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DETAILED TEXTURE AND HEAVY MINERALOGY OF RECENT SANDS ALONG THE NORTHEASTERN TEXAS GULF COAST AND A RESULTING MODEL FOR BARRIER FORMATION

Rice University

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DETAILED TEXTURE AND HEAVY MINERALOGY OF RECENT SANDS
ALONG THE NORTHEASTERN TEXAS GULF COAST
AND A RESULTING MODEL FOR BARRIER FORMATION

by

Mary Lou Cole

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE
DOCTOR OF PHILOSOPHY

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HOUSTON, TEXAS

APRIL, 1982
ABSTRACT

DETAILED TEXTURE AND HEAVY MINERALOGY OF RECENT SANDS

ALONG THE NORTHEASTERN GULF COAST

AND A RESULTING MODEL FOR BARRIER FORMATION

Mary Lou Cole

Numerous textural and heavy mineralogical analyses have been performed on sand samples from the northeastern Texas Gulf coastal region. Analyses of local point-bar samples result in the delineation of major river sand sources, with average histograms of grain-size data showing combinations of discrete modes characteristic of each river. Similar study of area coastal sands allows distinction of river, beach, and fluvial- and wave-dominated deltaic sands on the basis of texture. Kyanite/garnet/hornblende + pyroxene ratios are an excellent criterion for evaluating source contributions to the coast. Combining approximated age (radiocarbon) dates and heavy-mineral ratios results in the delineation of two distinct sand types. Spatial relationships between the two are used to develop a model for barrier formation. The model is then compared with previous models, applied to local problems of beach erosion, and discussed with regard to the ancient record.
ACKNOWLEDGEMENTS

This study was supported by research grants from the Gulf Coast Association of Geological Societies and Sigma Xi.

I would like to thank my thesis advisor, Dr. John B. Anderson, for his support and ideas. Thanks also go to the other members of my thesis committee: Drs. Richard E. Casey, Rudy R. Schwarzer, and Frank M. Fisher, Jr.

Major field assistance was provided by my husband, Steve Hoerster, who was involved in almost every stage of the thesis work; his constant support and encouragement are very gratefully acknowledged and deeply appreciated. Other assistance in the field was provided by Nathan Meyers, Dennis Kurtz, Carl Wolfteich, Peter Scholl, John Anderson, Chris Brake, and Rich Wheeler.

Thanks also go to all those who assisted me at the U. S. Army Corps of Engineers Galveston Branch, especially "Tommy" Thomas and his group at the Fort Point Soils Laboratory, Syd Tanner, Vivian Miller, Vernon Bennett (now retired), Jim MacManus, and Andy Langford. Soil data was provided by Gerald Crenwelge with the U. S. Department of Agriculture Soil Conservation Service in Angleton, Texas, and river discharge and flow data were furnished by the U. S. G. S. Water Service Branch in Austin. Harding-Lawson Associates of Houston loaned a mobile drilling rig and rotary wash equipment, and Bob Wood and Sam and Cindy Metcalfe kindly donated their time to assist in running it.

Pam Pearson and Leslie Askonas assisted with the printing and reproduction, Camille Hueni and Leslie Askonas assisted with the drafting, and Superscript of Houston typed the final manuscript. A big
"thanks" goes to my sister, Carol Ann Cole, my in-laws, Mr. and Mrs. Richard Hoerster, Miss Louise Powell, and numerous friends who also provided miscellaneous assistance and support.

This thesis is dedicated to my parents, Mr. and Mrs. Halbert N. Cole, who made it all possible.
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INTRODUCTION

Geologically, the Texas Gulf coast is one of the most extensively-studied areas in the world. Exploration for oil, gas, and uranium plus the proximity of a number of major marine-science institutes and dense population centers have resulted in a wealth of information from both published and unpublished sources. While some consider geology of the area to be well-understood and contend there is little left to be done, the fact is that most of the previous work, as all good work should, has resulted in many new and further questions to be answered. Rather than considering the Gulf coast "overworked," it should continue to be looked upon as a prime geologic research area where a firm literature base allows old and new problems to be attacked both by traditional methods used in greater detail and by more modern analytical techniques being tried for the first time.

The biggest geologic problems along the Texas Gulf coast are both academic and economic in nature. Although many models have been formulated and discussed, the question of how barrier islands form and develop has never been answered to total satisfaction. Ancient barrier sands are known to form extensive petroleum reservoirs and to sometimes contain uranium and other minerals. Also, approximately 47% of all U.S. coasts are bordered by some type of barrier (Shepard, 1973). Since coastal property values are high, it is important to understand the present position of barriers in their development so we may in turn have a better realization of what their futures will be, especially in the light of current problems with erosion.
Sand is the predominant constituent of barrier features along the Gulf coast. The present study involves characterization of sources of this sand for the Texas Gulf coastal area between Sabine Pass and Matagorda Bay (for locations, see Figure 1) on the basis of heavy mineralogy and textural parameters. These techniques work especially well in the area chosen for study due to substantial differences in lithology of drainage basins of the major river systems contributing sand to the region (see Figure 2). Other possible sand sources jointly evaluated are the Mississippi River and offshore continental shelf deposits (see Hsu, 1960). Samples taken in traverses across area barrier islands and peninsulas and from other coastal features are then similarly analyzed and their sand sources determined. The knowledge thus gained is correlated with available radiocarbon dates, records of historic shoreline and river-course data, and aerial photographs. A model for the origin and development of the various coastal features of the study area is then proposed, and this model is subsequently related to current coastal management problems and the ancient record.
FIGURE 1. Location map of places and features cited in the present study.
FIGURE 2. Generalized geologic map of Texas. Note the substantial differences in lithologies between drainage basins of the major river systems affecting the study area.
STUDY AREA

Location

The area of study along the northeastern Texas Gulf coast lies within the rectangle bounded by 28.5° and 30.0° north latitude and 94.0° and 96.5° west longitude. It is approximately 33,000 km² in area, and consists of the lower reaches of major rivers entering the coast plus 250 km of coastline containing various coastal features. A location map is shown in Figure 1.

Geomorphology

The study area is located within the Quaternary Gulf coastal plain of Texas (Figure 2). This plain consists of a series of coastwise terraces dipping gently seaward which are interrupted by broad river floodplains and older elevated terraces (Lankford and Rogers, 1969). Major drainage basins in the study area are the Sabine, Trinity, Brazos, and Colorado rivers; areas of these are listed in Table 1. The land surface is of low relief (approximately 30 m above sea level or less).

The northeastern Texas Gulf coast is a barrier coastline with barrier islands and peninsulas which separate the Gulf of Mexico from various bays (see Figure 1); it is part of a line which continues, with few interruptions, along the Texas and Mexican coast for approximately 1000 km (Bernard and others, 1959). Barriers to the south of Galveston Island have concave shorelines, while those to the east show increasingly greater convexity (Shepard, 1960a). Note the offset between major barrier features (peninsulas and islands) in the study area shown in Figure 1. Deltas in the area are of several different types: the
TABLE 1. Comparisons of drainage basin areas and relative sand contributions for major Texas coastal river systems. Data on areas from U.S.G.S. Water Data reports; relative sand contributions were estimated from soil maps and descriptions of soil formations furnished by the U.S. Department of Agriculture.
SABINE
T.D.B. = 24,500 km²
E.D.B. = 24,500 km²
Sand = 16,400 km²
(67%)

NECHES
T.D.B. = 20,600 km²
E.D.B. = 20,600 km²
Sand = 13,000 km²
(63%)

TRINITY
T.D.B. = 44,500 km²
E.D.B. = 44,500 km²
Sand = 20,915 km²
(47%)

BRAZOS
T.D.B. = 117,500 km²
E.D.B. = 93,000 km²
Sand = 40,000 km²
(43%)

COLORADO
T.D.B. = 107,200 km²
E.D.B. = 73,800 km²
Sand = 30,250 km²
(41%)

T.D.B. = total drainage basin area
E.D.B. = effective drainage basin area
(i.e., contributing only; see Figure 3)
Sand = area of sand available to drainage basin
(%) = percentage area of effective drainage basin contributing sand
Trinity River delta, located in Galveston Bay, is a birdfoot-lobate delta; the Brazos River has formed several cuspate deltas in the Gulf of Mexico; and the Colorado River once formed a birdfoot-lobate delta in Matagorda Bay but is now building a cuspate delta in the Gulf. Thus, delta-type in the area is clearly related more to wave energy than to tidal and fluvial processes.

The Galveston-Bolivar barrier complex averages 2 km in width and is approximately 90 km long. The Gulf shoreline of these barriers is typically straight or smoothly arcuate. Lagoonal shorelines are generally formed by a series of washover deltas, old tidal inlets and storm passes, and distal ends of recurved spits. The gulfward surfaces of the barriers are characterized by numerous narrow, parallel beach ridges (storm berms) and intervening swales (normal beach accretion). A maximum elevation of about 4 m for the barriers is reached on these beach-ridge crests. This "ridge-and-swale topography" trends approximately parallel to the present shoreline. "Tidal guts" (see Bernard and others, 1959) are swales between recurved beach ridges; these trend at an angle of about 30° to the long axis of Bolivar Peninsula and about 70° to the long axis of Galveston Island. The guts are kept open by heavy rainfall, tides, and washovers (Bernard and others, 1959). A few sand dunes are preserved at the surface of the barrier features, but most of these appear to be destroyed during storms. It should be noted, however, that beach and dune ridges can be difficult to distinguish (Shepard, 1960a).

Beach slopes in the study area average less than 5°, and prominent cusps are uncommon. Gulfward, the bottom slopes 2.4 m/km to the 9-m contour, which lies approximately 3 km offshore. Between the 9-m and
16-m contours, the bottom slopes about 1.3 m/km, and below 16 m, it
slopes less than 0.2 m/km. Normally there are four breaker bars off-
shore from Galveston and Bolivar (Bernard and others, 1959). Their
positions vary with wave height, tides, and possibly longshore currents,
and they are generally destroyed during severe storms.

Barrier features in the area of study are breached by three tidal
inlets: San Luis Pass (0.8 km long by 7.5 m maximum depth), Bolivar
Roads (2.1 km long by 9 m natural depth; dredged to 16 m), and Rollover
Pass, a man-made inlet on the site of a former natural tidal pass (60 m
long by 0.6 m deep) (see Figure 1). Bays lying behind the barriers are
less than 3 m deep.

Climate

Climatic zones of Texas are shown in Figure 3. A comparison of
this figure with Figure 2 shows that portions of the drainage basins of
area rivers are so arid as to make them essentially noncontributing.
Thus, the drainage basin areas in Table 1 have been revised to show
contributing as well as total drainage basin area for rivers affecting
the northeastern Texas Gulf coast.

The climate of the area of study is subtropical, with hot, humid
summers and mild, wet winters. The average mean free-air temperature is
approximately 22°C (70°F). The average low temperature in winter is 8°C
(43°F), and the average high temperature in summer is 35°C (94°F),
although it seldom exceeds 39°C in the summer. Rainfall averages 70-135
cm per year (all figures are from Anderson and Clark, 1977). This
rainfall is not steady, however, but generally occurs in periodic heavy
rainfalls that alternate with periodic droughts. Evaporation is approxi-
FIGURE 3.  A. Climatic zones of Texas (from Lankford and Rogers, 1969), showing contributing versus noncontributing river drainage basin areas (compare with Figure 2 and Table 1).

B. Rose diagram of wind directions and velocities in the area of study (from Lankford and Rogers, 1969).

C. Seasonal wind directions and resultant net wave-driven circulation patterns along the Texas Gulf coast (from McGowen and others, 1977).
mately equal to precipitation (Nienaber, 1963). The present climate is warmer and drier than 5000 years ago; major rivers along the Texas coastal plain were known to have been larger then (Brown and others, 1974).

Oceanography and Circulation

Winds along the northeastern Texas Gulf coast are generally from the southeast, with "northers" occurring less often, generally during the winter months (Figure 3). This results in a prominent longshore drift to the west with minor daily reversals (Figure 3). Tides are semidiurnal and diurnal, and range from less than 0.3 m to 0.8 m. Because tidal amplitude and diurnal period are low, nonperiodic tides have a much greater effect on current direction, force, and duration. Tropical cyclones and hurricanes blow in from the southeast, resulting in surges of water that are blown up onto shore and storm surges as high as 5 m. Conversely, northers blow water offshore, causing sea level to be as much as 1.2 m below normal so that bay bottoms are exposed. Both types of storms result in high-velocity offshore currents which erode and scour the coastal areas and flush the bays.

Inner shelf circulation along the northeastern Texas Gulf coast is seasonal: in summer, there is net onshore transport and offshore bottom flow; in winter, there is net offshore surface transport and onshore bottom flow, both of which are temporary (Morton and Winker, 1979). A prominent longshore drift with a net transport direction to the southwest (Figure 3.B.) is operative within 100 m of the shoreline. Spatial and temporal variations in current directions from changes in wind and wave direction occur regardless of season. Strongest currents are
found in the tidal passes (Figure 4). In Bolivar Roads, flood currents range from less than 1 knot to 3.3 knots, and ebb currents average about 4.3 knots (Bernard and others, 1959); these are also affected by wind. Values for San Luis Pass are similar.

Wind-wave heights for the area average 0.6 m in 3 m of water and 1.2 m in 15 m of water, but can reach 3-6 m during hurricanes (Bernard and others, 1959). Wind-waves in bays are generally small enough that they have no effect on the bottoms. The lower limit of effective wave action offshore is 18 m (Nienaber, 1963). Significant sediment transport below wave base on the inner shelf is periodic, infrequent, and chiefly the result of storms (Morton and Winker, 1979).

Surface water temperature averages 35° C in summer (28-39°C) and 17° C in winter (3-28° C). Salinity varies with runoff, and averages around 30 ppt in late summer and early fall and 22 ppt during winter and spring (figures from Bernard and others, 1959).
BACKGROUND AND PREVIOUS WORK

Explanation

As previously noted, literature on the Gulf Coast is vast. Therefore, only a summary of work pertaining directly to the present study is attempted here. Special emphasis has been placed on work pertaining to sand-sized material and barrier features.

Gulf of Mexico History and Setting

The Gulf coastal province is a segment of the Mesozoic-Cenozoic coastal geosyncline of eastern North America. This geosyncline can be traced from Newfoundland to Guatemala, and is approximately lens-shaped in cross-section (Murray, 1960). The study area lies on the northern flank of the Gulf Coast Geosyncline, which was probably formed in the Jurassic. Strata reflecting a long history of continued sedimentation and subsidence slope gently gulfward and result in a sedimentary and structural arc that trends from Florida to Mexico. Associated with this arc is warping and displacement of the basement beneath. Faulting along the arc has been related to downwarping of margins in early stages of its development and subsidence from rapid deposition (Murray, 1960). Stratigraphic studies have shown the major sedimentary units to be arranged in belts subparallel to the modern northern shoreline of the Gulf (see Figure 2).

A "hinge line" that appears to control sedimentation exists near the present northern Gulf coastline (Figure 5); alluvial sediments are found north of this line, and deltaic and marine sediments are found to the south. The hinge line is broken by several structural embayments and arches (Figure 5) which are situated adjacent to pronounced similar
FIGURE 5. Tectonic elements of the Gulf Coast Geosyncline
(by H.C. Clark; in Anderson and Clark, 1977).
Cenozoic sediment thickness after Hardin, 1961
Erosions and arches after Lankford, 1960
Vicksburg flexure after Murray, 1960
Subsidence after Gaubrysch, 1969
features in the Ouachita fold belt; they therefore appear to be related
to Paleozoic structures/crustal features (Lankford and Rogers, 1969).
The extent of these positive and negative features is controlled by:
a) the initial topography, b) the amount of tectonic uplift or downwarp,
and c) the amount of sediment deposition (Lankford and Rogers, 1969).
In addition, there is considerable evidence that these structural
features have migrated with time. River courses and deltas are affected
by variation and location of uplift and downwarp axes with time as well
as by variable subsidence rates at different locations. The Trinity,
Brazos, and Colorado rivers are known to have previously entered the
Gulf of Mexico well to the east of their present mouths (Lankford and
Rogers, 1969; Morton, 1979) (See Figure 6). Location along positive
or negative features has an important effect on river mouths: the
Trinity River, which lies within the Houston Embayment (Figure 5), is
deeply embayed and has formed a considerable estuary (Galveston Bay),
whereas the Brazos, Colorado, and Sabine rivers flow out across the San
Marcos and Sabine arches and have been able to entrench themselves while
at the same time completely filling their valleys.

Sedimentation along the Gulf coast thus tends to occur in depo-
centers rather than in even sheets. These depocenters, which can con-
tain greater than 15,000 m of sediment, shift with time and therefore
overlap.

Pleistocene and Holocene sediments along the Texas Gulf coastal
plain (Figure 2) consist of alluvial, deltaic, and marginal marine
deposits. The two major factors controlling their geometry are inland
uplift and seaward subsidence (separated by the hinge line mentioned
FIGURE 6. Location of Pleistocene deltas of the Brazos and Trinity rivers (from Lankford and Rogers, 1969), and locations of sand pits sampled in this study (see "River Study" section).
Sand Pits Sampled
previously), and Pleistocene glacial cycles which resulted in changes in sea level (Lankford and Rogers, 1969). These combine to produce deltaic sheets in an offlap pattern as resulting delta fans merge laterally and overlap towards the coast.

Active marine deltas are presently being formed by major streams entering the Gulf of Mexico. Bay-head deltas are forming in entrenched and shallow but broadly-embayed valleys of rivers not emptying directly into the Gulf. Evidence of drowned deltas out on the continental shelf is strong (Nienaber, 1963; Morton, 1979) (Figure 7).

There is some question as to the origin of major bays along the Texas Gulf coast. They have generally been described as drowned river valleys/estuaries, as river channels can be traced bathymetrically and/or mapped stratigraphically (Figure 8) (Lankford and Rogers, 1969). As previously discussed, they tend to lie within tectonic embayments and therefore may also be tectonically controlled. However, ancient positions of the Trinity and Brazos-Colorado deltas indicate these intendent bays to be interdelta-interdistributary bays of a deltaic coastal origin (Barton, 1930; Morton, 1979) (Figure 7). The answer may well be a combination of these explanations: as the rivers changed courses through a combination of shifts in the axes of local tectonic features with time and shifts in the locus of active delta-building, they tended to flow into the areas of low structural and physical relief.

Sea-Level/Subsidence History

Figure 9 shows various sea-level curves which have been constructed for the northeast Texas Gulf coast area. These curves show a rapid
FIGURE 7. Maps showing:

A. Morphogenic provinces of the Texas Gulf Coast,

B. Maximum shoreline changes between 1850–83

and 1973–75, and

C. Hypothesized late Holocene shoreline showing

major promontories and littoral drift cells

(from Morton, 1979).
FIGURE 8. Contour map of top of Pleistocene in Galveston area.
Note Ingleside barrier trend and position of ancient Trinity River channel (from Rehkemper, 1969).
FIGURE 9. Sea-level curves for northwestern Gulf of Mexico

(A.-C. in Rehkmper, 1969):

A. Rehkmper, 1969
B. After LeBlanc and Bernard, 1954
C. After Curray, 1960 and Shepard, 1960b
D. Nelson and Bray, 1970
post-Wisconsin rise in sea level beginning around 10,000 years B.P. in the region. This rise leveled off at about 5000 years B.P. A controversy over the portions of the curves from 5000 years B.P. to the present exists: Bernard and LeBlanc (1965) saw no evidence of further fluctuations in sea level and contend that it reached essentially the position it maintains today at that time, while Shepard (1960b) saw evidence for a continuing relative rise in sea level. Graf (1969) concluded that sea level reached its present height in the Galveston area around 3000-4000 years B.P., and Nelson and Bray (1970), working in the Sabine area, concluded sea level there reached its present position around 2800 years B.P. The modern sea-level rise, if present, is slight.

A relative stillstand of sea level similar to the present one is thought to have occurred along the northeastern Texas Gulf coast following a sea-level rise to approximately 4.5 m above present sea level that is associated with a mid-Wisconsin interstadial (Graf, 1966; Wilkinson and others, 1976; also see Figure 9). During this stillstand, a series of strandplain sands with well-developed ridge-and-swale topography (Wilkinson and others, 1975) similar to that presently observed along the coast today (see geomorphology section) was deposited. These older strandplain sands form intermittent but well-defined ridges subparallel to the modern coast from southwest Texas to western Louisiana, and are known as the Ingleside trend (Figure 8).

Rates of subsidence for the northeastern Texas Gulf coast are on the order of 1-4 cm per 1000 years (Anderson and Clark, 1977). Subsidence rates for the Galveston area have been estimated to be higher than this, about 0.5 mm per year (Lankford and Rogers, 1969). All of the
apparent Holocene rise in sea level can therefore be attributed to subsidence in the area.

Galveston Bay and Sabine Lake are inundated fluvial drainage systems cut when relative sea level was lower. The Trinity, Neches, and Sabine rivers could not keep pace with the last rise in sea level, probably due to a combination of local tectonics (see previous section) and lower sediment supplies than that of the Brazos River.

Stratigraphy

There are six major depositional surfaces of Quaternary age along the northwestern Gulf coast:

Holocene
- Modern
- Deweyville terrace (Early Recent)

Pleistocene
- Beaumont/Prairie terrace
- Montgomery terrace (Upper Lissie)
- Bently terrace (Lower Lissie)
- Willis-Williana terrace.

Each of these are river terraces deposited during successive Quaternary interglacial ages. These sections consist of a sequence of alluvial, deltaic, coastal interdeltic, and marine deposits, and individual terraces exhibit a fining-upwards trend (Bernard and LeBlanc, 1965).

For the purposes of the present study, only Beaumont (Uppermost Pleistocene) and Holocene sediments will be described in detail. The Beaumont Formation was originally described by Hayes and Kennedy in 1903 (in Lankford and Rogers, 1969). It consists predominantly of clays, with some sands, and is characterized by abundant calcareous nodules, some shells, and plant fragments. Rapid lateral facies changes occur. The sequence has been interpreted as fluvial and deltaic sediment with
intervening lagoonal and marine deposits, and has a gulfward gradient of 0.2 m/km (Lankford and Rogers, 1969).

The Beaumont Formation is unconformably overlain by Holocene sediments. Its upper surface is generally stiff and deeply weathered. Criteria for recognizing the unconformity are as follows (after Lankford and Rogers, 1969):

1) A rubble zone overlying the oxidized Pleistocene surface (looks similar to clay pellets found in Holocene natural levees);

2) Marked discontinuities in grain size, coarse-fraction constituents, and faunal assemblages;

3) A color change, from tan and red (Pleistocene) to gray (Holocene);

4) Greater dehydration and stiffness of Pleistocene deposits;

5) Ferruginous and calcareous nodules in the Pleistocene deposits (less abundant in natural-levee and delta-flat marsh facies);

6) Tracing of a known contact by continuous seismic profiling; and

7) General stratigraphic relationships of recognizable facies.

A greenish cast to the sediment may indicate the base of the Holocene in barrier-island sands (Shepard, 1969a).

Depth to the upper Beaumont surface is shown in Figure 8. Note that depths of 30 m (100 feet) or greater indicate the position of the ancient Trinity channel between Galveston and Bolivar. Depth to the Beaumont surface below Galveston Island is shown in Figure 10, and ranges between 2 and 20 m (6-60 feet) (Bernard and others, 1959).

The oldest Holocene sediments of the study area are fluvial sands and natural levees of ancient erosional channels of the various local rivers and streams. In places, these erosional channels cut deeply into

B. Generalized cross-section of Galveston along Eight Mile Road. The dotted lines are time lines (compare with Figure 11), illustrating the offlapping sequence of barrier deposits resulting from seaward growth of the island during the present standing sea-level substage (from Bernard and others, 1978). Note the 6-meter (20-foot) difference in height of the Pleistocene (Beaumont) surface between the gulf and bay sides of the island.
Beaumont deposits (see for example Figure 8) and were formed at least 10,000 years ago when sea level was approximately 30 m lower and shoreline about 64 km south of present (Lankford and Rogers, 1969). On barrier features along the modern coastline, Holocene deposits are predominantly barrier sands.

**Sedimentology**

Individual terrace sequences mentioned in the preceding section consist of ancient deltaic deposits. The sequences consist of basal gravels which are overlain by sands. Sands are in turn overlain by silts, and the sequences are topped by clays. They have been interpreted as having been deposited under conditions of rising sea level and a resultant decrease in stream velocity (Lankford and Rogers, 1969). Because Holocene sedimentation has been limited predominantly to the coastal areas in the form of barrier, deltaic, and interdeltaic sediments (see previous discussions), uppermost Beaumont clays are widely exposed over most areas mapped as Quaternary (see Figure 2).

Sands in the northern Gulf of Mexico are restricted to bays, barriers, deltas, and the nearshore zone, with the offshore mud-line occurring approximately at the 3.5 m depth contour (Shepard, 1969a). Barrier features are described as consisting almost entirely of sand, with resulting sand bodies being roughly 4.5–15 m thick (Bernard and others, 1959). The sand bodies are relatively narrow (less than a kilometer to greater than 13 kilometers) and long (a few kilometers to greater than 80 km), and lie parallel to regional depositional strike. The width of Galveston Island and Bolivar Peninsula averages 2.5 km, and the base of the sand bodies forming them extends about 3 km seaward and
about a hundred meters lagoonward from their shores (Bernard and others 1959) (see Figure 10).

Galveston Island, the best-studied barrier in the region, consists of approximately 670 cubic meters [?] of clean, well-sorted sand (Bernard and LeBlanc, 1965; in Bernard and others, 1978) that thickens both seaward and to the southwest (Figure 10) and ranges from fine- to very fine-grained in size (Bernard and others, 1959). Radiocarbon dating by Bernard, Major, and Parrot (1959) shows the island to consist of an offlapping sequence (Figure 11).

Sedimentary structures on Galveston Island have been described by Bernard and others (1959) as follows. Backshore, beach crest and foreshore sands contain essentially horizontal laminations and very low-angle cross-bedding, where the angle approximates the slope of the beach. They are commonly bored and churned. Aeolian sands exhibit festoon cross-beds and horizontal laminations, and are also contorted and bored. Bottom deposits from the beach gulfward are laminated, bored, or churned, and contain occasional cross-bedded sands. Their initial attitude approximates the slope of the bottom.

Other criteria for distinguishing barrier facies are less readily-apparent. Shepard (1969a) noted that nearshore sands tend to have more foraminiferans and glauconite than do beach and dune sands. He also concluded that beach and dune sands were difficult to distinguish except possibly by their silt content. Mica may be more common in beach sand as well.

Sand is also the dominant sediment type in presently-active deltaic and tidal delta systems along the northeastern Texas Gulf coast (Bernard
FIGURE 11. Radiocarbon dates of shell beds, Galveston Island (from Bernard and others, 1976). For locations of traverses, see Figure 10.A.
and others, 1959). Very little work has been done on the latter, and tidal-delta process in the region are poorly-understood. Finer-grained bay and lagoonal sediments, which lie behind and beneath coastal barriers, consist predominantly of silt and clay, as do muddy deposits offshore in the Gulf (see Figure 10B.) Sand occurs offshore only on topographic highs. Sedimentation rates for the Texas coastal zone have been estimated to be on the order of one centimeter per thousand years (Van Andel, 1960).

Texture

The average median grain size of shoreline deposits from the Mississippi River to the Rio Grande River is fine to very fine sand (Bernard and LeBlanc, 1965). Shepard (1969) found that Texas barrier beach sands averaged 3-4µ in size. Drowned barriers offshore were more similar to the back-barrier sands.

Hsu (1960), in his study of Gulf coastal sands, found that beach sands along the northeastern Texas Gulf coast are generally finer than those of local rivers, as shown in Figure 12. Also note how much finer sands from the study area are in comparison to Florida and Alabama beaches. Sand from Matagorda Peninsula is coarser than sand from Bolivar Peninsula, and Bolivar sand in turn is coarser than that from Galveston and Follets islands.

Grain-size data from Galveston Island were analyzed by Bernard and others (1959). Like the stratigraphic trends they noted (Figures 10 and 11), textural data through the island were similar to those observed across the island's surface, with grain-size decreasing offshore and
FIGURE 12. Mean grain size, in phi ($\phi$), of sand samples from
the northeastern Texas Gulf coastal region (data from
Hsu, 1960). Compare with mean grain size of contribu-
ting rivers (data from Hsu, 1960) and other Gulf
coastal beaches (data from Anderson and Clark, 1977).
with greater depth (Figure 10.B.). Grain orientation may possibly be perpendicular to the Gulf shore (Nanz, 1955; in Bernard and others, 1959).

Heavy Minerals

The area chosen for study is somewhat unique because the various river systems providing sand to the coast drain rocks of differing lithology: the Sabine-Neches river system drains polycyclic Tertiary sediments, the Trinity-San Jacinto system additionally drains Cretaceous carbonates and clastic sediments, the Brazos River originates in the Permo-Triassic red beds of West Texas, and the Colorado River flows through the Llano Uplift, which consists of uplifted granites and Precambrian gneisses and schists (Figure 2). These lithologic differences are reflected in relative differences in percentages of various heavy minerals found in each system.

A number of important studies of Gulf coastal heavy mineralogy have been made previously. Goldstein (1942) and Van Andel and Poole (1960) looked at heavy minerals in the Gulf of Mexico and proposed a number of petrologic provinces (Figure 13); the present study area lies mainly within the Western Gulf Province, with Bolivar lying in transition to the Mississippi Province. The Western Gulf Province is of complex origin and consists of a mixture of sand from the Mississippi and local rivers. Sources for the various provinces were delineated by Bullard (1942) and Van Andel and Poole (1960), who examined source-river point bars and determined criteria for the recognition of each (Table 2). Hsu (1960) used textural criteria along with various heavy-mineral
FIGURE 13. Heavy mineral provinces in the northern Gulf of Mexico
(from Van Andel, 1960; after Goldstein, 1942).
<table>
<thead>
<tr>
<th>Province</th>
<th>Source</th>
<th>Hornblende</th>
<th>Tourmaline</th>
<th>Epidote</th>
<th>Zircon</th>
<th>Garnet</th>
<th>Staurolite</th>
<th>Kyanite</th>
<th>Pyroxenes</th>
<th>Basaltic Hornblende</th>
<th>Others</th>
<th>No. of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Gulf</td>
<td>Cret., Tert., Quat., S. Appalachians</td>
<td>13</td>
<td>12</td>
<td>16</td>
<td>12</td>
<td>2</td>
<td>16</td>
<td>16</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>31</td>
</tr>
<tr>
<td>Mississippi</td>
<td>Mississippi River</td>
<td>40</td>
<td>2</td>
<td>16</td>
<td>2</td>
<td>9</td>
<td>25</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>Western Gulf</td>
<td>Complex</td>
<td>58</td>
<td>5</td>
<td>17</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>127</td>
</tr>
<tr>
<td>“Brazos Group”</td>
<td>Trinity, Neches, Brazos</td>
<td>32</td>
<td>8</td>
<td>15</td>
<td>20</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td>Rio Grande</td>
<td>Rio Grande River</td>
<td>23</td>
<td>3</td>
<td>15</td>
<td>6</td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>24</td>
<td>7</td>
<td>9</td>
<td>41</td>
</tr>
<tr>
<td>Texas Coast 2</td>
<td>Rivers between Brazos and Nueces; reworked Pleistocene</td>
<td>7</td>
<td>28</td>
<td>11</td>
<td>23</td>
<td>9</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>54</td>
<td>54</td>
</tr>
</tbody>
</table>

1 Not including basaltic hornblende.

2 No pure samples available.
ratios to expand previous work. He concluded that the Western Gulf Province is a zone of mixing of sand from three different sources: 1) sands supplied from the Mississippi River by longshore transport, 2) sands derived from local rivers and streams, and 3) sands derived through erosion and shoreward transport of continental shelf deposits.

Heavy-mineral content of Mississippi River sands has been examined by Russell (1937). He found them to contain a metamorphic assemblage reflecting the glacial and Appalachian-piedmont sediments drained by the river. This assemblage is quite distinct from those of local source rivers (Table 2). Offshore sands are more difficult to delineate on the basis of heavy mineralogy, as they consist of mixtures of sands from the various sources (see discussion above).

Presently, heavy minerals occur in significant amounts along the Texas Gulf coast only immediately along the coast and very locally at river deltas. Elsewhere, observed distribution patterns of heavy minerals are obscured by high concentrations of relict sediments whose distribution is controlled by: a) the post-Pleistocene sea-level rise, b) shifts in currents and longshore drift possibly associated with climatic changes in the early Holocene, and c) pre-existing drainage patterns formed by rivers on the exposed continental shelf (Van Andel and Poole, 1960). Hsu (1960) determined that dilution far outweighs processes of abrasion and solution in changing the heavy mineral composition of Gulf coast sands; thus, these processes are not considered to have appreciably altered distribution patterns. Also, Van Andel and Poole (1960) studied mineral abundances in various size fractions from Gulf coastal samples and determined that grain size does not appear to
significantly affect mineralogy. Observed distribution patterns are
controlled almost entirely by nearshore processes, as they are not
significantly modified by deep-water processes (Van Andel and Poole,
1960). The basal part of the Holocene transgression is thus preserved.

**Paleontology**

Foraminiferans and molluscs are the most commonly-used fossils for
making paleoenvironmental determinations along the Gulf Coast; there-
fore, only these forms will be discussed. It should be noted that
ostracods may be equally useful. *Elphidium gunteri* (Cole) and *Ammonium
beccarii* (Linne) are the most abundant foraminiferans in the nearshore
environment. Phleger (1960) has made a detailed study of faunal facies
for marsh, inner lagoon, lower lagoon, beach, fluvial marine, deltaic
marine, inner and outer continental shelf, and slope and deep-sea
environments (Table 3). The reader is referred to his work for all
taxonomy and more information on environmental determinations used in
the present study. Foraminiferan abundances from a traverse across
Galveston Island made by Bernard and others (1959) are illustrated in
Figure 14. *Ammonium beccarii* (Linne) is more abundant on the bay side of
the island, while *Elphidium gunteri* (Cole) is more abundant on the Gulf
side; thus, ratios between the two may serve as an additional environ-
mental indicator.

Molluscs can also serve as useful environmental indicators. Genera
helpful in identifying specific environments are as follows (from
Bernard and others, 1959):
Marsh

*Trochammina inflata* (Montagu)
*Ammotium salsum* (Cushman and Bronnimann)
*Trophotrecha comprimata* (Cushman and Bronnimann)
*Trochammina macrescens* Brady
*Jadammina polycta* Bartenstein and Brand
*Arenoparrella mexicana* (Kornfeld)
*Ammoastuta inepta* (Cushman and McCulloch)
*Discorinopsis aquayoi* (Bermudez)
*Millammina fusca* (Brady)
*Palmerinella palmerae* Bermudez

Inner Lagoon

*Elphidium delicatum* Bermudez
*Ammobaculites dilatatus* Cushman and Bronnimann
*Ammotium salsum* (Cushman and Bronnimann)
*Triloculina sidebottomi* (Martinotti)
*Elphidium gunteri* Cole
*Ammonium beccarii* (Linné)

Lower Lagoon

*Ammotium salsum* (Cushman and Bronnimann)
*Quinqueloculina funafutiensis* (Chapman)
*Quinqueloculina rhodiensis* Parker
*Triloculina sidebottomi* (Martinotti)
*Elphidium matagordanum* (Kornfeld)
*Elphidium poeyanum* (d’Orbigny)
*Elphidium delicatum* Bermudez
*Elphidium galvestonense* Kornfeld
*Quinqueloculina poeyana* d’Orbigny
*Bolivina striatula* Cushman
*Elphidium gunteri* Cole
*Elphidium incertum mexicanum* Kornfeld
*Elphidium cf. E. tumidum* Natland
*Ammonium beccarii* (Linné)

Beach

*Bigenerina irregularis* Pfleger and Parker
*Quinqueloculina lamarckiana* d’Orbigny
*Quinqueloculina cf. Q. compa* Cushman
*Massilina peruviana* (d’Orbigny)
*Elphidium incertum mexicanum* Kornfeld
*Quinqueloculina seminulum* (Linné)
*Ammonium beccarii* (Linné)
Beach, con't

Elphidium discoidale (d'Orgigny)
Elphidium advena (Cushman)
Hanzawaia strattoni (Apelin)
Elphidium matagordanum (Kornfeld)

Fluvial Marine

Elphidium gunteri Cole
Elphidium delicatulum Bermudez
Ammotium salsum (Cushman and Bronniman) variant
Palmarinella gardenislandensis (Akers)
Millammina fusca (Brady)
Ammonium beccarii (Linné) variants

Deltaic Marine

Bolivina lowmani Phleger and Parker
Nonionella opima Cushman
Epistomina vitrea Parker
Nonion sp.
Bulimina cf. B. bassendorfensis Cushman and Parker

Inner Continental Shelf

Nouria polymorphinoides Heron-Allen and Earland
Bolivina lowmani Phleger and Parker
Nonionella atlantica Cushman
Elphidium metagordanum (Kornfeld)
Bolivina striatula Cushman
Elphidium advena (Cushman)
Nonionella opima Cushman
Elphidium poeyanum (d'Orbigny)

Outer Continental Shelf

Cibicides aff. C. floridanus (Cushman)
Cibicides mollis Phleger and Parker
Siphonia pulchra Cushman
Eponides regularis Phleger and Parker
Valvulinera minuta Parker
Nonion formosum (Seguenza)
Lenticulina peregrina (Schwager)
Bolivina fragilis Phleger and Parker
Gaudryna cf. G. sequa Cushman
Uvigerina parvula Cushman
Cancri oblonga (Williamson)
FIGURE 14. Foraminiferal assemblages occurring in bottom sediments along Eight Mile Road traverse (after Bernard and others, 1978). For location of traverse, see Figure 10.A.
Bay — *Crassostrea, Rangia, Mercenaria*, (Venus), *Thais*

Marsh — *Littorina*

Gulf shore and tidal passes — *Anadara, Busycon, Dinocardium, Donax, Noetia, Oliva, Polinices*.

*Donax variabilis* is found commonly in the surf zone, and is a good indicator of a sand-beach environment; it is not seen in the surf zone if the Beaumont Formation or other muddy deposits outcrop nearby (Hulings, 1955). Finally, molluscs and other macro-invertebrates have been useful for obtaining carbon-fourteen dates in the region (see Figure 11).

**Models for Barrier Formation**

A barrier is a sand beach, island, spit, or peninsula that extends roughly parallel to the general coastal trend but is separated from the mainland by a relatively narrow body of water or marsh (after Shepard, 1973). Barriers are sometimes confused with offshore bars, similar features which are covered at high tide (true barriers are always exposed in part). Approximately 47% of U.S. coasts are bordered by some type of barrier (Shepard, 1973). Barrier features are almost continuous along the Gulf coast, and can be found along the eastern coast of the U.S. from Florida to New York. Other areas with long barrier coastlines are arctic Alaska, Holland, west-central Africa, southern Brazil, and southeastern Australia.

Most barriers have a number of common traits. They consist of a central sand body lying on and between bay and shelf muds (Figure 15), and they occur along essentially all lowland, gently-sloping coasts
FIGURE 15. Generalized cross-section through a barrier (after Shepard, 1960a).
of the world where tidal range is relatively low and wave energy is low. Barriers are especially common around active distributaries while the lobe has been slowly sinking due to compaction and other causes (Shepard, 1973). Barriers are lacking where the submerged delta plain is so gentle that incoming waves do not break. Age dates from the bases of many barriers correspond to the approximate time sea level neared or reached its present position, about 7000-3000 years ago. Many workers have therefore sought models of common origin for barrier features.

Barriers exhibit important differences, however. Gulf coast barriers have been shown to have prograded seaward during their development (see discussion below), while barriers along the eastern coast of the United States appear to have migrated shoreward due to washover processes (Hoyt, 1967; Komar, 1976). In addition, there are a number of different geomorphologic types of barriers, including four distinct types along the Gulf coast alone:

1) Long, straight, or smoothly-curving barriers,
2) Segmented chains of islands with passes having width comparable to the length of the islands,
3) Cuspate islands or spits, and
4) Lobate or crescentic islands and spits (Shepard, 1960a).

Texas barrier islands are of Shepard's (1960a) Type 1, being long and straight or smoothly curving. These differences in barriers must be considered and explained by any single model of formation if it is to be universally applicable.

While many models to explain barrier formation have been proposed, the process is still not well-understood. The first important model of barrier formation was that of de Beaumont who, in 1845, theorized wave
erosion of the bottom in the breaker zone caused sand to be piled up in a ridge on the inside (Figure 16, in Shepard, 1960a). This resulted in an offshore bar which accreted to form a barrier. De Beaumont's ideas were opposed by Gilbert, who, in 1885, came up with the theory that longshore drift formed a spit along the shore, resulting in a bar that subsequently accreted into a barrier (Figure 16, in Shepard, 1960a). In 1919, Johnson summarized the de Beaumont and Gilbert models and ended by supporting de Beaumont because offshore profiles he had observed indicated erosion (in Shepard, 1960a). Johnson also felt conditions were made favorable for barrier formation largely by emergence of the inner portion of a very gently-sloping continental shelf (in Shepard, 1960a and Shepard, 1973). Johnson's ideas were not supported by later work. Subsequent drilling showed that barriers form between bay and marine sediments (Figure 15), and radiocarbon dating and stratigraphic work indicate barriers are not associated with periods of emergence but rather have grown upward since the late Holocene sea-level rise.

On the basis of limited heavy-mineralogic evidence, Bullard (1942) proposed that rivers supplied the sand for Gulf coastal barriers by longshore drift. He noted that barrier peninsulas in the region are all attached to land on their northeastern ends and all have free ends to the southwest. Also, their northeastern ends are wide and blunt, while the southwestern ends taper to a point. Shepard (1960a) looked at stratigraphic evidence from drillholes along the Gulf coast and concluded by agreeing with Bullard. Shepard pointed out that barriers grew as sea level rose at the end of the Wisconsin. This would have caused a decrease in sand from the adjacent shelf because of gradual covering by
FIGURE 16. Cartoon illustrating the hypotheses of Gilbert (1885) and de Beaumont (1845) on the origin of barriers (in Shepard, 1960a). Gilbert believed the barrier was simply added to the slope, having been introduced by longshore currents; de Beaumont believed the waves excavated the sea floor on the outside and built the barrier on the inside.
1. **According to Gilbert**

2. **According to De Beaumont**
muds (unless it was removed by currents). He concluded that the sand must have been brought in via longshore transport. On the basis of radiocarbon (C\(^{14}\)) dates and the presence of reworked faunas, Shepard proposed a "sweeping action" of water during the transgression which formed a juvenile barrier from sand swept inward from the continental shelf. After formation/initiation, the barriers were subject to landward and seaward growth by supplementation from rivers. Shepard also noted that spit-breaching to form barriers had actually been observed and, although the process did not appear to be an adequate explanation for major barrier systems, Gilbert's original theory must be accepted at least on a limited basis along coastal segments with an abundance of material for longshore transport. Finally, he pointed out that some Gulf barriers such as such Dauphin Island off Mobile Bay appear to have no local source. Thus, he became the first to stress that all barriers did not appear to have formed in the same way.

Detailed stratigraphic work on Galveston Island by Bernard and others (1959) resulted in a better understanding of Gulf coast barriers and an alternative model for their formation. Their radiocarbon dates showed Galveston to consist of an offlapping sequence (Figure 11). They theorized that Galveston Island began as a small bar in shallow water on the southwest side of the estuary mouth at the time sea level reached its present position in the area, about 5000 years B.P. During standing sea level, the bar emerged and grew seaward through beach accretion and southward through spit accretion. Because of the offlapping sequence, lagoonward growth was considered to be secondary.
Otvos (1970), also doing stratigraphic studies along the Gulf coast, noted that barrier islands have been observed in historical times growing upward from submerged shoal areas and migrating downstream by a combination of erosion at the head and accretion at the tail. He therefore stressed that subsequent extensive migration might obscure conditions of formation.

Hoyt (1967) pointed out the lack of open marine beach and neritic sediments behind the barriers of the Georgia coast (see Figure 15) and used this as evidence against previous models. He also argued against barrier formation from emergent bars except in rare instances, pointing out there is no evidence sea level was higher than at present during the Holocene. Finally, Hoyt noted an absence of abundant examples of various stages of barrier development. He came up with an alternate theory of barrier formation based on his observations of Sappelo Island, Georgia, and other barriers along the east coast of the United States, proposing initial formation of a beach ridge landward of the shoreline from wind- or water-deposited sediments. Slow submergence in the late Holocene flooded the area landward of the ridge, resulting in a "juvenile" barrier. Once formed, the island was able to migrate parallel or normal to shore or remain stationary. Slow submergence and negligible sedimentation were needed to maintain the lagoon behind the barrier. Hoyt also noted that some barriers, always small ones, had occasionally been observed forming from wave action on gently-sloping sea floors and by spit growth across large bays and subsequent truncation during storms.
Otvos (1970) attacked Hoyt's model by pointing out that most Gulf barriers had already started to form when transgression had slowed or stopped. He also pointed out that Gulf barriers showed little evidence of having originated in the supratidal environment. Otvos explained the lack of open-water sediments landward of barriers in the following ways:

1) Barriers were originally submerged offshore bars that blocked circulation;

2) Shores behind newly-forming barriers were open-marine, with salt marshes instead of beaches; or

3) Earliest sediments from the transgression were from re-worked Pleistocene deposits and therefore indistinguishable from them; also, bay-mouth spits or bars may have developed quickly without allowing time for noticeable deposition of open-marine deposits before the sediment became lagoonal.

Cheniers (Figure 17) are prograding features occurring along barrier coasts which may or may not share a common mode of origin with barriers (Bernard and others, 1959). Whereas barriers form a continuous sand sheet, cheniers consist of alternating sand ridges separated by muddy deposits. Hoyt (1969) noted that cheniers tend to form near the mouths of large rivers. He theorized that prograding deltas began to stabilize and eventually retreat when the rivers changed course. This resulted in reworking and winnowing of the deltaic deposits, with coarser material being piled-up as beach ridges. Delta development subsequently shifted, sediment was deposited in front again, and the cycle repeated. Hoyt noted that cheniers do not migrate, whereas barriers do. Shepard (1973) reached approximately the same conclusions, but noted that the cheniers of southwestern Louisiana formed around 2800-3000 years B.P., during the growth phase of Galveston Island as opposed to the initial phase.
Figure 17. Chenier plain consisting of beach ridges on the southwest coast of Louisiana (from Komar, 1976).
METHODS

Sampling and Coring

Only sand-sized material was analyzed in the present study. Conclusions, therefore, apply only to sand, as pointed out by Van Andel and Poole (1960), gravels and muds along the Gulf coast may be distributed quite differently.

River point-bar samples were taken with a posthole digger, a single sample being taken at each location in a grid pattern (see "Pilot Study" discussions). Since the objective was to get gross average sample representation from each bar, sample depths ranged from 15-30 cm so that a variety of laminations were sampled. In addition, an attempt was made to take samples from all types of bedforms present on each bar and from a variety of different types of point bars on each river (see "River Study" section). A minimum of ten "good" (i.e., well-formed and fairly undisturbed by human activities) point bars from each river were sampled.

Coastal samples consisted of surface and core samples. Surface samples were taken in traverses (see "Coastal Study" section) using a posthole digger. Where groundwater did not close the postholes, samples were generally taken at or near the surface, 50-cm, and 100-cm levels in order to obtain a good representation of each locality. These subsamples were processed separately. Shallow offshore samples were taken from a small boat using a Ponar grab-sampler.

Core samples were of two types: those taken especially for this study, and those taken by the U.S. Army Corps of Engineers, Galveston District. Coring for this study was originally done with a portable
vibracorer after Lanesky and others (1979) with poor results: no matter how deeply the core barrel penetrated, only about a meter of very tightly-packed core was recovered. Apparently, coastal sand is so fine-grained that once the water table is reached, sand can more easily flow up and around the core barrel than it can enter it. Alternately, vibration of the core barrel may drive the water out from between the grains, causing the sand to become tightly-packed, and clogging the barrel. The actual cause is probably a combination of the two.

A single hole to a depth of 6 m (21 feet) was drilled on Galveston Island using a mobile "Minute-Man" drilling rig (Figure 18) furnished by Harding-Lawson Associates of Houston. Rotary wash with a bentonite slurry was used to keep the hole open. At 1-meter intervals, the rotary drilling apparatus was removed and a standard split-spoon sampling device introduced by means of blows from a 65-kg (140-pound standard) test hammer. Only uncontaminated portions of the resulting samples were used.

Core samples furnished by the U.S. Army Corps of Engineers, Galveston District, were obtained from the Soils Laboratory at Fort Point. These samples consisted of segments of cores taken by standard drilling methods (for more information on this, the reader is referred to various Army Corps of Engineer publications). Samples were stored in glass jars, and most had been previously dried; thus in no core samples used in this study were sedimentary structures preserved. Although the Corps of Engineers has taken many cores from the Texas coastal area over the years, most of the resulting samples, including nearly all of those from Galveston Island, have been previously disposed of. A wealth of
FIGURE 18. Photograph of truck-mounted "Minute-Man" drilling rig loaned by Harding-Lawson Associates of Houston. Used to acquire boring through Galveston Island (see Figure 31 for site location).
core samples from selected areas remains, however, and detailed
description sheets from all previously-taken cores are available.

A flow diagram illustrating preparation and handling of samples
used in this study is illustrated in Figure 19.

Textural Analysis

Textural analyses of samples for this study were performed using
the Rice University Automated Sediment Analysis (RUASA) system (Figure
20); the reader is referred to Anderson and Kurtz (1979) for a detailed
description of this system. The term "texture," rather than "grain
size," is used because the settling tube method of analysis measures a
combination of particle parameters, including size, shape, and density.
The portion of the RUASA system used in this study consists of a large
settling tube (140 cm long and 15 cm inside diameter) containing a basal
weight pan suspended from a universal transducing cell. The output of
this cell is amplified using a bridge amplifier, and voltage output from
this is in turn fed into a microcomputer. Raw data is stored on floppy
disks, and a statistical program is subsequently run which converts
cumulative voltage into weights for each sand-size fraction based on
Gibbs' formula (Gibbs and others, 1971). The micro-computer then rou-
tinely prints out frequency and cumulative weight-percentage data for
each size fraction, as well as mean grain size, standard deviation,
skewness, and kurtosis values, and digital graphic displays of frequency
and cumulative size distribution curves. Due to small sizes, the
gravel fraction is ignored in the analyses, although presence of gravel
and/or shell in samples was noted. Data is reproducible on the system
to within 1-2% (Anderson and Kurtz, 1979), and the entire analysis
FIGURE 19. Flow diagram illustrating preparation and analysis of samples used in the present study.
Original Sample (size variable) → Spooned or Split (wet) (dry) → Subsample (20-100 g)

Disaggregated in Caigon; Wet-sieved for > 4μm Fraction;

Dried; >1μm removed by Hand-sieving; H2O2 for Organics if Necessary → Sand Subsample

Split → Subsample (approx. 5 g) → Feldspar Analysis

Split → Subsample (5-10 g) → Textural Analysis (RUASA)

Split → Subsample (5-10 g) → Heavy-Mineral Analysis → Carbon Tetrachloride

Split → Foraminiferan Analysis
procedure takes a total of only about 20 minutes per sample, allowing large numbers of samples to be analyzed.

Two additional computer programs were used to analyze and interpret textural data. A program employing a technique described by Dowling (1977) was used to compare frequency data horizontally or vertically. The program, "GRID", converts individual frequency curves into a series of numbers laid out in a row. Rows of numbers representing spatially-related samples are then laid out in a grid and manually contoured (see Figure 35). A second program, known as "MNSTND", averages frequency and cumulative weight percentage data from a group of samples, resulting in a mean curve for the group and a standard deviation "envelope" around this curve.

Heavy Mineral Analysis

Heavy mineral analyses were done using a gravity separation method after Bates and Bates (1960) as follows (see also Figure 21):

1) Sand samples (see Figure 19) were hand-sieved for the 2-4ø interval in order to concentrate the heavy minerals and eliminate any effects of density-sorting of particular minerals.

2) The 2-4ø interval was split if necessary, in order to obtain a 5-10 gram sample for analysis.

3) Individual samples were introduced into a 500-ml separatory flask containing tetrabromoethane (specific gravity 2.85).

4) The flask was stoppered and shaken vigorously for 10 seconds.

5) Sides of the flask were washed down with more tetrabromoethane.

6) The flask was stoppered and allowed to settle undisturbed for 15-20 minutes.
FIGURE 21. Apparatus used for heavy-mineral separations (gravity method).
7) Heavy minerals were dropped into a filter below; the light fraction was then dropped into a separate filter (tetrabromoethane was retained and reused).

8) The remainder of the light fraction was washed down with acetone, and filters and separates were washed thoroughly with acetone and left to air-dry for several hours.

9) The heavy fraction was mounted on a glass slide with epoxy (index of refraction 1.54-1.56) and left to dry overnight (no coverslip was used).

10) Heavy-mineral slides were examined under a polarizing microscope; ribbon counts of only the ten minerals of interest were made to a minimum total of 200 grains per sample (the ten minerals were chosen as being the most abundant and/or the most important for differentiation).

11) Ribbon-count data for the minerals of interest was normalized to 100%.

Microscopic identifications of heavy-mineral grains were based on excellent descriptions found in Russell (1939) and Bullard (1942).

Analysis of duplicate samples shows reproducibility to be well within one standard deviation (Table 4).

Foraminifers

Selected coastal samples were analyzed for foraminiferan content. Sand fractions were floated in carbon tetrachloride in order to concentrate foraminifers present. Floats were then scanned under reflected light, and forms present were identified and noted. Assemblages were then matched with probable environments or combinations of environments of deposition according to Phleger (1960) (Table 3). No actual counts of foraminifers were made, although relative abundances, especially Ammonium/Elphidium ratios (see discussion under "Background and Previous work") were noted. Other forms present were also recorded.
TABLE 4. Reproducibility of heavy-mineral data (duplicate samples).
<table>
<thead>
<tr>
<th>Sample</th>
<th>To</th>
<th>Ep</th>
<th>Zr</th>
<th>Gt</th>
<th>St</th>
<th>Ky</th>
<th>Ru</th>
<th>Px</th>
<th>Hb</th>
<th>Sp</th>
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<td>5</td>
<td>55</td>
<td>4</td>
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<td>9</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>7</td>
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<td>4.5</td>
<td>14</td>
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<td>0</td>
<td>4.5</td>
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<td>45</td>
<td>9</td>
<td>5</td>
<td>25</td>
<td>3</td>
<td>2</td>
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<td>2</td>
</tr>
<tr>
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<td>0.5</td>
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<td>37</td>
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<td>0</td>
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<td>1</td>
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<td></td>
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<td>61</td>
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<td>4</td>
<td>0.5</td>
</tr>
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Feldspar-Staining

Feldspar stains were applied to selected point-bar samples after methods described in Carver (1971) for potash feldspar and by Laniz and others (1964) for plagioclase. Sand fractions were split down to about 1-2 grams and mounted on glass slides with black, nonacrylic roofing tar thinned with pentyl acetate. Slides were allowed to dry overnight and then etched by placing them approximately 1 cm above a small amount of hydrofluoric acid for 1-5 minutes, depending on grain size. The slides were then immediately dipped in a calcium chloride solution for about 15 seconds and allowed to dry. Next, they were immersed in sodium cobaltinitrite solution for 30 seconds and rinsed. After this step, slides were again allowed to dry and subsequently examined under a binocular microscope for comparison with standard percentage charts (Terry and Chilingar, 1955) in order to determine potash feldspar content. The slides were then etched again briefly (1 minute or less depending on grain size) and dipped into barium chloride solution for about 15 seconds. They were allowed to dry and immersed in amaranth for 1 minute. After careful rinsing and drying, they were examined microscopically as previously, this time for plagioclase percentages. Results of the staining were somewhat poor, in large part due to the variety of grain sizes represented, and the staining was eventually abandoned (see "River Study" section).
RIVER STUDY

Explanation

The situation along the northeastern Texas Gulf Coast is somewhat unique in that major river systems contributing sand to the coast drain rocks of very different lithologies (Figure 2; see also previous discussions). Previous study of river point bars in the region indicates the various rivers can be distinguished on the basis of heavy mineralogy (Russell, 1937; Bullard, 1942; Van Andel and Poole, 1960) (Table 6). Russell's (1937) study of Mississippi River point-bar sands involved extensive sampling; sampling of local rivers has been rather limited in the past, however (Table 6).

An important objective of this first portion of the study was to better-delineate ways to distinguish the various influencing river systems. More heavy-mineral analyses of local river point bars were made so as to increase the statistical accuracy of the data and to better-understand the differences between them. Also, it was hoped that similar fluvial systems, such as the Trinity and Sabine, might prove to be more easily-distinguishable. Hsu's (1960) data indicated local rivers might be distinguishable on the basis of grain-size criteria as well (Figure 12). The RUASA system (see "Methods" section) allows relatively rapid textural analyses of the large numbers of samples necessary to do this. Since individual grain-size analyses made on the RUASA system are much more rapid than corresponding heavy mineral analyses, it was hoped textural parameters alone would be sufficient for distinguishing sands from the various source rivers along the coast. Thus, heavy mineralogy would only be used periodically as a check.
Texture

Pilot Study

A pilot study was first undertaken in order to discover a sampling pattern that would give a good representation of individual point bars with the least possible number of samples. Two different point bars, one a large, finer bar along the Brazos River, and the other a smaller, coarser bar along the San Bernard River (Figure 22), were sampled for the pilot study.

Four different sampling patterns were tried (Figure 22): a random pattern of at least 10 samples, a central traverse of 10 samples, a traverse of 3 samples across the middle of the bar that were combined to form a single composite sample, and another traverse of 3 samples across the middle of the bar which were left separate. With each pattern, an attempt was made to sample all observed variability of grain size and bedforms. Resulting grain-size data are shown in Figures 23 and 24. Curves from those patterns resulting in more than one sample have been averaged by the MNSTND program (see "Methods" section).

From the curves, it is evident that the single composite-sample method gives results too poor for use. The two patterns with at least 10 samples yield almost identical curves, but the traverse of 3 samples appears to be almost as good. It was therefore decided to use the pattern of 3 samples with slight modification: field observations had shown that bars tended to be coarser on their upstream ends and finer on their downstream ends. Therefore, two additional samples, one at each end of the bar, were added (Figure 25.A.). Later on, it became neces-
FIGURE 22. Location and sampling patterns of point bars, pilot study.
FIGURE 23. Frequency curves of grain-size data from a Brazos River ("fine-grained") point bar as part of a pilot study to determine the smallest representative sampling pattern. Data averaged using MNSTND program (see "Methods" section). For location and explanation of the various sampling patterns, see Figure 22.
FIGURE 24. Frequency curves of grain-size data from a San Bernard River ("coarse-grained") point bar. See Figure 23 for further explanation and comparison.
FIGURE 25. Final sampling patterns, point bars.

A. Basic sampling pattern.

B. Sampling pattern for very long point bars.
sary to modify this 5-sample grid slightly when extremely long point bars were occasionally encountered (Figure 25.B).

Point-Bar Study

A minimum of nine (generally 10-13) point bars on the lower reaches of the four major rivers flowing into the northeastern Texas Gulf coastal zone (from east to west: the Sabine, Trinity, Brazos, and Colorado rivers) were sampled in the manner previously described in order to characterize each river according to grain size. Sampling localities are shown in Figure 26. An attempt was made to sample all observable varieties of bedforms and as many different stratigraphic horizons as possible, including a few samples from older point-bar deposits when they were exposed. This was done in order to get data representing the total sand load carried by the rivers under their various flow regimes.

Frequency curves for the point-bar samples were averaged using the MNSTND program (see "Methods" section), and are illustrated in Figure 27. Certain modes are quite pronounced within each individual river; these have been numbered as shown. In order to determine whether these modes are source-controlled or whether they simply represent hydraulic features of the different bedforms sampled, a comparison was made between sedimentary structures noted at each sampling site and modes present in the corresponding original curve (Table 5). No apparent correlations between structures and modes can be seen. This, plus the large numbers of samples analyzed for Figure 27, the persistence of the modes, and the fact that illustrated curves include some paleo-point-bar samples, strongly indicate a source control for the modes. Note that the same two modes found in the Sabine River, which drains reworked
FIGURE 26. Locations of point bars and sand pits sampled, river study.
FIGURE 27. Average frequency ("MNSTND"; see "Methods" section) curves for point-bar sands from major river systems along the northeastern Texas Gulf coast. Large numbers indicate distinct modes present. MGS = Mean Grain Size, $\phi$. 
TABLE 5. Comparison of sedimentary structures and major grain-size modes (Figure 27), river point bars. Modes appear to be a function of source rather than hydraulic regime.
<table>
<thead>
<tr>
<th>Sabine</th>
<th>Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>191.</td>
<td>Lg.-scale climbing ripples</td>
</tr>
<tr>
<td>192.</td>
<td>Lg.-scale climbing ripples</td>
</tr>
<tr>
<td>193.</td>
<td>Lg.-scale climbing ripples</td>
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<tr>
<td>203.</td>
<td>Sand + clay drape</td>
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<table>
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<td>85.</td>
<td>Good foresets</td>
</tr>
<tr>
<td>83.</td>
<td>Channel</td>
</tr>
<tr>
<td>97.</td>
<td>Sand + clay drape</td>
</tr>
<tr>
<td>98.</td>
<td>Sand + clay drape</td>
</tr>
<tr>
<td>153.</td>
<td>&quot;Mudflat&quot;</td>
</tr>
<tr>
<td>154.</td>
<td>&quot;Mudflat&quot;</td>
</tr>
<tr>
<td>155.</td>
<td>&quot;Mudflat&quot;</td>
</tr>
<tr>
<td>156.</td>
<td>&quot;Mudflat&quot;</td>
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**Brazos**

<table>
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<th>113a.</th>
<th>Lg. climbing ripples observed beneath in erosional trench; sm. structures covered by vegetation</th>
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<tbody>
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<table>
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<th>Lg.-scale cross-beds; sample from 2 separate foresets</th>
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</thead>
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<td></td>
<td>1 + 2 (Sev. lams.)</td>
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<table>
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<th>116.</th>
<th>Good med.-scale cross-beds</th>
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<th>118.</th>
<th>Sand + gravel + clay drape</th>
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Tertiary sediments, occur in all the other rivers. Tertiary sediments in this region consist of older fluvial and deltaic deposits, and it is quite reasonable to assume they are contributing a major portion of the sand load of all local rivers. If that is indeed the case, then possibly Mode #3 carried by the Trinity River consists of the Cretaceous contribution to its drainage basin, Mode #4 of the Brazos represents the Permo-Triassic contribution, and Mode #5 of the Colorado represents its Llano contribution (which, being first-cycle polycrystalline sands, would be expected to be coarser). However, sands from each of the modes were examined under reflected light with little or no discernable difference between modes on the basis of quartz-grain roundness and sphericity and estimates of relative heavy mineral and feldspar content. Later heavy-mineralogic comparisons between samples containing predominantly one mode were also inconclusive, although relatively few samples were examined.

Hsu (1960) noted that point-bar sands from Texas rivers appeared to be finer near the river mouths. This might indicate that point bars are presently undergoing erosion, coarser sand being trapped behind dams. The present study shows no indication of this, however (Figure 28). A correlation was instead noted between position of a point bar within a bend and mean grain size: those bars located deep in river bends or oxbows consisted of finer-grained sand, while those formed along straighter stretches were coarser.

**Heavy Minerals**

Ten sand samples each were selected for heavy mineral analysis from those samples already obtained from the Sabine, Trinity, and Brazos
FIGURE 28. Mean grain size, $\phi$, for center (Figure 25) samples, river point bars. No downstream trends in data are noted, indicating that point bars are not presently undergoing erosion (see text).
river point bars (See "Methods" section). Individual samples were chosen for maximum content in the 2-4φ interval, with no two samples being selected from the same bar.

Previous work has shown Colorado River heavy-mineral assemblages to consist mainly of a distinctive blue-green hornblende that is probably derived from the Llano uplift (Bullard, 1942; Van Andel and Poole, 1960), and it was felt that further data from this river was unnecessary. The Mississippi River, which also supplies sand to the Texas Gulf coast via longshore drift (Hsu, 1960), is characterized by a hornblende-pyroxene assemblage with lesser garnet and epidote (Russell '1937; Table 6). Mississippi River hornblende is brown or green-brown (Van Andel and Poole, 1960).

Individual results of the present heavy mineral analyses are given in Appendix I, and average results are compared with previous analyses in Table 6 (data from other sources has been normalized to the same minerals). Originally, only nine different minerals were counted for this study; however, later observations indicated that sphene, for which no previous data exists, might be useful for distinguishing the Sabine and Trinity rivers (Table 6).

From the present data, the Trinity and Sabine rivers can be characterized as carrying a zircon-kyanite assemblage that reflects their drainage of polycyclic sedimentary rocks. The Brazos River contains a zircon-garnet assemblage which appears to be derived from the Permo-Triassic of West Texas.

On the basis of the comparisons shown in Table 6, kyanite/garnet/hornblende + pyroxene ratios were chosen as the best mineralogic method
TABLE 6. Average percentages of selected heavy minerals for rivers in the study area plus the Mississippi River. Data is normalized to just the minerals of interest (see "Methods" section).
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for distinguishing those river systems making the greatest sand contributions to the coastal study area (Figure 29). Although there is a slight separation between the Trinity and Sabine rivers, they exhibit a good deal of overlap, and are difficult to differentiate (see above). Note that the limited analyses previously available tend to correlate poorly with the current data (Table 6; Figure 29). In comparing data between authors, it should be noted that mineral identifications can vary. Also, Van Andel and Poole (1960) examined a slightly different grain-size interval (1-4φ instead of 2-4φ), and counted only 100 grains total. The former method may account for their lower percentages of zircon, which tends to occur in the smaller size fractions (Bornhauser, 1940; Van Andel and Poole, 1960), while the latter method lowers their statistical accuracy considerably. For reproducibility of the present data, see the discussion under "Methods".

Occasional grains of Colorado (blue-green) hornblende were noted in Brazos River sands. This appears to be evidence that the Colorado River once flowed through lower portions of the channel now occupied by the Brazos River and emptied into the Gulf of Mexico where the Brazos does today (see discussion on tectonics and rivers in the "Background and Previous Work" section).

Feldspar

Petrographic observations of river feldspar content by Hsu (1960) indicated that percentage feldspar content might also be useful for determining relative river source contributions to the coast in the study area. Hsu determined feldspar percentages in sand samples by visual examination under a petrographic microscope only. Feldspars are notori-
Figure 29. Kyanite/garnet/hornblende + pyroxene ratios for river samples from the present study (solid values) and published sources. Sand-pit samples are taken from ancient river channels (Figure 6).
ously difficult to distinguish petrographically from quartz, however (see for example Folk, 1974), and it was decided that standard feldspar-staining techniques would be tried in order to simplify identifications and quantitative estimations of abundances. Separate stainings for potash feldspar and plagioclase were used (see "Methods" section).

Problems with the staining techniques resulted in relatively poor-quality data (see "Methods" section). Feldspar data from the various rivers are shown graphically in Figure 30. Relative differences in feldspar content between rivers are somewhat apparent, however, as overall feldspar content appears to increase going westwards (compare with Figure 2). Thus, while feldspar-staining was abandoned as a part of the present study, it may be useful for further, more detailed work.

Summary

Sand load from major river systems draining the northeast Texas Gulf coast is characterized on the basis of texture and heavy mineralogy. River sand occurs in distinct textural modes which appear to be source-controlled. No change in mean grain size of river point bars with proximity to the coast is noted. Point-bar grain size does correlate with geomorphology: bars in deep river bends contain finer sands than those formed along straighter stretches.

The Trinity and Sabine rivers are characterized mineralogically by a zircon-kyanite assemblage, while the Brazos River can be distinguished by its zircon-garnet assemblage. Trinity and Sabine sands may possibly be distinguished by sphene content, the occurrence being increased in Sabine sand. Kyanite/garnet/hornblende + pyroxene ratios appear to be
Figure 30. Comparison of estimated feldspar content, major local river sands.
an excellent tool for distinguishing sand from the various rivers contributing to the coastal study area (the Trinity/Sabine, Brazos, and Mississippi systems). Feldspar content also appears to differ between rivers; better staining techniques are needed to further define these differences.
COASTAL STUDY

Explanation

Objectives of the coastal portions of this study were to apply previously-gained information on distinguishing local sand sources to the coastal zone in order to learn more about formation and development of the coastal barrier features: Galveston Island, Bolivar Peninsula, and Follets Island. Surface traverses across and offshore from and cores and borings through these features were examined in the same manner as the river point bars, allowing relative determinations of sources to be made. This information was then correlated with available radiocarbon dates and aerial photographs of the coastal zone.

Locations of surface samples and cores are shown in Figure 31. Radiocarbon dates and previous stratigraphic studies from Galveston Island show it to consist of an offlapping sequence (Figure 11) (Bernard and others, 1959), indicating that horizontal traverses mirror vertical successions environmentally. Analysis of samples from surface traverses across area barriers and cores through the barriers should therefore yield similar information on changes in sand sources with time. Thus, the two sets of data can be used to check one another.

Texture

Samples taken from the northeastern Texas Gulf coastal zone were analyzed texturally using the RUASA system (see "Methods" section) (locations are shown in Figure 31). Mean grain size of 1-meter deep samples, those presumably below any upper-level zones of weathering and/or recent disturbance, are plotted in Figure 32. Values range from
FIGURE 31. Coastal study sampling locations. For explanation of the various sampling methods, see "Methods" section.
FIGURE 32. Mean grain size (MGS) and initial size (IS), or size of initial 10%, of 1-meter deep coastal samples and average river values. All data in $\phi$. 
1.9-3.4φ (medium to very-fine sand). No substantial trends in the data are immediately apparent, although there may be a slight fining towards the Gulf across the various features. Borings from Bolivar Peninsula seem to exhibit a slight coarsening-upwards trend within the individual upper-level sands which form the feature (Figure 33). This is in agreement with Bernard and others (1959; Figure 10.B.), who noted a decrease in grain size with depth and offshore on Galveston Island. However, the total sediment package comprising Bolivar Peninsula contains numerous interbedded fine deposits (Figure 33), and sections from eastern and western Galveston (Figure 34) also show interbedded fine sands and muds not really explained by Bernard and others (1959), who generally depict Galveston as consisting of a single large, clean sand body (Figure 10).

Also, a grid (see "Methods" section) of frequency data from a recent boring acquired in this study on central Galveston Island shows a rather homogenous sand section (Figure 35). Sorting (standard deviation) values from the 1-meter deep and boring samples (Figures 35 and 36 respectively) likewise show no discernable trends. This is probably due to the presence of shell hash, which was not removed from the samples (except for particles larger than 2 mm, which were removed by hand-sieving) and would tend to affect resultant sorting values greatly.

Mean grain-size values for modern beach (swash zone) samples are shown in Figure 37. Modern beach sands in the study area consist of fine- to very-fine sand. Because mean grain size is also influenced to some extent by shell hash content and because samples in the area are extremely well-sorted, the phi size of the first 10% peak in the frequen-
FIGURE 33. Army Corps of Engineers borings from Bolivar Peninsula.

For locations, see Figure 31.
FIGURE 34. Army Corps of Engineers borings from eastern Galveston Island. For cross-sectional lithologic relationships from western Galveston Island, see Figure 11.
FIGURE 35. Contoured GRID plot (see "Methods" section) of frequency and other data from rotary wash hole, central Galveston Island (HL locale in Figure 31). Each horizontal line represents data from an individual sample; sample data is laid out vertically according to position in the hole from top to bottom. Sampling interval is 1 meter. Contoured at 10%. Mean grain size, standard deviation, and initial 10% in phi ($\phi$). For discussion of foraminiferan data, see "Methods" section.
Top

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-1...... 0...... 1...... 2...... 3...... 4

PHI SIZE

Bottom
FIGURE 36. Sorting (standard deviation) values, in $\phi$, for 1-meter deep coastal samples.
FIGURE 37: Mean grain size (MGS) and size of initial 10% (IS= initial size), 1/4σ intervals, for modern beach samples, northeastern Texas Gulf coast. Samples generally taken from the surf zone. Areas of long-term net regression (i.e., accretion) from Morton, 1979 (see Figure 7).
cy curve was also examined to illustrate more subtle differences in grain size (Figure 37).

Morton (1979), in his study of historic shoreline changes along the Texas Gulf coast, noted areas of transgressive/eroding and regressive/accruing coastline; note the correlations between different coastal types and the corresponding first 10% value (Figure 37). Shoreline areas currently undergoing long-term net erosion are coarser than those areas undergoing long-term net accretion by about 1/40. This difference appears to be equivalent to textural differences previously noted by Shepard (1960a; see "Background" section). The difference is not reflected in a similar plot of standard deviation (Figure 38), again probably due to the presence of shell hash as noted above.

The mean grain sizes of modern and relict beach sands are considerably finer than those of point-bar sands from local rivers (Figures 27 and 37). Therefore, of the sand transported as bed load (traction) by these rivers, only a fraction is reaching the coast. This can be further documented by examining the grain-size data for sand samples collected from the deltas of those rivers. Average frequency curves for the Sabine, Trinity, Brazos, and Colorado deltas are shown in Figure 39. Curves for the wave-dominated Sabine, Brazos and Colorado deltas indicate that of the total sand-sized load being carried by these rivers, only the finer fractions (approximately 2.5–3.5%) are being contributed as beach sand. The fluvial-dominated Trinity River delta, located within Galveston Bay (see Figure 1), consists of only slightly finer material than that contained by its point bars (Figure 39.B.). The coarser portion of the load appears to be dropped out within the upper
FIGURE 38. Standard deviation (sorting) and size of initial 10%, in $\phi$, for modern beach samples shown in Figure 37. Areas of longterm net regression (i.e., accretion) from Morton, 1979 (see Figure 7).
Figure 39. Average frequency curves (MNSTD; see "Methods" section) for samples from the Sabine, Trinity, Brazos, and Colorado river deltas. Dashed curves are composite curves for river point-bar sands (from Figure 27); solid curves represent composite curves for deltaic beach sands.
reaches of the delta/lower reaches of the river, leaving finer, more well-sorted material to reach the nearshore system (the finest material is probably carried offshore in suspension).

Differences in sorting and grain size may therefore have applications for distinguishing fluvial-dominated from wave-dominated deltaic deposits. These differences may also prove useful for distinguishing ancient fluvial and beach sands, beach sands being extremely well-sorted and containing only a traction mode (Figure 39.D.) (see "Applications for the Ancient Record" section).

Faunas

Selected coastal-zone core and surface samples were processed and examined for foraminifers and other microscopic fauna, and assemblages were used to determine environments of deposition (see "Methods" section). Downcore environmental interpretations for borings from Bolivar Peninsula are shown in Figure 33, and for the deep boring from Galveston Island in Figure 35. Upper portions of the barriers tend to be barren. Further downcore on Galveston Island, a profound beach influence is noted. Basal portions of the Galveston boring and lower portions of Bolivar Peninsula sands contain a mixture of predominantly beach sediments with some lower lagoonal deposits that eventually changes with increasing depth to beach plus fluvial-marine deposition. Indeed, grain-size data from the deepest samples, those containing the beach plus fluvial-marine faunas, exhibit the poor sorting shown in the previous section to be characteristic of modern deltas in the area (compare, for example, Figures 35 and 39). These changes in faunal assem-
blages and grain-size distribution may correspond with the facies changes described by Bernard and others (1959).

Foraminifers thus indicate initial barrier formation along the northeastern Texas Gulf coast was associated with beach and fluvial-marine conditions. Gradually, the fluvial influence declined, and open-marine beach conditions became dominant. Initially, beaches must have been low, as attested by frequent interbedded lagoonal deposits. Eventually, open beaches became firmly-established on the barriers. In the latter stages of development, barriers began to be covered with a veneer of sand barren of microfossils that probably consists of dune and/or washover deposits.

Only a single agglutinated foraminiferan was noted in all the samples studied. Lankford and Rogers (1969) also noted an absence of agglutinated forms and attributed it to sample preparation methods, leaching and destruction, solution by acids formed by decaying vegetation, or possibly originally more highly-saline water.

Heavy Minerals

Heavy-mineral assemblages in modern and relict beach sands were examined in an attempt to establish past and present sand budgets. Heavy-mineral data for all coastal samples analyzed are listed in Appendix II. Various heavy-mineral percentages and ratios have been plotted in Figures 40-43. Hornblende + pyroxene (Figure 40) and epidote (Figure 41) percentages were plotted in an attempt to delineate sand contribution of the Mississippi River (see Table 6) to the area. No distinct changes with distance or position could be ascertained, how-
FIGURE 40. Average normalized hornblende + pyroxene percentages at each locality, coastal study. Average river values are also shown; values in parentheses are from Van Andel and Poole, 1960. Underlined values denote sampling locales in which cockscomb edges were seen on some grains.
FIGURE 41. Average normalized epidote percentages at each locality, coastal study. See also explanation, Figure 40.
FIGURE 42. Average normalized kyanite percentages at each locality, coastal study. See also explanation, Figure 40.
FIGURE 43. Average normalized garnet percentages at each locality, coastal study. See also explanation, Figure 40.
ever; the contribution appears to be approximately the same throughout the study area. Only rare Colorado-type (blue-green) hornblende grains were noted. Sand contribution from the Colorado River, which is also down-drift from the barriers studied, thus appears to be negligible, and is probably the result of weathering of offshore sands (see Goldstein, 1942). Hacksawed/cockscomb edges on hornblende and pyroxene grains, an indicator of chemical weathering due to solution, were rarely seen in samples from the study area. Changes in hornblende and pyroxene abundances do not therefore appear to be the result of or even much affected by solution processes.

A correlation does appear to exist between grain size and presence of corroded grains: those samples observed to contain hornblende and pyroxene grains with hacksawed edges are all from finer-grained, accreting-beach type deposits (see Figures 37 and 40 and discussions in the "Texture" section above). Since relatively much lesser quantities of sand are now being contributed to the coastal zone by rivers, which have been dammed, and offshore Pleistocene sands contain a large Mississippi component of hornblende and pyroxene (Figure 13 and Table 2), it appears that presence of hacksawed grains may be a good indicator of offshore sand contribution. Indeed, Van Andel (1960) noted upper Pleistocene pyroxenes and amphiboles from a core taken off Louisiana appeared to be severely weathered, whereas post-Pleistocene heavy minerals were not. Also, barriers have been shown to be retreating where the offshore shelf is covered with mud (Shepard, 1960). The correlation with presently-accreting beaches suggests the present major source of sand to northeastern Texas Gulf coast beaches is from offshore.
Average percentages of kyanite are plotted in Figure 42 in order to delineate areas of high sand contribution by the Trinity and Sabine river systems (see Table 6). Here again, however, no good pattern emerges, with kyanite appearing to be distributed fairly evenly throughout the study area in spite of the fairly distinct differences in abundance in the various rivers. Note the very high abundance of kyanite (39%) in the sample from Smith Point (East Bay Ridge), a ridge of sand that forms part of the Pleistocene Ingleside trend (see "Background and Previous Work" section). This would seem to indicate that during Ingleside time, the Trinity River emptied into the Gulf in very close proximity to this feature.

In an attempt to determine the extent of contributions to the study area by the Brazos River, garnet abundances were plotted in Figure 43. Here again, no distinct trends were observed. Garnet abundances in two samples from the eastern portion of the study area, including one sample from Rollover Pass, were anomalously high (other heavy mineral percentages from these same samples were also quite anomalous), indicating these sands are possibly fill material brought in from elsewhere (the Brazos River?) to combat local erosion. If that is the case, garnet values in the surf zone for some distance down-current might be artificially increased. Alternatively, the sand could be relict from an ancient depositional lobe of the Brazos River (see Figure 6). Sands from the Mississippi River also contain appreciable garnet (see Table 6). Overall, there does seem to be an increase in garnet abundances going westward in the study area, but it begins far updrift from the present entrance of the Brazos River (Figure 43).
Because of the complex heavy-mineral distribution patterns observed in the study area, kyanite/garnet hornblende + pyroxene ratios were plotted as for the coastal rivers (see "River Study" section). These are shown in Figure 44 superimposed on average values for the Trinity/Sabine, Brazos, and Mississippi rivers. (For locations of the samples plotted, see Appendix II and Figure 31). Coastal sands from the study area appear to represent mixtures of these components in varying proportions. Some samples consist of predominantly one component: the sample from Smith Point appears to be composed entirely of Trinity River sand, the various shallow offshore samples contain mostly Mississippi-derived material, and the anomalous sample from Rollover Pass previously described appears to consist of Brazos River sand (fill or relict material?). Most samples, however, contain contributions from two or, more commonly, all three river components (Figure 44).

Kyanite/garnet/hornblende + pyroxene ratios from the three separate barrier features, Galveston, Bolivar, and Pollets, do not differ greatly overall (Figure 44). Samples from Pollets Island tend to contain lower percentages of Trinity River minerals. As was noted in the garnet plot above, all samples except those of easternmost modern beaches contain a surprisingly high Brazos River contribution, as the mouth of the Brazos lies well down-drift from the area (Figure 1). Older channel deposits (Figure 6) indicate the Brazos once entered the Gulf considerably to the east of its present position, however. Samples from a number of sand pits cut in these channels support this conclusion, containing heavy-mineral assemblages strongly indicative of a Brazos source (Figure 29). Thus, it appears that during the developmental stages of the three
FIGURE 44. Kyanite/garnet/hornblende + pyroxene ratios for coastal study samples. The inner triangle has endpoints consisting of average composition, river sands: T/S=Trinity/Sabine, B=Brazos, M=Mississippi. Solid values indicate samples from the barrier proper; open values denote surf-zone or offshore samples.
barrier features, the Brazos River probably entered the Gulf of Mexico in the vicinity of Bolivar Roads (Figure 1). Perhaps during its westward migration, the Brazos later switched to a channel entering at San Luis Pass as supported by the position of remnant offshore deltaic sediments noted by Morton (1979). The river is known to have occupied the Oyster Creek channel, just to the west of that, prior to assuming its present course (Bernard and others, 1978).

In order to gain important information on changes in sand supply with time, kyanite/garnet/hornblende + pyroxene ratios for samples from Galveston Island have been plotted together with their approximate ages of deposition as estimated by their position in relation to radiocarbon isopachs across the island derived by Bernard and others (1959; Figure 11). This plot is shown in Figure 45. Samples in the plot have been further subdivided into groups: those samples from well-developed ridge-and-swale topography as shown on aerial photographs, samples from obvious washover features (also on the basis of aerial photographs), samples taken gulfward of Seawall Boulevard (U.S. Highway #87), which runs along the beachfront along what appears to be a natural boundary of modern effect of storm surge, and finally, modern swash-zone samples.

Considered in this manner, two major sediment types emerge (Figure 45). The first type, Type 1, (indicated by solid and open circles), consists solely of the first group of samples listed above; that is, samples from well developed ridge-and-swale topography. These samples are the oldest in age, and they appear to form the "nucleus" of the island. The second major sediment type, Type 2 (washover circles and all triangles), consists of the remaining sediment groups listed above in
FIGURE 45. Kyanite/garnet/hornblende + pyroxene ratios for Galveston Island samples, delineated on the basis of estimated age, location, and sample type. Solid symbols indicate the sample was from an area exhibiting good ridge-and-swale topography on aerial photographs. Samples connected by dashed lines denote recounted values. Numbers are approximate age of the sample in years B.P. as estimated from Figure 11. Zero age values indicate modern surf-zone samples.
combination: samples from washover fans, very young sand located gulfward of the highway, and swash-zone/offshore sands. Type 2 sand thus appears to consist of sediment that has been accreted to the island only in most recent times and to be the type of material added presently in those areas where net accretion is occurring. These are probably equivalent to the two different sand types noted by Shepard (1960a; see "Background" section).

Important mineralogic differences can be observed between these two major sand types (Figure 45). Type 1 sands contain more Trinity River sand, while Type 2 sands have a high Mississippi River contribution instead. Shallow offshore samples (Figure 31) appear to consist almost entirely of Mississippi River-type sand. Observation of hacksawed pyroxenes in samples did not yield sufficient information to determine whether this Mississippi contribution is of present or offshore-Pleistocene origin; composition of the shallow offshore samples possibly suggests the latter.

Samples from Eight Mile Road have been specially denoted in Figure 45 because they lie along the same traverse used by Bernard and others (1959) to obtain radiocarbon dates (Figure 11); thus, the approximate ages shown with these samples are probably considerably more accurate than those of other samples shown. The two oldest samples (from the bayside), whose ages appear to approximate the time of earliest formation of Galveston Island at 5500 years B.P., show a predominant Trinity River influence (Figure 45). At some time between then and the next-oldest sample, about 4000 years B.P., a major change in sand composition appears to have occurred, as sand of that age and younger consists of a
mixture of Trinity, Brazos, and Mississippi river sands. This sand of mixed source seems to comprise the bulk of the nucleus of the island (see above). Then, in very recent times (800 years B.P. or less), another major change in sand deposition on the island occurred, as Type 2 sands began to be accreted onto the seaward side of the island.

The observed differences in source between Type 1 and Type 2 sands are also reflected to some extent in mean grain size, Type 1 sands being slightly coarser than those of Type 2 (Figure 46). This would seem to be due to the fact that only finer material from the Mississippi River would be transported this far west.

Heavy-mineral ratios for samples from the deep boring taken on Galveston Island are also delineated in Figure 45. As expected, no Type 2 sands were encountered in the hole. Here again, however, a major shift in source during Type 1 deposition from predominantly Trinity sand (samples #624 and #625; c and d in Figure 35) to well-mixed river sand (remainder of samples) is evident. This time it does not occur during earliest formation of the island, but rather at some intermediate point in the development of Galveston roughly estimated by position at 2600-3000 years B.P. (Figure 45).

Heavy-mineral ratio data from Bolivar Peninsula and Follets Island are not as clear-cut, although a number of important generalizations can be made. On Bolivar, Highway #87 does not appear to make a good dividing line between Type 1 and 2 sands (Figure 47) as it does on Galveston Island, perhaps because it is much further back from the beach than on Galveston. Another problem with the data, and therefore with determining a division between sand types on Bolivar, is that very few Type 1
FIGURE 46. Mean grain size, $\phi$, Type 1 (solid) and Type 2 (open) sands. Slashes denote those samples whose initial 10% value on the frequency curve is 3.0$\phi$ or finer.
FIGURE 47. Kyanite/garnet/hornblende + pyroxene ratios for Bolivar Peninsula samples, delineated as in Figure 45. Connected samples denote a surf zone traverse from Sabine Pass westward to North Jetty, Bolivar.
samples were obtained. Those that were contain predominantly Trinity River sand (Figure 47) and appear to generally be associated with the Pleistocene Trinity River channel (Figure 8).

Holocene sequences in deep borings from Bolivar consist of interbedded sands and finer material (Figure 33). Unfortunately, no radiocarbon dates are available from these sequences. In general, the Bolivar barrier sequence appears to have been deposited in a predominately deltaic setting, as evidenced by poorer sorting of the sands and foraminiferan faunas (see Figure 33 and previous discussions). This again is probably related to the presence of the flooding Trinity River channel.

Modern swash zone samples, other than the anomalous ones previously mentioned and suspected of being fill, show progressive mixing trends with distance westward (Figure 47). The amount of material contributed by the Mississippi River increases progressively going westward from Sabine Pass to the North Jetty, Bolivar Roads. Garnet percentages also increase in a westerly direction to High Island, beyond which they fall off again. The areas of increasing garnet abundance are associated with eroding coastline, while diminishing garnet is associated with accreting beaches. Although many other factors can be involved in affecting local abundance of these minerals (see above), they may confirm what was previously observed: that areas of present accretion are associated with a dominance of Mississippi-derived sand, either contributed directly by the river today or, more probably, from the erosion of offshore deposits.
Data from Follets Island is more limited than that for the other features. No good aerial photographs of the Follets area were available for this study; thus, samples from washover fans could not be directly delineated. Also, no radiocarbon dates for determining relative ages of samples were available and no borings from the island were located. Field observations indicated the sand body forming the island to be extremely thin. Follets Island has much lower relief than Galveston (generally less than 1.5 m). Also, during digging for samples, the Beaumont Formation was observed at depths of a meter or less in a number of locales, and was seen locally outcropping along the beach.

The kyanite/garnet/hornblende + pyroxene triangle for Follets Island appears to indicate a reversal of the relationship between Type 1 and Type 2 sands (Figure 48). Sand samples from the island proper plot as Type 2 rather than Type 1 sands with the exception of one sample from the back side of the island (#456-PBR-1a). Other samples in the Type 1 field are from the modern swash zone. The combination of their mineral ratios and the fact that they appear to directly overlie the Beaumont surface (see above) indicates they are all Type 1 samples from the original nucleus of the island. Grain-size data bears out this conclusion, as sand in the swash zone is slightly coarser than that of the backshore environment (Figures 32 and 37).

Thus, on Follets Island, Type 1 sand which probably comprises the original barrier feature is found mainly at or near the modern beach. The remainder of the island is composed of Type 2 sand that was probably washed over, with occasional isolated pockets of original sand such as
FIGURE 48. Kyanite/garnet/hornblende + pyroxene ratios for Follets Island samples, delineated as in Figure 45.
the anomalous sample mentioned above still remaining. It appears that most of the original Follets barrier has been eroded away.

Summary

Textural relationships from the northeastern Texas Gulf coast barrier features are more complex than previously assumed. Sand forming the Galveston barrier appears to be more homogenous in size than was previously thought (see for example Bernard and others, 1959). Individual Bolivar barrier sand bodies show a coarsening-upwards trend, but the island as a whole consists of at least equal amounts of finer material. Modern barrier beach sands in the study area consist of fine- to very-fine sand. Finer sands are associated with areas currently undergoing longterm net accretion. Analysis of deltaic deposits indicate local rivers are contributing mainly the finer portions of their total sediment load to the coastal areas, with coarser material being trapped in lower reaches of rivers and/or in fluvial-dominated deltas. Fluvial-dominated deltaic deposits are coarser and more poorly-sorted than wave-dominated deltaic deposits, but do not contain as much coarse material or the distinct source-related modes that fluvial deposits do. Local beach deposits, in turn, can be distinguished by being even finer and more well-sorted than the wave-dominated deltaic deposits.

Foraminifers indicate initial barrier formation was associated with a combination of fluvial-marine and open-marine beach conditions. With time, low beaches were established that were frequently washed-over. As barrier development progressed, open beaches stabilized, and finally, dune systems developed. These faunal changes may correlate
with previously-described sedimentary facies.

Although time-consuming, heavy-mineral analysis continues to be the best method for distinguishing river sources of sand along the northeastern Texas Gulf coast. Contribution from the Colorado River, downdrift of the coastal study area, is negligible. Solution processes do not appear to appreciably alter mineral assemblages present, although a correlation between accreting beaches and presence of hacksawed pyroxene grains was noted that appears to indicate offshore Pleistocene deposits form the dominant source for present beach sands.

Kyanite/garnet/hornblende + pyroxene ratios appear to be an excellent criterion for evaluating various source contributions in the study area. Higher-than-expected contributions to the area by the Brazos River, now situated downdrift of the island, are explained by the fact that the river probably emptied into the Gulf in the Galveston area during the time of formation of the barriers or that relict Brazos sands were readily available, perhaps as an older deltaic body, for reworking during early barrier development. On Galveston Island, a combination of approximated age dates and mineral ratios for samples results in the delineation of two distinct sediment types. Type 1 deposits contain a mixture of Trinity/Sabine, Brazos, and Mississippi river sand. They appear to form the nucleus of the island, and are slightly coarser than modern beach sands. Early in Type 1 deposition, there were distinct periods when Trinity River influence was dominant in the area. Type 2 sands consist of more recent, finer material added onto the island: younger (800 years B.P. or less) deposits, modern beach sands, and washover fans. This material is
derived predominantly from the Mississippi River and/or offshore Pleistocene deposits. Sand body geometry of Bolivar Peninsula is complex and reflects the presence of the Pleistocene Trinity channel. Mississippi influence increases westward on modern beaches from Sabine to Bolivar and is again associated with accretion. On Follets Island, Type 1 sand occurs in a thin strip on the modern beach; sand behind is of Type 2, and appears to be wash-over material.
Discussion

With information gained from this study, the history of Galveston Island can be reconstructed as follows. The island originated about 5000 years ago (Bernard and others, 1959) as a sandy shoal area in open marine waters but with a strong fluvial influence (i.e., a deltaic environment), as evidenced by foraminiferan assemblages and periodic dominance of Trinity River mineralogies. Sand forming the island was predominantly a mixture of Trinity/Sabine, Mississippi, and Brazos river-derived sands in varying proportions. "Pockets" of essentially pure Trinity River sand and interbedded finer deposits toward the back side of the island indicate that older Trinity delta lobes served as the original seed for the barrier. Washovers added material to the island's back side, but gulfward and southwestward accretion dominated (Bernard and others, 1959). The island continued to grow in size and gain relief; eventually, dunes were established and washovers occurred only infrequently during major storms.

At some time in the recent past (around 800 years ago), sources of sand in the area changed. Sand accreted to the island by washover or beach accretion seems to now have been derived either from the Mississippi River or, more probably, from erosion of Pleistocene deposits offshore. In areas not experiencing active erosion, this type of sand continues to be deposited today. Presently, erosion appears to exceed beach accretion and washover deposition, and the island as a whole is retreating.
Although no radiocarbon dates are available from Follets Island, its history appears to have been similar to that of Galveston. On Follets Island, however, erosion of the barrier has been so severe that the only remaining sand from the original island is found immediately adjacent to and on the present beach, with modern washover deposition forming the bulk of the island. Note that Follets Island is situated further gulfward than Galveston Island along the coast today (Figure 1), and must have been even more so in the past.

The history of Bolivar Peninsula appears to have been similar but more complicated, with deltaic-type processes originally dominating. Here again, no dates are available, but borings through the island show this barrier to be comprised of interbedded sandy and muddy deltaic deposits of the ancestral Trinity River (Figures 6, 8 and 33) that were incorporated and reworked into the barrier. In recent times, it has been extensively washed-over, and here, as on Galveston and Follets islands, finer offshore sand is presently being accreted onto the Gulf side of the island.

Sand forming the original nucleus of these barrier features was predominately derived from local rivers and the Mississippi River. This mixing of sand sources implies reworking of sands by marine processes for formation and development of the barriers. Questions to be answered are twofold: First, how did the sand become available, and secondly, what marine processes were involved in concentrating them?

Texas coastal barrier formation is associated with rising sea level after a major sea-level drop during the Wisconsin glaciation (Figure 9). During the Wisconsin, sea level stood far out on the continental shelf.
Local rivers carried greater sediment loads than at present and carved channels, both on present land and across the shelf. According to Morton (1979), great deltaic headlands were also built out onto the shelves and became major promontories (Figure 7). These headlands amplified wave refraction and consequently were eroded. Morton estimates the headlands to have consisted of about 15-25% sand. Fine sand is the easiest material to move according to velocity diagrams (Schiller, 1935; in Middleton and Southard, 1978), and coastal sediment supply of this material in particular must have been extremely high as the post-glacial sea-level rise commenced and continued. Even greater sand deposition may have taken place behind the deltas in the lowest reaches of the river valleys where subsidence is great. Rice (1969) noted this occurrence in the modern Trinity River system. Thus, tremendous packages of river sands lay waiting until sea level rose to meet them. With continuing transgression, sand appears to have been swept shoreward by processes of coastal onlap (Vail and others, 1977). As material reached the coast, it must have been piled-up against and accreted onto pre-existing bathymetric highs, as evidenced by the 20-foot difference in height of the Beaumont surface between the front and back sides of Galveston Island shown in Figure 10.B. These highs appear to have consisted of relict lobes of the ancient Trinity River delta, but could also have been upthrown blocks of local faults (see "Comparisons" section), which are poorly-mapped in the region.

Other independent evidence of these theories exists. Hsu (1960) also reached the conclusion that Bolivar Peninsula had been formed by
marine incursion over the Pleistocene Trinity River delta and that the transgression had reworked these deposits. Indeed, molluscs have been shown to indicate extensive reworking of late Pleistocene Trinity deltaic deposits from Sabine to Boliver (Morton and Winker, 1979). By means of various calculations, Wilkinson (1975) concluded that at least half of the sand comprising Matagorda Island, another Texas coastal barrier (Figure 1), had already been deposited in the area before it became a well-developed barrier.

Thus, a combination of factors appears to have been responsible for formation of the northeastern Texas Gulf coast barriers. The Wisconsin glacial epoch, coupled with local subsidence, resulted in a large drop in the sea level along the gently-sloping Gulf coast, allowing tremendous amounts of sand to be left along the coastal plain and as valley fill. Subsequent rapid transgression (Figure 9) resulted in reworking and shoreward transport of this sand. Movement of sand along the shelf is thought to have decreased as water depths increased during the submergence (Morton and Winker, 1979). When sea level reached its present position, this material appears to have been piled up against the coast. According to Wilkinson (1975), the final resting place for the shoal that formed Matagorda Island depended on the slope of the Pleistocene surface beneath and the configuration of the shoreface at approximate stillstand; this seems to be the case for the study area as well (see previous discussions).

Another problem that must be addressed is the question of by what process or processes accretion took place following initiation of the barriers. Bernard and LeBlanc (1965) advocated chenier/beach ridge
accretion, noting that these features occur most frequently near the mouths of river distributaries. The buildup of sediment appears to dissipate wave energy at greater distances offshore, increasing the rate of deposition nearer shore. Once vegetation takes hold, additional sediment is trapped. An alternate explanation was provided by Shepard (1960a), who favored longshore accretion, noting that longshore bars formed during winter storms have been observed migrating landward and being added onto the barrier face. Beach-ridge accretion seems to be more applicable to the study area, as this process accounts for the mixed-source and offshore sediments observed and the good ridge-and-swale topography seen on local aerial photographs; perhaps the true method is some combination of the two. Chenier plains in the Sabine area (Figure 17) are probably of similar origin, but did not form barriers separate from the coastline because of lower subsidence rates at their location along the Sabine Arch (Figure 5).

Both of these processes account only for seaward and southwestward growth. As shown by aerial photographs and heavy mineral analyses, washover deposition is also an important mechanism of barrier accretion, accounting for landward growth. Landward or seaward growth are dependent on the balance between sand supply and wave conditions (Shepard, 1960a). During formation and initial accretion of Texas barriers (deposition of Type 1 sand), seaward and southwestward growth was dominant. With the change to deposition of Type 2 sand, however, washover/landward growth is more prominent, as evidenced by textures and mineralogy. Sand packages transgressed by the sea level rise were perhaps "used-up" to form the barrier systems during the stillstand; eventually, the only new
material available for accretion was sand eroded from older offshore deposits. Modern river sand is largely unavailable for barrier accretion because it is presently trapped in the estuaries formed by the transgression (see "Erosion" section). Thus, once original river sands are completely incorporated into barriers, further growth of the features is dependent on the relationship between subsidence and amount of other available sediment.

Alternately, a shift from stillstand or slight transgression to regressive conditions could account for the change in sand source. If transgressive conditions are responsible for sweeping sediment onshore, regressive conditions would tend to transport whatever sand remained offshore rather than into the barrier system (Vail and others, 1977). This would result in long-term net erosion of barriers because only sand eroded from relict material immediately offshore would be available for accretion. In this setting, accretion would tend to occur only during storms with the most severe surge, and washover-type accretion would exceed beach-ridge accretion, as is presently observed. If this is indeed the case, then the present is a rather unique moment in geologic time, as it may offer a chance to study the relationship between transgressive and regressive processes and facies. It may also have other implications, possibly suggesting a buildup in polar ice caps or increased subsidence perhaps due to recent renewal of growth-fault activity.

Summary of the Model

During the Wisconsin glacial advance, sea level stood much lower than at present. Rivers along the Gulf coast deposited great bodies of
sand in deltaic headlands on what is now the continental shelf and in their lower valleys, the present coastal region. This sand remained there until the continental shelf was flooded by the post-glacial transgression, at which time the sand was eroded, reworked, and mixed with sands from other rivers. When sea-level rise slowed radically or perhaps reached a stillstand, about 5000 years ago, sand began to shoal in the nearshore areas around some critical point in the offshore slope or bathymetry, probably a pre-existing delta lobe. Seaward and southwestward growth by a combination of beach-ridge and longshore-bar accretion, and periodic washover-fan deposition eventually resulted in stable barrier features along the northeastern Texas Gulf coast. As frontal accretion continued, washovers became less frequent, and beach-type deposition dominated.

Eventually, the reworked river sands were completely incorporated into the barrier features and/or sea level began to fall slightly. Local rivers were now, for the most part, drowned in estuaries and therefore providing little additional material to the coastal zone. The only remaining major sand sources were offshore Pleistocene deposits and, to a lesser extent, Mississippi River sands, both consisting of finer material. This new sand type was deposited in a similar fashion, but caused net erosion because the overall sand contribution was exponentially less, and if relative sea level was falling, most sand was now being swept in an offshore direction. Also, the finer grain size aided erosional processes (see "Erosion" section). As net erosion continued, washover deposition became more frequent again, especially on barriers
of lower relief. This continued deposition of finer material and net erosion continues today.

**Comparisons**

Many similarities exist between the present model of barrier formation and observations made by Wilkinson (1975) on Matagorda Island just to the southwest. As previously mentioned ("Discussion" section), sand forming the island appears to have a similar origin to that forming northeastern Texas Gulf coast barriers. Wilkinson also observed that formation of Matagorda Island was accomplished in two separate stages: reworked, mixed-source sands producing a migrating shoal or "early barrier" onto which river sands were later accreted. Note that he had no specific mineralogic data on which to base his source determinations. The difference in deposition was noted in detailed study of facies changes, the two types of deposition corresponding to his "back-island" and "fore-island" facies respectively. Perhaps these correspond to Type 1 and Type 2 sands in the present study area.

The Ingleside trend (see previous discussions) may also be of similar origin. If it did indeed form during a mid-Wisconsin interstadi- al as postulated by Wilkinson and others (1975), then sea-level conditions were quite similar to those resulting in formation of the present barriers. Indeed, if the sea-level curve of Graf (1969; Figure 9) and the present model are correct, one would expect to see similar features dating from that time, provided they were preserved. The Smith Point portion of the trend lies on the upthrown block of a major coastal fault
(H. C. Clark, personal communication). Possibly, this fault block influenced the location of Pleistocene barrier-type deposition.

The mixing of sand sources observed in northeastern Texas Gulf coast barriers argues in favor of the de Beaumont (1845; in Shepard, 1960a) over the Gilbert (1885; in Shepard, 1960a) "classic" model of barrier formation (see "Background" section). Instead of localized offshore erosion forming the barrier, however, the process was probably more similar to the "sweeping" movement of sediment towards the coast advocated by Shepard (1960a). Bernard and others (1959) noted facies differences on Galveston Island indicative of changing depositional conditions, but did not detect the shift in sand source. Also, grain-size relationships through Galveston Island and other barriers appear to be more homogenous than Bernard and others (1959) indicated. This is implied by the present model and born out by evidence shown in Figures 32 and 35. Note that their conclusions were based on limited grain-size analyses from the island proper (Figure 10.B.). Their radiocarbon dates form the basis of the present model, and their observations of beach-ridge accretion processes are quite reasonable in light of the present data. Barrier facies models from the Texas Gulf coast can be more complex than their work indicates, as evidenced by the Holocene section on Bolivar Peninsula and borings from eastern and western Galveston Island (Figures 10, 33, and 34).

A pure longshore-drift model such as that proposed by Bullard (1942) for the formation of Gulf coast barriers no longer seems applicable. If the barriers had formed from material brought in directly from local rivers and/or reworked deltaic lobes close to their original
depositional positions, barrier sands would be expected to contain heavy mineral assemblages indicative of a single river source. The well-mixed assemblages shown to be present clearly do not support this.

Hoyt’s (1967) model for barrier formation (See "Background" section) also does not appear applicable to the study area. As pointed out by Otvos (1970), northeastern Texas Gulf coast barriers started to form as transgression slowed or stopped. Also, Otvos’ possible explanations for the lack of observed open marine deposits behind the barriers (see "Background" section) are reasonable in view of the current model. The Hoyt theory may have applications for United States Atlantic coastal barriers such as Sappelo Island, as these islands differ in important ways from the barriers studied here. Facies relationships are more complex and supratidal in overall character on Atlantic barriers, and the islands are known to have migrated shoreward throughout their history rather than accreting seaward. One would suspect that the relationship between subsidence and current supply of sediment for accretion is different also. The present model might be applicable to these barriers if more were known of these local relationships, however.

The present model does not apply to smaller barriers which have been observed forming from wave action on gently-sloping sea floors and by spit growth across large bays and subsequent truncation by storms. The model may or may not apply to the different morphological types of Gulf coast barriers noted by Shepard (1960a) and to carbonate barriers. Usefulness of this model in explaining the origin and development of
other barrier features worldwide remains to be determined. Unfortunately, individual sand sources are probably not as easy to distinguish elsewhere.
BEACH EROSION

Scope of the Problem

Between 1960 and 1975, the Texas Gulf coastline experienced an average loss of 1.9 meters per year. This is equivalent to 2.9 million cubic meters of beach (Sonu and others, 1979). Increased growth of the greater Houston area in recent years has resulted in increasing development along the northeastern Texas Gulf coast, causing coastal property values to become quite high. Losses to erosion of this magnitude have quite adverse economic effects on the area, not to mention the mental anguish suffered by the owner who must watch his valuable property disappear. In order to understand why this erosion is occurring, possible causes must be evaluated.

Causes of Erosion

Natural

Climatic changes can result in increased erosion along the coastal zone. The present climate is warmer and drier than it was at the time of barrier formation (see "Study Area" section). Major rivers along the Texas coastal plain are known to have been larger then, and they probably transported greater volumes of sediment to the coast (Brown and others, 1974). Also, periodic droughts occur in the region (see rainfall figures, "Study Area" section). These hurt coastal vegetation, allowing greater erosion by later heavy rainfalls.

Major storms have catastrophic effects on the coastal system. "Northerns" (see "Study Area" section) result in large amounts of sand being blown offshore. Major tropical cyclones and hurricanes blow in
from the southeast, resulting in storm surges that breach barriers and
leave channels through which tides flow in and out. Large amounts of
sand are deposited on the continental shelf as water is pushed from the
bays by refluxing after major storm surges (Shideler, 1976); some of
this material is deposited by later storms in washover fans in the
estuaries and lagoons behind. Local beach profiles are characterized by
relatively gentle slopes which greatly facilitate washover. Dunes,
which can help prevent washover, are lower here than in most coastal
zones. Averaging 1.5 m in height presently, they ranged up to 4.5 m
before the 1980's (Brown and others, 1974). Vegetation cover, which
also inhibits washover, is generally sparse.

Beach sands along the northeastern Texas Gulf Coast are signifi-
cantly finer than those of other well-known beaches or major local
rivers emptying into the coast (Figure 12). There are a number of
reasons for this. First, sands from local rivers are generally no
longer reaching the beach system. Dams across the rivers trap much of
the available sediment, dredging operations dump sands below wave base,
and subsidence causes most of the remainder to be trapped in bays and
estuaries (see below). Also, the area is far enough from the Mississippi
River delta that only the finest material from this major sediment
source arrives via longshore transport. Most importantly, relict
Pleistocene sediments being eroded offshore are generally quite fine.
On beaches composed of coarse sand, swash percolates down through the
sand and back. On fine-sand beaches (grain size less than about 2.25 φ),
however, water must wash back as well, causing sand to be carried back
off the beach. Thus, grain size influences rates of beach erosion.
Sea-level rise/subsidence combined with overall sediment supply and location along various tectonic features (Figure 5) has caused the mouths of rivers such as the Trinity and Sabine to be drowned in bay/estuary systems. Sediment reaching the coast is trapped in the estuaries and lower river valleys instead of being available to the beaches. Sand from the estuaries flushed out through tidal passes during storms is deposited in tidal deltas or carried far offshore out of the range of longshore drift. More localized coastal subsidence may result in areas of anomalously high erosion, perhaps due to the presence of smaller offshore faults, which are poorly-understood.

Man-Made

Man-made structures can have important influences on the coastal system, and often result in erosion of the very coastline they were built to protect. The groin field on eastern Galveston Island traps sand in the immediate vicinity of the structure, but results in erosion of beachfront to the west. While the jetties at Sabine Pass, Bolivar Roads, and Freeport serve to protect the tidal passes from filling in, they trap an estimated one-half of the total beach sand presently supplied to the coastal system by longshore drift (Morton, 1979). Excessive groundwater withdrawal aggravates the subsidence problem discussed above, and dredging of channels allows more sand to be flushed offshore. Excavation of sand, especially from protective dunes, and removal of stabilizing vegetation greatly increases the chance of beach-sand loss by washover and storms. Even vehicle traffic compounds the beach erosion problem: vehicles destroy the protective dunes and vegetation,
and pack the beach sand down so firmly that swash cannot percolate down through it.

Evaluation

Robert Morton and others at the Texas Bureau of Economic Geology have recently completed detailed examinations of available records of historical shoreline changes along the Texas Gulf Coast in order to determine long-term erosional trends (see for example Morton, 1974). Types of data used included old maps and charts, historical accounts, aerial photographs, and topographic and coastal surveys. Illustrations from Morton’s (1979) summary of this work are shown in Figures 7 and 49. They show graphically the erosional effects from human activities in recent years. However, these are superimposed on a long-term net erosional trend. He inferred that natural processes are responsible for long-term coastal retreat, while short-term coastal shoreline changes are due to a combination of natural processes, human activities, and secular variations. Changes due to man correspond to the approximate time the first structures were built.

The present study and model for barrier formation may help to explain the long-term erosional trend observed by Morton. If local sea level is indeed beginning to drop, net transport of sand would be offshore rather than onshore. With the large post-Pleistocene river sandbodies now essentially gone from the shelf and incorporated into the barriers instead and little coarser river material presently available, only far less-abundant, finer offshore sand is available for barrier accretion. Thus, long-term net erosion may simply be the result of the present historical setting of Texas Gulf coastal barriers.
FIGURE 49. Variable rates of shoreline change:

A. Segment of Matagorda Island

B. Western flank, Brazos-Colorado delta

(after Morton, 1979).
One remaining problem is that of where the eroded sand is going ultimately. Most workers believe it is being transported well offshore by rip, tidal, storm surge, and other marine currents. However, Holocene sediments on the shelf overall are very thin to non-existent and generally consist only of foraminiferan oozes of very fine-grained material (Currary, 1960). A possible explanation is that eroded material winds up in washover fans behind the barriers, which would imply that Texas Gulf coastal barriers are presently migrating gradually shoreward rather than accreting gulfward as they have in the past. This is difficult to evaluate, but does seem to be the case at least for Follets Island. However, the question of where the sand is held between the time it is eroded and the time it is washed over must then be answered. An alternative explanation is that the sand is ending up in the tidal deltas of passes between barriers. Little is known of these features along the Texas Gulf coast, but they appear from aerial photos to contain appreciable sand, and would make worthy objects of future endeavors.

Solutions?

If the long-term erosional trend is indeed related to the present historical setting of barriers along the northeastern Texas Gulf coast as it appears, there would seem to be very little to be done in terms of viable solutions to the problem. Possible remedial measures include attacking some of the man-made causes of beach erosion, which are additive to long-term erosion. Perhaps tidal deltas could be dredged for sand to replenish the beaches. For now, however, the best solution
appears to be recognition of areas of erosion and subsequent adjustment in land use.
APPLICATIONS FOR THE ANCIENT RECORD

Barrier sands are excellent petroleum reservoirs, as they consist of clean, well-sorted sand and lie in close proximity to organic-rich, finer-grained sediments which serve as a hydrocarbon source. A number of known highly-productive fields such as the Bell Creek Field in Montana (McGregor and Biggs, 1968; in Weimer, 1973) are believed to be tapping barrier deposits. Also, Eocene barrier sands in southwestern Texas produce substantial uranium along roll-fronts. Thus, a better understanding of barrier formation and development has important economic, as well as academic, applications.

As noted by Shepard (1960a), barriers are related to slow submergence and essentially steady-state conditions, and therefore should be preserved. As has already been noted ("Barrier" section), current presence of the Ingleside trend indicates preservation is possible and definitely realistic provided certain conditions are met. As in the case of the Ingleside sands, sea level must drop quickly before subsequent erosion is too great; the resultant subaerially-exposed surface left behind must then be preserved later. Alternately, a sudden, more rapid sea-level rise must occur which drowns the barrier features. Possible examples of this are bathmetric highs on the shelf such as Sabine and Heald Banks, which may represent barriers formed during briefer stillstands.

Certain conditions appear to be necessary for initial formation of barriers that would tend to make them more common at certain times during geologic history. Sea level must drop sufficiently so that large
areas of the continental shelf are exposed in order to allow for deposition of large sand packages. The shelf, in turn, must have a gentle-enough gradient so that material is actually deposited there instead of being swept off via canyons, etc. Sea level must then rise rapidly to sweep the material shoreward by processes of coastal onlap. The combination of gently-sloping shelf and low tidal and wave energy would combine to insure that the material remains in the inner-shelf area. Pleistocene/Holocene times would be highly conductive to barrier formation and development because of substantial short-term, glacially-induced fluctuations in sea level. Thus, Galveston Island and other northeastern Texas Gulf coastal barrier features represent a rather unique situation in terms of the overall geologic record.

Conditions ideal for barrier formation can develop during non-glacial periods as well under special circumstances. During Upper Cretaceous time, anomalously high sea levels covered vast shallow continental platforms. Because of the abnormally gentle slopes, any slight drop in sea level would result in tremendous expanses of open shelf, and nearby tectonic activity would have provided the large amounts of sediment to be deposited out on it. With a subsequent rise in sea-level, barrier formation would have commenced as previously outlined. Thus, the current model can also be used to explain the presence of extensive barrier deposits dating from Upper Cretaceous time, including those of the aforementioned Bell Creek Field. Cretaceous sea-level fluctuations, being related to tectonic activity rather than glaciation, would have been of longer periods; therefore, they would potentially result in much
larger barriers than those observed today. This does indeed appear to be the case, as evidenced by the great Cretaceous barrier sequences of the western United States.

This study has important applications for the recognition of ancient barrier sequences. The Galveston-based model of Bernard and others (1959) of a clean, well-sorted sand body that coarsens upward has been referenced extensively in the literature in this regard (see for example Weimer, 1973). As has been shown in the present study, however, this model is in need of revision. Galveston Island actually consists of a large sand body with considerable pockets of incorporated fine material (Figure 10.A. and 34). The much-cited coarsening-upward sequence of Bernard and others (1959) appears to be based on only a single boring and offshore traverse (Figure 10.B.). Numerous surface traverses which cross time lines, coupled with detailed analysis of a deep boring, show sand of the Galveston barrier to be quite fine-grained and homogenous, with mean grain size and size of the initial 10% on the frequency curve rarely varying by more than 1/4φ (Figures 11, 32, and 35). By the present model, then, barrier sands would be expected to exhibit homogeniety rather than coarsening upwards.

The present study also indicates that proximal fluvial point-bar, fluvial-dominated and wave-dominated deltaic, and beach sands are distinguishable on the basis of a combination of grain size and sorting (see discussions under "Coastal Study--Texture" section). Point-bar sands are coarser and contain distinct modes that appear to be source-related. Fluvial-dominated deltaic sands are similar to those from point bars but slightly finer overall, reflecting the loss of coarsest
material in the lower reaches of the river/upper reaches of the delta (at the first major slow-down of stream gradient). Wave-dominated deltaic deposits contain finer sands able to be carried farther out, but not so fine as to be carried offshore in suspension; they are therefore finer and more well-sorted than either of the previous sand types described. Beach sands are similar in grain size to wave-dominated deltaic sands, having probably originated from them, but are very highly-sorted, reflecting the action of nearshore currents and processes.

Facies relationships ultimately preserved depend on a number of factors. Spatial relations of previously-active deltaic systems provide interbedded finer material for incorporation into the barriers. Offshore slope and bathymetry appear to determine the position of barrier development and therefore control to what extent individual barriers will erode relative to each other. Sand supply influences how extensive the barrier system will be. Most importantly, sea-level history determines whether the barriers will be preserved at all and if so, to what extent. Facies relationships between the three barriers studied are illustrated in Figure 50.

In summary, a list of characteristics of barrier sand bodies as based on Galveston-type barriers follows. This list is modeled after and based on one originated by Davies and others (1971).

1) Barrier sand bodies are lenticular, and thin landward and seaward for any given time interval.

2) Barrier sand bodies are elongate parallel to regional strike, and can be expected to be located near zones of coastal onlap as part of highstand sequences.
FIGURE 50. Summary cartoon of facies relationships:

A. Bolivar-type barrier
B. Galveston-type barrier
C. Follets-type barrier.
3) Barrier sands are underlain by either marine or nonmarine sediments or both, depending on sea-level/subsidence history during deposition.

4) The base of barrier bodies is non-erosive.

5) Facies relationships are more complex than previously thought; they are based on the incorporation of previously-existing prodelta sediments, sand availability, and sea-level/subsidence history. Associated fluvial point-bar, fluvial-dominated and wave-dominated deltaic, and beach sands may be distinguishable on the basis of grain size.

6) Tidal channels may be present and interrupt the typical barrier sequence.

7) Grain-size of barrier sands is almost totally homogenous, as opposed to the coarsening-upwards sequence previously assumed, almost never varying by more than 1/4σ. Besides the prodeltaic sediments mentioned above, washovers periodically bring in relict offshore material. This material may also be accreted to the front of the barrier.

8) Barriers are not necessarily flanked by lagoonal sediments on their landward side if they have migrated shoreward.

9) Thickness of barrier deposits depends on the complex inter-relation of sediment supply and rate of subsidence.

10) Barriers are capped by either marine or nonmarine sediments, depending on tectonic and sediment-supply conditions at the close of barrier formation.

11) This model is based only on clastic barriers and does not necessarily apply to carbonate ones, although it conceivably could.
CONCLUSIONS

1) Point-bar sands from major rivers contributing to the northeastern Texas Gulf coast contain distinct textural modes which appear to be source-controlled. Tertiary outcrops are providing the major portion of river sand loads in the region.

2) Kyanite/garnet/hornblende + pyroxene ratios appear to be the best criteria for characterizing sand from the various major river sources in the study area.

3) Sands from a number of different coastal environments can be distinguished on the basis of grain-size distributions. Fluvial point-bar sands are coarser and contain distinct modes as mentioned above. Fluvial-dominated deltaic sands are similar but slightly finer. Wave-dominated deltaic deposits are finer still and more well-sorted. Beach sands are similar in grain size to wave-dominated deltaic sands, but are very well-sorted, containing only a single mode.

4) "Classic" models for recognition of barrier deposits in the ancient record need revising. True upward-fining sequences are not observed. Rather, barrier sands tend to be quite homogenous, varying by little more than 1/4Φ in mean grain size throughout the thickness of the barrier. This is not surprising, as no significant grain-size differences exist in modern Texas beach and nearshore sediments of the Texas Gulf Coast (Wolfteich, 1982). Barriers also tend to contain residual pockets of incorporated finer material instead of consisting of a single clean sand body as previously described.
5) Two different types of barrier sands are distinguished along the northeastern Texas Gulf coast. Type 1 sands contain a mixed heavy-mineral assemblage consisting of Trinity/Sabine, Brazos, and Mississippi river sands in about equal proportions. Type 2 sands are comprised mainly of Mississippi River sand that appears to be eroded from relict offshore Pleistocene deposits. Type 1 sands tend to be slightly coarser than Type 2 sands. Approximated age (C$^{14}$) dates show Type 1 sands to be older and comprise the original nucleus of Galveston Island. Type 2 sands are associated with areas of long-term net beach accretion.

6) Formation of barriers along the northeastern Texas Gulf coast is modeled as follows. A major fall in sea level associated with the Wisconsin glaciation resulted in the growth of large deltaic headlands out on the continental shelf (Morton, 1979). The rapid post-glacial sea-level rise gradually swept sediment inward by coastal onlap. When sea level began its present stillstand (about 5000 years B.P.), sediment began accreting up against some pre-existing bathymetric high, probably a relict prodelta lobe, or possibly an upthrown fault block. Beach-ridge type accretion continued until material eroded from the previous headland (Type 1 sand above) was exhausted, about 800 years B.P. Subsequent to that time, washover and minor beach-ridge accretion of Type 2 sand have occurred. Sabine-area chenier plains are probably of similar origin to local barriers; separate barrier features did not develop in the area because of lower subsidence rates at their location on the Sabine Arch.
7) Barrier formation is therefore related to changes in sea level that cover a large areal extent. Presently, these changes are caused by substantial short-term, glacially-induced fluctuations in sea level, and Galveston Island and other northeastern Texas Gulf coastal barriers thus represent a rather unique situation in terms of the overall geologic record. Conditions for barrier formation can also develop during non-glacial periods, however. During Cretaceous time, tectonically-induced sea-level fluctuations of longer periods also resulted in major areal changes in coastal position due to the abnormally broad, shallow, gently-sloping continental shelves present at that time. Because of the exponentially longer time periods involved, however, Cretaceous barriers would potentially be much larger than those observed today. This does indeed appear to be the case, as evidenced by the large Cretaceous barrier sequences observed throughout the western United States.

8) Suggestions for future work in the study area include an investigation of shallow faults and their relation to barriers, sand-bugeting studies, detailed investigations of tidal deltas, further feldspar studies, and age-dating and source determinations of ancient channel deposits.
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APPENDIX I: HEAVY MINERAL ANALYSES,

RIVER STUDY
### Appendix I.

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146
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|------------|----|----|----|----|----|----|----|----|----|----| Size, # |
| 115-5A-1b  | 6  | 7  | 34 | 31 | 3  | 13 | 2  | 1  | 0  | 3  | 1.8 |
| 121-6A-2(1) | 4  | 1.5 | 43 | 29 | 4  | 11 | 4  | 2  | 0  | 1.5 | 2.1 |
| 121-6A-2(2) | 8.5| 2  | 35 | 37 | 2  | 6  | 6.5| 1.5| 0  | 1.5 | 2.1 |
| 220-7A-1   | 13 | 3  | 27.5| 31 | 4.5| 5  | 2.5| 0  | 0  | 6.5 | 1.3 |
| 225-A-1    | 2.5| 1  | 31.5| 47.5| 5  | 1  | 0.5| 1  | 3.4 |
| 227-A-2b   | 5  | 3.5| 32 | 38 | 6  | 10 | 2.5| 0  | 0.5| 0.5 | 2.9 |
| 234-9A-3   | 8  | 3  | 40 | 35 | 3  | 4  | 5  | 0  | 0  | 2  | 3.2 |
| 235-10A-1(1) | 2 | 3  | 56 | 32 | 2  | 1  | 0  | 1  | 2.5 |
| 235-10A-1(2) | 2.5| 1  | 61 | 28 | 3  | 2.5| 2  | 0  | 0  | 0  | 2.5 |
| 230-10A-2c  | 6  | 3  | 41 | 43 | 2  | 2  | 1  | 0  | 0  | 2  | 3.1 |
| Average    | 5.5| 3  | 39 | 37 | 3.5| 6  | 3  | 1  | 2  | 2  |

**Sand Pits**

| Sample     | Tu | Sp | Sr | Gt | St | Xy | Br | Px | Hb | Sp | Mean Grain
|------------|----|----|----|----|----|----|----|----|----|----| Size, # |
| 613-Ch-1a  | 5.5| 2.5| 42.5| 27 | 7  | 8.5| 2.5| 3  | 0.5| 1  | 2.9 |
| 615-Vg-1   | 1  | 3  | 47 | 23 | 5  | 11 | 3  | 4  | 0  | 3  | 2.5 |
| 620-Gg-1   | 4  | 1.5| 40.5| 20 | 6  | 16 | 5  | 3  | 1.5| 2.5 | 2.9 |
| 621-GQ-2   | 6  | 4.5| 32.5| 29.5| 6  | 14 | 3  | 1  | 0.5| 3  | 3.3 |
APPENDIX II: HEAVY MINERAL ANALYSES,

COASTAL STUDY
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