the resource, and (3) to administer the area. The Park Service serves Seashore visitors by providing information, by maintaining park facilities and roads, and by aiding those in need of assistance. Also for the benefit of visitors, the Park Service has established certain regulations governing camping, swimming, fishing, hiking, driving, boating, and other activities. Information concerning these guidelines, which help assure the greatest degree of safety and enjoyment for Seashore visitors and protection of natural environments, may be obtained either at Park Service headquarters or at the Ranger Station on the island.

The National Park Service is responsible for the development and maintenance of all facilities within the National Seashore, except for oil company facilities, roads, and channels. In addition, the Park Service cooperates with the State of Texas and the National Audubon Society in managing wildlife resources and works closely with the U.S. Coast Guard in rescue operations.

Visitor Facilities

Visitor facilities at Malaquite Beach are located near the end of Park Road 22 approximately 5 miles south of the Seashore entrance (fig. 6). This beach development (pl. I, photograph M4, and fig. 7) includes a snackbar, a gift shop, free showers, locker rooms, observation decks, and a large, paved parking lot. Although wells and tanks on the island provided fresh water for ranching operations, water is now piped to the Malaquite Beach development from Corpus Christi.

A tower near the main facility provides an observation deck and water storage below. A few hundred yards north of the visitor facilities is a paved campground (fig. 8), accessible from Park Road 22. The campground provides numerous sites for trailers and recreational vehicles. The beach in the Malaquite area is regularly cleared and maintained; it is closed to vehicular traffic between the two beach access roads, a distance of about 4.5 miles.

Plans for new developments within the National Seashore include expanding the present Malaquite Beach facilities, creating access to Laguna Madre in the Bird Island Basin area, extending the road system to Yarborough Pass, and constructing recreational facilities at Mansfield Channel. Future developments will provide easier access and service to remote parts of the island but will be designed to maintain the primitive nature of the beach and interior lands. The U.S. National Park Service Master Plan (1973) for Padre Island National Seashore, available at Park Service headquarters and the Ranger Station, describes these and other proposed changes.

Access to Island and Lagoon Environments

ISLAND ACCESS

Roads — Visitors may reach North Padre Island by way of Mustang Island on the north or via the John F. Kennedy Causeway, which crosses Laguna Madre from Flour Bluff to Padre Island (fig. 1). The road leading into the National Seashore is Park Road 22; it is a paved, two-lane highway winding down the middle of the island. Park Road 22 ends as a beach access road about 5.5 miles south

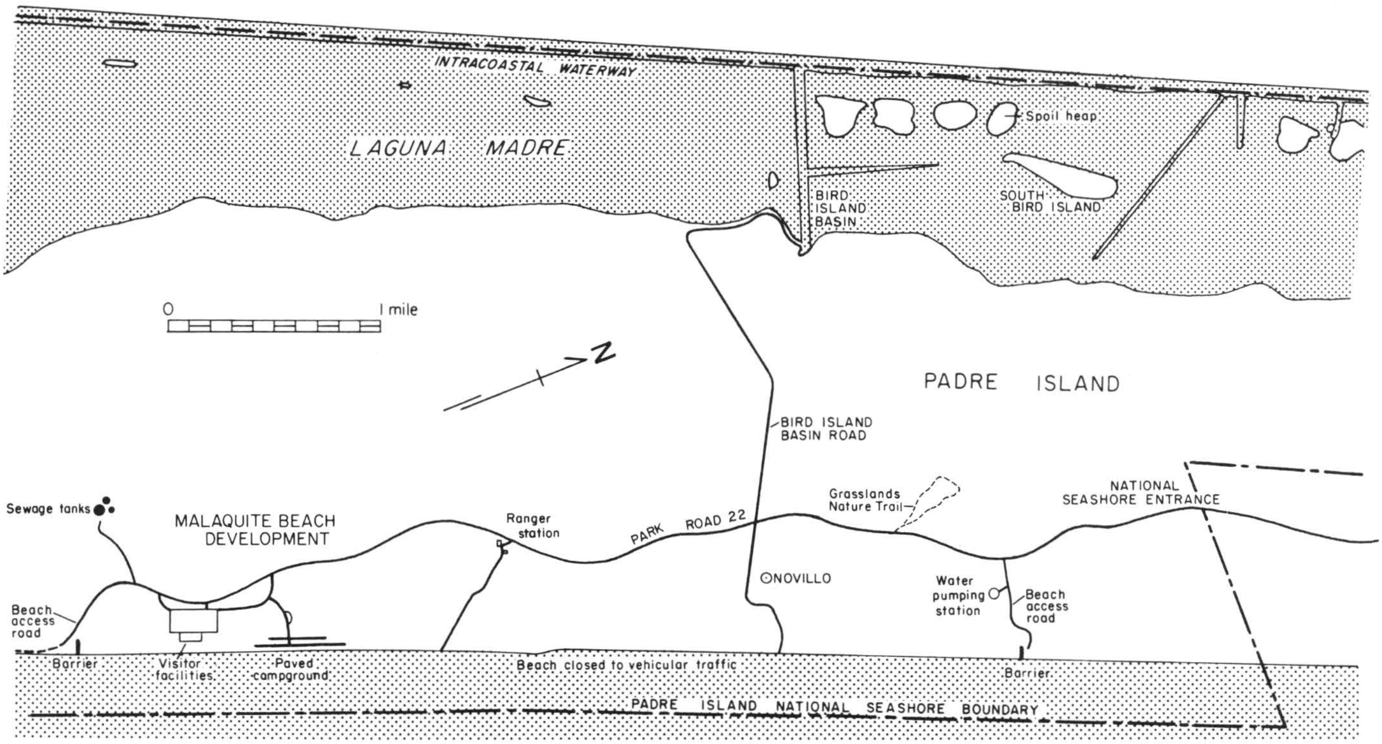


Figure 6. Index map of the northern part of Padre Island National Seashore.

of the Seashore entrance (fig. 6). Another beach access road branches from Park Road 22 about 1 mile south of the Seashore entrance. The beach may be reached also by taking the road to the paved campground just north of the Malaquite visitor facilities. The Bird Island Basin road, intersecting Park Road 22 about 2 miles south of the Seashore entrance, provides the easiest access to Laguna Madre.

Crossing the island are several sand or shell-covered roads, some of which were built and are maintained by oil companies. Most of these roads require a four-wheel-drive vehicle and often are impassable, especially after rains.

Beach Travel — Vehicular travel is permitted along the entire length of the National Seashore beach *except* between the two main beach access roads. Visitors can travel on the beach southward as far as Mansfield Channel, which is not bridged. Areas south of the channel can be reached only from the southern end of the island via Port Isabel.

Special vehicles are not necessary for travel on the beach to a point about 5 miles south of the end of Park Road 22. Southward from that point, four-wheel-drive vehicles are required. The point is marked on the beach by a warning sign (fig. 9 and pl. I, grid K-4). Even with four-wheel-drive vehicles, travelers run the risk of getting stuck, especially in the slippery, loose shell material on Big Shell and Little Shell Beaches. It is recommended that all beach travelers carry shovels, jacks, and tow chains.

To aid beach travel and rescue operations, large beach markers show the cumulative mileage from

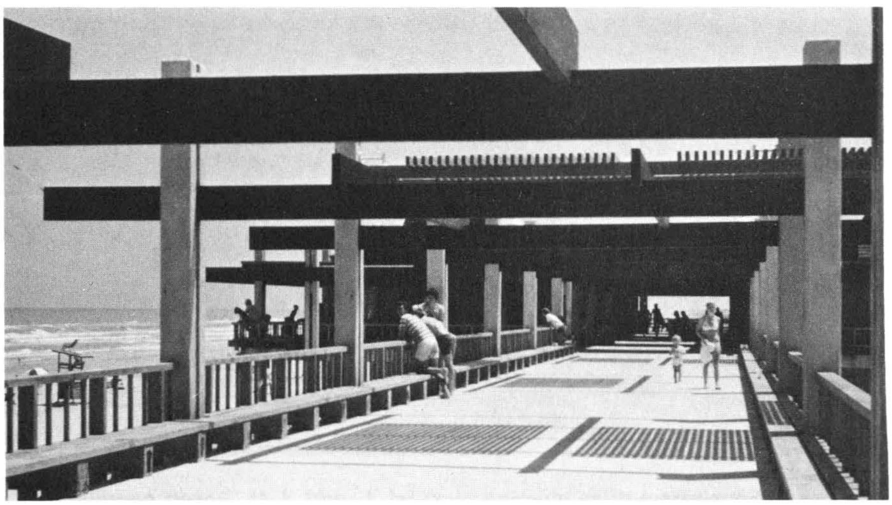


Figure 7. Observation deck and walkway at Malaquite Beach visitor facilities.

the south beach access road (end of Park Road 22) at approximately 5-mile intervals (fig. 10). Locations of these markers as of 1977 are indicated on the Geology and Natural Environments Map (pl. I). Where the markers are destroyed by storms or removed in some other way, however, their reestablished locations may not coincide with the original locations as plotted on plate I.

ACCESS TO LAGOON ENVIRONMENTS

Except along the Intracoastal Waterway or Mansfield Channel, shallow water depths restrict boating on Laguna Madre to small pleasure and fishing boats. In the northern part of the Seashore, the lagoon is deep enough during high tides to allow small boats to land on the lagoonal shores of the island. A launching facility at Bird Island Basin allows access to northern Laguna Madre from the island. However, only specialized craft, such as air boats, can navigate many areas of the lagoon. Some large areas of the lagoon are unsafe for any type of boat. In those areas, boats may become stranded during rapid lowering of water level, produced by unpredictable and irregular wind-generated tides.

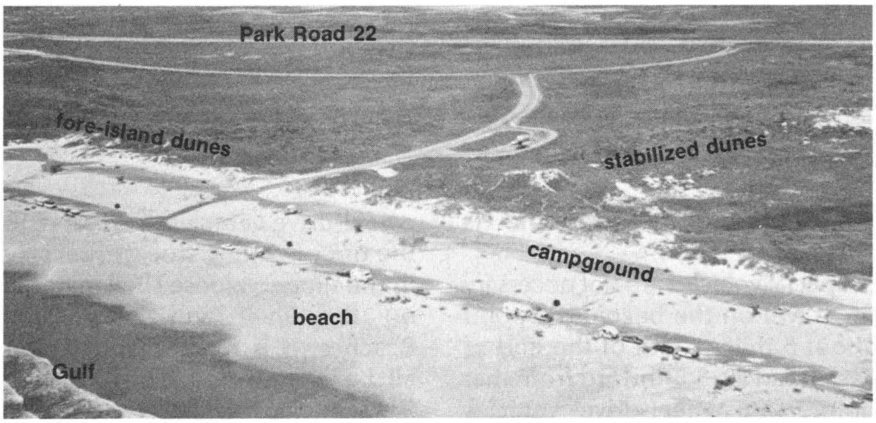


Figure 8. Paved campground just north of Malaquite Beach visitor facilities. The campground, located on the backbeach, was extensively damaged during Hurricane Allen in August 1980 (see p. 73). The above photograph was taken before the storm.

Figure 9. Four-wheel-drive warning sign (pl. I, grid K-4). Beach conditions, in particular the slippery, loose shell surface material, make vehicular travel possible only with four-wheel drive from this point south. View is to the south.

Gulf Intracoastal Waterway — The Gulf Intracoastal Waterway is a system of dredged channels providing an inland shipping route along the Gulf Coast of the United States. The principal use of the Waterway in the South Texas area is for commercial barge operations (pl. I, L7 photograph), but fishing and pleasure boats also use it heavily. The section of the Intracoastal Waterway through Laguna Madre on or near the western edge of the National Seashore (fig. 11) was completed in 1949. The U.S. Army Corps of Engineers maintains the canal's present depth of 12 feet and width of 125 feet through periodic dredging. Frequency of dredging near the National Seashore varies from 15 months to 5 years (Herbich, 1975).

A system of buoys and beacons aids navigation along the Intracoastal Waterway. These navigation markers are plotted and explained on nautical charts prepared by the National Oceanic and Atmospheric Administration. In addition, the locations of some of these markers are shown on the Geology and Natural Environments Map (pl. I).

Numerous small channels (fig. 12) branching from the Intracoastal Waterway (pl. I) were dredged to provide access to oil and gas operations. Many of these canals are now abandoned and have filled with mud and fine organic material.

Mansfield Channel — Mansfield Channel (fig. 13), located at the southern end of the National Seashore (pl. I), is 300 feet wide and 14 feet deep; it cuts through the island and lagoon to Port Mansfield on the Texas mainland. Mansfield Channel was dredged in 1957 by the Willacy County Navigation District and is maintained by the U.S. Army Corps of Engineers. The channel is used primarily by shrimp boats and pleasure boats.

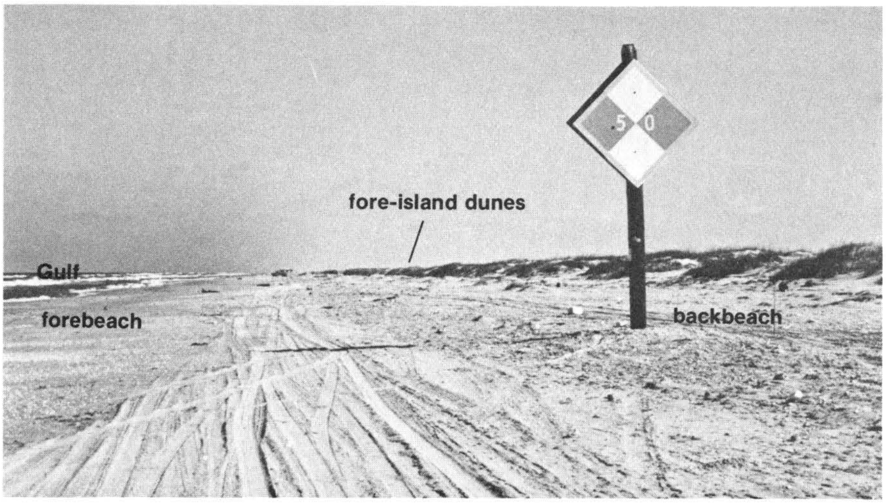


Figure 10. Beach marker showing the approximate mileage from the south beach access road near Malaquite Beach. Locations of beach mileage markers as of 1977 are plotted on plate I. Marker locations are subject to change, however, if markers are destroyed by storms or other means. View is to the south.

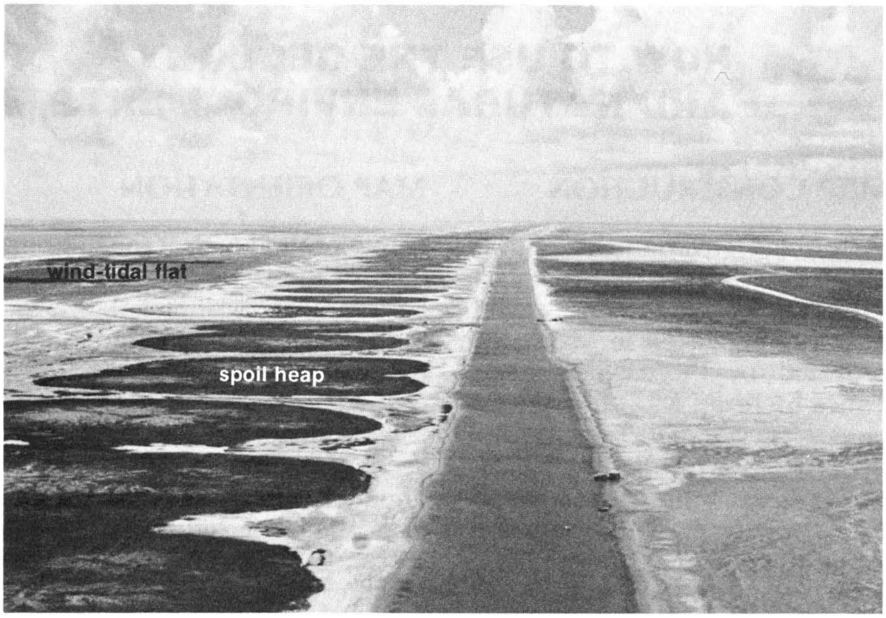


Figure 11. Intracoastal Waterway, approximately 12 feet deep, paralleled by a row of spoil heaps (pl. I, grids P-7 and Q-7). In this area the boundary of the National Seashore does not coincide with the Waterway but rather lies farther to the east (left). View is to the south.

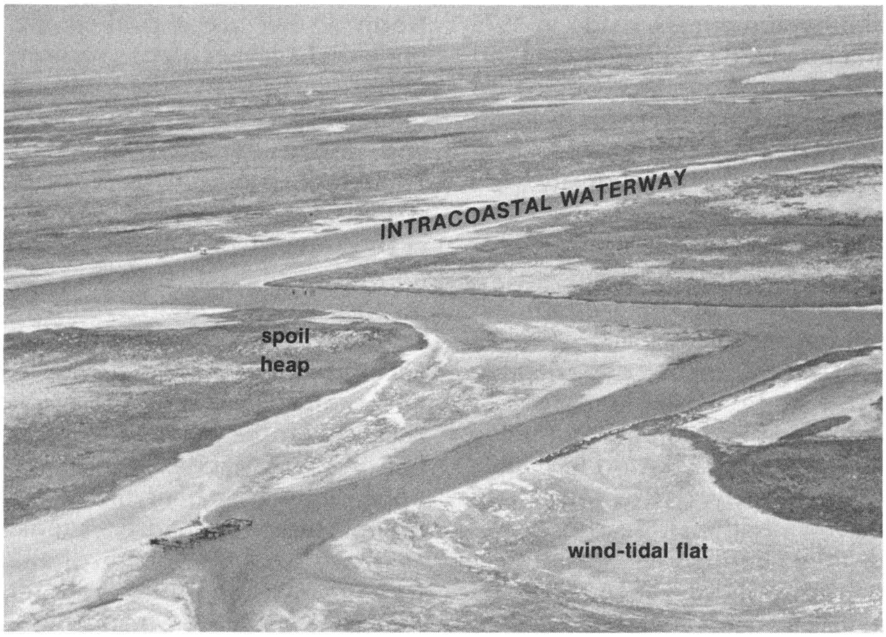


Figure 12. Petroleum company service channel dredged from the Intracoastal Waterway to provide access to a drilling site (pl. I, grid J-7). View is to the northeast.

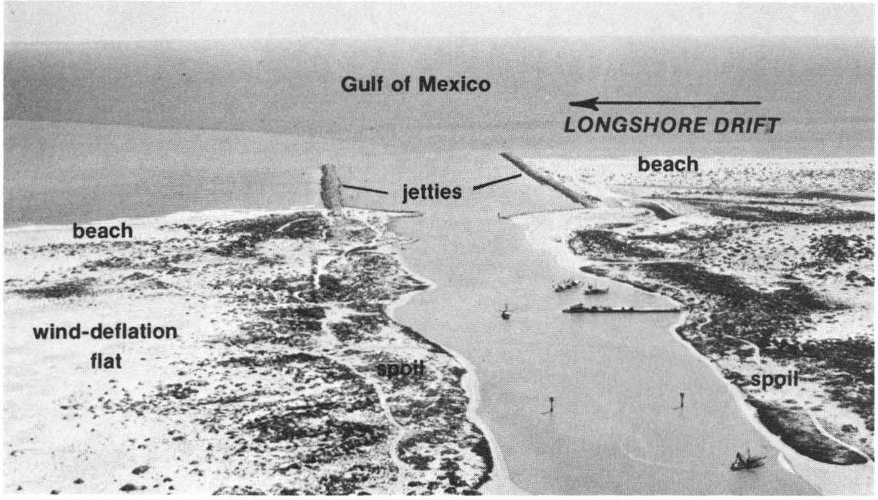


Figure 13. Mansfield Channel (pl. I, grid C-21). This channel, dredged through the island and lagoon in 1957, is used heavily by shrimp boats. The two jetties, constructed of large granite blocks, keep the channel mouth from being filled with sand transported by longshore currents, which generally move from south to north (right to left) here. View is to the east.

HOW TO USE THE GEOLOGY AND NATURAL ENVIRONMENTS MAP

MAP CONSTRUCTION

Geologic environments shown on plate I were mapped on color-infrared stereoscopic aerial photographs (taken in May 1975) provided by the General Land Office of Texas. Most of the map units were adopted from studies by L. F. Brown, Jr., and J. H. McGowen for the *Environmental Geologic Atlas of the Texas Coastal Zone* (Brown and others, 1976, 1977). The map base was constructed from orthophotographic maps made in 1975 and provided by the General Land Office and from U.S. Geological Survey topographic maps issued in the years from 1951 to 1969.

The environments initially were mapped on the photographs at a scale of 1:24,000 (approximately 2.5 inches on the photographs equal 1 mile on the ground) and printed on plate I at a scale of 1:48,000 (1.3 inches per mile). At this scale, the map offers considerable detail without being too large and awkward to handle conveniently. The long and narrow National Seashore was divided into three sections to permit printing at a scale of 1:48,000.

MAP ORIENTATION

The location map at the bottom right of the Geology and Natural Environments Map (pl. I) shows the position of Padre Island National Seashore along the Texas coast. The three map sections are labeled *North Section, Central Section,* and *South Section* and are oriented roughly parallel on the map sheet for efficient use of space. Because of this arrangement, each section has a different orientation with respect to north. North arrows are shown in the upper right corner of each section. Other means of determining directions are reference to latitude and longitude and Universal Transverse Mercator coordinate systems.

The three map sections can be mentally pieced together to reconstruct the entire National Seashore. The North and Central Sections can be joined at Matchline A, and the Central and South Sections can be joined at Matchline B. A small index map in the upper right corner of the North Section shows the entire National Seashore as a composite of the three map sections and indicates the positions of the matchlines. Note that the map boundaries of the three sections do not coincide with those of the National Seashore, but include some areas outside the limits of the Seashore. For example, the western boundary of all map sections is the Intracoastal Waterway, whereas in certain areas the Seashore boundary (dot/dash line) actually lies much farther east of the Waterway.

COORDINATE SYSTEMS

Three coordinate systems are shown on the Geology and Natural Environments Map. The standard latitude and longitude system is indicated by black tick marks, and the Universal Transverse Mercator (UTM) coordinate system is shown by blue tick marks. The third system, which uses letter-number coordinates, is a location grid designed specifically for this map.

Latitude and Longitude

Longitude lines can be projected across the map from values printed at the margins of each map section. Longitude lines run north-south and mark positions east or west of the Prime Meridian at Greenwich, England. For example, the longitude line of 97°25′ in the Central Section may be followed from one tick mark to another from north to south (right to left) across the map. This line is 97 degrees and 25 minutes west of the Prime Meridian. In this region, 1 degree of longitude equals about 62 miles (1 minute equals 1.03 miles).

Latitude lines run east-west and mark positions north or south of the Equator. For example, the 27°25′ line passing near the Malaquite Beach development is 27 degrees and 25 minutes north of the Equator. One degree of latitude equals 69 miles, and 1 minute equals 1.15 miles.

Universal Transverse Mercator System

The Universal Transverse Mercator (UTM) coordinate system is probably unfamiliar to most readers. The spacing between grid marks of this system represents a distance of 5,000 meters (16,400 feet). Coordinate values given at the margins of the map sections refer to the distance in meters from a central meridian of longitude and from the Equator. For a detailed explanation of the UTM system see *The Universal Grid Systems*, published by the Departments of the Army and the Air Force (1951).

Location Grid System

To aid in locating specific features, a letter-number grid system similar to those used on many street and highway maps has been superimposed on the Geology and Natural Environments Map. The solid black grid lines form a system of squares on the map. Vertical columns of squares are labeled "A" through "Y" (except "I") at the top and bottom of the map sheet; the horizontal rows of squares are numbered 1 through 21 along both sides of the map sheet. Thus, each square can be designated by a unique set of coordinates, such as N-4 or K-11. Do not confuse map coordinates, which are hyphenated (M-4, L-3), with map unit symbols, which are not hyphenated (M4, L3).

Map coordinates are given for location of photographs in the legend as well as for many of the natural and man-made features discussed in this guidebook. Specific features may be located by the intersection of the proper vertical column and horizontal row. For example, the Malaquite Beach development, shown as unit M4 in the map legend, is located at map coordinates Q-4. Follow the vertical column under Q at the top of the map downward to the row of squares designated 4. The square at the intersection of column Q and row 4 is the location of the development. Although the vertical grid lines are not printed between map sections, lettered columns apply to all three map sections.

MAP SCALE

Fractional and graphic scales are shown at the bottom of the Geology and Natural Environments Map. The fractional, or ratio, scale is 1:48,000. This means that one unit on the map equals 48,000 of the same units in the area mapped. For example, 1 inch on the map represents 48,000 inches (or approximately 0.76 mile) on the ground.

The graphic, or bar, scales are more useful than the ratio scale for determining distances. Distances can be quickly estimated or actually measured with a simple, easily constructed paper ruler with the same scale as the bar scale. Graphic scales for three different units—miles, feet, and kilometers—are printed on the map.

MAP LEGEND

Significant characteristics of the 23 map units, or environments, are briefly described in the map legend. These 23 units include 11 barrier island units (B1 through B11), 8 lagoon units (L1 through L8), and 4 man-made or man-modified units (M1 through M4). At the left of each unit description is a box showing the unique map color and letter-number symbol of the unit. Colors selected for most of the map units are similar to the dominant natural colors of the environments: greens are used for vegetated environments, blues for water units, and tans and yellows for barren sand units.

A color photograph illustrates each environment, or map unit. Locations of the photographs are indicated by means of the letter-number grid system explained above. These photographs, on which significant features are labeled, should help the map reader visualize the environment described.

Photographs were selected to be representative of the mapped environments described in the legend. Many variations occur in each geologic environment, however, and the reader should consult the appropriate section of this guidebook for a discussion of these variations and for additional photographs and illustrations.

MAP SYMBOLS AND LABELS

Map unit symbols (for example, B4 or L7) are printed on the map to aid in identifying the environmental units. Other symbols used on the map, including those for roads, facilities, dune orientations, water-level lines, and beach and navigation markers, are explained in the legend.

Positions and numbers of the navigation markers plotted on plate I for waters along the Intracoastal Waterway and Mansfield Channel were derived from nautical charts published by the National Oceanic and Atmospheric Administration (NOAA). Lights and light beacons are designated by numbers in quotation marks, as well as symbols. Because the Geology and Natural Environments Map does not show all markers or any depths, the nautical charts are needed for navigation.

Many of the symbols given on the map are accompanied by labels, giving more specific information about features such as cattle line camps. In addition, most of the other significant natural and man-made features are labeled. These features include specific Seashore elements, such as North Bird Island, as well as general areas, such as the Land-Cut Area.

ORIGIN AND GEOLOGIC HISTORY OF PADRE ISLAND

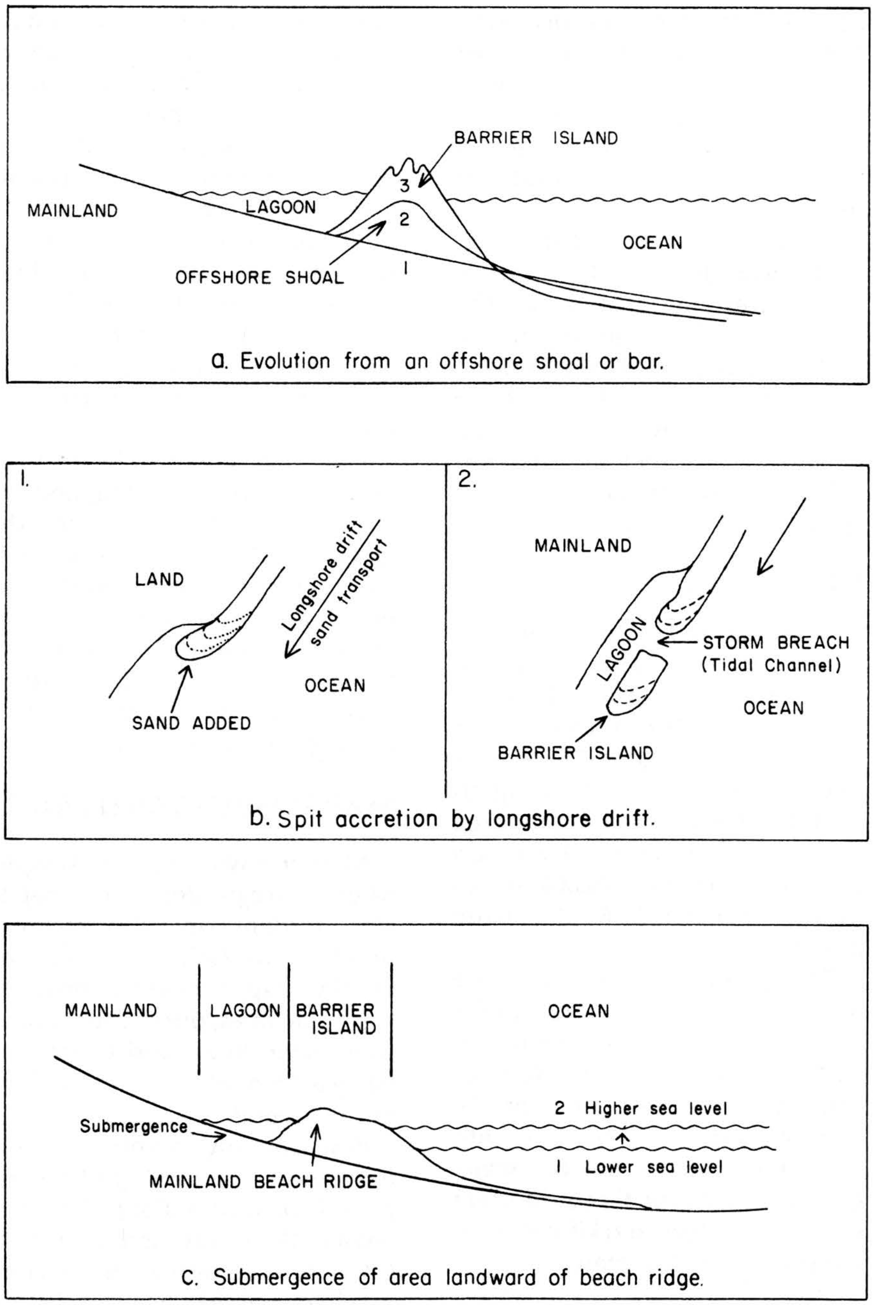


Figure 14. Three theories of barrier island origin: (a) evolution from an offshore shoal or bar, (b) evolution by spit accretion resulting from longshore drift of sand, and (c) evolution by flooding of area landward of mainland beach sand ridges during a rise in sea level (modified from Wanless, 1974).

Padre Island is a very young geologic feature when compared with the Earth. According to the most recent estimates, the Earth is about 4.5 billion years old. Padre Island began forming as a submerged bar no more than about 4,500 to 5,000 years ago, according to radiocarbon dating of shells (Fisk, 1959); it may be as young as 3,000 to 3,500 years old (J. H. McGowen and R. A. Morton, personal communications, 1978).

The origin of barrier islands has been debated for many years. However, it is obvious that barriers form and are modified by different processes, or combinations of processes (Schwartz, 1971), depending on such variable factors as the sediment source, the sediment type and supply, the rate and direction of relative sea-level changes, the basin shape, the slope of the continental shelf, the direction and strength of currents and waves, and the magnitude of tides. Three of the most discussed theories of barrier island origin are illustrated in figure 14. These theories are (1) development of a barrier island from an offshore shoal or submerged sandbar, (2) development by spit accretion (building) resulting from longshore drift, and (3) development by drowning of the area landward of mainland beach sand ridges (Wanless, 1974). One possible explanation for the origin of Padre Island (discussed later) is that it developed from offshore shoals (fig. 14a), with later growth aided by spit accretion (fig. 14b). The offshore shoals, however, might have been old mainland beach ridges submerged during the rise in sea level (fig. 14c). Consequently, all three processes may have played a role in the origin of Padre Island. Moreover, it is very likely that various segments of the island underwent different processes at different rates during their development.

HISTORY OF ISLAND DEVELOPMENT

Geologists generally agree upon the basic stages in Padre Island's development, although the precise time that each stage occurred is still debated. A discussion of the development of Padre should begin with geologic events immediately preceding its origin. Figure 15 is a schematic representation of the stages leading to the formation of Texas barrier islands, based on LeBlanc and Hodgson's (1959) interpretation of the history of the Texas Gulf Coast. The figure is not meant to show the exact geography of the coastline at the various stages but rather is a series of models illustrating probable relationships among sea level, rivers, divides, subaqueous shoals, and islands.

About 18,000 years ago, near the end of the final (Wisconsin) glacial stage (end of the Pleistocene[1]) worldwide sea level was about 300 to 450 feet lower than it is now (Curray, 1960). At that time, the shoreline was much farther gulfward on what is now the submerged continental shelf bordering the Gulf of Mexico. Rivers draining Texas carried sediments across the "shelf" and deposited them in the Gulf in areas that are now about 50 miles offshore. Upstream, however, rivers scoured deep valleys across the Coastal Plain and emergent inner shelf (fig. 15a).

By the end of the Holocene, 4,500 years ago[2], and after a long period of glacial melting, sea level reached within approximately 15

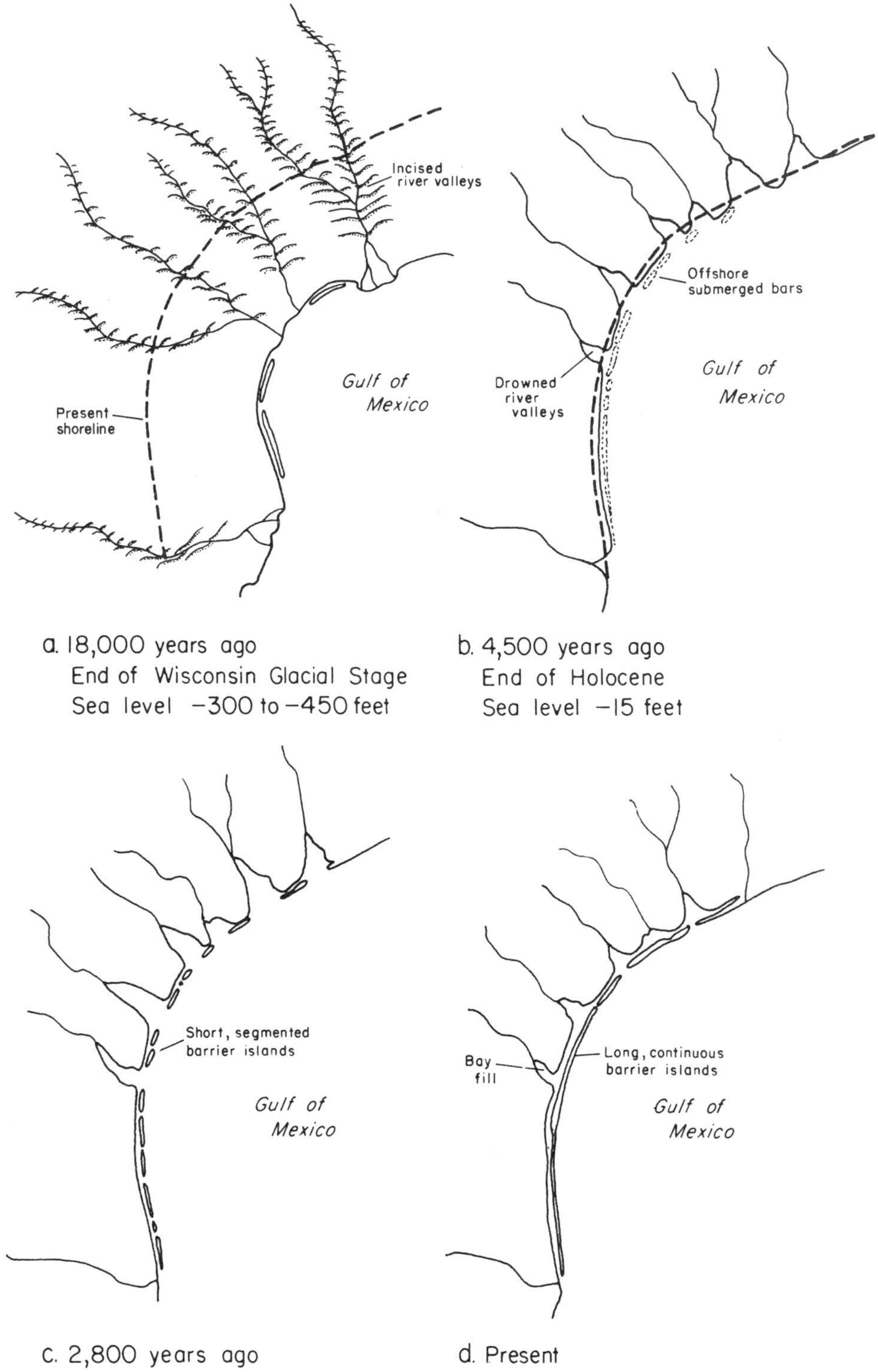


Figure 15. Sketches representing several stages in the history of the southern Texas coast: (a) 18,000 years ago, (b) 4,500 years ago, (c) 2,800 years ago, and (d) at present. The sketches do not indicate exact configurations of the shoreline but rather are meant to show relationships among sea level, rivers, divides, subaqueous shoals, and islands.

[1]The end of the Pleistocene (ice ages) is informally recognized as 18,000 years ago for the Gulf of Mexico; internationally, the time boundary is recognized as 10,500 years ago.

[2]According to informal Gulf of Mexico time boundaries, the end of the Holocene occurred 4,500 years ago; according to the formal geologic time table, the Holocene continues to the present.

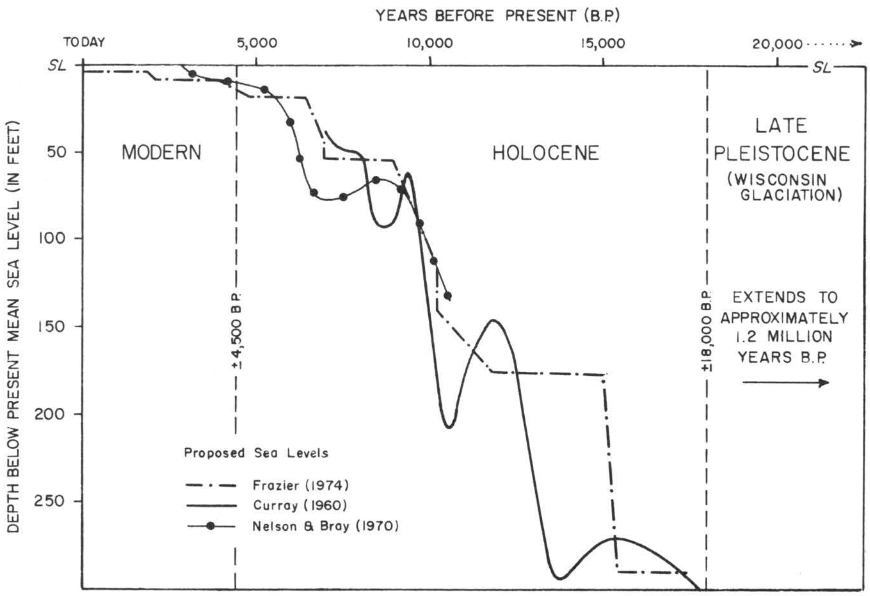


Figure 16. Sea-level changes during the past 18,000 years, as interpreted by various authors. Although the authors interpret minor sea-level fluctuations differently, all curves show a general trend of rising sea level. A generalized curve would show sea level 4,500 years ago to have been about 15 feet lower than at present. (After Fisher and others, 1973.)

feet of present sea level (fig. 16). The final small changes in sea level have resulted from compaction of sediment, subsidence of the Gulf Coast area, and minor glacial fluctuations (Brown and others, 1976). The old river valleys carved during the lower stand of sea level were flooded (fig. 15b) and became the bays and estuaries along the present Texas coast.

When sea level stabilized near today's level several thousand years ago, sand shoals, or bars, that had formed just offshore began to merge. The old submerged river-delta and barrier-island deposits laid down farther seaward during times of lower sea level (Pleistocene glacial episodes) were eroded to supply sand for the joining sandbars. As waves and currents carried the eroded sand in toward the shore from the submerged deposits and along the shore from rivers, the bars were built up and emerged as a chain of short barrier islands (fig. 15c). These initial islands were positioned primarily on the divides between the old Pleistocene river valleys. The stream valleys thus served as broad tidal passes leading to the bays and lagoons behind the emerging islands.

Much of the sand transported by longshore drift (currents moving parallel to the shore) was deposited on the downcurrent ends of the barrier islands, resulting in spit accretion (fig. 17). After a history of shifting, abandonment, and reestablishment by storm breaches, many of the tidal inlets were eventually closed. Consequently, a number of short islands were joined to form the longer islands present today (fig. 15d).

The barrier islands were built both vertically, principally by eolian (wind) processes, and slightly gulfward, by marine processes, as sand carried in from the shelf was added to the shorefaces of the islands. Padre also built lagoonward by storm washover deposition and eolian deposition (fig. 18). Today, both hurricane washovers and the wind carrying Padre's sand into Laguna Madre build the landward side of the island at the expense of the lagoon. In the line of the cross section (fig. 18), maximum thickness of Padre's sediments from sea level to the Pleistocene below is about 35 to 40 feet. Maximum total island thickness would vary considerably, however, depending on the height of the foredune ridge.

Once the modern barrier island had emerged, the wind, in addition to waves and currents, began reworking and shaping the barrier sands. All these forces, especially during storms, continue to rework the island's sediments, making Padre a barrier island with constantly changing environments. A section of this guide, *The Dynamic Barrier Island,* describes the processes at work on Padre, the agents responsible for them, and some of the natural records left behind.

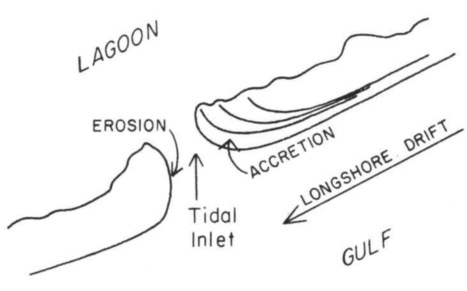


Figure 17. Spit accretion. Sand carried by longshore currents is deposited on the downcurrent end of a barrier island. The upcurrent end of the adjacent island may erode, causing the tidal inlet tó shift in the direction in which the currents move. The tidal inlet will be closed, however, if the rate of accretion exceeds the rate of erosion.

PRESENT SHORELINE CONDITIONS

There appears to be a natural sequence of stages in the life of a barrier shoreline: (1) an accretionary, or building, phase, (2) a phase of stability, or equilibrium, and finally, (3) a stage of erosion, or destruction (McGowen and others, 1977). Various segments of Padre Island probably have experienced these phases at different rates and at different times. For example, most of the northern half of Padre's shoreline is in an equilibrium phase. The southern half of Padre, as well as much of the rest of the Texas coastline, however, is now in an erosion stage. South Padre has been in the destructional phase for a long time, probably having retreated landward (along with the lagoon and mainland shoreline) from a position farther out in the Gulf where the Rio Grande delta had once existed (R. A. Morton, personal communication, 1979). Figure 19 shows the net shoreline changes within the National Seashore over the last 100 years.

FUTURE OF PADRE ISLAND

It is difficult to predict the fate of Padre Island (as determined by natural factors) at a particular location, especially in the zone where longshore currents converge on central Padre (see the section *Dynamic Gulf Shoreline*). In addition, shoreline processes can be locally influenced by humans. As part of a long-term trend of erosion, however, the shoreline of Padre Island will probably retreat landward at a slow rate (Morton and Pieper, 1977a and 1977b). Three principal causes of this erosion are (1) an interruption and decrease in the sediment supply, (2) a relative rise in sea level, and (3) the impact of tropical storms.

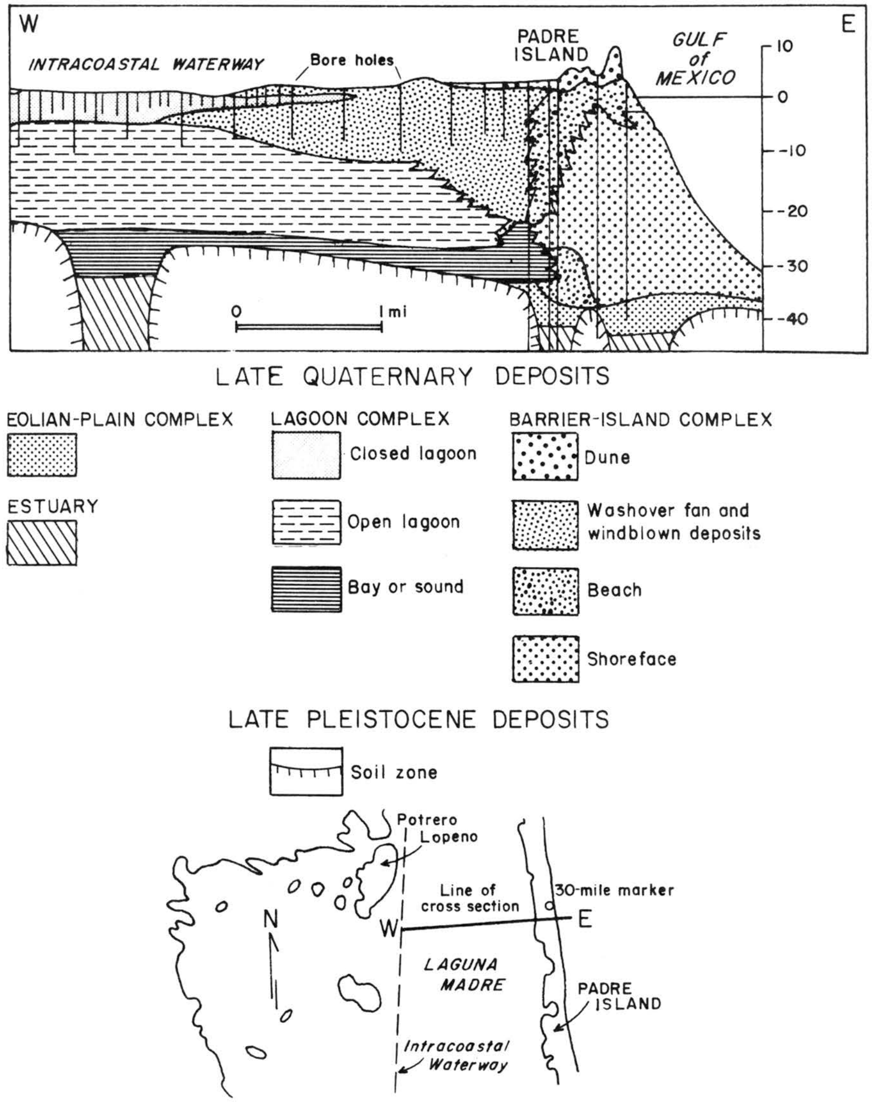


Figure 18. Cross section of central Padre Island near beach mileage marker 30. H. N. Fisk (1959) constructed this cross section using data from a series of borings across the island and lagoon. Note that the island has grown upward as shown by the vertical stacking of beach sediments; thus, Padre is classed as a vertical buildup barrier. However, lagoonward expansion by deposition of washover fans and windblown sand and seaward accretion of the beach have also been very important in the growth of the island. (Modified from Fisk, 1959.)

THE DYNAMIC BARRIER ISLAND

A casual observer visiting the National Seashore for only a day might notice many natural processes and conditions that reflect the changing or dynamic nature of barrier-island environments. For example, a visitor standing in an active dune field in the face of a strong wind can observe the dynamics of these mobile systems. In addition, on a windy summer day, sunbathers on the beach quickly realize the advantage of lying on moist firm sand near the shoreline in order to avoid the dry loose sand that is being transported landward by persistent onshore wind. Swimmers in the surf zone might notice being tugged along rather strongly by currents that literally sweep the sand alongshore. Observers of the surf zone might see that waves generally break along three relatively distinct lines that coincide with offshore submerged sandbars. Campers

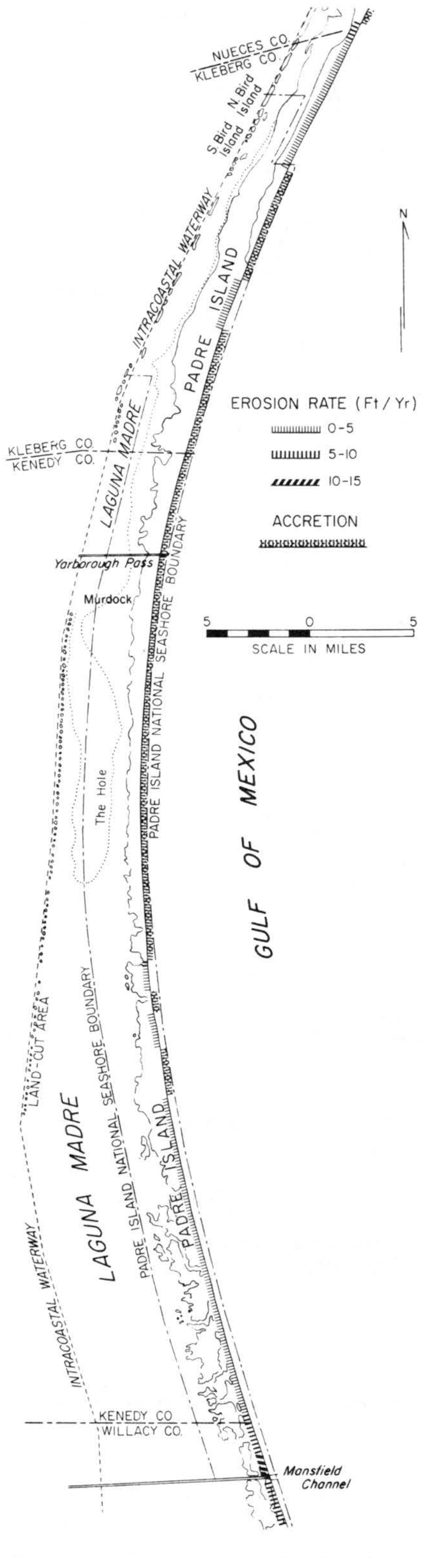


Figure 19. Net shoreline changes along Padre Island National Seashore based on time periods of various lengths between 1862 and 1975. Although the shoreline immediately south of the Mansfield Channel south jetty is now accreting, over the long term that section of shoreline was erosional, as indicated here. (Modified from Morton and Pieper, 1977a, 1977b.)

who drive along the beach on the edge of the Gulf may discover that a smooth, flat beach can be changed in a few hours into an irregular surface consisting of a series of rhythmic ridges and troughs that make driving slow and rough. Fishermen along Mansfield Channel at the southern end of the National Seashore know that their fishing lines might be strung out by currents moving lagoonward on one occasion and gulfward on another. Visitors who are in the park during the passage of a cold front or norther might observe that a shift in wind causes a corresponding shift in the direction of sand migration. The north winds also cause a change in the direction of wave approach and produce a higher and rougher surf (Robert Whistler, personal communication, 1979).

These and other casual observations result in several questions: What happens to sand that is blown landward from the beach day after day and year after year? Why do the currents in the surf zone change direction from time to time, and what happens to the sand that these currents transport alongshore? Are offshore submerged sandbars always present or are they temporary features that disappear for much of the year? What causes rhythmic irregularities in the surface of the beach and why are some beaches composed mostly of shells and others of sand? What is the internal structure of a beach or of a dune? What effect does vegetation have on sand migration? How strong are tidal currents that flow in and out of Laguna Madre? Does the wind affect water levels in bays and lagoons? What happens to island environments when a hurricane strikes?

In the following sections many of these and other questions will be answered. Some of the answers might lead to more questions. Many natural processes and their effects are difficult to understand, partly because the processes are complex and cannot be duplicated under laboratory conditions, and partly because natural island features can be interpreted in different ways. The fact that many island features and processes are not entirely understood challenges both amateur and professional naturalists.

THE DYNAMIC GULF SHORELINE

Perhaps the most dynamic environments on Padre Island are those along the Gulf shoreline, where processes of air, water, and land meet and interact. Gulf waves, produced by the wind, approach the shoreline, begin to "feel" bottom along the upper shoreface, steepen and break, reform and break again along a series of offshore submerged bars. The waves ultimately reach the beach, where their remaining energy is expended as they run up the beach and wash back to the Gulf, forming the swash zone (figs. 2 and 74).

Change is natural and common in these high-energy environments, where sediments are constantly being rounded and sorted, so that through time the particles become more and more uniform in shape, size, and composition. Clayey and muddy sediments that are transported to the Gulf by rivers are virtually absent from the beach and nearshore areas along Padre Island. These clay-sized particles are too fine (small) to settle in these high-energy environments; instead, they remain suspended in agitated waters and eventually settle in deep, calmer water offshore. Coarser sediments such as gravel do not reach the Gulf but are deposited in river channels in inland areas where reduced channel gradients cause a corresponding reduction in stream carrying capacity. Sand, however, composed predominantly of quartz and a small percentage of dark-colored heavy minerals, is small enough and durable enough to reach the Gulf, but is too coarse to be held in suspension. The sand rolls, bounces, and skips along the bottom of a stream until it is deposited near the mouth of the river. If the river discharges into the Gulf, then Gulf currents eventually sweep much of the sand along the coastline and concentrate it on beaches and the adjacent shoreface.

Along some stretches of Padre Island, shells and shell fragments derived from sources alongshore and offshore are also important components of the high-energy beach and nearshore environments. Additional sediments have been supplied from offshore submerged sand bodies. These sand bodies were deposited by ancient rivers discharging seaward of the present shoreline during past "ice ages," when sea level was much lower as a result of continental glaciers. These various sources of sediments—from rivers, shells, and offshore deposits—interact with waves and wave-induced currents, with tides, with storm-driven water, with sea-level changes, and with the wind to create the dynamic conditions that are present along the Gulf shoreline and beach of Padre Island.

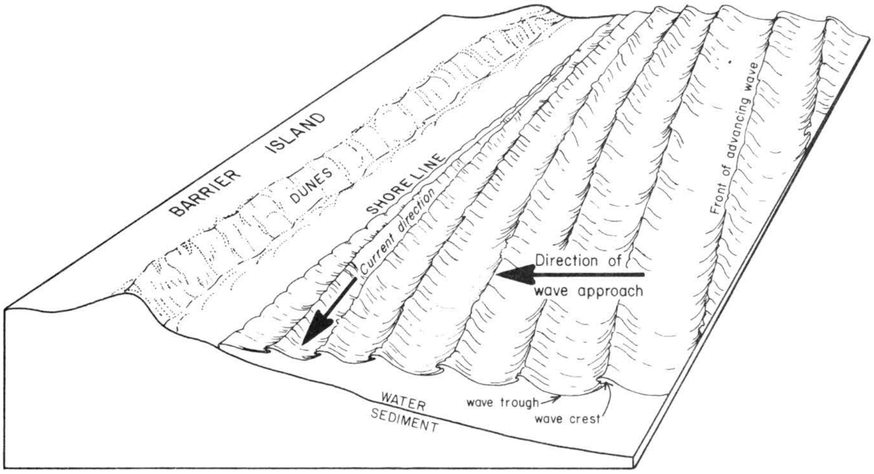


Figure 20. Waves approaching shoreline at an oblique angle, producing longshore currents. Note the direction of wave approach with respect to longshore current direction.

Waves and Longshore Currents

There are numerous types of currents in the Gulf of Mexico. The most important currents affecting the Gulf shoreline are those that result primarily from waves breaking alongshore. Swimmers in the surf are often pulled along by currents parallel to the beach. Such currents, which are capable of moving tons of sediment in the surf and swash zones, are significant in explaining many of the features and changes that occur along the Gulf shoreline. How do those currents form? What is their effect?

Generally, waves approaching land are not parallel to the shoreline. Instead, waves arrive and break at an angle to the shore. Currents that are produced move in a preferred direction, depending on the direction of wave approach (fig. 20). The movement of water alongshore in this manner is termed *longshore* or *littoral drift*. If waves approach a north-south oriented shoreline from the northeast, longshore drift will be toward the south. Conversely, waves approaching from the southeast will produce currents flowing north (fig. 21). Waves that are exactly parallel to the shoreline and, therefore, advancing in a direction that is perpendicular to it will not cause significant longshore drift. Depending on the size of the waves and the angle of wave approach, the current at times may be relatively strong (maximum movement occurs when waves approach at an angle of about 30°; King, 1972). Current velocities of up to 3.9 feet per second (fps), or 2.7 mph, have been measured along Mustang Island, immediately north of Padre Island. The average velocity, however, is less than 1 fps (Davis and Fox, 1972).

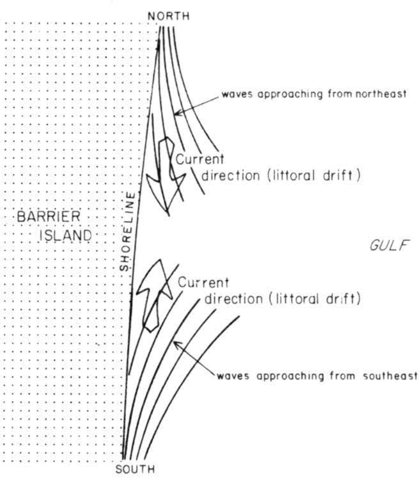


Figure 21. Direction of littoral, or longshore, drift along a straight shoreline. Drift direction is dependent upon the direction of wave approach.

Winds exert stresses on open waters. These wind-generated stresses direct waves that break on the shoreline. Hence, knowledge of wind directions provides information on the directions of longshore drift. But wind direction is only part of the story. A glance at the Texas Gulf Coast (fig. 22) reveals a curved shoreline that is oriented approximately northeast-to-southwest along the upper coast and northwest-to-southeast along the lower coast. Because of this curvature, waves approaching the shore from any specific direction will be parallel to only

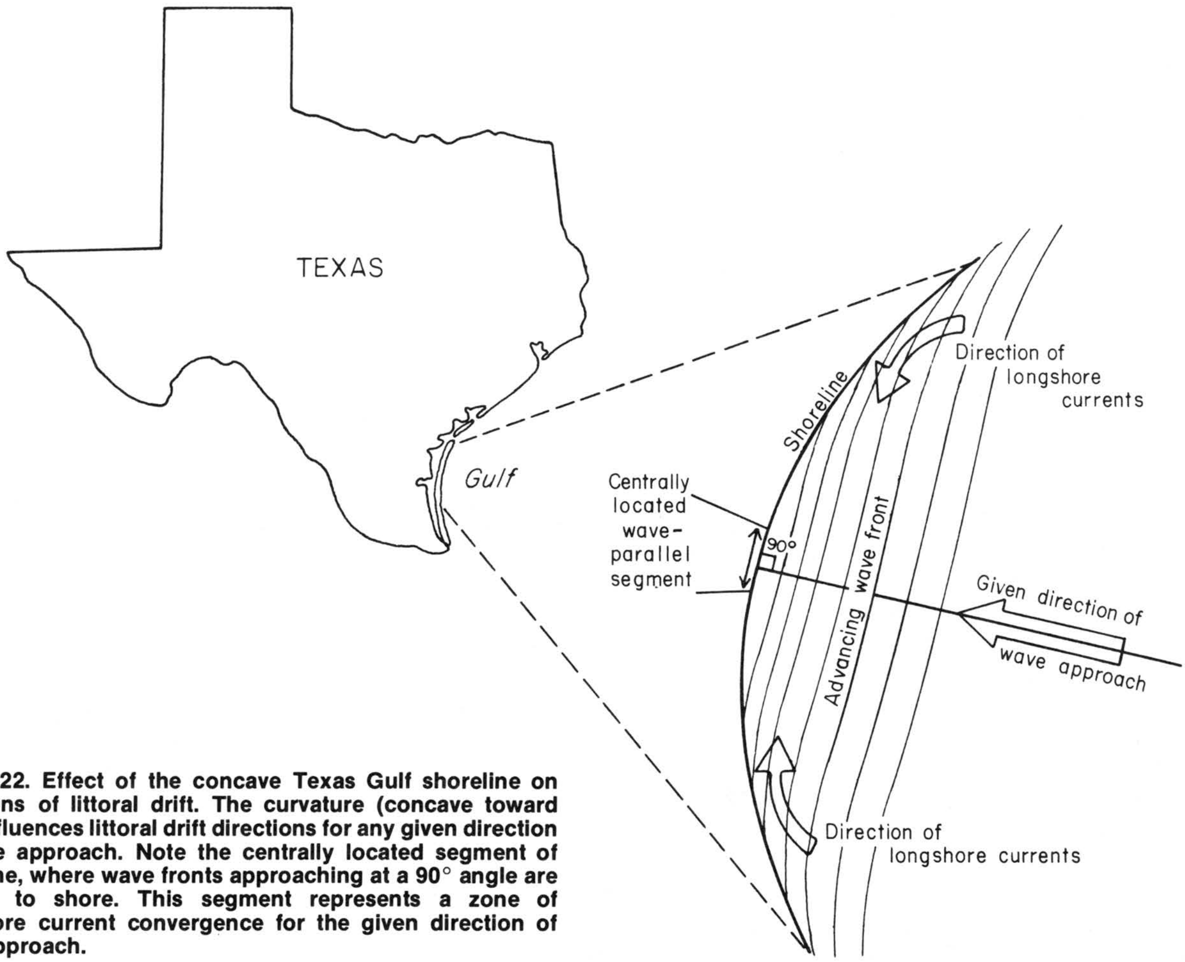


Figure 22. Effect of the concave Texas Gulf shoreline on directions of littoral drift. The curvature (concave toward gulf) influences littoral drift directions for any given direction of wave approach. Note the centrally located segment of shoreline, where wave fronts approaching at a 90° angle are parallel to shore. This segment represents a zone of longshore current convergence for the given direction of wave approach.

one relatively short segment of the beach and shoreface. Along the shoreline at either end of such a segment, waves will approach at an angle, and currents (longshore drift) will be formed that flow parallel to shore and toward each other (fig. 22). The area in which the opposing currents eventually meet is known as a *zone of convergence*.

By studying winds that occur over Gulf waters, E. A. Lohse (1952, 1955) noted that geologically effective winds (those producing waves that expend the most energy doing geologic work) are more or less uniformly distributed from the northeast, east, and southeast (fig. 23). By comparing the shoreline trend with the wind directions, Lohse (1952) concluded that the zone of convergence is located near 27°N latitude, which places it along the Central Section of Padre Island National Seashore (pl. I). If this is true, net longshore drift and sediment transport should be in a counterclockwise direction north of 27°N latitude and clockwise south of it.

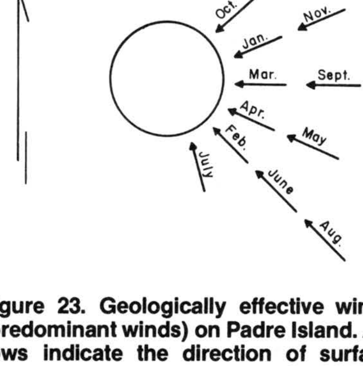


Figure 23. Geologically effective winds (predominant winds) on Padre Island. Arrows indicate the direction of surface winds that expend the most energy each month doing geologic work. (From Lohse, 1955.)

The phrase "*net* longshore drift and sediment transport" in the preceding sentence should be emphasized. Because wind directions vary seasonally, ranging generally between northeast and southeast, the zone of convergence does not remain stationary during the year but shifts in response to changes in wind direction, which controls wave approach. So, during winter northers when winds are blowing from the northeast, the zone of convergence shifts toward lower latitudes. When the winds blow predominantly from the southeast during summer months, it shifts back toward higher latitudes. The central area over which this convergence pendulum swings should reflect the area of net convergence and sediment accumulation. But is there physical evidence of net convergence along central Padre Island?

Evidence of Converging Longshore Currents

Because different rivers intersect, erode, and transport rock materials of differing composition, each river entering the Gulf can be characterized by the suite or assemblage of minerals it transports and deposits. Rivers such as today's Rio Grande, Colorado, Brazos, and Mississippi discharge directly into the Gulf and contribute sand to the longshore dispersal system of the Gulf. The sands of each river consist not only of quartz but also of heavy, dark minerals such as magnetite, garnet, zircon, tourmaline, and many others. Assuming that each river carries a distinctive suite of heavy minerals, an analysis of beach sands should allow one to estimate the sediment contribution made by the various rivers and thus to infer the net direction of longshore sediment transport. In 1942, F. M. Bullard initiated a study to do this. He discovered that minerals characterizing the Rio Grande sediment were traceable northward along Padre Island beaches from the mouth of the Rio Grande to central Padre Island (in the vicinity of 27°N latitude), north of which there was a significant decline in the Rio Grande heavy mineral suite. Bullard also found that heavy mineral assemblages distinctive of rivers to the north of Padre Island, such as the Colorado and the Brazos, could be traced southward to central Padre Island.

Thus, the distribution of minerals observed in Bullard's study and in later studies (van Andel and Poole, 1960; Hayes, 1965) supported the theory of a zone of sediment convergence on Padre Island (Central Section, pl. I). There are complications, however, if one bases conclusions entirely on sediments presently supplied by modern rivers. Sea level was much lower only about 10,000 years ago (fig. 16), and rivers discharged sediments gulfward of their present mouths. Many geologists believe that the sediments that compose today's barriers are partly derived from the offshore shelf sediments that were deposited by these ancient rivers. Because of past variations in shoreline configuration, and perhaps changes in dominant wind directions, directions of longshore sediment transport and river sediment distribution may have varied from those in existence today (Curray, 1960). Consequently, the distribution of minerals along the beaches may reflect, in part, past currents and conditions. Because of this, other evidence is needed to help resolve the question of longshore drift direction and convergence.

EFFECTS OF JETTIES ON LONGSHORE DRIFT

Man-made structures, such as jetties, constructed perpendicularly to the Gulf shoreline at inlets and channels interfere with longshore sediment transport and trap sediments on the upcurrent side. This clearly occurs at Mansfield Channel at the south end of the National Seashore (pl. I). These jetties are south of 27°N latitude, and aerial photographs show that sediments have accumulated along the south side of the southernmost jetty (figs. 13 and 24). The accumulation of sand has created a sand deficit on the downcurrent (northern) side of the channel, resulting in a narrow, erosional beach immediately north of the jetties. At Mansfield Channel, net sediment transport is apparently northward, thus toward 27°N latitude.

Other jetties are present on Mustang Island, just north of Padre Island (fig. 1). Since 1972, sediments have accumulated on both the north and the south sides of the jetties at the Water Exchange Pass (fig. 1); this indicates that longshore drift periodically changes direction at this location. Behrens and others (1977) substantiated that winds control the two-way littoral drift in this area. During winter, when winds accompanying passage of a cold front blow from the north and northeast, longshore drift is

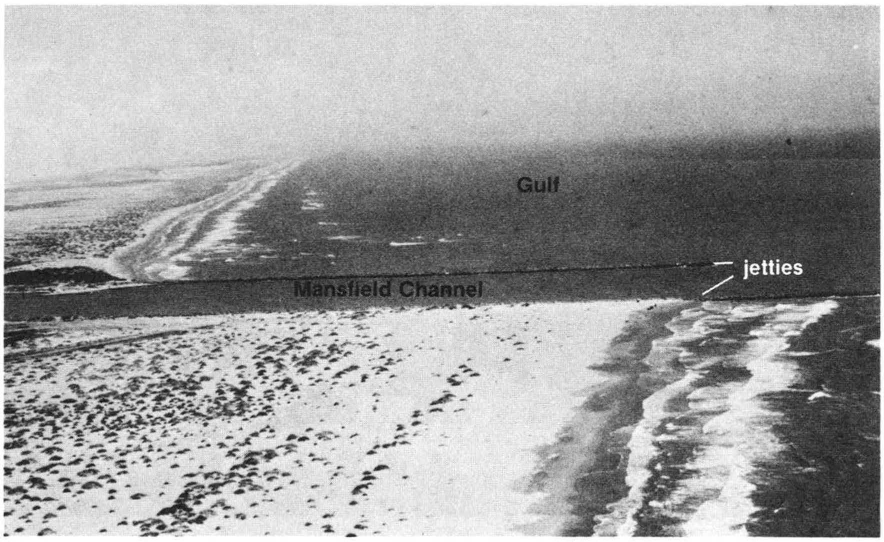


Figure 24. Jetties at Mansfield Channel. View is toward northwest. Note that sediments have accumulated on the south side of the jetties, which indicates that net longshore drift is northward at this location. Erosion has occurred on the north, or downcurrent, side of the jetties. The jetties are located in grid C-21 on plate I.

usually southward. During summer months, when southeasterly winds prevail, longshore sediment transport is northward. Although sediments are transported back and forth during the year, there is a net sediment transport southward toward central Padre Island, where the area of net longshore drift convergence apparently occurs (Behrens and others, 1977).

Additional evidence that sediment drift is southward along Mustang Island was presented by W. A. Price in 1933. He observed that before it was stabilized by jetties, Aransas Pass, which is a natural tidal inlet located at the north end of Mustang Island, moved southwestward in the direction of longshore drift. Sediments accumulated on the north side (upcurrent side) of the inlet, while sediments on the downcurrent side (south side) were being eroded as the channel moved southward.

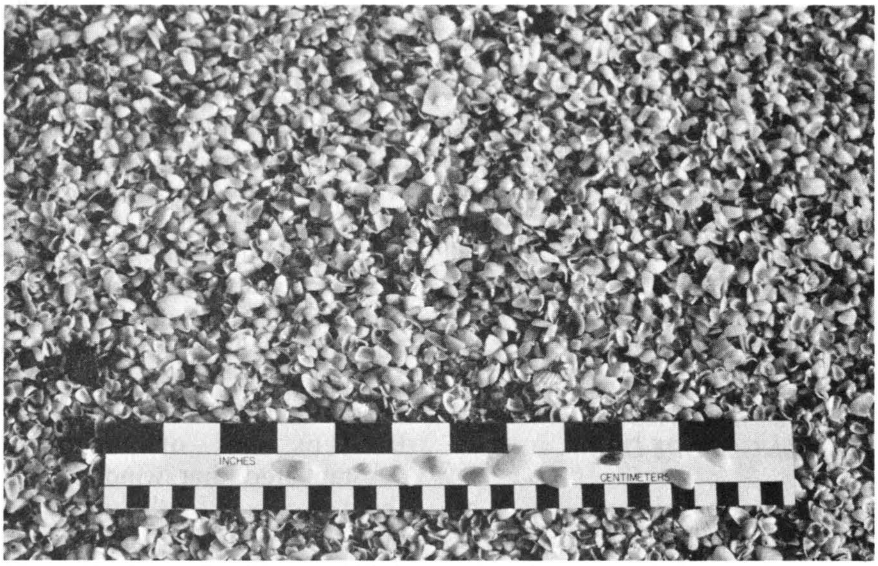


Figure 25. Little Shell Beach sediment, consisting primarily of shells of the small clam *Donax*.

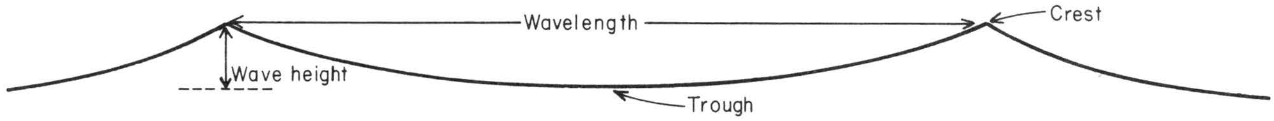
Figure 26. Big Shell Beach sediment, consisting primarily of abraded shells of the large clams *Noetia* (*Eontia*) *ponderosa* Say, *Mercenaria campechiensis* Gmelin, and *Echinochama arcinella* Linne. Comparison with figure 25 shows the difference in average size of shells of Big Shell and Little Shell Beaches.

ACCUMULATION OF SHELLS IN ZONE OF CONVERGENCE

The occurrence of beaches composed predominantly of shells and shell material provides additional evidence of converging longshore currents along central Padre Island. Southward from Malaquite Beach development, the sandy beaches change gradually to shelly beaches, as indicated first at Little Shell Beach and finally at Big Shell Beach (pl. I).

In a study of the origin of the shell beaches, Watson (1971) concluded that concentrated shells result from longshore drift convergence in the area of 27°N latitude. The smaller shells that characterize Little Shell Beach (fig. 25) were derived from beaches to the north, while the larger shells characterizing Big Shell Beach (fig. 26) were derived from a southern source area. A zone of transition that separates Little Shell and Big Shell contains a mixture of large and small shells (Watson, 1971). This transition zone coincides with the transition zone between heavy mineral suites derived from the northeast and from the south, identified by Bullard (1942) and van Andel and Poole (1960). Hayes (1965) identified a similar distribution of light mineral suites.

In explaining the origin of the shell beaches, Watson suggested that the converging longshore currents funnel both shells and sand into the area along central Padre Island. The shells accumulate and subsequently become concentrated by onshore winds that blow away the sand-sized particles. The sand accumulates in dunes, which may become stabilized by vegetation or which may migrate across the island and into Laguna Madre.



$$\text{Wave steepness} = \frac{\text{wave height (H)}}{\text{wavelength (L)}}$$

Figure 27. Characteristics of a wave that define wave steepness. If the H/L ratio exceeds 1/7, the wave will become unstable and break (King, 1972).

If sediments are funneled into the area of central Padre Island by longshore currents, then historical studies of the shoreline in this area should reflect it. This was confirmed by Morton (1977), who noted that although most of the Texas beaches are apparently undergoing a long-term net erosional trend, central Padre Island near 27°N latitude has exhibited long-term net shoreline accretion. Morton stated that "net accretion nearly coincides with the transition zones, established by heavy minerals, grain-size distribution and shell species," identified by Bullard (1942), van Andel and Poole (1960), Hayes (1965), and Watson (1971).

In conclusion, longshore or littoral drift and drift convergence are extremely important natural processes operating along the Gulf shoreline of Padre Island. There is substantial evidence that net convergence occurs in the area of central Padre Island near 27°N latitude. An understanding of littoral drift and net convergence helps to explain many natural shoreline phenomena, including accretion and erosion along jetties and inlets and the accumulation of shells at Little Shell and Big Shell Beaches. The importance of littoral drift is also reflected by the fact that it is the basis of one theory proposed to explain the origin of barrier islands along the Texas coast (fig. 14).

Effects of Waves on the Upper Shoreface and Beach

In addition to creating longshore drift, Gulf waves are responsible for numerous features occurring along the beach and immediately offshore on the upper shoreface (fig. 2). Gulf waves breaking along the shoreline of Padre Island are usually less than 1 m (3.3 ft) high, but occasionally reach heights of more than 2 m (6.6 ft) during fall, winter, and spring storms (Hill and Hunter, 1976). As waves break in the shallow water forming the surf zone, they constantly agitate the sediment, lifting sand grains into suspension so that even weak currents become effective in moving sand. W. Bascom (1964) noticed this constant motion of the sand grains:

> Uncounted millions of sand grains are picked up and relocated by every wave, and the beach constantly shifts position. They need not move very far each time, for there are some eight thousand waves a day. [Over 12,000 waves/day come ashore along Padre Island.] Sand grains that move a tenth of an inch per wave could migrate seventy feet in a day. Of course, all waves do not have the same effect, and the currents may change direction. Hence, it is difficult to say whether the sand is moving to or from shore at any given moment.[1]

Waves can be classified as (1) destructive or (2) constructive, depending on whether they tend to erode or deposit sediment along the beach. Laboratory studies using wave tanks show that destructive waves and constructive waves can be differentiated on the basis of wave steepness, which is the ratio of wave height (H) to wavelength (L) (King, 1972) (fig. 27). The flatter waves — those with a low H/L ratio — are more constructive and have a tendency to transport sand onto the beach; steeper waves are more destructive and tend to remove sand. Smooth, round, symmetrical waves, termed *swell*, generated by winds blowing over Gulf waters far offshore, are among the most constructive of waves. Local strong onshore winds tend to generate steep waves that are closer together and more destructive. These constructional and destructional waves explain, in part, many features that occur along the Gulf shoreline.

OFFSHORE SUBMERGED SANDBARS (WAVE BREAKPOINT BARS)

Immediately offshore and approximately parallel to it, there may be as many as three or four subparallel submerged sandbars separated from each other by troughs. If waves are sufficiently high when they arrive alongshore, they break along the bars (fig. 28), re-forming in the troughs that lie between them. Bars and troughs closest to shore are easily detected by swimmers and surfers who may seek temporary refuge in the troughs, where waves seldom break. Although the bars might shift back and forth, become discontinuous and curved, or disappear at times depending on wave characteristics and nearshore conditions, they are relatively stable features that remain in a sort of dynamic equilibrium with the waves and currents that form them.

[1]Excerpt from *Waves and Beaches* by Willard Bascom. Copyright © 1964 by Doubleday & Company, Inc. Reprinted by permission of the publisher.

Exactly how these offshore submerged bars are formed and maintained is only partly understood. C. A. M. King (1972), from whom much of the following information is obtained, proposes that the submerged bars are identical to wave breakpoint bars that can be formed in laboratory wave tanks. The bars are formed along the usual breaking point of steep destructional waves. Bars in deeper water are formed by larger waves, and bars in shallower water by intermediate and smaller waves. By varying the size of waves generated in a wave tank, a bar that has formed will migrate into deeper or shallower water, depending on whether the waves increase or decrease in size, respectively. Inner bars (closest to shore) are most susceptible to change because they are affected by both large and small waves, in contrast to the outermost bars that are affected only by large waves. King (1972) observed that because submerged bars are formed at the breaking point of the wave, the bars cannot be built up above the still water level and, therefore, will never become emergent.

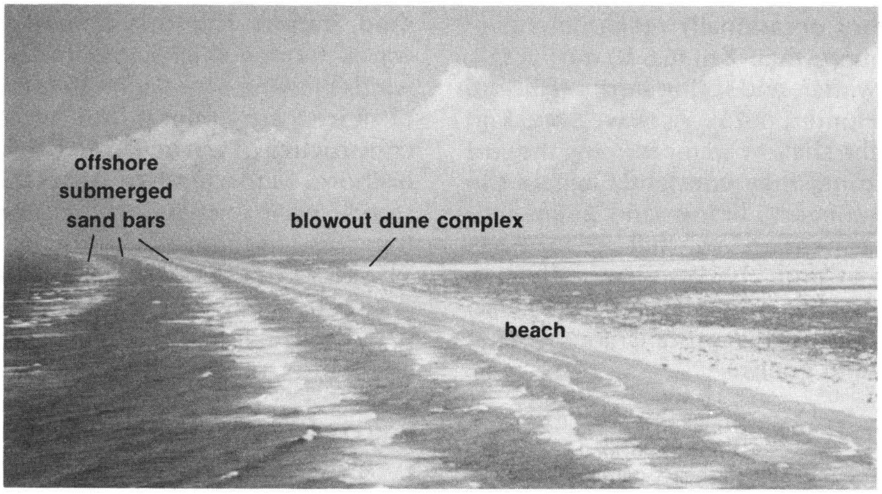


Figure 28. Waves breaking along offshore submerged sandbars (wave breakpoint bars). View is southward.

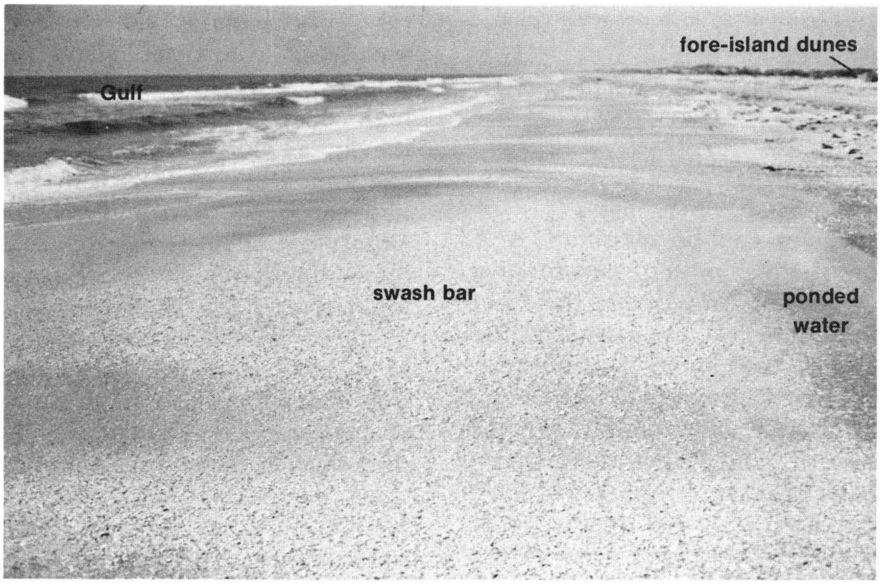


Figure 29. Swash bar on a shell beach on central Padre Island. Note that water has been temporarily trapped on the landward side of the bar. View is southward.

SWASH BARS

Swash bars are formed in the swash zone along the beach where waves rush up on the beach and wash back to the Gulf (King, 1972). These bars are parallel to the shore, but unlike the submerged offshore bars, they are formed by flat, constructional waves that break and transport sediment landward, depositing it in the form of a low ridge. As the swash bars are constructed, water may be trapped or ponded in shallow troughs that lie landward of the bars (fig. 29). Occasionally, the ponded water flows rapidly along the troughs and back to the Gulf through narrow channels eroded through the bars. Large, constructional waves form higher swash bars because they rush higher onto the beach to deposit sediments. A swash bar deposited during Hurricane Cindy had an average width of 50 feet and a height of 2 to 4 feet (Hayes, 1965).

BERMS

Berms are relatively horizontal beach deposits generally formed by constructional waves that transport sediment and deposit it on the backbeach (figs. 30, 31a and 31b). The location of these deposits (backbeach) indicates that berms are constructed by larger than normal waves that can reach high up on the beach. More than one berm may occur on the beach, reflecting different wave characteristics and tidal levels.

The highest berms on Padre Island occur along shell beaches. Their profiles may be emphasized by a steep, erosional scarp that separates the berm from the more steeply gulfward-dipping forebeach (fig. 30). Berms are normally constructed by large, flat, constructional waves. The height of a berm may be increased by steep storm waves that transport sediment over the berm crest to build it higher. Such storm waves generally erode the berm and remove sediment from its seaward slope; eroded sand is distributed seaward (Bascom, 1964). Storm tides and steep, destructional waves that accompany hurricanes and other storms may occasionally level and smooth the entire beach, temporarily eradicating the berms.

BEACH STEEPNESS

Along the Gulf beaches south of Malaquite, the forebeach becomes steeper where beaches are composed predominantly of shells. The steepness of a beach is directly related to the size of the sediments that compose it. The steepest beaches on Padre Island occur along Big Shell Beach where there is an abundance of large shells and shell fragments.

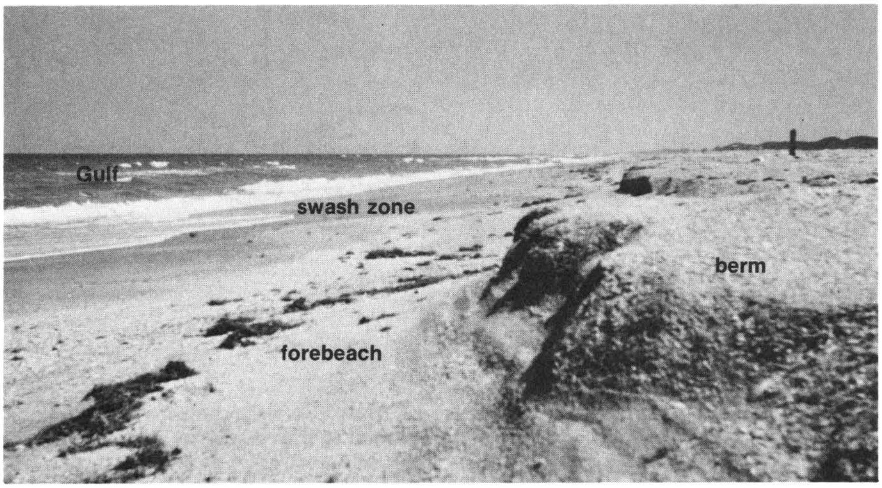
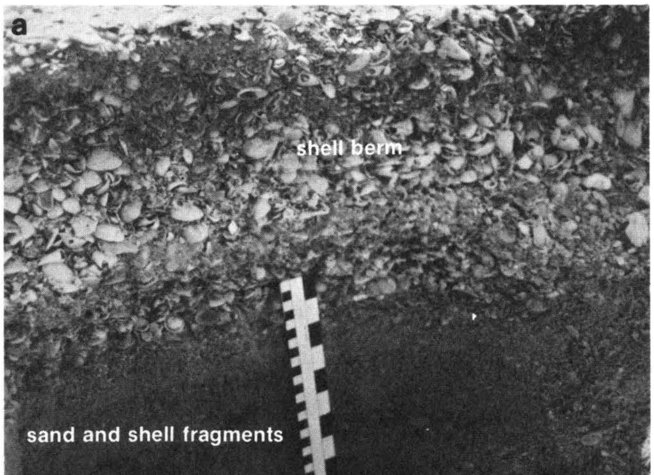


Figure 30. High, partially eroded berm of a steep, central Padre shell beach. Generally, beaches with coarser sediment will have higher berms and steeper profiles. View is southward.



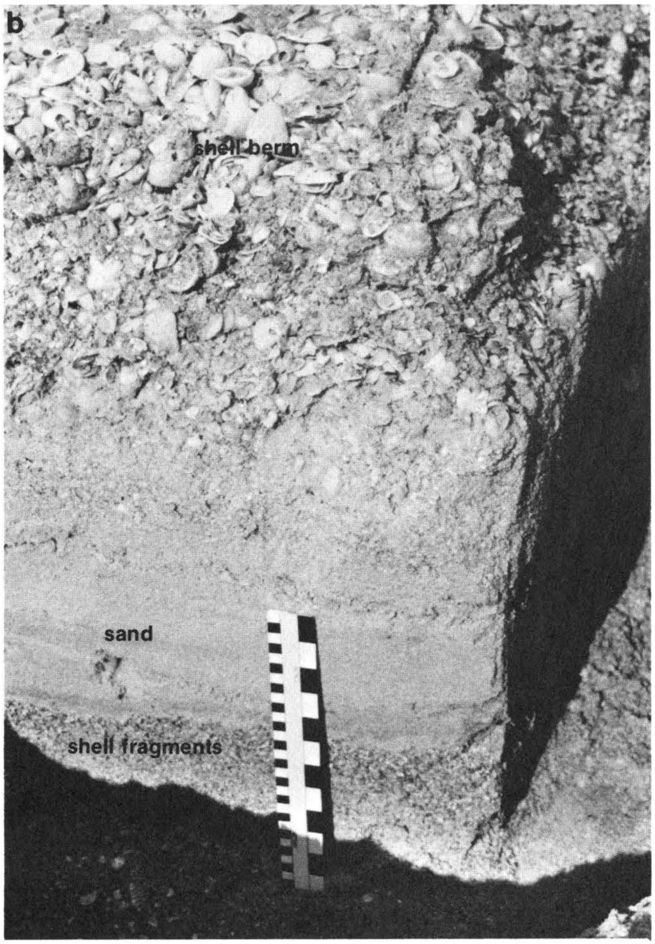


Figure 31(a) and (b). Observation trenches dug along the gulfward edge of berms on Big Shell Beach. Note that shells in photographs (a) and (b) are concentrated near the surface and are underlain by sand and shell fragments. This suggests that, in at least some areas, the shell berms are surficial deposits little more than 1 foot (30.5 cm) thick. Scale is 12 inches (30.5 cm) long. In trench in photograph (b), the base of the exposed sequence is composed of shell fragments overlain along a distinct boundary by sand, which grades upward into the shell berm. The concentration of shells is partly the result of wind action blowing the finer sand landward, but wave action can also concentrate sediments of different sizes. This is evidenced in beach cusps (fig. 32), where the horns of depositional cusps are composed of sediments (shells where available) that are coarser than the sediments on which they are deposited.

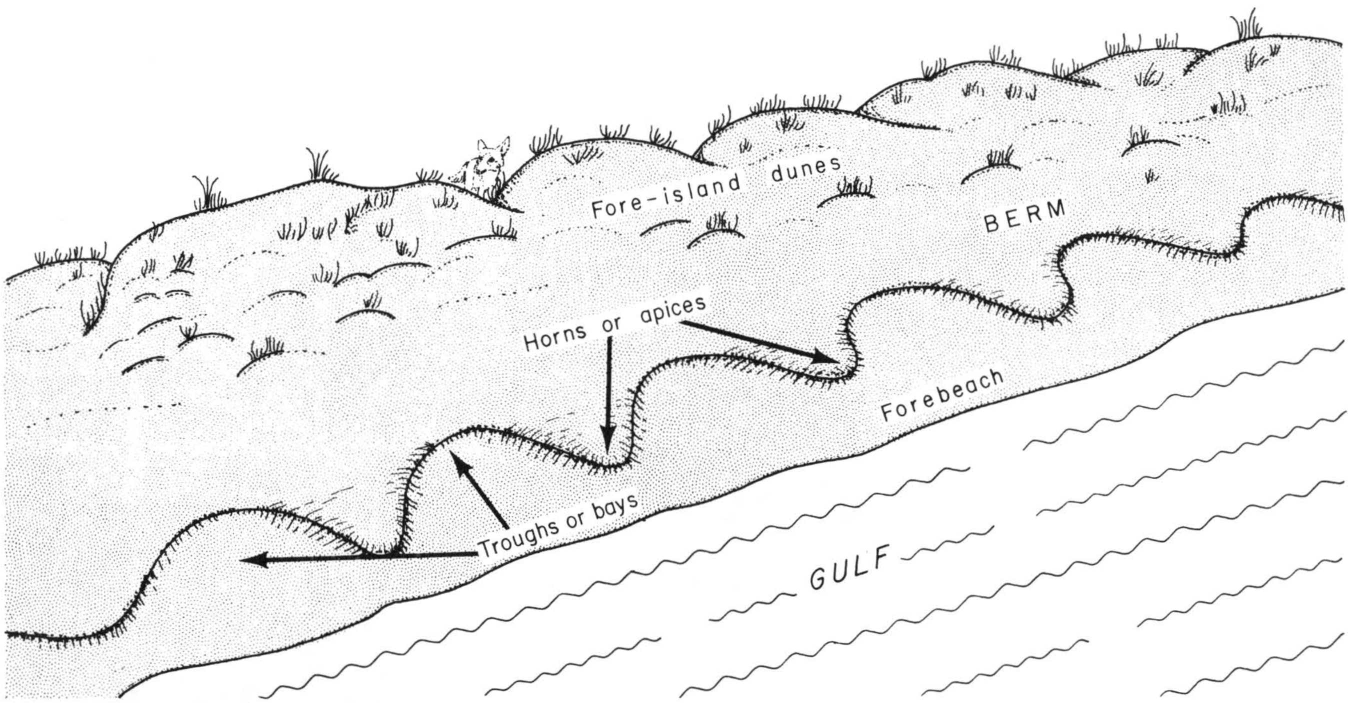


Figure 32. Beach cusps. These relatively uniformly spaced beach features are composed of a series of ridges (horns or apices) and troughs (bays) that are roughly perpendicular to the shoreline. The horns are composed of coarser material than the material found in the bays. Along shell beaches (Big Shell and Little Shell) the horns are composed of the coarser shells.

In addition to sediment size, wave steepness and wavelength also affect beach gradient, so that beaches of uniform composition may have varying steepness (King, 1972). In general, steep, destructive waves tend to erode material from the beach and move it seaward to form a more gently sloping beach. Flatter, constructional waves tend to increase the steepness of a beach. Because beaches partly reflect this variation in wave characteristics, the beaches and their profiles are constantly changing, while remaining in dynamic equilibrium (King, 1972).

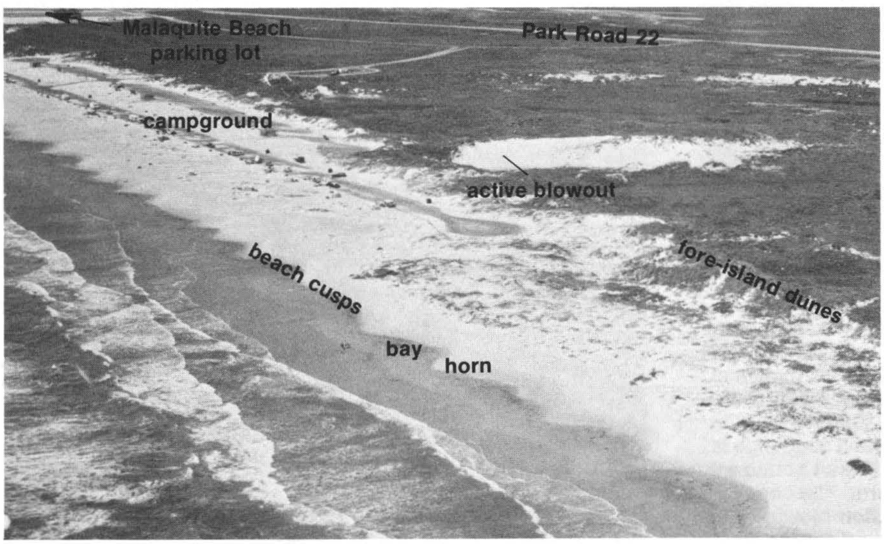


Figure 33. Beach cusps near Malaquite Beach. Note the horns and bays, as labeled in figure 32. Beach area included in photograph lies within grids Q-4 and R-4, plate I. View is southwestward.

BEACH CUSPS

Beach cusps are temporary features that occur along the Gulf shoreline, usually in a series of more or less uniformly spaced mounds or ridges called *horns*, separated by crescent-shaped troughs called *bays* (fig. 32). Cusps form in the swash zone with their horns oriented roughly perpendicular to the shoreline (figs. 32, 33, and 34). These rhythmic forms may develop in only a few hours and can change a smooth, relatively flat beach into an uneven surface, causing rough driving conditions along the gulfward edge of the island. Cusps may be formed at different levels along the beach as wave and tidal conditions change.

Beach cusps are related to wave characteristics, but their exact origin and their sometimes remarkably uniform spacing (distance between horns) are not entirely understood, even though they have been studied since the mid-1800's. Beach cusps can be formed in laboratory wave tanks. Several explanations have been proposed regarding their origin and spacing, but none are entirely satisfactory. There is evidence that the uniformity of cusps is due to nearshore water circulation cells and rip currents or to edge waves, which are nearshore waves trapped by refraction (Komar, 1971, 1973). Some studies show that the horns of cusps are primarily the result of depositional processes, but other studies (for example Sallenger, 1977) suggest that they can be formed by erosion of existing ridges or berms. Cusps appear to develop optimally at times when waves are parallel to shore, approaching it at a 90° angle, but they may also form when waves approach at an oblique angle.

The spacing of cusps becomes more uniform if favorable wave conditions persist. Pronounced longshore drift in the swash zone as a result of oblique waves will commonly cut into the horns, forming asymmetrical cusps with erosional scarps; eventually, such longshore currents will destroy the cusps. Large, steep, destructional waves that tend to smooth and flatten a beach will also erode the cusps.

R. J. Russell and W. G. McIntire (1965) made many observations of beach cusps and their formation along ocean beaches. Much of the following is based on their observations and conclusions.

Cusps may form along beaches composed of a variety of deposits, ranging from boulder-sized material to fine-grained sand. The most favorable conditions for cusp development seem to be during a period of decreasing wave energy when steep, destructional waves are replaced by waves of less intensity. Horns that are depositional in origin form on the seaward face of the berm and may grow across the forebeach as sediments are added by wave uprush. Horns are composed of coarser material (in many cases shell, where available) and have a steeper slope than the interlying bays. Newly deposited horns are generally soft and contain considerable interstitial water. Along Big Shell Beach on Padre Island, newly deposited, soft, and water-saturated shell sediments composing the horns of cusps make vehicular passage difficult, even for four-wheel-drive vehicles.

Distances between horns (cusp spacing) may range from 20 to 185 feet (cusps with spacing of less than 1 foot have been observed along the shores of lakes; Komar, 1973). Wider cusps seem to be produced by higher waves. Cusps at higher levels of a beach may remain undisturbed for a relatively long period (up to 2 years or more) until conditions similar to those that formed them recur.

The Beach — A Source of Sand for Dunes

The Gulf beach is a complex environment where water and air interact and compete for sediments. Sediments deposited high on the beach by waves and currents are dried, picked up, and transported landward by persistent onshore winds. Much of the migrating sand is trapped along the back edge of the beach by a wide variety of salt-tolerant grasses and flowering plants (fig. 35a-f). Some of the plants thrive on the sand, keeping pace with its accumulation, and stabilizing it with roots and spreading vines. Along much of the Gulf shoreline, just landward of and parallel to the beach, a relatively continuous dune ridge has been established as a result of the onshore wind and the sand-stabilizing vegetation. The fore-island dune ridge traps additional sand and prevents it from migrating into back-island areas. Dunes along the fore-island area, however, might hold the sand only temporarily, because during storms, high tides cut into the dunes, washing the sand back to beach and Gulf. Yet it is possible for the sand to escape from the fore-island and be deposited on the back sides of barrier islands and in bays and lagoons. This has happened on Padre Island.

Vegetation is relatively dense on northern and central parts of the Seashore (fig. 36), but along southern stretches of Padre Island, vegetation is sparse (fig. 37). Along sparsely vegetated coastlines, fore-island dune ridges are not well

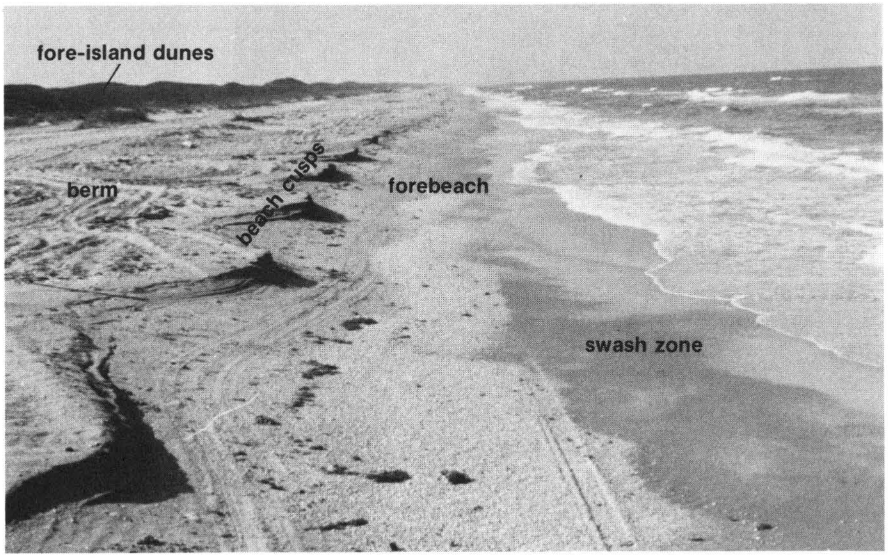


Figure 34. Closely spaced cusps on a steep, central Padre shell beach. Compare these cusps with those of Malaquite Beach (fig. 76). Erosion has obviously been active in forming or at least modifying these particular cusps, as evidenced by the exposed sediment layers along the cusp edges. View is to the north.

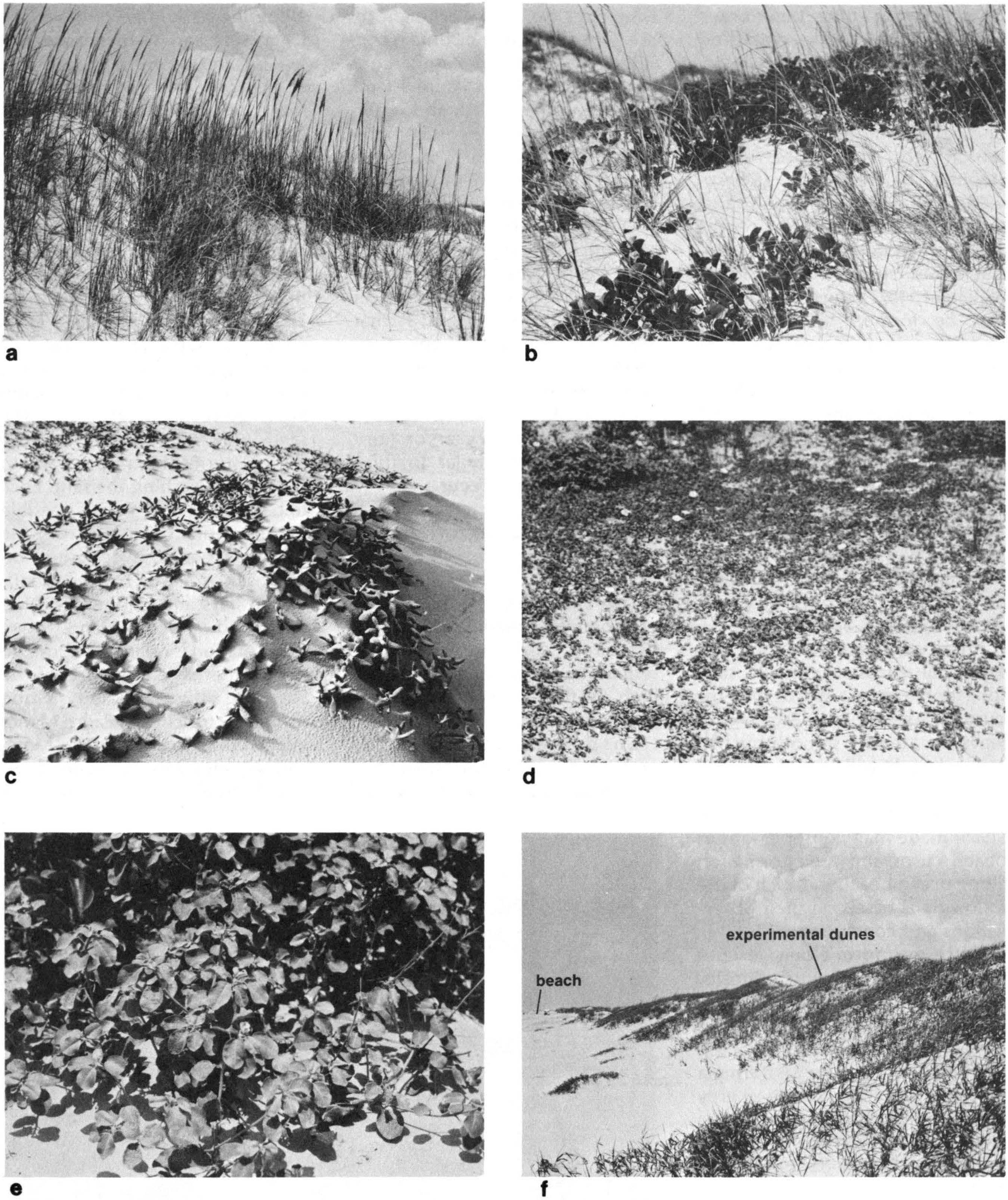


Figure 35(a) through (f). Examples of salt-spray-tolerant plants that help trap and hold sand to form stabilized dunes along the Gulf shoreline: (a) sea oats (*Uniola paniculata*), (b) goatfoot morning-glory (*Ipomoea pes-caprae*) and sea oats (*Uniola paniculata*), (c) sea purslane (*Sesuvium portulacastrum*), (d) fiddleleaf morning-glory (*Ipomoea stolonifera*), (e) beach tea (*Croton punctatus*), and (f) bitter panicum (*Panicum amarum*).

developed and they contain gaps or breaks through which sand is blown. Gaps in dunes commonly result from hurricanes and rarely from human activities. Where fore-island dunes are poorly developed or breached, active blowout dunes and back-island dune complexes commonly form and move lagoonward across the island, incorporating additional sand along the way. As long as the gap exists in the fore-island dune ridge, a link with the beach allows nourishment of the active dune complex. If sand accumulates in the gap and is eventually stabilized by vegetation, the supply of sand from the beach is eliminated. But the active dunes that have already formed continue to move across the island. Unless these migrating dunes are stabilized by vegetation, they eventually migrate into Laguna Madre.

WINDS AND DUNES ON PADRE ISLAND — A DYNAMIC SYSTEM

Driven by solar energy, winds are perhaps the most important geologic agent at work on barrier-island and associated Gulf and lagoon environments (fig. 38). Winds create waves that break and dissipate their energy in the surf and swash zones, depositing, eroding, and reworking sediments, and forming currents that transport large amounts of sand alongshore. Wind-driven tides also dramatically affect water levels and circulation patterns, particularly in Laguna Madre. But the wind's influence does not end at the water line. Winds are the driving force behind sand dunes that have so significantly shaped and modified the surface of Padre Island.

An important question arises: If the winds blow primarily from two different quadrants, that is, the southeast and northeast quadrants (fig. 23), in which direction is most sand on the island being transported, and how does the transport direction relate to the two dominant wind directions?

Winds as Agents of Sediment Transport

Wind frequency data alone, depicting the amount of time or the frequency with which the wind blows from a specific direction, indicate that southeast winds should have the greatest control over direction of sand migration (fig. 5). Of course, wind velocity is also an important factor. Without sufficient velocity, winds blowing year-round from a single direction will transport little sand. Moreover, if

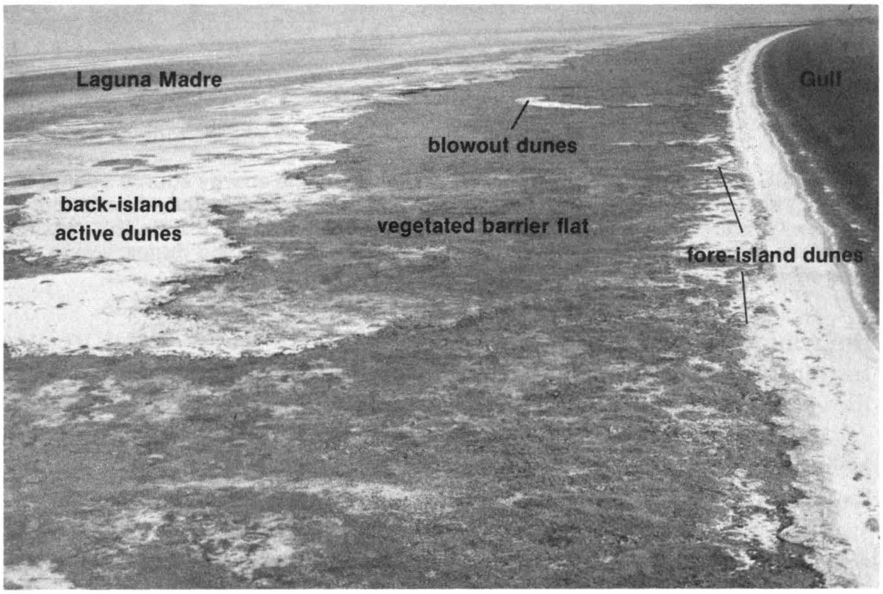


Figure 36. Well-vegetated portion of central Padre Island in the vicinity of grids H-11, J-11, and K-11, plate I. Compare with the sparsely vegetated segment of island shown in figure 37. View is to the north.

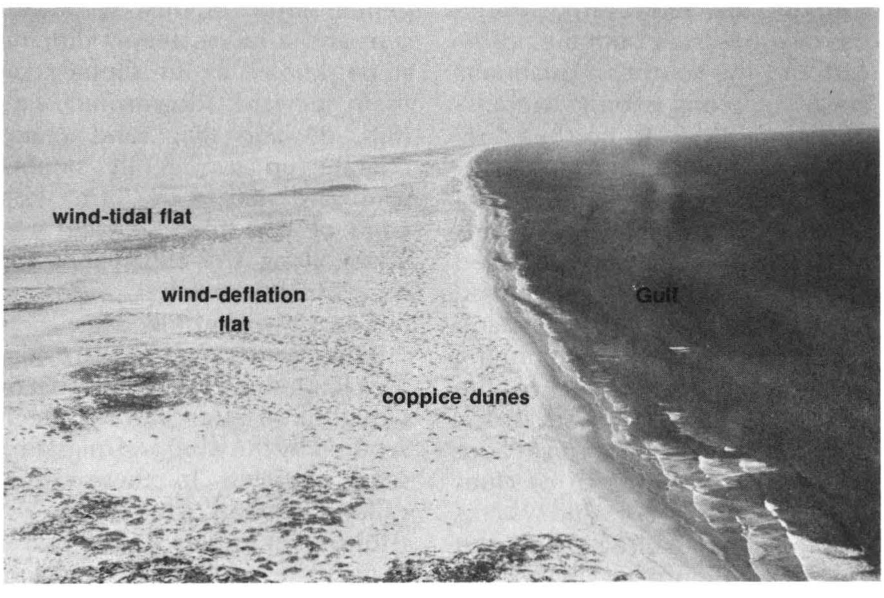


Figure 37. Sparsely vegetated segment of Padre Island immediately north of Mansfield Channel (see pl. I). View is to the north.

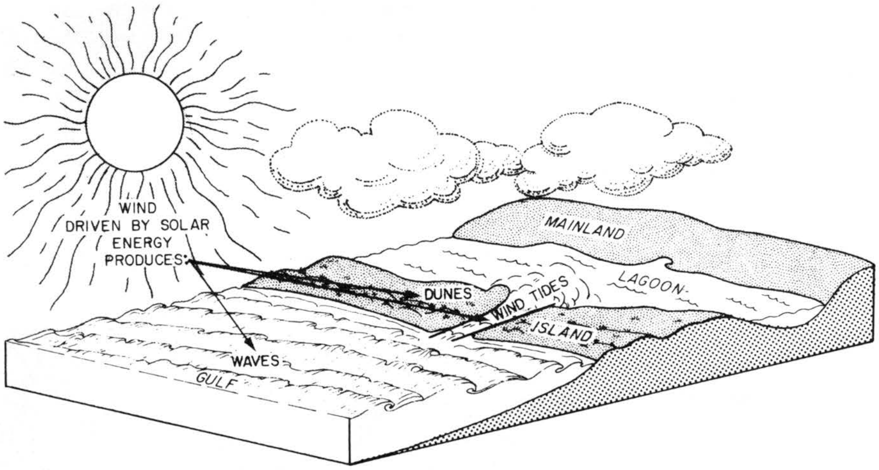


Figure 38. Generalized diagram depicting the sun as the energy source behind the wind. The sun, aided by the Earth's gravitational pull, sets the atmosphere in motion, producing the winds, which are in part directed by the Earth's rotation (Coriolis force). Winds are the driving force behind active sand dunes, waves and currents, and wind tides and are an important agent of change.

the wind is blowing hard enough to transport sand, a small increase in velocity will substantially increase the amount of sand that is being transported. For example, Bagnold (1954) noted that "a strong wind blowing at 16 meters per second, or 35 miles an hour, will move as much sand in 24 hours as would be moved in 3 weeks by a wind blowing steadily at 8 meters per second, or 17.5 miles an hour."

Weather records maintained at Corpus Christi indicate that velocities of winds from both the northeast and the southeast quadrants are often strong enough to transport sand. North to northeasterly winds are often characterized by high velocities, but the frontal systems from which these winds originate are relatively shortlived and are sometimes accompanied by rain that moistens the sand and holds it in place, thus diminishing the transporting power of the winds. Do the dunes and associated eolian features on Padre Island contain evidence or clues that reflect the major wind systems and the ultimate direction of sand migration? Before looking for the evidence, it will be helpful to consider, in general and greatly simplified terms, some typical characteristics of dunes and related features.

Characteristics of Dunes and Associated Deflation Areas

Dunes are windblown accumulations or mounds of sand that, unless impeded by obstacles, will take on a certain natural form or shape and move, mostly as a unit, downwind. Generally, active dunes (unvegetated dunes) have a gentle slope on their windward side and a more steeply dipping slope, known as the slipface, on their leeward (downwind) side (figs. 39 and 40). Sand grains migrate up the gently sloping windward side to the brink (top edge of the steep slipface) and down along the slipface of the dune. In this manner, the dune moves downwind (fig. 39).

As a dune moves forward, the area left behind is generally flat or troughlike, after having been scoured by the wind and migrating sand particles. In these areas, called *deflation flats* or *troughs* (Hunter and others, 1972), sand is generally eroded down to a level where moisture from the underlying water table holds the remaining sand in place, preventing further deflation or erosion (fig. 41). Because the water table helps control the depth to which sand is eroded, a drop in the level of the water table during drier periods (droughts) is accompanied by a drop in the elevation to which the sand can be eroded by the wind. Deeper deflation troughs are formed during dry periods or droughts (fig. 42). Interestingly, these basins pond water during wet periods and provide a wetlands habitat for flora and fauna.

During wet periods, rate of dune migration commonly decreases. This reduced rate of migration, coupled with the increased moisture, enables vegetation to encroach onto the margins of the sand mass, stabilizing the margins and inhibiting further movement along them. Assuming that the central mass of the dune is not stabilized but moves on, the deflation trough and vegetated sandy margins lag behind. These "stabilized" features provide a clue or record, although often relatively temporary, to the past positions and directions of dune migration and dune fields (fig. 43).

Now, with these general ideas about dune morphology and movement, the effect of wind on island features and the direction of net dune migration should be easier to decipher.

Influence of Southeasterly and Northeasterly Winds on Sand Migration

Figure 44 is an aerial photograph (taken in May 1975) of a dune field located on the southern part of the National Seashore (South Section, pl. I). The slipfaces of the dunes are oriented approximately northeast-to-southwest and dip toward the northwest. These transverse dunes (fig. 39) were shaped by southeasterly winds as indicated by the position of the slipfaces on the northwest side; thus the sand must be migrating toward the northwest.

But do these dunes maintain this shape, orientation, and direction of travel year-round? Figure 45 is an oblique, low-altitude, aerial photograph of the same dune field taken during the winter (February) of 1976, when winter seasonal winds were in effect. Slipfaces are now dipping toward the southwest instead of the northwest, indicating that the northeasterly winds temporarily have gained control over the shape of the dunes and have modified the direction of sand migration.

In another May 1975 photograph (fig. 46), position and orientation of the slipfaces (as shown by shadows) suggest that winds from the southeast recently had been effective in moving the sand and shaping the dunes. Closer observation of the active dunes (fig. 46), however, reveals faint shadows oriented in a northwest-southeast direction. These shadows reflect remnant traces of south west-dipping slipfaces that were developed by winds from the northeast. With these two different orientations of slipfaces in mind, some of the patterns and features apparent in the dunes (fig. 46) can be inferred. The dunes are in a state of transition, moving from control by northeast winds characteristic of winter months to control by southeast winds that characterize summer months.

Both wind systems seem to be effective in transporting sand, and both may control to some degree the direction of sand migration. Another example of the effect of southeasterly winds is presented in figure 47.

Net Direction of Sand Transport

Net annual direction of migration of the dunes and sand on Padre Island is indicated in figures 48 and 49. Close inspection of figure 48 reveals some recurring patterns. Because of the persistent onshore summer winds from the

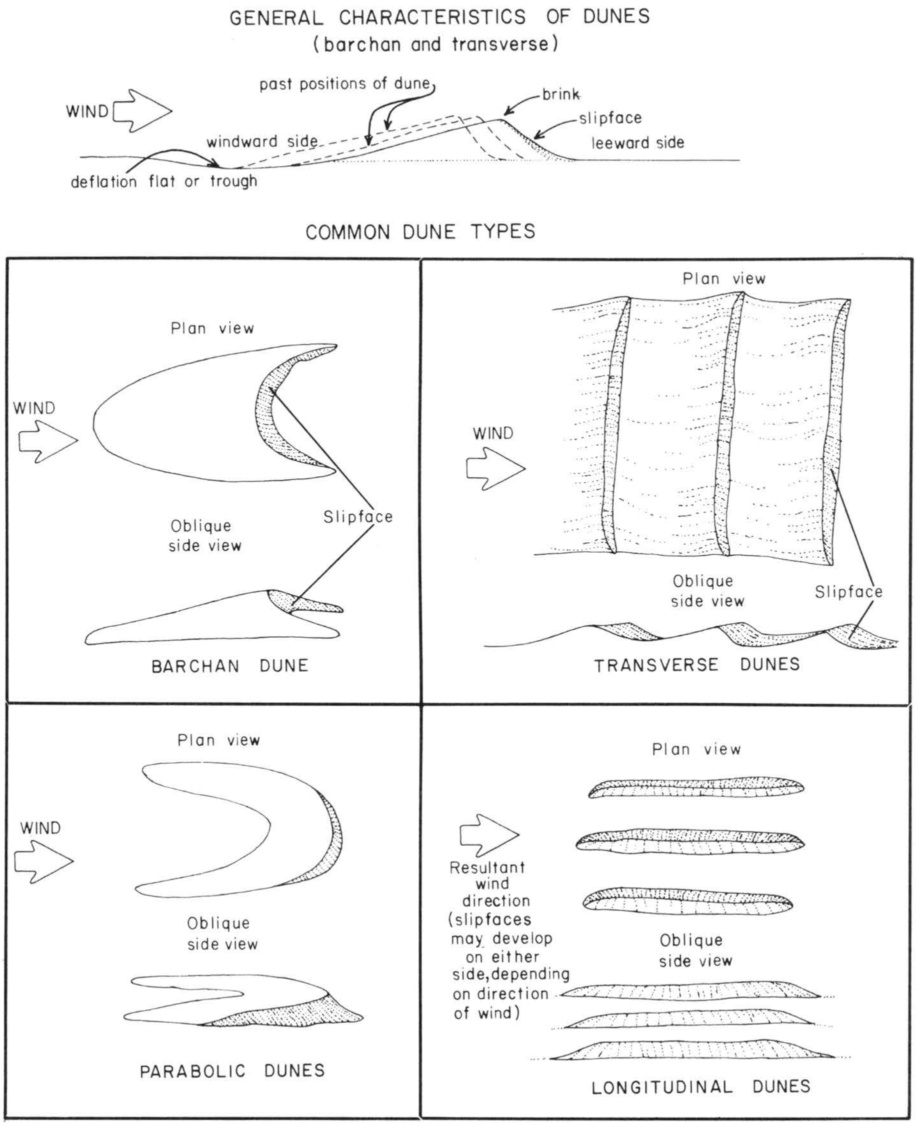


Figure 39. General characteristics of dunes and common dune types, shown in relation to wind direction.

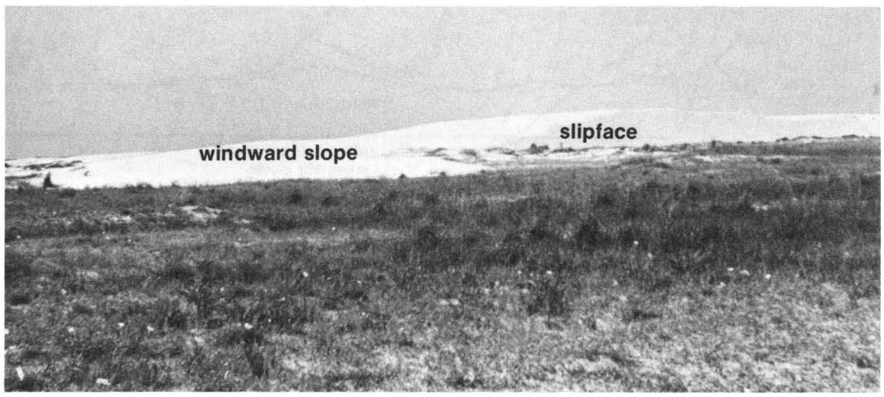


Figure 40. Active back-island dune on Padre Island. View is southwestward. Compare the steeply dipping leeward slipface, which is outlined by a slight shadow, with the more gently sloping windward side of the dune. The highest point on the slipface is about 10 to 12 feet above the vegetated flat over which the dune is migrating. This dune is also shown in figures 41 and 120.

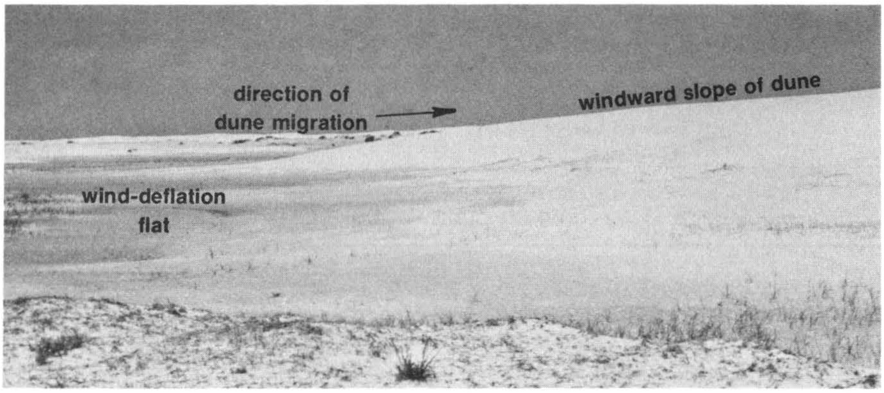


Figure 41. Deflation trough or flat formed along the trailing edge (windward side) of an active dune. As the dune migrates downwind to the right, sand is eroded by the wind down to a level where moisture from the underlying water table prevents further removal of sand. The darker, moist sand that characterizes the deflation flat contrasts with the whiter, dry sand that constitutes the dune. Eventually, the deflation flat may become stabilized with vegetation. Note the gentle windward slope of the dune; this is the same dune that is shown in figures 40 and 120.

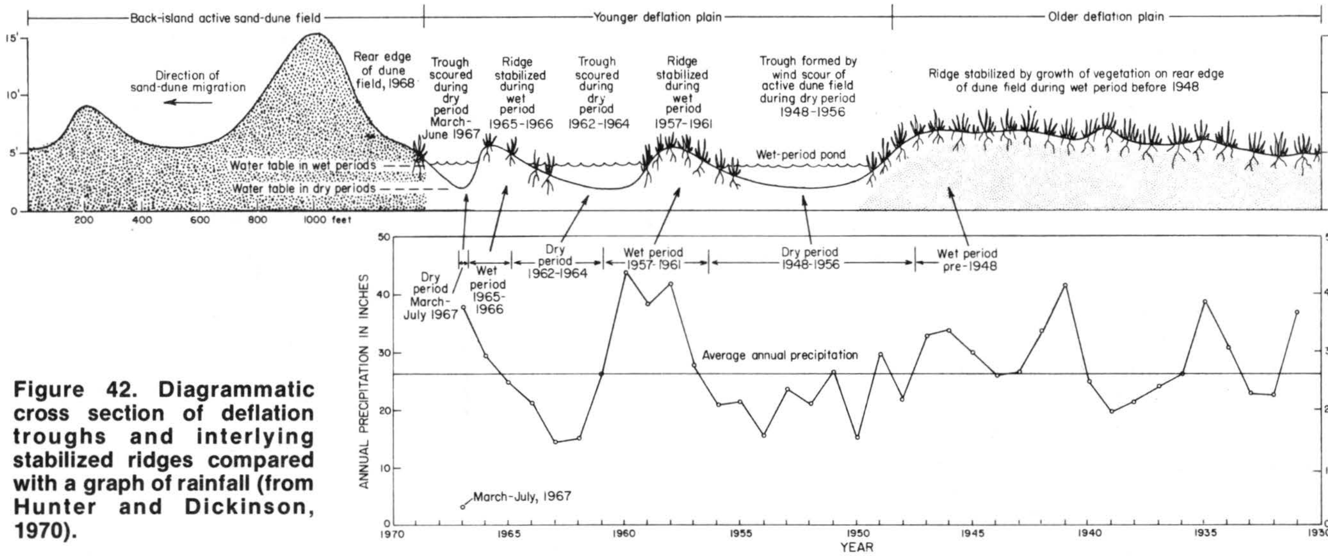


Figure 42. Diagrammatic cross section of deflation troughs and interlying stabilized ridges compared with a graph of rainfall (from Hunter and Dickinson, 1970).

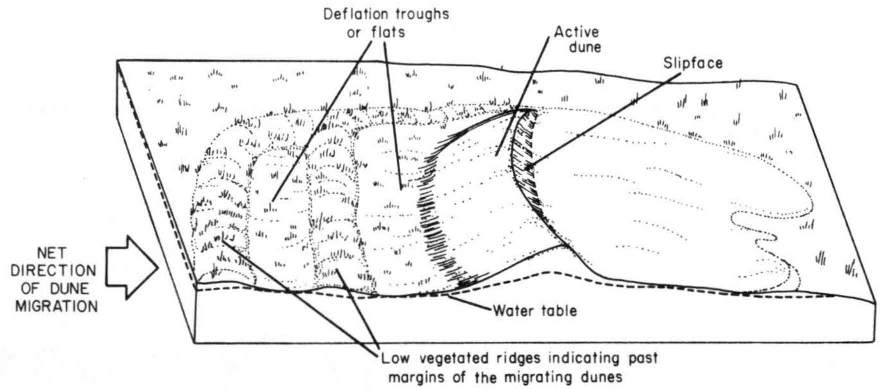


Figure 43. Generalized sketch of an active dune and related deflation troughs. Past positions of the dune, which is migrating toward the right, are indicated by the deflation troughs and low vegetated ridges (past margins). Distinction between the vegetated margins and deflation troughs can often be made through field observation on the basis of differences in types of vegetation on these features.

southeast and south-southeast, blowout dune fields in the fore-island area tend to become elongate in an approximate north-northwest direction. But the northeasterly and easterly components of winds that predominate during winter months modify the overall movement of the dune field into a more westerly direction, approaching west-northwest, as denoted by past position of the dunes shown in figure 48. These two directions — the elongation of the sand dune field in a north-northwest direction and the overall sand migration in a more westerly (WNW) direction (fig. 49) — help to explain the orientation and patterns of many island features. For example, maps prepared from photographs taken during different years show that an interesting and predictable pattern develops in the wake of migrating dune fields (fig. 50).

One more significant pattern emerges in the back-island dune fields as noted by Boker (1953),

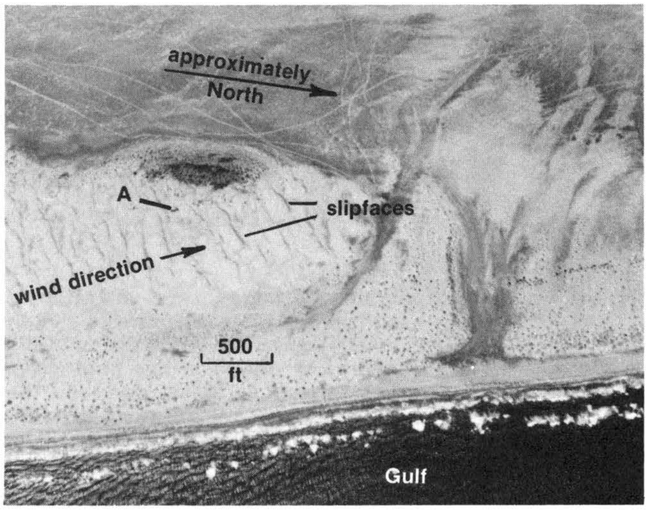


Figure 44. Aerial photograph of active dunes shaped by southeasterly winds. Slipfaces dip toward northwest (note shadows). Photograph, taken in May 1975, is of dune field located in grids H-20 and J-20, South Section, plate I. The clump of vegetation at "A" is also shown in figure 45 for reference purposes. Note the difference in scale between the two photographs.

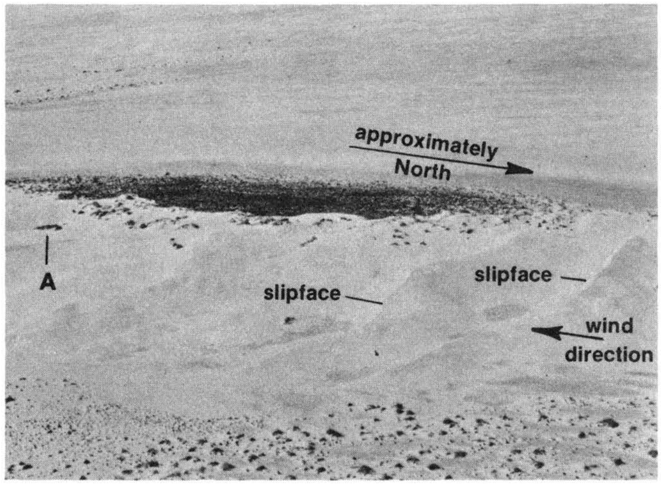


Figure 45. Oblique, low-level aerial photograph of active dunes shaped by northeasterly winds. Slipfaces dip toward the southwest. This is the same active dune field shown in figure 44. Photograph was taken in February 1976. Clump of vegetation indicated at "A" is also noted in figure 44. Note in lower right-hand corner of photograph that sand has accumulated downwind from clumps of vegetation (in wind-shadow zones).

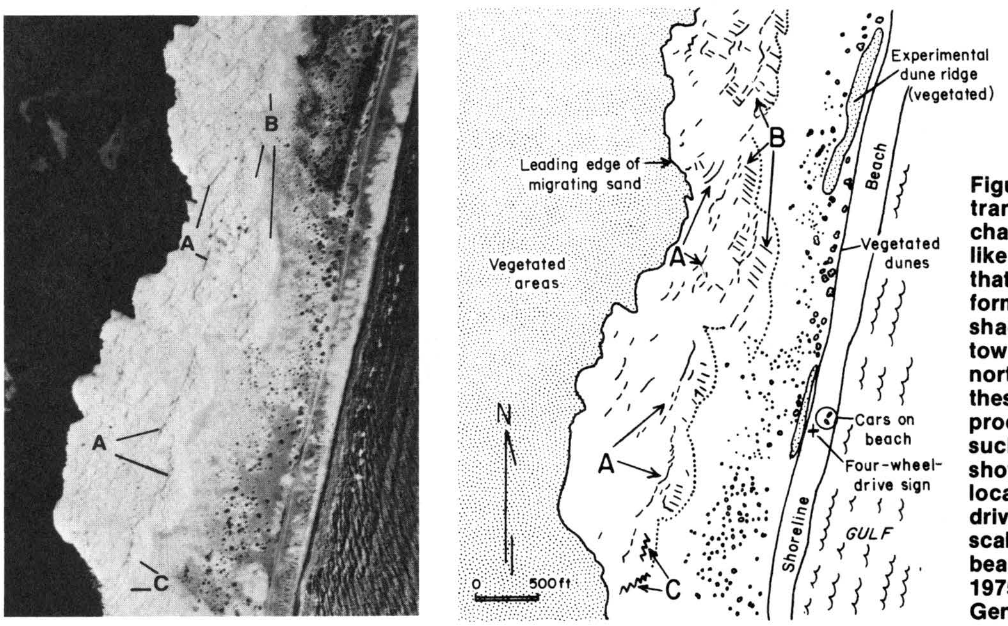


Figure 46. Active dunes in a state of transition as they respond to changing wind directions. Shadows like those shown at "A" are slipfaces that dip toward the northwest, formed by southeast winds. Faint shadows at "B" are slipfaces that dip toward the southwest, formed by northeast winds. The combination of these differently oriented slipfaces produces some interesting patterns, such as those that look like sawteeth shown at "C." These dunes are located landward of the four-wheel-drive sign (North Section, pl. I). For scale, note size of cars parked along beach. Photograph, taken in May 1975, provided courtesy of the General Land Office of Texas.

Price (1958), and Hunter and others (1972). The dunes in many back-island dune fields are aligned approximately east-west (fig. 51). These back-island dunes are relatively stable features that generally maintain their alignment and orientation throughout the year; this is indicated by aerial photographs taken during different months and years. Many of the lines representing orientation of active dunes shown on the map of Padre Island (pl. I) reflect this east-west alignment.

Rate of Dune Migration

Migration rates of active dunes vary from year to year, but average rates can be determined by comparing the position of a selected dune on aerial photographs taken over an interval of several years. The position of the trailing edge (windward side) of the main body of sand of dune "C" shown in figure 48 was accurately measured and compared on photographs taken in 1956 and 1975. The trailing edge moved about 665 feet during the 19-year period. The average rate of movement was approximately 35 feet per year. Sand dunes on north Padre Island have been reported to migrate at up to 75 and 85 feet per year (Hunter and Dickinson, 1970; Price, 1971).

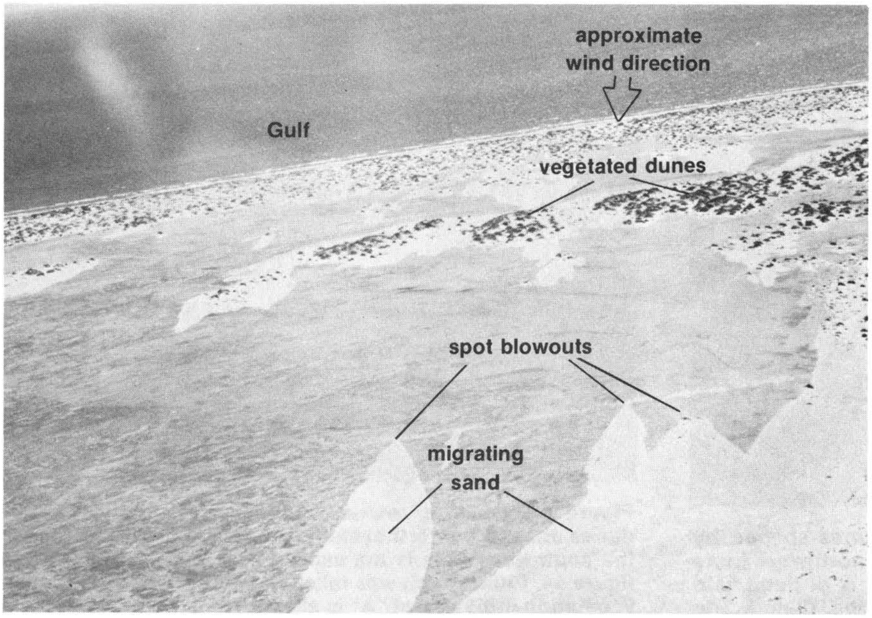


Figure 47. Lagoonward migration of sand in response to onshore (southeasterly) winds. Gulf is in distance. The patterns displayed in this photograph were formed as loose, dry sand (the white areas) migrated downwind across darker-colored, rain-moistened sandy flats. The drier sandy areas that flare or spread outward downwind originated from small areas ("spot" blowouts) upwind. Part of the unique appearance occurs where the flare patterns from two different spot blowouts overlap.

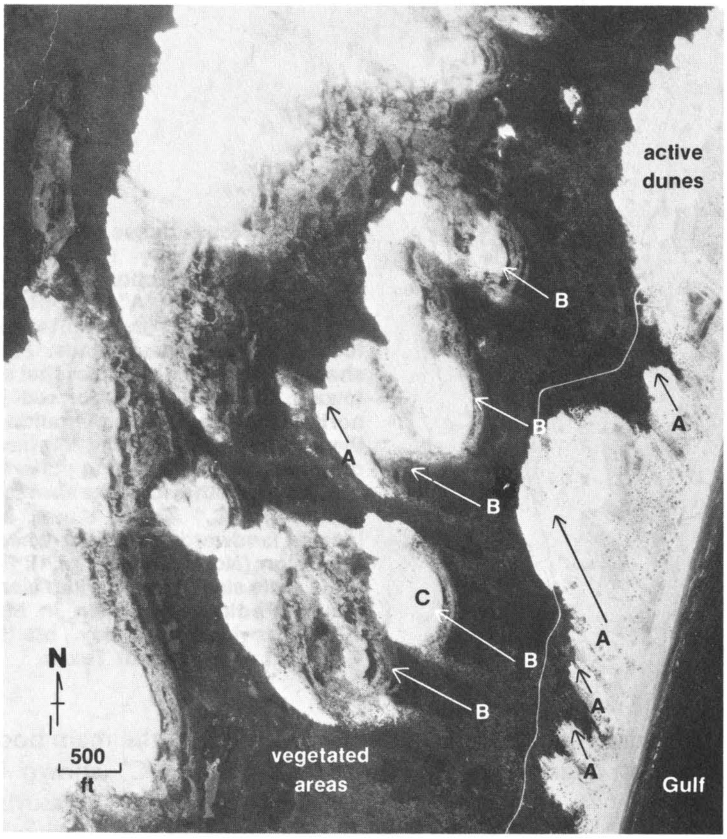


Figure 48. Aerial photograph showing the direction of elongation ("A" arrows) of active dune fields in relation to their net direction of migration ("B" arrows). See figure 49. Note that the net direction of migration as shown by "B" arrows is evident from the dark-colored (vegetated) deflation troughs (that lie below the arrows) and the lighter-colored lateral margins (parallel to the arrows) that were left behind as the dunes migrated landward. At an average rate of migration of 35 ft/yr for the trailing edge of the dune labeled "C," it took approximately 23 years for dune "C" to travel the length of the arrow. Photograph, taken in June 1974, provided courtesy of the General Land Office of Texas.

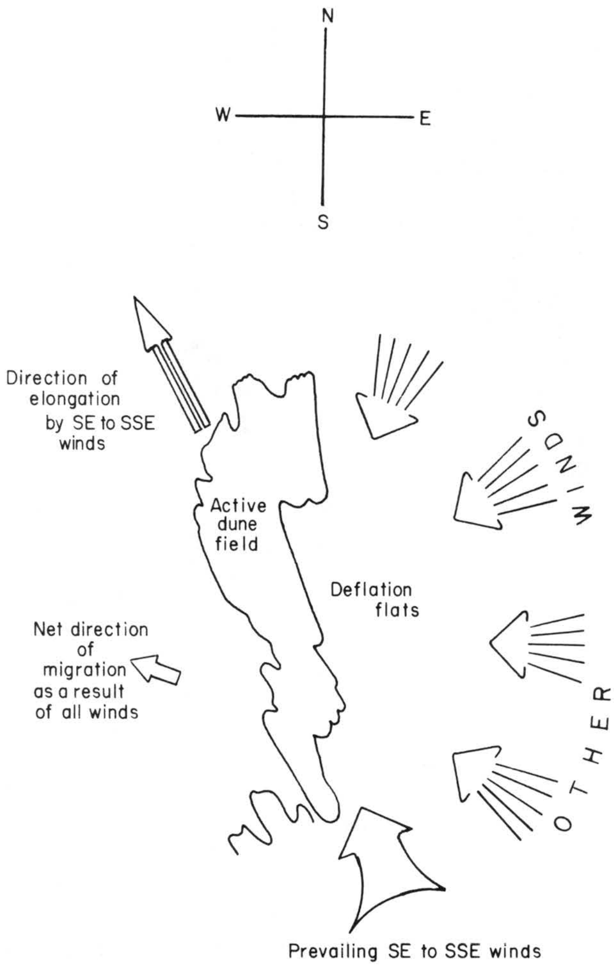
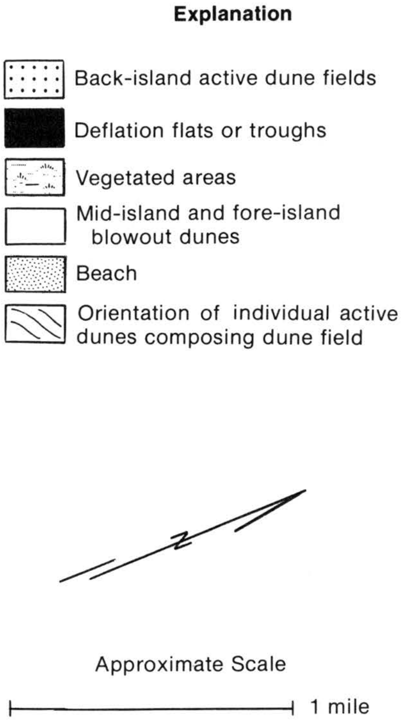


Figure 49. Movement of active dunes with respect to major wind directions. Refer to figure 48 for additional explanation.



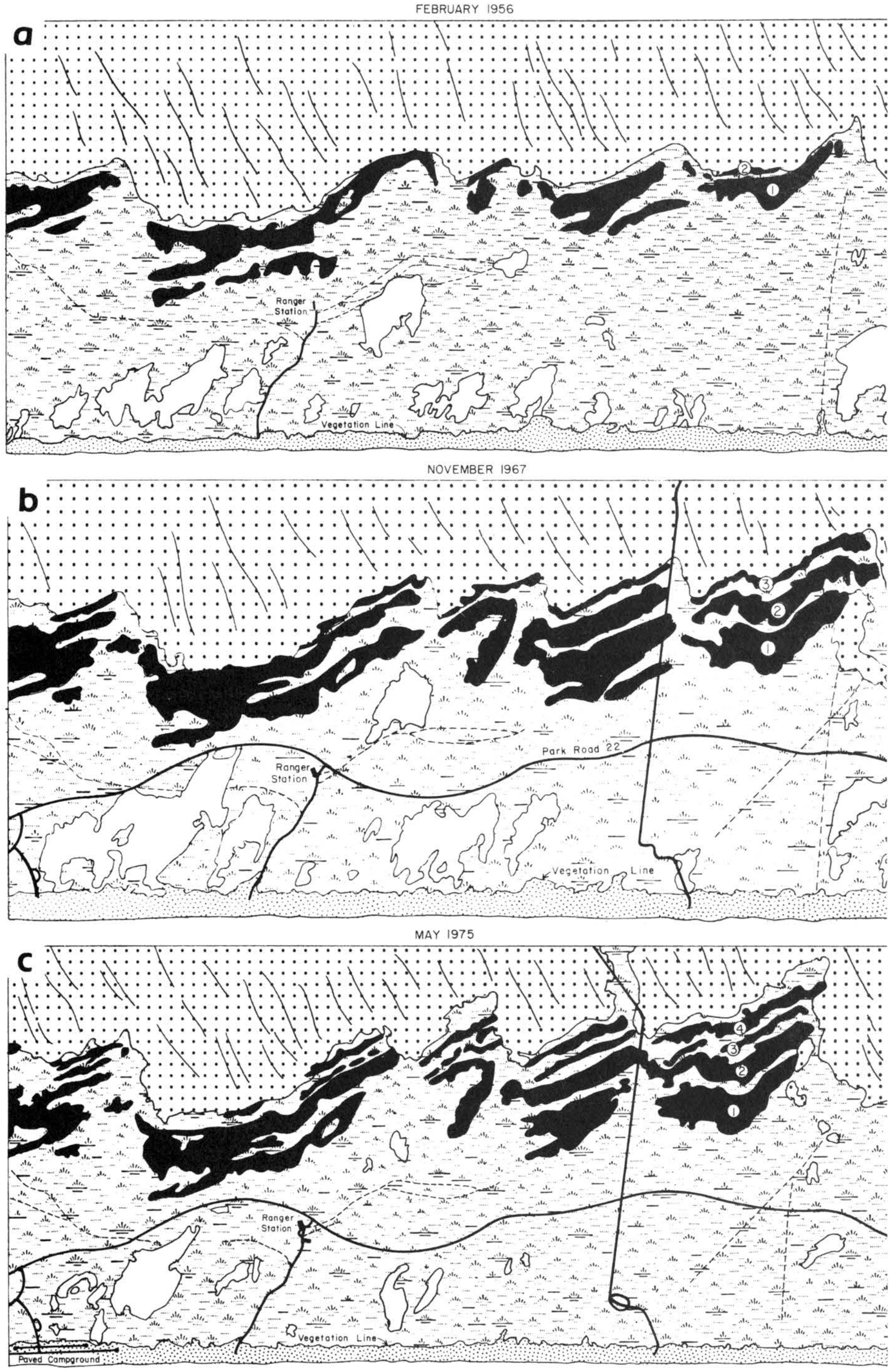


Figure 50. Comparison of the distribution of island environments as they appeared in (a) 1956, (b) 1967, and (c) 1975. Note the north-northwesterly orientation of the successively formed deflation troughs labeled (from oldest to youngest) "1," "2," "3," and "4" on the 1975 map. Maps were prepared from aerial photographs taken during February 1956, November 1967, and May 1975. The area mapped is just north of Malaquite Beach and coincides approximately with vertical grid columns R, S, and T, shown on the North Section of plate I.

Internal Structure of Dunes

Information on wind direction and sand movement can also be ascertained from internal structures of dunes. Dunes progress as sand is blown up gentle windward slopes and is deposited on the steeper leeward slipface. Accumulations of sand on dune surfaces, such as the slipfaces, form layers that are commonly visible in cross section because of slight differences in grain size and composition of the sand. These differences result from sorting or segregation of the material as it is transported and deposited by the wind (figs. 52 and 53). Generally, the result is visible bedding or layering that is normally parallel to the surface on which the sediments accumulate (figs. 54 through 57).

If the surface on which sand layers accumulate is at an angle to a horizontal plane, these dipping layers (in cross section) are said to be crossbedded (figs. 58a and 58b). Accordingly, layers formed on the

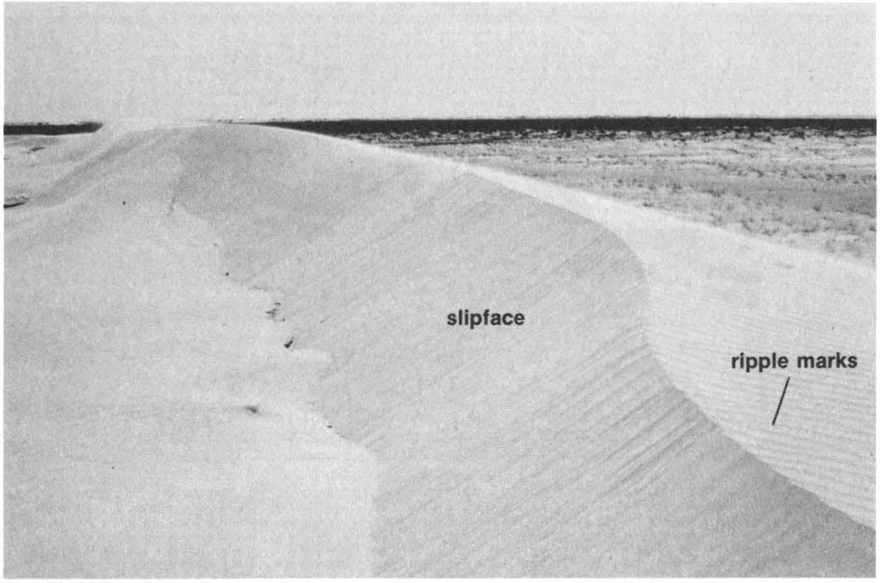


Figure 51. Active longitudinal dune on the lagoon side of Padre Island. View is to the southeast. The long dimension of this dune is lined up approximately east-west. Dunes similar to this one, oriented either parallel (longitudinal dunes) or obliquely (oblique dunes) to the resultant (vector sum of) direction of winds that blow across Padre Island, are relatively stable features and may develop slipfaces on their northern or southern sides, depending on the wind direction at a given time. In the photograph at left, the slipface is on the northern side (left side), indicating the influence of south to southeasterly winds. Note the ripple marks on the southern side of the dune crest. This particular dune is located in grid square P-3 (pl. I).

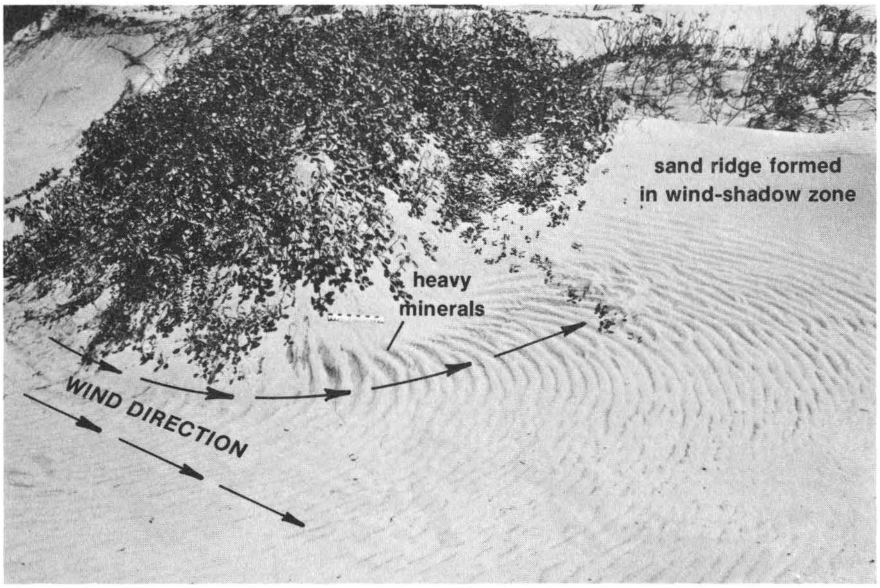


Figure 52. Ripple marks showing sorting or segregation of sediments by the wind. The ripples, which formed perpendicular to the wind direction (see arrows), are accentuated by dark, fine-grained heavy minerals, which are concentrated in the ripple troughs (low points). The wind sorts sediments primarily on the basis of differing sediment size, the heavy minerals being finer grained than the other sediments. Wind sorting produces distinct layers in the accumulating sand, which are visible when the sand body is viewed in cross section (see fig. 54). Note pile of sand that has accumulated downwind from the clump of vegetation (in the wind-shadow zone). Scale is 12 inches (30.5 cm) long.

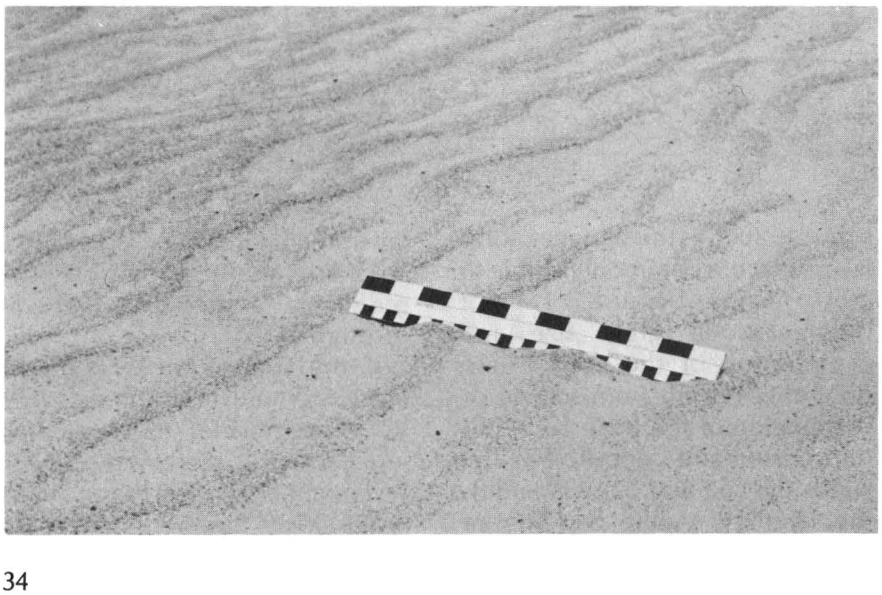
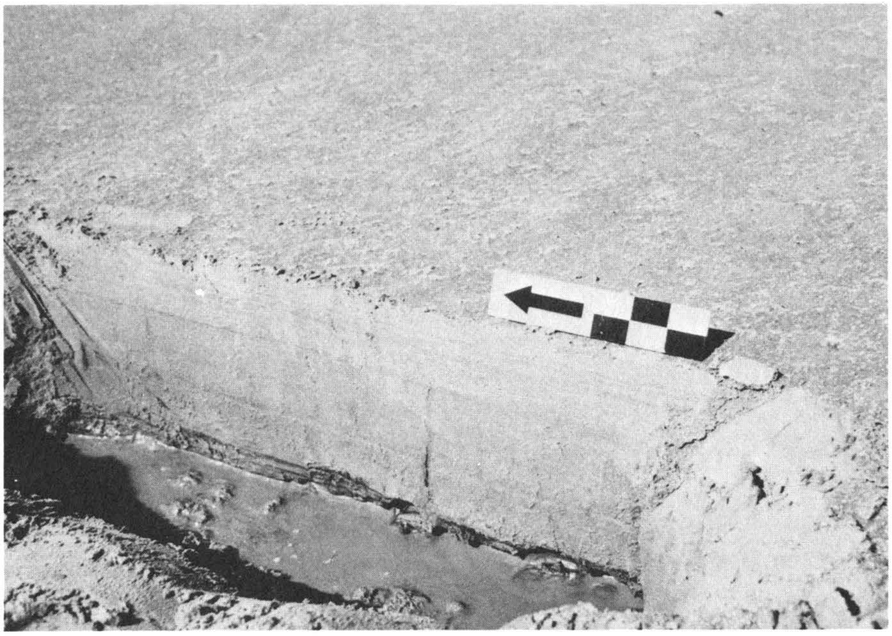


Figure 53. Ripple marks in which flakes of shell material have been sorted or segregated from finer grained quartz sand by the wind. The coarser materials (shell fragments) have become concentrated in the crests (high points) of the ripples, while the finer sand remains in the more protected troughs (low points). Sorting of the shell material from the quartz sand produces distinct layers (see fig. 55) as the sediments are transported and deposited by the wind. Wind direction is from left to right, and is parallel to the scale, which is 12 inches (30.5 cm) long.

Figure 54. Trench dug in hurricane washover channel on Padre Island. Note the parallel, horizontal layers of sediment that are visible as a result of sorting of dark-colored, fine-grained heavy minerals (dark layers) and light-colored predominantly quartz sand, which has a slightly coarser grain size than the heavy minerals. Layers of fine-grained sediment, similar to those exposed in the trench, can be formed by wind or water. Numerous studies have been conducted in an attempt to establish criteria that will allow wind-deposited sediments to be differentiated from those deposited by water, but total success has not been achieved. Organic material, such as that associated with the growth of algae on tidal flats, may also produce dark-colored layers that are interbedded with layers of light-colored sand. Note that in the photograph at right, the water table has been intersected at the bottom of the trench. Arrow on scale is parallel to washover channel and pointing toward Laguna Madre. Scale is 11.8 inches (30 cm) long.



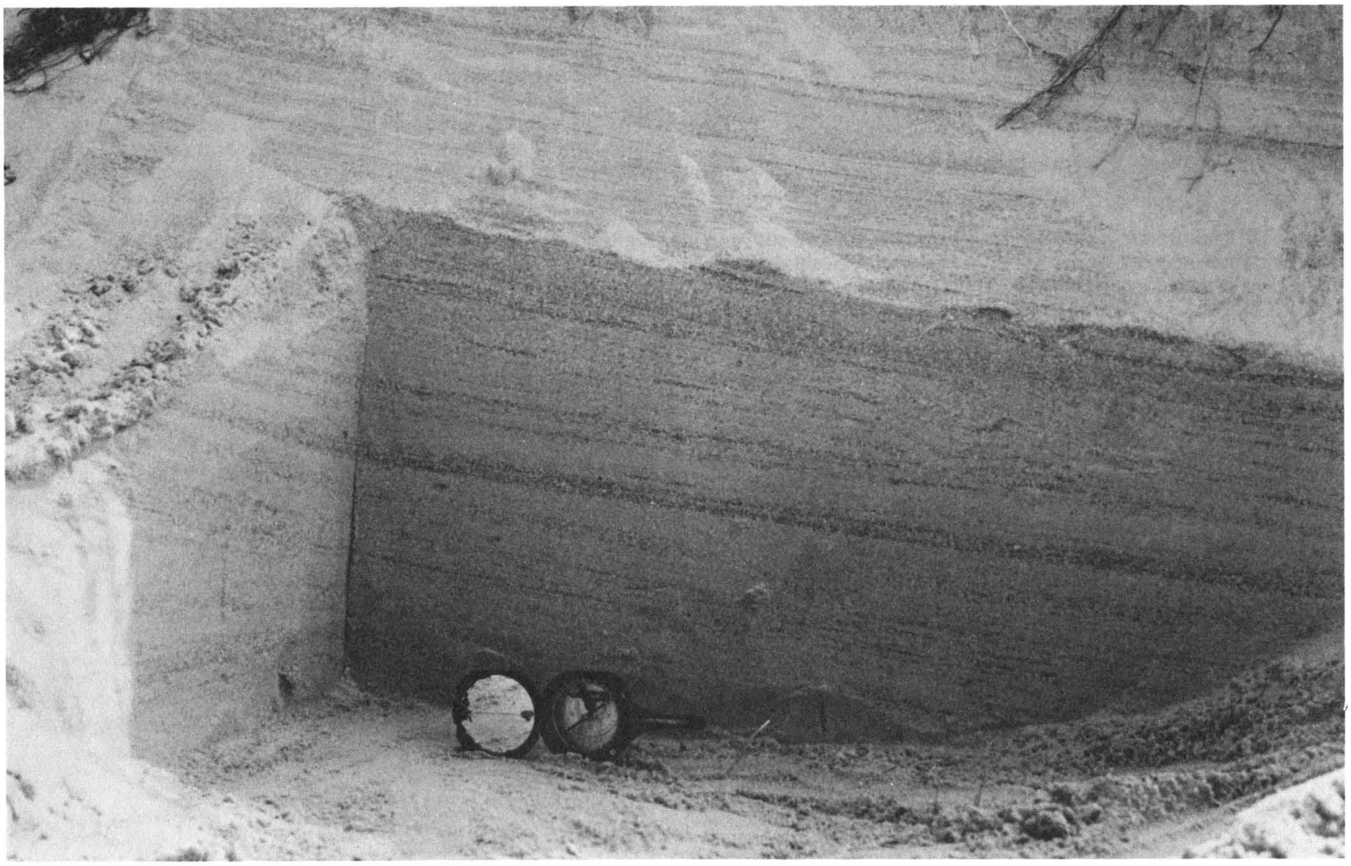


Figure 55. Alternating layers of sediment, composed predominantly of quartz sand and shell fragments, in a fore-island dune on Padre Island. The exact mechanism by which the wind sorts or segregates sediments of different sizes into distinct layers during deposition is not fully understood, but as shown in this photograph, sorting obviously occurs. Layers of fine-grained quartz sand (light-colored layers) are readily distinguishable from the coarser-grained layers composed of shell fragments (dark-colored layers). The small trench was cut along a barren and exposed side (blowout) of a fore-island dune ridge about 15 feet above mean sea level. Source of the thin platy shell fragments is Little Shell Beach, which lies gulfward (to the right) of the dune. The shells are broken into a hash by wave action along the beach and are subsequently transported toward the dunes by onshore wind. The Brunton compass shown in the photograph is about 8.5 inches long and is positioned so that the top edge is horizontal; note dip direction of the sedimentary layers.

Figure 56. Trench dug behind a small dune (vegetated with sea oats) located near the beach on Padre Island. A close-up gulfward view of this trench is shown in figure 57. Scale resting on bottom of trench is 12 inches (30.5 cm) long. View is gulfward.

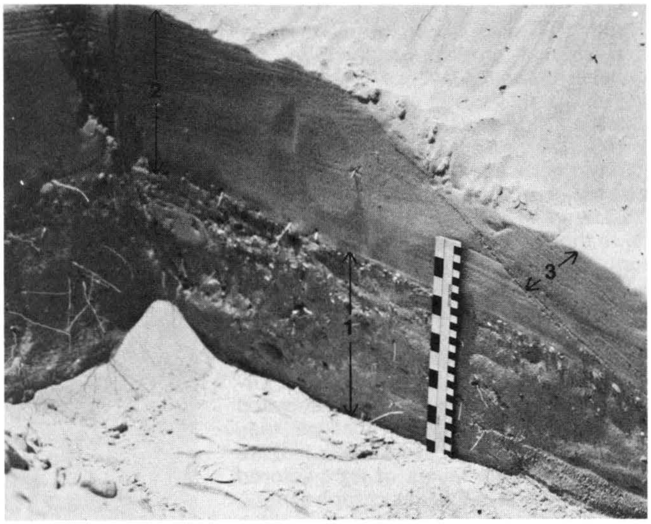


Figure 57. Close-up view of trench shown in figure 56. Note the different sedimentary sequences labeled "1," "2," and "3." The presence of shells in sequence 1 suggests that this sequence was formed primarily by the action of waves that washed across the backbeach, depositing sand and scattered shells; numerous roots have changed the original appearance (primary structures) of this sequence. Sequence 2 is composed of gently dipping layers of well-sorted, fine-grained sand that were deposited above sequence 1 by the wind. Note the well-defined contact that separates sequences 1 and 2. The more steeply dipping layers (crossbeds) of sequence 3 were deposited after sequence 2 was truncated by deflation (wind erosion). The thin layers of shell fragments that mark the contact between sequences 2 and 3 were probably formed as wind removed the finer sand, leaving the shell fragments concentrated along the deflation (wind-eroded) surface, which was eventually covered with the fine-grained, well-sorted, wind-deposited crossbeds that make up sequence 3. The scale extending vertically along one wall of the trench is 12 inches (30.5 cm) long.

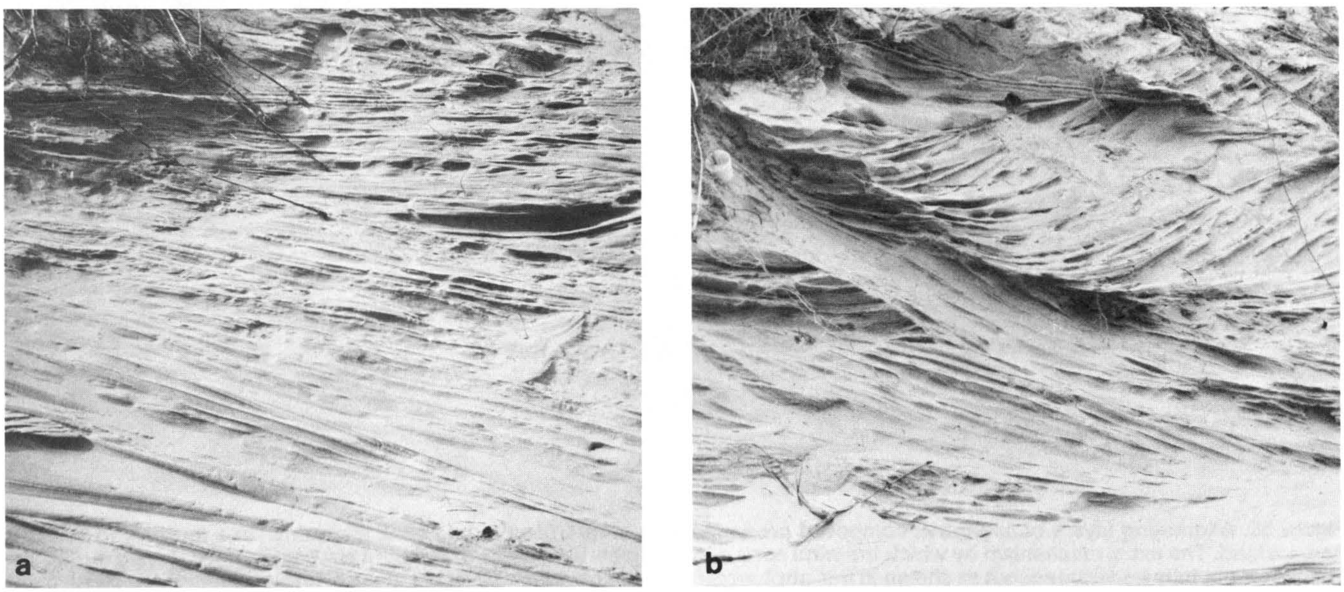


Figure 58(a) and (b). Dune crossbedding, Padre Island. These photographs are of naturally occurring exposures of near-vertical, northward-facing walls in the fore-island dunes. Gulf is to the left. The bedding has been etched or "sand blasted" by north winds, revealing the intricate internal structure of the dunes. Note that in photograph (a), most crossbedding dips in one direction, whereas in photograph (b), crossbeds dip in different directions. The paper cup in the upper left-hand corner of photograph (b) serves as a rough measure of the size of the layers.

slipface of a dune are crossbedded with angles of dip ranging between 25° and 34° (Bigarella, 1972). The maximum dip angle, approximately 34°, is near the angle of repose of the windblown sand. Angle of repose is the steepest angle or slope that the sand can maintain without beginning to slide, flow, or avalanche down the slope.

Direction of dip exhibited by crossbeds normally indicates the direction of sand migration. Thus, by measuring the dip direction of exposed beds, the general wind direction that formed the slipface can be estimated.

Figures 59a and 59b are photographs of a deflation "flat" just upwind from the gentle windward slope of an active dune located in the northern part of Padre Island National Seashore. Visible in figure 59a are truncated (eroded) crossbeds that were left behind as the dune moved downwind (northwest) in response to the prevailing south-southeasterly winds. The exposed layers of sand, which are held together by moisture, dip in two principal directions—north-northwest and south-southwest—and reflect the influence of the south-southeasterly and north-easterly winds, respectively. Figure 59b shows another complicated pattern of truncated crossbeds that dip in two directions. An explanation for crossbeds that dip in two directions (figures 59a and 59b) is shown in figure 60.

This explanation of dune crossbedding and its relation to wind direction is highly simplified; steeply dipping beds are not always indicators of wind direction. This is true in fore-island areas where dunes are stabilized and shaped by vegetation and modified by erosion during storms. For example, M. O. Hayes (1967) observed that Hurricane Carla's storm tides and waves eroded fore-island dunes to form steep seaward-facing cliffs. Isolated dunes that remained were stabilized by clumps of vegetation. When normal onshore south-easterly winds began to blow after the hurricane, sand accumulated against the wave-cut cliffs, forming seaward-dipping crossbeds. In this instance, then, the beds that formed dipped upwind instead of downwind. Sand blown by onshore winds accumulated in a wind-shadow zone behind the eroded dunes to form slopes (slipfaces) and crossbeds that

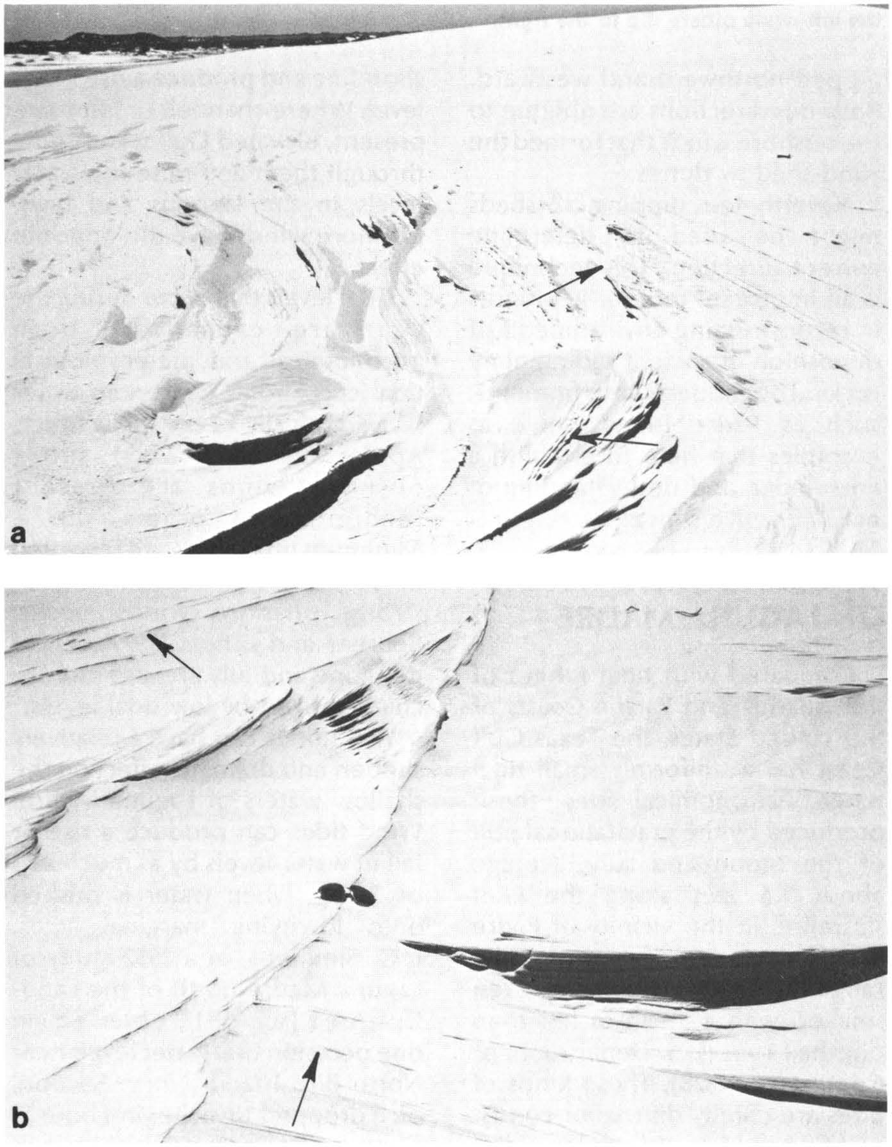


Figure 59(a) and (b). Truncated crossbedding exposed on nearly horizontal surfaces windward of an active back-island dune on Padre Island. The dipping beds (crossbeds) were exposed as sand was deflated (eroded by the wind) down to underlying layers of moist sand that lie slightly above the water table. Moisture helped hold the exposed layers of sand together and allowed the crossbeds to be etched as dry sand migrated over the moisture-stabilized surface. In photograph (a), the truncated crossbeds in the upper half of the photograph dip about 30° toward the right (see top arrow) and reflect the past positions of the dune's slipface as it migrated toward the right, or north-northwestward, in response to south-southeasterly winds. Crossbeds in the bottom central portion of the photograph (see bottom arrow) dip about 30° toward the left (southwest), indicating that a northeasterly wind was directing the slipface on which these layers were deposited. In photograph (b), sunglasses (approximately 6 inches or 15.2 cm long) mark the contact between crossbeds that dip in two different directions (see arrows), suggesting that they too were deposited by two different wind systems.

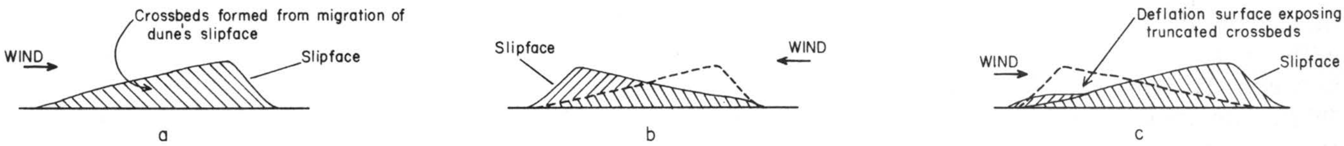


Figure 60. Sequence of events that can produce crossbeds dipping in different directions: (a) wind blows from left to right, forming crossbeds that dip to right as dune migrates downwind; (b) change in wind direction forms crossbeds that dip downwind toward left; and (c) wind again changes directions after rains have raised the water table, which moistens layers of sand. The layers of sand are eventually uncovered and exposed along the deflation surface shown in (c). Some of the exposed beds dip to the left while others dip to the right.

dipped northward and westward. Both dip directions are oblique to the onshore winds that formed the wind-shadow dunes.

Nevertheless, dipping crossbeds might be used to determine current direction. This technique is an important tool for geologists in reconstructing environments of deposition in ancient sedimentary rocks. The modern environments, such as Padre Island, serve as examples that help to establish a knowledge and understanding of natural, active processes.

TIDES AND THEIR EFFECTS ON LAGUNA MADRE

Compared with tidal ranges of the Atlantic and Pacific Coasts of the United States, the Texas Gulf Coast has a uniformly small tidal range. Astronomical tides—those produced by the gravitational pull of the moon and sun—average about 1.4 feet along the Gulf shoreline in the vicinity of Padre Island; the astronomical tidal range in Laguna Madre is even smaller, with a mean of less than one-half foot (U.S. Department of Commerce, 1978). These kinds of tides are chiefly diurnal or consist of only one high and one low tide a day, although they may be semidiurnal (two high and two low tides a day) or mixed during certain times of the month.

More important than astronomical tides in the Padre Island area are wind tides. Wind tides are produced when strong and steady winds elevate the water surface, flooding areas of low elevation (wind-tidal flats). Strong onshore winds force Gulf waters against the shoreline and produce a rise in sea level. Where channels or inlets are present, elevated Gulf waters flow through them and raise the water levels in the lagoons and bays. Offshore winds have the opposite effect.

Tidal levels that occur during the year are caused by both astronomical and meteorological tidal conditions. Maximum water levels typically occur in October, April, and May when strong onshore winds are present (Behrens and others, 1977). Minimum tidal levels are recorded in January and February when strong offshore winds occur. Behrens and others (1977) report that June and July are also months characterized by low tidal levels.

Wind tides can have a relatively sudden and dramatic effect on the shallow waters of Laguna Madre. Wind tides can produce a rise or fall in water levels by as much as 1 or 2 feet when water is pushed onto low-lying marginal areas. E. G. Simmons, in a 1957 study of Laguna Madre north of the Land-Cut Area (see pl. I), observed on one occasion that water levels near North Bird Island (North Section, pl. I) dropped 18 inches in 1 hour as a result of strong (50 mph) winds from the west. Such rapid changes in shallow Laguna Madre can leave boats stranded because of insufficient water depths. Occasionally, air boats that have maneuvered into shallow water in some parts of Laguna Madre have been stuck for hours because of a fall in water level as a result of strong, steady winds.

Fisk (1959) reported that before the Intracoastal Waterway was dredged through that section of flats now known as the Land-Cut Area, winds occasionally would drive waters completely across the flats, thereby joining the waters of north and south Laguna Madre. North winds are especially effective, causing water to advance over the flats at rates as high as 7.6 miles per day to cover the entire Land-Cut Area within a period of 36 hours (Fisk, 1959).

HURRICANES AND THEIR EFFECTS ON PADRE ISLAND

> On September 4, 1961, the U.S. Weather Bureau advised that a tropical depression had formed in the Caribbean Sea just off the coast of Nicaragua. This was the first warning of one of the greatest storms of this century. One week later, the tropical depression, now grown to a full-sized hurricane designated as "Carla" crossed the Texas coastline near the small town of Port O'Connor. ... The Gulf coast from Grand Island, Louisiana westward to the Rio Grande felt the storm to some extent. ... Hurricane surge and wind destruction damages reached a total estimated at about 408 million dollars and disrupted all normal activities for four days in the coastal areas of some 38 counties. The hurricane winds wreaked major damage to roofs, fences, and small buildings; eroded Gulf beaches, roads, levees, and bayshores; severed communications and power supplies; stopped utility systems in cities and towns; contaminated food and water supplies; and destroyed or damaged agricultural crops through the area (U.S. Army Corps of Engineers, 1962).

It is not surprising that coastal inhabitants view hurricane season (June through October) with apprehension and fear. Hurricanes are the most devastating natural events that occur along the Gulf Coast. In addition to the threat to man and his activities, these high-energy storms can produce significant changes in natural environments (Brown and others, 1974). Hurricanes are the most destructive of all storms, primarily because of their size and intensity. A hurricane is "defined technically as a storm of tropical origin with a cyclonic wind circulation (counterclockwise in the Northern Hemisphere) of 74 mph or higher" (Dunn and Miller, 1964). Although hurricane wind velocities of up to 200 mph cannot compare with tornado winds that may exceed 300 mph, the great size of hurricanes and the length of time during which they expend their energy result in a much greater overall impact. Hurricanes often spawn tornadoes, as demonstrated by Hurricane Beulah in 1967, when more than 100 tornadoes were reported (U.S. Army Corps of Engineers, 1968).

Hurricanes can be characterized by their most destructive properties as described by Orton and Condon (1970):

> Carla in 1961 wrought devastation primarily with mountainous storm tides; Beulah in 1967 inundated thousands of square miles with 20- to 30-inch rains; Celia did it all with winds.

A more detailed comparison of these three hurricanes is presented in table 1.

TABLE 1.

Characteristics of Hurricanes Carla, Beulah, and Celia, as measured at Texas stations *(compiled from U.S. Army Corps of Engineers, 1962, 1968, and 1971).*

Characteristics	**Carla (1961)**	**Beulah (1967)**	**Celia (1970)**
Wind *(mph)* peak gust			
measured	154	109	160
estimated	170	120	180
Fastest mile*	115	115 *(est.)*	130
Storm-surge tide height *(feet)*			
Gulf shoreline	12.2	9.4	9.2
Bay shoreline	22	10.9	11.4
Coastal area inundated by storm surge *(acres)*	1,700,000	630,000	325,000
Rainfall *(inches)*	15 (for 4-day period)	36 (24 hr. high = 15)	6.5
Size of destructive core	Large	Medium	Small
Accompanying tornadoes	26	115	8
Minimum atmospheric pressure *(from Texas stations)*	27.62	28.07	28.03
Dollar damage			
Tidal inundation	200,195,000	5,449,000	27,573,000
Wind and rain	203,389,000	108,158,000	439,738,000
Flooding by storms and runoff		46,491,000	
Total	**403,584,000**	**160,098,000**	**467,311,000**

**"Fastest mile" is the maximum speed of the wind sustained for a period long enough to travel a distance of 1 mile, as determined from velocities recorded at a given point.*

One of the most destructive features of hurricanes is the storm tidal surge. Storm surge expends a vast amount of energy by eroding, transporting, and depositing great volumes of coastal sediment. The effects of storm surge produced by Hurricane Celia on the Texas coast are documented by McGowen and others (1970). Although the tide (known as the *forerunner*) rises slowly while the storm is offshore, the surge, which accompanies the hurricane as it makes landfall, is a rapid rise in water level resulting from strong onshore winds and low atmospheric pressures (Dunn and Miller, 1964). Superimposed on the elevated water level are storm waves. Because a hurricane spirals in a counterclockwise direction in the Northern Hemisphere, it develops a larger surge on its right side as it approaches the coastline. Flooding will be greater in low-lying areas to the right of the hurricane as viewed from the approaching eye of the storm.

As a hurricane approaches the mainland along the central Gulf Coast of Texas, barrier islands are the first land feature in the path of the surge. Where a well-developed fore-island dune ridge exists, such as along Big Shell Beach on central Padre Island, the barrier island provides a major line of defense for the mainland. The barrier helps to block the surge and to dissipate large amounts of wave and current energy. But the impact of the storm still leaves its mark on the island. Hayes (1967) observed that fore-island dunes were eroded landward as a result of Carla's storm surge and wave attack. Steep, gulfward-facing, wave-cut cliffs up to 10 feet high were evident along parts of the fore-island dune ridge. The normal beach profile was replaced by a broad, flat, hurricane beach. Furthermore, in some areas, the newly formed beach was strewn with an assortment of material plucked from offshore, from water as deep as 50 to 80 feet. The material included coarse, heavy shells and rock fragments, coral and caliche blocks, and a large Pleistocene elephant tooth. The tooth perhaps serves as a reminder of the lower stands of sea level (figs. 15a and 16) that were witnessed by prehistoric animals inhabiting the North American continent during the Pleistocene "ice ages."

The storm surge that is produced by hurricanes such as Carla does not always stop at the beach and

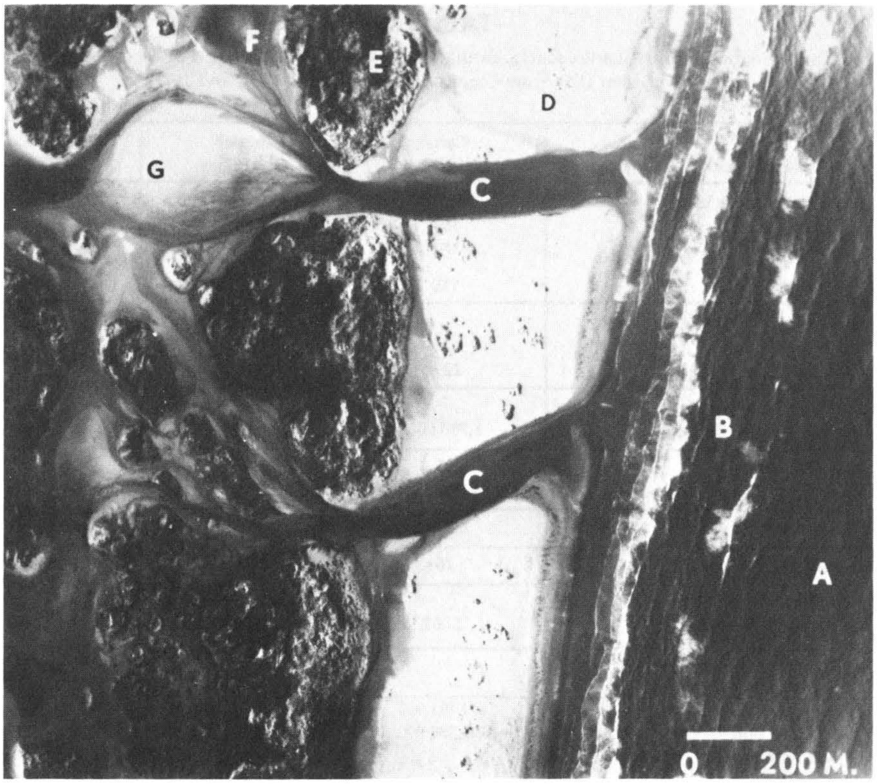


Figure 61. Aerial photograph of washover channels along central Padre Island (pl. I, grid V-20,) that were activated by storm surge accompanying Hurricane Beulah. Photograph was taken 15 days after Hurricane Beulah crossed the south Texas coast on September 20, 1967. As Gulf waters flooded through the washover channels "C," which cut through coppice dune fields "D" and vegetated fore-island dunes "E," sediments were eroded and flushed lagoonward, depositing the washover fan at "G." As the hurricane passed, elevated waters flowed back through the washover channels and branch channels "F," transporting sediments toward the Gulf "A" and forming channel-mouth bars; note the seaward displacement of the surf zone at "B," which reflects the submerged sandbars. As normal shoreline processes resumed after the hurricane, the channels were closed and the beach reconstructed across the mouths of the channels. (Photograph courtesy of Scott and others, 1969.)

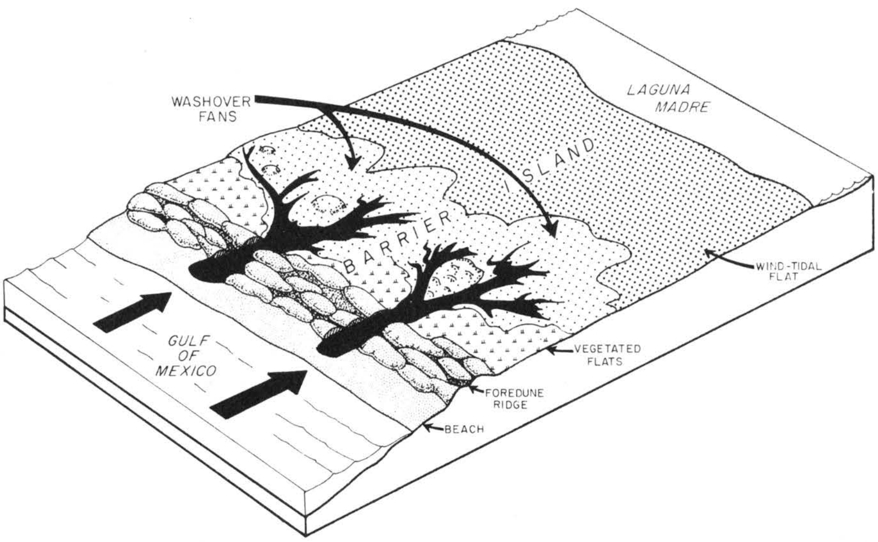


Figure 62. Sketch of washover channels and washover fans, shown in relation to other natural environments on central Padre Island. (Modified from Scott and others, 1969.)

fore-island area. Along low-lying segments of the island, the surge washes across, breaching the fore-island dune ridge and scouring washover channels (Scott and others, 1969) (fig. 61). Sediments eroded from the beach and adjacent dunes are spread lagoonward over the tidal flats, forming fan-shaped deposits called washover fans (figs. 61 and 62). In some areas along the southern end of the Seashore (South Section of pl. I), "pavements" composed of large shells and shell fragments can be found lagoonward of the backbeach and fore-island dunes, offering evidence of the storm surge that accompanies hurricanes such as Carla, and the subsequent effect of the wind, which deflates the sand and leaves the shell concentrated at the surface (fig. 63). Hayes (1967) discovered shells 2.5 miles landward of the beach as a result of Carla's surge.

Although Hurricane Carla's surge height was estimated to be between 5 and 10 feet along the Gulf shore of central Padre Island, it reached more than 12 feet in the vicinity of Port O'Connor, where it made landfall (approximately 90 miles northeast of Padre Island). Where natural inlets or man-made channels (such as Mansfield Channel, pl. I) connect Gulf and bay or lagoon waters, hurricane surge may produce strong currents that dramatically raise bay and lagoon water levels. For example, a surge height of 22 feet was recorded at the head of Lavaca Bay near Port Lavaca during Hurricane Carla (U.S. Army Corps of Engineers, 1962). When the surge passes through channels and inlets, it flushes sediments bayward, commonly forming deposits at the ends of the channels. As the hurricane passes, elevated bay and lagoon waters, which are produced by surge and winds, create gulfward-flowing currents that transport sediments back through washover channels and inlets.

When the hurricane has passed, normal processes resume and, in time, a normal beach profile is restored. Longshore drift smooths irregularities in the Gulf shoreline and builds bars and beaches across the mouths of the hurricane channels. Major washover channels that were eroded below mean sea level may continue to pond water after normal nearshore processes have reconstructed the beach across the channel mouths, severing their connection with Gulf waters (pl. I, B7 photograph). Major washover channels are commonly reactivated during subsequent hurricanes. Washover-fan deposits that are deposited over the wind-tidal flats are reworked later by the wind to provide a source of sand for the formation of back-island dune fields (Boker, 1953). After a hurricane has passed, its mark remains on coastal barriers, such as Padre Island, for many years.

HUMAN INTERACTION WITH THE DYNAMIC BARRIER ISLAND

When people occupy a barrier island, either temporarily or permanently, they become involved in the natural dynamic processes that operate on the island. The interaction between people and the island works two ways: human activities affect the environments and natural processes, and the environments and natural processes affect people and their activities. Often this interaction is not harmonious, particularly in the more dynamic environments along the Gulf shoreline. An example of human impact on barrier islands occurs when someone builds a structure along a beach that is eroding. This is a common trend along much of the Texas Gulf Coast. When shoreline erosion threatens a structure, an attempt must be made to control the erosion or abandon the structure. To control erosion and to protect investments, groins or seawalls may be constructed, but often with far-reaching consequences. Groins, for instance, extending perpendicularly to the shoreline into the surf zone, are designed to interrupt longshore sediment transport and trap sediment along the upcurrent side of the groin, causing the beach to accrete (grow seaward). Property owners immediately upcurrent are happy that their beach is restored and their property saved, for the time being. Unfortunately, their downcurrent neighbors are unhappy with this temporary, localized solution, because they begin to lose their beach by erosion at an accelerated rate. The sand supply transported by littoral drift that helped to maintain their beach has been cut off by the groin.

Seawalls also pose complications because the beach in front of the walls and in adjacent areas along the shore will continue to erode. Seawalls interfere with the equilibrium of processes affecting beach and foredune environments. For example, where fore-island dunes are present, the dunes provide natural protection against storm surge by helping to dissipate wave and current energy. They also act as natural sand "reservoirs" that help to replenish the beach during wave attack. This natural interplay is lost when dunes are leveled and cemented behind a seawall. Accordingly, the capability of the natural system to recover and maintain itself under erosional conditions, or under wave attack during hurricanes, is greatly diminished. As the shoreline retreats, the waves will eventually break directly on the seawall; an expensive maintenance program will have to be initiated to reestablish and maintain the beach in front of the seawall or to maintain the seawall itself (fig. 64). Once the beach has disappeared, a valuable property asset and a major point of attraction has been lost.

Figure 63. Natural shell "pavement" lagoonward of the fore-island dunes on Padre Island (South Section, pl. I). These shells, which include *Dinocardium robustum*, *Mercenaria campechiensis texana*, and other species, were apparently washed from the beach into the interior of the island by hurricanes and were concentrated at the surface by the wind, which removes (deflates) the finer sand, leaving the shells behind.

Because the National Park Service's recreational development plans are to maintain most of the island in a natural condition, many conflicts between natural processes and human activity that occur elsewhere along the Gulf Coast should not occur along the National Seashore. For instance, structures placed too near an erosional shoreline are not a problem along the National Seashore. Littoral drift convergence, which occurs along central Padre Island, helps to balance sediment supply and demand; this reduces the amount of erosion that takes place and adds stability to much of the beach along Padre Island.

Some human activities far removed from Padre Island can affect environments of the National Seashore. This was demonstrated in the summer of 1979 when an oil well being drilled offshore from Mexico, approximately 500 miles southeast of the Rio Grande, blew out and for several months released thousands of barrels of oil a day into Gulf waters. Currents transported the oil northward where it eventually reached the Texas shoreline and beaches. A massive effort was undertaken by the U.S. Coast Guard, scientists, environmentalists, and others to clean oil off beaches and to prevent it from entering tidal passes and the biologically sensitive and productive environments of Laguna Madre and other bays and estuaries to the north. Scientists estimated that even after the well was brought under control, oil already released would continue to arrive along the Texas shoreline for months. In the fall of 1979, the seasonal southward shift in longshore currents provided relief to the Texas coast. At this time, the effect of the oil on the National Seashore, its environments, and associated plants and animals is unknown and may prove difficult to assess.

Linking Gulf and Lagoon Waters

Mansfield Channel and accompanying jetties are one example of how people have interacted with and locally modified natural conditions along Padre Island. Mansfield Channel (South Section, pl. I), which was dredged across Padre Island, connects Port Mansfield directly to the Gulf and serves commercial and recreational fishing boats that operate out of the port. This connection with the Gulf locally moderates the salinity of Laguna Madre, which normally has a much higher salinity than the Gulf. Fish are able to migrate in and out of the lagoon via the channel. Jetties constructed mostly of granite blocks extend the channel a short distance into the Gulf. The jetties help maintain flow within the channel.

Jetties constructed of precast concrete tetrapods were emplaced in 1957 directly upon existing bottom sediments "without a stone blanket to distribute the load and prevent erosion" (Hansen, 1960). The north and south jetties were 1,600 feet and 900 feet long, respectively, and generally were elevated about 5 feet above mean low sea level. Within a few months after completion, both jetties had undergone extensive subsidence; the gulfward end of the north jetty was 3.5 to 7 feet below the water's surface (Hansen, 1960). The effectiveness of the jetties was greatly reduced, and shoaling occurred rapidly in the channel seaward from the original shoreline.

The present jetties were designed using modern engineering techniques and have consequently been more effective. They were engineered to be impermeable to longshore drift, to undergo a minimum of subsidence and erosion, and to take advantage of natural tidal and wind-tidal currents that help to scour sediments and prevent shoaling of the channel mouth. The jetties have caused localized changes in the Gulf shoreline by interrupting longshore sediment transport. Deposition of sediments has occurred on the upcurrent side of the jetties, and erosion has

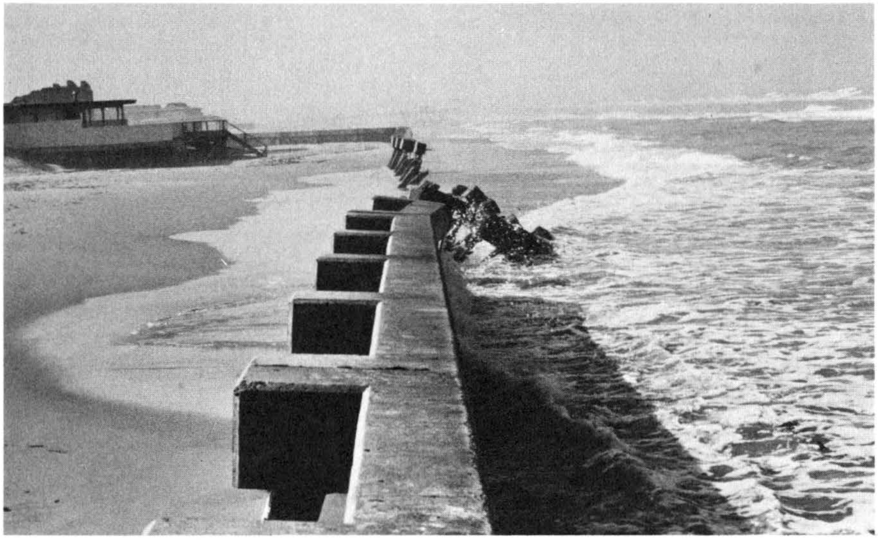


Figure 64. Seawall on south Padre Island, south of the National Seashore. Portions of the seawall have collapsed as a result of frequent attack by daily wave and tidal activity and as a result of less frequent but more intensive assault by very high tides accompanying tropical storms and hurricanes. Note the absence of a usable beach in front of the seawall.

occurred on the downcurrent side (figs. 13 and 24).

Yarborough Pass is another example of human interaction with natural processes along the National Seashore. The channel was dredged to provide an exchange between Gulf and lagoon waters to reduce the high salinities in north-central Laguna Madre. The pass, which did not have jetties, was initially dredged in April 1941, but remained open for only 5 months (Breuer, 1957). Its closure was a result of natural processes — primarily deposition resulting from longshore sediment transport. The pass was reopened by dredging in November 1942, May 1944, and November 1944, but each time, it closed in a few months. Breuer (1957) reported that during "the four years of dredging, the pass remained open for a period of 10 months, and reasonable flow was maintained for only 6 months." Gunter (1945) observed that while the pass was open, salinity in Laguna Madre was altered only about 0.5 percent and that was localized to within 0.5 mile of the pass. In February 1952, the Texas Game and Fish Commission reopened Yarborough Pass. The channel was dredged 60 feet wide; 3 weeks later it was only 3 feet wide (Simmons, 1957). Since then no attempts have been made to reopen it. Although the channel has been closed to the Gulf, boats can be launched on the lagoonward side of the island, where the channel still provides access to the Intracoastal Waterway (Central Section, pl. I). The fate of Yarborough Pass is an example of how efforts to modify the Gulf shoreline are sometimes thwarted by natural processes that work to reclaim and restore the island to its former conditions.

Effects of People on the Beach and Fore-Island Area

Vehicular traffic on the beach is another human activity along the National Seashore that creates changes. Comparing beaches where vehicular traffic is permitted with those where it is prohibited, one can easily see the difference (fig. 65; see *Field Trip Road Log*, Observation Point 2, fig. 114). On beaches where traffic is prohibited, vegetation on the backbeach encroaches much closer to the Gulf shoreline, where it traps windblown sand and forms small coppice mounds (small dunes stabilized by clumps of vegetation) and wind-shadow dunes. In areas where vehicular traffic is permitted, the vegetation cannot survive long enough to trap and accumulate sand, so the backbeach is much smoother, flatter, and broader than in the nonvehicular areas.

Pedestrian traffic has also affected vegetation. In areas where Seashore visitors regularly hike up the fore-island dune ridge to get a better view of the island, deep trails have developed in the dune ridge because the vegetation is unable to tolerate the constant trampling (fig. 66). The ease with which the vegetation is destroyed by pedestrian traffic reflects the fragile relationship between the vegetation and underlying loose sand in this semiarid climatic region.

Where vegetation is destroyed, particularly along the fore-island dune ridges, the erosional forces of both wind and water are more effective. Unvegetated fore-island dune ridges are much more susceptible to breaching by storm tidal surge than are well-vegetated ridges. In turn, surge might engulf and destroy adjacent areas of vegetation and initiate a cycle of wind erosion that gains momentum in the form of migrating and expanding dune fields.

Creation of Experimental Dunes

Because well-stabilized fore-island dunes are instrumental in protecting the island and mainland against storms, attempts have been made to artificially initiate dune formation and stabilization along areas that lack continuous dune ridges. From 1969 to 1974, an experimental project was conducted by B. E. Dahl and others (1974) to test the capability of various beach grasses to grow and stabilize fore-island dunes along

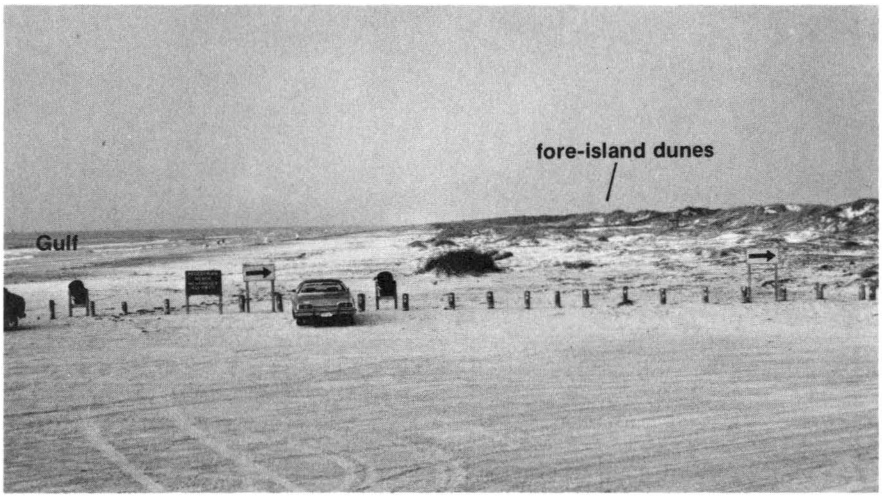


Figure 65. Northern end of pedestrian beach, along which vehicular traffic is not allowed. View is southwestward. Vegetation, which traps sand blown from the beach, grows much closer to the shoreline in areas where it is protected from the constant impact of vehicular traffic (also see fig. 114). Photograph was taken before Hurricane Allen (August 1980) destroyed the low vegetated dunes. With time, dunes will be reestablished.

Figure 66. Trails worn in fore-island dunes by pedestrians. View is westward. In areas where vegetation is trampled and destroyed by excessive traffic, the loose sand is exposed to the action of the wind, which may erode the previously vegetation-stabilized areas and form active blowout dunes that migrate lagoonward, thereby covering and smothering other areas of vegetation.

Figure 67. Experimental fore-island dune ridge. View is toward the northwest. The dune ridge that lies parallel to and along the back edge of this beach was formed by vegetation that was planted to trap and accumulate the sand blown from the beach by onshore winds. This particular dune ridge, one of a series that was artificially established, is located in the area of the four-wheel-drive sign, which is visible in the photograph (see pl. I, grid K-4, for location of sign). Note the streaks of dry, white sand that have formed downwind from clumps of vegetation on the backbeach. These accumulations of sand show effects of the onshore winds that were blowing when the photograph was taken. Also note that sand piles up along the dune ridge, but where there are gaps in the ridge, sand migrates into the interior of the island.

two segments of Padre Island. The northern test segment was located along the National Seashore approximately 5 miles south of Malaquite Beach (North Section, pl. I; fig. 67). Several plant species, including both exotic and indigenous (native) species, were tested to select the ideal plants and planting techniques for dune formation and stabilization. Two grasses—sea oats (fig. 35a) and bitter panicum (fig. 35f), both indigenous to the island—were selected as having the most ideal attributes of the species tested. Bitter panicum was the more desirable of the two.

The success of the experimental plantings and the subsequent establishment of a continuous fore-island dune ridge illustrates that a process occurring naturally along the Gulf shoreline can be accelerated. Dahl and others (1974) noted that the "artificial process can create in just a few years what probably takes 10 to 20 or more years to occur naturally."

Human Reaction to Windblown Sand

The effects of the blowing sand and human response to it are apparent in many areas of the National Seashore, including the Malaquite Beach area, where bulldozers are frequently used to scrape sand from the parking lot (fig. 68) and paved roads (fig. 69). Some back-island roads have been rerouted around mobile dune fields to reduce the constant maintenance required to keep the roads clear (compare figs. 48 and 70). Relocation of some facilities is not possible, however, and a continuing maintenance program must be employed (fig. 71).

Various techniques have been used to control migrating sand. These preventive measures include planting vegetation and erecting fences and signs to discourage pedestrian traffic and

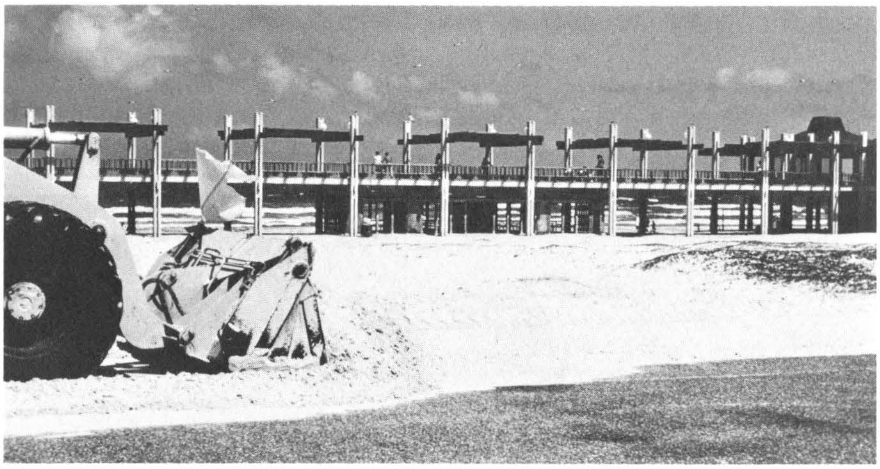


Figure 68. Bulldozer scraping windblown sand off the paved parking lot at Malaquite Beach. View is gulfward.

Figure 69. Tongues of sand blown by onshore winds onto a road near Malaquite Beach. Gulf is to the left.

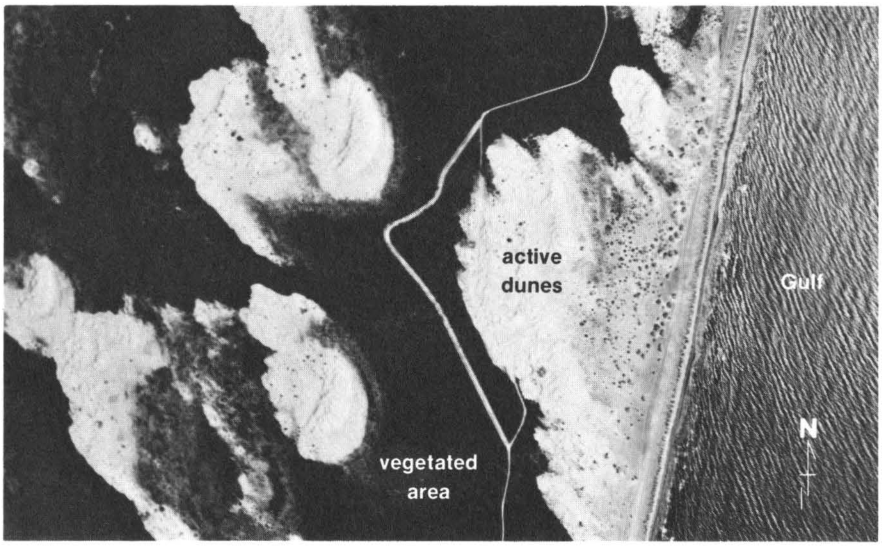


Figure 70. Road rerouted because of migrating dunes. Note the old road has been engulfed by active dunes that are migrating across the island. Gulf is to the right. Compare this figure (photograph taken in 1975) with figure 48 (photograph taken in 1974 before the new road was constructed).

prohibit vehicular traffic in vegetated areas (figs. 72a and 72b). Oystershells and native grasses (which have been cut and baled) are occasionally spread over barren sand to inhibit its movement (figs. 72c and 72d). Many of the attempts to stabilize sand have been partly successful, but total success requires the cooperative effort of all Seashore visitors to protect the wide variety of native plants that offer natural stability to the dunes.

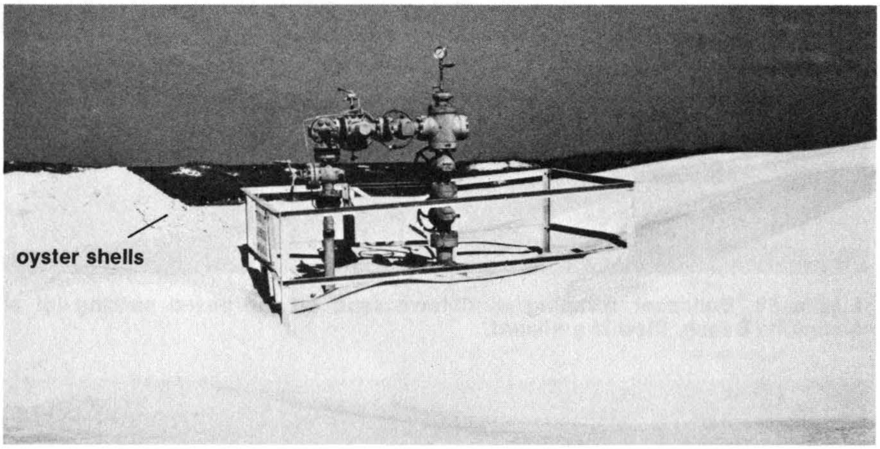


Figure 71. Natural gas wellhead threatened by burial under windblown sand. Attempts to stabilize the sand include the use of a covering of oystershells, which can be seen in the background to the left of the well. View is eastward to the Gulf of Mexico.

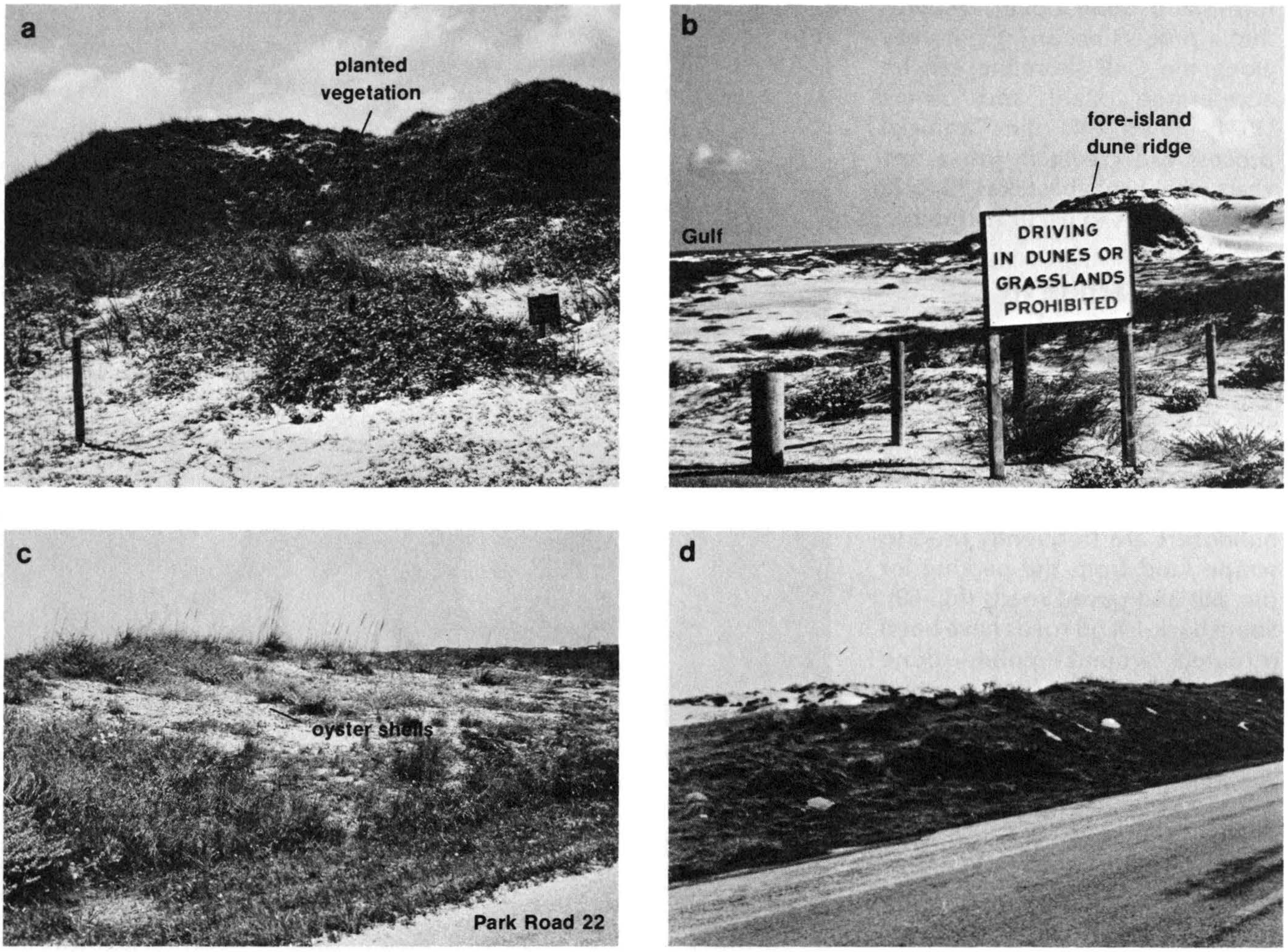


Figure 72(a) through (d). Methods used to stabilize loose sand and prevent it from being blown by the wind: (a) planting vegetation and erecting fences and signs to protect it (planted vegetation was used to stabilize a previously existing blowout on this dune); (b) using signs to discourage traffic on existing vegetation; (c) spreading oystershells over barren areas; and (d) covering barren areas with native hay.

ENVIRONMENTS OF PADRE ISLAND AND LAGUNA MADRE

The active processes of the wind, waves, and currents on the barrier island and in the adjacent lagoon have created and continue to shape the natural environments. Each of the environments that presently compose the barrier and lagoon systems has a unique set of physical and biological characteristics. These distinguishing characteristics are related to sediment texture and composition, sedimentary structures, density and types of vegetation, topography, position on the island and in the lagoon, size, areal configuration, relation to other environments and to sea level, and the types of processes affecting the environment. Following is a description of the natural environments and man-made or man-modified features as mapped on plate I.

BARRIER SYSTEM

The environments composing the barrier system are the beach, sandflat and/or coppice dune fields, fore-island dune ridge, barrier flats, stabilized blowout dunes, washover channels, wind-deflation flats, ponds and marshes occupying wind-deflation troughs, back-island dune fields, fore-island blowout dunes, and back-island sandflats. These terrestrial environments are affected by storms, the day-to-day forces of the wind, waves, and longshore currents, and biological activity. Except for part of the beach, the barrier environments are never flooded by astronomical or average wind tides but only by storm surge and, in certain places, by abnormally high wind tides.

Beach (B1)*

Of all island environments, the beach is perhaps the most familiar to Seashore visitors. But the Padre Island beach certainly is not just one long stretch of shoreline with uniform conditions. A journey from north to south along the beach will show the visitor marked differences in the amount of shell material, the kinds of shells, and the beach profile and width.

Most of the sediment composing Padre beaches is classed as fine sand, which coarsens slightly from north to south (Hayes, 1965). The sand consists primarily of quartz, but it also contains subordinate amounts of feldspar, rock fragments, and heavy minerals, such as hornblende, pyroxene, garnet, staurolite, rutile, zircon, and tourmaline (Bullard, 1942). In addition to land-derived sediments, shells and shell fragments make up varying percentages of the total beach sediment.

The highest concentrations of shell (up to 80 percent of the total sediment) are found on the beaches of central Padre (fig. 73), where converging longshore currents concentrate shell and sand. Winds carry the sand landward, leaving the shell behind on the beach (Watson, 1972). Little Shell Beach, so named for the abundance of shells of the small clam *Donax* (fig. 25), occupies a stretch of shoreline immediately north of Yarborough Pass. The maximum shell accumulation on Little Shell Beach occurs between the four-wheel-drive warning sign and Yarborough Pass (pl. I). The shells on Big Shell Beach (fig. 26) south of Yarborough Pass are characterized by the large clams *Noetia (Eontia) ponderosa* Say, *Mercenaria campechiensis* Gmelin, and *Echinochama arcinella* Linne (Watson, 1972). The

Figure 73. Shell beach. This shell beach lies within a zone where longshore currents converge, concentrating sand and shell. Much of the fine sand is carried landward by the wind, leaving the shells behind on the beach. View is to the south.

*Map unit symbol used on plate I.

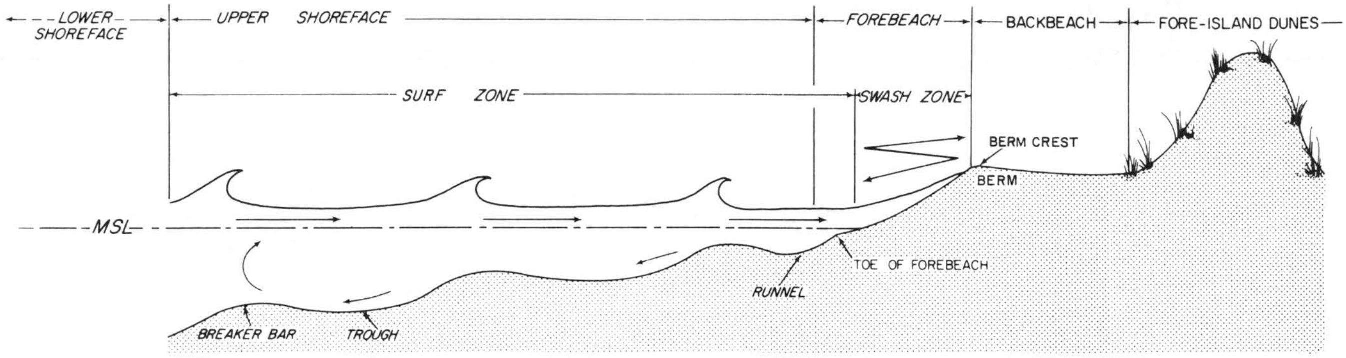


Figure 74. Generalized profile from upper shoreface to fore-island dunes. The beach is divided into two parts — the forebeach and the backbeach. (From McGowen and others, 1977.)

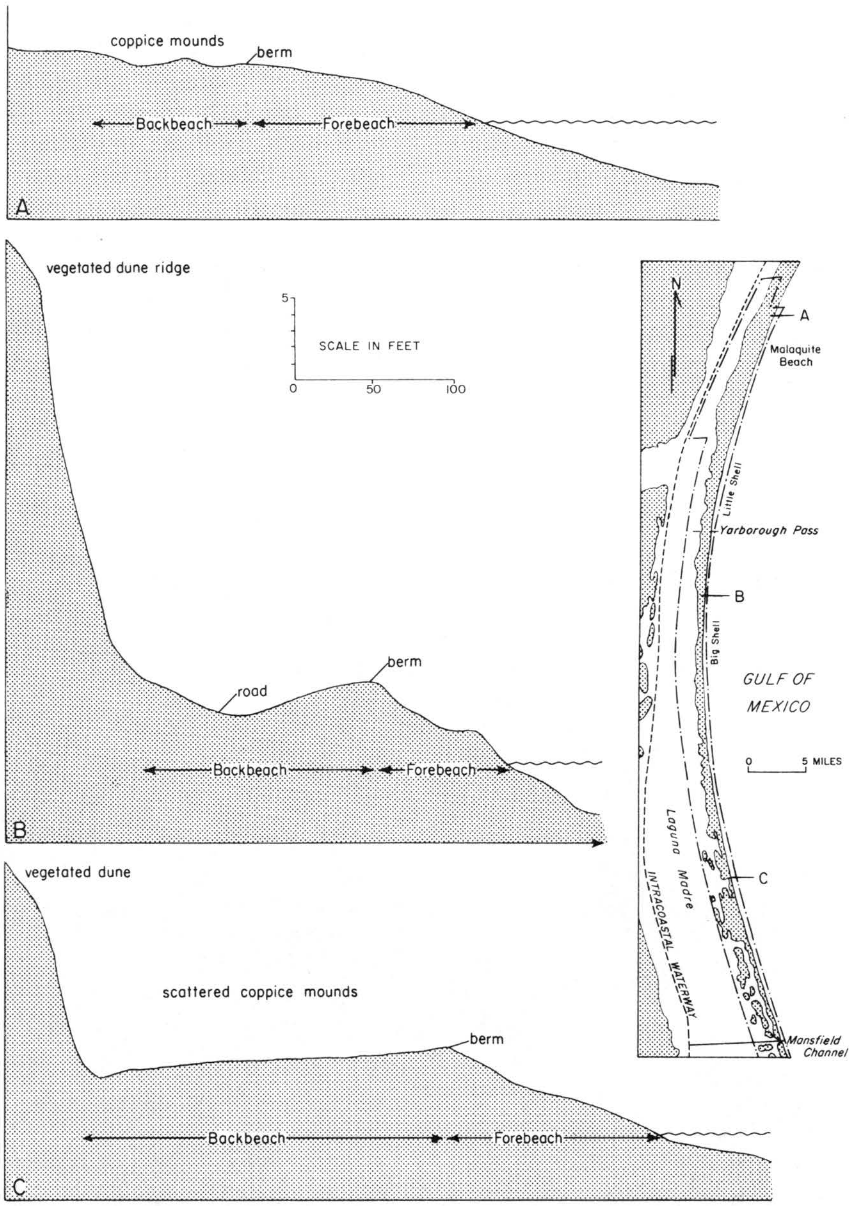


Figure 75. Beach profiles recorded June 17-18, 1975. Locations, plotted on the index map, are at points "A," located 4 miles north of Malaquite; "B," located along Big Shell Beach 8 miles south of Yarborough Pass; and "C," located 15 miles north of Mansfield Channel. Note that the profile at "B," recorded on Big Shell Beach where sediment is the coarsest, shows the steepest forebeach and highest berm. (Modified from Morton and Pieper, 1977a and 1977b.)

zone of densest shell accumulation on Big Shell Beach occurs 30 to 40 miles north of Mansfield Channel (Watson, 1972), or approximately 5 to 15 miles south of Yarborough Pass (pl. I). In addition to those shells that are characteristic of particular beaches, several species of the clam *Anadara* are fairly common on all of Padre's shell beaches.

The beach environment lies between the submerged upper shoreface (breaker and surf zones) and the fore-island dunes. The beach can be divided into two zones — the forebeach and the backbeach (fig. 74). The forebeach slopes seaward and is subject to the daily swash of waves. The backbeach, which includes a berm normally constructed and affected during spring and storm tides, is separated from the forebeach by the berm crest. Generally, the backbeach is either horizontal or gently landward-sloping, creating a shallow trough between the berm crest and fore-island dunes.

Obvious variations in beach profiles occur along Padre Island within the National Seashore (fig. 75). North Padre beaches such as at Malaquite (fig. 76) are relatively flat with a very low berm, if any. Because of differences in shoreline processes and sediment types and availability, the beaches of central Padre are characterized by steeper forebeaches and higher berms, in some places accentuated by erosion (fig. 30). Generally where sediments are coarser, as on the shell beaches, a higher berm will be maintained.

The top of the berm is the site of a very large accumulation of flotsam and jetsam, especially south of the maintained beach at Malaquite. Many of the bottles, boards, trees, shoes, rope, coconuts, and other things that make Padre a beachcomber's paradise have washed ashore after drifting hundreds or thousands of miles across the ocean. In addition to man-made materials, lumps of beach tar are concentrated on top of the berm. There are several ideas about the origin of tarballs, but most probably the asphaltic material is derived from a variety of sources, including natural sources such as offshore oil seeps, as well as industrial activities. Human effect on the quantity of beach tar was dramatically illustrated by the results of a large oil spill from a blown-out well in the Gulf of Mexico in 1979, described in the section on *Human Interaction with the Dynamic Barrier Island* (see p. 42). Some of the spilled oil reached Padre beaches in the form of sticky tarballs.

Beach cusps are locally pronounced on Padre Island. Size and shape of the cusps vary from one segment of beach to another, as well as along any given beach when wave conditions change. Figure 76 shows broad, flat, and widely spaced cusps on Malaquite Beach; much more prominent and closely spaced cusps on a central Padre shell beach are shown in figure 34. Refer to the discussion of beach cusps in the section on the *Dynamic Barrier Island* (p. 24) for a more detailed discussion of these interesting features.

Anyone who has camped overnight on the beach or who has gone out to the beach early in the morning might have observed small white creatures scurrying over the sand and suddenly disappearing. These are ghost crabs *(Ocypode quadrata)*, which live in burrows in the backbeach and upper part of the forebeach. Primary inhabitants of the forebeach include the mud or ghost shrimp *(Callianassa islagrande)*, snails *(Olivella* and *Terebra)*, and the clam *Donax*, which hurriedly burrows into the beach sediment after the backwash of each wave. Other animals living in the beach environment are various species of polychaete worms and mole crabs *(Lepidopa* and *Emerita)*. The beach is relatively barren of plant life, although spreading vines of goat-foot morning-glory *(Ipomoea pes-caprae*, fig. 35b), sea purslane *(Sesuvium portulacastrum*, fig. 35c), and fiddleleaf morning-glory *(Ipomoea stolonifera*, fig. 35d) are among the salt-spray-tolerant plants that occupy the backbeach.

On aerial photographs, the beach appears as a narrow, barren band (200 to 300 feet wide) that stretches down the gulfward edge of Padre Island. For purposes of environmental geologic mapping (pl. I), the beach is defined as the area between the low tide line and either the fore-island dune ridge (B3) or coppice dune fields (B2). Small coppice dunes that develop around vegetation clumps seaward of the dune ridge are actually part of the backbeach environment. However, where coppice dunes are large and numerous landward of the forebeach and can be easily distinguished on aerial photographs, they are mapped separately as the sandflat and/or coppice dune field unit (B2) on plate I.

Sandflat and/or Coppice Dune Field (B2)

Sandflats with or without coppice dunes have been mapped in fore-island areas immediately landward of the beach and in back-island areas at the edges of large dune fields (pl. I). Where there is no vegetation, the sand can be spread out by wind and water to create a sandflat. If vegetation is present, however, the blowing sand will collect around the vegetation clumps to produce mounds of sand called *coppice dunes*. Wind-shadow dunes commonly form by accumulation of sand in protected areas (wind shadows) downwind of coppice dunes.

The most accessible coppice dune fields lie between the beach and the fore-island dune ridge (fig. 77). These fields are narrow bands paralleling the beach along miles of Padre's shoreline. In the southern part of the National Seashore (pl. I), where the dune

Figure 76. Malaquite Beach, typical of north Padre beaches, having a flat profile and broad, shallow cusps. View is to the north.

ridge is absent or present as only short segments, broader coppice dune fields extend landward from the beach and occupy a large part of the island (fig. 78).

The sediment composing the coppice dunes is the fine beach sand that has been blown landward and has collected in backbeach vegetation clumps and in the wind shadows behind them. Coppice mounds normally remain small (less than 3 feet high), but they may grow to 6 or more feet in height if the vegetation on which they build remains healthy and is not destroyed by storm waves or by man. The larger coppice dunes may merge and become part of the fore-island dune ridge (B3). Some coppice dune fields mapped on plate I are actually beginning to form a dune ridge (fig. 78).

Other, less accessible coppice dune fields fringe back-island dune fields. Many of these back-island coppice dunes form around sparse vegetation that has become established on sandflats where other larger dunes have been destroyed by storm waters or wind. In some places, coppice and wind-shadow dunes may develop from the erosional remnants of older dunes that have been partly stabilized by vegetation.

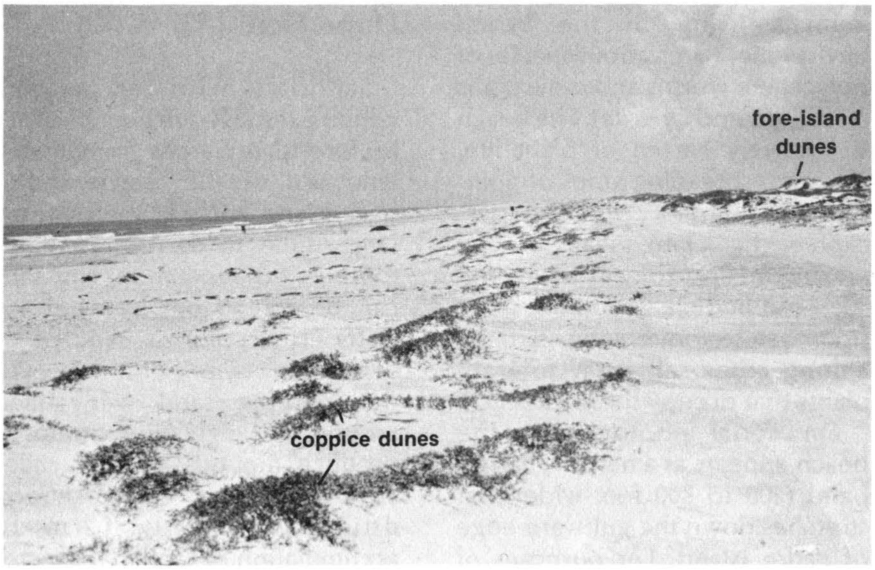


Figure 77. Coppice dune field lying between the beach (left) and the fore-island dune ridge (right). The coppice dunes occupy what is usually considered the backbeach, but they have been mapped on plate I as a separate environment. These coppice mounds, which develop in and around vegetation clumps, are no more than 1 to 2 feet high, although in other areas they may be 6 feet or higher.

Figure 78. Broad coppice dune fields in the southern part of the National Seashore near Mansfield Channel. The largest dunes are those nearest the beach; they appear to be joining to form a fore-island dune ridge. View is to the southwest.

Fore-Island Dune Ridge (B3)

Immediately landward of the backbeach or coppice dune fields and parallel to the shoreline is a row of high, grass-covered dunes called the *fore-island dune ridge.* In the northern and central parts of the Seashore (pl. I), the dune ridge is fairly continuous and reaches its maximum height. When viewed from the Gulf side, as from the surf zone in figure 79, the fore-island dunes appear to be a high wall of sand and vegetation, an island barricade that protects the barrier flat from the full force of hurricanes and other storms. In the southern part of the Seashore, however, the ridge is either absent or broken into low, discontinuous, sparsely vegetated dunes providing little or no protection against storm winds, waves, and tides.

The fore-island dunes consist of fine, very well-sorted sand that has been blown from the beach and stabilized by vegetation. In addition, fairly coarse pieces of shell are carried onto the foredunes by strong onshore winds. Although the size of the dunes is partly determined by the amount of sand available to form them, vegetation is necessary to keep the sand from blowing farther inland. The fact that the drier and more sparsely vegetated southern part of the Seashore (fig. 37) lacks well-developed foredunes demonstrates the importance of vegetation. The sparse vegetation will not prevent the sand from blowing onto the sandflats. The low ridges formed by merging coppice dunes are easily breached by storm attack. In the northern half of the Seashore, the denser vegetation traps sand and results in high foredunes. Maximum elevations along the dune ridge in that area may exceed 50 feet, but elevations generally range from about 20 to 40 feet.

Width, as well as height, of the fore-island dune ridge is not uniform along the island. Generally, the ridge is about 200 to 300 feet wide. However, in some areas (for example, grids P-11 through U-11 on pl. I) where the foredune sand was once blown out a short distance landward and later restabilized (fig. 80), the dune ridge appears wider (up to 1,200 feet across). Where stabilized blowout dunes are continuous with the dune ridge, they were mapped with the fore-island dune ridge (B3) on plate I rather than mapped separately as stabilized blowout dunes (B6).

Types of plants constituting the important vegetative cover (fig. 35) of the ridge are generally zoned according to elevation on the dunes. Marshhay cordgrass *(Spartina patens)*, morning-glory *(Ipomoea* spp.), and sea purslane *(Sesuvium portulacastrum)* are common on the lower parts of the dunes. Middle and upper parts of the dunes support sea oats *(Uniola paniculata)*, bitter panicum *(Panicum amarum)*, and gulf croton *(Croton punctatus)*. Seacoast bluestem *(Andropogon scoparius littoralis)* is a grass limited to the more protected and better vegetated back sides of the foredunes (Brown and others, 1976).

Vegetated Barrier Flat (B4, B5)

Behind the fore-island dune ridge lie vast barrier flats vegetated by various types of grasses and small shrubs (fig. 81). The flats slope very gently lagoonward from an elevation of about 5 feet behind the dune ridge to sea level at the lagoon shoreline. Breaking the uniformity of the flats are linear and curved ridges of stabilized blowout dunes (B6) and smaller isolated stabilized dunes that are mapped with the barrier-flat environment. Several active blowout dunes (B10) are currently migrating landward across the

Figure 79. Fore-island dune ridge of central Padre Island, as viewed from the surf zone. The dune ridge, which protects the island from storm winds, waves, and tides, reaches its maximum heights and is most continuous on central Padre. In the southern part of the Seashore, however, the ridge is low and segmented or is absent altogether.

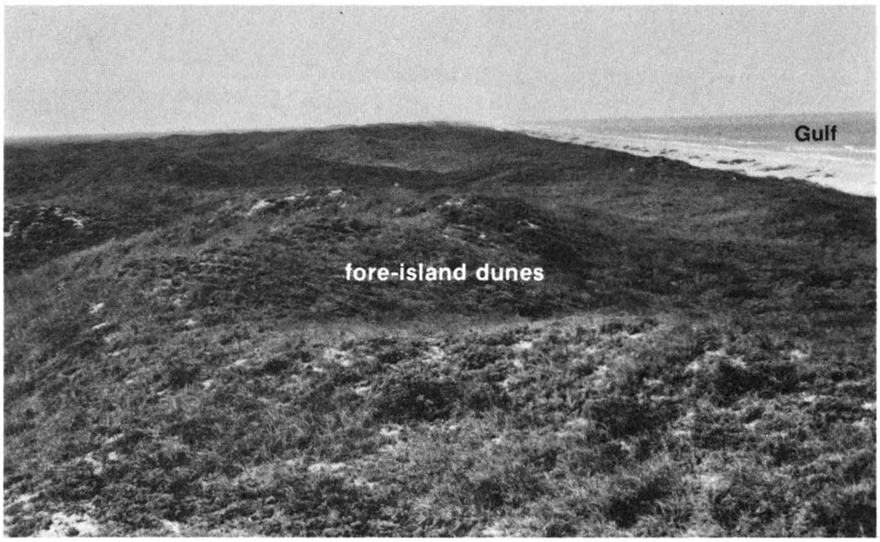


Figure 80. Fore-island dune ridge at one of its widest points (pl. I, grid R-11). At places such as this, sand was at one time blown out landward from a narrower dune ridge and then restabilized with vegetation. Because there is no well-defined topographic break between these restabilized blowout dunes and the foredunes, the restabilized dunes were mapped on plate I together with the foredunes as part of the fore-island dune ridge (B3). View is to the north.

barrier flat, smothering and destroying vegetation as they move toward the back side of the island.

Most barrier flats at one time were barren wind-deflation flats or sandflats. The more sparsely vegetated barrier flats (B5) are simply areas where the grasses have recently been established and have not had enough time or moisture to develop a dense cover (fig. 82). Plate I shows that most sparsely vegetated barrier flats occur on the southeast, or windward, edge of migrating dune fields. These areas were recently wind eroded and have supplied sand to the active dunes. In time, most of the sparsely vegetated flats will evolve into the more heavily vegetated flats (B4), depending on the amount of rainfall. In the southern part of the Seashore near Mansfield Channel, wind-deflation flats remain barren because of lower annual rainfall and a higher rate of evaporation.

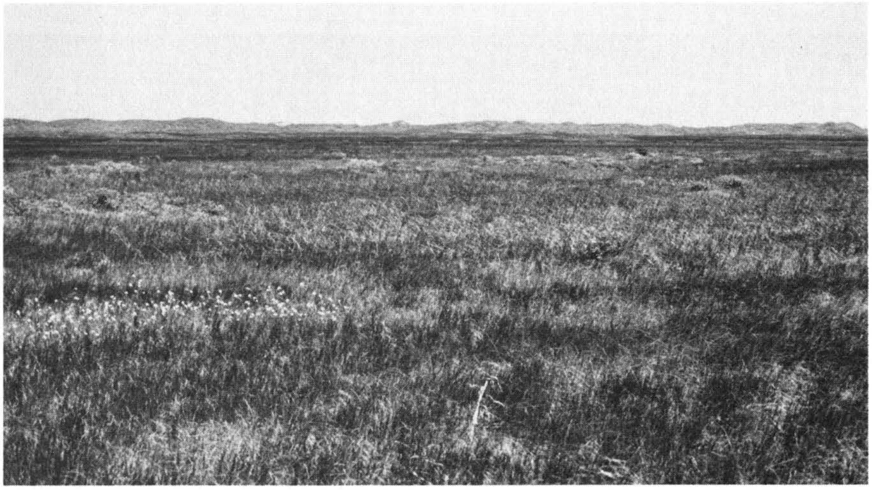


Figure 81. Heavily vegetated barrier flat supporting various grasses and small shrubs (pl. I, grid T-4). The grass-covered dunes in the distance are part of the fore-island dune ridge. View is eastward from Park Road 22 toward the Gulf.

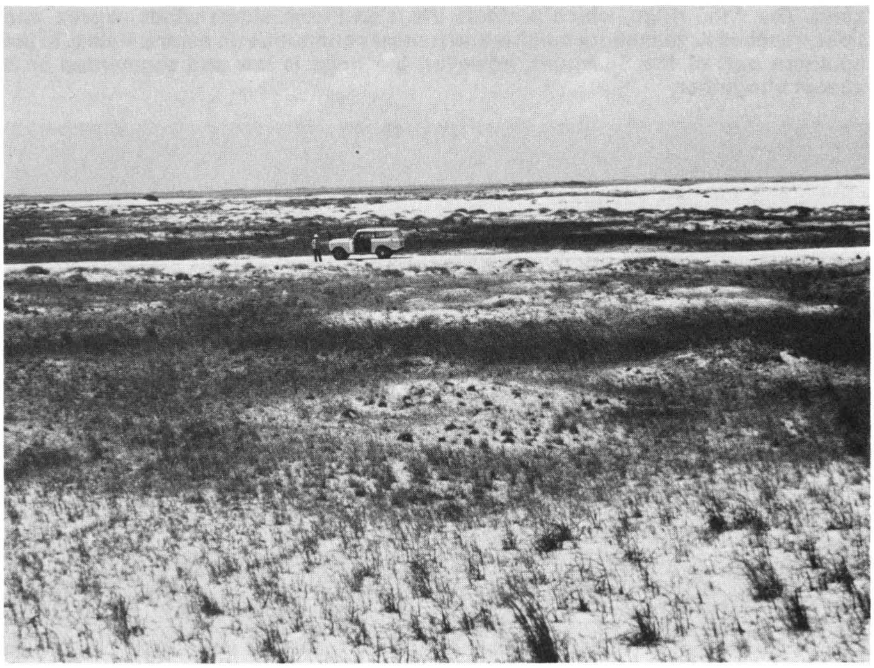


Figure 82. Sparsely vegetated barrier flat (pl. I, grid T-3). This flat was previously a wind-deflation flat, or wind-eroded barren area, that had supplied sand to the active dune fields visible in the distance. Grasses are now being reestablished on this barrier flat. The flat can be seen along the Bird Island Basin road near Observation Point 6 of the Field Trip described at the end of this guide. View is to the northwest.

Local ponds and marshes occupy low, depressed areas, commonly linear wind-deflation troughs (see discussion of B8) left behind by migrating back-island dune fields and blowout dunes (B10). Larger ponds and marshes were mapped separately on plate I as unit B9. There are more water bodies in the north and central parts of the Seashore where the rainfall (somewhat greater than that of the southern part) is sufficient to maintain the ponds and keep their water fresh to brackish.

Sand and shell, most of which has been washed or blown from the fore-island area, lies beneath the vegetative cover. Coarse and fine material is transported from the shoreline by floodwaters during large storms. Winds move fine sand from the fore-island area and from nearby blowout dunes and dune fields. Beneath these recent surficial deposits, however, are older barrier sediments, normally beach and dune sand (Hunter and others, 1972). The older sediments are exposed in places, especially in the younger deflation scars that have not been healed by vegetation or covered by a new layer of wind- and water-deposited sand.

The long strips of vegetated barrier flat served historically as cattle rangeland. Remains of three line camps, where ranchers temporarily held cattle on their drive up the island, are still standing on Padre's barrier flats (fig. 83). Although cattle no longer graze within the National Seashore, the barrier flats are still permanent homes for various wild animals, such as pocket gophers, moles, weasels, ground squirrels, mice, and snakes. Other animals that visit the island occasionally are coyotes, shrews, bats, raccoons, skunks, rats, jackrabbits, and armadillos (Hunter and others, 1972). In addition, insects abound on the barrier flats; during spring and summer, mosquitoes may make themselves a little too obvious to Seashore visitors hiking across the flats. These insects thrive in the thickly vegetated and, in places, marshy environments that are protected by the dune ridge from onshore winds.

Stabilized Blowout Dunes (B6)

In many parts of the Seashore, vegetated elongate and curved sandy ridges or fields of low dunes extend lagoonward from the dune ridge. These dunes, up to 20 feet high, were once active blowout dunes (described below under map unit B10) that originated at the dune ridge and, after migrating some distance lagoonward, were stabilized by vegetation (fig. 84). Such vegetation consists primarily of grasses commonly found on the barrier flat.

If the grass cover is destroyed either naturally or by people, the dunes may be reactivated and begin migrating downwind toward the back-island area. They may go through several cycles of stabilization and reactivation before becoming either "permanently" stabilized or merged with the back-island dunes.

Because the sediments of the stabilized blowout dunes were derived from the fore-island dune ridge, they resemble foredune sediments. The stabilized deposits include fine, well-sorted sand. Nearest the fore-island area, they contain small shells and shell fragments that were blown or washed from the beach.

Washover Channel (B7)

During hurricanes, the storm surge cuts through the fore-island dune ridge at low, weak points, scouring channels generally perpendicular to the shoreline. Nearshore (shoreface), beach, dune, and barrier-flat sediments are transported into the back-island areas (pl. I, B7 photograph, and fig. 85). Hurricane washovers generally consist of single channels up to 700 feet wide through the dune ridge. On the barrier flats behind the ridge, however, washover channels split into two or more smaller channels (fig. 85). The sediments in the washover channels are primarily sand and shell; some mud, however, settles from suspension in open channels during the waning stages of the storm ebb flow and in ponds remaining after the flow ceases.

Most ponds that form in the deepest parts of the inactive washover channels between storms exist only briefly. Where channels are scoured below the water table, however, the ponds retain brackish water and will not dry completely (fig. 85). Thin algal mats develop around the edges of the ponds and in other moist parts

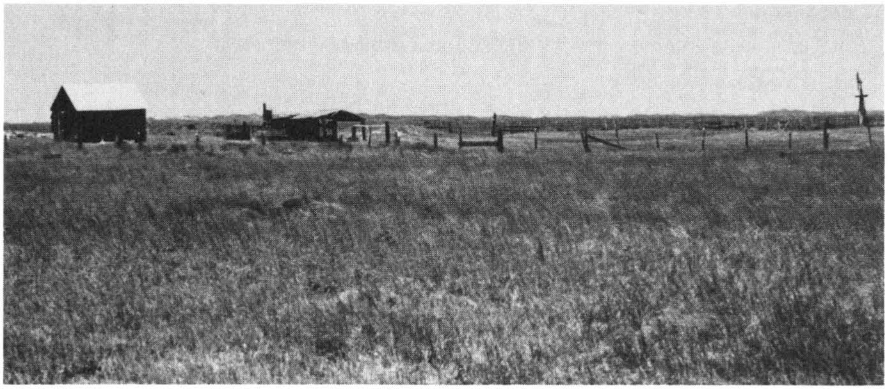


Figure 83. Novillo (pl. I, grid T-4), the northernmost line camp constructed by Pat Dunn for cattle ranching on the island during the late 1800's and early 1900's. View is to the northeast. Padre Island's grass-covered barrier flats were good rangeland, and Laguna Madre on the west and the Gulf of Mexico on the east served as natural fences for the long, narrow island. When herding the cattle in preparation for market, Dunn's vaqueros, or cowboys, drove the cattle up the island in stages, holding them overnight in corrals at the line camps.

Figure 84. Park Road 22, which cuts through stabilized blowout dunes just north of the Bird Island Basin road intersection (pl. I, grid T-4). View is to the southwest. At one time, loose sand was blown out from the fore-island dune ridge by the prevailing southeasterly winds. The sand migrated lagoonward across the barrier flats and eventually was stabilized by vegetation in the middle part of the island.

Figure 85. Hurricane washover channel at the 35-mile beach marker (pl. I, grid C-12). View is to the northwest. Generally, a single channel cuts through the dune ridge in the fore-island area, but the channel splits into two or more smaller channels on the flats beyond. After the storm, water may be ponded in the deep scours and occasionally replenished by rain, very high wind tides, or even ground water if the scour is below the shallow water table. Large coppice dunes are merging and forming an incipient dune ridge to close the mouth of this channel.

Figure 86. Wind-deflation flat at the trailing edge of a back-island dune field (pl. I, grids W-20 and X-20). View is to the northeast. The flat, which was the sand source for the large dune field, now serves as a storm runway. Storm water is fed into the low flat from the washover channel and then flows parallel to the shoreline along the deflation flat.

of the inactive channels. Mollusks are common in the ponds.

All washovers eroded during recent hurricanes, and those most likely to be reactivated during the next large storm, occur in the southern part of the National Seashore where the dune ridge is low and segmented. The first washover channel south of Malaquite Beach is about 17 miles south of Yarborough Pass. Older, healed washovers are located in grid U-11 (pl. I), almost 4 miles south of Yarborough Pass, and in grid H-4, 9 miles south of Malaquite Beach. These relict channels are not mapped on plate I as hurricane washovers, but rather as the various environments that have developed in them.

Wind-Deflation Flat, Storm Runway, and Washover Fan (B8)

Barren flats, generally parallel to the Gulf shoreline, occur windward of large back-island dune fields (fig. 86). These wind-deflation flats (B8) are created when sand and finer sediments are scoured by the wind, commonly down to the water table. Sand is blown out into dunes, with coarser material lagging behind. Large shell and cobble lag constitute what is called "desert pavement" (fig. 63).

In the northern parts of the Seashore, where the deflation flats have become vegetated, they are mapped on plate I as one of the barrier-flat units (B4 or B5). In the south, however, the drier climate prevents the vegetating of the deflation flats, which occupy a large part of the barrier island.

During storms, much of the sediment eroded from and transported through the washover channels is deposited on wind-deflation flats to produce washover fans. The fans are very low-relief lobes of sand and shell deposited where the washover channels widen and the storm waters lose velocity (fig. 87). In addition, some sediment is carried by the storm waters parallel to the shoreline along the wind-deflation flats, which serve as storm runways (Hayes, 1965). The deflation flats are normally connected with wind-tidal flats (L1, L2, and L3) between the dune fields. This means that very high wind tides in the lagoon will flood the flats. Thus, the boundary between the deflation flats and wind-tidal flats in some areas is not clearly defined.

Drapes of mud are deposited on the flats and fans by the calmer water that is drained off or remains ponded on them at the end of a storm. Mud drapes may also be deposited during wind tides. The mud layers crack and crumble as the exposed flats dry, and the fine material, as well as the sand below, is reworked by the wind. The loose sediment is either added to the back-island dunes or blown out onto the wind-tidal flats. Thin algal mats form and seal the sediment where the deflation flats are more frequently flooded by wind tides.

Ephemeral Fresh- to Brackish-Water Ponds and Marshes (B9)

In the northern part of the National Seashore (pl. I), the deeper, troughlike wind-deflation flats become sites of ponds or marshes. Because most of the mapped ponds and marshes occupy long, linear deflation troughs left behind by migrating back-island dune fields (B10), the ponds parallel the trailing edges of the dune fields (fig. 88). Ponds and marshes nearer the fore-island area (fig. 89) occupy deflation flats left by fore-island blowout dunes (B10). As stated earlier, ponds and marshes too small to be mapped separately on plate I are included within the barrier-flat map units (B4 and B5).

The ponds and marshes are largely ephemeral, or short lived, but some retain fresh to brackish water over long periods and are replenished occasionally by rain. Plants in the marshy environments include various forms of algae, common cattail *(Typha domingensis)*, American bulrush *(Scirpus americanus)*, spikerushes *(Eleocharis* sp.) and others (Baccus and Horton, 1979).

The depressions in which the ponds and marshes develop are originally floored by the sediments, mostly sand, exposed in the deflation trough. During the periods of water ponding and marsh growth, however, mud and plant debris settle and cover the bottom. Windblown sand is

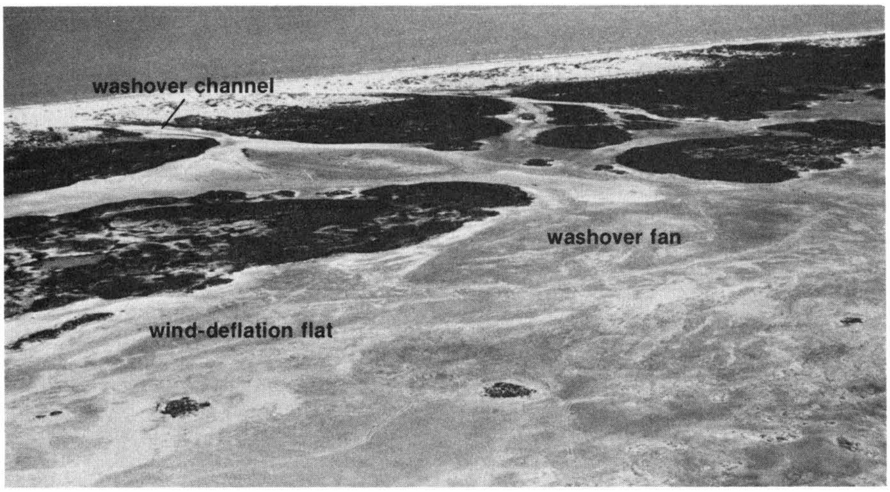


Figure 87. Washover fan spreading onto a deflation flat. The washover fan originates from the end of a washover channel (pl. I, grid V-20).

trapped in the ponds, settles, and is mixed or interlayered with mud and organic material.

Back-Island Dune Field and Fore-Island Blowout Dunes (B10)

Those parts of the fore-island dune ridge that become devegetated naturally or through the actions of man are vulnerable to erosion by the strong southeasterly winds. Sand is blown from the dune ridge over the barrier flat in a northwesterly direction (fig. 90). The result is a blowout dune complex, which may consist of several dune types, including parabolic, transverse, and barchan dunes (fig. 39). Most dune forms change rapidly with changes in wind direction and intensity. The sediment composing these blowout dunes is mostly fine, well-sorted sand derived from fore-island dunes.

As blowout dunes migrate toward the northwest across the barrier flat, they may either become stabilized by grasses or eventually become merged with a back-island dune field. The back-island dune fields are large barren areas of shifting dunes (fig. 91). Barchans and transverse dunes aligned perpendicularly to the wind direction are common in the back-island fields. These relatively small dunes are generally less than 10 feet high. Large (up to 25 feet high), elongate, longitudinal dunes (fig. 51) shift much less readily and may retain their orientations throughout the year. Hunter and others (1972) studied the large dunes on Padre and refer to them as *oblique dunes* because they are elongate in an east-west direction, or oblique to the net sand transport direction (fig. 49), which is a result primarily of the dominant southeasterlies and the north winter winds. One possible explanation for the relatively stable orientation of these dunes is that they are parallel to one arm of summer barchans and perpendicular to the north winds of winter (Hunter and others, 1972).

In the northern part of the National Seashore, fine sand is supplied to the back-island dune fields by the migrating blowout dunes. The back-island dunes in the southern part, however, are supplied largely by sand reworked from sediments that washed into the back-island area during storms. Presently, neither washovers nor large blowouts occur in the central part of the Seashore; consequently, the back-island area is starved of sand necessary to build large dune fields. What were once dune fields are now patches of vegetated barrier flat fringing

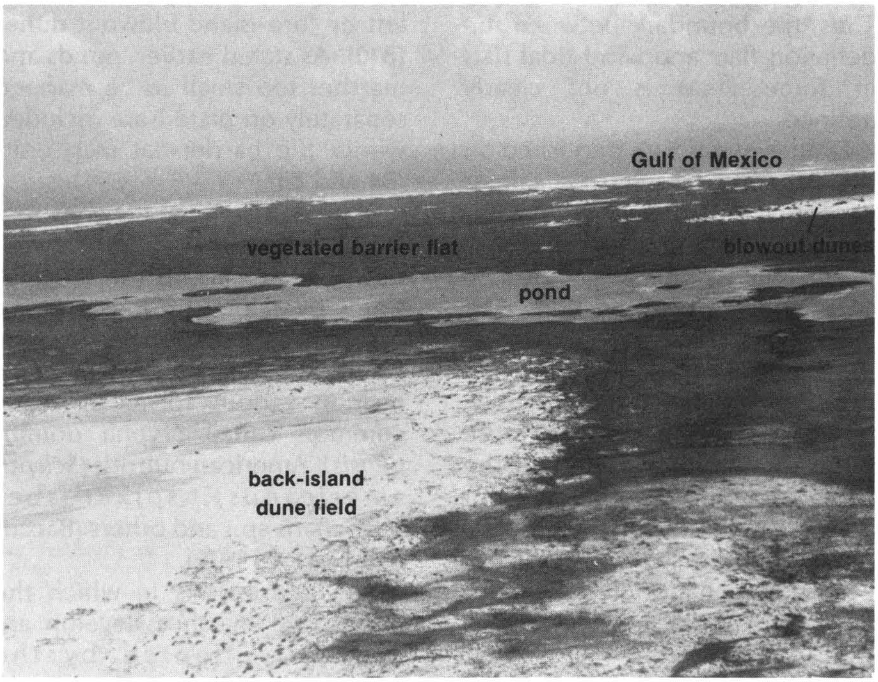


Figure 88. Ponds occupying long wind-deflation troughs, which parallel back-island dune fields (pl. I, grid O-3). View is to the east.

Figure 89. One of the marshy ponds that have developed in deflation flats left by fore-island blowout dunes. Several of these ponds can be seen near the Malaquite Beach development. View is to the west.

the back-island area (for example, grids J-10 through M-10, pl. I).

Back-Island Sandflat (B11)

Environments that undergo rapid changes in size and dune forms are the barren back-island sandflats with small migrating dunes (pl. I, B11 photograph). These are environments transitional between the back-island dune fields (B10) and wind-tidal flats (L1, L2, and L3). Although a particular dune field may evolve in a number of ways, the back-island sandflat is one possible last stage in the life of a dune field.

Sandflats have developed only in the southern half of the Seashore, where fine sand from large dune fields blows across vast wind-tidal flats. There is no vegetation or lagoon water to trap the sand as occurs on north Padre Island. As large dunes are destroyed, the sand spreads to form the sandflats. Sand within the flats may form much smaller, rapidly migrating dunes—dominantly small barchans and transverse dunes. Elevation is low enough that the environment is flooded by storm tides and the highest wind tides. As the sand continues to spread and dunes become smaller, the elevation is reduced sufficiently so that the area is flooded by normal wind tides, and the environment evolves into a true wind-tidal flat.

LAGOON SYSTEM

Environments of the lagoon system mapped on plate I are wind-tidal flats, lagoon sand and shell berms, subaqueous lagoon-margin sand, grassflats, lagoon-center sand, and serpulid reefs. These are natural aquatic environments of Laguna Madre that, except for two islands made of sand and shell berms (North and South Bird Islands), either remain subaqueous at all times or are flooded by wind tides as well as storm tides.

Wind-Tidal Flat (L1, L2, L3)

Extensive barren flats on the periphery of Laguna Madre that are subject to flooding by wind tides are called *wind-tidal flats*. In the Land-Cut Area of Laguna Madre (Central Section, pl. I), wind-tidal flats occupy the entire lagoon. These vast flats are broken by the Gulf Intracoastal Waterway,

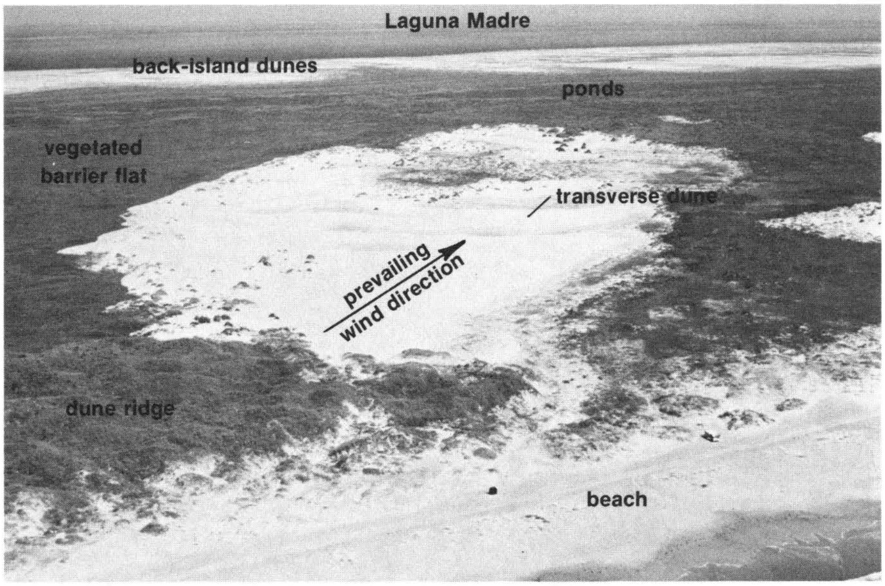


Figure 90. Blowout complex that originated at the dune ridge, where stabilizing vegetation had been destroyed, and loose sand was free to blow out (pl. I, grid O-4). Prevailing southeasterlies cause the blowout to migrate across the island in a northwestward direction, although strong north winds modify the complex every winter by blowing much of the sand to the south edge of the barren dune complex (left side in photograph). Several dune forms, depending on wind direction, speed, and duration, occupy the complex at different times. Transverse dunes perpendicular to wind direction dominated this complex at the time the photograph was taken.

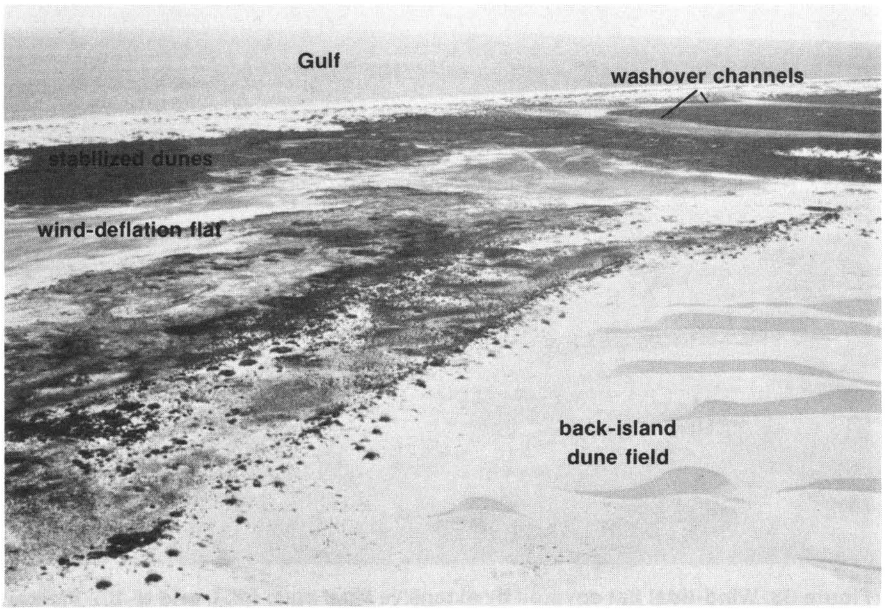


Figure 91. Back-island dune field including several large, shifting dunes (pl. I, grid O-19).

which is presently the only constant link between waters of northern Laguna Madre and those of southern Laguna Madre.

Wind-tidal flats are generally less than 3 feet above mean sea level. Because the flats lie so low and have an extremely gentle slope, lagoon water pushed by strong winds can quickly flood large areas of the flats. The frequency of inundation, controlled primarily by slight differences in elevation, determines the types of wind-tidal flats that will develop in an area. Within the map area of plate I, three main types are recognized: (1) flats with loose windblown sand forming small dunes (L1), (2) flats with finer sand and mud (L2), and (3) flats covered with extensive algal mats (L3). There are, however, many variations and transitional types.

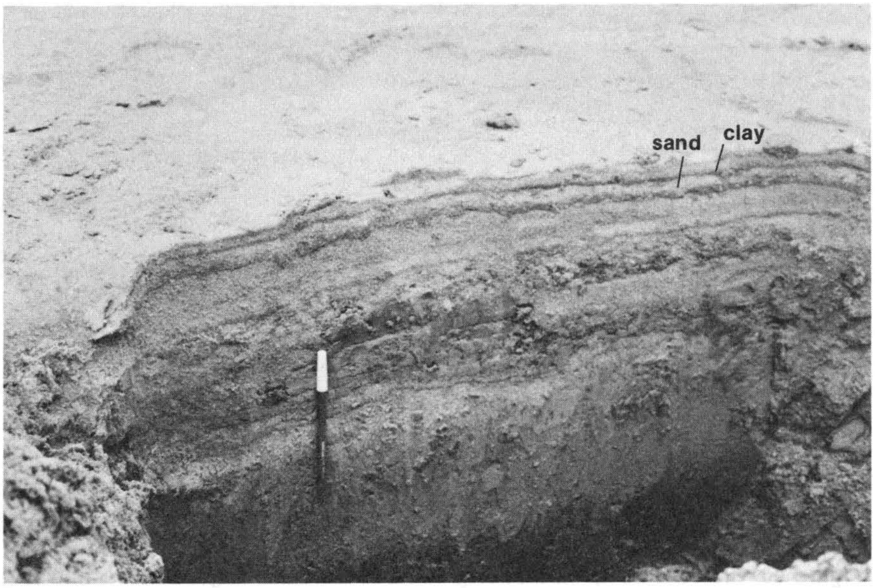


Figure 92. Trench dug on a wind-tidal flat, showing the alternating layers of sand (light layers) and clay (dark layers). Most of the sand is carried to and deposited on the flats by the wind. Thin clay layers are deposited as clay settles from water flooding the flat during high tides. The pen (about 6 inches long) serves as a scale for the vertical face of the trench.

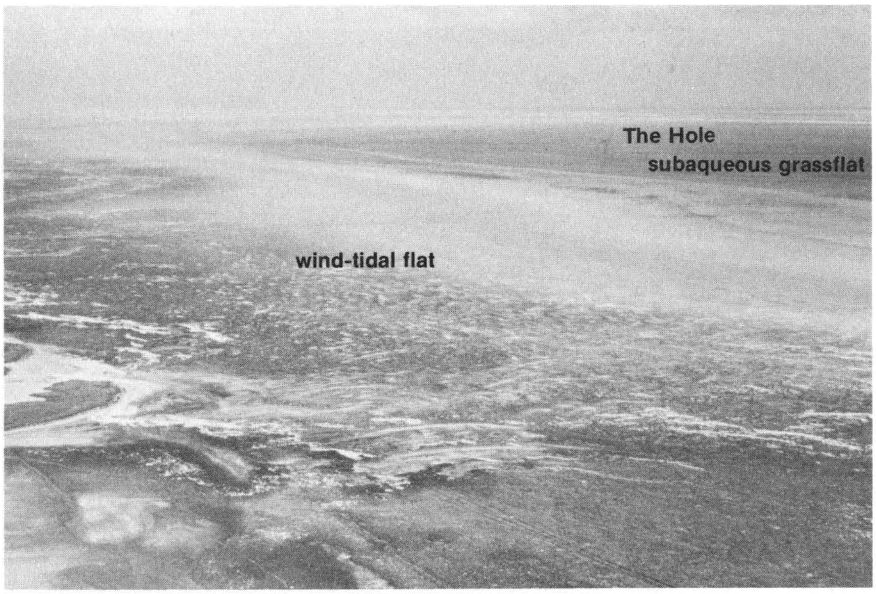


Figure 93. Wind-tidal flat covered by extensive algal mats (pl. I, grid N-10). View is to the southwest. In aerial photographs such as this, the algal flats always appear as dark-gray zones, whereas the wind-tidal flats covered by firm sand are a very light color.

The highest wind-tidal flats (L1 unit), which are rarely flooded, are in the Land-Cut Area. The sand there dries for long periods between high wind tides and remains loose enough to be blown into small dunes that migrate rapidly across the flats (pl. I, L1 photograph). In most places there is not sufficient loose sand to cover the flat completely, however, and the dunes migrate over the firm, wet sand or over local algal mats developed in depressed, moist areas. The windblown sand in the small dunes is fine and well sorted. Thin clay layers may be deposited on these tidal flats during the rare tidal inundations.

On wind-tidal flats that are flooded more frequently (L2 unit), the sand and clay substrate (fig. 92) remains relatively firm. Consequently, there is not enough dry, loose sand available to form dunes (pl. I, L2 photograph). Algal mats occur locally but are very thin and not as prominent as those in environments labeled L3. This intermediate wind-tidal flat occurs throughout the map area but is most common in the southern part of the Seashore. The wind-tidal flats with firm sand (L2) characteristically occupy (1) tidal-flat areas within the lagoonward fringes of the back-island area, and (2) tidal environments that are submerged too frequently for the development of extensive algal mats.

Extensive algal mats develop on flats that are alternately emergent and submergent in fairly regular cycles. In aerial photographs and on the ground these algal flats appear as very dark areas surrounding the lagoon (fig. 93). Sand is blown onto the algal flat from the barrier island, and with each tidal inundation, thin layers of clay are deposited from suspension. The algal mats that develop on the moist surface commonly break up and peel from the underlying sand and clay during drier periods between tidal floods (pl. I, L3 photograph).

Bladelike crystals and rosettes (clusters of crystals resembling a rose, figs. 94a and 94b) composed of the mineral gypsum (calcium sulfate) have been found in the sediments of wind-tidal flats in the Land-Cut Area on both sides of the Intracoastal Waterway. Gypsum rosettes have also been reported in the dredged spoil along Mansfield Channel. Masson (1955) postulated that the crystals are formed by waters of high salinity that periodically flood the wind-tidal

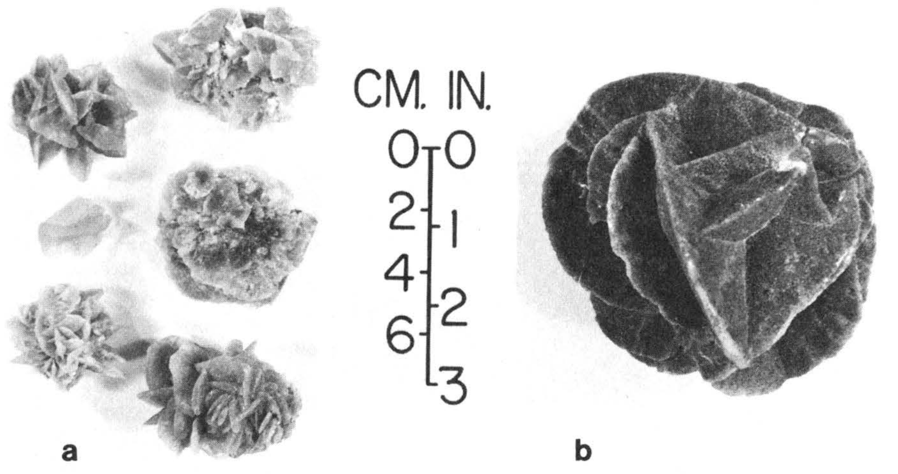


Figure 94(a) and (b). Gypsum rosettes. The smaller rosettes, in photograph (a), are composed of transparent to translucent crystals with relatively smooth crystal faces. The crystals composing the large rosette in photograph (b) are gray; its crystal faces have a grainy, sandpaperlike texture produced as the crystals grew larger and incorporated sand from the surrounding sediments.

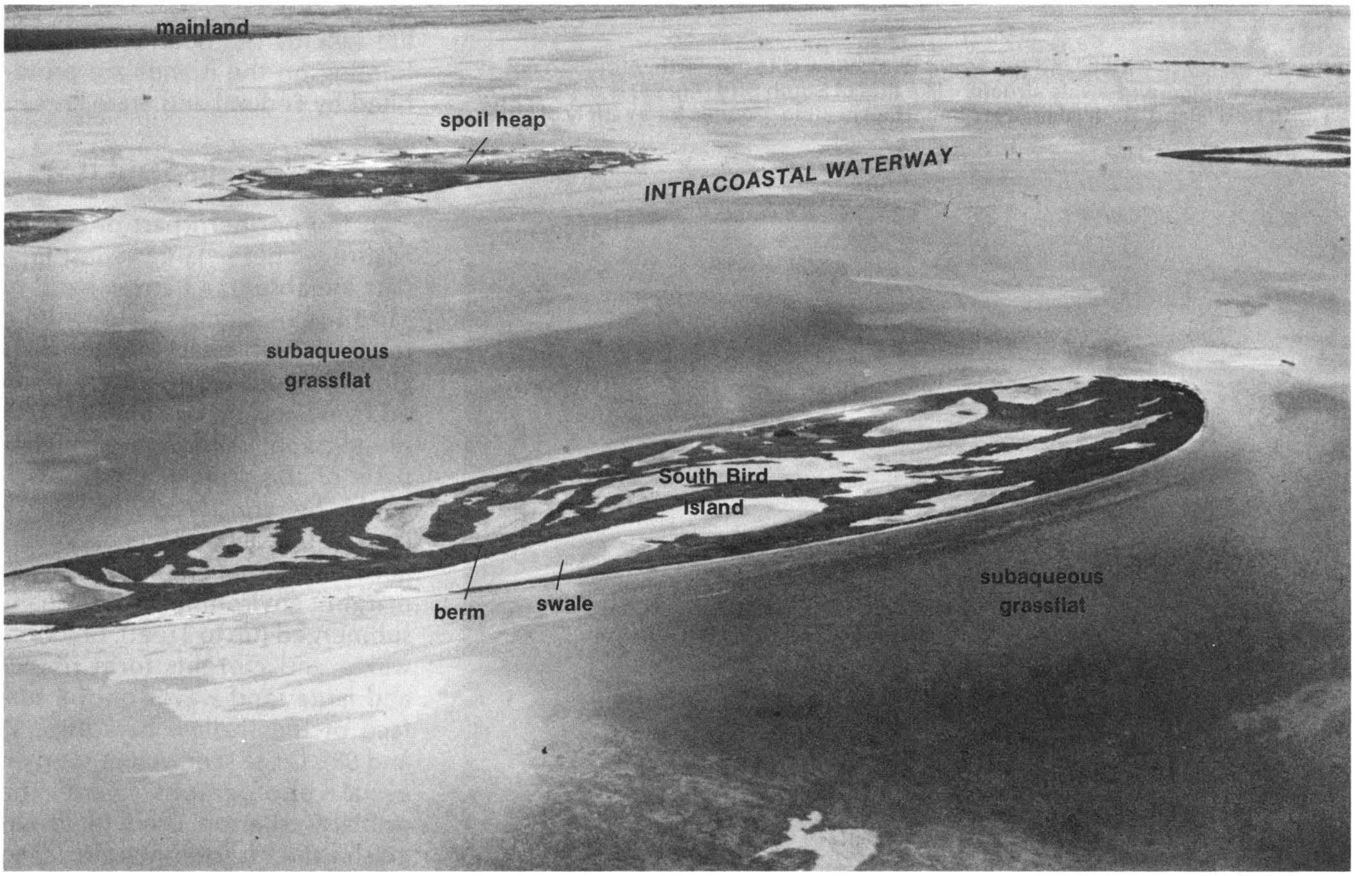


Figure 95. South Bird Island, a natural island in Laguna Madre (pl. I, grid U-2). View is to the north. The island is a series of sand and shell berms (ridges), built by storm waves on a shoal. The ridges have become vegetated, but the intervening low areas, or swales, remain barren and are often flooded.

flats. As the mineral-laden waters seep into the underlying sediments, gypsum is precipitated, forming the crystals, which grow larger with successive periods of infiltration and precipitation.

Lagoon Sand and Shell Berms (L4)

Within Laguna Madre in the northern part of the National Seashore are two natural islands, North Bird Island (grid W-3, pl. I) and South Bird Island (grid U-2). These islands are composed of sand and shell that were deposited on shoals by breaking storm waves generated within the lagoon. As more and more sediment was added to the islands in the form of beaches and spits, series of berms and interlying low areas, or swales, were created, giving the islands the characteristic topography seen today (figs. 95 and 96). The old spits and beach ridges, or berms, have become vegetated, but the swales between remain barren and are usually partly submerged. On plate I most of the swales were mapped as subaqueous lagoon-margin sand (L5).

Islands in Laguna Madre are popular nesting grounds for a variety of bird species. The importance of protecting these rookeries has been recognized, and North and South Bird Islands have now been designated as wildlife sanctuaries. Boat landing and hunting on the islands are prohibited by Federal and State laws.

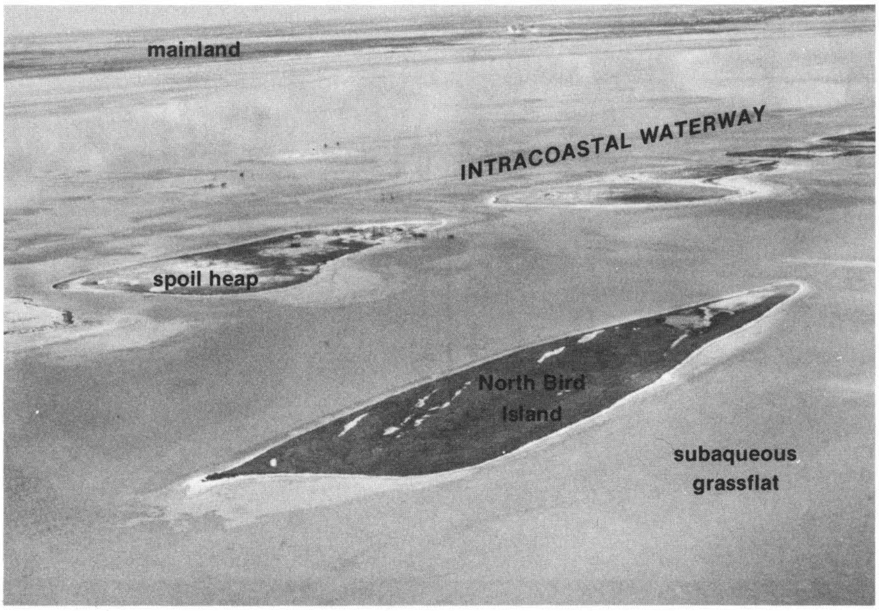


Figure 96. North Bird Island (pl. I, grid W-3). View is to the north. Although not as distinct, a ridge-and-swale structure like that of South Bird (fig. 95) is apparent on North Bird Island. Both islands are important nesting grounds for a variety of birds.

Lagoon-Margin Sand (L5)

In the northern part of Laguna Madre, where large wind-tidal flats are absent, a narrow band of sand (L5) occurs along the relatively high-energy lagoon margin. This sand is constantly reworked by waves and currents (pl. I, L5 photograph). Although the higher parts of this strip of sand, which could be considered in part a lagoonal beach, are occasionally above water, much of this lagoon-margin environment is usually submerged (up to 3 feet). Lagoonal waves and currents form ripples and large sand waves on the surface of the shallow bars (figs. 97 and 98). Large sand waves seen on aerial photographs were the primary criterion used to distinguish the lagoon-margin sand from wind-tidal flats.

During very high wind tides, water may be driven over the

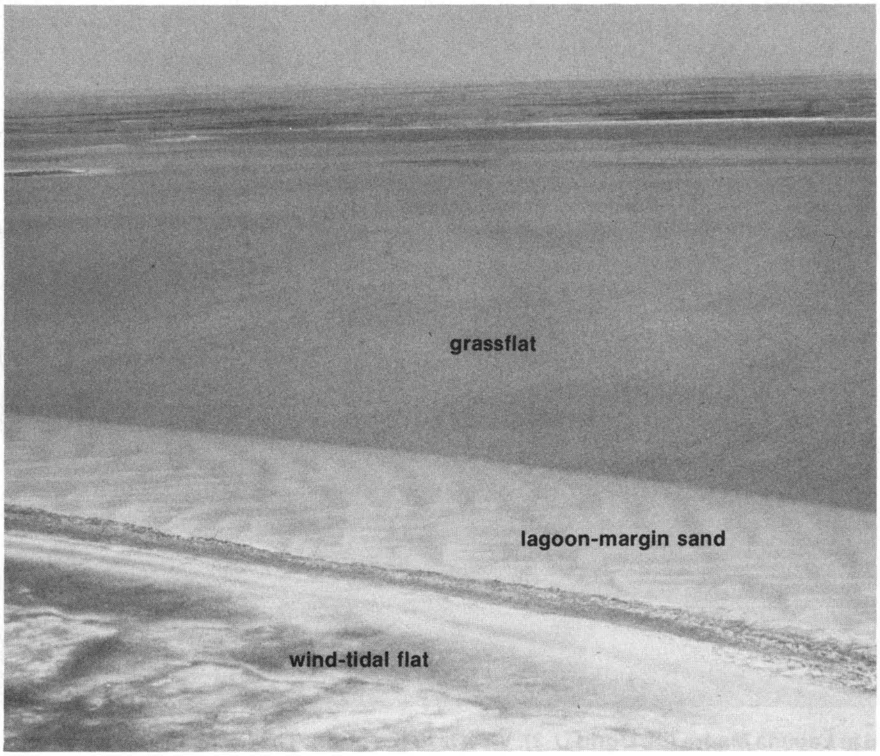


Figure 97. Lagoon-margin sand (pl. I, grid N-2). View is to the southwest.

lagoon-margin sand and lap onto back-island environments, eroding small cliffs at the edges of the barrier flats (fig. 99). At very low tides, almost all of the lagoon-margin sand may be exposed (fig. 98).

Lagoon-margin sand is carried into the lagoon either by wind eroding back-island dunes or by waters eroding small channels on the wind-tidal flats. The subaqueous sand forms lobes deflected toward the south in the direction of dominant currents along the island shoreline in northern Laguna Madre (pl. I and fig. 100). The sand lobes are generally less than 300 feet wide but are constantly reshaped by shoreline processes. Other areas mapped as lagoon-margin sand (pl. I) include a shoal area near the shoreline in grid X-3 and the unvegetated subaqueous fringes and swales of North and South Bird Islands (grids W-3 and U-2).

Grassflat (L6)

In shallow, quiet areas of the lagoon, away from the high-energy shorelines, are broad, subaqueous flats upon which thrive marine grasses and a variety of invertebrates. As shown on plate I, grassflats occur in all sections of Laguna Madre. The largest and densest grassflats occur in the northernmost part of the Seashore and in the central part between Middle Ground (U-9) and The Hole. The grassflat environment can be identified by its dark, mottled texture on aerial photographs (fig. 101).

The grassflats (L6) generally are covered by less than 4 feet of water, and the shallowest parts commonly are exposed at the lowest tides (fig. 102). The water depth, as well as the salinity and turbidity, determines the types of grasses that grow on the muddy sand and shell bottom. Shoalgrass *(Halodule wrightii)*, the dominant marine grass in Laguna Madre, can

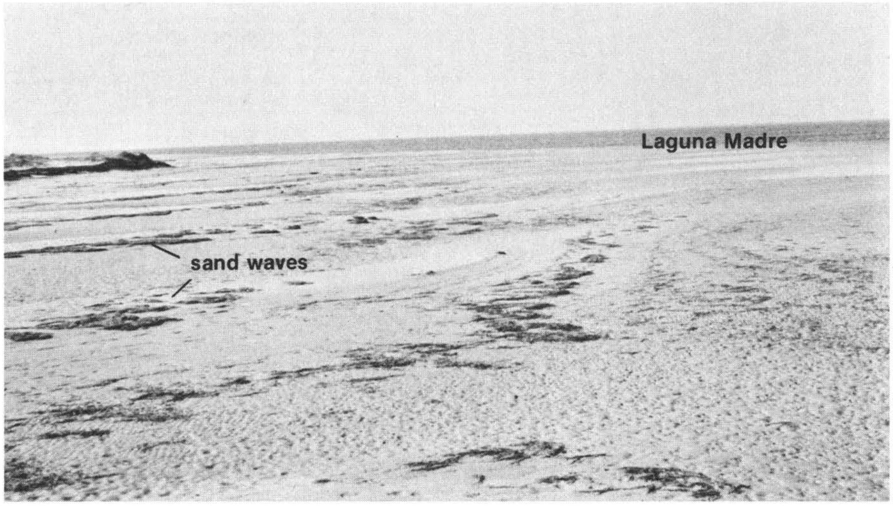


Figure 98. Large sand waves and ripples on lagoon-margin sand exposed during very low tide. View is to the southwest.

Figure 99. Small cliff at the edge of the barrier flat, eroded by high wind and storm tides. View is to the northeast.

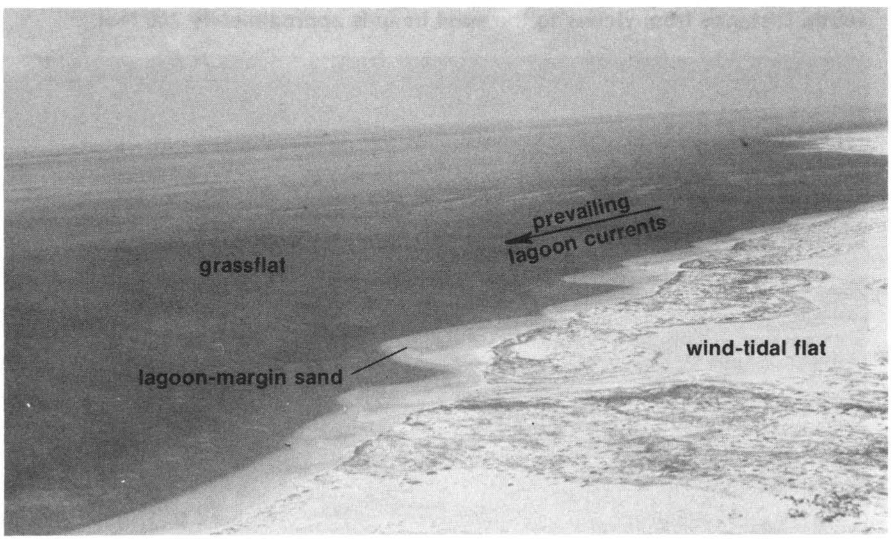


Figure 100. Lobes of lagoon-margin sand oriented southward (bottom left), in the direction of prevailing lagoonal currents.

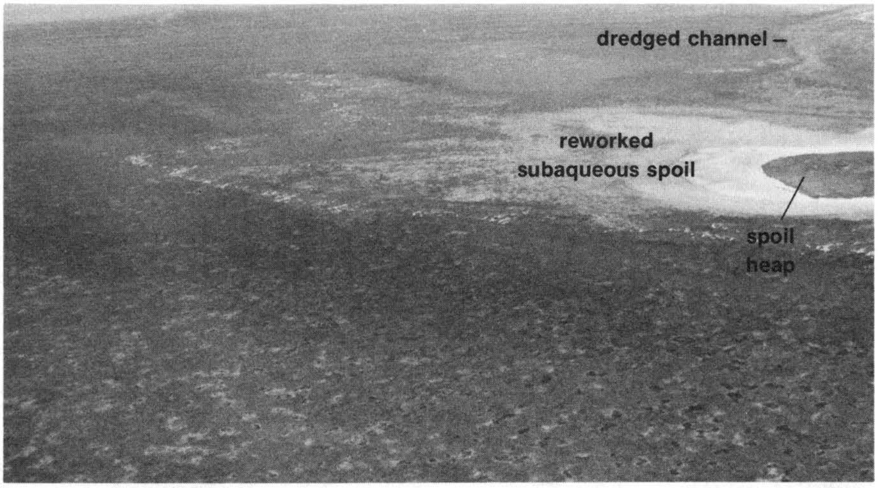


Figure 101. Subaqueous grassflat in Laguna Madre (pl. I, grids Q-9 and R-9). View is to the southwest; for scale, the diameter of the spoil heap is about 200 feet. The grassflats are environments of high biologic productivity, serving as homes, spawning grounds, or nurseries for many fish and invertebrates.

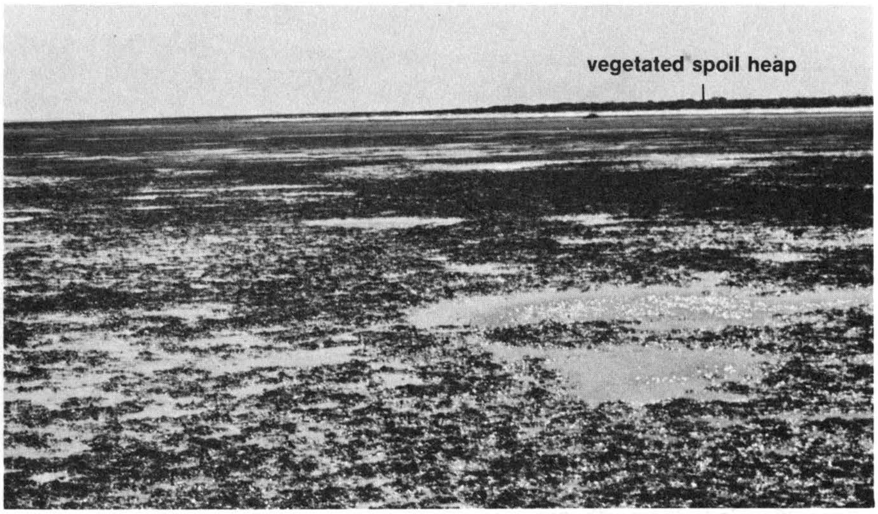


Figure 102. Lagoon grassflat exposed during low tide (pl. I, grid P-8). View is to the south. Distance from viewer to the spoil heap is approximately 700 feet.

Figure 103. Dead shoalgrass that has been washed onto a wind-tidal flat, dried in mats, and bleached white by the sun.

tolerate the highest salinity and turbidity and prefers the shallower depths (Brown and others, 1977). It is usually shoalgrass that can be seen washed onto the lagoon shore or tidal flats, where it dries in carpet-like mats and bleaches a brilliant white in the sun (figs. 103 and 104).

Other grasses growing on lagoonal grassflats are widgeongrass *(Ruppia maritima)*, turtlegrass *(Thalassia testudinum)*, clovergrass *(Halophila engelmannii)*, and manateegrass *(Cymodocea manatorium)*. Manateegrass and widgeongrass are generally restricted to southern Laguna Madre, where salinities are commonly lower than those of the lagoon north of the Land-Cut Area. In addition to the marine grasses, algae such as the leafy, calcareous alga *Acetabularia*, are common in shoal areas such as Middle Ground (pl. I and fig. 105).

Grassflats support a large invertebrate population, predominantly a variety of snails and clams. The grassflats are spawning grounds or nurseries for many fish and for crustaceans such as shrimp and crabs. This environment of high biologic productivity, which is important in the coastal ecosystem and to the Gulf fishing industry, is maintained by a delicate balance of salinity, turbidity, and water depth (Brown and others, 1977).

Lagoon-Center Sand (L7)

Like the grassflats, lagoon-center sand (fig. 106) occupies broad areas of the lagoon. Most of the lagoon-center sand is located south of the Land-Cut Area, although some occupies the southern part of The Hole and the area north of Middle Ground to grid K-1 (pl. I). Although locally sparse marine grass grows on this lagoon-center sand, the environment can be easily distinguished from grassflats on aerial photographs by its light color and smooth photographic texture.

Sand in this environment is generally muddy. Mud is concentrated in the deepest, quietest parts of the lagoon where depths are about 8 feet, the greatest depths occurring within the map area of plate I. Substrates of deeper lagoon environments outside the map area are composed almost entirely of mud.

Serpulid Reefs (L8)

Serpulid patch reefs and associated interreef environments of shell, sand, and mud occur locally near the mouth of Baffin Bay (fig. 1 and pl. I, grids G-1 and H-1). The reefs are constructed of serpulid (annelid) worm tubes composed of calcium carbonate. The L8 photograph on plate I shows a 6-inch sample of the serpulid reef rock oriented so that the top is toward the viewer. The marine worms that secreted the tubes were attached to the underlying substrate.

Living annelid worms have not been observed in the reefs, and the reefs are considered dead (Andrews, 1964). Although the reefs are no longer growing, the hard worm tubes remain resistant to attack by waves and are dangerous to boaters unaware of their locations. The tops of the reefs are commonly at the water surface or are exposed during low tides; water depths around the reefs are generally 2 to 3 feet (Andrews, 1964). The Gulf Intracoastal Waterway is cut through the serpulid reefs in grids G-1 and H-1, and boats straying beyond the boundaries of the Waterway in that area are likely to run aground on the reef rock.

The reefs in the map area occur as isolated patches. The patch reefs range from small, circular reefs 25 feet in diameter to larger, ellipsoidal ones up to 130 feet long (Andrews, 1964). Although the

Figure 104. Rows of bleached shoalgrass marking varying tide levels on the wind-tidal flats and reworked spoil (pl. I, grid Q-8). View is to the south.

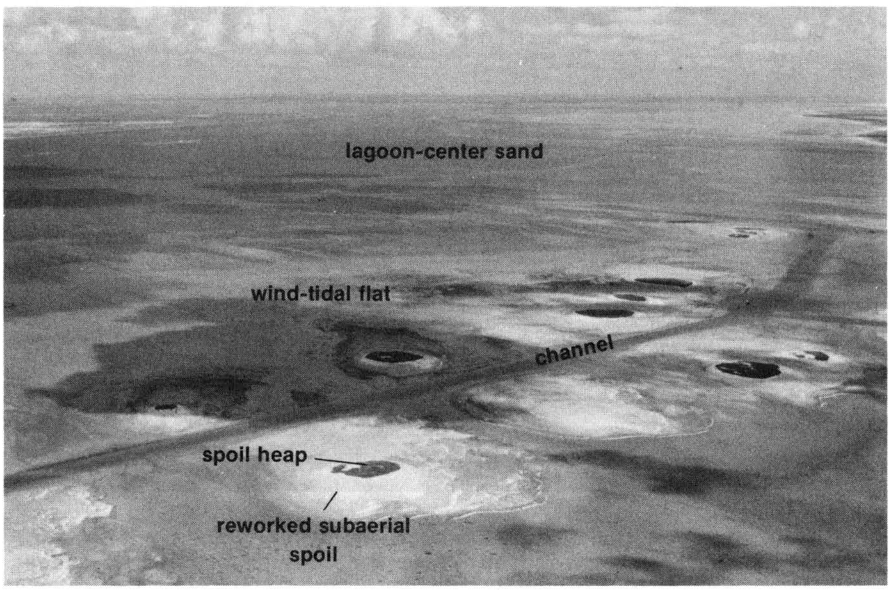


Figure 105. Middle Ground, an area of wind-tidal flats and shallow grassflats (pl. I, grids U-9 and U-10). View is to the north.

serpulid patch reefs and the interreef environments cover only a very small part of the map area of plate I, broader fields of serpulid reef rock are found in Baffin Bay to the west of Laguna Madre (fig. 1).

MAN-MADE AND MAN-MODIFIED UNITS

Besides the natural environments of Padre Island and Laguna Madre, there are some environments formed or modified by people. Three categories of spoil (M1, M2, and M3), which is the material dredged from channels through Laguna Madre or the barrier island, have been mapped on plate I. Land modified by human activity (M4) includes the areas covered by the Malaquite Beach development and petroleum exploration and production sites.

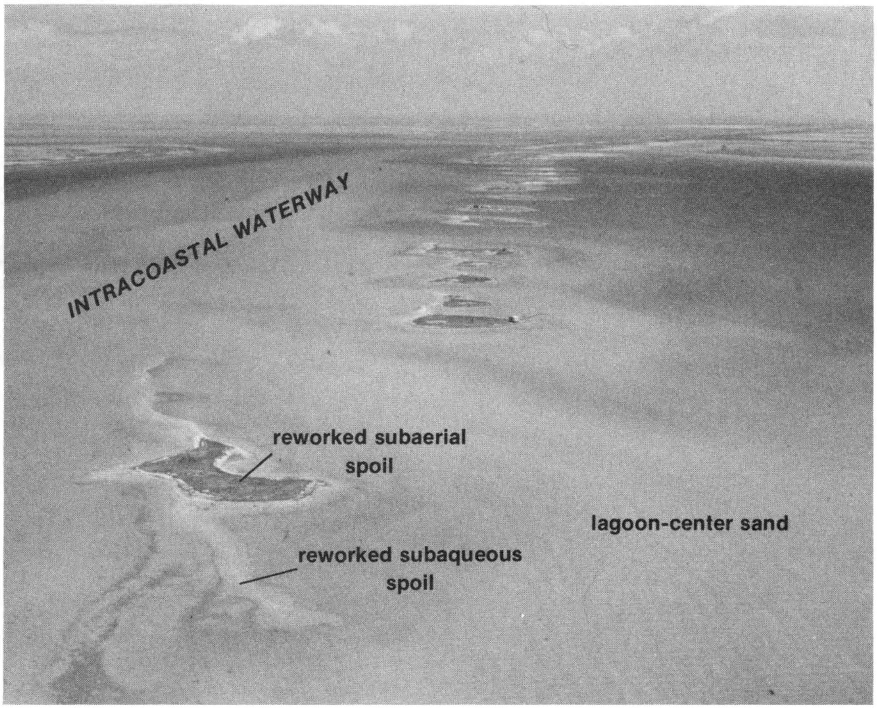


Figure 106. Muddy sand on the center bottom of Laguna Madre, just south of the Land-Cut Area (pl. I, grid S-13). View is to the northwest.

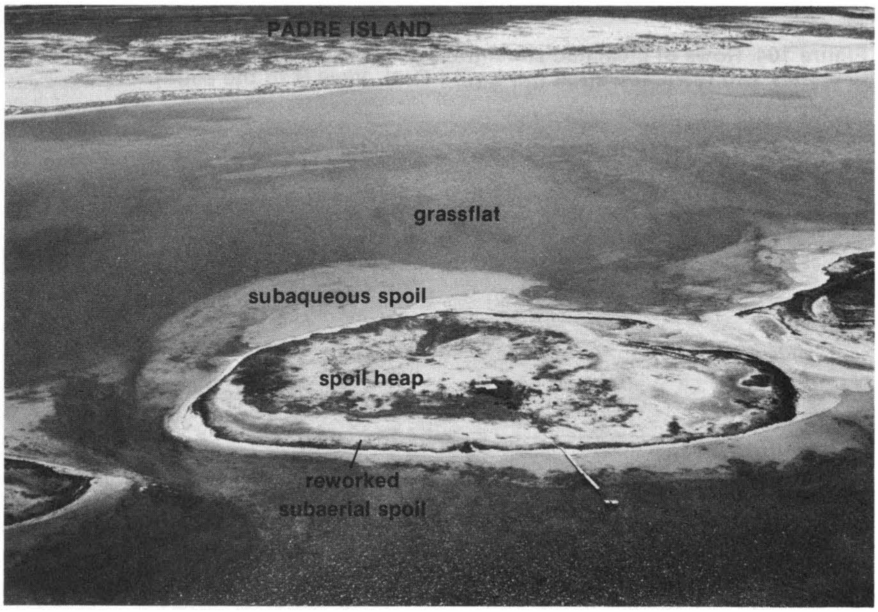


Figure 107. Dredged spoil along the Intracoastal Waterway (pl. I, grids V-2 and W-2). The central heap is surrounded by reworked subaerial spoil and subaqueous spoil. Grasses have begun to migrate onto the subaqueous spoil from the adjacent grassflat. View is to the southeast.

Spoil (M1, M2, M3)

Sediment dredged to produce and maintain the Intracoastal Waterway, Mansfield Channel, Yarborough Pass, and numerous smaller channels in Laguna Madre has been piled into mounds adjacent to the channels. Most of the spoil heaped above the water surface (M1) subsequently became vegetated (fig. 107 and pl. I, M1 photograph). Like the natural Bird Islands, some of these man-made islands have become important bird nesting sites, particularly in grids T-2, U-2, and N-1 (pl. I). Many spoil islands have also become popular havens for fishermen. Cabins built on these spoil mounds by sportsmen now require a use permit from the State of Texas.

Spoil is generally composed of sand, mud, and shell, but it varies considerably. The original composition depends on the substrate through which the channel is dredged. Later subaerial (above water) and subaqueous (underwater) reworking may winnow out the finer sediment. Some channels were dredged completely through the thin layer of recent sediments and into the more compacted Pleistocene sediments below. Consequently, pieces of hard, cemented Pleistocene sandstone or coquina (cemented shell), the deepest materials to be dredged, occur on the tops of many spoil heaps.

The spoil mounds are reworked by wind, rain, and lagoonal waves and currents. For example, wind has reshaped some of the larger subaerial spoil mounds that have dune fields developed on them in areas where no vegetation exists. This reworking spreads out the spoil and lowers the elevations of the heaps. Reworked subaerial spoil (M2) surrounding the central spoil heap (M1) (fig. 107) is often flooded by wind tides and reworked by lagoonal currents and waves. Thus, this reworked spoil, covered in many places by algal mats, may be considered the man-made environmental equivalent of wind-tidal flats. Where dredged sediment has been piled onto wind-tidal flats, as in the Land-Cut Area, the spoil around the edges of the heaps has undergone natural processes so long that it is almost indistinguishable from the tidal flats.

Subaqueous spoil (M3) is the third spoil category mapped on plate I. When spoil is dumped into lagoon waters, some of the sediment spreads out below the water surface and can immediately be classed as subaqueous spoil. With time, erosion of originally subaerial spoil contributes reworked sediment to the subaqueous environment. Most of the subaqueous spoil is devoid of marine grasses, but in some areas, species that prefer the generally shallow environment have migrated from surrounding grassflats onto the spoil (fig. 107).

The M1 unit also includes *made land* in several places where spoil dredged nearby or fill material brought in from elsewhere was used to build land out into the lagoonal environments to serve as subaerial earthen piers (grids E-3, F-3, G-3, and X-11). Although all subaerial spoil is a kind of man-made land, the term *made land* refers only to that land which is built with the primary purpose of creating new land area above sea level.

Land Modified by Human Activity (M4)

Areas mapped on plate I as land modified by human activity (M4) include a variety of features designated on plate I by either labels or symbols. Most of these features are land modifications necessary either for petroleum exploration and production or for construction of facilities to serve National Seashore visitors. The modified land areas are relatively small compared with most natural environments. Most modified lands lie in the northern part of the National Seashore where development for Seashore visitors has taken place. Modified land was mapped where the alteration of natural environments was evident on aerial photographs.

The Malaquite Beach development (grid Q-4) was carefully planned and constructed, and is maintained without harmful effects to the surrounding natural environments. Areas indicated as modified land at Malaquite include the visitor facilities, parking lot, sewage treatment ponds, and paved campgrounds.

Several petroleum production sites (fig. 108) and some abandoned exploration sites occur on Padre Island (examples in grids W-4 and K-4). Exploration and production activities have caused little disturbance of island or lagoon environments; devegetation scars left at the end of drilling projects are small and have either healed quickly or remained stable without much wind erosion and damage to adjacent environments. Land modifications on Padre Island were made for specific purposes and were controlled so that the natural environments would not be endangered. However, carelessness and abuse of the land and vegetation can cause considerable damage by altering the balance of natural processes in the environments.

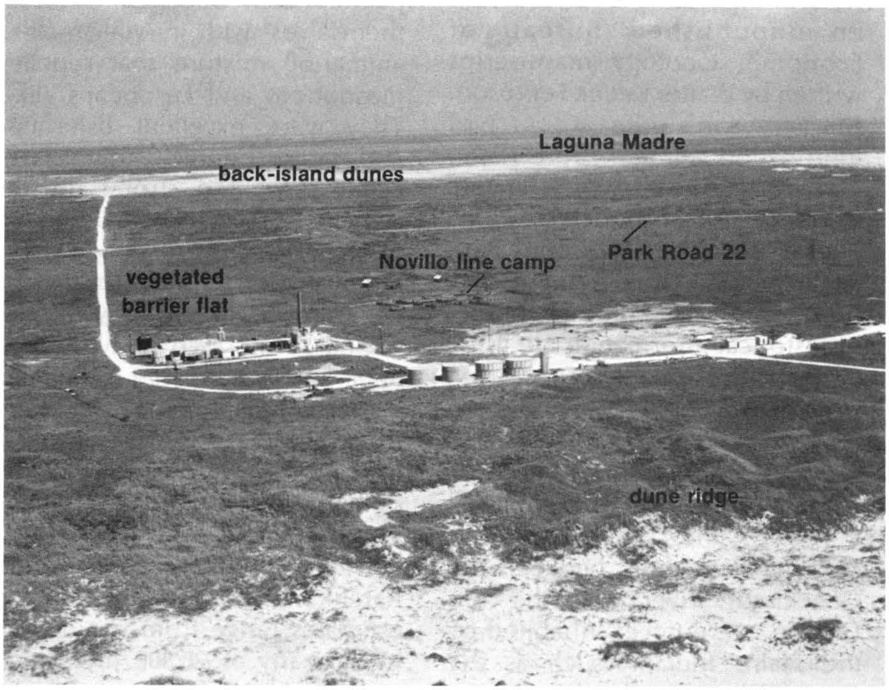


Figure 108. Petroleum company facilities on the northern part of the Seashore (pl. I, grid T-4). View is to the northwest. Corrals and sheds of the Novillo cattle line camp are visible just beyond the facilities.

HISTORY OF HUMAN ACTIVITY ON PADRE ISLAND

Most of Padre Island has remained in its primitive state since humans first set foot on it. The natural resources of Padre Island and Laguna Madre have been used in simple ways by the three main groups who have visited and inhabited the island — Indians, Spaniards, and Americans. Small tribes of nomadic Indians hunted on the island and fished in Laguna Madre. Both Spaniards and Americans recognized the value of Padre as rangeland and took advantage of it. Now, with the establishment of Padre Island National Seashore and the preservation of a large part of Padre's environments, most of the island will be maintained in its primitive character.

Following is a brief account of the history of the Indians Spaniards, and Americans on Padre Island and their interaction with the natural environments. Most of this history is derived from an unpublished Bureau of Economic Geology manuscript written by Walter Keene Ferguson. Mr. Ferguson's primary source of information was the *Padre Island National Seashore Historic Resource Study* conducted by J. W. Sheire for the National Park Service (1971). The Historic Resource Study and other sources of historical information are listed under *Historical References* on page 84.

KARANKAWA INDIANS

The semiarid lands of the South Texas coastal bend, between the Guadalupe River and the Río Grande, were never inhabited by the Plains Indians, such as the Comanches and the Lipan Apaches. Instead, small tribes of Indians maintained a subsistence off the coastal lands by hunting and gathering food. One of the groups dwelling within this area was the Karankawas. The exact origin of the Karankawas is uncertain because little is known about their language and culture.

After sifting the tons of oystershells that formed the bulk of the "kitchen" middens, or trash heaps, left by the Karankawas, archeologists have been able to piece together some of the basic aspects of Karankawan culture. T. N. Campbell, author of *An Appraisal of the Archeological Resources of Padre Island, Texas* (1964), reports that there are 20 different Karankawa campsites in the northern 20 miles of Padre alone. The location of one of these northern campsites, as well as of two others farther south, is shown in figure 109. The reports of explorers, traders, and missionaries provide other sources of information on this culture.

The Karankawas tattooed and painted their bodies and coated themselves with a vile-smelling animal-oil mixture that repelled mosquitoes and Europeans alike. They were excellent fishermen and good hunters, using large cedar bows too strong for the average person to bend. Canoes, or pirogues, were made from hollowed-out logs. The food of the Karankawas varied with the seasons. Although they hunted deer and other large game and gathered nuts, berries, and cactus fruit, their diet consisted mostly of fish, shellfish, birds, and bird eggs obtained from Laguna Madre and vicinity.

The total population of the five Karankawa tribes is unknown, but estimates range from about 1,000 to as many as 28,800 (the larger estimate by W. W. Newcomb, Jr., personal communication, 1979). Separated into groups of 30 to 40, the Karankawas lived a nomadic life. They set up summer camps on Padre and wintered in crude, portable huts on the mainland. The tentlike lodges made of willow poles and deer skins would accommodate two families, or about seven or eight people.

Archeologists have gathered little evidence of Karankawan religion. The Indians apparently worshiped two deities called Pichini and Mel and held ceremonies for giving thanks and for imploring the assistance of these gods. The Karankawas evidently practiced cannibalism, but not to provide a food source. Cannibalism instead involved the superstitious belief that by eating the flesh of an enemy, the Karankawas could transfer the victim's strength to themselves.

As explorers and settlers invaded their country, the Karankawas resisted fiercely. Disease, lack of organization, and the Indians' small numbers, however, doomed them to extinction once others desired their land. The Karankawas became impediments to the expansion of Anglo-American and Mexican settlements.

The final fate of the Karankawas is uncertain. In the mid-1840's remnants of the once sizable Indian tribe reportedly fled southward. One group settled on south Padre Island and another group settled in Tamaulipas, Mexico. Conflicting reports exist about those who settled on Padre Island. A sensational account in 1846, by Samuel Reid of the Texas Rangers, maintained that some of the warriors, driven to desperation by their sufferings, murdered their women and children and chose Padre Island as a suitable place to linger out the remnant of their miserable lives (Sheire, 1971). Another final Karankawan account was in 1858. Problems in Tamaulipas forced a number of Karan-

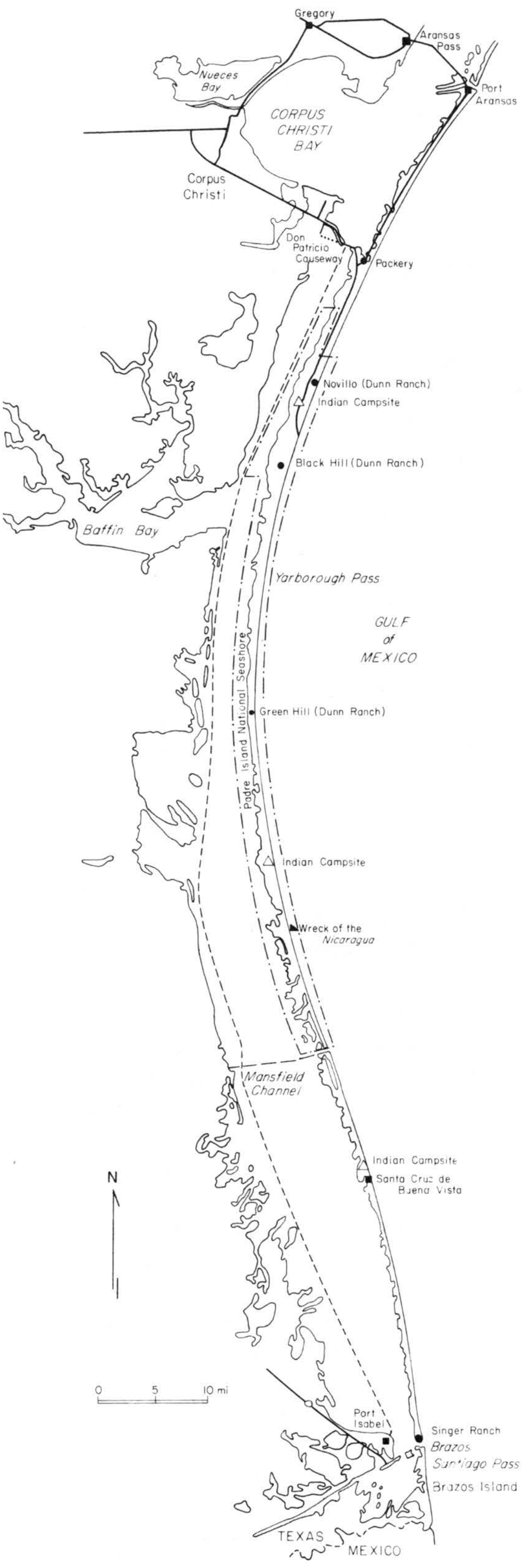


Figure 109. Historical sites on Padre Island.

kawas to flee back across the Río Grande into Texas where they were "exterminated" by ranchers (Gatschet, 1891). In his book, *The Indians of Texas: From Prehistoric to Modern Times*, W. W. Newcomb, Jr., (1961) commented on the Karankawas' endurance:

> The Karankawas of the Texas Gulf Coast are gone, yet they will forever stir our imaginations. Perhaps this is because, unlike ourselves, they faced daily and directly the stark realities of remaining alive. To those who have seldom been too cold, hot, or wet, never really hungry, and confidently expect to see many tomorrows, a people who had none of these advantages come as something of a shock. Our civilization is like a great blanket cushioning and protecting us from the raw world; the Karankawa blanket was thin and patchy. Yet, they survived, even thrived, and were happy with their ways. To Europeans and Texans it was astonishing and insufferable that such a people should prefer their own gods, food, and customs to civilization's blessings. But they did, and they clung to these ancestral ways. And for this they perished. To persevere to such ultimate tragedy is a highway to continuing remembrance.[1]

SPANIARDS

Exploration

Invention of the printing press and the mariner's compass marked the beginning of the end for American Indians, for these inventions made possible the boom of European exploration and expansion in the 1500's. Exploration of the Padre Island region began in 1519, when Spanish Jamaican Governor Francisco Garay, eager to match the golden successes of Hernando Cortés in Mexico, ordered Alonso de Piñeda to explore the north and west coasts of the Gulf of Mexico.

[1]Excerpt from *The Indians of Texas: From Prehistoric to Modern Times* by W. W. Newcomb, Jr. Copyright © 1961 by University of Texas Press, Austin, Texas. Reprinted by permission of the publisher.

Piñeda's main objective was to find the Strait of Anian — the rumored water passage to India. He did not find the nonexistent strait, but he did chart the Gulf coastline from the tip of Florida to Tampico. In the process he discovered and named the Bay of Corpus Christi and Isla Blanca (Padre Island) and touched ashore at the mouth of the Río de las Palmas — the Río Grande.

The Shipwrecks of 1554

In April 1554, a group of Spaniards landed on Padre Island, but certainly not by choice (Arnold and Weddle, 1978). Four ships had set sail from Veracruz carrying treasures and some of Mexico's wealthiest residents back to Spain. As the fleet reached Texas latitudes, it was struck by a fierce storm. The Spanish vessels were scattered by the raging storm. Three of the ships ran aground on Padre Island, but one made it safely to Havana. The survivors, exhausted and starving, took some supplies from the wreck and spent 6 days on Padre's beaches before they were greeted by a band of Indians. The Spaniards, fleeing southward under showers of arrows, were gradually reduced in number. Only a few Spaniards survived the ordeal, eventually making their way southward to a Mexican settlement and safety.

One shrewd nobleman who survived the shipwrecks, Francisco Vásquez, had left the group early and returned to the wrecks, where there remained a plentiful supply of food and other goods. Vásquez reasoned that ships would be sent to search for survivors and, particularly, the lost treasure. Within 3 months, Vásquez was rescued from Padre Island.

Colonization

When Piñeda had reported to Governor Garay on the 1519 expedition, he suggested that the region of the Río de las Palmas be colonized. Two subsequent colonization attempts failed, however, and these failures marked the area as unfit for habitation. But when Robert LaSalle established a French stockade, Fort Louis, on Matagorda Bay in 1685, Spanish interest in the South Texas region was rekindled. Alonso de León led five expeditions into the coastal region before he found LaSalle's abandoned fort in 1689. On one of these journeys he explored Baffin Bay (fig. 109).

In a half-hearted effort to forestall any more French designs on this region, the Spanish authorities in Mexico ordered a presidio, or fort — La Bahía — built near the confluence of the San Antonio and Guadalupe Rivers at what is now Goliad. The Spaniards also established a mission, called Nuestra Señora Espíritu Santo de Zúñiga, to pacify the coastal Indians, especially the Karankawas. The mission, however, was finally abandoned as a failure. The Karankawas refused to give up their traditional life patterns, and the Spanish could not provide them security against the Comanches and Apaches.

This same concern with the defense of the Texas region, which the Spaniards considered an invaluable buffer between Mexico and the expanding British and French colonial empires in North America, prompted the Spanish authorities to order José Escandón to explore the region and initiate civilian settlements in the late 1740's. Escandón launched a carefully planned and successful colonization program, which led to the establishment of settlements on both sides of the Río Grande from its mouth northwest to the site of Laredo (fig. 110). These settlers were the first to use this region for cattle grazing.

After the English defeat of the French at the end of the Seven Years' War in 1763, the English gained all French and Spanish territory east of the Mississippi. Soon rumors spread that they were establishing forts along the Gulf in an effort to expand their empire. Escandón was ordered to investigate these rumors, and one of the expeditions that he sent under the direction of Diego Ortiz Parrilla was to explore Isla Blanca — now Padre Island. Parrilla's report contains probably the first description of Padre Island.

Padre Ballí

By 1760, Spanish cattle grazed on land from what is now Mexico north to the Nueces River (fig. 110). This region was no longer a wilderness but a territory of large ranches. One story tells of a hurricane flood in 1791 that inundated Padre Island and the mainland shore, killing 50,000 head of cattle belonging to one Spanish cattle baron. But an extensive ranching enterprise was not begun on Padre Island until 1800, when the Portuguese priest, Padre Nicolas Ballí, a member of a land- and cattle-rich family settled near the Río Grande, finally succeeded in gaining a grant to the island from King Charles IV of Spain. Padre Ballí established ranching operations on the island and was joined in the venture by his nephew, Juan Jose Balli, although neither of them actually lived on Padre Island. The ranch headquarters, Santa Cruz de Buena Vista, was located about 26 miles from the southern end of the island (fig. 109).

When Padre Hidalgo launched the successful struggle for Mexican Independence in 1810, Padre Ballí fled to Santa Cruz, as he was known to be sympathetic to the Spanish establishment, which had granted him and his family land. After the revolution, Ballí had to work long and hard to get the Mexican government to reconfirm his title to "Padre's Island." Unfortunately, Padre Ballí died in the same year that the grant was verified — 1828. The Ballí family continued to ranch on the island until 1840, but they had begun to sell parts of their land as early as 1830.

AMERICANS

Smuggler Kinney

As the Mexican ranchers were developing the grazing potential of South Texas, the first Anglo-American settlers were colonizing the fertile lands along the Brazos and Colorado Rivers in central Texas. When the Texas Revolution broke out in 1836, the sparsely settled ranching country to the south became a no-man's-land. In the midst of this confusion, notorious smuggler Henry Lawrence Kinney established trading operations in the Corpus Christi Bay area. By 1840, he had established a trading post on the south rim of the bay and had a personal police force of 40 men.

A Boundary Dispute and the Mexican War

A dispute over the border between the new Republic of Texas and Mexico intensified when the United States voted to annex Texas in 1845. The American government chose to support Texas' claim of the Río Grande as its southern boundary rather than the Nueces River farther north, as held by the Mexican government (fig. 110). In a show of power, President Polk ordered General Zachary Taylor to occupy the disputed area between the two rivers, a region including Padre Island. Taylor and his troops traveled by sea to Rockport and, after a 6-month stay at Kinney's trading post, moved on to Port Isabel to establish the main supply base. Fort Brown was established at this time. Captain Ben McCulloch and his Texas Rangers first brought the American flag to Padre Island

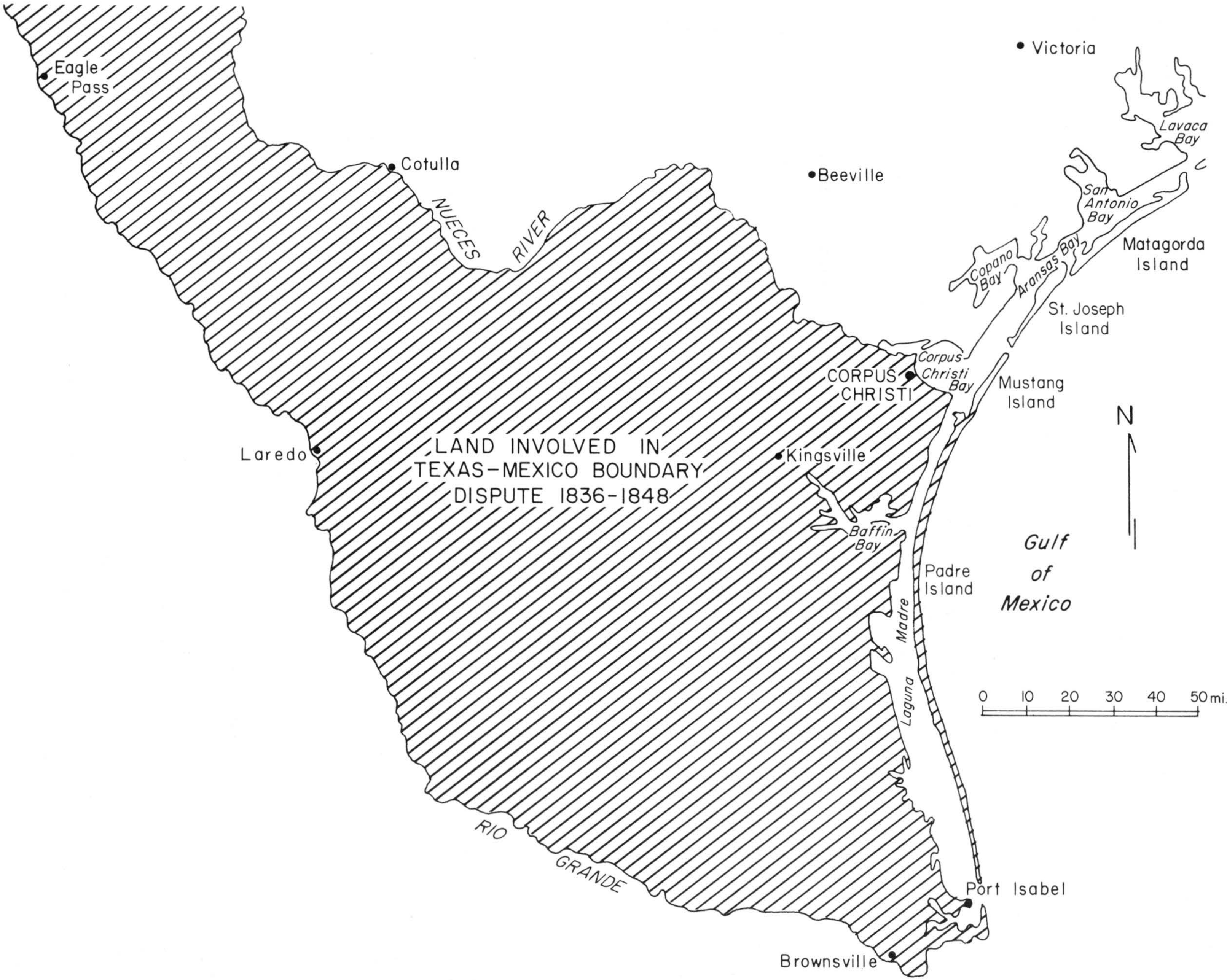


Figure 110. South Texas. Between 1836 and 1848, Texas and Mexico both claimed the land between the Nueces River and the Rio Grande.

as they traveled its length to report for duty with Taylor's forces. And, on Taylor's orders, Lieutenant George Gordon Meade, later to gain fame as the commander of Union forces at Gettysburg, conducted a 10-day survey of the navigability of the waters of Laguna Madre and transportation routes on the island itself. Meade's map, made in November 1845, was the first detailed map of the island. At the end of the war with Mexico in 1848, the Treaty of Guadalupe Hidalgo established the Río Grande as the boundary between Texas and Mexico, and finally, Padre Island became a part of the United States.

Port Isabel (fig. 110) was the vital link in the American supply system during the Mexican War. Brownsville and Corpus Christi also experienced a wartime boom, and during the gold rush years in the mid-1800's, they became important as supply stations for the forty-niners' trek across the arid Southwest. Richard King and Mifflin Kenedy, later of King Ranch fame, made a small fortune off their 200-ton, shallow draft sternwheeler steamboats that plowed up the Río Grande, almost as far as Laredo (fig. 110).

John Singer and His Buried Treasure

The booming Port Isabel trade had attracted the attention of John Singer, whose brother Isaac was starting his sewing machine empire. In 1847, the adventurous Singer and his wife and son set out for Port Isabel to establish a shipping business. They were swept off course by a storm, however, and their schooner was dashed aground on southern Padre Island. The Singers took a liking to their new home and set up housekeeping on the southern tip of the island (fig. 109).

The last of the Ballí descendants had left the island in 1844 in the face of the American annexation of Texas with its Río Grande border. After the Mexican War, land-hungry Texans turned their attention to the Mexican ranching lands south of the Nueces. They posed such a threat to the Mexican landowners that most of the Mexicans felt compelled to sell out at any price in order to salvage anything. By such purchases, payment of back taxes, or simply squatter's rights, Americans had acquired most of these lands by the outbreak of the Civil War. As of 1846, José María Tovar owned the northern half of Padre, and the southern half was owned by Ballí's seven heirs. But by the mid-1850's, almost all of the original Ballí grant was in American hands. The Singers purchased one seventh of the south half from one of the Ballí heirs in 1851 and by 1855 had leased much of the rest of the southern part for their thriving ranching business.

Six Singer children were born on the island, and at the height of the ranching boom, the Singer headquarters consisted of about 15 buildings. The Singers' profitable ranching business was shortlived, however. Because of the Singers' Union sympathies, the Texas Confederates ordered them off the island in 1861. Singer was forced to make a hasty departure and quickly buried $80,000 in a jar near his home. This was the basis of one of the island's most intriguing treasure stories, for after the Civil War, Singer was unable to find the cache. A short time later Mrs. Singer died, and the Singer family permanently left the island in 1866, selling their holdings to railroad entrepreneur Jay Cooke.

The Civil War

During the Civil War, the effective Union blockade cut off all direct Confederate trade with Europe. The Confederates, however, quickly found a solution to the blockade. They transported cotton overland to Mexico south of Brazos Santiago Pass at the southern tip of Padre (fig. 109). From there it was shipped out on European vessels and traded in Europe for drugs, food, clothing, and war supplies. The Mexican port of Bagdad became a boom town full of deserters, spies, and gamblers. In an effort to cut the flow of Confederate goods to Bagdad, 7,000 Union soldiers stormed ashore on Brazos Island south of Padre in November 1863. They captured Brownsville, which forced the cotton caravans to enter Mexico as far north as Eagle Pass (fig. 110).

The King Ranch

During the confusion of the Civil War, the unattended cattle herds in South Texas expanded tremendously. Throughout the 1850's, Richard King and Mifflin Kenedy had been acquiring the lands that would constitute the legendary King Ranch, which now covers almost 1 million acres. As early as 1854, King purchased 12,000 acres on Padre Island from a niece of Padre Ballí. And in the early 1870's King and Kenedy leased additional acreage on the island. At the height of their operations on the island, there were some 70 people located at the headquarters near the site of Ballí's old headquarters, Santa Cruz (fig. 109). King's ranching operations on the island, however, were severely curtailed after a damaging storm in 1880.

The Meat Packeries

One sidelight to the history of ranching on Padre was the appearance of meat packeries along the coast and on the island during the 1870's. The tremendous oversupply of cattle in relation to the Texas market had dropped beef to a few cents per pound. The cattle hides became more valuable than the meat. At these packeries, cattle were slaughtered for their hide and tallow, and some beef was packed in salt to be shipped. During 1872, 300,000 hides were shipped out of Rockport and Corpus Christi alone. One large packery (fig. 109) was located just south of Corpus Christi Pass on Packery Channel. By the end of the 1870's the packery boom was over as the cattle drives to railheads in Kansas and Nebraska poured Texas beef into midwestern and eastern markets.

Patrick Dunn — The "Duke" of Padre

The profitable days of the open range came to an end at about the same time as the packeries did. In 1882, Kenedy fenced in his La Parra ranch; this marked the beginning of the end of the open range. This prompted the appearance of the real successor to the Padre Island ranching heritage of Ballí and Singer — Patrick Dunn. Dunn was the son of Irish immigrants who came to Corpus Christi in the 1850's. He became a successful rancher by taking advantage of the free open range. Then the advent of barbed wire fencing directed his attention to the natural "fences" of Padre, bounded by the Gulf on one side and the lagoon on the other. He first leased land on the northern part of the island in 1879. By 1926, he owned almost all of Padre's 130,000 acres. During the periodic roundups, Dunn's cowboys, or vaqueros, started at the south tip of the island and drove the cattle from line camp to line camp, holding them in corrals at night. The line camps were built 15 miles apart, the distance the cattle could be driven in 1 day and corralled before dark. The remains of Novillo, Black Hill, and Green Hill camps are visible today (fig. 109, also fig. 83). The cattle were then driven to market across the lagoon at a point below Flour Bluff.

Dunn — the "Duke" of Padre — became a legend in his own time. He closely supervised his extensive ranching operations and conducted experiments with nonnative grasses. A notable in the Democratic party, he was a State legislator from 1910 to 1916 and helped launch John Nance Garner into politics. In 1926, Dunn sold his surface rights to real estate developer Colonel Sam Robertson. The Duke retained grazing and mineral rights and ranched until his death in 1937. His son, Burton Dunn of Corpus Christi, continued to run the Dunn ranching business. The Dunn line camps were still used as collecting points for cattle during roundups until 1971, when grazing was terminated within the Padre Island National Seashore.

The Wreck of the *Nicaragua*

Protruding above the waters of the surf about 10 miles north of Mansfield Channel are parts of the rusted boilers and 180-foot frame of an old steamship (fig. 109 and pl. I, grid M-20). The *Nicaragua* went aground on Padre in 1912. The purpose of the boat's trip, its cargo, and the cause of the wreck remain mysteries. One popular theory is that the *Nicaragua* was carrying guns and ammunition to Mexico to be used in an overthrow of the Mexican government. The boat supposedly ran aground after it was sabotaged by Mexican spies who had slipped on board. Another story, however, is that the *Nicaragua* was merely a banana boat.

Colonel Sam's Dreams of an Island Resort

Colonel Sam Robertson, a former scout for General Jack Pershing, was the first representative of the age of the automobile and tourism to foresee the resort potential of Padre. After purchasing Dunn's Padre holdings for $125,000, Robertson began work on a wooden causeway from Corpus Christi to Padre. This Don Patricio Causeway (named after Patrick Dunn) opened on July 4, 1927. It consisted of two wooden troughs just wide enough to fit the wheels of a Model T Ford. The causeway was destroyed by a hurricane in 1933, but the supports are still visible across Laguna Madre (fig. 109). Colonel Sam also provided ferry service to both ends of the island and access to his Twenty-Five Mile Hotel on the southern end of the island.

Robertson's big hopes for a tourist boom fizzled, and then the Depression hit in 1929. No longer able to keep up his payments, Colonel Sam sold his island property to Albert and Frank Jones, two brothers from Kansas City. The Jones brothers established the Ocean Beach Drive Corporation but did not expand Robertson's developments. The hurricane of 1933 that destroyed the Don Patricio Causeway also destroyed most of Colonel Sam's buildings, wiping out any ideas the Jones brothers may have had of continuing with Robertson's schemes.

Movement Toward an Island Park

During the 1920's, Governor Pat Neff established the foundations for Texas' State park system, and during the 1930's Federal funds made the parks more usable and accessible to the public. It was at this time that the drive began to establish a State park on Padre Island. In 1937, Representative W. E. Pope of Corpus Christi introduced a bill authorizing the State Parks Board to acquire acreage for a park on the island. The promoters of this bill established the Padre Island Park Association, which rallied support from all over South Texas. The Legislature passed the bill, but Governor James Allred vetoed it. The basis of his veto was that the State might already own most of Padre because the island was much larger than the 11½ leagues included in Ballí's original grant. In 1945, however, the Texas Supreme Court upheld the private ownership of all of the island.

Obviously, Allred's veto, along with the drawn-out title suit and World War II, slowed the movement for establishment of a park. Meanwhile, Robertson's successors were hard at work. A causeway from Corpus to the island was completed in 1950, and the construction of a causeway and bridge from Port Isabel to Padre followed 4 years later. This obviously stimulated resort development. John L. Thompkins led this drive with plans for a multimillion-dollar development, Padre Beach. And today, both the northern and southern ends of Padre are lined with resort motels and condominiums.

While this development was beginning, the National Park Service in 1954 undertook a comprehensive survey of America's 3,700 miles of coastline. The survey noted that only 6.5 percent of the coastline was reserved for public recreation. It was recommended that three coastal areas be included within the National Park domain: (1) Point Reyes, California, (2) Cape Cod, Massachusetts, and (3) Padre Island, Texas. Senator Ralph Yarborough introduced the first Padre Island National Seashore bill in 1958, and the National Seashore became a reality in September 1962.

SUMMARY OF NATURAL RESOURCE USE

Use of the natural land, water, and mineral resources of Padre Island and Laguna Madre has changed over the several hundred years that people have inhabited the area. Primitive use by the Karankawa Indians changed to the more ordered Spanish and American ranching operations and then to still more sophisticated uses such as petroleum exploration and production and resort development. The Karankawas relied heavily on the island and lagoon for their food sources, but their needs were simple, and their use of the land and water environments was minimal. Setting up temporary camps on Padre in the summers, the Indians hunted birds and other game on the island and fished in Laguna Madre. Around 1805, the Spaniards brought cattle to graze on Padre's grass-covered barrier flats. Americans later continued the ranching operations. Cattle raising was the primary use of the island until 1971, when the last cattle were removed from the area of the National Seashore.

Other recent uses of the resources of Padre Island and Laguna Madre include oil and gas exploration, resort development, recreation, commercial fishing, and shipping along the Intracoastal Waterway. Entrepreneurs began planning resort developments for Padre as early as the 1920's. Although the middle part of the island is now preserved as the National Seashore, resort communities cover both ends of the island. Petroleum production began in the Seashore area in the late 1930's. The first discovery was in Laguna Madre, west of South Bird Island. Exploration and production continue on the island, in the lagoon, and offshore in the Gulf of Mexico.

Man's use of island and lagoon resources has had some adverse effects on the environments. Overgrazing of the vegetated barrier flats and dunes of Padre, coupled with droughts, at one time destroyed much of the plant cover on the island. This left large barren areas covered with loose dune sand that was free to migrate. Much of the loose sand blew into and filled certain parts of Laguna Madre (Price and Gunter, 1943), especially in the Land-Cut Area and just north of the mouth of Baffin Bay (pl. I, grids J-2 and K-2). Thus, the overgrazing may have indirectly had a lasting impact on the lagoon, but Padre's environments seem to be recovering well from devegetation caused either by natural processes or by man.

Other adverse alterations of lagoon environments have been those produced by the deposition of dredged spoil. The spoil not only blots out the habitats of numerous fish, invertebrates, and marine plants but also alters the circulation patterns of lagoonal waters. The location and manner of deposition of spoil are carefully studied by the U.S. Army Corps of Engineers before dredging so that disturbance of lagoon environments will be minimal.

Activities of the petroleum companies are carefully planned so that the natural environments are not greatly affected. Very little disturbance of the environments is visible either at drilling and production sites or along buried pipelines laid to transport gas from producing wells. Large-wheeled vehicles used by seismic crews have destroyed little vegetation.

In spite of changes in natural resource utilization and certain effects of human interaction with the environments, most of Padre has remained in a primitive state. Establishment of the National Seashore in 1962 now limits the use of much of this wilderness to recreation and ensures that a large part of the island will remain undeveloped. Those who visit the National Seashore can help protect the natural environments by preventing the careless destruction of vegetation, especially along the fore-island dune ridge, which serves as a barricade to storm winds, waves, and tides.

FIELD TRIP THROUGH THE ENVIRONMENTS OF NORTH PADRE ISLAND

A short field trip has been designed for Seashore visitors wishing to take a close look at various island environments found within the northern end of the National Seashore. By using the following road log and the accompanying map (fig. 111), visitors can guide themselves through the environments and observe them at their own pace. This drive, only a few miles long, affords a look at a complete cross section of barrier-island environments, ranging from Gulf beach to lagoon. The trip uses maintained roads and does not require a four-wheel-drive vehicle.

The following road log describes the various environments or points of interest that can be seen along a route beginning at the Seashore entrance on Park Road 22 and ending at the Laguna Madre shoreline in the Bird Island Basin area. Mileage, approximated to the nearest 0.1 mile, is shown both in cumulative miles and miles between observation points or convenient landmarks. The environments do not necessarily have to be seen in the order given in the road log; one can reverse the trip and recalculate the cumulative mileage. Although odometers of different vehicles vary, use of the map, which shows environments and observation points (fig. 111), should prevent confusion. Observation point numbers on the map correspond to those used in the road log.

For a more detailed description of the environments and the active processes affecting them, see sections on *Environments of Padre Island and Laguna Madre* and *The Dynamic Barrier Island.*

HURRICANE ALLEN

While this guidebook was in final preparation in August 1980, the eye of Hurricane Allen made landfall near Port Mansfield. One of the greatest hurricanes of the century, Hurricane Allen stalled and lost strength as it approached the Texas coast. Nevertheless, the hurricane's impact was severe along the National Seashore, where storm tidal surge heights were estimated at approximately 10 feet above mean sea level. All mapped washover channels (pl. I, in pocket) were activated by the storm tides.

The myriad effects of Hurricane Allen on Padre Island and its environments followed closely the scenario of previous hurricanes described in this guidebook (p. 38-41). The beach, fore-island dunes, and associated features were modified extensively in places by the storm as it moved across the National Seashore, eroding, transporting, and depositing the loose sediments that compose the island.

Normal day-to-day processes involving waves, currents, and winds will slowly reconstruct most of the features modified by the storm. Locally, however, some changes produced by Hurricane Allen will remain. These changes, of course, are to be expected and are part of the overall evolution of the dynamic barrier island.

FIELD TRIP ROUTE

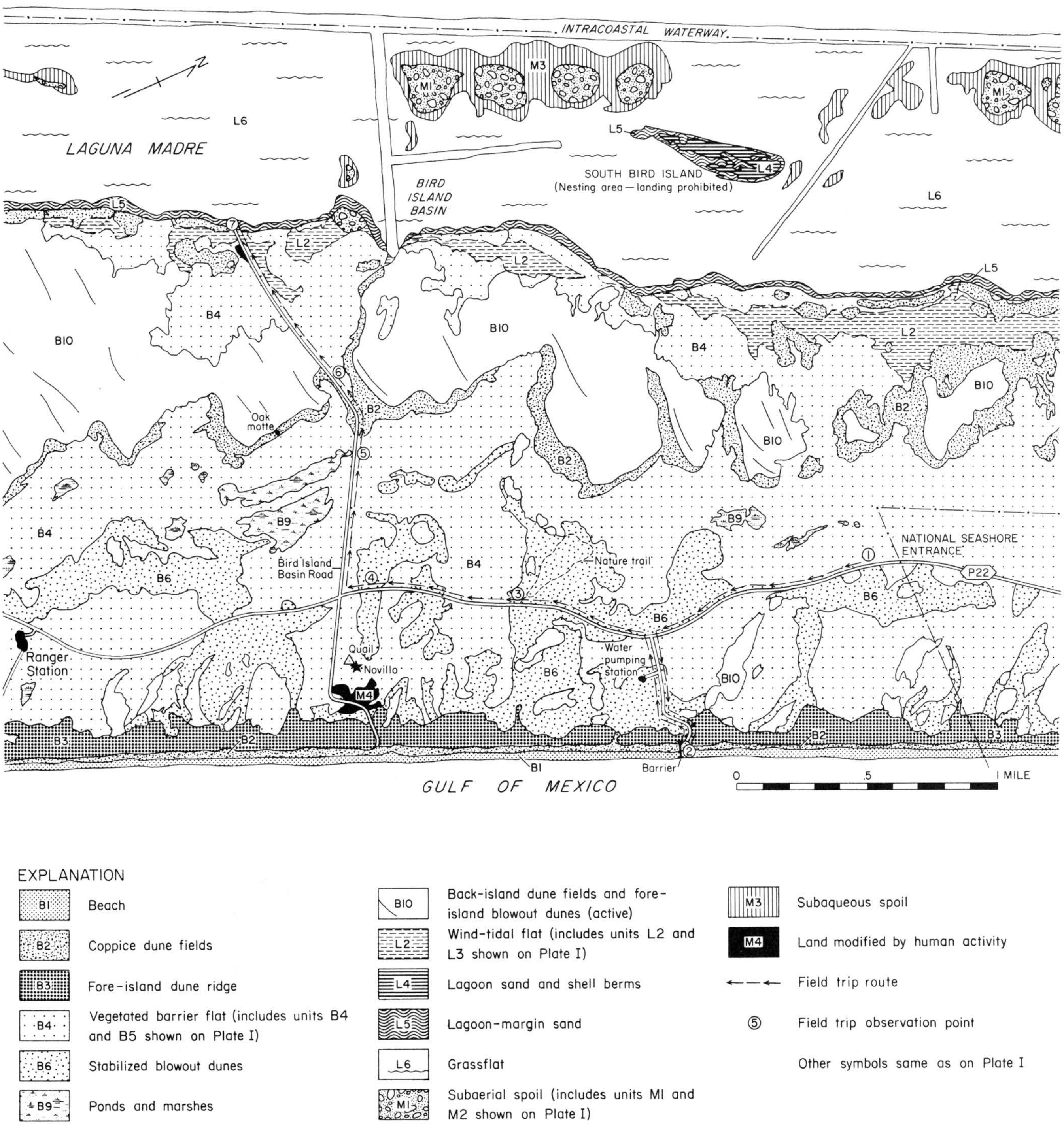


Figure 111. Route for north Padre field trip. Observation points are described in the Road Log.

MILEAGE		
Interval	Cumulative	
0.0	0.0	SEASHORE ENTRANCE (Observation Point 1). Begin the 5-mile field trip at the National Seashore entrance (fig. 112) by driving south on Park Road 22. This section of the trip is down the middle of the barrier island. For the first 0.4 mile, the grass-covered, hummocky terrain of stabilized blowout dunes (B6) can be seen on the left, adjacent to the highway. On the right is the gently sloping surface of a vegetated barrier flat (B4). At about 0.5 mile, the barren, white sands of an active blowout dune (B10) can be observed in the distance on the left. Farther down the highway, more stabilized blowout dunes are visible, this time on the right, and a vegetated barrier flat can be seen on the left.

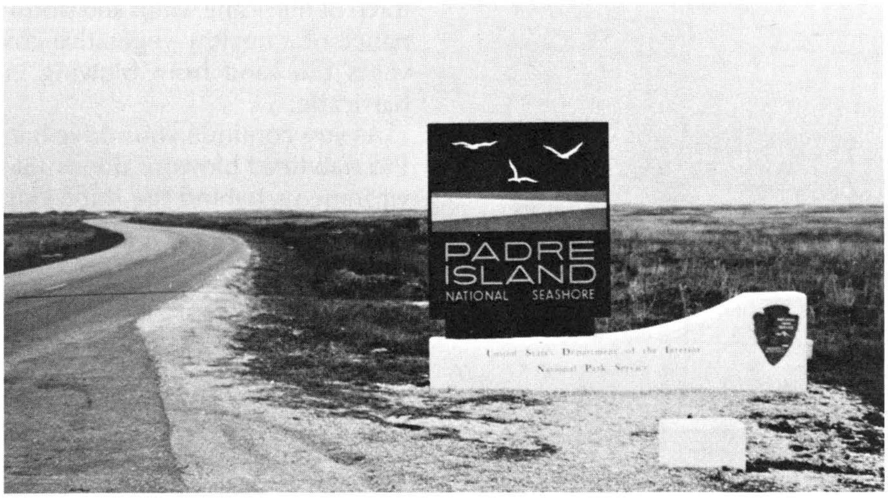


Figure 112. Padre Island National Seashore entrance on Park Road 22 (Observation Point 1). View is to the south.

0.9	0.9	NORTH BEACH ACCESS ROAD. Turn left onto the beach access road, pass the water pumping station on the right, and continue to the beach.
0.5	1.4	BEACH (Observation Point 2). The beach (B1) sediments on this part of Padre consist of fine sand with very little shell material. The profile (slope) of this beach is quite gentle (fig. 113) compared with the profiles of some central Padre beaches (fig. 75). The beach berm is low, and cusps, when present, are broad and widely spaced.

In 1968, the section of the beach between the north beach access road and the beach access road south of Malaquite was closed to vehicular

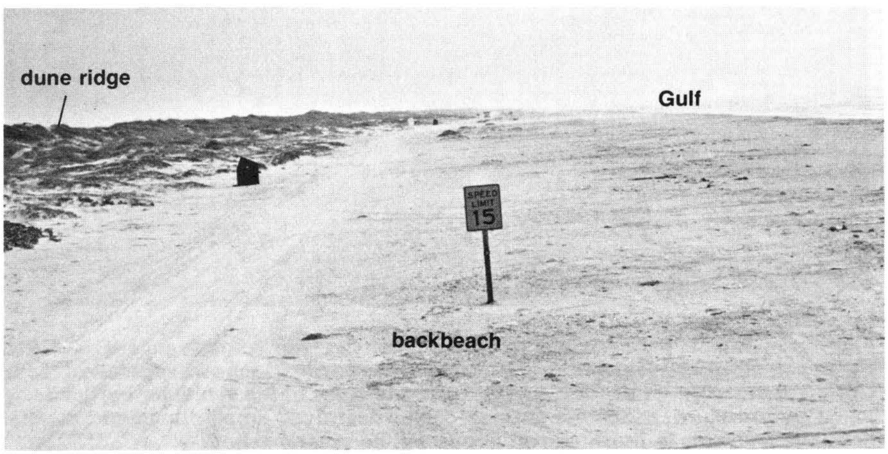


Figure 113. Beach at north beach access road (Observation Point 2). Northern Padre beaches such as this have very low berms and gentle profiles. View is to the northeast.

MILEAGE
Interval Cumulative

traffic. Before that time, the traffic had destroyed the vegetation in the backbeach area and endangered the vegetation of the protective fore-island dunes (B3). This lack of vegetation allowed the sand to blow about freely. When the beach was closed to traffic, vegetation began to recover, and it has now advanced gulfward. An aerial view of this area (fig. 114) shows the advance of vegetation on the closed section of the beach (left) as compared with that on the open beach to the north (right). Adequate vegetation has now been reestablished on the protected backbeach, allowing fairly large coppice dunes (B2) to form in and around vegetation clumps (fig. 65).

Begin your return to Park Road 22. A short distance after leaving the beach, you will pass between high dunes that are part of the fore-island dune ridge (B3). This dune ridge protects the barrier island from the full force of hurricane winds and storm surges that strike the Texas coast. Maintenance of a healthy vegetative cover on the dunes is important, as it prevents the sand from blowing inland and leaving gaps in this natural barricade.

As you continue your drive back to Park Road 22, you will pass through the stabilized blowout dunes (B6) and the vegetated barrier flat (B4) environments behind the dune ridge.

0.5 1.9 PARK ROAD 22. Turn left.

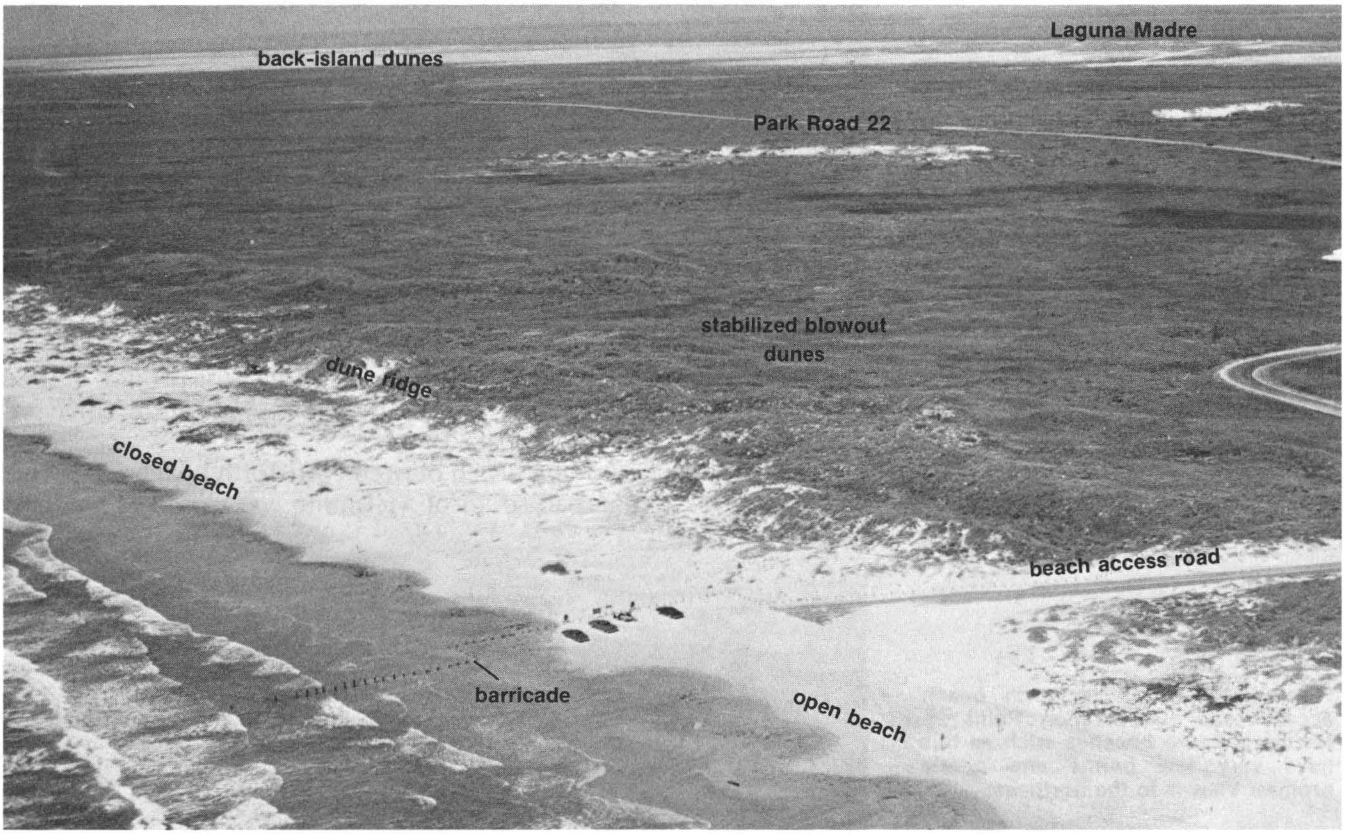


Figure 114. Effects of beach traffic on vegetation near north beach access road. At the time the photograph was taken, that part of the beach closed to vehicular traffic south of the barricade shows vegetation recovering on what was once a barren backbeach. Compare the width of the beaches on opposite sides of the vehicular barricade. View is to the southwest. The photograph was taken before Hurricane Allen (August 1980) destroyed small dunes and vegetation on the backbeach. With time, however, conditions similar to those shown above will be reestablished.

MILEAGE

Interval | Cumulative

0.5 | 2.4

GRASSLANDS NATURE TRAIL (Observation Point 3). As part of a nature study program, the National Park Service has established a short nature trail through the grasslands of north Padre. No special equipment or boots are necessary for hiking along this trail, which is indicated by a dashed line on figure 111 and on plate I. Most of the trail lies within the hummocky, grass-covered stabilized blowout dunes (fig. 115). The trail also passes near a small active blowout dune (B10) that remains barren because of trampling of vegetation by visitors straying from the trail (fig. 116). The dominant southeasterly winds cause the blowout dunes to migrate lagoonward.

Continuing southward down Park Road 22, you will pass through more stabilized dunes and a large expanse of vegetated barrier flat (fig. 81).

0.5 | 2.9

ARTIFICIALLY STABILIZED SAND (Observation Point 4). On either side of the road you may notice a cover of oystershells *(Crassostrea)* on the slopes of dunes that were cut when the road was constructed (fig. 117). The shells,

Figure 115. Trailhead of the Grasslands Nature Trail (Observation Point 3). The trail winds through hummocky, grass-covered, stabilized blowout dunes and also passes near a small, active blowout dune (fig. 116). View is to the west.

Figure 116. Barren, active blowout dune near the Grasslands Nature Trail. Pushed by the dominant southeasterly winds, this dune is migrating slowly toward the lagoon. View is to the west.

MILEAGE
Interval Cumulative

Figure 117. Shells of the oyster *Crassostrea*, dredged from nearby bays and placed on barren dunes on the east side of Park Road 22 to prevent loose sand from blowing across the highway (Observation Point 4).

dredged from nearby bays, have been placed there to prevent the barren sand in the road cut from blowing and reactivating these stabilized dunes. If the dune on the east (left) side of the road were reactivated, the dominant southeasterly winds would cause the dune to migrate across the road. This road maintenance problem is common in coastal dune areas.

0.2 3.1 BIRD ISLAND BASIN ROAD. As you approach the Bird Island Basin road, you will see in the distance on the left the facilities of one of the petroleum companies that is actively exploring for and producing oil and gas on the island. In addition, somewhat nearer Park Road 22, the corrals of one of the historic cattle line camps, Novillo, are visible. Such line camps were used by Pat Dunn in his ranching operation (fig. 83). Turn right onto Bird Island Basin road.

0.5 3.6 PONDS AND MARSHES (Observation Point 5). Linear wind-deflation (wind-eroded) troughs are left in the wake of back-island dune fields that are advancing lagoonward. Here on the wetter northern part of Padre, these troughs commonly become fresh- to brackish-water ponds and marshes, some of which may be seen on the south (left) side of the road (fig. 118). The troughs originate when the wind blows sand from barren areas during dry spells, deflating (eroding) the areas down to the water table. The system stabilizes during wetter spells. Alternating wet and dry periods cause a ridge-and-trough topography to develop as troughs are formed successively downwind. The troughs either are stabilized with

Figure 118. Marshy ponds occupying wind-deflation troughs (Observation Point 5). The few remaining trees of what was once a large live-oak motte are visible in the distance. View is to the southwest.

vegetation or may collect water as do the ponds and marshes seen here. Although these water bodies generally have a short lifespan, some may retain water for several years. Typical marsh plants that inhabit the wet areas include common cattail *(Typha domingensis)*, American bulrush *(Scirpus americanus)*, and spikerushes *(Eleocharis* sp.).

In the distance on the left, or south, side of the road is a live oak motte, or clump, of four or five trees (fig. 118). This small motte is all that remains of a much larger motte that once covered the area (Dahl and others, 1974). The trees occupy a wind-deflation flat (mapped as a sandflat, or unit B2, on plate I), which originated in the same way as the troughs occupied by the ponds and marshes. Large back-island dunes, which will be seen at Observation Point 6, migrated through the area, leaving the barren flats. Roots of the live oak trees were exposed (fig. 119) as wind eroded the sand around the trees, supplying it to the migrating dunes. These deflation flats are gradually being naturally revegetated with grasses.

Figure 119. Exposed roots of live oaks. Sand around the trees was eroded by wind and supplied to the back-island dune field seen at Observation Point 6.

0.3 3.9 BACK-ISLAND DUNES (Observation Point 6). On the left side of the road, large dunes (fig. 120), part of a back-island dune field (B10), may be observed. The largest, elongate dunes, with heights up to about 15 feet in this area (up to 25 feet in some other areas), are oriented in an east-west direction. When the photograph in figure 120 was taken, this dune was being shaped by the dominant southeasterly winds and was migrating northward toward the road (to the right in the photograph). However, the dune sand is blown toward the south during winter by strong north winds. The steepest face of the dune is the slipface, which maintains a slope of about 30° as the dune migrates downwind. Migration takes place when sand blown to the top of the dune slides down and adds to the slipface. Crossbedding resulting from this periodic addition of sand to the slipface may be later partially eroded and exposed in the deflation flat after the dune passes (fig. 59a and b). Refer to the *Internal Structure of Dunes* discussion (p. 33) in the section on *The Dynamic Barrier Island* for a

MILEAGE
Interval Cumulative

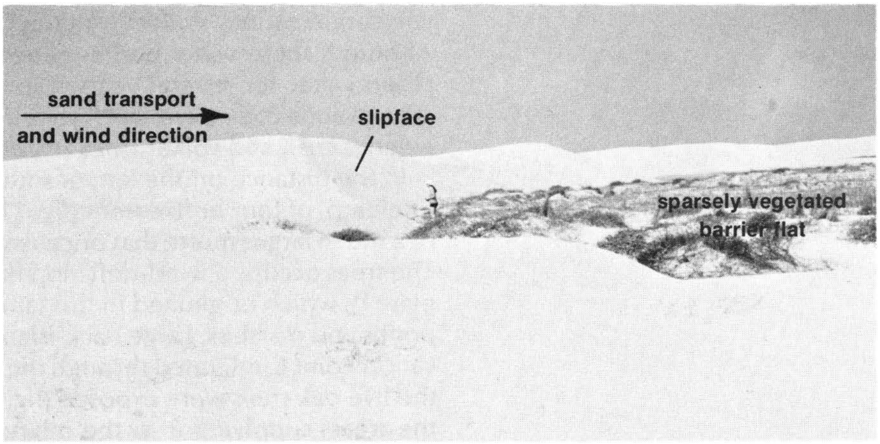


Figure 120. Large, elongate dune in a back-island dune field (Observation Point 6). View is to the southwest. When this photograph was taken, sand was being worked by the dominant southeasterly winds and was migrating northwestward (to the right). During the winter, however, this dune would be modified by strong north winds.

more detailed explanation of processes involved in dune and cross-bedding formation.

0.7 4.6 LAGUNA MADRE (Observation Point 7). Continue to the shore of Laguna Madre. Most of the broad, flat, barren areas at the edge of the island are wind-tidal flats covered with firm sand and mud (L2). These areas are flooded occasionally during high tides that are created by wind pushing lagoonal water into the back-island areas.

The sand belt exposed at the lagoon "beach" and submerged adjacent to it is called *lagoon-margin sand* (L5) (fig. 121). Sand waves and ripples commonly form in this shallow (less than 3 feet deep) environment by lagoonal current and wave action. Beyond the lagoon-margin sand are grassflats (L6), which constitute the darker subaqueous areas visible in figure 121. The grassflats are sites of high biologic productivity, serving as habitats for a variety of invertebrates and as nurseries or spawning grounds for many fish and crustaceans.

This trip has provided a look at characteristic environments from the Gulf beach to the lagoon shoreline and grassflats. Environments observed include (1) beach and coppice dunes, (2) fore-island dune ridge, (3) stabilized blowout dunes and vegetated barrier flat, (4) wind-deflation trough or flat, (5) back-island dune field, (6) wind-tidal flat, (7) lagoon-margin sand, and (8) subaqueous grassflats. The island cross section (fig. 2) illustrates the locations of these environments.

Figure 121. Grassflats, environments of very high biological productivity, lying in calm water just beyond the lagoon-margin sand (Observation Point 7). View is to the southwest. This photograph was taken during a high wind tide. During low tides, however, the entire width of lagoon-margin sand may be exposed (see fig. 98).

ACKNOWLEDGMENTS

The authors wish to thank many individuals and organizations who contributed to this guidebook. L. F. Brown, Jr., Associate Director of the Bureau of Economic Geology, initiated the project, reviewed the manuscript, and provided technical advice throughout the guidebook's completion. Robert J. Finley, David K. Hobday, Mary W. McBride, J. H. McGowen, Robert A. Morton, and Charles M. Woodruff, Jr., research geologists with the Bureau of Economic Geology, reviewed the manuscript and made many useful suggestions. Final review of the manuscript was by Debra L. Richmann. Cartography was by D. F. Scranton; illustrations were drafted by Margaret L. Evans under the direction of J. W. Macon, Chief Cartographer. The preliminary manuscript was edited and indexed by Eddie Selig. Final manuscript editing and indexing were by Michelle Pemberton. Becky P. Lasley assisted with final indexing. The Geology and Natural Environments Map (pl. I) was edited by Karen White and reviewed by Ann St. Clair. Charlotte J. Frere and Fannie M. Sellingsloh composed the manuscript and map explanation. Design and layout were by Judy Culwell and Judith Johnson. David Stephens printed text photographs.

Other staff members of the Bureau of Economic Geology who helped in manuscript preparation were manuscript typists Myrtle L. Bashara and Thomas W. Kelly, under the direction of Lucille Harrell; proofreaders Jane Hedgepeth, Becky P. Lasley, and Susan H. Shaw, and editors R. Marie Jones, Amanda R. Masterson, and Martha C. Wright, under the direction of Susann Doenges.

The authors express appreciation to staff members of the National Park Service for their cooperation and especially to Chief Naturalist Robert G. Whistler and Park Naturalist Rich Harris, for providing information about the National Seashore and reviewing preliminary copies of the map and text.

Several individuals of the General Land Office of Texas made valuable contributions, specifically H. E. White, Jr., Jesse Cox, Lloyd Mullins, and Jack Bowen, who provided aerial photographs, equipment, and field support.

Grateful acknowledgment is made to Barto Arnold and Curtis Tunnell of the Texas Historical Commission and to W. W. Newcomb, Jr., Professor of Anthropology, The University of Texas at Austin, for reviewing the historical section of the guidebook.

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GLOSSARY

The glossary below defines terms as used in this guide. Many of the definitions are modifications of those listed in the American Geological Institute's *Glossary of Geology,* edited by M. Gary, R. McAfee, Jr., and C. L. Wolf (1977), and in *Land Resources of Texas* by R. S. Kier, L. E. Garner, and L. F. Brown, Jr. (1977).

Accretion — The gradual extension of land by the deposition of sediment.

Active processes — Natural phenomena, commonly involving movements of water or the wind, that produce continuous or periodic changes in physical and biological environments.

Algal mat — A thin, matlike, and occasionally leathery layer of algae growing on a moist surface that is alternately emergent and submergent, such as a tidal flat.

Angle of repose — The maximum angle or steepness that can be naturally maintained by loose sand or other sediment on a stable slope.

Backbeach — The horizontal or gently landward-sloping part of the beach that is affected only by storm waves and extremely high tides and not by normal waves and tides. The backbeach includes the storm berm and lies between the crest of the berm and the point landward where there is a definite change in physiographic form, such as at a fore-island ridge.

Back-island dune field — A large area of nonvegetated, migrating sand dunes of various types, mostly large elongate dunes, found in the back, or lagoonward, side of a barrier island.

Back-island sandflat — A sandflat with scattered, small, migrating dunes, found on the lagoonward side of a barrier island and representing an environment transitional in characteristics between a large, active dune field and a tidal flat.

Backwash — The seaward return of water running down the forebeach following an uprush of waves.

Bar — An elongate, submerged, offshore ridge, bank, or mound of sediment, built up by the action of waves or currents.

Barchan dune — A moving, isolated, crescent- or horseshoe-shaped sand dune situated perpendicularly to the direction of the prevailing wind, with the horns (ends) of the crescent pointing downwind.

Barometric pressure — The pressure (force per unit area) caused by the Earth's atmosphere. Normal pressure at sea level is defined as 14.66 pounds per square inch or 29.92 inches (76.0 cm) of mercury.

Barrier flat — A relatively flat area, at least partially vegetated, located between the foredunes of a barrier island and the lagoon. Barrier flats generally originate as wind-eroded plains or wind-deflation flats.

Barrier island — A long, low, narrow island separated from the mainland by a lagoon and commonly having dunes, vegetated zones, and marshy environments extending lagoonward from the beach.

Barrier system — The group of geologic environments, primarily subaerial, that compose a barrier island.

Beach — The narrow strip of land immediately bordering a body of water; specifically the zone between the low-water line and the point landward where there is a definite change in physiographic form, such as at a fore-island dune ridge. The Gulf beach, like most beaches, is subdivided into a forebeach and a backbeach.

Beach cusp — Any of a series of low, crescent-shaped mounds or ridges of beach sediment built by wave action and separated by smoothly curved, shallow depressions, spaced generally at regular intervals along and at right angles to the shoreline.

Beach tar — A black, gummy asphalt formed from offshore natural oil seepage or from various hydrocarbon-based substances introduced into the ocean by man and subsequently washed ashore.

Berm — A low, nearly horizontal or landward-sloping bench or ridge on the backbeach, formed of sand and shell washed up and deposited by storm waves.

Berm crest — The gulfward edge of a berm, usually coinciding with the highest point of the berm and marking the break in slope between the berm and forebeach.

Blowout — A saucer- or trough-shaped depression formed by intense wind erosion of a dune or other sand deposit.

Blowout dune — A dune formed in association with a blowout. See *blowout.*

Brackish water — Water with a salinity between that of normal sea water and normal fresh water.

Breaker — A wave that becomes unstable, steepens, and breaks as it moves into shallow water, producing a mass of foam and turbulent water.

Calcareous — Containing calcium carbonate.

Canal — An artificial watercourse of relatively uniform dimensions, cut through an inland area to connect two or more bodies of water and designed for navigation.

Channel — (a) A watercourse; a natural passageway or depression through which water flows, forming a connecting link between two bodies of water. (b) An artificial waterway, such as a canal, generally constructed and maintained by dredging.

Channel-mouth bar — Sandbar deposited at the mouth (gulfward end) of a washover channel by strong ebb currents that are produced when lagoon water, swollen by storm surge, flows back to the Gulf after a storm. Channel-mouth bars also form at the mouths of other channels.

Cold front — The leading edge of an advancing cold air mass. The passage of a cold front is usually accompanied by a rise in pressure, a shift to northerly winds, a decrease in temperature, and precipitation.

Constructive waves — "Flat-crested" waves (waves having a low wave-height to wavelength ratio) that transport and deposit sediments onto the beach.

Coppice dune — A small mound of sand stabilized in and around a clump of vegetation.

Coquina — A sedimentary rock composed mostly of weakly to moderately cemented shells and shell fragments.

Crossbedding — An internal arrangement of layers in sediments or sedimentary rock, characterized by beds or layers that are inclined or sloping with respect to a horizontal plane.

Cyclone — A circular, atmospheric low-pressure system around which wind blows in a counterclockwise direction in the Northern Hemisphere and clockwise in the Southern Hemisphere.

Deflation scar — A barren flat produced by wind erosion of sand and finer material.

Delta — The low, nearly flat, triangular or fan-shaped body of sediment deposited at the mouth of a river, stream, or tidal inlet.

Desert pavement — A concentration of wind-polished pebbles or shells covering an area from which the sand has been removed by wind erosion (deflation).

Destructive waves — Steep waves (waves having high wave-height to wavelength ratios) that end in plunging breakers which in turn erode the beach and transport sediments gulfward.

Divide — The boundary between two adjacent drainage basins.

Dominant wind — The wind that has the greatest effect in transporting sediment in a given area, determined primarily by wind velocity and duration.

Dune — A mound, ridge, bank, or hill of loose, wind-blown material (generally sand). Dunes may be barren and thus capable of movement, or vegetated and stabilized.

Dune ridge — Same as *fore-island dune ridge*.

Dynamic — Characterized by active processes and conditions that produce continuous activity and change.

Ebb flow — Tidal current associated with an outgoing tide (a decrease in the height of an astronomical or a wind- or storm-generated tide). The direction of flow is generally seaward.

Ebb-tidal delta — Fan- or delta-shaped accumulations of sediment deposited by gulfward-flowing tides (ebb tides) at the gulfward end of a tidal inlet or channel.

Ecosystem — A unit in ecology consisting of the environment and the physical, chemical, and biological factors that exist in and affect it.

Environment — Surroundings characterized by a unique set of physical, chemical, and biological features, conditions, influences, or forces; for example, a vegetated barrier flat, hurricane washover channel, or wind-tidal flat.

Eolian — Of or relating to wind and its effects in eroding, transporting, and depositing sediments.

Ephemeral pond — Temporary pond.

Erosion — The process by which rock, sediments, and soil at the Earth's surface are loosened, dissolved, or worn away by natural agents, such as water and wind.

Evaporation — The process by which a substance passes from the liquid state to the vapor state.

Exotic plant species — Plants that do not occur naturally in an area but instead are brought in from other locations.

Eye (of a storm) — The roughly circular area (4 to 40 miles in diameter) of relatively light wind and calm weather in the center of a tropical cyclone.

Flood-tidal delta — Fan- or delta-shaped sediment accumulations deposited by flood currents (lagoonward-flowing tides) at the lagoonward end of a tidal inlet or channel.

Flotsam — The wreckage of a ship or its cargo found floating on the sea or washed ashore.

Forebeach — The seaward-sloping surface lying between the low-water line and the landward reach of wave uprush.

Foredune — A dune occurring at the landward margin of the beach and generally forming part of a fore-island dune ridge. See *fore-island dune ridge*.

Foredune ridge — Same as *fore-island dune ridge*.

Fore-island dune ridge — A ridge of dunes parallel to the shoreline of an ocean or gulf, occurring immediately landward of the beach and at least partially stabilized by vegetation.

Fractional scale — The numerical ratio between the linear distances on a map and the corresponding actual distances on the surface mapped. A fractional, or ratio, scale of 1:48,000 means that one unit on the map represents 48,000 of the same units on the ground.

Geographic north — Same as *true north*.

Graphic scale — A bar or line on a map, marked off in units such as feet, miles, or kilometers, that indicates the proportion between the linear distances on the map and the corresponding actual distances on the surface being mapped.

Grassflat — Shallow subaqueous environment of high biologic productivity, characterized by a dense growth of marine grasses and typically found in shallow areas of a lagoon.

Grassland — Land supporting a dense growth of grasses, such as the heavily vegetated barrier flat of a barrier island.

Groins — Long, rigid, man-made structures extending seaward from the shoreline and constructed for the purpose of blocking longshore currents and protecting the shoreline from erosion.

Heavy mineral — A rock-forming mineral generally having a specific gravity of 2.8 or greater.

High sea level — Average maximum level of the sea's surface during tidal cycles.

High tide — The highest point in the alternate rise and fall of sea level, which results from the gravitational attraction of the moon and sun and is modified by effects of the wind on the water surface.

Holocene — Same as *Recent*.

Hurricane — A tropical cyclone with sustained wind velocities greater than 74 miles per hour. See *cyclone*.

Index map — A map depicting the location of one or more smaller areas within a larger area and also indicating special features in the larger area.

Indigenous plant species — Plants that are native to (occurring naturally in) an area, rather than having been introduced by man.

Infrared photograph — A photograph produced by film that records wavelengths just beyond the red end of the visible spectrum, as well as certain wavelengths of visible light.

Jetsam — Cargo discarded from a ship and washed ashore.

Jetty — A man-made structure extending from the shore into a body of water that prevents natural filling of a navigable channel. Jetties are often built in pairs, with one extending from each side of the channel entrance.

Lagoon — A shallow body of water near the sea, partly or completely separated from it by a low, narrow strip of land, such as a barrier island.

Lagoon-center sand — The generally barren, muddy sand occupying the deeper, central parts of a lagoon.

Lagoon-margin sand — Barren sand, usually submerged, bordering a lagoon shoreline and characterized by sand waves and ripples.

Lagoon system — The group of geologic environments, primarily subaqueous, that compose a lagoon.

Landform — Any physical, recognizable form or feature of the Earth's surface having a characteristic shape and produced by natural causes; for example, a dune or tidal flat.

Latitude — Imaginary lines on the Earth's surface running east and west parallel to the Equator. Each line indicates locations that are an equal number of degrees north or south of the Equator.

Leeward — Downwind; facing away from the wind.

Light mineral — A mineral, such as quartz, that has a specific gravity of about 2.8 or less.

Line camp — A corral, or set of corrals, located along the line of a cattle drive and used to hold cattle temporarily.

Lithosphere — The solid part of the Earth that lies below the hydrosphere (the water on the surface of the Earth) and atmosphere (air surrounding the Earth).

Littoral drift — Same as *longshore drift*.

Location map — An index map showing the location of a specific feature or features or the location and outline of a smaller area within a larger area.

Longitude — Imaginary lines on the Earth's surface that extend north and south between the geographic poles. Each line indicates locations that are an equal number of degrees east or west from the Prime Meridian, which runs through Greenwich, England.

Longitudinal dune — A long, narrow sand dune, oriented parallel to the direction of the dominant dune-building winds, that is wider on the windward end, tapering to a point on the leeward end.

Longshore current — An ocean current created as waves approach and break at an oblique angle to the shoreline. Longshore currents flow parallel to and close to the shore.

Longshore drift — (a) The moving, or drifting, of material, such as sand and shell, caused by a current flowing near and parallel to a shoreline. (b) The material being moved by such a current.

Low tide — The lowest point in the alternate rise and fall of sea level, which results from the gravitational attraction of the moon and sun and which is modified by effects of the wind on the water surface.

Made land — Land built with artificial fill above water level for the primary purpose of creating new land area.

Magnetic declination — The horizontal angle between true north and magnetic north in any given location.

Magnetic north — The uncorrected direction indicated by the north-seeking end of the needle of a magnetic compass.

Map legend — A brief explanatory list of the symbols, map units, patterns, colors, and other features appearing on a map.

Map scale — An indication of the proportion between linear distances on a map and the corresponding actual distance on the surface mapped.

Map unit — One of the mappable features, such as a geologic environment, distinguished from other physical features in a mapped area on the basis of a unique set of characteristics and indicated on the map by a unique color, pattern, or symbol.

Maritime — Oceanic.

Marsh — Poorly drained area that is frequently flooded with fresh or salt water and that supports hydrophytes (plants that can grow partially submerged in water).

Matchline — The line marking the common boundary between two separate maps or map segments of adjacent areas and along which a map reader may mentally or physically join the two pieces to produce one continuous map.

Mean sea level — The average height of the surface of the sea for all stages of the tide during a 19-year period.

Modified land — Land, the natural environments of which have been changed by man, either purposely or inadvertently.

Motte — Thicket, grove, or clump of trees, such as a live oak *motte*.

Mud drape — A thin layer of very fine sediments settled from water and deposited on a surface when water turbulence is not great enough to maintain suspension, usually during the waning stages of a flood or in some low-energy aquatic environment.

Norther — A cold front marked generally by strong north winds. See *cold front*.

Oblique dune — A long, narrow sand dune similar to a longitudinal dune but oriented at an angle (usually slight) to the direction of the dominant dune-building winds.

Orthophotographic map — A map prepared from one or more photographs formed by a perspective projection in which the distortion due to relief and camera angle has been removed.

Packery — A meat-packing house.

Parabolic dune — A sand dune shaped like a parabola (or horseshoe), with its ends pointing upwind.

Pass — A channel, natural or artificial, connecting a body of water with the sea, for example, a narrow opening between two closely adjacent islands.

Patch reef — A small flat-topped organic reef forming a part of a reef complex.

Peninsula — An elongate body of land nearly surrounded by water but connected on one end with a larger land area.

Pirogue — A canoe made from a hollowed-out log.

Pleistocene — Geologic block of time that encompasses the "ice ages" or periods of glaciation during the Quaternary Period. More specifically refers to an epoch of the Quaternary Period, between the Pliocene of the Tertiary and the later Holocene of the Quaternary.

Presidio — A military post; a fort.

Prevailing wind — The wind direction that is recorded most frequently during a year.

Quartz — A mineral, usually colorless and transparent, and composed of silicon and oxygen (SiO_2), that constitutes most of the sand along the Gulf shoreline.

Radiocarbon date — The age of a rock or sediment determined by measuring the concentration of carbon-14 remaining in an organic material, such as a shell, contained in the rock.

Recent (Holocene) — An epoch of the Quaternary Period, extending from the end of the Pleistocene, when the last continental glaciers melted, into the present. Some researchers informally use 4,500 years ago as the final time boundary for the Holocene in the Gulf of Mexico and refer to the 4,500 years since as the Modern Epoch.

Reworked subaerial spoil — Dredged material originally deposited in a heap but later scattered and acted upon by wind, waves, or currents.

Ripple marks — A series of small, parallel ridges and troughs that resemble water ripples but are formed on the surface of sand or other sediment by the movement of wind or water.

Salinity — A measure of the concentration of salt or total dissolved solids. The amount of salt or dissolved solids in normal sea water is about 3.5 percent (35 parts per thousand or 35,000 parts per million).

Sand — Rock and mineral fragments ranging from 0.063 to 2 mm (0.0025 to 0.078 inch) in diameter.

Sandflat — A sandy plain devoid of vegetation.

Sand migration — Movement of sand by some natural agent such as the wind.

Sand wave — A relatively large, linear wave (sandbar) resembling a water wave but formed in sand by wind or water currents. Wave orientation is usually perpendicular to current direction.

Sediments — Rock, mineral, or organic particles deposited by agents such as water and wind.

Serpulid reef — A reef, usually a patch reef, built of the contorted calcareous tubes formed by annelid worms of the family Serpulidae.

Serpulid worm — An invertebrate belonging to the family Serpulidae that characteristically builds a contorted calcareous tube on a submerged surface. Serpulids are annelids (worms belonging to the phylum Annelida) and are characterized by a segmented body with a distinct head and appendages.

Shoreface — The relatively steeply sloping zone between the low-tide line of a shore and the more nearly horizontal surface of the offshore zone.

Shoreline — The intersection of the surface of a water body with the shore or beach.

Slipface — The steeply sloping surface on the lee side of a dune, standing at or near the angle of repose of loose sand, and advancing downwind by a succession of slides, or avalanches, wherever that angle is exceeded.

Specific gravity — The ratio of the mass or weight of a substance to the mass or weight of an equal volume of a standard substance — usually water. The specific gravity of quartz is about 2.6, which means that quartz weighs 2.6 times as much as an equal volume of water.

Spit — A low, narrow tongue of sand extending from a mainland shoreline and formed by the longshore drifting of sediments. See *longshore drift*.

Spit accretion — The building of a spit by longshore drifting of sediments. Spit accretion is often responsible for the building and extending of barrier islands in the direction of longshore currents. See *spit, longshore drift, longshore current.*

Spoil — Material excavated during dredging of channels in bays and lagoons or through land and commonly deposited nearby in heaps.

Spoil heap — A pile or mound of the material excavated during dredging operations.

Stabilize — To prevent loose sediment from being transported by wind or water, such as by binding and covering naturally with vegetation or by covering artificially with some material too heavy to be blown by the wind or moved by water.

Stabilized blowout dune — A blowout dune whose movement is arrested by the growth of vegetation. See *blowout dune*.

Storm runway — A linear flat or trough, usually produced by wind deflation and along which water flows during storms.

Storm surge — An abnormal, sudden rise of sea level along a coast during a storm. Onshore wind stresses and barometric pressure reduction result in water piling up against the shore as the storm hits land.

Strait — A relatively narrow waterway connecting two larger bodies of water.

Subaerial — Above water; emergent.

Subaqueous — Below the surface of the water; submergent.

Subaqueous spoil — Dredged material, presently below the water's surface, that has been deposited in a body of water, such as a lagoon. Subaqueous spoil usually has been reworked by waves and currents.

Substrate — (a) Rock or sediment below the soil zone. (b) Surface on which a fixed organism is attached.

Subtropical — Refers to the climate of the subtropics, falling between tropical (see *tropical*) and temperate climates and characterized by moderate or mild temperatures. A subtropical climate is more like the tropical than the temperate climate.

Surf zone — That part of the shoreface where waves break, located between the most seaward wave breakpoint bar and the lower part, or toe, of the forebeach where the waves begin their uprush.

Swale — A long, narrow, generally shallow trough-like depression between two ridges.

Swash — The uprush and backwash of waves on a beach.

Swash bars — Low, elongate bars of sand and/or shell formed along and parallel to the beach by wave swash; water is commonly trapped in narrow troughs landward of newly formed bars.

Swash zone — The sloping part of the forebeach that is alternately covered and uncovered by the uprush and backwash of waves.

Swell — Smooth, symmetrical, flat-crested waves that have traveled out of the area of the ocean where they were formed.

Terrigenous — Refers to material eroded from the land surface.

Texture (sediments) — The physical nature of sediments relating not only to particle size, but also to sorting, roundness, sphericity, and grain surface features.

Threshold velocity — The minimum wind or water current velocity necessary to initiate sediment movement. Threshold velocity varies as conditions such as sediment size vary.

Tidal flat — An extensive, nearly horizontal tract of land in a very low-lying coastal area that is alternately covered and uncovered with water by the rise and fall of the tide.

Tidal inlet — A narrow passage cutting into a shore and through which water flows landward with the rising tide and seaward with the falling tide.

Tornado — An intense, destructive storm of small diameter, characterized by a funnel-shaped cloud in which winds circulate at extremely high velocities.

Transpiration — A process whereby water absorbed by plants is evaporated into the atmosphere from the plant surface.

Transverse dune — A sand dune elongated perpendicularly to the direction of the dune-forming wind and having a gentle windward slope and a steep leeward slope.

Triangulation station — A point on the Earth's surface, the position of which is determined by means of bearings taken from two fixed points a known distance apart. Surveyed stations are usually permanently marked.

Tropical — Type of climate characterized by high temperature, high humidity, and abundant rainfall.

Tropical storm — A tropical cyclone with sustained wind velocities between 40 and 74 miles per hour. See *cyclone*.

True north — The direction from any point on the Earth's surface toward the geographic North Pole, or the northern point of intersection between the Earth's surface and axis of rotation.

Turbidity — Cloudy appearance of a fluid due to the presence of suspended material.

Vaquero — Spanish word for a cowboy in Spanish America and the Southwest.

Washover channel — Channel scoured through a barrier island or peninsula at a low, weak point during attack by storm waves and tides.

Washover fan — A fanlike body of sediment transported through or eroded from a storm washover channel and deposited at a point where the channel opens onto a broad flat.

Water table — Upper level or surface of ground water in an unconfined aquifer.

Wave breakpoint bars — Offshore submerged sandbars (usually numbering three on the Texas Gulf Coast) that parallel the shoreline and underlie the breaking point of waves.

Wave height — The vertical distance between the crest and trough of a wave.

Wavelength — The distance from one point on a wave (such as the crest or trough) to the corresponding point on the succeeding wave.

Wave steepness — A physical characteristic of a wave defined by the ratio of wave height to wavelength. Waves with high ratios (1/25 to 1/7) are considered steep compared with those with lower ratios (less than 1/100).

Wave tank — A laboratory tank in which waves are artificially generated for experimental purposes.

Wind deflation — A form of wind erosion in which loose, dry sand and finer material is removed from an area.

Wind-deflation flat — A barren, relatively flat area from which sand and other loose fine material has been removed, or eroded, by the wind.

Wind shadow — The area or zone on the downwind side of an obstacle where air motion is blocked or reduced by the obstacle. Sediment may accumulate in this area as a result of lower wind velocity and turbulence.

Wind-shadow dune — A dune formed on the downwind side of some obstacle. See *wind shadow*.

Wind-tidal flat — Tidal flat flooded primarily by wind tides. See *tidal flat* and *wind tide*.

Wind tide — A rise in water level on the downwind side of a body of water, such as a lagoon, caused by the force of wind on the water surface.

Wind tunnel — Man-made tunnel through which artificially generated wind is directed for experimental purposes, such as to observe the effect of wind velocity on sand migration.

Windward — Upwind; facing into the wind.

Wisconsin glacial stage — The fourth and last glacial stage of the Pleistocene Epoch in North America.

Zone of convergence (longshore drift convergence) — Stretch of shoreline along central Padre Island, near 27°N latitude, where southward- and northward-flowing longshore currents generally meet or converge.

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