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Natural Resource Stewardship and Science Directorate
Geologic Resources Division



Palo Alto Battlefield National Historical Park

Ancillary Map Information Document

Produced to accompany the Geologic Resources Inventory Digital Geologic Data
for Palo Alto Battlefield National Historical Park

paal_geology.pdf

Version: December 2012

Geologic Resources Inventory Map Document for Palo Alto Battlefield National Historical Park

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Geologic Resources Inventory Map Document



Palo Alto Battlefield National Historical Park, Texas

Document to Accompany Digital Geologic-GIS Data

[paal_geology.pdf](#)

Version: December 2012

This document has been developed to accompany the digital geologic-GIS data developed by the Geologic Resources Inventory (GRI) program for Palo Alto Battlefield National Historical Park, Texas (PAAL).

Attempts have been made to reproduce all aspects of the original source products, including the geologic units and their descriptions, geologic cross sections, the geologic report, references and all other pertinent images and information contained in the original publication.

National Park Service (NPS) Geologic Resources Inventory (GRI) Program staff have assembled the digital geologic-GIS data that accompanies this document.

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About the NPS Geologic Resources Inventory Program

Background

Recognizing the interrelationships between the physical (geology, air, and water) and biological (plants and animals) components of the Earth is vital to understanding, managing, and protecting natural resources. The Geologic Resources Inventory (GRI) helps make this connection by providing information on the role of geology and geologic resource management in parks.

Geologic resources for management consideration include both the processes that act upon the Earth and the features formed as a result of these processes. Geologic processes include: erosion and sedimentation; seismic, volcanic, and geothermal activity; glaciation, rockfalls, landslides, and shoreline change. Geologic features include mountains, canyons, natural arches and bridges, minerals, rocks, fossils, cave and karst systems, beaches, dunes, glaciers, volcanoes, and faults.

The Geologic Resources Inventory aims to raise awareness of geology and the role it plays in the environment, and to provide natural resource managers and staff, park planners, interpreters, researchers, and other NPS personnel with information that can help them make informed management decisions.

The GRI team, working closely with the Colorado State University (CSU) Department of Geosciences and a variety of other partners, provides more than 270 parks with a geologic scoping meeting, digital geologic-GIS map data, and a park-specific geologic report.

Products

Scoping Meetings: These park-specific meetings bring together local geologic experts and park staff to inventory and review available geologic data and discuss geologic resource management issues. A summary document is prepared for each meeting that identifies a plan to provide digital map data for the park.

Digital Geologic Maps: Digital geologic maps reproduce all aspects of traditional paper maps, including notes, legend, and cross sections. Bedrock, surficial, and special purpose maps such as coastal or geologic hazard maps may be used by the GRI to create digital Geographic Information Systems (GIS) data and meet park needs. These digital GIS data allow geologic information to be easily viewed and analyzed in conjunction with a wide range of other resource management information data.

For detailed information regarding GIS parameters such as data attribute field definitions, attribute field codes, value definitions, and rules that govern relationships found in the data, refer to the NPS Geology-GIS Data Model document available at: <http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm>

Geologic Reports: Park-specific geologic reports identify geologic resource management issues as well as features and processes that are important to park ecosystems. In addition, these reports present a brief geologic history of the park and address specific properties of geologic units present in the park.

For a complete listing of Geologic Resource Inventory products and direct links to the download site visit the GRI publications webpage http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

GRI geologic-GIS data is also available online at the NPS Data Store Search Application: <http://irma.nps.gov/App/Reference/Search>. To find GRI data for a specific park or parks select the appropriate park (s), enter "GRI" as a Search Text term, and then select the Search Button.

For more information about the Geologic Resources Inventory Program visit the GRI webpage: <http://www.nature.nps.gov/geology/inventory>, or contact:

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The Geologic Resources Inventory (GRI) program is funded by the National Park Service (NPS) Inventory and Monitoring (I&M) Division.

GRI Digital Map and Source Map Citations

The GRI digital geologic-GIS map for Palo Alto Battlefield National Historical Park, Texas (PAAL):

GRI Digital Geologic Map of Palo Alto Battlefield National Historical Park and Vicinity, Texas (GRI MapCode PAAL)

Brown, L.F., Brewton, J.L., Evans, T.J., McGowen, J.H., White, W.A., Groat, C.G., and Fisher, W.L. with cartography by Hartmann, B., Scranton, D.F., and Macon, J.W., 1980, Environmental Geology Sheet, Environmental Geologic Atlas of the Texas Coastal Zone - Brownsville-Harlingen Area, Bureau of Economic Geology, The University of Texas at Austin, 1:125,000. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

** Only a portion of the Environmental Geologic Atlas of the Texas Coastal Zone - Brownsville-Harlingen Area map was used for the GRI digital geologic map.

Caran, S.C., McCulloch, S.D., and J. Jackson, 2005, Report on a Geoarchaeological Investigation at the Palo Alto Battlefield National Historic Site (41CF92) Cameron County, Texas, McCulloch Archaeological Services, order no. p73500-40016, report number 1. ([Geoarchaeological Investigation](#)). (GRI Source Map ID 74983).

** The report was used to generate geologic sample localities in the GRI digital geologic map.

Additional information pertaining to each source map is also presented in the GRI Source Map Information (PAALMAP) table included with the GRI geology-GIS data.

Map Unit List

The geologic units present in the digital geologic-GIS data produced for Palo Alto Battlefield National Historical Park, Texas (PAAL) are listed below. Units are listed with their assigned unit symbol and unit name (e.g., Qya - Alluvium, undivided). Units are listed from youngest to oldest. No description for water is provided. Information about each geologic unit is also presented in the Geologic Unit Information (PAALUNIT) table included with the GRI geology-GIS data.

MODERN-HOLOCENE SYSTEMS

[water](#)

Artificial Units

[Hml](#) - Made Land

[Hsr](#) - Reworked spoil, subaerial

[Hsae](#) - Spoil, subaerial

[Hsaq](#) - Spoil, subaqueous

Bay-Estuary-Lagoon System

[Hblv](#) - Berm, vegetated

[Hble](#) - Berm, occasionally emergent

[Hg](#) - Grass flat

[Hbls](#) - Bay and lagoon sand

[Hblm](#) - Bay and lagoon mud

[Hw](#) - Wind-tidal flat, rarely flooded

[Hwa](#) - Wind-tidal flat, algal mats, emergent-submergent

[Htz](#) - Transitional zone

Barrier-Standplain and Offshore System

[Hs](#) - Shelf mud

[Hsb](#) - Shoreface

[Hb](#) - Beach

[Hfi](#) - Fore-island

[Hsf](#) - Sand flats

[Hwc](#) - Washover distributary channel

[Hwf](#) - Washover fan

[Hwd](#) - Washover distal fan

[Htc](#) - Tidal channel

[Hi](#) - Inlet-related shoal

Fluvial-Deltaic System

[Hls](#) - Levee and local crevasse splay deposits

[Hms](#) - Meander belt

[Hds](#) - Distributary sands and silts

[Hfe](#) - Flood basin

[Hf](#) - Flood basin grading to interdistributary mud

[Hmf](#) - Fresh-water marsh

PLEISTOCENE SYSTEMS

Fluvial-Deltaic System

[HPEa](#) - Abandoned channel

[HPEcl](#) - Coastal lake or pond

[HPEda](#) - Gavilans (clay-sand dunes)

[HPEdi](#) - Clay-sand dune complexes

[HPEss](#) - Sand sheets

Map Unit Descriptions

Descriptions of all geologic map units, generally listed from youngest to oldest, are presented below.

water (Modern)

Extent of water in 1980 ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hml - Made land (Modern)

Made land occurs adjacent to the boat basins at Port Mansfield (fig. 13) and Port Isabel and along almost 6 miles of the western side of the southernmost part of South Padre Island (fig. 18). A narrow manmade dike extends across Bahia Grande. A total of 1.6 square miles of made land was mapped. Extensive development in the Port Isabel and South Padre Island area since 1970 has slightly increased the total area of made land on the Brownsville-Harlingen Map. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hsr, Hsae, Hsaq - Spoil: reworked, subaerial, or subaqueous (Modern)

Approximately 30 square miles of spoil occur in the Brownsville-Harlingen map area. Most of the spoil has been derived from the original excavation and maintenance of the Intracoastal Waterway, which extends the entire length of Laguna Madre, and of the interconnected ship channels: Port Mansfield Channel, Arroyo Colorado Cutoff, Brownsville Ship Channel, and Port Isabel Ship Channel (figs. 18, 19, 22, and 24). Some spoil deposits lie along small channels dredged into shallow water and wind-tidal flats to provide access to oil and gas well drill sites.

Common practice is to pile dredged sediment from the channels along the margin of the cut. The natural environment is altered not only by the cut or channel but also by the discharge of disposed dredge sediments. Dredged spoil is reworked and redistributed by natural processes. On the wind-tidal flats and the coastal plain, the spoil is eroded and redeposited mainly by rainfall sheetwash and, within Laguna Madre, by currents and waves. The area of wind-tidal flat and lagoon bottom that is covered by spoil is, therefore, increased markedly. Piling of spoil into mounds and ridges on the wind-tidal flats creates local artificial relief; on the lagoon bottom, it serves as a partial dam to current circulation. On the wind-tidal flats, spoil heaps and reworked subaerial spoil have been dissected by gullies, and small alluvial fans have developed where the gullies discharge onto the flat. The ridge of the subaerial and subaqueous spoil and the Intracoastal Waterway has effectively subdivided Laguna Madre into several major compartments.

The three kinds of dredged spoil mapped on the *Environmental Geology Map* are subaerial spoil heaps or mounds (6.8 square miles), subaerial reworked spoil (8.6 square miles), and subaqueous bay-bottom spoil (16 square miles). Subaqueous spoil distribution is based on navigational and topographic map data. Subsequent dredging and disposing operations coupled with reworking of spoil by storms undoubtedly has increased the distribution of both subaerial and subaqueous spoil. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hblv, Hble - Berm: vegetated or occasionally emergent (Holocene-Modern)

Along the mainland shore and locally along the lagoonward side of Padre Island, environments mapped as *subaerial bay- or lagoon-margin sand and shell berms* occupy about 2 square miles (figs. 14 and 24). More detailed investigations since the *Environmental Geology Map* was printed suggest that Deer Island, Los Bancos de en Medio (located about 3 miles south of Deer Island), and Green Island have different origins than bay- or lagoon-margin sand and shell berms mapped along the mainland. Mainland berms, formed by the action of storm waves and currents, are generally narrow, elongate features 2 or 3 feet above mean sea level. The area just south of Port Mansfield is an exception; it is a relatively broad bay-margin feature 5 feet above mean sea level. Some of the mainland berms are relict and most actively accrete only during storms when high-energy waves are generated by northern or southeastern wind regimes (fig. 8). Price and Kornicker (1961) have reached similar conclusions concerning the origin of shell berms in Laguna Madre. Several of the berms in the Brownsville-Harlingen area, such as those east and south of Rattlesnake Island, however, are probably no longer actively accreting. Construction of islands and shoals from dredged spoil along the Intracoastal Waterway has reduced the fetch of predominant winds blowing across Laguna Madre, thereby reducing the wave energy impinging on the berms. No longer actively accreting, these berms are likely to be eroded and incorporated into adjacent wind-tidal flats or subaqueous lagoon-margin sand. The berm mapped in Bahia Grande has probably accreted, in part, through eolian processes, which are active when wind-tidal flats to the southeast are dry and thereby provide a deflationary source of sediment for prevailing southeasterly winds. The berm near Gabrielson Island has been built up across the mouth of the wind-tidal flats that extend lagoonward from Stover Cove. The berm apparently accumulated during storms when abnormally high waves and currents carried sand and shell along shore from adjacent erosional areas. Successive building of storm berms gradually accreted or extended the shoreline in local areas. Small areas of salt-water marsh may occur behind and along the bay-and lagoon-margin berms. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hg - Grass flat (Holocene-Modern)

In the Brownsville-Harlingen map area, subaqueous marine plants (spermatophytes) compose the *grassflat environment* that underlies almost 160 square miles of Laguna Madre and South Bay. Grassflats occur as subaqueous lagoon-margin and lagoon-center environments. They compose almost 8 percent of the total map area and about 65 percent of the subaqueous area in the bay-estuary-lagoon system. These shallow (less than 4 feet deep) environments occupy broad subaqueous flats extending the length of Laguna Madre in the map area. The grasses are sparse or absent primarily along some shallow lagoon margins and in deeper bay center areas such as in Redfish Bay (fig. 24). Substrates in which the grasses are rooted vary from sand and muddy shelly sand to muddy sand and sandy mud.

Five species of marine grass occur in Laguna Madre and South Bay: *Halodule (Diplanthera) wrightii* (shoalgrass), *Cymodocea manatorum* (manatee-grass), *Ruppia maritima* (widgeongrass), *Thalassia testudinum* (turtlegrass), and *Halophila engelmannii* (clovergrass). *Halodule* and *Cymodocea* are the two most common grasses, occurring over much of the total grassflat environment. *Thalassia* is relatively rare, growing primarily at the south end of Laguna Madre and in South Bay. *Halophila* occurs sparingly in various parts of the lagoon, and *Ruppia* occurs primarily along the Intracoastal Waterway north of Three Islands. Sample transects across Laguna Madre (McMahan and others, 1965-67) indicate the occurrence of locally dense communities within widespread areas inhabited by less dense vegetation. Variations in the density of marine grass communities occur seasonally; maximum growth occurs during spring and summer months, and growth is essentially static during fall and winter.

McMahan and others (1965-67) and McMillan and Moseley (1967) have indicated general salinity limits for various marine grass species. McMahan (1968), in a study of *Halodule* and *Cymodocea* in lower

Laguna Madre, found that *Halodule* tolerates salinities between 3 and 70‰, optimum salinities being 44‰. *Cymodocea* was found to be less tolerant of salinity, its optimum salinity being 35‰ and lethal salinities being slightly over 50‰. Chin (unpublished manuscript), referring to a study by McMillan and Moseley (1967), ranked the various grasses according to hypersalinity tolerance from most tolerant to least tolerant: *Halodule*, *Thalassia*, *Ruppia* and *Cymodocea*. Studies of *Halophila*'s tolerance were inconclusive, but it is suspected to be between *Halodule* and *Cymodocea*.

Studies of grass distribution in lower Laguna Madre (for example, Breuer, 1962; and McMahan, 1966) indicate an expansion of grassflats toward the north in lower Laguna Madre; *Cymodocea* is encroaching into areas previously vegetated by *Halodule*. McMahan (1968) views the expansion of *Cymodocea* at the expense of *Halodule* as a possible undesirable occurrence in the ecosystem because *Halodule* is important as a food for waterfowl and as a spawning ground for fish.

Chin (unpublished manuscript) conducted a detailed analysis of the distribution of marine grasses over an approximate 17-mile segment of Laguna Madre centered roughly on the mouth of the Arroyo Colorado Cutoff. The five previously mentioned marine grasses, with the exception of *Thalassia*, were present in this area in 1977 when the sampling was conducted. A comparison of the distribution of grasses found in 1977 with earlier studies revealed significant changes in species distribution and density including (1) an overall expansion of the grassflat environment; (2) a reduction in the distribution and density of *Halodule* and *Ruppia*; and (3) an increase in the distribution of *Cymodocea*, making it a codominant species with *Halodule*. Chin speculated that conditions contributing to the expansion of the grassflat environments included (1) establishment of a relatively stable physical setting (as previously reported by other researchers) with regard to such factors as salinity and circulation, caused partly by the construction of the Intracoastal Waterway and Port Mansfield Channel and a reduction of fresh-water inflow from mainland streams; and (2) natural subsidence from compaction of sediments (Fisk, 1959) resulting in a relative sea-level rise, a corresponding areal expansion of submerged environments, and a more effective wind-tidal regime. Expansion of marine grasses as a result of relative sea-level rise has also been reported in north Laguna Madre (White and others, 1978a).

Algae, such as leafy calcareous *Acetabularia*, thrive within some of the grassflats. A variety of fish and invertebrates, especially arthropods, spawn within the grassflat environment, where there is food and protection for larvae and fingerlings. The grassflat environment is the habitat of a large number of mollusks, such as the pelecypods (clams) *Cumingia*, *Tellina*, *Tagelus*, and *Mysella* and the gastropods (snails) *Bittium*, *Caecum*, and *Mitrella* (McGowen and others, 1977). As in bay-margin areas, a large part (57 percent) of the molluscan assemblages collected in grassflat areas between La Punta Larga and Mullet Island (McGowen and others, 1977) was composed of dead shells of *Anomalocardia*. Only a few live specimens of *Anomalocardia* were collected. The composition of the molluscan assemblage changes from south to north in Laguna Madre with increasing distances from the tidal influence of Brazos Santiago Pass.

The grassflat environment exhibits very high biologic productivity, as evidenced partly by its contributing large amounts of biomass to the ecosystem—a role occupied by the extensive marsh system along the upper Gulf coast. It is also an environment that is tenuously balanced by such conditions as salinity, turbidity, and water depth. The dynamic nature of this highly productive yet sensitive environment makes it a critical unit in the Brownsville-Harlingen area. An increase in turbidity resulting from spoil disposal or other man-induced development may be sufficient to destroy or severely restrict the grassflat environment. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

HbIs - Bay and lagoon sand (Holocene-Modern)

Bay- or lagoon-margin sands occupy 6.6 square miles of the map area. This shallow (1 to 3 feet) environment becomes emergent periodically because of radically fluctuating wind tides in Laguna Madre. Lagoon-margin sands occupy a narrow fringe along the landward side of the lagoon, extending from Port

Isabel along the south and southwestern lagoon margins (fig. 18) northward to the Arroyo Colorado Cutoff. Locally these marginal environments are replaced by marine grassflats. Grassflats are the predominant subaqueous lagoon-margin environment in the sand-deficient area between the Arroyo Colorado Cutoff and a point about 2 miles north of Mullet Island. North of this point, a narrow fringe of lagoon-margin sand borders the mainland shore. Lagoon-margin sands occur along Padre Island just north of Brazos Santiago Pass. North of this area, the island's lagoon margin is characterized by marine grassflats and by bay and lagoon muddy sand.

Detailed sampling of lagoon bottom sediments (McGowen and Morton, 1979) shows that areas along the mainland shore mapped as lagoon-margin sand on the *Environmental Geology Map* of this Atlas have a relatively high mud content. Much of the mainland lagoon-margin environment can be classified as a muddy sand and sandy mud between Laguna Vista Cove and Mullet Island. This contrasts with the lagoon margin along Padre Island, which is predominantly sand.

Bay- and lagoon-margin sands are derived principally from eroded Modern-Holocene deposits along the mainland shore. Longshore transport along the lagoon shoreline (fig. 8) continually redistributes the winnowed sediment. Onshore waves generated by southeasterly and northerly winds move the sand landward into shallow subaqueous bars and berms. Lagoon-margin sands along Padre Island are derived from sediment transported across the island by storm-surge tides and eolian processes. Toward the lagoon, the sandy, relatively high-energy environment grades into the broad, shallow, low-energy grassflats underlain by sand, muddy sand, and shell. ([Environmental Geologic Atlas](#)). (*GRI Source Map ID 68689*).

Hblm - Bay and lagoon mud (Holocene-Modern)

The bay and lagoon muddy sand substrates cover approximately 22 square miles in the Brownsville-Harlingen map area, where they occur primarily as lagoon-margin environments in Laguna Madre and South Bay. This environment is restricted to areas of low wave and current energy and locally supports sparse marine grass. In Laguna Madre, the muddy sand substrate occurs primarily along the margin of Padre Island, and a relatively wide band parallels the broad wind-tidal flats north and south of Port Mansfield Channel (fig. 22). This area of relatively low wave energy is partly shielded from southeasterly and northerly winds. Sand is contributed from across the island by storm surge and by southeasterly winds.

Between the Arroyo Colorado and Fourmile Slough, bay and lagoon muddy sand occurs in relatively narrow sinuous channels that are mostly restricted from Laguna Madre by broad wind-tidal flats. The channels connect to mainland drainage systems that, under normal conditions, contribute negligible amounts of fresh-water inflow. In recent years, marshes have become established along the channels. These restricted low-energy inlets may have evolved from relict channels that were associated with once-active delta distributaries. In South Bay, muddy sand substrates underlie much of the shallow bay area. The muddy sand environment grades lagoonward into grassflats (figs. 22 and 24); water depths are generally less than 3 feet.

The sedimentary substrate within this environment is variable. Recent sampling of lagoon sediments (McGowen and Morton, 1979) shows this unit has a much higher mud content in South Bay and in the area between the Arroyo Colorado and Fourmile Slough than along the margin of Padre Island where it is predominantly sand. The sediments are mixed by burrowing organisms, including clams. Recent preliminary studies of molluscan distribution in Laguna Madre (McGowen and others, 1977) indicate that live mollusks are more abundant in a mixed substrate of mud and sand and shell than in a substrate composed predominantly of one sediment type such as sand. Because marine grasses grow to the edge of Laguna Madre in much of the map area, it is difficult to identify a unique molluscan assemblage that is characteristic of the marginal muddy sand environment. Analysis of a few samples (Calnan and

others, in progress) taken from the margin of the lagoon along Padre Island between Brazos Santiago Pass and La Punta Larga show a live mollusk community that includes the clams *Laevicardium*, *Chione*, and *Anadara*. The occurrence of *Laevicardium* in these samples corresponds to Parker's (1959) findings that *Laevicardium* seems to characterize the sandier substrates along Laguna Madre in the open lagoon environment. Preliminary investigations (McGowen and others, 1977) of mollusks collected in samples along Laguna Madre's east and west margins farther north (the segment of the lagoon that lies approximately between La Punta Larga and Mullet Island) show the occurrence of a live clam population characterized by *Mulinia*, *Tellina*, *Tagelus* and *Ensis*, *Ensis* being the only species collected exclusively in margin sediments. The bulk of the mollusk shells collected, however, was composed of dead shells of the clam *Anomalocardia*, which accounted for 86 percent of the total fauna (from bay-margin samples). The fact that *Anomalocardia* constituted only 2.5 percent of the live clam assemblage collected suggests that its decline was caused by a change in conditions in Laguna Madre—perhaps related to the reduction in average salinity coincident with dredging of the Intracoastal Waterway and Port Mansfield Channel. *Anomalocardia* apparently is characteristic of a hypersaline environment (Simmons, 1957; and Parker, 1959).

In South Bay, where a relatively wide muddy sand substrate surrounds a central area of grassflats, the live molluscan assemblage (including those collected from grassflats) is characterized by the clams *Chione*, *Macoma*, *Mulinia*, *Anadara*, *Laevicardium*, and others (Calnan and others, in progress). The presence of some of these species (for example, *Anadara* and *Chione*) suggests that the area is influenced by Brazos Santiago Pass. Unique in the South Bay area is the oyster *Crassostrea*, which has been commercially harvested (Breuer, 1962). South Bay contains the only significant occurrence of *Crassostrea* south of Corpus Christi Bay. Breuer (1962) suggests that these particular oysters may be a "new physiological race" that has become adapted to higher-than-normal salinities (in excess of 40‰). ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hw, Hwa - Wind-tidal flat: rarely flooded or algal mats, emergent-submergent (Holocene-Modern)

Broad, flat, barren, virtually featureless *wind-tidal flats*, generally less than 3 feet above MSL, occur along lagoon margins adjacent to both the mainland and South Padre Island (see *Environmental Geology Map* and figs. 21 and 22). These wind-tidal flats are frequently inundated by lagoonal waters that are driven by the wind—wind tides. Wind-tidal flats adjacent to the mainland are irregularly shaped and are patchily distributed; width of these flats ranges from about 0.1 mile to 7 miles. On the mainland side of Laguna Madre, the wind-tidal flats are developed upon the subsiding Holocene Rio Grande delta plain; two areas of maximum development are in the vicinity of Arroyo Colorado and the South Bay-Bahia Grande area. Sediment that underlies the wind-tidal flats that abut the mainland is mostly clay and silt derived from ephemeral streams that drain the mainland, from erosion of clay dunes that occur along the flats, and from Laguna Madre. Wind-tidal flats associated with South Padre Island range from about 0.2 mile to 4 miles wide and form a continuous band about 39 miles long. Sediment supplied to the flats associated with South Padre Island is derived from the shoreface, beach, and dune areas and is transported to the flats by hurricane storm surge and by the prevailing southeast winds. Studies by Price (1958), Fisk (1959), and Zupan (1970) have provided data on sedimentary processes and sediment characteristics of these environments.

A spectrum of wind-tidal flats occurs in the Brownsville-Harlingen area: from high, predominantly firm, sand flats that are rarely flooded, to soft, frequently wet, mud and sand flats that occupy depressed relief. Four environments compose the spectrum of wind-tidal flats. The two most extensive environments occur along the mainland and island margins of Laguna Madre as well as near and inland from South Bay. These two wind-tidal flat environments—(1) composed predominantly of *firm sand and mud flats* which extend from frequently flooded low elevations to higher elevations where inundation is comparatively rare, and (2) composed of *sand and mud flats that are alternately emergent-submergent*,

contributing to the development of extensive algal mats—together occupy about 160 square miles in the Brownsville-Harlingen area and compose 95 percent of the wind-tidal flat spectrum. The remaining two wind-tidal flat environments occur only on the mainland side of Laguna Madre in the area between the Arroyo Colorado Cutoff and Texas Highway 186. These two wind-tidal flats—(1) composed of *firm gypsiferous mud and sand with algal-bound mud*, and (2) composed of *soft mud and sand with extensive algal mats that are frequently wet* because of locally depressed relief—together cover less than 10 square miles of the map area and constitute only 5 percent of the wind-tidal flat spectrum. Recent aerial photographs of these two wind-tidal flat environments show a substantial development of marsh vegetation particularly in association with the depressions that frequently pond water.

Wind-tidal flats are flooded rapidly, mostly by wind-driven water, but flooding may also result from a drop in barometric pressure. Flooding of the mainland flats occurs when winds blow from the southeast and when north winds accompany polar fronts. Flats associated with South Padre Island are similarly flooded by north winds and by south and south-southeast winds. East and southeast winds drive water off the flats, thereby exposing the flats to the atmosphere.

The higher or upper wind-tidal flats are less frequently flooded than are the middle and lower flats. Mainland wind-tidal flats and many of the flats associated with South Padre Island are higher flats. Strong north winds drive lagoonal waters onto these flats, and the upper flats on South Padre Island are frequently inundated to the back-island dunes. Uppermost flats (elevations 3 to 5 feet above MSL) on the landward side of Laguna Madre are rarely flooded. Sediments underlying the upper flats on South Padre Island are composed of sands and shelly sands that are massive to parallel laminated with rare algal-bound mud units. Sediments above the water table are brown, whereas sediments below the water table are green. Much of the wind-tidal flat sediment is structureless (primary sedimentary structures have been destroyed) because air that is trapped in the sediment locally expands, thereby creating cavities as the flats are inundated by wind tides. Comparable flats adjacent to the mainland contain much more mud than do the flats associated with South Padre Island. When initially deposited, the muddy sediments are parallel laminated, the uppermost laminae being algal bound. Upon exposure, the muddy sediment underlying the flats is thoroughly desiccated, which destroys primary sedimentary structures. Prolonged subaerial exposure promotes such severe desiccation that the surface sediment is fragmented into sand- and silt-sized particles, which are blown to the northwest where these particles accumulate to form clay-sand dunes (see *Eolian System*).

Wind-tidal flats containing extensive algal mats are present throughout the central part of the flats (middle flats) associated with South Padre Island and on the mainland flats between Fourmile Slough and Stover Cove, and along the Brownsville Ship Channel in the areas of South Bay, Los Montes, Bahia Grande, and San Martin Lake. The central (middle) flats that are associated with South Padre Island are slightly lower in elevation than the upper flats and consequently are flooded more frequently. The surface of these flats is characterized by a continuous cover of blue-green algae; these algae exhibit several morphological types, including rope-like ridges, dome-like gas-filled features up to 3 feet in diameter and 3 inches high, irregular-shaped tufts, and desiccation polygons. Within the central flats are numerous small, shallow depressions, which commonly are sites of mud accumulation. Sediment underlying the central flats is predominantly well sorted, fine-grained sand derived from beaches and dunes of South Padre Island. Interbedded with sand are thin beds and laminae of algal-bound mud and sandy mud. Commonly associated with the algal-bound mud and sandy mud are laminae of white aragonitic carbonate mud. Sands are massive, parallel laminated, and ripple cross laminated with abundant air-filled cavities. Algal-bound muds and sands are thinly laminated. On the surface and in the shallow subsurface they exhibit desiccation cracks and rip-up clasts. The surfaces of these flats are near the water table; the upper few inches of the wind-tidal flat deposits are oxidized light brown, whereas the sediment beneath the water table is light green. Interstitial water is hypersaline, and secondary gypsum is precipitated in the zone just above the water table. Equivalent mainland wind-tidal flats are predominantly mud with minor amounts of sand; surfaces of these flats are covered with blue-green algae, and desiccation cracks are common. Primary sedimentary structures are mostly parallel laminae;

ripple cross-laminae are minor features; rip-up clasts are numerous. Secondary gypsum is common.

A slight depositional rise occurs along the lagoon margin of the wind-tidal flat (the distal flat) associated with South Padre Island. This rise occurs as a consequence of reworking of the distal wind-tidal flat by wind-generated waves and currents. Water commonly is 0.5 foot deep on these distal flats. Surface sediment consists of light brown to light gray mud and sand; sand is well sorted and fine grained, and mud occurs mostly as silt- to sand-sized aggregates or pellets. Mud or clay pellets are the feces generated by the prolific infauna of the wind-tidal flat and adjacent Laguna Madre grassflats. Blue-green algae are common sediment binders in these outer wind-tidal flats, but they assume a form different from that of the algae on the middle flats. Blue-green algae develop a continuous, thin layer in the outer wind-tidal flats. Since they seem alw

Unlike the upper and middle parts of the wind-tidal flats associated with South Padre Island, the lower flats do not exhibit desiccation features; the lower flats are less frequently exposed and therefore do not dry as readily as do the upper and middle flats. Whole, articulated valves of the clam *Pseudocyrena floridana* are abundant on the lower flats and in depressions on the middle flats. Valves of *Pseudocyrena floridana* locally form shell pavements on the lower and middle flats. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Htz - Transitional zone (Holocene-Modern)

Unique to the Brownsville-Harlingen and Kingsville map areas, *transitional environments* are closely associated with and genetically related to the extensive wind-tidal flats of the South Texas coastal region. They are considered part of the bay-estuary-lagoon system because their origin is closely tied to wind-tidal processes. The *transitional zone*, located along the mainland margin in the area around Port Mansfield, marks the area of transition between the wind-tidal flats and the South Texas eolian system (fig. 13). The areal extent of this environment is about 8.5 square miles. The transitional zone is composed of wind-tidal flats containing many remnants of the deflated margin of the sand sheet, numerous clay dunes which have accreted windward of these relict erosional features, and large landward-trending blowout depressions intermittently flooded by wind tides. These mixed wind-tidal and eolian elements were mapped together in the Kingsville map area and southward into the northern part of the Brownsville-Harlingen map area because the individual elements are generally too small to be mapped as separate units. South of Port Mansfield in the Brownsville-Harlingen map area, individual elements in the transitional zone could be mapped as independent elements.

The transitional zone is periodically flooded by wind-driven tides and rains, but during much of the year the zone is the site of wind deflation, winnowing of airborne sediment, and windward accretion of small eolian clay dunes. The highly serrate landward margin of the zone is the result of wind-tidal flooding and wind deflation of banner dune complexes. During wet cycles, the water table rises and remains high; marshes become established in ponds; grasses cover the flats; and active deflation of the flats stops. Near Texas Highway 186 leading to Port Mansfield, many deflation areas mapped as part of the transitional zone have become vegetated and are currently stabilized with salt-tolerant grasses such as *sacahuista*. Future droughts will drop the water table and contribute to the demise of established vegetation and to the resumption of active deflation of the flats. Such cyclic conditions have been documented in wind-deflation areas on northern Padre Island (Hunter and Dickinson, 1970). ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hs - Shelf mud (Holocene-Modern)

The area gulfward from the lowest part of the fore-beach is included on the *Environmental Geology Map* as the offshore system (figs. 21 and 22). Offshore environments include the shoreface (42.5 square miles) and inner continental shelf.

The inner continental shelf, as shown on the Brownsville-Harlingen Map, extends from 5 fathoms, or 30 feet, to the eastern map limit. In fact, the transition between inner continental shelf and shoreface occurs at about 7 fathoms, or 42 feet (McGowen and Morton, 1979); this transition is marked by a decrease in slope.

Offshore from South Padre Island, accumulation of Modern sediment is rather slow, and the area is floored principally by relict Holocene sand, shelly sand, muddy sand, mud, shelly mud, and sandy mud. Modern and Holocene deposits are thin (locally only inches of Modern-Holocene sediments overlie Pleistocene deposits). Distributed patchily throughout the inner shelf in an area south of the Port Mansfield Channel are Pleistocene deposits exposed on the seafloor (McGowen and Morton, 1979). ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hsb - Shoreface (Holocene-Modern)

The shoreface is the gulfward section of South Padre Island that extends seaward from mean sea level to about the 7-fathom line. Along South Padre Island, the shore-face is between 1.3 to 1.4 miles wide; it rests on Pleistocene and Holocene Rio Grande fluvial-deltaic deposits (fig. 23). The shoreface is a zone of high physical energy, especially along the upper shoreface (generally less than 15 feet deep) where breaking waves have constructed a series of breaker bars that may be en echelon or may be approximately parallel to the shoreline. Greatest wave intensity occurs in areas where waves begin to touch bottom to a zone along which they finally break. Waves begin to break when wave height is about 0.8 times that of the water depth. Normal wind-driven waves are 2 to 4 feet high and break on the upper part of the shoreface. Only during storms, when wave heights are great, do waves break on the lower shoreface. The absence of breaking waves, except during storms, and the slow rate of sediment accumulation on the lower shoreface results in mixing of suspension load (clay and silt) and traction load (sand) materials in this zone; accordingly, biologic activity is dominant over physical processes; hence the lower shoreface is characterized by extensively burrowed (mottled) sand and muddy sand.

The upper shoreface extending from near sea level to a depth of 12 to 15 feet is a zone where waves, driven by the prevailing southeast winds and by northeast winds that accompany polar fronts, touch bottom and break. Several lines of breakers commonly can be observed on the Gulf waters that overlie the upper shoreface. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hb - Beach (Holocene-Modern)

Almost 3 square miles of Gulf beach occur between low tide and the first inland line of vegetation (see *Environmental Geology Map*). Where fore-island dunes are present (from the Port Mansfield Channel southward to the vicinity of Deer Island, and between Brazos Santiago Pass and the mouth of the Rio Grande), the vegetation line coincides approximately with the gulfward side of the fore-island dune ridge. In many areas of South Padre Island where the fore-island dunes have been removed, no sharp demarcation exists between the beach and the other barrier island depositional environments; for example, in areas where wash-over channels and washover fans are present, the back-beach grades imperceptibly into washover and eolian depositional environments (figs. 21 and 22). South Padre Island beaches have developed across the mouths of washover channels; the beach is repeatedly eroded by hurricane storm-surge floods in areas where fore-island dunes are absent. Big Shell Beach (Brown and others, 1976) extends from the Kingsville map area into the Brownsville-Harlingen map area southward almost to the Willacy-Kenedy county line. Big Shell Beach contains abundant large clams: *Eontia*, *Mercenaria*, and *Echinochama*. Shell content of Big Shell decreases southward, and correspondingly so do the well-developed fore-island dunes. Watson (1971 and 1972) suggests that a relationship exists between high, well-developed, fore-island dunes and abundant shell on adjacent beaches. According to Watson, shell is trapped on the beach, whereas sand is transported westward by the wind; shell is thereby concentrated on the backbeach as a shell pavement, or lag.

Padre Island beaches consist of two distinct zones: forebeach, the seaward-sloping smooth part of the beach that is affected daily by swash and backwash, and back-beach, which is normally separated from the forebeach by a berm. The backbeach slopes gently seaward or locally may slope away from the sea to produce a backbeach trough or runnel. Beach cusps are common features of the forebeach. Primary sedimentary structures in the forebeach are predominantly parallel inclined laminae that dip toward the Gulf of Mexico at an angle of approximately 5°; sedimentary structures are accentuated by dark heavy minerals (principally magnetite) that have been concentrated in forebeach deposits by swash and backwash. These heavy mineral particles have been concentrated according to grain density. Backbeach deposits are texturally similar (in places) to forebeach deposits; however, the backbeach may be locally covered with a shell pavement representing a lag, or wind-deflation deposit. Stratification of backbeach deposits consists of (1) parallel laminated sand and shell, (2) trough-fill cross-strata, (3) ripple cross-laminae, and (4) local channel-fill deposits.

Beaches on South Padre Island are mostly in an erosional condition (Morton and Pieper, 1975). Net shoreline accretion over the long term has occurred between the mouth of the Rio Grande and Brazos Santiago Pass. At present, net accretion is taking place on the upcurrent (south) side of the jetties of Brazos Santiago Pass and Port Mansfield Channel. The beach on the north side of these jetties is experiencing erosion. Elsewhere, the beaches of South Padre Island (including the beach between the mouth of the Rio Grande and Brazos Santiago Pass) are currently in an erosional state. In 1956, Magnolia (Mobil) Oil Company drilled a well about 330 feet from the beach (about 1.7 miles north of La Punta Larga). In 1972, the well-head was in the swash zone; average rate of shoreline erosion for that 16-year time interval was about 21 feet per year (McGowen, Garner, and Wilkinson, 1977). South Padre Island beaches are being eroded because of several factors: (1) there is a deficit of sand; (2) for given wave or storm conditions, South Padre Island erodes more rapidly than do other segments of Padre Island because South Padre Island is a thin sand body; (3) waves generated by the dominant southeast winds strike the shoreline at a high angle, setting up strong longshore drift that moves sand northward out of the area; (4) the dominant southeast winds and hurricanes transport sand from the beach zone onto the wind-tidal flats and into Laguna Madre, thereby effectively removing a large volume of sand from the buffer zone; and (5) the Rio Grande deltaic muds continue to undergo compactional subsidence, which causes a relative rise in sea level and a landward shift in the shoreline (Swanson and Thurlow, 1973; Brown and others, 1974; McGowen, Garner, and Wilkinson, 1977). ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hfi - Fore-island (Holocene-Modern)

The greatest relief on South Padre Island occurs along the narrow ridges of moderately to poorly stabilized sand dunes that parallel the beach discontinuously between Port Mansfield Channel and Brazos Santiago Pass, and for a distance of about 4 miles north of the mouth of the Rio Grande. Approximately 0.2 square miles of fore-island dune ridge exists in the Brownsville-Harlingen map area.

The fore-island dunes rise from an elevation of about 5 feet on the backbeach to about 30 feet on the highest ridges. The dune ridge is the product of sands that are blown from the backbeach, toward Laguna Madre, and are stabilized by a sparse to moderate cover of salt-tolerant grasses and vines. This important environment occurs principally on Mustang and northern Padre Islands and is best developed where there is a delicate balance between persistent onshore winds to deflate backbeach sands and where there is sufficient rainfall for vegetation to stabilize the dunes, which in turn promote vertical accretion of eolian deposits. In the more humid parts of the upper coast, fore-island dune ridges are low and poorly developed where annual precipitation is high, evapotranspiration is less than precipitation, and vegetation is dense. Under these conditions, there is volumetrically less eolian transport of sand from the back-beach to the fore-island dune area. Another factor that determines the volume of sand transported yearly from the backbeaches to the fore-island dunes is that on the upper coast and parts of the middle coast, winds from the two north quadrants tend to transport sand from fore-island dune and backbeach

areas into the Gulf of Mexico, whereas on the South Texas coast, winds from the northeast quadrant, in particular, transport sand from the backbeach to the fore-island dune areas. South of central Padre Island, the low rainfall (and high evaporation rate) and persistent onshore winds tend to prevent the stabilization of wind-blown sand by vegetation, thereby hindering the development of high fore-island dune ridges. The fore-island dunes of South Padre Island have undergone numerous changes caused by droughts in the late 1800's and early 1900's (Price and Gunter, 1943), overgrazing when the island was being ranched, and by numerous hurricanes that breached the island. All these activities tend to destroy either the vegetation that stabilizes the dunes or the dunes themselves. The fore-island dunes were virtually destroyed by droughts and overgrazing, and succeeding incipient dunes were readily destroyed by hurricanes and tropical storms. In the past two decades, however, the fore-island dunes have been established in several areas; the chain is once again being established.

Internally, the dune ridge is composed of well-sorted sand arranged in steeply dipping eolian crossbeds displaying a complex history of deflation and deposition. High storm or hurricane tides may erode the dune ridge many feet (Hayes, 1967). Sands blown from the beach will slowly accrete the ridge gulfward; many years may be necessary to heal or return the ridge to its prestorm position. The fore-island sand ridge protects the barrier island from the full impact of the hurricane-tidal surge. Since the Gulf shoreline of South Padre Island is rapidly eroding, it is unlikely that a high, continuous fore-island dune ridge will ever develop again.

The configuration and life of the fore-island dune ridge are delicately balanced; long-term climatic cycles may modify significantly dune height, rate of growth, or state of equilibrium. Any activity that reduces the vegetation cover may initiate a period of erosion. For example, nineteenth- and early twentieth-century ranching on the island reduced the vegetation cover, and in turn led to destruction of the fore-island dunes and promoted growth of the large back-island dune fields. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hsf - Sand flats (Holocene-Modern)

Fore-island dunes on South Padre Island were initially destroyed during the latter part of the nineteenth century and early part of the twentieth century by droughts, overgrazing, winds, and hurricanes. Much of the area of South Padre Island formerly occupied by fore-island dunes is currently characterized by a broad, flat area that averages about 4 feet above mean sea level. The sediment underlying this area (approximately 10.5 square miles) is a mixture of fine-grained sand and shell; depositional features are low coppice and wind-shadow sand dunes and broad sandflats (figs. 21 and 22). In the presence of vegetation, the wind builds low coppice or wind-shadow dunes. During the past two decades, rainfall has been sufficient for coppice dunes to have accreted into fore-island dunes. (The Brownsville-Harlingen area was mapped from 7.5-minute controlled photomosaics made in 1960, and the area presently occupied by fore-island dunes is considerably greater than the area shown on the Brownsville-Harlingen Map.) Although fore-island dunes attain heights in excess of 20 feet, they have not as yet (1980) coalesced to form a continuous dune chain. According to Brown and others (1974), South Padre Island (in the Brownsville-Harlingen map area) has 16 active or potentially active washover areas; no fore-island dunes are within these areas. Within these active or potentially active washover areas, sand is transported during hurricanes from the shoreface onto the back side of South Padre Island, and the persistent onshore winds also transport sand from the backbeach onto the back side of South Padre Island.

Between the northern map limit and La Punta Larga, there are some 12 active and potentially active washover areas. Coincident with this density of washover areas is the broadest segment of South Padre Island (see figs. 21 and 22). This great width (in places up to 4.5 miles) is the result of sand transport by wind and storms through these washover areas onto the back side of South Padre Island. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hwc, Hwf, Hwd - Washover: distributary channel, fan, or distal fan (Holocene-Modern)

During hurricanes, storm-surge tides breach South Padre Island in many places. Storm currents erode channels through the thin barrier island sands and transport shell and sand to the lagoon side (actually onto the wind-tidal flat) where it accumulates as washover fans (in the area between the northern map limit to about 1 mile south of the Cameron-Willacy county line) and as washover aprons (in the area from about 3 miles south of the Cameron-Willacy county line to about 13.5 miles north of the mouth of the Rio Grande) (see figs. 21 and 22). Numerous washover channels occupying approximately 8 square miles have been mapped on South Padre Island within the Brownsville-Harlingen map area. Additional hurricane washover sites are shown in figure 8. Within a few weeks after the passage of a storm, hurricane channels are sealed at their seaward ends by sand that is transported onshore by breaking waves and parallel to the shore by longshore drift (Hayes, 1967; McGowen and others, 1970).

The channels are floored by shell and sand that, during storms, moves as dunes and sand waves through the breach. The washover channel not only carries the storm-surge tide from the Gulf into the lagoon, but as the hurricane moves inland, water from the lagoon returns to the Gulf through the washover channels. This ebb flow, which is caused by excessively high tides in the lagoon, returns some sediment to the Gulf. After the channel is sealed at its Gulf terminus, clay and silt settle from suspension and drape the bottom of the channel; this fine-grained sediment will be eroded if the channel is reactivated with the passage of another hurricane.

Much of the broad wind-tidal flat area on South Padre Island that lies between the northern map boundary and La Punta Larga derived its sand directly or indirectly from hurricane-washover fans. Within the area defined above, at least 12 washover channels have served as conduits through which sediment moves from the shoreface and beach onto the wind-tidal flats.

Two washover fan types were mapped on South Padre Island. One type is vegetated; the other is barren. Vegetated washover fan deposits have been severely altered by wind activity and are not (at least on the surface) recognizable in the field as washover deposits; instead, they more closely resemble eolian deposits as they exhibit alternating ridge-and-swale topography, are hummocky, locally densely vegetated, and attain heights greater than 6 feet. The vegetated washover fans are, in effect, low vegetated dunes. These vegetated environments cover about 5 square miles in the Brownsville-Harlingen map area.

Unvegetated washover fans are low sandy shell, shelly sand, and sand lobes that accumulated where the hurricane channel opens out onto the wind-tidal flats. Between storms, wind processes erode and redistribute some of the sands of the washover fans, thereby nourishing back-island dune fields, wind-tidal flats, and vegetated transverse dunes, such as those near the Gulf beach in the area between Deer Island and La Punta Larga. Unvegetated washover fans exhibit two patterns: (1) distinct, individual lobes which have developed at the lagoonward terminus of washover channels that transect back-island dunes, and (2) more-or-less continuous sheets of sand where back-island dunes are missing and the washover channels are unconfined. Unvegetated wash-over fans cover an area of 4.5 square miles. The fans have provided most of the sand that is filling Laguna Madre and has produced the extensive wind-tidal flats. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Htc - Tidal channel (Holocene-Modern)

Tidal channels occupy 10 square miles of the Brownsville-Harlingen map area. This environment, composed of channels through which tidal exchange occurs, functions principally in association with bay and lagoon environments and accordingly is classified in the *Bay-Estuary-Lagoon System*. Tidal channels are also classified in the *Barrier-Strandplain and Offshore System* because one channel

crosses Brazos Island. This particular channel, near Del Mar Brazos Island State Park, connects the Gulf beach with South Bay. Although normally functioning as a tidal channel activated by changing wind-tidal conditions in South Bay, it also functions as a washover channel and temporary tidal inlet during hurricanes and major storms.

Tidal channels that are part of the bay-estuary-lagoon system are located primarily within the complex network of wind-tidal flats and lakes inland from Brazos Island (fig. 18); the only exception is the channel located along the south margin of Gabrielson Island near Laguna Atascosa National Wildlife Refuge. This channel, which separates Gabrielson Island from the mainland shore, aids in the exchange of water between Laguna Madre and the wind-tidal flats around and inland from Stover Cove. Of the four channels in the lagoon system that radiate outward from South Bay, three extend into the extensive wind-tidal flat environment located south and west of the bay, and the fourth is at the mouth of the bay and connects to the Brownsville Ship Channel and south Laguna Madre. This latter channel, although modified by subaqueous and subaerial spoil (fig. 18), is the major inlet through which water is exchanged with Gulf-tide influenced south Laguna Madre. The tidal influence of nearby Brazos Santiago Pass is reflected in the molluscan community in South Bay (Calnan and others, in progress).

Two other tidal channels are located west of South Bay. One is associated with the vast wind-tidal flats of Bahia Grande and the other with the Laguna Madre/Larga Lake complex. Both channels connect to the Brownsville Ship Channel, with which water is exchanged during rising and falling wind tides and storm tides. The channels also function as drainage channels when the inland basins to which they are connected are flooded by runoff from heavy rains.

The substrates of active tidal channels are predominantly sand with local pockets of muddy sand and shell. Currents flowing through the channels tend to winnow out suspended sediments, transporting them into the flats or water bodies located at the ends of the channels. Currents are particularly strong during flood and ebb tides associated with storms. Small fan-shaped deposits may develop at the ends of the channels where current velocity and transporting power diminish as the water flows into the adjacent flats or water bodies.

Although tidal channels constitute only 0.5 percent of the Brownsville-Harlingen map area, their function as conduits through which water from adjacent basins is exchanged is important. This is particularly true for the tidal channel connecting South Bay to the tidally influenced area of Laguna Madre near Brazos Santiago Pass. Without this connection, conditions such as salinity and circulation patterns would be substantially different. South Bay would probably develop into an enclosed hypersaline basin flushed only by hurricanes and major storms. The flora and fauna, which presently include marine grasses and oysters, would also change, resulting in a substantial reduction in biologic productivity. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hi - Inlet-related shoal (Holocene-Modern)

Natural breaks between barrier islands and peninsulas, through which there is tidal exchange between the bays or lagoons and the Gulf of Mexico, are called tidal inlets or tidal passes. Artificial cuts have been made through barrier islands and peninsulas on the Texas coast to facilitate ship and barge traffic, or to enhance water exchange between the bays and lagoons and the Gulf of Mexico. Irrespective of the purpose for which an artificial cut was made, the cut functions similarly to a natural pass in water and sediment movement. Two inlets through South Padre Island accommodate boat and barge traffic and serve as avenues of water and sediment exchange between the Gulf of Mexico and south Laguna Madre. Both inlets are jettied, and depths are maintained by dredging.

The northernmost inlet (Port Mansfield Channel, fig. 22) was cut through South Padre Island in 1957. By 1961 this inlet was closed at its seaward side by a sandbar. Storm surge associated with Hurricane Carla (1961) effected the removal of the sandbar (Hayes, 1967). Following the advent of Hurricane Carla,

a new jetty system was constructed at this inlet. The channel that connects Port Mansfield with the Gulf of Mexico currently has a maintained depth of 12 feet.

Brazos Santiago Pass (the southernmost inlet) is now jettied and has a maintained depth of 36 feet to accommodate shipping to and from the Brownsville area through the Brownsville Ship Channel. Although there are two inlets between south Laguna Madre and the Gulf of Mexico, the volume of water exchange between the Gulf and the lagoon is small. Most of the sand that would normally move from the Gulf of Mexico through these inlets into south Laguna Madre is now trapped by the jetty systems.

Sand accumulates within these inlets (totaling 0.8 square miles of inlet-related sand shoals). Sand that accumulates in the inlets is transported by longshore currents within the shoreface environment; consequently, inlet-related sands have properties similar to those of shoreface sands. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hls - Levee and local crevasse splay deposits (Holocene-Modern)

Less than 4 square miles of periodically active levee and crevasse splay environments and substrates were recognized in the Brownsville-Harlingen map area. These environments occur mostly along the present Rio Grande channel (International Border) and are active only during periods of major flooding following the passage of tropical storms and hurricanes. Consequently, these silty, muddy, and locally sandy units are covered with sparse grass (fig. 15). They are formed when floodwaters breach levees and discharge for a time into adjacent floodbasins or interdistributary depressions. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hms - Meander belt (Holocene-Modern)

Within the entrenched San Benito Rio Grande system, meanderbelts are generally inactive and sparsely vegetated with grasses and shrubs. Some small active, underfit point bars along the present Rio Grande channel (International Border) were too small to map. The meanderbelts average about 2 to 3 miles wide and are up to 30 miles long within the map area (figs. 10 and 15). It is estimated that each belt may be up to 60 feet thick since fluvial deposits near the river mouth are known to be about 65 feet thick. The meanderbelts display sharp bases eroded into older floodbasin muds. Relict point bars in the upper reaches of the Rio Grande within the Brownsville-Harlingen map area may exhibit basal gravels and coarse-grained sand that becomes finer upward. The distribution of meander-belts on the Mexican side of the Rio Grande has not been mapped, but apparently they resemble the Texas deposits. The meanderbelts are slightly elevated (5 to 10 feet) relative to adjacent floodbasins (fig. 15). Most recently active meanderbelts exhibit maximum relief and preservation of depositional grain or morphology. The unit is composed of sandy point bars, silty levees and splays, and mud-filled oxbow lakes. Accretionary point-bar grain and abandoned channels and meander loops or scrolls document the fluvial processes that constructed these distinctive depositional units.

Geometrically, the meanderbelts exhibit a large-scale anastomosing pattern (fig. 10), which converges inland with the principal trunk stream of the Rio Grande. Gulfward, the meanderbelts are transitional with finer grained, low-relief distributaries (fig. 16) of the Holocene-Modern delta plain, which is undergoing subsidence, marginal erosion, and transgression by Laguna Madre and the minor lakes and wind-tidal flats of the Bahia Grande region (figs. 17 and 18). Approximately 200 square miles of distinctly fluvial Holocene-Modern meanderbelts were recognized and mapped in the Brownsville-Harlingen area. Typical soils are those in the Rio Grande, Matamoras, and Laredo series. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hds - Distributary sands and silts (Holocene-Modern)

The subsiding and inactive San Benito Rio Grande delta plain is crisscrossed with about 75 square miles of relict meandering to slightly sinuous sand bodies which represent relict distributary channels of the Modern-Holocene delta system (figs. 10, 14, 16, and 17). As previously mentioned, the distributaries are transitional landward with meanderbelts. Distributaries are arbitrarily defined where meanderbelts become smaller and tend to bifurcate gulfward (fig. 16). Abandoned channels indicate that the distributaries meandered over the delta plain, typical of deltas built by higher bed load rivers. Meandering distributaries probably extended to respective channel mouths of cusped, wave-dominated delta lobes that now are buried beneath the transgressive shelf.

Distributary bodies are composed of sandy point bars, silty/sandy levees and splays, and abandoned mud-filled channels. They closely resemble meanderbelts, but gulfward they contain progressively finer grained sediments.

Distributary channels supplied sediment to prograding delta-front/barrier-bar environments. Larger meanderbelts extended gulfward over the delta plains until progradation of the San Benito Rio Grande delta diminished and net retreat or transgression began between 3,400 to 1,900 years B. P. Wind-tidal flats along the western margin of Laguna Madre and South Bay/Bahia Grande area are transgressive over the eroded, subsiding San Benito delta plain. Many distributaries, however, extend gulfward beneath the Laguna Madre and the South Bay/Bahia Grande area (figs. 17 and 18). McGowen and others (1977) have recorded carbon-14 dates of $2,680 \pm 740$ years B. P. from distributaries buried beneath Laguna Madre near the Cameron-Willacy county line.

Saline soils occur on the distributaries, precluding cultivation of the saline Jackass Prairies (fig. 16). Soils and typical vegetation are saline silty clay loams of the Laredo and Sejita series, which support salt-tolerant grasses, alkali weeds, and some thorny shrubs. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hfe, Hf - Flood basin or flood basin grading to interdistributary mud (Holocene-Modern)

Associated with the Modern-Holocene San Benito meanderbelts are large ovate to elongate, grass-covered (now cultivated) areas underlain by mud and clay deposits (figs. 10 and 15). These flood-basin muds occupy about 140 square miles of the map area and were sites of overbank deposition when adjacent meanderbelts were active. Some of the floodbasins are now isolated from the active Rio Grande channel, but following intense rainfall in the lower Rio Grande Valley, the floodbasins are flooded. Overbank muds are thin, blanket deposits that veneer older meanderbelt sand bodies. The San Benito Rio Grande system is composed three-dimensionally of numerous meanderbelts separated vertically and laterally by floodbasin deposits. Floodbasin areas are intensively cultivated and are characterized by clay soils of the Harlingen and Benito series. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

Hmf - Fresh-water marsh (Holocene-Modern)

Fresh-water marsh occupies 0.5 square mile of a small headward-eroding stream system on the northwest side of San Martin Lake. Numerous fresh-water lakes in the region contain fringes and small unmapped patches of similar marsh environment. During drier years when fresh-water inflow is reduced, the fresh-water marsh assemblage is replaced by an assemblage characteristic of brackish-water conditions. Ephemeral fresh-water marshes probably exist in filled, occasionally flooded coastal lakes during wet cycles. Similarly, small marshes exist in perennial ponds, lakes, and abandoned channels throughout the map area, but size of the areas precludes map presentation. ([Environmental Geologic](#)

[Atlas](#)). (GRI Source Map ID 68689).

HPEa - Abandoned channel (Holocene-Modern and Pleistocene)

Rivers frequently alter their courses in response to changes in flow characteristics of the stream system. Evidences of channel changes in a meandering river are meander cutoffs, which subsequently become oxbow lakes. Channels that are abandoned slowly fill with mud and plant debris. Pleistocene meander segments are common throughout the Pleistocene fluvial systems (figs. 11 through 14). The oxbow lakes are filled with Pleistocene and Modern-Holocene sediment. Cultivation has somewhat obscured the filled oxbow lakes in the Brownsville-Harlingen map area. The complex pattern of filled channels in the Pleistocene Raymondville system (see *Environmental Geology Map*) documents the shifting, meandering nature of the system. Some filled oxbows pond water following severe rains. The deficient rainfall budget in the South Texas region precludes development (except during wet cycles) of fresh-water marshes that commonly occupy abandoned channels in the more humid upper Texas Coastal Zone. About 130 square miles of the map area is underlain by the distinctive filled meander channels, and at least 100 square miles of this unit occur in the Pleistocene fluvial systems. Use of infrared aerial photographs will permit more precise mapping of the cutoffs and channel segments because of thermal differences exhibited by the mud-filled channel and adjacent sands. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

HPEcl - Coastal lake or pond (Holocene-Modern and Pleistocene)

Coastal lakes and ponds associated with Pleistocene fluvial systems in the Brownsville-Harlingen map area total 3 square miles and are principally of Holocene-Modern age. Numerous unfilled to partially filled lakes occur within abandoned Pleistocene channel segments in the Raymondville fluvial system. Unlike the more humid upper and middle Coastal Zone, floodbasin lakes are rare within the Brownsville-Harlingen area. Several filled lakes in the El Jardin deflation area (see fig. 25) are associated with eolian erosion into Pleistocene meanderbelt sands. These filled lakes are floored with low-permeability clays. Marsh is present but areally restricted because of the arid climate; some unmapped fresh-water marsh and high-moisture hydrophytes occupy the depressions during extended periods of higher rainfall. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

HPEda - Gavilans, clay-sand dunes (Holocene-Modern and Pleistocene)

Gavilan accretionary *clay-sand dune fields*.—An accretionary clay-sand dune field that occurs on and borders extensive wind-tidal flats south and southwest of Port Isabel is herein called the "Gavilan accretionary clay-sand dune field" (fig. 10). The dune field is named for Mesa del Gavilan (fig. 18), an accretionary dune complex that is shaped like the head of a hawk (Price, 1958). Similar hawk-shaped accretionary elements occur throughout the Gavilan, as well as in the Hawk Island dune fields. Price (1958) infers that the gavilan mesas are produced by windward accretion of salty clay/silt particles against a nucleus composed of remnants of Holocene-Modern distributary levees exposed on wind-tidal flats. He infers that "capture" of the gavilan mesas by barrier islands, such as Brazos Island, explains the origin of at least some of the accretionary deposits that compose the western side of South Padre Island generally south of the Cameron-Willacy county line. We believe that many accretionary features on South Padre Island are formed by periodic eolian accretion of sandy storm-washover sediments and are not analogous to the gavilan mesas (see *Barrier Island System*).

Clay-sand dunes of the Gavilan dune field typically occur on the northwestern margin of wind-tidal flats associated with South Bay, Laguna Madre, Laguna Larga, Bahia Grande, and San Martin Lakes (fig. 18). Some of the linear to crescent shaped dunes apparently are located on the downwind side of

deflation depressions, and others, such as the "hawk-shaped" mesas (see Los Montes dunes), are scattered rather randomly across the wind-tidal flats and may have nuclei composed of relict levees or erosional remnants of the Rio Grande delta plain. Deflation of these wind-tidal flats along the margin of the Holocene-Modern delta plain produces salty, silt-sized airborne particles that are deposited on the saline Jackass Prairie.

Development of the Gavilan and Hawk Island accretionary dune fields is similar to the origin of the accretionary potrero and rincon dunes on the wind-tidal flats of the Kingsville map area. The reader can refer to the Kingsville Atlas for further discussion of these kinds of eolian elements. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

HPedi - Clay-sand dune complexes (Holocene-Modern and Pleistocene)

Active clay-sand dunes (6 to 8 square miles) are associated with the erosional margin of the Pleistocene Raymondville fluvial system along the western margin of Laguna Madre from Cayo Atascosa to Fourmile Slough (Hawk Island clay-sand dune complex, fig. 10). Most of these accretionary dunes have formed around nuclei composed of erosional remnants of the Raymondville meanderbelts. Others in the vicinity are accreting to levees of the Arroyo Colorado delta.

Several large stabilized (inactive) clay dunes occur along the Kenedy-Willacy county line in the El Jardin deflation area. Probably Holocene-Modern in age, these dunes were formed by deflation of the underlying Raymondville fluvial deposits. These units are discussed in more detail under Eolian Systems. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

HPEss - Sand sheets (Holocene-Modern and Pleistocene)

The sands within several stabilized eolian dune trains or narrow lobes were deflated from underlying Pleistocene fluvial sediments. These are the Rio Hondo, Edinburg, and Faysville (west of the map area) dune trains (fig. 10). Other similar features occur within the South Texas eolian system in the northern part of the Brownsville-Harlingen area and the southern part of the Kingsville map area. These eolian features cover almost 40 square miles of the Brownsville-Harlingen map area. On aerial photographs the sharp boundaries of the units can be readily detected. The unit consists of inactive elongate dune fields or trains that were produced by deflation of relict fluvial and deltaic sediments. The Rio Hondo dunes were constructed from sands that were deflated principally from sandy Raymondville deposits. The Edinburg and Faysville dune trains were constructed from sands that were deflated from a variety of Pleistocene fluvial and deltaic deposits exposed along the northern side of the Modern Rio Grande Valley (see McAllen-Brownsville Geologic Atlas Sheet, Barnes, 1976). The deflation features have been partly obscured by cultivation. ([Environmental Geologic Atlas](#)). (GRI Source Map ID 68689).

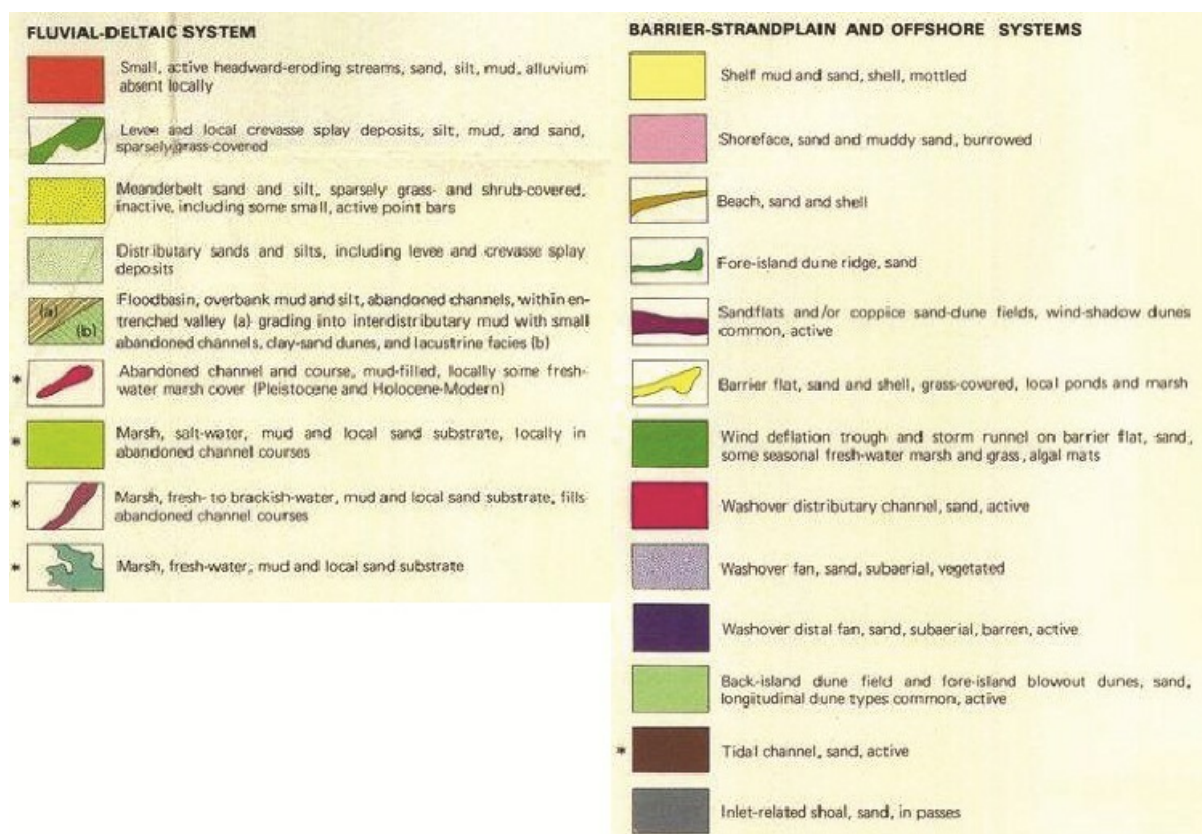
GRI Source Map Citations

Environmental Geologic Atlas

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Environmental Geologic Atlas Explanation

MODERN-HOLOCENE SYSTEM



* Facies or environments present within more than one system.

MODERN-HOLOCENE SYSTEMS (continued)

EOLIAN SYSTEM		MARSH SYSTEM	
	Active dune complex, sand, commonly banner dunes, local barchan dunes	* 	Marsh, salt-water, mud and local sand substrate, locally in abandoned channel courses
	Active dune blowout areas, sand, local depressed relief, eolian grain prominent, hummocky, local fresh-water marsh in wet seasons	* 	Marsh, fresh- to brackish-water, mud and local sand substrate, fills abandoned channel courses
* 	Sand sheet, strong relict grain of base-leveled dunes, grass-covered	* 	Marsh, fresh-water, mud and local sand substrate
	Sand and loess (silt) sheet, no relict grain, sparse grass		
	Moderately stabilized dunes, sand and loess (silt) sheet, brush-covered		
	Well-stabilized dune sands, dense live-oak mottes and scrub		
	Sand and loess (silt) sheet deflation area, active, grass-covered, high water table, occasionally flooded, poorly drained		
* 	Clay-sand dunes (locally called gavilans), eolian, accretionary, active, local sparse grass, wind-tidal flat or playa source common		
* 	Clay-sand dune complexes, eolian, inactive, grass- or brush-covered		
* 	Sands and silts, caliche-capped, thin veneer of eolian sand, numerous small circular (karst) depressions		
OTHER MAP UNITS		BAY-ESTUARY-LAGOON SYSTEM	
	Barchan dune orientation in banner dune complexes		Bay- or lagoon-margin sand or shell berms, accretionary, sub-aerial, relict depositional grain, vegetated
	Longitudinal dune orientation in back-island dune field		Bay- or lagoon-margin sand, locally with shell and mud, normally bare sand, may be locally covered by sparse marine grass, occasionally emergent
	Point bar (fluvial) accretion		Sand shoal, some oolites, slight bathymetric relief
	Spoil heap or mound, subaerial		Grassflat, muddy sand with shell, normal to hypersaline
	Reworked spoil, subaerial		Bay and lagoon sand, muddy, local sparse marine grass
	Spoil, subaqueous		Bay and lagoon mud, mottled, some mixed shell
	Made land		Wind-tidal flat, sand and mud, firm, locally upper flat rarely flooded
			Wind-tidal flat, sand and mud, extensive algal mats, alternately emergent-submergent
			Wind-tidal flat, mud and sand, algal-bound mud, gypsiferous, firm, locally upper flat rarely flooded
			Wind-tidal flat, mud and sand, extensive algal mats, depressed relief, wet and soft, locally upper flat rarely flooded
			Transitional zone, wind-tidal flat to eolian sand sheet, wind deflation, concentrated clay-sand dunes, sand (tidal flats and clay-sand dunes south of Port Mansfield mapped independently)
		* 	Tidal channel, sand, active
		* 	Coastal lake or pond, mud-filled, occasionally flooded (Pleistocene and Holocene-Modern)

* Facies or environments present within more than one system.

PLEISTOCENE SYSTEMS



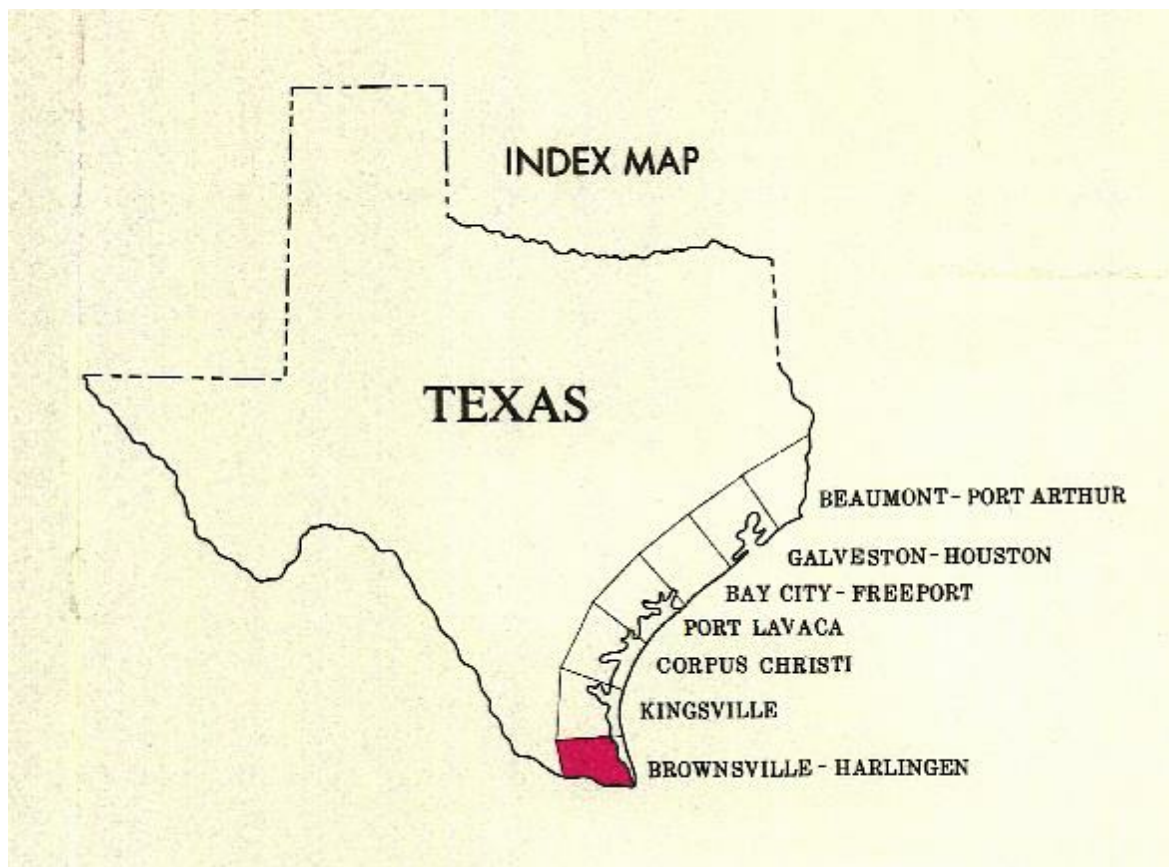
* Facies or environments present within more than one system.

Other map symbols.—A variety of symbols have been employed to portray the orientation of various environmental features. These include the orientation of transverse or barchan dunes within the banner dune fields, the orientation of dunes in the back-island dune fields, and the position of wind-accretion ridges within clay-sand dunes and gabilan mesas. The dune symbols illustrate only general orientation of active dunes since the dunes continuously change position. Clay-dune accretion symbols accurately depict these features as observed on aerial photographs.

Point-bar accretion is shown for the Pleistocene and Holocene-Modern meanderbelts. These accretion lines are based on aerial photographic interpretation.

Extracted from Environmental Geologic Atlas of the Texas Coastal Zone - Brownsville-Harlingen Area. ([GRI Source Map ID 68689](#))

Environmental Geologic Atlas Index Map



Extracted from Environmental Geologic Atlas of the Texas Coastal Zone - Brownsville-Harlingen Area. ([GRI Source Map ID 68689](#))

Environmental Geologic Atlas Report

ENVIRONMENTAL GEOLOGIC ATLAS OF THE TEXAS COASTAL ZONE BROWNSVILLE-HARLINGEN AREA

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INTRODUCTION

The Texas Coastal Zone is marked by diversity in geography, resources, climate, and industry. It is richly endowed with extensive petroleum reserves, sulfur and salt, deep-water ports, intracoastal waterways, mild climate, good water supplies, abundant wildlife, commercial fishing resources, unusual

recreational potential, and large tracts of uncrowded land in proximity to major population centers. The Coastal Zone is a vast area of about 20,000 square miles, including approximately 2,100 square miles of bays and estuaries, 367 miles of Gulf coastline, and 1,425 miles of bay, estuary, and lagoon shoreline. About one-third of the State's population and one-third of its economic resources are concentrated in the Coastal Zone, an area including about 6 percent of the total area of the State.

The Texas shoreline is characterized by interconnecting natural waterways, restricted bays, lagoons, and estuaries, low to moderate fresh-water inflow, long and narrow barrier islands, and extremely low astronomical tide range. Combined with these natural coastal environments are bayside and intrabay oil fields, bayside refineries and petrochemical plants, dredged intracoastal canals and channels, and a diverse array of satellite industries. The attributes that make the Texas Coastal Zone attractive for industrialization and development also make it particularly susceptible to a variety of environmental problems.

Parts of the Coastal Zone are among the fastest developing industrial, urban, and recreational regions in Texas; the Zone is at best a precariously balanced natural complex of dynamic environments with a history of almost yearly hurricane impact. Adequate plans to meet the potential problems of pollution, land and water use, and conservation are critically needed to ensure proper use of this vital Texas region. Regional analysis and inventory of the total coastal resources of Texas are vitally important and must be based on accurate maps of physical and biological environments, landforms, areas of significant processes, genetic sedimentary or substrate units, and man-made features. The Environmental Geologic Atlas of the Texas Coastal Zone is being developed to show the rate changes are taking place. Such information is needed for long-range resource planning and management. Mapping is the fundamental base necessary to provide answers to these critical questions.

ROLE OF ENVIRONMENTAL GEOLOGY IN THE COASTAL ZONE

Development of guidelines for proper and prudent management of the Texas Coastal Zone depends upon adequate knowledge of the nature and distribution of natural environments, land and water capability, and man's impact on the Coastal Zone. Processes and environments are a fundamental part of the geological character of this dynamic region. Many areas of the Coastal Zone are changing under man's accelerating impact. Because the area is balanced in terms of hurricane impact damage, salinity variations within bays and estuaries, plant stabilization of sediments, and a myriad of other critical features, man's impact can significantly affect the natural environmental balance. At the same time, the necessity of resource use in man's modern industrial society is obvious. Development, exploitation, and industrialization practices, however, should be compatible with the natural limitations imposed on the region by its physical, chemical, and biologic setting.

Regional climatic, sedimentary, biologic, and physical process variations along the Texas coast clearly preclude a rigid coastwide system of resource management. Any fair system of management must be based upon the concept of natural variation of environments locally and regionally; correspondingly, flexible guidelines should be firmly based upon these variations in properties, composition, and behavior under various land uses. Environmental geologic maps provide part of the fundamental data needed to create such a system of resource management.

One principal goal of the Environmental Geologic Atlas of the Texas Coastal Zone is to obtain an understanding of the natural systems before human impact irreversibly changes the character of the Zone. Only by understanding the natural coastal system can proper and compatible use of the region be determined. Maps of environmental units within the 367-mile-long Coastal Zone provide a benchmark with which to evaluate future changes and to diagnose appropriate use of the coastal regime.

Wise conservation should include the proper use of Coastal Zone resources within prudent guidelines

that will ensure minimum modification of the environmental quality of the region. For this reason, each kind of land use should be evaluated in terms of its potential effects on the geological and biological units of the Zone. Proper use will result when each of man's coastal activities is located in a manner that minimizes environmental damage.

The key to proper land and water use is the basic inventory of the coastal environments, sediment types, processes, and biological conditions. The Environmental Geologic Atlas provides this fundamental information that can serve as the basis for evaluating coastal legal problems, socioeconomic problems, industrial development, pollution, recreational needs, problems of public and private ownership, and other factors involving the natural framework of the Coastal Zone.

Several aspects of the Texas Coastal Zone make a long-term resource management program imperative; in turn, this requires a thorough knowledge of the environmental geology of the Coastal Zone. Since the Coastal Zone is the center of rapid geologic and physical changes coupled with a rapidly expanding population, an environmental atlas provides a current record of the status of dynamic coastal environments and processes, as well as a base for continued monitoring of erosion and human modification and exploitation. Dynamic environments can be monitored by periodic mapping that indicates the significant direction and approximate rate of physical, biological, and chemical changes. The environmental map is the common denominator for communication among coastal scientists through which technical input can be integrated and applied. Just as important, economists, planners, utilities specialists, power suppliers, sanitary engineers, lawyers, legislative councils, industrial organizations, regional councils of government, and many other groups can better plan, plot, refer to, and digest environmental data by using the Atlas maps.

THE COASTAL ENVIRONMENTAL ATLAS PROJECT

The Environmental Geologic Atlas project was initiated in 1969 when the need for a thorough regional analysis of natural processes, environments, lands, water bodies, and other coastal factors became urgently apparent. Without an adequate environmental inventory, further specialized scientific studies, as well as regional planning for improved use of coastal resources, could proceed neither efficiently nor effectively. Because of impending environmental problems in the region, staff members of the Bureau of Economic Geology assigned the project a high priority and proceeded with the mapping in the summer of 1969. Approximately 25 man-years of geologic and cartographic effort were expended in the five-year period of preparation.

The Coastal Zone, defined from the inner continental shelf to about 40 miles inland, includes all estuaries and tidally influenced streams and bounding wetlands. For purposes of presentation, the Zone was divided into seven areas (fig. 1) from the Texas-Louisiana boundary southwestward to the Rio Grande: (1) Beaumont-Port Arthur, (2) Galveston-Houston, (3) Bay City-Freeport, (4) Port Lavaca, (5) Corpus Christi, (6) Kingsville, and (7) Brownsville-Harlingen. Each of these seven coastal areas is covered by a separate Environmental Geologic Atlas containing a descriptive text, statistical tables, an environmental geology map (scale 1:125,000), and eight special-use environmental maps (scale 1:250,000). The seven coastal atlases cover approximately 20,000 square miles.

Environmental Geology Map

Environmental geology units for the entire Coastal Zone (fig. 1) were interpreted from and plotted on 320 7.5-minute Edgar Tobin Aerial Survey photomosaics and corresponding U. S. Geological Survey topographic maps, both at a scale of 1:24,000 (approximately 2.5 inches per mile). All environmental maps were printed on a regional base map of the Coastal Zone constructed especially for the Atlas by the Bureau of Economic Geology. The base map was compiled from 7.5-minute U. S. Geological Survey quadrangle maps; 5-foot topographic contours, available bathymetric contours, updated cultural features,

and all paved roads are included.

Mapping involved extensive aerial photographic interpretation, field work, aerial reconnaissance, and utilization of available published data for the region.

General sources and flow of data used in mapping are shown in figure 2; specific sources of data are noted in the text and itemized under "Sources of Supplemental Data." Interpretation and mapping of environmental geologic units were based on a genetic grouping of the major natural and man-made features of the Coastal Zone. Units mapped were interpreted to be of first-order importance to the environmental character of the Zone. First-order environmental units include the following: (1) a wide variety of sedimentary substrates (sand, mud, shell) and associated soil units displaying distinct properties and composition; (2) units displaying a variety of natural processes, including storm channels, tidal passes, wind-tidal flats, fluvial channels, wind erosion, and other dynamic properties of significance in maintaining and modifying the coastal environments; (3) biologic features such as oyster and serpulid reefs, marshes and swamps, subaqueous grassflats, and plant-stabilized sediment where biologic activity is of principal importance; and (4) man-made features such as spoil heaps, reworked spoil, dredged channels, and made land where man's activities have resulted in significant environmental modification. Approximately 135 specific environmental geologic units are recognized and mapped in the Texas Coastal Zone.

Environmental geology map units are grouped into higher order natural systems. Fluvial-deltaic, barrier-strandplain, marsh, eolian, and bay-estuary-lagoon systems, for example, include a variety of natural substrate, biologic, or process units and environments that are interrelated with respect to their origin and distribution within the Coastal Zone. Man-made features are separately grouped to differentiate clearly natural and artificial features.

Environmental geology maps are presented at a scale of 1:125,000, or 2 miles per inch. The currentness of aerial photographs, topographic maps, and navigational charts used in the project can be determined by referring to figure 3, which provides specific information on the dates of photography and map or chart revision. Edgar Tobin Aerial Survey photomosaics provided uniform coverage of the entire Coastal Zone. Compilation work maps (1:24,000) are maintained on open file at the Bureau of Economic Geology.

Remapping in future decades with updated aerial photography and other multispectral remote sensing devices carried by aircraft and satellites will provide a valuable historical reference to rates and degree of both natural and man-made changes in the Coastal Zone. The Atlas is, therefore, an open-ended document which can be updated to maintain a current record of the change and modification of the region. It is also anticipated that the Atlas will serve to stimulate interest in and provide the environmental baseline for many more specialized and localized studies addressed to specific pollution, land use, ecologic, economic, and resource problems.

Special-Use Environmental Maps

Following preparation of the Environmental Geology Map for each of the seven areas of the Coastal Zone, a series of special-use environmental maps was prepared to present more specific information for a variety of potential users. These special-use maps represent but a few of the kinds of maps that can be compiled or interpretatively derived from the basic environmental geology map. Maps prepared include the following: (1) *Physical Properties*—characterizing substrate and landform conditions for specific uses such as engineering, construction, and waste disposal, based on properties such as permeability, fluid transmissibility, shrink-swell potential, water-table position, load strength, local relief, and potential for surface faulting; (2) *Environments and Biologic Assemblages*—characterizing bottom-living plants and animals in bays, estuaries, and lagoons, and principal plant communities on land areas; (3) *Current Land Use*—inventorying use patterns in the area, including such classifications as agricultural lands, range-pasture lands, woodland-timber lands, spoil, made land, general recreational lands, wildlife

refuges, residential-urban lands, and industrial lands; (4) *Mineral and Energy Resources*—presenting extensive information about current resources and facilities, such as salt, sulfur, oil and gas, quarries, lime and cement plants, LPG storage, major metal-refining and petrochemical complexes, power-generation plants, and pipelines, and about the distribution of potential sources of sand and fill material; (5) *Active Processes*—displaying features such as storm-surge flood areas, shoreline erosion and deposition, areas of rapid and slow deposition, and hurricane-washover areas; (6) *Man-Made Features and Water Systems*—depicting the distribution of features such as made land, types of spoil, jetties or piers, seawalls, residential and industrial developments, artificial and natural water bodies, drainage or irrigation canals, ship channels, abandoned streams and cutoffs, wind-tidal flats, and other related features; (7) *Rainfall, Stream Discharge, and Surface Salinity*—displaying data collected for a representative 3-year period, including U. S. Weather Service rainfall data, U. S. Geological Survey gauging station data, and contour maps of surface salinity within bays, estuaries, and lagoons for periods of high and low rainfall, as well as calculated 3-year averages; and (8) *Topography and Bathymetry*—utilizing U. S. Geological Survey topographic data and U. S. Coast and Geodetic Survey bathymetric data.

Special-use environmental maps focus attention upon properties and characteristics of a specific nature, allowing a user to evaluate the Coastal Zone in terms of specific properties that are desirable or specific conditions to be avoided. Data such as pipeline distribution and oil-field areas are compiled from other sources, but most critical data were derived from the Environmental Geology Map by grouping or combining map units possessing common properties.

SOURCES OF SUPPLEMENTAL DATA

The Environmental Geologic Atlas of the Texas Coastal Zone is constituted primarily of basic information generated and presented by the research and cartographic staff of the Bureau of Economic Geology. In addition to field work, mapping, and other basic studies by the Bureau staff, certain published and commercial sources of data were utilized in preparation of the Atlas. The writers are responsible for selection, interpretation, and conclusions based on compiled data used to supplement original work of the research staff. Although a bibliography credits sources of scientific and technical information and ideas, the writers wish to acknowledge specifically those data compiled all or in part from the following sources: *see printed document*

GEOLOGIC HISTORY

The Texas Coastal Zone is composed of several active, natural systems of environments: fluvial-deltaic, barrier-strandplain-chenier, and bay-estuary-lagoon systems, as well as an eolian (wind) system in South Texas and marsh-swamp systems in the more humid middle and upper coastal regions. Geologists are also aware that the Coastal Zone is underlain by sedimentary deposits that originated in ancient but similar coastal systems. These ancient sediments were deposited by the same natural processes that are active in shaping the present coastline: longshore drift, beach swash, wind deflation and deposition, tidal currents, wind-generated waves and currents, delta outbuilding, river point-bar and flood deposition, and other processes.

Active and relict coastal systems in the Brownsville-Harlingen area (fig. 4) are divided into three principal groups based on their relative ages: (1) natural systems that originated more than 18,000 years B. P. (before present) during various interglacial periods of the Pleistocene ice age; (2) natural systems, termed Holocene, that originated between approximately 18,000 and 4,500 years B. P.; and (3) natural systems, herein termed Modern, that have been developing since about 4,500 years B. P. and are currently active (fig. 5). Carbon-14 dates (Nelson and Bray, 1970) indicate that, following numerous Late Pleistocene glacial and interglacial episodes, sea level began its final rise about 18,000 years B. P. (fig. 5C). Sea-level rise was punctuated by numerous stillstands and even some reversals. At 6,600 years B.

P., sea level was -72 feet MSL (present mean sea level); at 3,600 years B. P., it was -16 feet MSL; and by 2,800 years B. P., sea level had reached its approximate present level. At about 4,500 years B. P., many significant coastal processes began that are in operation today. For convenience in this Atlas, therefore, post-Pleistocene time has been divided into Holocene, when principal sea-level rise occurred (18,000 to 4,500 years B. P.), and Modern, which includes all events since 4,500 years B. P.

Modern coastal systems are characterized by a distinctive suite of natural environments in which certain geologic processes result in deposition of unique sedimentary units. Older sedimentary deposits of Pleistocene and/or Holocene age are similar in every respect to Modern deposits; therefore, these relict deposits can be interpreted as having originated within genetically similar ancient environments. For example, Modern river or fluvial systems are composed of levee, point-bar, and floodbasin environments in which certain types of sediment accumulated by specific depositional processes. Similarly, point-bar, levee, and floodbasin deposits of Pleistocene or Holocene age can be interpreted as having been deposited in similar environments within an ancient river system. Many basic ideas about the geologic history of this region have been the result of studies by Price (1933 and 1958).

A knowledge of Modern depositional processes is critical to the evaluation of the environmental impact of various types of human activity. Stated simply, natural environments must be properly understood if they are to be managed and protected. Just as important environmentally, but perhaps less obvious to most citizens, is an understanding of the ancient sedimentary substrates underlying the Coastal Zone. These relict deposits of ancient coastal environments determine to a great extent the suitability of coastal lands for various uses and human activities. Similarly, the sedimentary deposits of Pleistocene and Holocene systems dictate the character of soils, wildlife, vegetation, ground water, natural resources, and other aspects that are important to the environmental quality of the region. For these reasons, it is critical that the nature of the environments, processes, and sediment substrates for all active coastal systems and the relict sedimentary substrates for all ancient coastal systems be determined and mapped so that a scientific basis for environmental management can be developed.

A principal goal of the Environmental Geologic Atlas of the Texas Coastal Zone is to describe active environments and relict sedimentary deposits. An appreciation of the geologic history of this dynamic region will enable the reader to envision the sequence of geologic events that has created and shaped the present Texas Coastal Zone. The geography of the region has evolved slowly through time as climate, sea level, and other environmental factors have changed. The present Coastal Zone is, therefore, but one frame in a kaleidoscope of changing rivers, shifting beaches, and subsiding plains. Past geologic events and current geologic processes join in characterizing the nature of the total coastal environment and in denoting inevitable future changes that man must learn to understand, predict, and manage. In short, the Coastal Zone is characterized by natural change; man's activities may significantly affect the rate and direction of these changes.

Publication of this Atlas completes the mapping of all outcropping Texas coastal Pleistocene and Modern-Holocene deposits. It is now appropriate that additional studies be undertaken to date and correlate fully the many depositional systems and erosional events documented during the preparation of the seven Atlases that compose the *Environmental Geologic Atlas of the Texas Coastal Zone*.

PLEISTOCENE HISTORY

The Pleistocene ice age encompassed more than a million years of complex glacial and interglacial climatic and sea-level changes (fig. 5A). It consisted of at least four principal glacial episodes separated by warmer interglacial periods; many minor warming periods, or interglacial events, complicated the history of each major glacial episode. Sea levels during maximum glaciation were 300 to 450 feet lower than those during warm interglacial periods because a large volume of the world's water was trapped in thick continental ice sheets (Curry, 1960; Bernard and LeBlanc, 1965).

During interglacial stages of the late Pleistocene (fig. 5A), while glaciation had diminished and sea level was approximately at the present level, large rivers transported vast amounts of suspended mud and bed-load sand from remote areas of Texas to deltas within broad embayments along the ancient Gulf shoreline. As sediment passed through these ancient rivers, sandy point bars were deposited in shifting meander loops, and levees were built along vegetated riverbanks. During flood stages, the rivers left their banks and sediment was introduced into adjacent floodbasin depressions, in part as sandy crevasse splays but mostly as mud and silt flood-plain deposits. Over thousands of years, the shifting, meandering Pleistocene rivers deposited meanderbelt sediment composed primarily of point-bar sand, but local pockets of floodbasin mud and silt were preserved within the dominantly sandy river sediment.

Two apparent episodes of fluvial deposition are recorded in late Pleistocene deposits (fig. 5B) exposed in the Brownsville-Harlingen map area (fig. 4): (1) older fluvial and deltaic sediments of probable Sangamon age called the Lissie and older Beaumont (*Oberlin*, Doering, 1956; or *Montgomery*, Fisk, 1944) Formations, respectively, that are exposed in the northwestern part of the area between Raymondville and La Sal Vieja, and (2) younger Beaumont (*Eunice*, Doering, 1956; or *Prairie*, Fisk, 1944) fluvial (and local marine) deposits probably of interglacial Wisconsin (Peorian?) age that are exposed over an extensive area in the central part of the map area (see Price, 1958, p. 41 and 49). Names herein applied to these and associated systems are shown on figure 10. Detailed discussions of mapped units within these and later Holocene-Modern systems will follow in a subsequent chapter. At this point, these depositional systems will be briefly described and related to the geologic history of the Brownsville-Harlingen area. It is possible to interpret the relative sequence of depositional and erosional events within the Brownsville-Harlingen map area or any of the other Atlas map areas. Absolute age determination and correlation of depositional systems throughout the Texas Coastal Zone are more subjective.

Oldest deposits in the Brownsville-Harlingen map area are Pliocene fluvial deposits, probably part of the calichified, karstic Goliad Formation, covered by thin loess deposits in the vicinity of La Sal Vieja (fig. 4). These deposits extend northward beneath the South Texas eolian system.

Older Pleistocene fluvial deposits (Lissie Formation) are exposed along the southern margin of the South Texas eolian system north and west of Raymondville (fig. 4). This fluvial system extends northward beneath thin loess sheet deposits of the eolian system. Wind deflation and deposition has generated sand dunes, locally supplied with sand from the underlying meanderbelts. Playa lakes and clay dunes occur where wind deflation has eroded into the shallow ground-water table. Eolian deposits overlie these older Pleistocene (Lissie) fluvial deposits along the northwestern margin of the map area.

Streams of the ancient Pleistocene Rio Grande (Lissie Formation) changed coastward from meandering to relatively straight to slightly sinuous delta distributary courses extending across broad, low deltaic plains (fig. 4). Sand and mud deposits at the mouths of the distributaries slowly extended the delta lobes into a broad embayment, building land at the expense of the ancient Rio Grande embayment. Currents redistributed some of the deltaic sand and mud, but most of it compacted and subsided beneath the advancing delta lobes.

Along the distributary channels, overbank flooding added mud, silt, and some sand to broad interdistributary embayments; lower or coastward parts of the embayments were occupied by small marine to brackish bays and lagoons fringed with salt marsh. Farther inland, interdistributary bays gave way to brackish- and fresh-water lakes and marshes and eventually to floodbasin swamps. Delta lobes became overextended as they built farther into the marine embayment. Sudden upstream shifts of rivers sent water and sediment pouring into the bay along shorter, more direct, and higher gradient courses. Distributaries were thus abandoned and later reoccupied repeatedly as the embayments filled with deltaic sediment.

Several coastward-trending segments of Pleistocene delta distributaries and adjacent interdistributary

deposits (older Beaumont) are exposed within the coastal prairies northwest of Raymondville (fig. 4). The sand-filled distributaries are slowly subsiding into underlying delta mud. Thin, unmapped loess deposits cover the relict delta plain. Courses of the relict distributaries are marked locally by higher levee deposits that still stand a few feet above the old alluvial and delta plain. Channel-mouth sandbars and prodelta-mud deposits are now buried beneath the more distal or coastward floodbasin mud and silt. Older Beaumont deltaic mud and sand are exposed near Raymondville, but delta sediments are inferred to extend northward under the South Texas eolian system (fig. 4).

As previously indicated, the precise age of these older Pleistocene fluvial and deltaic deposits (Lissie and older Beaumont Formations, respectively) that are exposed in the map area is questionable. They are probably of Sangamon interglacial age (fig. 5A and B). This ancient Rio Grande fluvial/delta system apparently terminates near the present Gulf coastline, although these high-stand deltaic deposits may extend some distance offshore beneath the inner shelf. The system is extensively covered by a younger superimposed Pleistocene (Beaumont) fluvial system (fig. 4).

Trends of the older Pleistocene Rio Grande fluvial meanderbelts and deltaic distributaries are speculative beneath eolian loess and sand sheets in the northern part of the Brownsville-Harlingen and southern part of the Kingsville map areas. Sand bodies are probably oriented essentially east-west. The older Pleistocene Rio Grande deposits provide a local sand substrate for wind deflation and associated dune development within the southern part of the South Texas eolian system.

During a Wisconsin (late Pleistocene) interglacial stage (Peorian?), the Rio Grande deposited extensive fluvial sediments, herein called the Raymondville fluvial system (see figure 10). The Raymondville system (fig. 4) may be contemporaneous with the Ingleside system in the Corpus Christi (Brown and others, 1976) and Port Lavaca (McGowen and others, 1976) map areas. This younger Pleistocene Rio Grande system (younger Beaumont Formation) is exposed over a broad region in the central part of the map area. In the outcrop area, relict sandy meanderbelts and associated mud-filled floodbasins exhibit northeast-southwest alignments. Near Laguna Atascosa, younger Beaumont marine sand and thin mud deposits, herein called the Atascosa system, overlie Raymondville fluvial deposits (see figure 10).

Collectively, these late Pleistocene (younger Beaumont) sediments represent the youngest Pleistocene deposition in the map area. The Raymondville fluvial system extends northeastward beneath the South Texas eolian system where Holocene-Modern eolian processes (Norias lobe, see figure 25) have eroded much of the relict sandy river deposits (fig. 4). The fluvial system extends coastward beneath Holocene-Modern deposits. Southward, the Raymondville system was, at least partly, eroded by valley incision related to sea-level fall during latest Wisconsin glaciation (post-Peorian low stand, fig. 5B). The Rio Grande became a superimposed stream when latest Wisconsin sea level began to drop, leading to extensive late Pleistocene valley erosion.

The Raymondville (high stand) system apparently grades gulfward into a delta that lies beneath Laguna Madre, Padre Island, and the inner part of the shelf. How far the Raymondville fluvial system and its buried delta system prograded over the submerged (high stand) Peorian (?) shelf is unknown. Coring and seismic-stratigraphic studies will be required to chart its gulfward distribution. We do know, however, that apparent delta-front (and/or marine transgressive) deposits are locally exposed in the Atascosa marine system. These exposed sediments may be the most updip preserved delta deposits associated with Peorian (?) fluvial-deltaic deposition. Marine reworking associated with the Atascosa system could range from intra-Peorian reworking of a delta lobe to Modern transgression of the Raymondville system. Latest marine activity in the Atascosa system apparently was before development of the Resaca de los Cuates distributary of the Holocene-Modern Rio Grande delta.

The gulfward extent of the Raymondville fluvial system and its contemporaneous delta system (now buried beneath Holocene-Modern deposits) marks the position of the South Texas shoreline about 50,000 to 60,000 years B. P., just before the last episode of continental glaciation (late Wisconsin).

When sea level began to drop in response to the final episodes of glaciation, rivers along the Texas coast, as well as throughout the world, could no longer shift their courses. Dropping sea level caused extensive down-cutting and lateral erosion into older, underlying deposits by streams, such as the late Pleistocene Rio Grande (fig. 5A and B). As sea level dropped more than 400 feet, a deep, broad scalloped-shaped valley was eroded into older Pleistocene fluvial and deltaic plains by vertically incising and laterally shifting courses of the Pleistocene Rio Grande.

According to shallow seismic records, the Texas shelf exhibits a number of eroded valleys that developed during this final drop in Pleistocene sea level (see Atlases of other coastal areas). The valleys normally exhibit a dendritic tributary pattern, and depths of buried valleys near the present coastline averaged approximately 100 feet below current sea level. Rainfall was greater in South Texas during glacial stages because of the climatic effect of masses of continental ice in Canada and northern United States. All over the world, valleys extended to the late Pleistocene shoreline, normally near the present continental shelf edge. Maps of buried Pleistocene valleys beneath the South Texas continental shelf are unavailable at this time, but interpretation of seismic data for the inner shelf may permit mapping of these features.

HOLOCENE HISTORY

As final glacial episodes diminished about 18,000 years B. P. and meltwater began to reach the oceans, sea level began its last rise (fig. 5C). At that time, the South Texas shoreline stood near the continental shelf edge about 50 to 55 statute miles to the east of present Padre Island. The 18,000-year-B. P. shoreline outlined the terminus of the late Wisconsin Rio Grande (low stand) delta. As sea level rose, the Rio Grande Valley was transgressed slowly by brackish to marine waters. The resulting estuarine system occupied a broad submerged valley now buried beneath the shelf, Padre Island, the southern part of Laguna Madre, and the lower part of the Rio Grande Valley. Wave erosion along the margins of the Rio Grande estuary and subaerial erosion of valley walls widened the original Pleistocene valley. Sea level rose at varying rates, sometimes pausing because of variations in glacial activity (fig. 5C). Pauses and minor reversals in sea-level rise are evidenced by submerged shoreline sands and carbonate-cemented beach rock that occur on the floor of the shelf, far from the present shoreline; these sands were deposited as beaches and offshore shoals that mark temporary positions of the transgressing Holocene strandline.

During the Holocene, the South Texas climate became progressively arid, and persistent southeast wind systems began to develop. Eolian (wind) deflation or erosion of coastal plain sediments increased in intensity. Deflated sands accumulated in large, shifting dune fields and dune trains that covered much of the mainland between Baffin Bay (in the Kingsville map area) and the Rio Grande delta. Locally, eolian deflation of Pleistocene fluvial-deltaic deposits produced narrow, elongate dune trains in the Brownsville-Harlingen map area south of the eolian system. The precise nature and distribution of Holocene eolian deposits are still uncertain, but the Modern South Texas eolian system certainly evolved from its Holocene counterpart.

From 18,000 to about 10,000 to 7,000 years B. P., the late Pleistocene Rio Grande Valley was filled progressively (up-valley) with Holocene deposits composed of tide-transported open marine sediments, estuarine sediments, deltaic sediments and, in upper reaches of the valley, with meandering fluvial sediments. As a result of gradually rising sea level, this succession of estuarine/valley-fill deposits slowly and irregularly shifted up the valley to produce a transgressive early and middle Holocene sequence composed (upward) of basal fluvial deposits followed by successively younger fresh to brackish estuarine deltaic sediments and finally by near-shore and open marine deposits. These early and middle Holocene sediments currently are buried beneath late Holocene and Modern deltaic and fluvial deposits.

Beginning in mid to late Holocene, perhaps about 10,000 to 7,000 years B. P., the Rio Grande reversed estuarine transgression and began to prograde its delta over earlier Holocene transgressive deposits

(Fulton, 1976). At least three major late Holocene delta lobes (one in Texas, one in Mexico, and one centered along the present Texas-Mexico border) prograded beyond the present coastline (Lohse, 1952 and 1958). The gulfward limits of these lobes have not been defined, but they probably did not extend more than 10 to 15 miles beyond the present coastline. Contemporaneous with delta progradation, the upstream Rio Grande slowly filled its subaerial valley by meanderbelt (point bar) and flood-basin mud deposition. Sediment supply and, consequently, delta progradation began to diminish about the time sea level reached its approximate present level (4,500 years B. P.). Modern South Padre Island formed and began to transgress slowly landward over the subsiding and eroding late Holocene Rio Grande delta between 3,400 and 1,900 years B. P. (McGowen and others, 1977).

MODERN HISTORY

During approximately the past 4,500 years, compaction of sediment, slow subsidence of the Gulf Coast Basin, and minor glacial fluctuations (4,500 to 2,800 years B. P.) have resulted in relative changes in sea level of probably less than 15 feet (fig. 5C). Since about 2,800 to 2,500 years B. P., when sea level stabilized, the Coastal Zone has gradually evolved to its present condition by erosion, deposition, compaction, and subsidence—processes still important and operating today. Gradual subsidence continues as Pleistocene and older deltaic muds compact and as the Gulf Coast Basin continues its inevitable structural development.

When sea level approached its present level 4,500 years B. P., several changes began along the coastline in the Brownsville-Harlingen area: (1) estuarine erosion and deposition, initiated during Holocene sea-level rise, rapidly terminated; (2) mid- to late-Holocene Rio Grande fluvial and deltaic deposition diminished significantly by 3,500 years B. P.; (3) the Arroyo Colorado continued headward erosion into the late Pleistocene coastal plain (Raymondville system) and eventually pirated drainage from the northern part of the Holocene-Modern Rio Grande floodbasin; (4) eolian processes slowly modified the coastal plain in response to prevailing southeasterly winds; (5) southern Laguna Madre and associated small bays were gradually formed as South Padre and Brazos Islands formed and began to transgress landward over the subsiding Rio Grande delta about 3,400 years B. P.; (6) Padre Island became repeatedly subjected to intense eolian processes and local breaching by hurricane storm tides, which shifted the island landward and transported large volumes of shoreline sediment into Laguna Madre; and (7) Laguna Madre began filling by deposition of extensive wind-tidal flat and marine grassflat sediments along the mainland side of Laguna Madre and by stormwashover deposits along the lagoon side of the transgressive Padre Island.

Estuarine Erosion and Deposition

As previously stated, lowered sea level during the last glacial episode caused the Rio Grande to erode a broad, deep valley eastward across the map area and across the exposed continental shelf. With Holocene rise in sea level caused by diminishing glaciation about 18,000 years B. P., the large valley was flooded to form an estuary. By about 10,000 years B. P., the submerged valley probably extended 20 to 30 miles inland (westward) from the present shoreline, but insufficient core data are available to chart its maximum distribution. During early and middle Holocene, some sediment was probably introduced into the valley by transgressing brackish estuarine and marine environments. By 4,500 years B. P., estuarine sedimentation had ended (McGowen and others, 1977; Herber, in progress). Older Holocene estuarine deposits are buried beneath younger Holocene and Modern Rio Grande delta sediments.

By mid to late Holocene (10,000 to 7,000 years B. P., Fulton, 1976) and perhaps earlier, the Rio Grande had begun to fill the upper end of its estuary by prograding deltaic and aggrading fluvial sands and muds. Sufficient sediments were available to permit delta progradation even during final Holocene sea-level rise.

Rio Grande Delta System

By the time Holocene sea-level rise had reached its approximate Modern position about 4,500 years B. P., the Rio Grande fluvial-deltaic system (fig. 4) had filled its estuary and was prograding gulfward near the present shoreline (Lohse, 1952 and 1958; Fulton, 1976). Shifting delta lobes are evident from the distribution of meander-belts (fig. 4). Holocene lobes that filled the estuary were generally lobate in geometry resulting from limited wave energy. When the Modern Rio Grande delta began to discharge directly into the open Gulf of Mexico, it constructed a sandy, wave-dominated delta exhibiting a cusped areal geometry like the Modern Brazos delta.

Beginning at the mouth of the Rio Grande and extending northward to the vicinity of the Port Mansfield Channel, there are at least three lobes of the Modern-Holocene Rio Grande delta. The youngest lobe was constructed in the area of the present mouth of the Rio Grande. The oldest lobe, which now underlies the deeper parts of south Laguna Madre, is north of Port Isabel and east of Laguna Atascosa National Wildlife Refuge. Delta-plain deposits of this lobe lie some 10 feet below the surface of south Laguna Madre; a carbon-14 age of 5,000 years B. P. was determined from wind-tidal flat deposits that immediately overlie the delta plain (Herber, in progress). The next to the youngest lobe occupied an area approximately defined by the broad wind-tidal flats between the Port Mansfield Channel and La Punta Larga. Organic material obtained from a distributary channel of this delta lobe has a radiocarbon age of $2,680 \pm 740$ years B. P. (McGowen and others, 1977); then sea level was approximately at its present position.

Sediment discharge has diminished during the past 4,500 years, and during the past 40 to 50 years discharge has almost ceased because of extensive irrigation and dam construction along the Rio Grande and its principal tributaries. Consequently, today the Modern Rio Grande delta is undergoing wave destruction (principally by storm impact). South Padre Island and Laguna Madre are retreating (or transgressing) landward over the subsiding late Holocene-Modern Rio Grande delta.

How far the Rio Grande delta prograded over the inner continental shelf can be determined by coring and shallow seismic studies. We can estimate its probable extent by carbon-14 dates (McGowen and others, 1977) and by adjusting the estimate with observed erosional rates during past decades along southern Padre Island (Morton and Pieper, 1975). Conservative estimates indicate that about 3,500 years B. P. the South Texas delta shoreline stood about 10 miles gulfward of the present shoreline (fig. 4). The current prognosis for South Texas is continued subsidence and gradual retreat of the Gulf and mainland shorelines.

Headward-Eroding Streams

Because of low rainfall and stream discharge in the Brownsville-Harlingen area, development of headward-eroding streams has been limited principally to the Arroyo Colorado. A few other small, ephemeral streams are slowly eroding headwardly into Pleistocene fluvial deposits and Holocene-Modern floodbasin deposits.

High rainfall that is associated with hurricanes normally produces flooding along these small stream systems. Streams may be active for a few days to 2 weeks following passage of a tropical storm or hurricane.

The Arroyo Colorado probably began headward erosion when late Wisconsin sea level began to fall during the final glacial episode (fig. 5). It eroded headward into late Pleistocene (younger Beaumont) Raymondville fluvial deposits (fig. 4). Headward erosion has continued since the sea reached its Modern level, and the stream has pirated extensive runoff from the northern floodbasin of the Holocene-Modern Rio Grande near Rio Hondo. The Arroyo Colorado has eroded westward beyond the map area. Runoff from the large impermeable floodbasin originally drained coastward from near Lozano along an area of natural coastal lakes (now site of man-made Sweeney and Cross Lakes) on the north side of Resaca de

los Fresnos levees and eventually into Laguna Atascosa and Cayo Atascosa. While active headward erosion continues within the pirated floodbasin, the downstream segment of the Arroyo Colorado is depositing a meanderbelt. Discharge of the Modern Arroyo Colorado into Laguna Madre produced a lobate delta of undetermined size. Only leveed distributaries of the Modern Arroyo Colorado lagoonal delta rise above the broad tidal flats near Hawk Island. Levees have served as nuclei for windward-accreting clay dunes to produce part of the Hawk Island clay-dune fields (see figure 10).

Two other areas of actively eroding streams are located along the western side of Laguna Atascosa and Cayo Atascosa and 5 miles west of Port Mansfield. The former are small, marsh-lined streams cutting into the late Pleistocene Atascosa marine deposits (see figure 10). The latter system has pirated drainage from the large El Jardin eolian deflation basin and discharges into Laguna Madre in the Fourmile Slough area.

Price (1958) described the Mercedes-Raymondville Recent floodway and suggested that it was an abandoned, short-lived discharge channel for the Modern Rio Grande (see figure 10). The floodway was locally erosional and depositional and apparently discharged into Laguna Madre in the vicinity of Fourmile Slough. Its precise course is uncertain, but it apparently flowed along the north side of the Raymondville fluvial system and possibly through the El Jardin deflation depression.

Eolian Deflation and Dune Development

The degree of eolian activity in South Texas during the Pleistocene is difficult to assess. Studies of subsurface Pleistocene deposits may show that wind was an important agent in South Texas during various interglacial stages, but at this time its significance is purely conjectural. In the Kingsville area, Fisk (1959) showed that some of the oldest Holocene deposits are eolian in origin. These wind-deposited sediments lie directly upon late Pleistocene soils and intertongue with Laguna Madre sediments. A sample of eolian sediments was dated by carbon-14 at 11,450 years B. P., a middle Holocene age. In the Brownsville-Harlingen map area, the South Texas eolian system directly overlies and is derived from late Pleistocene sediments (fig. 4).

As glaciation diminished and sea level rose, the Holocene climate in South Texas became increasingly arid. This aridity, coupled with persistent southeasterly onshore winds, led to wind deflation and development of extensive dune fields. Dunes in the Port Mansfield vicinity were supplied with sand deflated from late Pleistocene Raymondville fluvial meanderbelts (fig. 4). Broad eolian sand sheets along the northern margin of the map area were deflated from older Beaumont and Lissie delta and fluvial sands, respectively.

Several stabilized dune trains exhibiting precise northwesterly orientation occur far south of the conterminous South Texas eolian system. The Faysville, Edinburg, and Rio Hondo stabilized dune trains document the aridity and persistence of southeasterly winds in the southern part of the map area (see figure 10).

Distribution of Modern-Holocene eolian dunes was affected principally by variable depth of local ground-water table, average orientation of the southeast wind regime, and distribution of deflatable sand substrates in the region. During the past several thousand years, climatic rainfall cycles resulted in alternating periods of extensive dune activity and of moderate stability accompanied by the spread of vegetative cover. Older, stabilized dunes are covered with live-oak mottes; active dune fields are barren to sparsely grass covered. Cyclic reactivation of dune fields has developed large eolian sand lobes characterized by hummocky topography dominated by strong northwest-southeast blowout ridges and deflation troughs. Silt, winnowed from the dune field by wind deflation, is blown downwind and deposited as a thin, locally discontinuous loess sheet covering Pleistocene and Holocene-Modern fluvial and deltaic deposits. Thin and extensive, but unmapped, loess sheets extend inland from 10 to 15 miles along the western margin of Laguna Madre and associated small bays. The loess is derived by deflation

of wind-tidal flats and Pleistocene and Holocene-Modern fluvial-deltaic sediments along the western margin of Laguna Madre and in the vicinity of South Bay and Bahia Grande. Principal loess lobes occur downwind (northwest) of the Hawk Island clay-sand dune fields and the Gavilan clay-sand dune fields (see figure 10). Downwind from the Gavilan source, salty loess has draped the Holocene-Modern delta plain and has produced the highly saline soils of the Jackass Prairie.

Barrier Island and Lagoon Development

The Holocene-Modern Rio Grande fluvial-deltaic system prograded the South Texas shoreline to a position estimated to have been at least 10 miles east of its present location (fig. 4). The delta prograded into the open Gulf of Mexico and probably deposited a complex cusate delta system composed of accretionary barrier bars, delta-plain meanderbelts, lakes, and brackish lagoons. Between 3,400 and 1,900 years B. P., the sediment supply delivered to the delta began to diminish slowly as increasing aridity and decreasing rainfall combined to reduce discharge of the Rio Grande. In the absence of sufficient sand to maintain delta building, the Rio Grande delta began to subside slowly with consequent net erosion of the delta-front barriers. Modern Padre Island probably originated when lobes of the Rio Grande delta in Texas began to subside between 3,400 and 1,900 years B. P., permitting Gulf waves and storm surges to erode and rework the shoreline sands into transgressing offshore shoals. Shoals gradually coalesced to form South Padre Island, a peninsula attached to the retreating Rio Grande deltaic headlands. The sandy transgressive peninsula eventually was connected northward to middle and northern Padre Island. Southern Laguna Madre developed upon the subsiding Rio Grande delta plain and was restricted between Padre Island and the mainland. Padre Island and Laguna Madre have both shifted progressively landward, transgressing the relict delta; however, it appears that transgression is accelerating as the volume of relict (shelf) and river-derived sand decreases. Morton and Pieper (1975) documented a maximum net rate of more than 12 feet per year of island retreat over approximately the past 100 years. This rapid transgression of the thin sands of South Padre Island is filling Laguna Madre with storm washover and eolian dune sediments. Under the present sediment/subsidence regime, the fate of South Padre Island is projected to be continued erosion and landward retreat, which may ultimately fill south Laguna Madre, similarly to the Land-Cut Area to the north where Fisk (1959) estimated that the central part of Laguna Madre was filled about 150 years ago (Kingsville map area). The South Texas barrier coastline is becoming progressively starved for sediment necessary to maintain its position.

Lagoon Deposition

When South Padre Island was formed and began to retreat westward between 3,400 to 1,900 years B. P., broad, shallow waters between the island and the subsiding relict delta shoreline formed Laguna Madre. The lagoon had slowly encroached onto the mainland by subsidence of the relict delta system and by wave and wind erosion of the western shoreline. Subsidence is documented by small islands, such as Three Islands, Rattlesnake Island, Green Island, La Punta Larga, and Los Bancos de en Medio, which are interpreted to be remnants of Holocene-Modern delta-plain distributary levees and accretionary clay dunes that have foundered beneath encroaching Laguna Madre waters. Similarly, aligned shallow sand and oolite shoals in Redfish Bay possibly originated in areas of submerged late Pleistocene Raymondville meanderbelt sands that have been reworked by lagoon waves and currents. In turn, the broad lagoon has been progressively narrowed by the rapid encroachment of Padre Island. Padre Island is being pushed persistently into Laguna Madre by storm surges which transport sands of the critically thin barrier into the eastern side of the lagoon. During dry seasons, southeasterly winds continually move sand dunes lagoonward onto wind-tidal flats where the sand is distributed into the lagoon by wind-tides and periodic storm-surge tides.

Laguna Madre is less than 3 feet deep, except at its southern end where 3 to 6 feet of water occur near Brazos Santiago Pass and in the northern part of the map area where Redfish Bay is almost 9 feet deep. Extensive spoil dredged to build the Intracoastal Canal, Mansfield Channel, and Brownsville Ship

Channel has been deposited in the lagoon where waves and currents are eroding and depositing the sediment over large areas of the lagoon.

As the lagoon fills, extensive marine grassflats, the spawning habitat of many marine organisms, are being reduced substantially. This long-term trend contrasts with the short-term trend that indicates grassflats in some areas of Laguna Madre are expanding. Lagoons and complementary barrier islands are short-lived, relatively ephemeral geologic features which depend upon an adequate sediment supply and the maintenance of a delicate balance among various coastal processes. The ultimate fate of southern Laguna Madre appears to be its eventual elimination by sediment filling both by natural processes and human intervention.

Wind-Tidal Flats

Broad, low wind-tidal flats have developed during the past several thousand years in the Brownsville-Harlingen map area. These unique geologic environments and processes have become important in the geologic development of the region because of the dominant influence of winds on the low, poorly vegetated barrier islands and the adjacent mainland bounding southern Laguna Madre and associated small bays.

Wind-tidal flats within Laguna Madre (fig. 4) occupy many square miles of sandy to muddy, commonly hyper-saline areas. Wind-tidal flats are developed along parts of the mainland shoreline and on the lagoon side of Padre Island. Flats on the mainland side are underlain dominantly by mud, whereas the flats on the lagoon side of Padre Island are underlain mostly by sand. Muds along the mainland flats are derived from fluvial sources and from Laguna Madre; deposition occurs on the flats when the east and southeast winds drive lagoonal waters onto these low-relief features. The sandy sediment that underlies the flats associated with Padre Island is transported predominantly from South Padre Island by hurricane-tidal surge and by prevailing southeasterly winds. Elevations on the flats that are associated with South Padre Island are generally less than 3 feet (MSL), but some mainland flats are as high as 5 feet above MSL and generally are flooded only by tropical storms and hurricanes, but rarely by northers. Flats below 3 feet (MSL) are regularly flooded by wind tides that are generated by southeast, south, and north winds; the flats are also flooded under low barometric pressure conditions when there may or may not be a significant wind.

Fluctuating winds and related tides preclude a precise, stationary shoreline position since it can shift several miles within hours. Wind tides smooth and redistribute sediments contributed to the flat by washover fans, sand dunes, and river discharge (Arroyo Colorado, Cayo Atascosa, and Fourmile Slough). In addition, flood-tidal waters transport suspended clay, which settles out within local, depressed shallow basins on the flats associated with Padre Island and over broad areas of the mainland flats. Algae bloom on the shallow, submerged flats, but after emergence, the clay on the mainland flats becomes cracked, pelletized, and blown downwind to form thin, extensive loess sheets and local accretionary clay dunes. Evaporite minerals form within wind-tidal flat deposits at approximately the top of the water table. Marine grasses flourish below mean sea level adjacent to the flats, but the wind-tidal flats are mostly barren of rooted vegetation. Blue-green algae, however, are prolific on the flats. The flats occupy the niche that coastal marshes occupy in the more humid middle and upper parts of the Texas Coastal Zone. Very limited marsh development occurs in the Brownsville-Harlingen map area. Broad wind-tidal flats are a unique part of the coastal environment in the arid South Texas coastal region. Wind-tidal flats typically develop where Laguna Madre is encroaching upon the subsiding deltaic coastal plain and where Padre Island is encroaching westward into Laguna Madre.

HISTORICAL SUMMARY

The upland prairies of the Brownsville-Harlingen area are underlain by sediments deposited during at least two Pleistocene (ice age) fluvial and deltaic episodes. The older systems, the Lissie fluvial system

and older Beaumont delta system, were deposited more than 100,000 years ago during one or more interglacial stages (fig. 5). The younger Pleistocene systems, the (younger Beaumont) Raymondville fluvial system and its contemporaneous delta system (now deeply buried beneath the inner continental shelf, Padre Island, and Laguna Madre), were deposited during a late interglacial stage (Peorian?). About 30,000 years ago, in response to final stages of continental glaciation, sea level was lowered about 450 feet, resulting in erosion of a broad, deep valley by the Rio Grande (fig. 5). When sea level reached its lowest point, the Rio Grande flowed through a valley that extended across the continental shelf to a shoreline near the present edge of the continental shelf.

By 18,000 years ago, sea level began its last irregular rise, marking the beginning of the Holocene. During sea-level rise, the Rio Grande valley that extended across the shelf was slowly filled by a transgressive sequence made up in ascending order of fluvial, deltaic, estuarine, and finally with marine sediments. By at least 7,000 years B. P., the Rio Grande estuary that extended inland beyond the position of the present Gulf shoreline began to be filled by the late Holocene Rio Grande delta and fluvial systems. The estuary was filled progressively by prograding delta sand and mud and aggrading fluvial sand and mud.

When sea level reached its approximate Modern position about 4,500 years ago, the Rio Grande delta continued to prograde into the open Gulf of Mexico, where a large, wave-dominated delta prograded to a position at least 10 miles east of the present coastline. Between 3,400 and 1,900 years ago, sediment supplied to the large cusped Rio Grande delta diminished as aridity increased and rainfall decreased in South Texas. The delta could not maintain net growth; consequently, delta destruction and marine transgression were initiated and continue today.

As the last major delta lobe in Texas subsided and storms reworked its delta-front barrier bars, discontinuous offshore shoals eventually coalesced between 3,400 and 1,900 years B. P. to form South Padre Island, a sandy peninsula attached to the retreating Rio Grande headland. The peninsula eventually connected with the offshore barrier of middle and northern Padre Island, and Laguna Madre was formed between the island chain and the mainland shoreline. As the volume of sand, which was derived from the relict Rio Grande delta and directly from the Rio Grande, diminished, the island became increasingly sediment starved. Consequently, Padre Island sands have become thinner, and the island has shifted landward faster as it has become increasingly sediment deficient.

South Padre Island and the inner shelf continued to shift (transgressed) landward filling Laguna Madre progressively with storm-washover sediments and eolian deposits. Contemporaneously, Laguna Madre has shifted westward to a lesser extent over the subsiding Pleistocene and Holocene-Modern coastal plain composed of Rio Grande deltaic and fluvial deposits. Consequently, Laguna Madre has become progressively narrower, and parts of the lagoon have become shallower, as Padre Island has become thinner and increasingly erosional. Broad wind-tidal flats have developed along the eastern margin of Laguna Madre where washover sands and wind-blown sand are filling the lagoon. Along the western margin of Laguna Madre, wind-tidal flats mark the gradual subsidence and transgression of the Rio Grande delta plain. Ultimately, Laguna Madre will be filled, and the Gulf shoreline will impinge directly upon the coastal plain.

Climatic changes that accompanied the decline of worldwide glaciation slowly led to increasingly arid conditions in South Texas. Consequently, eolian processes became the dominant geologic process in the Brownsville-Harlingen map area. While Holocene sea level was rising, persistent southeast winds deflated poorly vegetated Pleistocene sand deposits on the mainland and created extensive dune fields in the northern part of the map area. Repeated, perhaps cyclic, arid episodes of dune development alternated with wetter periods when dune fields were stabilized by vegetation.

Southeasterly winds sculptured the mainland shore, locally generating large sand dune trains that migrated inland for tens of miles. Relict Pleistocene fluvial and deltaic sands provided the sediment necessary to maintain the eolian system. Clay- and silt-size sediment that was deflated from the

mainland shoreline and from marginal wind-tidal flats was carried further inland where it settled to form thin blankets of loess.

The South Texas eolian system along with the Laguna Madre and Padre Island systems has combined to produce a unique section of the Texas Coastal Zone. The arid climate, sparse vegetation, persistent onshore winds, and occasional hurricanes are principal natural factors that are responsible for the present natural systems of South Texas: erosional Padre Island, shallowing and shrinking Laguna Madre, extensive wind-tidal flats, and a mainland sculptured by eolian processes. The distinctive active processes of South Texas, combined with inevitable sediment compaction and tectonic subsidence, will continue to operate in this dynamic region.

HUMAN IMPACT ON COASTAL GEOLOGY

During the past 100 years, man has significantly modified much of the Texas Coastal Zone. The Brownsville-Harlingen region, principally an area of large ranches and irrigated and dry land farms, has experienced considerable impact from man's developments. Man has principally affected coastal geology by the extensive dredging of channels and passes, which results in discharge of spoil into bays and lagoons. Spoil discharge has modified the natural circulation patterns in Laguna Madre. Sediment supplied by dredging activities during the past few decades has far surpassed the volume of sediment supplied by natural erosion. About 16 square miles of spoil on the bottom of Laguna Madre in the Brownsville-Harlingen area are currently being redistributed, while almost 25 square miles of spoil that were piled above sea level are now undergoing erosion and redistribution within Laguna Madre. Very little made land occurs in the Brownsville-Harlingen map area.

Widespread modification and development have occurred during the past several decades at the south end of Padre Island. Marinas have been dredged into the lagoonal margin of the island to service a growing tourist population. Dunes on the island have been extensively leveled to build recreational homes and condominiums. Structures have been built in former storm-washover channels. The impact of rapid natural shoreline erosion upon the extensive man-made changes on Padre Island is inevitable. Future hurricanes that strike the island carry the potential for exceedingly high property losses and perhaps human casualties.

In the northern part of the region, large ranches covered by brushland underlain by eolian deposits have been cleared and reseeded with forage grasses. Ranchers have followed excellent land management practices. A long period of unusually severe drought might result in wind damage to reseeded pasture land. Such a problem probably can be precluded, however, by limiting the intensity of grazing on such tracts.

Extensive irrigated farms in a broad belt along the Rio Grande utilize vast quantities of river water. Complex networks of drainage and irrigation canals and ditches crisscross the southern one-third of the map area. Intensive dry land farming, principally on the Raymondville fluvial system, has resulted in the clearing of scrub brushlands and the plowing of sparse grasslands. Careful maintenance is required to sustain soil cover in this arid, windy region on the margin of the South Texas eolian system.

Limited tidal exchange with the open Gulf coupled with low stream discharge makes the southern part of Laguna Madre a restricted system. For this reason, it is critical that industrial or urban waste materials not be released into the system unless their quality is equal to the natural water quality. The lagoon system is thoroughly flushed only by hurricane-tidal surge and hurricane-aftermath rainfall. Since hurricanes cause water and some sediment to be flushed from the lagoon system, storms provide the principal means for exchanging Gulf and lagoon water. Man-made structures designed to block hurricane storm surge may severely limit this flushing mechanism. Similarly, the placement of oil-field sludge pits and solid-waste disposal sites on sandy substrates can be a threat to ground-water purity; leachate from solid-waste sites also threatens the bay and lagoon system.

There is a steady trend toward filling or modifying marine grassflats. Elimination of grassflats may destroy a critical link in the production of food for lagoon and shelf organisms as well as critical spawning grounds for many species. A principal problem in the Brownsville-Harlingen area is the elimination of grassflats within Laguna Madre by spoil disposal along the Intracoastal Waterway and along many navigation channels.

The underground disposal of liquid wastes, especially radioactive or toxic chemicals, must be based on a thorough understanding of the geology of the disposal reservoir—its geometry, hydrology, and geochemical character. Unusual care should be exercised in casing, cementing, and maintaining these kinds of disposal wells.

CONCLUSIONS

The natural environments of the Brownsville-Harlingen area are directly tied to Modern geologic processes and deposits, as well as to relict geologic deposits of the past several hundred thousand years (fig. 4). If the environmental quality of the area is to be maintained acceptably and if proper and fair use and exploitation of coastal resources are to be realized, the physical, biological, and geochemical nature of these systems and deposits must be understood. Within the region, the physical properties of sediment substrates are highly variable, and, therefore, environmental management must consider the nature of these geologic variations. The entire Coastal Zone has been the locus of dynamic processes and events for thousands of years; unless these natural systems are understood and respected, man can cause irreversible change in this important area of natural resources.

Coastal geology, environments, and processes are unusually susceptible to modification by human activities; for this reason, therefore, caution will be required to maintain a satisfactory level of environmental quality during coming decades. Scientific and engineering efforts must involve a proper understanding of and compatibility with the geological substrates and active physical processes.

HOW TO USE

The Environmental Geologic Atlas of the Texas Coastal Zone contains two kinds of information: (1) an *Environmental Geology Map* and eight *Special- Use Environmental Maps* with legends; and (2) a text including description of map units, tables, illustrations, bibliography, and other pertinent material. Preparatory to using the maps of the Atlas, one should be familiar with several aspects of map reading and interpretation. The maps have been constructed to be as self-explanatory as possible, but a brief review of maps and map interpretation may be desirable.

Map Orientation

The maps in the Atlas are oriented parallel to the curving Gulf coast shoreline rather than having the standard orientation with north at the top and east and west to the right and left, respectively (fig. 1). *North-south direction* on the maps parallels *longitude lines* that can be projected across the map from values printed at the map margin: 97°15', 97°30', and 97°45'. The 97°15' longitude line, for example, is 97 degrees and 15 minutes west of the Prime Meridian at Greenwich, England. In the Brownsville-Harlingen area, 1 degree of longitude equals about 63 miles, or 1 minute of longitude equals 1.05 miles. Similarly, *east-west direction* on the maps parallels *latitude lines* that also can be projected across the map from the values printed on the map margin: 26°00', 26°15', and 26°30'. The 26°30' latitude line is 26 degrees and 30 minutes north of the Equator. One degree of latitude equals 69 miles, and one minute of latitude equals 1.15 miles. When using the maps, therefore, it is important to be aware of the cardinal directions of north, south, east, and west; the small index map at the lower right of each map provides immediate visual orientation of the Brownsville-Harlingen area within the Coastal Zone.

Magnetic declination in the center of the Brownsville-Harlingen area during 1975 was approximately 9 degrees 16 minutes easterly; magnetic North Pole is thus 9 degrees 16 minutes east of the geographic North Pole in the area. This simply means that a compass will read 9 degrees 16 minutes more easterly or clockwise than true, or geographic, North. Nine degrees 16 minutes must be subtracted from any magnetic bearing in this area if the bearing is to be converted to true, or geographic, North Pole.

Map Scales

Two kinds of horizontal scales are printed near the bottom of each map: fractional and graphic. The *Environmental Geology Map* was prepared with a fractional scale of 1:125,000. This means that one unit on the map equals 125,000 similar units in the area mapped: for example, 1 inch on the map equals 125,000 inches on the ground, or 1 inch on the map equals approximately 2 statute miles (63,360 inches per statute mile). The fractional scale for the eight *Special-Use Environmental Maps* is 1:250,000, or 1 inch on a map equals approximately 4 miles in the Brownsville-Harlingen area.

The *graphic scale* is convenient for determining distances or areas. The *Environmental Geology Map* has three graphic scales printed below the fractional scale: statute miles (5,280 feet per mile); kilometers (0.62 of a statute mile); and nautical miles (6,076 feet per nautical mile or about 1.15 statute miles). The eight *Special-Use Environmental Maps* have graphic scales in statute miles. The selection of scales for maps of this Atlas was based on maximum utility for detailed site evaluation and regional planning and analysis. Each map is presented on a controlled base, permitting accurate location and measurement. Conversion factors enabling the reader to convert to other measurement systems are provided in tables 3 and 7.

Topography and Bathymetry

Elevation and the topographic configuration of the land surface are shown by brown *contour lines* on the *Environmental Geology Map*. These lines trace equal elevations above mean sea level; *topographic contour interval*, or vertical distance in feet between the successive contour lines, is 5 feet, as shown on the map beneath the graphic scale. Each contour line value can be identified at points along the line by a number indicating the number of feet above the blue mean sea-level line; for example, contour lines have values of 5, 10, 15, 20, 25, and so forth. To determine the approximate elevation of any point in the map area, simply estimate the position of the point relative to the next higher and lower contour lines (a point will rarely occur directly on one of the contour lines); if a point is about midway between the 30- and 35-foot contours, the elevation is approximately 32 or 33 feet above mean sea level.

Similarly, on the *Environmental Geology Map*, the depth of bay bottom and the Gulf floor is shown by blue *bathymetric lines* tracing equal depths. *Bathymetric contour interval* is commonly 6 feet, or at 6-foot vertical intervals (1 fathom) below mean sea level (-6, -12, -18, -24 feet), but in shallow parts of bays and inlets, 3-foot bathymetric contours are locally shown. The approximate depth at any point in a bay or the Gulf can, therefore, be determined in the same manner as estimating elevations above sea level.

One of the special-use environmental maps, *Topography and Bathymetry*, has both land elevations and bay-Gulf bathymetry shown in shaded colors. Each 5-foot topographic contour interval above sea level and each 6-foot bathymetric contour interval below sea level is depicted by a distinctive color, enabling easy interpretation of the land and bay-Gulf bottom configuration.

Other General Map Information

Cities, towns, ranches, airports, lakes, rivers and streams, highways, pipelines, railroads, county lines, city limits, canals, oil tanks, and other cultural and natural features are shown by symbols on the maps. Such features are commonly labeled for easy identification. All paved highways are included on the maps, but only Texas and U. S. numbered highways are labeled. Conventional map symbols used to

represent this general geographic information are not included in the map legend. Users should, however, be aware of the extensive data that can be obtained by a careful study of each map.

The base map with its contours and natural and cultural features was constructed specifically for the Environmental Geologic Atlas of the Texas Coastal Zone from U. S. Geological Survey 7.5-minute topographic maps. This base map is the most accurate available regional map of the Texas Coastal Zone.

MAP LEGEND

Each map includes a legend designed to explain briefly and concisely every map unit delineated. For convenience, legends are standardized for each of the seven map areas within the Coastal Zone. The same color and order of legend units are followed on similar maps throughout the Zone. For example, any specific map unit can be readily identified and traced throughout the Coastal Zone by its distinctive color. Standardization of map colors permits joining of maps of the seven areas into a single sheet for the entire Coastal Zone. Slight differences in the color of a specific map unit, however, may occur from one map area to another because of minor variations in printing conditions.

Legend descriptions of a specific unit may change slightly from one map area to another because of natural regional environmental variations. As long as an environmental geologic unit represents virtually the same genetic process, substrate unit, vegetational type, or man-made feature, or as long as a special-use environmental unit represents the same general properties or characteristics, the map unit carries the same name and map color or symbol. A few map units may vary in color on different special-use environmental maps within the same Atlas in order that the color will be compatible with the specialized legend and color code of the specific map.

Units on the *Environmental Geology Map* are listed under respective *natural systems*. These systems are designated either *Pleistocene* or *Modern-Holocene*. This distinction refers to the relative ages of the systems. In general, *Pleistocene* refers to older units deposited before sea level began to rise at the end of the last principal glacial episode about 18,000 years B. P. During the rise in sea level from 18,000 to 4,500 years B. P., *Holocene systems* developed. All substrate, process, vegetation, and man-made units of the past 4,500 years, since sea level reached its approximate present position, are herein called Modern. For convenience, Holocene and Modern units have been grouped together because some units are of both late Holocene and early Modern age. Properties and characteristics of environmental geologic units are emphasized rather than age relationships.

Some map units, such as marsh, are component parts of more than one natural system; these are denoted in the legend by an asterisk. Also, some Modern units, such as clay-sand dunes may occur superimposed on an older Pleistocene system; these are clearly denoted within the legend. Legend description of units on each map is purposely brief; each unit is, however, thoroughly described and its special significance discussed within the text. Table 1 shows the page number(s) where each unit is described and the map(s) on which the unit occurs. The order of units presented in map legends and within the text is generally similar, in order to facilitate use of the text descriptions.

The areal extent of each map unit, the length of linear features, and the number of specific environmental units within the Brownsville-Harlingen map area are noted in tables 3, 7, and 9-14. For example, the area covered by fresh-water marsh and the area being used as rangeland are listed in the tables. In addition, the percentage of each unit within the Brownsville-Harlingen map area is listed. The total length of features such as pipelines, erosional shorelines, or transportation canals and channels is tabulated, as is the number of specific sites such as power-generation plants, waste-disposal pits, and airports. The areal extent of units is listed in square miles; linear features are in miles. Measurement of areal data is based on point-count methods and is crosschecked by planimeter techniques. Average values proved to exhibit greater than 90-percent accuracy. Linear features were measured by map-measuring wheels, and

average values display greater than 95-percent accuracy. Accuracy of quantitative data is principally limited by the scale of the maps and the nature of the polyconic map projection.

ENVIRONMENTAL RESOURCE SUBJECT GUIDE

An extensive alphabetized index of information concerning the Coastal Zone has been compiled to afford easy access to desired information (table 2). The table provides a subject guide for locating general information, as well as information not specifically included in the map legends; both map and text sources are indexed. Following is an example of how this material may be used. One may wish to determine areas with very low permeability that would serve as satisfactory solid-waste disposal sites. By referring to permeability on table 2, the reader is directed to the Physical Properties Map, to specific pages in the text, and to a table evaluating land use suitability in the Brownsville-Harlingen area (table 6). In this manner, the areas of low permeability can be located on the Physical Properties Map. Reference to the text and table 7 provides additional description and evaluation of landfill suitability. In addition, if the user wants to know the percentage of improperly located solid-waste disposal sites within the Brownsville-Harlingen area, he can evaluate the sites based on the properties at each location (Physical Properties Map) and determine the percentage. Interpretation of data in this manner will naturally depend upon the experience of the user in the subject of interest.

GENERATING ADDITIONAL DATA

For cartographic convenience and feasibility, basic data are presented on a series of nine maps. Combining information from two or more maps may provide additional insight into an area or provide a specific solution to an environmental problem. Many other special maps can be prepared by the user to present any combination of properties or characteristics necessary. For example, to evaluate an area in terms of potential for recreational parks, characteristics desirable for this particular land use must be defined. If the desired recreational land should be well drained, above hurricane-tidal effects, accessible to the bay areas, vegetated with live-oak mottes, and remote from oil fields, pipelines, power lines, and residential or populated ranching communities, then the coincidence of these several factors, obtained by overlapping the special-use environmental maps depicting the required properties, outlines areas suitable for this type of recreational development. All of the recreation requisites can be obtained from various maps of the Environmental Geologic Atlas of the Texas Coastal Zone; a map that locates and rates potential recreation sites can, thereby, be prepared by the user.

If an industrial site is desired within a region, the area can be analyzed using the Atlas. For example, the *Physical Properties Map* outlines areas with suitable foundation strength and related properties; the *Current Land Use Map* indicates the current use and approximate value of the land, as well as location of residential areas for employees; the *Mineral and Energy Resources Map* indicates availability of construction materials, pipeline facilities, railroads and highways, and principal power lines; the *Topography and Bathymetry Map* shows the slopes and land configuration which might bear on the site selection; the *Rainfall*, *Stream Discharge*, and *Surface Salinity Map* illustrates climatic data that might be critical; the *Man-Made Features and Water Systems Map* shows drainage systems, reservoirs, made land, and other related elements within the area; and the *Environments and Biologic Assemblages Map* provides information on vegetation at potential sites. In this manner, an environmental analysis may be made to evaluate a site or area for a specific potential land use, or a broad area may be analyzed in order to outline favorable sites for specific uses.

Other maps may be made from the Atlas outlining areas of positive or negative suitability for a specific use, and the entire area can be grouped into various capability or use grades from excellent to poor on the basis of the number of desirable land factors which coincide. The varieties of special-use environmental maps that can be prepared from the basic *Environmental Geology Map* and units on the eight *Special-Use Environmental Maps* are virtually unlimited. By combining maps of this Atlas with

other sources of economic, planning, industrial, transportation, or sociological data, a broad spectrum of environmental problems and management goals can be solved or at least outlined and properly defined.

ENVIRONMENTAL GEOLOGY MAP

The *Environmental Geology Map* of this Atlas is designed to be a basic document and inventory of the natural resources of the Texas Coastal Zone. It is the basic map from which most of the special-use maps were derived and compiled; it serves as a data source for the generation of other special-use maps. The map is also a base on which a variety of other information can be projected. Units delineated on the *Environmental Geology Map* are of first-order significance for both resource preservation and use (table 1). Four basic kinds of units are (1) physical units, including geologic substrates, soils, and subaqueous sediments where composition and physical properties are of principal importance; (2) biologic units, including chiefly subaerial units such as salt marsh, fresh-to-brackish marsh, fresh-water marsh, upland woodlands, as well as some subaqueous or submerged units, where biologic activity and productivity are dominant features in potential use or environmental maintenance; (3) active-processes units, such as storm channels, tidal passes, wind-tidal flats, and beaches, where specific active or potentially active physical processes are of first-order consideration; and (4) man-made features, such as spoil heaps, spoil wash, dredged channels, and made or reclaimed land, where these products of man's activity have resulted in significant land units. The first three kinds of mapped units—physical, biologic, and process—are natural units; the fourth kind—man-made—is an artificial unit.

Two broad classes of natural units exist within the Brownsville-Harlingen area of the Texas Coastal Zone. These include (1) natural units that are products of active processes within Modern environments, and (2) natural units formed at various earlier periods in the geologic history of the area by processes within ancient environments. All mapped areas and systems classed as Pleistocene on the *Environmental Geology Map*, forming chiefly the coastal uplands of the central part of the Brownsville-Harlingen area, are relict substrates formed in previously active coastal environments. These Pleistocene substrates also underlie the veneer of Modern-Holocene eolian deposits in the northern part of the Brownsville-Harlingen area.

The Pleistocene ice age ended about 18,000 years B. P. (fig. 5), when melting glaciers caused sea level to rise. Older Pleistocene deposits in the Brownsville-Harlingen area were deposited during interglacial periods before the beginning of the last glacial episode (Wisconsin), about 100,000 years B. P. Younger, widespread Pleistocene sediments probably were deposited, however, during a brief interglacial stage during the Wisconsin episode. Units classed herein as Modern-Holocene on the *Environmental Geology Map* include (1) deposits and landforms developed during the last rise in sea level, from about 18,000 to 4,500 years B. P. (Holocene); and (2) deposits and landforms developed during the past 4,500 years, when sea level has been approximately at its present position (Modern).

On the *Environmental Geology Map* of this Atlas, natural mapped units are further grouped into large-scale natural systems. Such grouping reflects the natural association and origin of specific mapped environmental categories. The origin of various natural units in the Coastal Zone is basic to considerations of resource evaluation and use since it determines the main textural features, composition, and morphology of the area. Natural systems delineated in the Brownsville-Harlingen area (fig. 4) are (1) fluvial-deltaic systems, a series of Pleistocene relict substrates formed by the older Rio Grande rivers and deltas and the late Holocene-Modern Rio Grande fluvial-delta system; (2) barrier-peninsula system (South Padre Island), a suite of Modern environments and substrates formed at the interface of the land and Gulf; (3) very limited marsh system, including small unmapped areas of occasionally wet grasslands of the low-lying coastal area and hummocky, interior eolian plains; (4) offshore system, embracing various units of the Modern barrier island shoreface and the inner Texas continental shelf developed seaward of Gulf beaches; (5) bay-lagoon system, consisting of Modern, restricted,

subaqueous or submerged environments (South Bay-Laguna Madre) occurring between the mainland and barrier island, and connected with the Gulf via Brazos Santiago Pass (south) and Port Mansfield Channel (north); and (6) environments produced and dominated by eolian or wind processes that occupy most of the land surface within the northern quarter of the map area. Certain specific environments, or mapped units, may occur in more than one natural system. The areal extent of these natural systems and their component map units are recorded in table 3.

PLEISTOCENE SYSTEMS

Three fluvial-deltaic systems constitute the exposed Pleistocene deposits of the Brownsville-Harlingen area (fig. 10). These include older fluvial (Lissie Formation) and delta (older Beaumont Formation) systems deposited before 100,000 years ago during interglacial stages; exposed deposits are probably of Sangamon age (fig. 5). A younger Pleistocene fluvial system (younger Beaumont Formation), herein called the Raymondville system, was probably deposited before 50,000 years ago during a brief Wisconsin interglacial stage (Peorian? fig. 5). Deltaic sediments contemporaneous with the Raymondville fluvial system are inferred to lie buried gulfward beneath Holocene-Modern deposits constituting south Laguna Madre, South Padre Island, and the inner shelf. However, exposed sediments composed of marine-reworked sands and mud-veneered sands, herein called the Atascosa marine-deltaic (?) system (fig. 10), may represent either (1) late Pleistocene reworked delta-front deposits and/or (2) Holocene-Modern marine or lacustrine deposits reworked from the Raymondville fluvial sands. Refer to Geology and Geologic History in this Atlas for discussions of the interrelationships and inferred depositional history of the Pleistocene systems.

Calichified/karstic Pliocene fluvial sands (Goliad Formation) lie buried beneath Modern loess deposits in a small area southwest of La Sal Vieja.

These older deposits of the Coastal Zone form the coastal uplands generally situated at elevations greater than 10 feet above present sea level. Pleistocene substrates are exposed in the central half of the sheet (fig. 10) north of the Holocene-Modern Rio Grande system and south of the southern margin of the Modern South Texas eolian system. The veneer of South Texas eolian sediments along the northern quarter of the Brownsville-Harlingen map area is composed of sand and loess (silt) eroded by wind deflation from underlying Pleistocene fluvial and deltaic deposits. Individual sedimentary units within the Pleistocene systems are distinguished largely by composition of geologic substrates and overlying soils, trend and distribution of sediments, and local occurrence of relict landforms.

Fluvial-Deltaic Systems

There are 15 units that were recognized and mapped within the Pleistocene fluvial and deltaic systems of the Brownsville-Harlingen map area. These include units that are entirely Pleistocene in age, those that were created during the Pleistocene and may be today receiving some sediment, and Modern-Holocene features (for example, channel courses, coastal lakes, clay-sand dunes, marine-reworked deltaic (?) sand and mud-veneered sand) that have modified Pleistocene fluvial and deltaic deposits. Excluded in this discussion are extensive eolian sand, loess, and associated units that modified Pleistocene fluvial and deltaic substrates within the conterminous South Texas eolian system. Pleistocene and younger associated units include (1) meanderbelt sands with little depositional grain preserved, (2) meanderbelt sands with depositional grain well preserved, (3) floodplain-overbank muds, (4) floodplain mud veneer over meanderbelt sands, (5) distributary and fluvial meanderbelt sands and silts, (6) interdistributary mud with sand veneer, (7) interdistributary (and floodbasin) muds, (8) marine-deltaic and/or marine-reworked deltaic and fluvial sands, and (9) mud veneer over marine-deltaic and/or reworked deltaic and fluvial sands. Other Pleistocene and/or Modern-Holocene units that are local components of fluvial-deltaic systems include (1) mud-filled abandoned channels and courses, (2) mud-filled coastal lakes or ponds, (3) active clay-sand dunes, (4) inactive and vegetated clay-sand dunes, (5) eolian sand sheet with strong relict depositional/erosional grain, and (6) eolian sand and silt veneer (on

caliche-capped fluvial sands). Older Pleistocene meanderbelt sands compose the Lissie Formation. Older deltaic sands and muds are called the Montgomery or (older) Beaumont Formations, and younger fluvial and deltaic sands and muds of the Raymondville and Atascosa systems, respectively, have been equated with Prairie or (younger) Beaumont Formations (Price, 1958). This terminology may or may not correlate with usage in the middle and upper coastal plain (Aronow, 1971; Bernard and LeBlanc, 1965). Barnes (1976) included all non-Lissie Pleistocene coastal deposits of the Brownsville-Harlingen map area in the Beaumont Formation. The Pleistocene (and locally Pliocene) fluvial and deltaic deposits occupy the central half of the Brownsville-Harlingen map area (fig. 10).

As previously mentioned (see Geology and Geologic History), absolute dating and correlation of Pleistocene deposits throughout the Texas Coastal Zone remains speculative. The Environmental Geologic Atlas of the Texas Coastal Zone can now provide the framework for further surface and subsurface studies to integrate and date the Pleistocene history of the Texas Coastal Zone.

MODERN-HOLOCENE SYSTEMS

Five major systems and one minor system are currently active in the Brownsville-Harlingen area. They have existed mostly during the past 4,500 years since sea level reached its approximate present position (fig. 5C). Deposition began in some of these systems, however, during the Holocene. Major Modern-Holocene natural systems of the area include fluvial-deltaic systems, barrier system, offshore system, bay-estuarylagoon system, and eolian system; the marsh system is of minor importance in the region. In addition, several man-made units occur within the Brownsville-Harlingen area. Forty-eight distinct and separate environments are delineated and mapped within these systems (see *Environmental Geology Map*). Specific environments are recognized by floral and faunal assemblages, geomorphic expression, depositional grain and morphology, sediment composition, and dominant active processes.

Fluvial-Deltaic System

The Brownsville-Harlingen map area is dominated by Pleistocene and Modern-Holocene fluvial systems (fig. 10). Except for the Arroyo Colorado and several other minor headward-eroding streams, all Modern-Holocene fluvial deposits are components of the Rio Grande. The entire Brownsville-Harlingen map area is dominated by either Pleistocene or Holocene-Modern Rio Grande deposits that compose three-fourths of the coastal uplands of the area.

The Rio Grande has been a major, meandering fluvial system throughout its Pleistocene, Holocene, and Modern history. Deposits of Modern-Holocene Rio Grande have accumulated in a valley that was eroded during the Pleistocene. Modern-Holocene deposits, herein called the San Benito fluvial-deltaic system (fig. 10), have almost filled the Pleistocene valley with Holocene and Modern fluvial and deltaic sediments. The San Benito system is characterized upstream by sinuous, elevated meanderbelt deposits, meander cutoffs, and level to depressed muddy floodplains. The lower or gulfward part of the San Benito Rio Grande system is composed of delta plains characterized by meandering distributary channels, crevasse splays, and saline inter-distributary basins. Because the Rio Grande system has been undergoing net retreat (or destruction) since at least 3,400 years B. P., its subsiding Gulf margin is being wind-deflated and is undergoing transgression by Laguna Madre and Padre Island (fig. 10). During the past several decades, dams and irrigation have essentially eliminated sediment discharge through the Rio Grande.

The Arroyo Colorado, the only other significant stream in the map area, has headwardly eroded into Pleistocene and Holocene-Modern fluvial deposits. Its upper reaches continue to erode, but its lower reaches are depositional and are characterized by meanderbelt deposits. The Arroyo Colorado debouched through a distributary network onto broad wind-tidal flats along the western margin of Laguna Madre. Relict levees outline the shape of the relict lagoonal delta. Most of the flow of Arroyo Colorado is

now directed through a dredged cutoff channel into Laguna Madre.

Within the Brownsville-Harlingen area, Modern-Holocene San Benito fluvial-deltaic environments are depositional and erosional sites for (1) meanderbelt sands and silts, (2) floodbasin muds, (3) distributary sands and silts, (4) interdistributary muds, (5) crevasse splays, (6) abandoned channel and course muds, (7) local marshes (salt-water, fresh-to-brackish and fresh-water), and (8) headward-eroding streams. These units principally compose the Rio Grande system, but several units also occur in the small Arroyo Colorado system.

Most of the meanderbelts, floodbasins, distributary channels, and interdistributary areas within the San Benito Rio Grande system are inactive environments that were abandoned by the shifting river earlier in its Modern-Holocene history (fig. 10). Only the present Rio Grande channel periodically floods and actively deposits sediment. Because of dams, irrigation, and limited rainfall, flow through the Rio Grande ceases at times. Only following passage of intense tropical storms and hurricanes is there sufficient discharge to activate the Rio Grande to accrete point bars, to build levees and crevasse splays, and to discharge floodwaters into floodbasins and interdistributary areas. When intense hurricane-related storms, such as Hurricane Beulah, are centered over the lower Rio Grande Valley, rainwater floods the abandoned channels and courses (called *resacas*) as well as the many depressed floodbasins and interdistributary areas of the relict delta plains. *Resacas* are filled, and the limited marshes are rejuvenated. The Arroyo Colorado also becomes an active system, discharging a vast volume of water from the northern floodbasin of the Rio Grande into Laguna Madre. Hurricane-aftermath rains may maintain discharge through the Rio Grande, the Arroyo Colorado, and the many abandoned channels, or *resacas*, for several weeks. Eventually, the Rio Grande system becomes almost inactive until the next tropical storm or hurricane strikes the area. Consequently, the Modern Rio Grande is an underfit stream characterized by ephemeral flow. Most of the Modern-Holocene San Benito Rio Grande system, therefore, is composed of relict to periodically active environments.

Barrier Island and Offshore Systems

An important natural system within the Brownsville-Harlingen area is the Modern barrier island system. Environments that make up this system result from the interaction of marine and terrestrial processes; the barrier system forms at the interface of land and ocean. South Padre Island, which constitutes the barrier system in the southern part of the Texas Coastal Zone, is a continuous strip of sand (and shell) from 0.5 to 2.5 miles wide that extends along the entire Gulf shoreline of the Brownsville-Harlingen area except for the 7.5-mile shoreline segment that lies between the Brazos Santiago Pass and the Rio Grande; this shoreline is made up of part of the Holocene Rio Grande delta, which is now in an erosional state. Two tidal inlets, Port Mansfield Channel and Brazos Santiago Pass, break the continuity of South Padre Island; the former is a man-made inlet, and the latter is a natural inlet that is jettied. A cut was made through South Padre Island in 1957 (Kieslich, 1977), and a channel (Port Mansfield Channel) was dredged across south Laguna Madre to provide the town of Port Mansfield access to the Gulf of Mexico. Throughout most of its length, Padre Island is separated from the mainland by Laguna Madre, a broad, shallow lagoon that ranges in width from about 4 to 7.5 statute miles. Broad wind-tidal flats are developed on the lagoon side of South Padre Island beginning at the northern map boundary and extending southward to La Punta Larga (approximately latitude 26° 20' N).

These wind-tidal flats are developed upon sediments transported into Laguna Madre by prevailing southeast winds and by hurricane washovers. Unlike the northern part of Padre Island and barrier islands of the central and upper Texas coast, South Padre Island lacks well-developed fore-island dunes. Fore-island dunes are present but broken by hurricane-washover channels from the northern map limit southward to the Willacy-Cameron county line. Fore-island dunes are present but poorly developed from the Willacy-Cameron county line southward to Brazos Santiago Pass; within this area, dunes are separated by broad washover channels. Fore-island dunes, although not continuous, attain heights in excess of 20 feet within the area between Brazos Santiago Pass and the Rio Grande. Washover deposits are extensive immediately to the west of fore-island

dunes beginning in the vicinity of the Port Mansfield Channel and extending southward to within about 3 miles of the mouth of the Rio Grande. Back-island dune fields are well-developed immediately to the west of hurricanewashover channels, washover fans, and wind-deflation troughs and storm runnels; back-island dunes are almost absent from the Willacy-Cameron county line southward to the Rio Grande. South Padre Island beaches consist mostly of sand; however, some beach segments contain large volumes of whole and fragmented shell. The vegetation cover on South Padre Island is sparse because of low rainfall and high evapotranspiration rates; consequently, there is little resistance to water erosion during the passage of hurricanes or to wind deflation by prevailing southeast wind and northers.

The barrier-strandplain system in the Brownsville-Harlingen area consists of 11 units which cover approximately 49 square miles, or 2.4 percent of the map area. Extending landward from the Gulf shoreline, the main components of the barrier system are beach, fore-island dune ridge, sand flats, washover distributary channels, washover fans, and back-island dunes. Other environmental geologic units along the South Padre Island barrier system include barrier flat, wind-deflation troughs and storm runnels, tidal channels, and inlet-related shoals. The island is veneered principally by soils in the Mustang series.

The offshore system of the Brownsville-Harlingen area includes the inner continental shelf that is floored in most of the area by a veneer of mud, shelly mud, sandy mud, muddy sand, and sand that overlies relict Pleistocene mud, sand, caliche, and sandstone (McGowen and Morton, 1979). Exceptions are areas where buried valleys beneath the Modern inner continental shelf are filled with thick Holocene deposits. The shoreface environment of South Padre Island is developed on relict Pleistocene deposits in the area north of Port Mansfield Channel and on Holocene fluvial and delta deposits from the Port Mansfield Channel southward at least to the U. S.-Mexico border. The shoreface extends seaward from the beach to a depth of about 42 feet, where it grades into the shelf environment (McGowen and Morton, 1979).

Probably the single most important process affecting South Padre Island is longshore drift. Currents moving parallel to the shore, combined with onshore wave and swash action, transport and deposit sediment that builds, or maintains, the shoreface and beach environments. Periodic hurricanes contribute large volumes of sediment to the longshore system by onshore storm transport of relict shelf sediments. McGowen (1979) presented a subsurface cross section of the Modern-Holocene barrier island, wind-tidal flat, and lagoon (fig. 20); also shown on this cross section is the Pleistocene erosional surface upon which Holocene transgressive strandplain deposits accumulated when Gulf waters were approximately - 70 feet MSL. Modern barrier sands of South Padre Island are thin (fig. 20). If sands contained in the fore-island dunes are discounted, then South Padre Island sands are about 4 feet thick just north of the Rio Grande and about 12 feet thick just south of the Port Mansfield Channel.

Bay-Estuary-Lagoon System

An extensive network of shallow-water bays, lagoons, and estuaries characterizes the Texas Coastal Zone; lagoons constitute a major natural system in the Brownsville-Harlingen area (fig. 4). Texas bays and lagoons are relatively low-energy environments protected on the seaward side by well-developed barrier islands. Water exchange between the lagoons and Gulf is normally limited to natural and artificial tidal passes through the barrier islands. During storms, Gulf waters also enter the bay through washovers and breaches eroded across the barrier islands. Fresh water is supplied to the bays and lagoons by larger river systems terminating at the bayheads and by several small streams that drain local areas of the adjacent coastal uplands. The series of inland water bodies that compose the bay-estuary-lagoon system along the Texas coast were formed during the Holocene when rising sea level flooded river valleys and delta plains, and offshore shoals coalesced into barrier islands and peninsulas. The general morphology or outline of the lagoon margins locally reflects relict erosional topography. For example, many of the natural islands located along the mainland shore of Laguna Madre are interpreted to be remnants of delta-plain distributary levees and accretionary clay dunes that have been inundated

and eroded by compactional subsidence and relative sea-level rise.

In the Brownsville-Harlingen region, subaqueous depositional systems include (1) Laguna Madre, a narrow, elongate lagoonal system landward of Padre Island, (2) South Bay, a small lagoon landward of Brazos Island, and (3) Redfish Bay, which is part of the Laguna Madre system north of Port Mansfield. Excluding wind-tidal flats, the lagoons and bays, ranging in width between about 3 and 8 miles, occupy 238 square miles of the Brownsville-Harlingen map area. The widest parts of southern Laguna Madre occur near its southern end just north of Port Isabel. North of a line through Three Islands and La Punta Larga, the lagoon narrows because of broad wind-tidal flats that have developed lagoonward of Padre Island. Averaging approximately 3 feet deep, Laguna Madre deepens to more than 8 feet along its axis in Redfish Bay and in the area of tidal influence near Brazos Santiago Pass. The shallowest segments of the lagoon occur landward of the broad wind-tidal flats north of La Punta Larga. Depths in shallow South Bay range from 1 to 2 feet.

The Intracoastal Waterway extends the entire length of Laguna Madre and connects with the Port Mansfield Channel, the Arroyo Colorado Cutoff, and the Brownsville Ship Channel. Dredged spoil deposited along the channels has locally modified depths and circulation patterns in Laguna Madre and South Bay.

In the Brownsville-Harlingen map area, Laguna Madre is connected to the Gulf of Mexico through Brazos Santiago Pass and Port Mansfield Channel, and to the northern part of Laguna Madre via the Intracoastal Waterway. Since dredging of the Intracoastal Waterway and the Port Mansfield Channel, the average depth of water in Laguna Madre has increased. Salinities in the lagoon are variable, but generally are greater than those in the Gulf; hypersalinity develops and is maintained by extensive evaporation of waters within the restricted lagoons and bays. Extreme hypersaline conditions that have caused massive fish kills have not occurred since the Intracoastal Waterway was dredged (Breuer, 1962). Immediately following hurricane-aftermath rainfall, the system may become temporarily freshened. Because of the hypersaline environments of Laguna Madre, the restricted biologic assemblages are unique for the Texas Coastal Zone. Oyster reefs are currently absent, except for small unmapped, scattered clumps in South Bay.

Bay-Estuary-Lagoon Environments

The various environments composing the bay-estuary-lagoon system in the Brownsville-Harlingen area form two broad categories—lagoon-margin environments and lagoon-center environments. Environments of the central part of the bay-lagoon are subaqueous. The bay-lagoon margin includes both shallow subaqueous environments and subaerial environments developed as part of the shoreline complex. Waves and currents are critical in controlling bay-lagoon margin environments (fig. 8). Various environments of the bay-estuary-lagoon system shown on the *Environmental Geology Map* are defined by the dominant physical and biologic processes and composition and by the nature of the bay-lagoon substrate.

Subaerial bay-lagoon margin environments.—The principal subaerial bay-lagoon margin environments include local mainland beaches, relict berms and accretionary bay-lagoon margin deposits, frequently flooded wind-tidal flats, and marginal eolian and transitional environments. *Mainland beaches* are poorly developed along the margin of Laguna Madre and associated bays. The beaches are erosional, and deposits are principally related to storm deposition of shell debris and some sand eroded from Modern-Holocene and Pleistocene bluffs. Mainland beaches are too small and discontinuous to map at a scale of the *Environmental Geology Map*. Most of the mainland shoreline is bounded by low, erosional escarpments cut into Modern-Holocene or Pleistocene sediments. Wind-tidal flats are developed along much of the mainland shore of Laguna Madre and inland from South Bay. Extensive wind-tidal flats that border the landward side of Padre Island do not exhibit beaches.

Subaqueous bay- or lagoon-margin environments.—The submerged margin of Laguna Madre is characterized by marginal shallow-water environments composed of narrow lagoon-margin sand, broad

low-energy areas of muddy sand with sparse to absent marine grass, and marine grassflats which extend from the lagoon margin into the lagoon center. Submerged lagoon-margin environments occur in less than 3 feet of water.

Eolian System

Most of the land surface within the Kingsville map area and almost 20 percent (350 square miles) of the Brownsville-Harlingen area are occupied by environments that have been dominated or affected to some degree by various eolian (wind-related) processes. These environments are underlain by a variety of sand and some clay deposits. Called the South Texas eolian system (or sand sheet), this complex of wind deposits and associated active processes extends more than 60 miles west (inland) of the Kingsville and Brownsville-Harlingen map area (see Laredo and McAllen-Brownsville Geologic Atlas maps, Barnes, 1976). Much of the research and many of the fundamental ideas about the eolian system are based on the work of W. Armstrong Price, who summarized his concepts in a 1958 report. Hayes (1967) and Fisk (1959) also contributed to a better understanding of eolian processes in the region.

Ten eolian environments compose the South Texas eolian system in the Brownsville-Harlingen area (table 4). Some of these and other eolian environments are also associated with the Modern lagoon, barrier island, and Pleistocene fluvial systems.

Extensive areas of the South Texas system are occupied by active sand dunes that move slowly inland (northwestward) during dry summer months under the influence of the predominant southeasterly wind regime (figs. 7 and 8). The source of dune sands is variable, but in the Brownsville-Harlingen area sand is derived principally from wind erosion of relict Pleistocene meander-belt deposits (fig. 4). At the surface, the South Texas eolian system is principally of Modern age, but older, buried wind deposits are at least as old as early Holocene (Fisk, 1959). Pleistocene eolian deposits probably occur in the subsurface within the region.

As a consequence of the wind erosion (or deflation), silt- and clay-sized sediments are winnowed from various deposits of Pleistocene, Holocene, and Modern age. Residual sands may migrate slowly northwestward across the eolian plain as sand dunes. The finer grained sediment is removed, carried downwind (inland), and deposited as extensive, relatively thin blankets of silt-sized quartz and clay particles. This airborne silt deposit is called "loess," a term that has been applied to similar deposits of windblown glacial sediment. Extensive areas of loess occur downwind from principal sand dune fields and deflation areas. In the Brownsville-Harlingen area, extensive deflation of tidal flats along the western margin of Laguna Madre and in the South Bay/Bahia Grande region produces discontinuous loess blankets along the eastern part of the coastal plain that are too thin to map.

Other large areas of the eolian system are composed of sandy to silty plains that are covered either by sparse grasslands or by brushlands. No evidence of dune development exists in these broad eolian plains. The sandy plain is, in part, composed of a veneer of loose, highly winnowed lag sand derived locally from subjacent Pleistocene sand deposits. Other areas within the eolian plain are mantled by a loess veneer derived locally from deflation of sandy and silty Pleistocene deposits. In areas underlain by a shallow water table, the amount of deflation is controlled by soil moisture derived from the intersected water table; during wet climatic cycles, deflation is prevented. Sparse grass communities cover most of the eolian plains, but brushlands have developed on areas of thicker sand veneer.

Locally, intensive wind deflation of dry playa lakes supplies the silt-sized clay pellets that are blown onto the leeward margin of the lake to produce accretionary clay-sand dunes. Relict dunes of similar origin are moderately stabilized by grass and brush vegetation. Similar accretionary deposits occur on or adjacent to wind-tidal flats (clay dunes and gabilan mesas).

Artificial Units

Small areas of made land are irregularly distributed within the Brownsville-Harlingen map area, but sub-aerial and subaqueous spoil compose continuous belts along the entire length of the Intracoastal Waterway, Mansfield Channel, Brownsville Ship Channel, and along much of the Arroyo Colorado Cutoff.

Extracted from Environmental Geologic Atlas of the Texas Coastal Zone - Brownsville-Harlingen Area. ([GRI Source Map ID 68689](#))

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Extracted from Environmental Geologic Atlas of the Texas Coastal Zone - Brownsville-Harlingen Area. ([GRI Source Map ID 68689](#))

Geoarchaeological Investigation

Caran, S.C., McCulloch, S.D., and J. Jackson, 2005, Report on a Geoarchaeological Investigation at the Palo Alto Battlefield National Historic Site (41CF92) Cameron County, Texas, McCulloch Archaeological Services, order no. p73500-40016, report number 1. (*GRI Source Map ID 74983*).

Geoarchaeological Investigation Report

Report on a
Geoarchaeological Investigation
at the

Palo Alto Battlefield National Historic Site (41CF92) Cameron County, Texas

S. Christopher Caran, Samuel D. McCulloch, and Jan Jackson
with contributions by
B.M. Albert, PhD, B.M. Winsborough, PhD, and
Isotope Geochemistry Laboratory of the Illinois State Geological Survey

Submitted To:

National Park Service,
Johnson City, Texas

Order No. P73500-40016
Report No. 1

January 2005

Samuel D. McCulloch, RPA
Principal Investigator

McCulloch Archaeological Services LLC, San Marcos, Texas

Extracted from Geoarchaeological Investigation. ([GRI Source Map ID 74983](#))

Geoarchaeological Investigation Sample 1A

APPENDIX C

Radiocarbon Date Comment Form
Illinois State Geological Survey
615 East Peabody Drive
Champaign, Illinois 61820
Telephone: (217) 244-2192

ISGS-5679

Age: 390 ± 70 Radiocarbon Years BP $\delta^{13}\text{C} = -19.5$ per mil PDB

Sample: BHT4 Sample 1A

Site: Palo Alto Battlefield site

Material: Soil A horizon

Location: 8.5 km north of Brownsville, TX

County: Cameron

State: TX

Country: U.S.A.

Latitude: 26°01'26" N

Longitude: 97°28'21" W

26.0238

-97.4725

Stratigraphic Position:
From A horizon, 12-28 cm.

Submitted by: Samuel McCulloch

Submitters Institution: National Park Service.

Year collected: 2004 By: Chris Caran

Comment By (initials only): _ _ _

Comment:

Please check this form for accuracy, fill in any blanks, and return to the ISGS within two weeks (see reverse side for instructions).
October 28, 2004

Geoarchaeological Investigation Sample 2A

Radiocarbon Date Comment Form
Illinois State Geological Survey
615 East Peabody Drive
Champaign, Illinois 61820
Telephone: (217) 244-2192

ISGS-5682

Age: 1190 ± 70 Radiocarbon Years BP

 $\delta^{13}\text{C} = -18.0$ per mil PDB

Sample: BHT4 Sample 2A

Site: Palo Alto Battlefield site

Material: Soil Ag horizon

Location: 8.5 km north of Brownsville, TX

County: Cameron

State: TX

Country: U.S.A.

Latitude: 26°01'26" N

Longitude: 97°28'21" W

Stratigraphic Position:

From 80-100 cm below surface.

Submitted by: Samuel McCulloch

Submitters Institution: National Park Service.

Year collected: 2004

By: Chris Caran

Comment By (initials only): _ _ _

Comment:

Please check this form for accuracy, fill in any blanks, and return to
the ISGS within two weeks (see reverse side for instructions).
November 5, 2004

Geoarchaeological Investigation Sample 3A

Radiocarbon Date Comment Form
Illinois State Geological Survey
615 East Peabody Drive
Champaign, Illinois 61820
Telephone: (217) 244-2192

ISGS-5670

Age: 2990 $\pm$ 70 Radiocarbon Years BP

$\delta^{13}\text{C}$ = -17.3 per mil PDB

Sample: BHT4 3A

Site: Palo Alto Battlefield site

Material: Soil

Location: 8.5km north of Brownsville, Cameron Co. TX

County: Cameron

State: TX

Country: U.S.A.

Latitude: 26°01'26" N

Longitude: 97°28'21" W

Stratigraphic Position:

From stratum 3, Bgyc horizon, 130-155cm.

Submitted by: Chris Caran

Submitters Institution: Quaternary Consulting in TX

Year collected: 2004

By: Chris Caran

Comment By (initials only): _ _ _

Comment:

Please check this form for accuracy, fill in any blanks, and return to the ISGS within two weeks (see reverse side for instructions).
October 8, 2004

Geoarchaeological Investigation Sample 4A

Radiocarbon Date Comment Form
Illinois State Geological Survey
615 East Peabody Drive
Champaign, Illinois 61820
Telephone: (217) 244-2192

ISGS-5669

Age: 4730 $\pm$ 70 Radiocarbon Years BP $\delta^{13}\text{C}$ = -19.2 per mil PDB

Sample: 4A

Site: Palo Atlo Battlefiled site

Material: Soil

Location: 8.5km north of Brownsville, Cameron Co. TX

County: Cameron State: TX Country: U.S.A.

Latitude: 26°01'26" N Longitude: 97°28'21" W

Stratigraphic Position:

From stratum 4, Bg horizon, 205-235cm.

Submitted by: Chris Caran

Submitters Institution: Quaternary Consulting of TX

Year collected: 2004 By: Chris Caran

Comment By (initials only): _ _ _

Comment:

Please check this form for accuracy, fill in any blanks, and return to the ISGS within two weeks (see reverse side for instructions).
October 8, 2004

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Extracted from Geoarchaeological Investigation. ([GRI Source Map ID 74983](#))

GRI Digital Data Credits

This document was developed and completed by Andrea Croskrey (NPS GRD) for the NPS Geologic Resources Division (GRD) Geologic Resources Inventory(GRI) Program. Quality control of this document by Stephanie O'Meara (Colorado State University).

The information contained here was compiled to accompany the digital geologic-GIS map(s) and other digital data for Palo Alto Battlefield National Historical Park, Texas (PAAL) developed by Rachel Yoder (Colorado State University) and Andrea Croskrey (NPS GRD).

GRI finalization by Stephanie O'Meara (Colorado State University).

GRI program coordination and scoping provided by Bruce Heise and Tim Connors (NPS GRD, Lakewood, Colorado).