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RICE UNIVERSITY

DETAILED FACIES ANALYSIS OF THE BRAZOS WAVE-DOMINATED DELTA, FREEPORT, TEXAS

by

MICHAEL HAMILTON

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF ARTS

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April, 1995
ABSTRACT

Detailed Facies Analysis of the Brazos Wave-Dominated Delta, Freeport, Texas

by

Michael Hamilton

In order to better define the facies architecture and controlling processes of a wave-dominated delta, a detailed sedimentary and geomorphologic study was undertaken on the New Brazos River delta. The study indicates a much more complex facies architecture than previously postulated and expands the facies model for wave-dominated deltas.

The New Brazos delta is primarily composed of fine-grained sediments. Prodelta clay composes more than half of the sediment volume in the delta. Sands are isolated to the bar and nearshore environments. The facies architecture is distinct from adjacent interfluvial zones and not representative of the strandplain model for wave-dominated deltas.

The unique facies architecture is a function of the primary depositional process for the delta—floods. In early 1992, statewide flooding facilitated a major constructional phase of the delta. Significant quantities of fine-grained sediments were deposited in the prodelta. One year after the onset of flooding, a bar emerged offshore of the river mouth, and enabled progradation of the delta.
ACKNOWLEDGMENTS

This project was made possible by the generosity and hard work of several individuals. I cannot possibly express my sincere gratitude to all of those individuals in such a brief statement. However, I want to use this format to express my appreciation to several of my colleagues and mentors. Dr. John Anderson has had a profound affect on this project as well as my entire outlook on life. The most important lesson that he taught me is that individual performance can only be judged by one's own conscience. Ultimately, responsibility lies within, and one must persistently strive to improve. John led by example and challenged me as well as my peers to achieve excellence. In addition, John exemplifies the perfect balance between work and play. I only wish that I could play and work as hard as he does. In more practical terms, John enabled me to attend Rice, he funded my education and provided the tools and equipment necessary for this project. For all these things, I am especially indebted to John Anderson.

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I also want to express thanks to my fellow graduate students, especially Ken Abdullah, Fernando Siringan, Phil Bart, Geoff Haddad, Olivier Aubert, Jana DaSilva, Stephanie Shipp and Lou Bartek. These individuals helped me in critical periods, when time was of the essence and deadlines were imminent. As a friend, Juan DiCroce also assisted me in many ways, both academic and personal. He is a dedicated friend to whom I owe much. Finally, Antonio Rodriguez saved the day. Thanks to you all.
Financial support for this product was contributed by the Industrial Research Consortium, the Minerals Management Group and the Department of Geology and Geophysics at Rice University. The generosity of these groups enabled the Gulf Research Project, of which this study is a small part, to continue pursuing scientific research and academic inquiry into the sedimentological regimes along the Texas coast.

I want to express my gratitude on a more personal note to my family. My parents were patient and understanding throughout my stay at Rice. They supplemented my income and gave me a warm meal and a safe home. My brothers, Ken and Morgan, are inspirational to me, for all their career accomplishments and individual excellence. Without such a supporting family, these endeavors would have been much more difficult.

Finally, Megan FitzGerald, my friend and companion, proved her devotion to our success in her consistent support of me and my activities. She has taught me to never settle for anything less than perfection, and I feel that I have accomplished that goal in having her by my side. Thank you, My Megan.
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INTRODUCTION

Purpose

The questions addressed by this study are:

- How do morphologic patterns of wave-dominated deltas relate to complete depositional sequences?
- What is the preservation potential of wave-dominated deltaic facies?
- Are wave-dominated deltaic systems more complex than previously thought?
- What are the roles of various forcing agents on a wave-dominated delta facies architecture?

To address these questions, this study identifies four primary research objectives. None of these objectives are mutually exclusive, that is the conclusions from one objective greatly enhance the approach to other objectives.

The foremost objective of this project is to identify the active depositional environments for the Brazos Delta, Texas and to describe the horizontal distribution and vertical stratigraphy of lithofacies. From an accurate lithofacies surface map, the predicted depositional sequence evolves. Moreover, this composite sequence lends itself to comparison with other modern analogs and to ancient outcrop sequences. From this comparison, weaknesses in the models for wave-dominated systems are defined, and are considered in discussions of ancient deltaic sediments.
Second, recognition of the active subenvironments of the delta is the most important step towards understanding the mechanism(s) of deposition. Horizontal distribution of facies is correlated to basin dynamics, fluvial discharge, and sediment budgets. Depositional environments are then determined and related to the genesis of the entire system.

Third, variations in delta morphology throughout historical time are also fundamental descriptors of depositional agents. Specific periods of morphologic change are identified and correlated to oceanographic and climate data, so as to pinpoint the controlling mechanisms of Brazos delta morphology. Depositional effectiveness of specific variables, i.e. floods or storms, is also delineated from the sediment volumes and distribution. In addition, establishment of fixed time intervals with identifiable morphologic changes leads to estimated accumulation rates in the delta.

Finally, a unique opportunity arose during the course of this study with the occurrence of significant flooding during 1992. A summary of relevant data acquired before, during and after the flood is given, including climatological variables, fluvial discharge, sediment transport and volumes, timing of sediment input, and monthly aerial photographic reconnaissance. The role of infrequent, yet strong magnitude events in the complete depositional sequence is assessed.

In summary, the principal research objectives are:

1. to characterize the facies and environments of the Brazos Delta, and define any implications for ancient sequences,
2. to infer genetic explanations for Brazos deltaic facies architecture,

3. to analyze the growth and destruction of the Brazos delta in historical and recent time, and

4. to document the effect of a catastrophic flood on the Brazos Delta.

Study Area

New Brazos Delta

The New Brazos Delta\(^1\) is located immediately southwest of Freeport, Texas at coordinates 28\(^°\)52'N and 095\(^°\)23'W (Figure 1). The delta is approximately 35 km\(^2\) and extends seaward to water depths of 20 meters. The morphologic outline of the coast at the delta is lobate to lunate, with a significant headland on the western flank of the delta. Deposition is asymmetrical, and accretes to the west along the projecting headland. Overall morphology is controlled by sediment flux and wave energy and is continually evolving. The east flank of the delta is composed of a series of amalgamated beach ridges at the former shoreline position, a large lagoon immediately seaward, and another set of beach ridges parallel and adjacent to the shore (Figure 2). Not immediately apparent are intermediate beach ridge sets which project into the lagoon from the Old Delta to the east.

---

\(^1\) "New" is used to describe the delta that was made possible by the dredging of a new channel in 1929. This channel diverted the Brazos River at Freeport, and diverted the depositional lobe from its "old" Surfside position to the current position. This study will consistently use the term "old" for the pre-1929 delta, and "new" for the post - 1929 delta.
Figure 1: Navigational chart, NOAA #11321, showing the location of the study area, and highlighting the Old and New Brazos deltas. The diversion of the river occurred immediately northwest of Freeport, Texas.
Figure 2: Aerial photograph of the east flank of the New Brazos Delta. The photo illustrates the orientation of the pre and post 1929 beach ridge complexes. The genesis of the New delta ridges is partly due to the erosion of Old delta deposits after the river diversion.
The west flank of the delta is composed of a series of ridges that occur as amalgamated and nonamalgamated ridge sets. In the amalgamated sets, several ridges are laterally buttressed against one another, while the nonamalgamated sets occur as single isolated ridges separated from one another by interridge troughs. A distinct set of amalgamated ridges exists at the site of pre-delta coastline. In addition, tidal channels and washover channels are profuse throughout the area. Figures 3a-c shows several of the subenvironments of the west flank. Water depths in the interridge lagoons are tidally controlled, averaging 0.25 to 0.5 meters. The orientation of the beach ridges corresponds to the development of the headland and subsequent wave refraction around this promontory.

In water depths of 3.0 to 4.0 meters, immediately offshore of the mouth, an emergent lunate bar is present (Figure 4). The bar is approximately 0.3 kilometer wide and 1.0 kilometer long. Relief on the bar exceeds 0.75 meters, with average elevation at 0.5 meters above sea level. The intertidal bar area is roughly fifty percent larger than the subaerial portion. The bar is presently growing to the west and moving landward, and could possibly weld to the shore at its western extent. The bar was originally approximately 0.8 kilometers long by 0.15 kilometers wide. Latest reconnaissance indicates that the bar is presently (January, 1995) approximately 1.6 kilometers long by 0.25 kilometers wide. In addition, the bar has migrated shoreward and nearly closed a preexistent water body approximately 0.3 kilometers wide (the distance from the headland to the bar). The entire genesis of the bar has occurred during this study.
Figure 3 A, B: Subenvironments of the New Brazos delta. See the expanded caption on the following page.
Figure 3: Subenvironments of the New Brazos delta (west flank). A.) Oblique photograph, from 152.4 meters looking southwest, which illustrates the ridge and interridge environments. In the upper right corner of the photo, spit accretion into the San Bernard River mouth is evident. Also, note the lower middle of the photograph which faintly shows ridges without interridge lagoons. These ridges evolved under different sediment supply circumstances than the ridge and interridge system (see discussion section). B.) Aerial photo, from 304.8 meters of the ridge and interridge environments. C.) Oblique photograph, from 152.4 meters looking northwest, illustrating a tidal channel and flood tidal delta on the modern shoreline. In the upper right corner of the photo, notice the oblique orientation of a ridge to surrounding parallel ridges. Different ridge orientations evolve when wave approach is refracted around a projecting headland.
Figure 4: Oblique photograph, from 914 meters looking southeast, illustrating the offshore lunate bar and the headland. Note in the lower left corner of the photo, the shore and the lunate bar are nearly welded.
The subaqueous delta is deflected to the west and is present along shore for approximately 10-15 kilometers. The lobe of deposition extends into water depths of twenty meters, or approximately 8 kilometers offshore (Figure 5). During winter storm conditions associated with "northers", deposition offshore is enhanced as the river plume extends farther seaward. During floods, similar advances into deeper waters are also observed. In all, the subaqueous delta comprises nearly seventy percent of the total area of the delta.

Old Brazos Delta

The old delta was located east of Freeport near Surfside Beach at coordinates 28°55.5'N and 095°17.5'W (Figure 1). Wave energy has significantly reworked the old delta but aerial photographs reveal a similar morphology as the new delta (Figure 6). It was approximately 30-35 km² and extended seaward to 20 meters water depth. The old delta was also asymmetrical to the west, with amalgamated ridges on the eastern flank and an alternating ridge/trough system on the west flank. The morphology of the shoreline was lobate with the significant headland on the west flank. Evidence of preserved deltaic deposits for the Old delta and implications for more ancient analogs are addressed in the discussion section. Since the Brazos River was diverted in 1929, considerable erosion has taken place, and the Old delta coastline is now cuspate (Figure 7).

Depositional Basin Setting

The coastal zone encompassing the Brazos Delta is a climatically dynamic region. On average, the zone experiences tropical storms or hurricanes once every two years. Just west of the new delta, hurricane channels are historically significant, as indicated by the relative vegetation density decreases to the west. Average annual rainfall ranges from 103.7 centimeters to 124.87 centimeters, with
Figure 5: Depositional lobe of the New Brazos delta. The shaded area is the offshore portion of the delta.
Figure 6: Aerial photographs of the New and Old Brazos deltas immediately before and after the diversion of the river. The photos depict similar morphologies for the two systems, suggesting that modern deltaic evolution is an accurate analog for the Old delta. This photo was scanned from Bernard et al (1970).
Figure 7: Oblique photograph from 304.8 meters looking southeast. This photo illustrates the remaining onshore section of the Old Brazos delta. The shoreline has been greatly altered since river diversion, and jetties have enhanced the generation of a cuspatc shoreline.
large deviations during flooding and tropical storm-induced precipitation. Winds are dominantly southeasterly averaging 5-10 knots. During winter months, short lived "northers" of 15-20 knots occur. Dominant southeasterlies set up waves trending northeast-southwest which approach the shore in a northwesterly direction. Figure 8 summarizes the climatological data for the area. Plume orientations are distinctly different during different times of the year and appear to be recordable events in the offshore sequences. Bartek and Anderson (1990) defined a "fair weather" plume which deposits the bulk of clayey silt/silty clay sediments in the prodelta, and a "storm/flood" plume that is responsible for sand and coarse silt deposition in the prodelta (Figure 9). Finally, longshore drift is a primary component in this area, deflecting deposition to the southwest.

Subsidence plays a significant role in most areas along the Texas - Louisiana coasts. This creates a situation of adequate accommodation space for sediments. Consequently, complete depositional sequences are deposited and preserved. The shallow shelf gradient and high sediment yields also favor rapid progradation of facies into the marine environment. Bernard et al (1970) revealed that the subaerial Brazos Delta prograded approximately 2.5 kilometers during a twenty year period. Moreover, the entire delta has prograded approximately 6.5 kilometers since depositional inception in 1929.

**Drainage Basin**

The drainage basin of the Brazos River includes large sections of central-north Texas and eastern New Mexico (Figure 10). The Brazos is the eleventh longest river in the nation, meandering from its source in Curren County, New Mexico approximately 2000 kilometers to the Gulf. The Brazos watershed,
Figure 8: Summary of climate factors for the Texas Gulf coast (from Morton et al., 1980).
Figure 9: Postulated facies patterns for the Brazos delta. Note the distinction between "fair weather" and "storm plume" deposits (from Bartek et al., 1990). Also, the diagram depicts a transgressed paleo Brazos delta at the Oyster Creek location. Several of these transgressed deltas are preserved on the shelf.
Figure 10: Drainage basin of the Brazos River. The head of the river is fed from numerous tributaries extending from northern New Mexico and Texas (adapted from Water Data Reports, USGS, 1993).
encompassing 118,000 square kilometers, ranks nineteenth nationally, and the Brazos leads all Texas rivers in rates of flow. The large watershed and great length add a diversity of climatic variables to this study. The effects of excessive or diminished precipitation are easily discernible in sediments of the delta. Because the drainage basin contributes sediments from precipitation deficit and precipitation surplus areas, and because we can directly monitor precipitation rates for specific regions historically, we are able to correlate the depositional effectiveness of individual climate events within the semi-arid northern basin and the humid, southern-coastal basin.

**Sediment Types**

Sediments of the delta are derived from a variety of rock types ranging from igneous rocks of the northern sections to sedimentary clastic rocks of paleo shorelines of the lower Texas coastal plain. Table 1 lists the mineralogical types for surface sediments of the Brazos delta. The distinct signature of mineralogy, relative to adjacent rivers, aids greatly in the classification of sedimentary provenance throughout the Texas shelf and distinguishing otherwise indistinct depositional environment transitions. Mineralogy is also a useful factor in determining depositional time constraints related to anthropogenic influence, i.e. dredge spoils, river diversions, etc.

The Brazos River transports in suspension mostly fine-grained sediments. These sediments comprise approximately 65% of the total deltaic package. The total volume of sediments carried by the Brazos is the highest of all rivers in Texas, 398 tons per square mile (Curtis et al., 1973). The predominance of clay in suspension complicates otherwise straightforward assumptions concerning flow
Table 1
Mineralogic Components for Several Gulf Coast Rivers
(Van Andel, 1967)

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>Hornblende</th>
<th>Pyroxene</th>
<th>Zircon</th>
<th>Staurolite plus Kyanite</th>
<th>Ratio Bluegreen to Brown/Green Hornblende</th>
<th>Ratio Hornblende to Tourmaline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mississippi</td>
<td>40</td>
<td>25</td>
<td>&lt;5</td>
<td>&lt;1</td>
<td>1-2</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Mississippi, weathered</td>
<td>52</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;1</td>
<td>1-2</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Rio Grande</td>
<td>23</td>
<td>24</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>0-1</td>
<td>1-10</td>
</tr>
<tr>
<td>Rio Grande, weathered</td>
<td>29</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>0-1</td>
<td>1-10</td>
</tr>
<tr>
<td>Colorado</td>
<td>77</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>5</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Brazos; rivers west of Colorado</td>
<td>1-10</td>
<td>30-40</td>
<td>&gt;10</td>
<td></td>
<td></td>
<td>0-1</td>
</tr>
<tr>
<td>Rivers east of Brazos</td>
<td>1</td>
<td>&gt;20</td>
<td>5-10</td>
<td></td>
<td></td>
<td>0-1</td>
</tr>
</tbody>
</table>

All components expressed as percentages.
Note: Hornblende component does not include basaltic hornblende.
velocities, grain size, and transport modes. This also complicates hypotheses about sand transport to the delta.

Deltaic sediments of the Brazos are primarily immature to submature, and are poorly sorted. The sorting of sediments within depositional environments is one indicator of the transport mechanism for those sediments. These poorly sorted sediments with certain identifiable sedimentological structures and textures are inferred to have been deposited rapidly, such as in flood-related suspension deposits. Sediments which are more well sorted and possess structures, such as ripple laminations and cross beds, are believed to be transported by other modes (i.e. saltation), and are therefore representative of more stable ("noncatastrophic") periods.

Geomorphologic Agents

The major processes that influence sedimentation in fluvial and deltaic systems are shown in Figure 11 (Coleman and Wright, 1973). An implied argument in this diagram is that each component acts in conjunction with other components, and that reference to individual components can only be useful for short time periods. While some factors might temporarily outweigh others, there is an overall trend toward equilibrium.

For the Brazos, the least influential component is tides; all other factors contribute to the shoreline and deltaic morphology. A systematic discussion of each component’s influence is merited in order to further understand the nature of sedimentation in the area.

1.) Vegetation & Soil--the type of sediments and the amount of sediments deposited within a delta are primarily dependent on the input from the drainage
Figure 11: Major morphological processes affecting deltas (adapted from Coleman and Wright, 1980).
basin and alluvial valley. Vegetation controls the amount of sediment input into fluvial systems by affecting erodability of soils. If there is extensive vegetative cover, fewer sediments will be derived from precipitation run-off, and hence fewer sediments will reach the delta. In addition, sediment run-off for long rivers will certainly be different between the upper and lower reaches of the drainage basin/alluvial valley. For the Brazos, this is clearly the case, where the upper reaches of the drainage basin are semi-arid environments with much less vegetation than the lower reaches of the humid coastal plain (Figure 12). The type of sediment that reaches the delta is controlled by the soils eroded upstream. This is obvious for the Brazos River in the distinctive red color and the notable fine grain sizes of the delta sediments. These sediments are derived primarily from the upper reaches of the drainage basin in northwestern Texas and northeastern New Mexico where the Brazos is supplied with soils derived from Triassic red beds.

2.) Morphology—the river morphology is another controlling factor on the amount of sediment reaching the delta. Fluvial systems which meander can store significant quantities of sediment in point bars. This sediment is stored until increased water levels and discharge erode the point bars and transport the sediment downstream. Thus, because the Brazos is largely sinuous from source to mouth, there is an extensive sediment source within the point bars. Figure 13 shows an example of the broad point bars that are present within the Brazos fluvial system.

3.) Climate—weather patterns drastically affect sediment input into the delta. Increased precipitation will increase surface runoff, increase sediment load of the river, and ultimately increase discharge at the mouth into the delta. Because the drainage basin for the Brazos is so expansive, the river draws from distinctly different climates—semi arid upper drainage system to humid lower basin
VEGETATIONAL AREAS OF TEXAS

1. Pineywoods
2. Gulf Prairies and Marshes
3. Post Oak Savannah
4. Blackland Prairies
5. Cross Timbers and Prairies
6. Rio Grande Plains
7. Edwards Plateau
8. Rolling Plains
9. High Plains
10. Trans-Pecos, Mountains and Basins

Figure 12: Vegetative areas of Texas (adapted from Larkin and Bornar, 1983). The variety of vegetation throughout the Brazos watershed influences the sediment supply from different localities. One can also discern the extent of basin flooding by examining the types of tree materials deposited in the delta.
Figure 13: Point bar of the Brazos River. This photo is taken from 152.4 meters. The point bar is located just north of the Brazos Bend State Park.
(Figure 14). In addition, climate is also significant within the receiving basin where tropical storms/hurricanes can substantially alter deltaic morphologies.

4.) Tides--although tides are relatively insignificant for the region, they are observed to affect the subenvironments of the Brazos delta. During spring and neap tides, and when amplified by winds or storm swells, numerous tidal channels and small tidal deltas are created/destroyed on the delta. Figure 15 is an example of the larger tidal channels and flood tidal deltas which are active during high - high tides. During this research project, several areas along the delta's western shores rapidly aggraded due to sediment overwash during highest tides and winter storms. In addition, several tidal channels were healed and deactivated. Figure 16 shows the relief created from overwash aggradation in the span of a month.

5.) Waves--when wave energy is sufficiently strong to counteract sediment input, a delta is referred to as "wave-dominated". That is, the overall morphology is not characterized by sediment input and outbuilding, but sediment input and reworking; the primary growth agents being wave transport onshore/alongshore and nearshore aggradation.

6.) Currents (not illustrated on Figure 11)--alongshore transport is also a source of sediments in the delta. And, alongshore currents shape the shorelines near river mouths. This is well - defined in the asymmetry of deposition in the Brazos delta. Furthermore, when waves and currents jointly act on a system, as in the case of the old delta, they can greatly enhance sedimentation down current. Sediments on the west end of the New Brazos delta reveal the influence of longshore transport near the San Bernard River mouth (Figure 17)
Figure 14: Climatic zones of Texas. The Brazos drains all of the major divisions except the subtropical arid zone. Thus, it is a sensitive monitor to climatic forces (adapted from Larkin and Bomar, 1983).
FIGURE 15: Large tidal channel and flood tidal delta on the modern shore of the New Brazos delta (west flank). The aerial photo is taken from 304.8 meters, and the Gulf (south) is to the left of the photo.
Figure 16: Relief of a single overwash. This overwash was part of a larger aggradation event during which an adjacent channel was completely deactivated, and the relief on the beach, in front of the channel, exceeded 0.75 meters. This overwash was deposited during the winter of 1993. Height of the crest is approximately 1 meter above surrounding marsh.
Figure 17: San Bernard River mouth. Oblique photograph, from 152.4 meters looking southwest, showing the mouth of the San Bernard River. The mouth has been significantly deflected to the west due to longshore-directed spit accretion from the west flank of the New Brazos delta.
Assessing the relative importance of each of these variables, classification schemes have generally followed the outline set forth by Galloway (1970) and Fisher (1969). The tripartite scheme set forth by Galloway (1970) divided the deltas into wave-, tide-, and fluvial-dominated. Fisher (1969) described deltas in more general terms as either "highly constructive" or "highly-destructive", and would have categorized the Brazos as the latter. Fisher's (1969) formulation assumed all of the inherent variables of Galloway (1970), i.e. fluvial input, wave energy and tidal constraints, but also incorporated sea level as an agent of change. As will be seen throughout this work, the methodology of these classifications is discrete. The primary weakness of such categorical methods is the failure to address temporal relationships between these variables, i.e. when a less significant process temporarily dominates the most significant process, or when the truly dominant morphologic agent is episodic. One central question therefore that evolves from this study is whether the Brazos is definitively "wave-dominated" when appropriate genetic models are considered. This is discussed in the conclusion section.

**Why the Brazos Delta?**

The Brazos is an excellent natural laboratory for study of deltaic sedimentation because:

1.) The date of depositional inception is known.

2.) The sediment supply to the delta changed during its recent history—early phase with high alongshore sand supply but no major floods (i.e. strongly wave-dominated) to more recent reduced sand supply but high suspended load influx during floods (i.e. sporadically fluvial dominated).
3.) The delta is frequently referenced as an appropriate modern analog to ancient wave-dominated systems.

The abundance of other research in the Northwestern Gulf of Mexico also contributes to the scientific relevance of the Brazos delta. Numerous studies have confirmed that the Brazos has significantly affected the coastal and offshore morphology of Texas since at least the Late Pleistocene. Moreover, the dynamic and energetic system is actively reshaping the coast, thus allowing direct observation of the most significant depositional processes.

There are also more fundamental reasons for studying the Brazos delta. Galloway (1975) was instrumental in his ternary classification scheme for modern deltas. He divided deltas into three types, wave-, fluvial- and tide-dominated, primarily based on receiving basin dynamics and shore morphologies (Figure 18). Literature reviews revealed an extensive collection of studies done on fluvial- and tide-dominated deltas. However, the wave-dominated deltas have received less attention. Specifically, those deltas explicitly labeled "wave-dominated" (cuspate region of the Galloway (1970) diagram), i.e. Sao Francisco and Brazos, have only been reviewed in cursory manners. Other wave-dominated deltas--Niger, Rhone and Grijalva--have been thoroughly documented, but emphasis was placed on the nearshore and onshore facies (Coleman and Wright, 1980). Previously unrecognized deposits in the distal offshore sections are instrumental to a thorough depositional model and are a central conclusion of this study. Thus, the Brazos delta offered an opportunity to describe systematically the lithofacies, subenvironments and genesis of a widely postulated "wave-dominated" delta without preconceived notions concerning offshore deltaic facies.
Figure 18: Galloway (1969) classification scheme for deltas. The Brazos is classified as strongly wave-dominated. The inferred morphology of the Brazos delta, according to this classification, is much like the Sao Francisco.
The Brazos Delta has repeatedly been referred to as an analog for ancient outcrops worldwide (Tankard and Barwis, 1982; Coleman and Wright, 1973; Elliott, 1986). Authors interpreting rock sequences as “wave-dominated deltas” often relate the sequences to the earlier Brazos delta study done by Bernard et al. (1970). Although Bernard et al (1970) illustrated the major lithofacies of the delta, the data set was limited to onshore core sites, and their interpretation of facies lacks discussion of a genetic mechanism for deposition. This mechanism is vital to recognizing the subenvironments of the delta and its overall stratigraphic sequence. And, offshore data is critical in order to understand the evolution and complexity of depositional settings. This study contends that the genetic mechanism and subaqueous sedimentary lithology and environments of the Brazos delta will require many analogies of the Brazos to ancient sequences to be reconsidered.

Finally, much focus is placed on sandy deposits of the Cretaceous Western Interior Seaway as sources of fossil fuels and water, thus legitimating the need for an analogous basin and comparable depositional systems. The northwestern Gulf of Mexico is believed to be the most similar basin for comparison. The climate of the northwestern Gulf is similar to that hypothesized for the Cretaceous Western Interior. Rainfall averages 102 cm a year with seasonal fluctuations; average temperature is 21°C; the entire area is influenced greatly by extra-tropical cyclones in the winter and tropical cyclones in the summer (Bartek, 1990). Similarly, the Cretaceous experienced average temperatures of 17°C and was equally as influenced by tropical and extra-tropical storms (Marsagalia and DeVries Klein, 1983). Just as modern Gulf Coast sedimentary deposition is enhanced by alongshore currents, with only minor tidal signature, the Cretaceous Western Interior experienced microtidal flux and parallel-to-shore current patterns. Most
importantly, sediment supply is strikingly congeneric for both locations. Swift and Rice (1984) concluded that sediments of Cretaceous deltas were high in volume and fine in size. Correspondingly, the Gulf Coast fluvial systems, specifically the modern Brazos Delta possesses high sediment volume of primarily clay, silt and very fine sand.
Literature Review

This overview intends to convey the following points: (1) ancient deltaic systems played a significant role in the Gulf Coast evolution, (2) documentation of "highly destructive" ancient systems is voluminous, and (3) modern wave-dominated deltas are similarly significant in the coastal environment, but (4) modern wave-dominated deltas lack sufficient data, particularly from the offshore environments. Detail of these studies is included to demonstrate the current state of knowledge concerning wave-dominated deltas.

Ancient Gulf Coast

Many deltaic systems have existed within the Texas Gulf coast and lower Texas coastal plain. As the shoreline occupied various positions throughout geologic time, deltas were existent from the present day upper continental slope inland to the central sections of Texas. Depending on the nature of sea level change (generally accepted as the controlling factor on paleo-shoreline position), the deltaic deposits were either overstepped and/or portions of the delta were ravined and reworked. The general oceanographic parameters are not believed to have changed significantly throughout the history of the northwestern Gulf, thus allowing direct comparison to modern systems. More importantly, facies interpretations of presently active systems adds complexity and unforeseen characteristics to more ancient Gulf coast depositional environments.

San Miguel Delta

The San Miguel Formation was a wave-dominated delta of the mid to late Cretaceous. (Lewis, 1977; Weise, 1979). It is representative of the complexities of wave-dominated systems, and offers characteristic signatures for certain variables,
i.e. sea level, subsidence and sediment input. Weise (1979) illustrated the varying shoreline geometries associated with different degrees of marine influence (Figure 19), and incorporated this into interpretations for net sand distributions of the San Miguel. Weise (1979) also stressed the concentration of sand into strike-aligned bodies within delta front environments immediately adjacent to thin, prodelta fine-grained sediments amalgamated with marine shelf deposits.

Sparta Delta

In south Texas, the Sparta Formation (Paleogene -- ?Eocene?) was also part of a wave-dominated, highly destructive system as described by Ricoy and Brown (1977). Similar to other investigators of Gulf Coast ancient depositional systems, these authors invoke strandplain/barrier models with allowance for channel mouth bar and back-barrier lagoons. Unlike most studies, well logs and representative cores indicate preserved and distinct prodelta fine-grained sediments underlying the barrier facies and distinguish these sediments from the adjacent shelf facies. The model also invokes separate mechanisms for stacked barrier-bar channel-mouth bar facies. The former occurs during periods of relative sediment deficiency while the latter is representative of fluvial-dominated pulses (ephemeral).

Wilcox Delta

Fisher (1969) coined the classifications "highly constructive" and "highly destructive" based on sandstone distributions within deltas. He focused on east-central Texas paleo deposits. The lower Wilcox (Eocene) represents a time of vast coalescing deltas across south-central to east Texas. "Highly constructive" deltas prograded seaward behind extensive back barrier and barrier-strandplain
Figure 19: Shoreline geometry as a function of marine reworking within the San Miguel Formation (Weise, 1980).
environments. Broad delta plains and thick prodeltaic fine-grained sediments are most characteristic of this time. Upper Wilcox deltas were primarily "highly destructive", lacking significant delta plains and distal deltaic deposits. They also had numerous sand bodies oriented along strike (Fisher, 1969). Fisher infers that the destructive delta receives little suspension load and therefore is characteristically prodelta-mud starved. In summary, one might equate "highly constructive" with Mississippi-like, fluvial dominated systems, and "highly destructive" with Orinoco-like, wave-dominated deltas. Based on Figure 20 and Figure 21, the most immediate differences are the subaerial expression of the deltas, and the feeder channel(s) geometry. This is an important point, for the number and type of feeder channels remains a distinctly recognizable feature in ancient outcrops. The rule of thumb for this classification system is that wave-dominated deltas generally form at the mouth of smaller, and less competent fluvial systems, with washloads less than traction loads. On the contrary, "highly constructive" implies numerous distributaries with significant washload and distinct suspension plumes at fluvial mouths.

Vicksburg Delta

Gregory (1961) described a lower Oligocene delta (Vicksburg Formation) made up of two primary depositional lobes of the ancestral Brazos, Colorado, and/or Trinity Rivers. Based on microfossil assemblages, Gregory (1961) was able to map the overall lobate shoreline morphology, and furthermore, characterize the depositional environment of an actively producing sand trend.

Other Ancient Deposits

One significant aspect of this study is refinement of the general model for wave-dominated systems so as to better identify modern analogies for ancient
Figure 20: Distributary systems associated with end member deltaic systems (from Fisher, 1969).
Figure 21: Facies architecture of end member deltaic systems (from Fisher, 1969).
deltas. Typically wave-dominated deltaic systems of the ancient are analogously compared with the modern Brazos and Niger deltas (Coleman and Wright, 1980; Allen, 1969). This is especially true for studies of ancient western interior deltas, for the wave and tidal regimes are strikingly similar. Preliminary investigation, however, of the modern Brazos delta revealed fundamental differences with previous stratigraphic models of ancient wave-dominated systems, and thus suggested the need for more detailed facies analysis. The following review discusses the most relevant interpretations and previous stratigraphic models.

Wright Dunbar, et al. (1992) challenge conventional models that restrict wave-dominated delta facies architecture within strandplain progradational systems. Whereas, most authors assume a strandplain/barrier-like stratigraphy, Wright Dunbar et al (1992) identify several distinct characteristics reflective of fluvial influence. In their analysis of the Upper Cretaceous Point Lookout Sandstone, they draw upon shoreline perturbations, grain texture and sand body thicknesses to discern local wave-dominated deltas within more regional strandplains. Figure 22 and Figure 23 illustrate the progression from strandplain to delta for the Point Lookout. Note the Horse Gulch measured section which illustrates cyclic sedimentation as repeating facies downcore. This type of stratigraphy is strikingly similar to the stratigraphy for the Brazos delta, which is developed in the discussion section. Furthermore, the identifiable textural and structural characteristics of the Point Lookout are similar to the distinguishing features of the Brazos, e.g. mineralogy, number of interbeds, volume of sediments, etc.

Chafetz (1982) examined the Beartooth Sandstone of southwestern New Mexico and reported several features similar to the observations of this study.
Figure 22: Comparison of Point Lookout Formation strandplain and deltaic sections (from Wright Dunbar et al. 1992).
Figure 23: Stratigraphic cross section from the Point Lookout Formation (from Wright Dunbar et al., 1992).
Figure 24 is the composite sequence for the Beartooth with environmental interpretations of Chafetz superimposed on the diagram. The fundamental assumption of this author is that systems and the stratigraphic record respond instantaneously to delta lobe shifting or sea level rise. And, these events are easily identified in the sediments. This assumption is critical to the evaluation of the "siltstones & sandstones" unit stratigraphically between the "lower" and "upper trough cross - stratified sandstone". Chafetz (1982) calls on rapid transgression and/or lobe shifting at the base of the "siltstones & sandstones" in order that higher energy environments stratigraphically underlie lower energy environments (also known as increase in accommodation space). An alternative mechanism for a similar sequence is considered for the Brazos delta (see discussion section).

The Gallup Sandstone is composed of numerous environments analogous to modern wave-dominated/influenced systems. According to Flores et al. (1991), the Gallup is made up of three primary facies, a lower sandstone - dominated unit, a middle coal bearing unit and an upper sandstone - dominated unit. The overall sequence is regressive with the lowest section representing shoreline facies grading upward into the lower delta plain and finally into the upper delta plain and lower coastal plain deposits. The lowest sandstone unit in the sequence is composed of various coastal facies, including delta front, distributary mouth bar, reworked mouth bar, back - bar/barrier, flanking barrier and strandplain, and bay fill sequences. These environments are also representative of typical Brazos shore facies. One digression—the similarity of this system to the modern Brazos is considered with the different eustatic regimes in mind.
Figure 24: Composite vertical sequence of the Beartooth Sandstone (from Chafetz, 1982).
Any similarities at this point are only acknowledged for the geomorphic expression of wave influence on deltas and no assumptions are made concerning preservation potential.

Rice and Gautier (1980) supported the wave-dominated, strandplain stratigraphic model in their analysis of the Eagle Sandstone Formation. They contend that wave and marine reworking of distributary mouth bar deposits result in strike-aligned sand bodies alongshore which are indistinct in the stratigraphy from a typical strandplain. They directly compare the Virgelle Sandstone (lower Eagle Formation), an interdeltaic shoreface, to the Middle Member of the Eagle Sandstone, a wave-dominated delta. One potential pitfall of their interpretation is the demarcation of the coastal (as opposed to offshore) sediments to the base of the sandy facies. By definition, they restrict the facies of the Virgelle and Middle Member to environments lacking fine-grained deposits. They restrict underlying fine-grained sediments to offshore shelf sequences and deny the importance of silts, muds and clay within the wave-dominated delta environment. The Middle Member of the Eagle sandstone is very similar to the Virgelle, according to Rice (1980). The most distinct characteristic is a sheet sand in the upper section where numerous distributary channels were identified, thus indicating deltaic deposition. "Otherwise, the sequence is superficially similar to that of the interdeltaic strand plain sequence" (Rice, 1980). These authors systematically conclude that wave-dominated deltas are difficult to discern in the ancient record.

"Wave-dominated deltas are easy to identify in modern settings where distributary channels can be recognized and the geometry of the overall delta can be observed. However, ancient wave-dominated deltaic systems, such as those which occur in the Cretaceous of the Western Interior, are difficult to identify for the following reasons: (1) distributary channel deposits make up a volumetrically small part of the overall system, (2) areal extent of deltas is limited, (3) most of the sediment was
redistributed by marine processes, such as waves and longshore currents, and (4) geometry of overall deltaic complex cannot be determined because of limited outcrops and (or) subsurface control."

This conclusion highlights why detailed work on modern wave-dominated deltas is critical to ancient interpretations. Any observable modern features, even at the local scale, should assist with the proper recognition of wave-dominated deltas in otherwise nondistinctive shoreface deposits.

Ancient rocks from other parts of the globe also record wave-dominated/influenced systems, and are consistently similar in geomorphic and stratigraphic expression.

Whitbread and Kellig (1982) studied the Mrar Formation of Western Libya, an early Carboniferous delta system. This delta is exemplary of how systems cannot be relegated to one specific zone of the Galloway (1969) classification, but instead must be viewed as dynamic, changing systems which are dominated at different times by different processes. Specifically, the Mrar delta developed over a 15 million year period, during which it was fluvial - dominated initially, then became wave-dominated, and finally abandoned its original depositional location. Figure 25 is a summary of Mrar delta development.

The Devonian Bokkeveld Basin of South Africa was the site of thick (500-700 meters) wave-dominated deltaic sediments, according to Tankard and Barwis (1982). These authors recorded the complexity of subenvironments in wave-dominated environments and incorporated barrier island (emergent distributary bar) and back - barrier lagoonal/tidal facies. Moreover, the entire Bokkeveld sequence is composed of numerous coalesced deltas organized into *en echelon* lenses on scales of tens of kilometers. Thus, this study is useful to understanding
paleo Brazos deltas preserved on the middle Texas shelf where numerous deltas overlap due to frequent lobe shifting.

An upper Paleozoic delta system in Southern Morocco described by Vos (1977) also demonstrates the transition from fluvial dominance to wave influence. According to the author, this transition is easily recognized in modern systems, and can therefore be predicted for ancient outcrops. Vos (1977) identifies the constructive phase of delta development during which well developed channel bars pass laterally through a narrow delta front into the marine shelf. Also, abundant silty clay to fine sand-sized sediment is flushed onto the marine shelf during the phase of construction. The author also contends that the southern Moroccan sequence recorded two phases of destructive delta building. First, poorly developed channel bars of the delta plain begin to intertongue and pass laterally into a beach which, in turn, passes into a marine shelf. "This facies relationship indicates a less actively depositing fluvial system being overpowered by a moderate wave energy sea, the margin of the nearshore shelf being reworked, together with sediment introduced by the diminished fluvial system (Vos, 1977)." Beach development is the incipient stage for this phase of destruction. The second phase is development of tidal flats adjacent to poorly developed channel mouth bars. "This facies relationship indicates detrital influx to be almost absent and the deltaic plain converting to a tidal flat, protected from the moderate wave energy sea by a beach barrier (Vos, 1977)." Both of these phases are recognizable in the modern Brazos, therefore implicating the Brazos as a transitional delta with partial wave and partial fluvial influence.

Mazzulo (1973), in his study of the Hamilton Group (Middle Devonian) of Southeastern New York State, utilized four separate Holocene analogs to interpret ancient deltaic sediments. Rather than restricting interpretation into environments
Figure 25: Summary of development of Mrar Formation (Whitbread and Kellig, 1982). This is an example of alternating wave and fluvial dominance within a single delta.
for a single system, the Middle Devonian clastics were classified as a composite of several characteristic environments for fluvial, tide and wave-dominated systems. Most notably, Mazzulo (1973) recognizes 244 meters of claystone as prodelta deposits, within an overall framework of strong wave influence. In the end, the author does, however, point to several features of this delta that are closely analogous to a single modern analog, the Holocene Niger delta. He notes the lack of well developed bar-finger sands, and the more arcuate rather than lobate (Birdfoot) geometry. He also points out the significance of wave structures, i.e. wave ripples, and cross stratification in the upper delta front as indicative of longshore current modification. Finally, the deciding factors were the 15-23 meter thick sheet sands postulated as beach sandstones, presumed to evolve from reworked bar-finger sands and channel-mouth bar deposits.

Modern Deposits

A review of modern deltaic systems follows and is intended to display the spectrum of variables and complex interaction of geomorphic mechanisms that control delta evolution. The focus is on those deltas previously postulated as fluvial to wave-dominated, such that the groundwork is established for comparison to the modern Brazos and for delineation of the proper architectural controlling agents. The result of this section will be similar to the conclusion of Mazzulo (1973), where the Brazos delta model incorporates numerous depositional patterns from throughout the classical tripartite division of Galloway (1969).

Maldonado (1975) described the Ebro River delta on the eastern coast of Spain. The climate and coastal regime in that region is very similar to the Brazos, where tides are minimal, waves exert significant influence, and longshore currents are instrumental for delta development. The delta has a morphology characterized
by significant fluvial levee, broad deltaic plain, narrow delta front and distinct prodelta. The delta has occupied several lobes through time, and therefore is suitable for studying the preservation potential of abandoned lobes. The mechanisms that control delta morphology are complex, with fluvial dominance during high discharge and wave dominance during diminished fluvial input and post depositional lobe shifts. Galloway (1969) was precise in classifying the Ebro delta half way between fluvial and wave-dominated endmembers.

Ancient studies of wave-dominated systems frequently cite the Niger as the most analogous modern deltaic system. Allen (1975) discussed in great detail the facies architecture of the Niger delta and he implicated several morphologic controls. Tides (approx. 1m range), waves, onshore and alongshore currents, and weather patterns all exert significant influence on the distribution of sediments in the delta. The radial, symmetric shape of the delta is primarily controlled by direct wave approach at the mouth of the Niger, such that divergent alongshore currents are created around the headlands. The lithofacies of the Niger are shown in Figure 26. The significance of perpendicular - to - shore mouth bars in Figure 27a is significant, for ancient analogous (postulated) systems generally have parallel - to - shore mouth bars and flanking ridges. This bar morphology lends itself to fluvial dominance and reveals that the Niger is also a mixed system of fluvial, wave, and tide dominance. Grain size distributions are notably sand - rich (Figure 27b) and deltaic sediments are assumed to be isolated in the high energy zone (inferring minimal offshore deltaic sediment).

Unlike the climates of most deltaic systems studied, the Gascoyne Delta of western Australia is an arid climate delta. Johnson (1982) identified this delta as wave-dominated and suggests that offshore lithologic profiles at the delta are indistinct from surrounding strandplain/interdeltaic environments, including lack of
Figure 26: Major lithofacies and depositional environments of the Niger delta
(from Allen, 1979).
Figure 27: A.) Depositional environments of the Niger delta and adjacent coastline. B.) Surface sediments of the modern Niger delta (from Allen, 1975).
fine-grained prodelta sediments. Prodelta sediments are absent due to the nature of the drainage basin sediments. That is, insignificant volumes of fine-grained suspension load are transported by the river. Because the Gascoyne River is not continually discharging, this delta offers a unique opportunity to isolate flood events, and observe geomorphic change between flood discharge. Thus, the individual dominating factors are isolated in time. For example, during floods, most of the constructive phase for the delta occurs, with the deposition of mouth bars and minor amounts of delta front sediments. During more normal periods, waves dominate the morphology and rework the sediments into beach ridges and upper shoreface bars. As will be seen, this is similar to the proposed scenario for the Brazos delta.

Other modern deltas such as the Rhone and Po (discussed by Oomkens, 1955) lend insight into the interplay between hydrography, sea level, and sediment flux. Geomorphic patterns are linked to these variables, and the significance of each becomes evident. Previous studies emphasize the role of suspended sediment volume and lithology to delta geometry. Although ratios of fluvial discharge to tides and waves might be similarly low for several basins, overall stratigraphy will be grossly different according to the suspended sediment concentrations and whether those sediments are sandy or muddy.

A recurring theme among all of the deltaic literature is that stratigraphies can be vastly different, even though certain (or even a majority of) parameters are similar. It is, therefore, critical to adjudge the combined effects of many variables. In other words, to infer a regressive strandplain stratigraphy from an area where tides are low, and fluvial input to wave energy ratios are low is simplistic. One must ask what affect basin geometries have on sediment distribution. Consideration of anomalous, rather than typical events, (i.e. floods or storms) is necessary. The
sediment types must be assessed and bedload transport must be estimated. Changes throughout the evolution of the delta cannot be dismissed, and antecedent topography merits precaution. Most of all, the spectrum of geomorphologic functions is never so straightforward that stratigraphy can be predicted and categorized from a three-fold comparison of waves, tides and fluvial discharge.

**Previous Studies on the Brazos Delta**

Bernard et al. (1970) described the sediments of the Brazos alluvial and deltaic plains. Sediment cores from the onshore sections of the delta were used to identify the various depositional environments of the delta, and to map these facies in two and three dimensions. The authors identified the basic depositional sequence in the Brazos delta as follows (from Bernard et al 1970):

- Beach sand or organic-rich clays of the subaerial deltaic plain
- Bar back--interbedded silty clay and sand layers
- Bar crest--laminated or cross bedded sand
- Bar front--interbedded silty clay and sand
- Distal--prodelta clay, uniformly laminated
- Marine clays--deposited in Gulf before the development of the new delta
- Recent--Pleistocene unconformity.

Bernard et al. (1970) also distinguished marine transgression in the delta from transgression occurring along other sections of the Gulf Coast. They note that after diversion of the river, "the balance was changed between deposition of river sediments and redistribution of these sediments by marine processes. Thus, the marine transgression at this locality has not been caused by a rise in sea level." Distinction between eustatically-induced transgression and transgressions initiated by changes of sediment supply are critical factors when reconstructing the history of depositional systems. By identifying the modern
signature of changes in sediment supply, we can more accurately depict the evolution of ancient depositional systems.

Bartek et al. (1991) investigated the preservation potential of the coastal lithosomes of small deltaic systems, including the Brazos delta. The authors integrated high resolution seismic stratigraphy with sediment cores, in order to identify ravinement surfaces and any preserved deltaic lithosomes. Using the seismic facies patterns within the modern Brazos delta, the authors were able to identify older deltaic deposits farther offshore. Bartek et al. confirmed that during transgression, the preservation potential of wave-dominated deltaic lithosomes is minimal. This conclusion was based on the absence of any significant deltaic deposits preserved offshore of Oyster Creek, the approximate location of the Brazos distubutary until about 1,000 years b.p.
Geologic History

More than 30,000 years ago, during intervals of diminished glaciation, meander belts built across the coastal plain and transported sediments to deltas within broad embayments along the Gulf Coast. Late Pleistocene deposits primarily consist of fluvial deposits updip and large extensive deltas and delta plains down dip. Marine reworking of these deltaic sediments probably occurred during the Late Wisconsinan interstadial time (McGowen, 1976).

Sea level during the Late Pleistocene was approximately 120 meters below present, which resulted in valley incision across the shelf and subsequent deltaic deposition at the outer shelf and upper slope. At 18,000 B.P., the sea began to rise and created numerous estuaries (Nelson and Bray, 1970). The estuaries filled as sedimentation kept up with the rate of rise. Some estuaries were completely filled, i.e. Colorado, while others were not, i.e. Trinity. Numerous still stands occurred throughout the gradual rise, during which rivers prograded across embayments and the open shelf. At 6600 B.P., sea level was at -24 meters; at 3600 B.P., it was at -5 meters; by 2800 B.P., sea level was approximately at its present position (Fairbanks, 1989). "Still - stand" coastal bodies are scattered across the shelf and are interpreted in many ways--fluvial deltas, barrier islands, tidal deltas, or incised valley-fill. The Brazos/Colorado system deposited numerous deltas during these times, and the relict deposits are easily discernible in core and seismic data (Figure 28).

At approximately 8000 B.P., the Brazos delta occupied the shelf region known as the Freeport Rocks Bathymetric High (Bartek et al., 1990). This delta was subsequently overstepped, and deposition began inland. A broad estuary existed at about 4500 B.P., and this was the site of 22 miles of progradation by the
Figure 28: High resolution seismic data from offshore of the Brazos delta. The lines cross two remnant deltaic bodies: the Freeport Rocks Bathymetric High and the Oyster Creek/Brazos delta (from Banek et al., 1990).
Brazos/Colorado deltas (McGowen, 1976) between 2500 to 1200 B.P. The Oyster Creek/Brazos delta lobe existed here until approximately 1000 B.P. (ibid). The channel was abandoned and few deltaic sediments remain offshore. Occupation of the Old Brazos delta lobe commenced and deposited significant sediments offshore of Surfside, Texas. Human alteration in 1929 added a final lobe switch to the present area west of Freeport. Figure 29 is a summary of the Brazos history from 15,000 B.P. to present.

**Historical Evolution**

Because the most recent lobe switch of the Brazos River occurred during historical times, we can accurately describe the depositional history in much detail via aerial photographs and navigational charts. Panel 1 is a historical photographic record of Brazos delta evolution. Note how efficiently the Old delta is eroded and reworked; presently there is very little of the Old deltaic coastline remaining. The New delta developed rapidly, with a significant portion of its sediment being derived from the Old delta. To date, the subaerial delta has prograded approximately 6.5 kilometers seaward, and has deposited a large volume of sediment alongshore, to its natural boundary at the San Bernard River.

Bathymetric information (Figure 30) also reveals extensive removal of sediments from the old delta, and deposition into the New delta. Since 1929, the subaqueous lobe of the New delta has prograded approximately 8 to 10 kilometers and is depositing significant volumes of sediment below wave base. The alongshore component of subaqueous deposition extends for nearly 10 kilometers and is most voluminous in water depths of 4-6 meters. The subaqueous lobe is by far the most voluminous depositional environment.
Figure 29: History of the Brazos delta since 18,000 years before present (Bartek et al., 1990).
Figure 30: Modern bathymetric contour map which indicates the depositional lobe of the New Brazos delta and the return to equilibrium shoreline conditions in the Old delta.
Time reconstructions (Figure 31) trace the development of the delta during the last six decades. Prior to diversion, as seen in the 1922 reconstruction, the Brazos entered the Gulf southeast of Freeport. A lobate shoreline is apparent and the delta flanks are asymmetrical with the west flank dominant. A significant subaqueous lobe also existed and prograded into water depths of -15 meters. The diversion occurred in 1929, and the January 1931 map shows the initial subaqueous pulse of sediment as revealed in bathymetric irregularities near -5 meters. The subaqueous portion of the Old delta has also begun to be reworked. By December 1931, extensive erosion had taken place on the Old delta, and sediments were moved alongshore and deposited near the east flank of the New delta. Shoaling and ridge evolution in the new delta are readily apparent. Shoreline progradation and beach ridge evolution are discernible from 1931 to 1933. Wave erosion by 1933 had nearly removed all of the subaqueous Old delta that was above wave - base. Large lagoons were created as the sea encroached on the subaerial portions of the old delta. In addition, stranded bodies of water existed on the west flank of the New delta, as sediments were quickly piled onto the shore, creating extensive low lying subaerial progradation. Between 1935 and 1938, significant subaqueous deposition occurred, generating a distinct lobe of deposition offshore. The 1940 map reveals headland development and progradation on both flanks of the New delta and continued erosion of the Old delta. By 1950, few remnants of the Old delta remained. Headland progradation on the New delta was extensive. A chain of small emergent bars was also visible on the west flank of the New delta. By 1957, the shoreline of the Old delta was straight, except for slight cusping directly adjacent to the mouth where jetties2

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2 Jetty construction at the old Brazos River mouth was an ongoing project, occurring from 1889-1895, and resuming in 1921 until completion in 1927. Construction interruptions emanated from Washington, where federal funding for such projects was often first on the cutting board.
Figure 31: Evolution of the Brazos delta since 1922. In the lower right corner of each subfigure, the date is indicated by month/year. These figures are constructed using NOAA charts and historical aerial photographs.
has been a new delta growing since 1922. In the lower right corner
of each map is the specific month/year. These figures are
based on historical aerial photographs.
trapped sediment. Erosion of the west flank headland and development into a series of bars was seen between 1950-1957 (notice that the orientation of these bars is dependent on wave orientation around the headland). These ridges and the prominent headland of the west flank encapsulated a large lagoon, which was affected by tidal influx through several tidal channels. On the east flank, rapid sedimentation similarly enclosed a series of lagoons with axial orientation corresponding to beach ridge alignment. Headland accretion occurred between 1957 and 1964 and an additional bar evolved which accreted to the west. By 1980, the bar had thinned and extended alongshore until it was nearly welded to the shore. Offshore in water depths of 6-7 meters, two small banks became visible, and the eastern extent of deposition was outlined by the marked change of bathymetry. Headland accretion was once again generated between 1980-1984, although isolated to the existent shoreline, with no significant projection seaward. The bar, which was created in the early 1960's, completely welded itself to the western portion of the delta, and the shoreline assumed a smooth lobate morphology. The shoreline maintained this shape throughout the 1980's and into the early 1990's, until 1992 when a large bar emerged offshore.

The delta has changed rapidly throughout historical time, and is continually evolving today. Monthly reconnaissance flights reveal extensive change of the bar area and onshore sections. Numerous subenvironment alterations have also occurred -- bedform migration, tidal channel creation/destruction, bar dynamics -- but are too extensive to discuss in detail.

**Beach Ridge History**

The old and new regions of the Brazos Delta are composed of a number of beach ridge sets that reveal much about the sediment supply history of the system.
The sediment budget is discernible from several characteristics of the ridges including ridge spacing, height and frequency. The longitudinal shape of the ridge reveals wave approach. Ridge taper is related to sediment input locality, wave approach/refraction and longshore drift. Longitudinal continuity is a function of erosion or deposition. By delineating where ridges taper, and where ridges flare, sources of sediment can be determined. Subsequently, a historical development for the area is evident. Psuty (1969) did a similar study for the Tobascan Coast, and many of the techniques he used are incorporated into this study.

The longshore transport mechanism is believed to be responsible for early accretion and progradation of the New Brazos Delta. After diversion of the Brazos in 1930, marine agents were effective in eroding the Old Brazos Delta. Sediment plumes diverted by longshore transport in the region confirm that these sediments would have been transported alongshore and to the southwest. Aerial photographs of the old and New Delta from 1930 -1936 show considerable removal of sediments from the Old Delta and rapid progradation of the New Delta. However, it is not evident that all of the Old deltaic sediments were simply removed from one location and deposited in another. The sediment volumes within the New Delta that can be attributed to longshore transport are considerably less than the volumes eroded from the Old Delta.

In order to separate ridge histories, Figure 32 is a line drawing of the 1989 wide scale aerial photograph of the area. The area shaded in green is the pre-1930 shoreline. In the Old delta, the shoreline has been efficiently eroded such that the modern coastline occupies the latitudinal position of the pre-1930 shoreline.
Figure 32: Line drawing of the most recent wide-scale aerial photograph (Panel 1, 1989 figure). This illustrates the evolutionary history of beach ridges for the Old and New Brazos deltas. The colors correspond to the approximate time of deposition within each delta:

- ICW = Intercoastal waterway.
On the eastern flank, remnants of old delta ridges are present and identified in light blue. The seaward extent of these ridges (including eroded sections) is shown in the figure by several dotted lines. The two sets of dotted lines indicate the orientation of ridge sets that existed at different times. The age of each ridge set was not determined. The lineations flare to the east and taper to the west, indicating sediment input to the east from the pre-1929 channel. In general, the direction of taper is farthest from the primary source of sediments. These ridges are also correlative to earlier photographs of old delta when it was still visible.

Erosion of the Old delta and subsequent longshore transport supplied the sediment marked in brown. The difference of total sediment eroded from the old delta and total sediment deposited in the new delta is considerable. Lineation discontinuity and incomplete taper to the west indicate some period of erosion along this ridge set. Thus, a lag in sediment supply is inferred, which might represent diminishing erosion of the old delta.

Considerable fluvial discharge must have built a prominent cuspatate foreland (bar) in front of the delta during the time of dark blue deposition. Lineation of the ridges is deflected markedly to the southeast, suggesting wave refraction around a prominent headland. The continuity of the ridge is interrupted by marsh sediments and tidal channels. Along trend projection, however, reveals that the ridges are truncated at their southern most extent. This truncation indicates active erosion.

Red deposition appears to succeed a period of erosion in the dark blue indicated by truncation of older ridges by younger ridges. Erosion along the headland is once again indicated by discontinuity of the blue ridges along the southern most shoreline.
Yellow represents periods of deposition primarily from longshore transport of persistent fluvial discharge. Although less evident, truncation of the ridges might be indicative of diminished discharge. During these last phases of deposition, the delta grew considerably to the west. Vast lagoons are preserved between ridges and typify back ridge infilling during times of high sediment discharge from the river. The spit aggradation within the San Bernard River mouth supports the longshore transport deposition.
METHODS

The issues discussed above are addressed with numerous types of data, including vibracores, gravity cores, pneumatic hammer cores,surficial grab samples, suspended sediment samples, basic oceanographic data (i.e. salinity, temperature, transmissivity), high resolution seismic data, coastal navigation charts, bathymetric profiles, fluvial hydrograph data, and aerial and surface photography.

Vibracores and gravity cores were collected from two boats; the R/V Lonestar and the R/V Shiner (Figure 33), each licensed to Rice University. The vibracore device is a standard cement vibrator with an 8 horsepower gasoline engine. The vibracore head is adapted to 5.08 cm (2 in.) or 7.62 cm (3 in.) diameter aluminum barrels. Gravity cores were taken with approximately 70 kilogram lead weight and 5.08 cm (2 in.) diameter core barrels, falling through 3-5 meters of water.

A pneumatic hammer (Figure 34) was employed to core the large volumes of clay in the prodelta. The hammer is attached to the top of the core barrel (7.62 cm, 3 in.), and two to five hundred pounds of pressure are pumped to the hammer for 2 to 5 minutes. Recharge of the air pressure requires significant storage and generation of high pressure air. The R/V Lonestar has a 40 cfm air compressor and 4 large air tanks to facilitate such operations. Pneumatic hammering penetration averages 4 meters, with a maximum of 7 meters (the height of the coring stand).

Several cruises were made to collect vibracores, including before, during and after the floods of 1992. Pre-existing cores from the study by Bartek et al. (1990) were also utilized.
Figure 33: Research vessel R/V Shirer. The boat has an internal well (where the tripod is shown) through which cores can be taken in water depths up to 5 meters.
Figure 34: A pneumatic hammer is used on the research vessel *R/V Lonestar*. It has proved to be the most successful coring device for all types of sediment. The hammer is actually a large pneumatically-driven (400 pounds per square inch) piston which is attached to the top of aluminum irrigation pipe. The hammer and pipe are attached to a sled on a large tripod which stands vertically and guides the pipe into the sediment. This device consistently takes five to seven meter cores within a three to five minute time period.
Surface grab samples were collected with a MacIntosh grab sampler. Grab samples were collected primarily to assess present day lithologies, in order to aid in the identification of depositional environments in the cores. Grab samples were also useful in determining the lateral extent of flood deposits throughout the three months of intense river discharge.

Suspended sediments were collected with a miniature water pump and a 38/63 micron mesh sieve at the onset of flooding and after flood waters had receded. The hose on the intake was lowered to different water depths and the pump was operational for 3-5 minutes. Samples were washed from the sieve with seawater, collected in plastic bags and placed immediately into refrigeration.

All cores and grab samples were kept in the refrigerated storage facility at Rice University, where the cores were eventually split lengthwise and divided into archive and sampling halves. The grab samples remained in refrigeration until analyses were complete. Refrigeration of all samples preserved the integrity of the core, and did not allow for intergranular water to evaporate, thus preventing drying and cracking. An archive half of each core was preserved in its original wrapped barrel at the Department of Geology and Geophysics at Rice University.

Analyses of sediments included raw water content, grain size, gross mineralogy, volume calculation (for suspended sediment), and minor paleontologic examination. Standard settling tube analysis, as outlined by Anderson et al (1982), were used. The methodology of Folk (1972) was relied upon for typical texture and mineralogic analysis. Sand percentages were calculated by wet sieving through a 63 micron mesh screen sieve.

Minor amounts of oceanographic data were collected during the 1992 flood to assess the role of fluvial discharge and basin response. Salinity, transmissivity
and temperature were all calculated using a Yellowstone Instruments Turbidity/Salinity/Temperature sensor. Bathymetric data was collected using a Raytheon depth recorder in waters greater than 9 meters depth and a Hummingbird depth scanner in shallower water.

Historical coastal navigation maps dating to the early 1900's were purchased from the U.S. National Archives in College Park, Maryland, courtesy of NOAA and the former U.S. Coastal and Geodetic Service. Historical aerial photographs were acquired from Tobin Aerial Photographic Services in San Antonio, Texas. And, historical fluvial discharge data was acquired from the Houston office of the U.S. Department of Interior, Water Resources Division.

Statistical analyses of discharge and flood data was greatly facilitated by staff members at the Houston office of the U.S. Department of Interior, Water Resources Division.

Recent aerial photography was acquired with a 35/50 mm Canon from a contracted air service. Photographs were taken from 152.4 meters (500 ft) to 2438 meters (8000 feet).
RESULTS

Facies Analysis

Detailed examination of approximately 100 vibracores and pneumatic hammer cores revealed both the modern facies and the overall stratigraphy of the Brazos delta. After describing the modern facies, the cores are grouped into transects to show stratigraphic facies patterns. Core locations are shown in Figures 35 and 36.

Modern Facies

The modern facies are systematically ascribed to one of three designated bathymetric zones: Offshore (>3 meters), Nearshore (<3 meters) and Onshore. Note that the designation to a particular zone does not imply that the facies is exclusive to that zone, but most commonly occurs in that area.

Offshore

(1) Muddy Sand: This facies primarily occurs west of the river mouth and was sampled in water depths of -3 to -5 meters. Sand percentages from this facies are highly variable (from 60-90%). The sands are visually estimated to be 80% quartz, 10% heavy minerals, 5% mica, and 5% microfauna. Individual quartz grains are rounded to subrounded and have opaque to red color. Heavier minerals and micas are angular to subangular, and slightly larger than quartz grains. The sands are well sorted (standard deviation (sd) = .364 phi), have a dominant grain size mode of 3.0 to 3.25 phi and are strongly fine skewed (skewness (sk.) = .334). The color of the sediments is generally 10YR5/4, but this changes with increasing mud content. Shell fragments are
Figure 35: Offshore Sample Locations
scattered throughout and are sometimes concentrated within vertically oriented burrows. Bioturbation is relatively intense in this facies, especially at the top of the individual beds.

The muddy sands are commonly laminated. Laminae are parallel, crossed, and rippled, but are often disturbed by bioturbation and burrows. Numerous forams and other microfauna exist in these sediments; most common forams are *Ammonia beccarii* and *Quinqueloculina compta*.

The muddy sand units collected during coring range from 20 to 100 centimeters thick. Thicknesses are greatest in shallow water depths, and show marked decreases offshore. The muddy sands are not seen in the surface sediments in water depths greater than 5 meters, or approximately 0.8 kilometers offshore. The mud percentage in this facies increases dramatically along-strike towards the river mouth. The facies is no longer distinguishable within 1.5 to 2 kilometers radially from the mouth. Cores BDP 30, BDP 29, BDP 21, BD 93-2, BD 93-4 and BD 93-5 have the "muddy sand" facies in the uppermost sections. Figure 37 photographically illustrates the facies from sediment cores.

(2.) **Interbedded/interlaminated muddy sands and sandy muds:** This facies is most commonly seen in water depths of -5.5 to -9 meters, and west of the river mouth. It begins to occur at the toes of the "muddy sand" facies, and it is transitional between shallower water "muddy sands" and deeper water open marine sediments (e.g. prodelta clays). The sediments are very muddy (as the name depicts) and are texturally separated into sandy mud and muddy sand interbeds. Occasional clay beds (<10cm thick) occur within this facies and have erosive contacts with underlying sediments. The color of the sediments is mixed but is typical of Brazos sediments (i.e. reddish brown). The sands are
**Figure 37:** Muddy Sand Facies. This facies occurs between 3 and 5 meters water depth on the margins of the delta lobe and along the shorelines adjacent to the delta. The sedimentary composition is variable from 60 to 90% sand. The sands are well sorted and are composed of approximately 80% quartz, 10% heavy minerals, 5% mica and 5% microfauna.
moderately sorted (s.d.=.796 phi), coarse skewed (sk=2.88 phi) and have modal grain sizes of 3.0-3.5 phi. Visual examination identifies the sands as 85% quartz, 5% mica, 5% heavies, and 5% microfauna. Typical microfauna are the forams *Ammonia beccarii*, *Quinqueloculina compa*, *Quinqueloculina lamarckiana*, and *Elphidium deliculatum*. Numerous sponge spicules were also observed. Throughout this facies, shell fragments are concentrated in burrows and at bed boundaries (upper). Interbeds of homogenous clay lack shell fragments.

Individual beds of muddy sand or sandy mud average 10-20 centimeters thick. The complete bedsets collected during coring range from 20-80 centimeters thick nearshore to 20-50 centimeters offshore. Within the facies, individual beds become interlaminations further offshore. This lateral transition from beds to laminations is also seen vertically in core sections. The base of this section is generally laminated and the upper sections are interbeds. Bounding surfaces between individual beds/laminae are parallel. Bioturbation has masked the sharpness of the surfaces in many cases.

The "interbedded/interlaminated muddy sand and sandy muds" do not occur in the upper layer of cored sediments beyond 9 meters water depth, or 4.5 kilometers offshore. In a west to east trend towards the river mouth, the facies dissappears at approximately 6 kilometers from the mouth.

Cores BDP 31, BDP 27, BD93-6, BD 93-7 BDP 32, and BDP 22 all penetrated the muddy sand/sandy mud interbeds and interlaminations. Figure 38 illustrates the interbedded and interlaminated muddy sand and sandy mud.

(3.) **Clean shelly sand:** Thin beds of this facies were sampled in cores from various depths and distances from shore. The sands are very fine (mean gs=3.5 phi), well sorted (excluding shell fragments, sd=.596 phi), and coarsely
Figure 38: Interbedded and Interlaminated Muddy Sand and Sandy Mud. This facies occurs at 5.5 to 9 meters water depth throughout the delta. The sand percentages are highly variable, and the sands are moderately sorted. The sands are composed of approximately 85% quartz, 5% heavy minerals, 5% mica and 5% microfauna.
skewed (sk=.285). Graphic kurtosis (k) indicates the leptokutic nature of the sediments (k= 1.682). The sands are predominantly very opaque, well rounded quartz, and have an estimated 2% microfauna including *Ammonia beccarii* and *Quinqueloculina compta*. Color of the sediments ranges from 10YR5/4 to 5Y4/1. Shells within the sand are both normally and reversely graded and are highly fragmented.

This facies is interbedded with almost all other sediments in the delta and surrounding coastal region. The beds have erosive lower contacts and sharp upper surfaces. They are generally less than 10 centimeters thick, but exceed 20 centimeters in a few cores. The facies was sampled at the surface in the most distal core site (relative to shoreline), BDP 01, approximately 16 kilometers offshore at 20 meters water depth.

Figure 49 photographically depicts the "clean shelly sand" facies.

(4.) **Olive Gray Clay**: This facies was sampled at the surface beginning 4.5 kilometers offshore at 7.5 meters water depth. The sediments are primarily clay with typically less than 15% sand and silt. The clay is extensively bioturbated, and has sand-filled burrows near the surface. The clay lacks organic material (a primary distinguishing characteristic) and often contains shell fragments and fully articulated shells. The clay is olive gray (5Y4/1) farthest from the river mouth, but changes to dusky yellow gray (10YR6/2) in the more distal deltaic zones.

The thickness of this facies is highly variable in core sections, from individual beds of 2-3 centimeters thick to beds greater than 100 centimeters thick. Beds are thicker farther offshore. The "olive gray clay" facies is deposited throughout the region, but its occurrence is significantly deflected offshore near the delta. This clay is often interbedded with the "clean shelly sand" facies; the
Figure 39: Clean Shelly Sand: This sand occurs throughout the delta and surrounding coastal zone. The sand occurs in beds less than 0.5 meters thick, and typically contains lower erosional surfaces. This facies is typically 95% sand which is approximately 95% quartz, 2% shell fragments, and 3% preserved microfauna. The sands are gray to dark gray which is typical of shelf sands in the area.
sand-clay contacts being highly erosive. Also, laminations of heavily bioturbated sandy clay are present in the upper part of this facies.

Cores BDP 7, BDP 8 and BDP 39 sampled the "olive gray clay" facies in the surficial sediments. Figure 40 photographically depicts these sediments.

(5.) **Reddish brown clay:** Within the depositional lobes of the New and Old Brazos delta, significant volumes of reddish brown (5YR3/4 and 5YR4/4) clay are deposited. This clay generally has less than 10% sand, but is often interbedded with sandier or siltier lithologies. Organic material is scattered throughout the clay and occurs as individual beds (<5 cm.) and preserved wood fragments. In the proximal delta, these clays have very fine laminations of silty clay. The uppermost portion of this facies is typically fluidized with approximately 30% water (by mass). After flood events, these clays are even more water saturated, averaging 50-60 % water.

Surficially, the unit is first noted at 2 kilometers offshore in water depths of 6 meters. The maximum offshore extent of the deposit is 7 kilometers and 15 meters water depth (directly offshore of the river mouth). Alongshore to the southwest, the reddish brown clays are isolated to a zone closer to shore. The clays occur at the surface and downcore between two facies already discussed- - the "interbedded/interlaminated muddy sands and sandy muds" and the "olive gray clay" facies. Specifically, the reddish brown clays are focused in a zone between -6 and -9 meters water depth west of the river mouth.

Beds range in thickness, depending on location relative to the central deltaic depositional lobe. For example, within the main lobe of the delta, individual clay beds often exceed 100 centimeters. On the flanks of the main delta lobe, beds are thinner, averaging 10-20 centimeters. Also, abundance of
Figure 40: Olive Gray Clay. This facies is inferred to be nondeltaic due to its similarity with adjacent marine sediments. The clay occurs at water depths greater than 7.5 meters. The clay has 0 to 10% sand and is highly bioturbated.
interbedded "olive gray clay" facies and "clean shelly sand" sediments is more frequent on the margins of the delta lobe.

In all of the cored sections, the reddish brown clay is the most abundant facies. It occurs throughout the delta, including the nearshore and onshore portions. Almost every core in the BDP series possesses the "reddish brown clay" sediments either at the surface or downcore. Core BDP 11 is illustrated in Figure 41 and shows a section with greater than 50% "reddish brown clay" facies.

(6.) Thinly-bedded red and gray clay: A large portion of the delta is composed of thinly-interbedded "olive gray clay" and "reddish brown clay" facies. The facies occurs as the transitional clay between the "olive gray" and "reddish brown" clays. The individual characteristics of the component clays are preserved in each subfacies. For example, at a sharp surface separating overlying "reddish brown clay" from "olive gray clay", laminae of organics are observed. Also, scattered shell fragments and sand-filled burrows are often found in the "olive gray clay" beds.

The farthest offshore occurrence of this facies is approximately 16 kilometers in -14 meters water depth. Most frequently, in surficial sediments, the "thinly bedded red and gray clay" facies is deposited between "reddish brown clay" nearer to shore and "olive gray clay" farther offshore. However, as discussed in the previous section, the distribution of sediments is more complex west of the river mouth, such as in cores BDP 22-25.

The thinly-bedded red and gray clay facies is illustrated in Figure 42.

East of River Mouth

Sediments east of the river mouth are lithologically distinct from sediments west of the mouth; in the west, mud percentages are much higher.
**Figure 41**: Reddish Brown Clay. This is the primary sediment transported by the Brazos River. The river "runs red" due to the abundance of red clay in suspension. The red clay is deposited at depths generally greater than 7.5 meters, but is found within the stratigraphy throughout the delta. The clay has 5-10% sand. Organic matter is abundant within the clay.
**Figure 42:** Thinly-bedded Red and Gray Clay. This is a unique facies restricted to the Brazos depositional region. The red clay is derived from Triassic red beds of northern New Mexico and transported along the Brazos fluvial system. The alternating beds/laminae of red and gray clay are a result of pulsing discharge from the Brazos River. The red clays represent increased flow from the river. The gray clay is representative of the clayey/muddy sediments typical on the Texas shelf. This facies occurs at water depths of greater than 7 meters and is deposited both alongshore and to the east of the modern river mouth. The red clays lack sand but have abundant organic fragments.
Sediments deposited while the Old delta was still active, however, are similar to the New delta facies. Two facies that are depositionally related to the river's diversion are discussed below.

(7.) Very fine, clean sand: Very fine, clean sands are the spatial equivalent of the "muddy sand" facies to the west. They occur within 2 to 2.5 kilometers of shore, and within 3 to 8 meters water depth. These sediments are composed of approximately 90% sand (by mass). The sands are visually estimated to be 90% quartz, 5% heavy minerals, and 5% microfauna. 
*Ammonia baccarii* are the most common forams. The grain size for the sand is 3.0-3.5 phi, and the sands are moderately sorted (sd=0.836 phi). Sediments are coarsely skewed, perhaps reflecting shell fragments or heavy minerals. Individual grains are rounded to well rounded. The sediments have a light olive gray (5Y6/1) appearance. Individual quartz grains are much more opaque than their counterparts to the west.

The sands are often highly bioturbated and contain vertical sand-filled burrows. Laminations in this facies are abundant and are frequently rippled or crossed. Individual beds have average thicknesses of 20-40 centimeters. Interbeds of "reddish brown clay", "olive gray clay" and "thinly bedded red and gray clay" are generally stiffer than their modern equivalents. Bounding surfaces between beds are highly erosional/bioturbated.

Core BDP 34 contains the "very fine, clean sand" and is illustrated in Figure 43.

(8.) Distal very fine sand: This facies is found in water depths of 15 to 18 meters and 8 to 10 kilometers offshore. The sands are visually estimated to be 80% opaque quartz, 10% heavy minerals and 10% mica. The sands have mean grain sizes of 3.5-4.0 phi and are poorly sorted (sd=1.06 phi). The sediments
Figure 43: Very Fine Clean Sand. This facies occurs from 3 to 8 meters water depth and was observed primarily in the Old delta area. The facies lies above the Old delta deposits and generally contains an erosional lower contact. The photo shown above indicates the 1929 contact between underlying Old delta clay and the very fine clean sand facies.
are also coarsely skewed (sk = -.731 phi). Microfauna are scarce, and when present, they are highly fragmented.

The thicknesses of the sands exceeded the penetration of cores, and the offshore limit appears to be beyond the study area. Maximum penetration into the facies was approximately 60 centimeters. The sands are interfingered with the "thินly-bedded red and gray clay" facies nearest the delta lobe, and are interbedded with the "olive gray clay" facies in more distal positions.

Bioturbation is abundant in the sands, and burrows are frequently observed. "Tube worms" were also collected in grab samples within the facies.

The distal very fine sand facies is shown in Figure 44.

**Nearshore and Onshore**

**Nearshore**

(1.) **Bar Sands:** This facies occurs within the emergent bar 0.5 to 1 kilometer offshore of the Brazos River mouth. Sands are very clean, very fine (from core BDB 07: gs = 3.0-3.5 phi) and moderately well sorted (sd = .399). There is grain texture variability on the bar, with coarser and better sorted sands on the seaward-facing beach (from core BDB 03: gs = 2.375 phi, sd = .434). The "bar sand" facies contains abundant heavy minerals and mica. Visual estimates for the sand compositions are 80% quartz, 15% heavy minerals and 5% mica. The mica and heavy minerals are often concentrated in the swash zones of the seaward-facing and landward-facing beaches, and within tidal pools across the bar (Figure 45). Note that heavy minerals are rarely observed on Texas beaches, and their presence here was a useful tool in the identification of previous delta shorelines.

The "bar sand" facies in core is a very clean sand with abundant sedimentary structures. Distorted laminations are common and are interpreted
Figure 44: Distal to Very Fine Sand. This facies contains approximately 80 to 85% sand and 15 to 20% mud. The sand is composed of approximately 80% quartz, 10% heavy minerals, 5% microfauna, and 5% fragmented shell. The sands are very poorly sorted. The facies occurs in the sediment cores taken farthest from the mouth of the Brazos.
Figure 4.6: Heavy mineral concentrations on the beaches of the offshore bar and mainland. Scale is indicated by the red pen, approximately 15 centimeters in length.
as dewatering features. Also, laminations throughout the "bar sand" facies are frequently crossed, rippled, or inclined. The laminations are related to both mineralogical and textural variability. The former is most obvious in middle sections of the facies, while the latter is most common near the base. Also, organic debris is often concentrated within the laminae. Bioturbation is common throughout the "bar sand" facies. Silt and mud filled burrows are also observed. Fragmented shells are scattered throughout the unit.

The bar thickness is highly variable in strike and dip directions. The bar sands are thinner to the west, where cores indicate average thickness of 130 centimeters. To the east, maximum penetration of the "bar sand" facies was approximately 250 centimeters, of which the upper 200 centimeters was very clean "bar sands" and the lower section was laminated "bar sands". On the landward facing edge of the bar, "bar sand" facies occur as thin deposits (5-10 cm.) interbedded with back bar facies. The lower contacts between the interbeds are often highly erosional, while the upper contact is sharp and often inclined or rippled. In the seaward direction, the "bar sand" facies tapers to several small interbeds with average thicknesses of 10 cm. The underlying and laterally adjacent facies is much more muddy, and highly laminated. The actual boundary between laminated "bar sand" facies and seaward adjacent facies is not easily defined. Distinctions are made simply on muddiness and nature of laminations. Also, coring operations were abandoned in the transition zone, from the "bar sand" facies seaward, because of breaking waves in the surf zone.

The BDB core series is most representative of the "bar sands". With the exception of core BDB 04 and BDB 05 (which sample the beach of the river and mainland), these cores illustrate intrafacies variability. Figure 46 illustrates sediments from the BDB series, collected on or in the vicinity of the bar.
(2.) **Highly laminated, muddy sand:** Although this facies does not appear at the surface in any of the cores, it does appear directly below the "bar sand" facies in many of the BDB cores. It is inferred to exist at the surface seaward of the bar to approximately -2 meters water depth (where as mentioned, coring operations were not feasible).

This facies is composed of muddy sands with abundant and very fine laminations. The sediments are (by mass) 85% sand. The sand is visually estimated to contain 95% quartz, and 5% heavy minerals. The sediments have a light brown color (5YR5/6).

Laminations in this facies are abundant. In the uppermost section of the unit, laminations are spaced farther apart than the tightly-spaced, very fine laminae of the lower sections. Also, organic concentrations in laminae decreases downcore. Distortion of laminae (dewatering?) is apparent at the top of the facies, while most laminae of the mid to lower sections are parallel.

Total thickness of this facies is unclear; cores did not completely penetrate the facies. However, cores did collect up to 80 centimeters of the "highly laminated, muddy sand." This facies and is illustrated in Figure 47.

(3.) **Back bar mud:** In the lagoon, encapsulated behind the offshore emergent bar, very fluidized mud is rapidly accumulating. This zone is influenced by several competing factors including tidal flux, fluvial input, washover and eolian transport from adjacent beaches.

The muds have less than 10 % sand, and nearly 50% water by mass. The sands are very poorly sorted (sd=5.93 phi) and bimodally distributed with modes at 2.5 phi and 3.5-4.0 phi. Microfauna are absent from the muds.
Figure 46: Bar Sand. The bar sands occur within the emergent bar immediately offshore of the Brazos River mouth. The sand is very clean and contains less than 2% mud. This facies consists of approximately 80% quartz, 15% heavy minerals, and 5% microfauna.
Figure 47: Highly Laminated Muddy Sand. This facies occurs seaward of the emergent bar, and underlies the bar sand facies. The laminae are textural. The facies is approximately 85% sand and 15% mud. The sand is moderately sorted with average grain size of 2.5 phi to 3.0 phi.
The sediments have characteristic Brazos color—moderate brown (5YR4/4 or 5YR3/4). On the margins of the lagoon, the "back bar mud" facies is interbedded with beach sediments of the bar and mainland. In the western portion of the back bar, sediments are highly influenced by the encroaching bar, such that sand percentages are significantly greater in the surficial sediments. Also, in the eastern back bar region, near the most eastern extent of the emergent bar, the "back bar mud" facies has approximately 50% sand—thus making it a muddy sand. This sandier facies was sampled in core BDC 94-1. The sands in this core are trimodally distributed with modes at 2.25-2.5 phi, 2.75 to 3.0 phi and 3.25-3.5 phi. Sorting is obviously poor with sd. values of 2.803 phi. Visual observations of these sands reveal 90% quartz, 5% heavies and 5% mica. Individual grains are rounded to angular, and highly angular vesicular igneous fragments are also seen.

Abundant organic matter is also observed in the "back bar mud" facies, and occurs as sand-size grains to large wood fragments. Bioturbation is noticeably absent. Shell fragments are scattered throughout the facies, and occasionally, a highly fragmented oyster shell is found in the sediments. Few microfauna were observed in the sediments of the back bar.

Total thickness of the contemporaneous "back bar mud" facies is approximately 50 centimeters. Core BDC 94-2 penetrated 50 centimeters of very wet, moderate brown clay, underlain by sand and clay interbeds. These lower beds of clay have the same appearance and lithology of the "back bar mud" modern facies, and are inferred to be part of a larger bedset. Thus, it is more accurate, perhaps, to include the sand interbeds within the overall "back bar" facies. Inclusion of sand interbeds makes the average thickness for the back bar facies approximately 150 centimeters.
Core BDC 94-2 is most typical of the "back bar mud" facies (Figure 48). Nearly all of the BDBB cores illustrate the lithofacies of the back bar at the surface and downcore.

Onshore

1. Beach sands: This facies is very similar to the bar sediments, but the sands are generally coarser and more poorly sorted. Specifically, mean grain size is 2.687 phi (modal size = 2.0 phi) and the sediments are very poorly sorted (sd=2.065 phi). The sands are coarsely skewed, perhaps reflecting the 2% (visually estimated) heavy minerals. The sands are rounded to subrounded, 97% quartz, and mostly opaque. Shell fragments constitute the remaining one percent.

Like the beaches on the bar, the mainland beach sediments also have concentrations of heavy minerals in the swash zone. Within partially eroded storm berms, laminae of heavy minerals and organics are identifiable. This is also the same observation made for cored sediments. Within the "beach sand" facies (as revealed in core), laminae are abundant, and often contain significant concentrations of heavy minerals, organics and shell fragments. Bioturbation in the sediments is common, and burrows are frequently observed. The laminae are also distorted, parallel, rippled and crossed with no trend up or down section. Also, within the storm berms, small-scale cross bedding is apparent.

The "beach sand" facies shows varying thickness in core, depending on the particular sample site. Those cores nearest the headland (i.e. core BD 8/92-01,2) have sand bed thicknesses of 10-25 centimeters, and the lithofacies occurs as actual bedsets of "beach sand" facies interbedded with "back bar mud" facies. Contacts are fairly sharp between beds, and there is reverse grading in the "beach sand" facies, including loss of mud upcore. In other parts
Figure 48: Back Bar Mud. Immediately landward of the emergent bar, a lagoon is infilling with this facies. The back bar mud contains less than 20% sand. A thin veneer of the bar sand facies overlies the back bar mud.
of the shoreline, the "beach sand" facies is thicker--nearly 80 centimeters (core BDB 05). These thicker beds show only minor amounts of grading. Instead, there is a sharp contact between underlying muddy sediments and overlying clean, "beach sands".

Very few cores were actually taken from the beach, but those that show the "beach sand" facies are cores BDB 05, BD 8/92-01, BD8/92-02, BD 8/92-04 (close to river mouth) and BDBB 01. Figure 49 is a photograph of the upper section of core BD 8/92-02.

(2.) Beach Ridge Sand: The beach ridge sand has highly variable textural properties, depending on the specific sample locality relative to the ridge crest. Those sediments directly on the crest have been significantly altered by eolian and washover processes since original deposition, such that the sands are very clean and fine-to-medium grained. The intertidal sediments, on the margins of the ridge, are sandy, but have approximately 10% mud by mass. These sands have dominant grain size mode (mean is skewed due to sand-sized shell fragments) of 2.75-3.0 phi and are poorly sorted (sd=1.75 phi). They are also coarse skewed (sk=-.803 phi). Kurtosis values (6.808 phi) indicate that the coarse fractions are less well sorted than the modal size grains. The "beach ridge sands" are heavily bioturbated, including root casts.

The "beach ridge sand" facies has thicknesses similar to the "bar sand" facies. In some cases, however, cores penetrate a number of "beach ridge sand" facies units with interbedded fine-grained deposits of the "interridge clay" facies (to be discussed). When these facies are amalgamated, the bedset thickness exceeds 4.5 meters (in core BDBR 04). When the "beach ridge sand" facies occurs as a single sand body, its average thickness is 1.5 to 2 meters (in cores BDBR 01, BDBR 02, and BDBR 03). Underlying contacts with "interridge mud facies" are almost always sharp, except nearest the margins of the sand
Figure 49: Beach Sand. The delta beaches are composed of this facies. The beach sand contains less than 5% mud and is composed of 95% quartz, 2% shell fragments and 3% heavy minerals.
body where some coarsening upward units are observed. The lateral extent of the facies is less than 0.5 kilometers across the crest, and greater than 2 kilometers along the crest.

The "beach ridge sand" facies was sampled in the BDBR core series. Figure 50 is a photograph of the upper section of core BDBR 01.

(3.) Interridge Mud: This facies is similar to the "back bar mud" facies, except that bioturbation is much more profuse. Marsh vegetation is present in the interridges and not the back bar. The sediments of the interridges are predominantly clay, with abundant laminae and very thin beds of sand. Large sand-filled burrows cross cut interbed boundaries, often making boundaries less distinct. Oyster colonies are widespread in the interridges, thus distinguishing them from the laterally adjacent and/or overlying "beach ridge sand". Color of the "interridge mud" is typically dark to yellowish brown (5YR2/2 or 10YR 2/2).

Thickness of the "interridge mud" facies is variable from 25 cm between stacked "beach ridge sands" to nearly 200 centimeters where adjacent beach ridges are "isolated." On the margins of the interridge areas, interbeds of "beach ridge sand" are common and are interpreted as overwash deposits.

Core BDM 01 illustrates the typical "interridge mud" facies. Figure 51 is a photograph of this core.

An additional facies was sampled in the base of core BDC 94-1. The intent of collecting the BDC core series was to sample the channel facies. We tracked the channel from the mouth, and core BDC 94-1 was was taken on the margin of this channel. The facies that is believed to be representative of the channel facies is discussed below:
Figure 50: Beach Ridge Sand. This facies occurs within the delta plain and is the onshore equivalent of the bar sand. The beach ridge facies is composed of 90% sand and 10% mud, and the sediments are poorly sorted. The sand is approximately 95% quartz, 2% heavy minerals, and 3% shell fragments.
Figure 51: Interridge Mud. The interridge areas contain surficial sediments of tidal origin which are underlain by thick beds of slightly sandy, very clayey mud. The base of the unit consists of the highly laminated muddy sand facies. By composition, the interridge mud is 10% sand.
**Clayey Sand:** These sediments are 65% sand and 35% clay. The sediments contain 15% water by mass. The sands are visually estimated to be 80% quartz, 10% heavies, and 10% mica. The grains are rounded to subrounded and slightly opaque to reddish yellow. The overall color of the sediments is dark reddish brown (5YR2/4).

The thickness of this facies is unknown because cores did not penetrate through the complete section. The facies lacks any internal structure. "Back bar mud" facies sharply overlies this unit.

Core BDC 94-1 (Figure 52) is the only core that sampled this facies.

Table 2 summarizes the lithofacies and postulates a depositional environment for each lithology. Figure 53 is a surficial facies map summarizing all of the facies discussed above. Bathymetry is superimposed on the map in order to illustrate the bathymetric zonations of lithofacies. In the discussion section of this study, this lithofacies map is redrawn so as to interpret these lithofacies into depositional environments.

**Stratigraphy**

The stratigraphic signature of the Brazos delta and surrounding coastal environments is defined in the context of cored lithostratigraphic variations. Because the delta has not had adequate time to generate complete vertical depositional sequences, facies variation in core segments is generally limited to two or three facies. In order to assess actual lithofacies variation downcore and along depositional dip, core logs are grouped into transects perpendicular to mainland shores as shown in Figures 54 and 55.
Figure 52: Clayey Sand. This facies was observed while attempting to core the channel sediments immediately offshore of the modern river mouth. It is composed of 65% sand with a stiff clay matrix. The sand is 80% quartz, 10% heavy minerals, and 10% mica.
<table>
<thead>
<tr>
<th>Lithofacies of the Brazos Delta</th>
<th>Occurrence*</th>
<th>Sand %</th>
<th>Mineralogy**</th>
<th>Sorting</th>
<th>Grains Size Mode***</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muddy Sand</td>
<td>3 to 6</td>
<td>60-00</td>
<td>85:10:5:5</td>
<td>wall</td>
<td>3.0:3.25</td>
<td>Upper Shoalface (west–interfluvial)</td>
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<tr>
<td>Intercalated/Interfingled Muddy Sand and Sandy Mud</td>
<td>6.5 to 9</td>
<td>highly variable</td>
<td>85:55:5:5</td>
<td>moderate</td>
<td>3.0:3.5</td>
<td>Lower Shoalface</td>
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<tr>
<td>Clean Shelly Sand</td>
<td>throughout</td>
<td>95</td>
<td>95:0:0:2:3</td>
<td>wall</td>
<td>3.0:3.5</td>
<td>Storm Deposits</td>
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<tr>
<td>Olive Gray Clay</td>
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<tr>
<td>Reddish Brown Clay</td>
<td>delta lobe &gt; 6</td>
<td>0-10</td>
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<td>na</td>
<td>na</td>
<td>Pudula</td>
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<td>Thicky Bedded Red and Gray Clay</td>
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<td>1 to 8</td>
<td>00</td>
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<td>3.0:3.5</td>
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<td>Distal Very Fine Sand</td>
<td>15 to 18</td>
<td>05</td>
<td>90:10:5:5</td>
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<td>3.5:4.0</td>
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<td>2.75:3.5</td>
<td>Mouth Bar</td>
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<tr>
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<td>2 to 4</td>
<td>55</td>
<td>90:5:5:0</td>
<td>moderate</td>
<td>2.6:3.0</td>
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<td>&lt; 20</td>
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<td>poor</td>
<td>2.25:3.5</td>
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<tr>
<td>Beach Sand</td>
<td>delta beach</td>
<td>95</td>
<td>95:2:5:0</td>
<td>very poor</td>
<td>2.0:2.679</td>
<td>Delta Beach</td>
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<td>Beach Ridge Sand</td>
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<td>90</td>
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<td>2.70:3.0</td>
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<td>na</td>
<td>na</td>
<td>Inсадige Trough</td>
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<tr>
<td>Clayey Sand</td>
<td>channel axis</td>
<td>65</td>
<td>80:10:10:0</td>
<td>poor</td>
<td>2.6:3.0</td>
<td>Distribute Channel Mouth</td>
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</table>

* Water depth (meters)
** % Clr:% Heavy:% Mica:
  %Mud/fines:% Shell
***Mode (phi) of sands
The sediment core transects are shown in Figures 56 A through M, the following observations are made:

**West of the River Mouth**

- The "muddy sand" facies is primarily transitional offshore into the "interbedded/interlaminated muddy sand and sandy mud" (IB/IL) facies as seen in Transect A. In some cases, the "muddy sands" sharply overlie stiff clays of the Pleistocene Beaumont Formation (Transects A and C).
- The "muddy sand" facies becomes muddier from west to east towards the river mouth (compare from Transects A-E). Simultaneously, the "IB/IL" facies thickens (in core section) from west to east towards the mouth (compare Transects A-D).
- The "IB/IL" facies is transitional downcore and offshore into one of three facies, depending primarily on proximity to the river mouth. Farthest west of the mouth (in Transect A), this facies is transitional into the "thinly bedded red and gray clay" facies. On the margins of the delta lobe in the west (Transects D and E), the "IB/IL" facies is transitional to the "reddish brown clay" facies. Finally, in some cases, the "IB/IL" facies is sharply underlain by the stiff clays of the Pleistocene Beaumont Formation (Transect C).
- The "reddish brown clay" facies is transitional offshore and downcore to "thinly bedded red and gray clay." (Transect B).
- The "thinly bedded red and gray clay" facies is transitional offshore and downcore to the "olive gray clay" facies (Transects F, G, H, I) with exception in Transect D.
- In Transect D, the "reddish brown clay" facies is interbedded with "thinly bedded red and gray clay" in the vertical and horizontal planes.

**Offshore of the River Mouth**

- The "muddy sand" facies to the west is no longer apparent and is replaced by coarsening upward, multiple beds of "highly laminated muddy sand" facies (Transects F, G).
- "Highly laminated muddy sands" are interbedded downcore and offshore with "reddish brown clay" facies. And, the reddish brown
Legend for Sediment Core Logs

- Red Clay
- Silt
- Fine Sand
- Marine Sands
- Silty Clay
- Sandy Silt
- Medium Sand
- Olive Gray Clay
- Sandy Clay
- Clayey Silt
- Muddy Sand
- Marine Muddy Sand
- Mud and Sand Interbeds
- Clayey Sand
- Transitional Muddy Sand
- Fine Sand and Clay Laminae
- Pleistocene Clay
- Convoluted Bedding
- Organics
- Bioturbation
- Shells
- Cross Laminations
- Missing Section
- Burrows
- Organic Laminae

Sharp contacts are indicated by straight lines.
Irregular lines at contacts indicate erosion.
The core logs indicate changes in overall lithology by width of individual strip.
Figure 56 A: Transect A. See Figure 55 for core locations.
Figure 56 B: Transect B. See Figure 55 for core locations.
Figure 56 C: Transect C. See Figure 55 for core locations.
Figure 56 D: Transect D. See Figure 55 for core locations.
Figure 56 E: Transect E. See Figure 55 for core locations.
Figure 56 F: Transect F. See Figure 55 for core locations.
Figure 56 G: Transect G. See Figure 55 for core locations.
Figure 56 H: Transect H. See Figure 55 for core locations.
Figure 56 I: Transect I. See Figure 55 for core locations.
Figure 56 J: Transect J. See Figure 55 for core locations.
Figure 56 K: Transect K. See Figure 54 for core locations.
Figure 56 L: Transect L. See Figure 54 for core locations.
Figure 56 M: Transect M. See Figure 54 for core locations.
clays" are transitional to "thinly bedded red and gray clay" (Transects F, G).

- The "reddish brown clay" facies thickens significantly downcore and offshore of the river mouth.
- Transect H is marginal to the delta lobe and thus shows close-to-shore transition to clay facies and more variable downcore stratigraphy nearshore.

East of the River Mouth

- The "olive gray clay" facies is transitional to "distal very fine sand" facies. Contacts between these two facies are sometimes sharp or erosional (Transect H).
- The "very fine clean sand" facies is transitional downcore and offshore into the "IB/IL" facies (Transect I, J).
- On the margins of the delta lobe, to the east, the "IB/IL" facies is interbedded with the "reddish brown clay" facies. The "reddish brown clay" facies is transitional offshore and downcore to the "thinly bedded red and gray clay" facies (Transect I).
- Farther to the east, in Transect J, the "IB/IL" facies is transitional downcore to the "reddish brown clay" facies. Offshore, the "IB/IL" facies is replaced by the "thinly bedded red and gray clay". In the distal sections of the transect, these are transitional to "reddish brown clays" which are sharply underlain by "distal very fine sand.
- In the transects sampling Old deltaic deposits, the distal sections show a thin sand bed covering "reddish brown clay" and "thinly bedded red and gray clay" facies. The contacts between these facies are erosional and contain abundant shell fragments.

Nearshore

- Nearest the mainland shore, "beach sand" beds multiply stack with thin interbeds of "back bar mud" facies. The "beach sand" bedsets sharply overlie a thicker section of "back bar mud" facies. The cores that penetrated through the "back bar mud facies" sampled the "highly laminated muddy sand facies" at their base. Downcore increase in sand is gradational, but overlying contacts with "back bar mud" are very sharp (Transects K and L).
• Mid back-bar regions are very muddy and are gradational downcore to "highly laminated muddy sand" facies (Transects K and L).
• "Back bar mud" facies are thinner towards their margins.
• Thicker sections of homogeneous clay are preserved between overlying "back bar mud" facies and underlying "highly laminated muddy sand" facies. Thickness of the clay is nearly 1 meter in core BDB 05 (of Transect L).
• The "bar sand" facies sharply overlies the "highly laminated" muddy sand facies (Transect K,L).
• Thickness and first occurrence downcore indicates thickening of the "highly laminated muddy sand" facies in the offshore direction (Transect L; specifically between core BD 8/92-04 and core BDB 16).

Onshore (Transect M)
• Cores from the edges of the beach ridges indicate "beach ridge sand" facies overlying "inter-ridge mud" facies. Bounding surfaces between the facies are erosional.
• "Beach ridge sand" facies are primarily isolated stratigraphic units (cores BDBR 1,2 in Transect M), but stack to form multiple units near the modern shoreline (core BDM in Transect M).
• Inter - ridge sediments are thinner near their margins.
• "Highly laminated muddy sand" facies sharply underlie thick homogenous clay beds of the "inter-ridge mud" facies. Muddiness of the basal facies decreases downcore.

In all of the transects, the "clean shelly sand" facies is observed with no apparent depositional trend. Its occurrence is widespread as thin individual beds within various lithofacies.

**Flood Analysis**

During late December 1991, numerous drainage basins across Texas experienced large increases in precipitation. Climatological reports confirmed that
numerous records of excess precipitation were set during December 1991 through February 1992. Moreover, these reports attest to the dramatic impact on all aspects of life in the drainage basin (Panel 2). The major watersheds experienced dramatic increases in fluvial discharge, and river dwellers saw waters rise to unsurpassed heights. Continued precipitation occurred throughout the three month period and was unusually widespread across the entire state. Monthly mean discharges at four long-term hydrologic index gaging stations during for 1992 (wy) are compared to median of the monthly mean discharges for 1951-1980 in Figure 57. There is a noticeable gap between average discharge (1941-1980) and discharge for the 1992 water year (October to October)--indicating greater than normal runoff due to increased precipitation.

Tables 3 and 4 are the daily discharge and historical records for the Brazos River at the Richmond gaging station. The following observations are made:

1.) On December 20, 1991, discharge increased by 2678 cubic feet per second, indicating the onset of flooding.

2.) Discharge was initially increasing from December 20 to January 2.

3.) Discharge was increasing for additional periods of seven more days between January 17 and January 24, February 4 and February 11, and February 21 and March 1.

4.) The maximum monthly mean data for January through March 1992 is greater than any previous years on record.

5.) 1992 had the highest annual mean discharge for the period of record (1941-1992).
Figure 57: Monthly mean discharge data for the Brazos River, 1941-1992. These figures are intended to demonstrate the relative severity of flooding in 1992.

Table 4
Historical Discharge Statistics

| Statistics of Monthly Mean Data for Water Years 1941 - 1992, By Water Year (WY) |
|-----------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| MEAN | 4959 | 5628 | 6921 | 7932 | 8943 | 9299 | 9183 | 15750 | 12330 | 5052 | 2524 | 3305 |
| MAX  | 28760 | 32360 | 52060 | 60500 | 54410 | 54050 | 41900 | 72200 | 58330 | 17100 | 9013 | 19850 |
| MIN  | 203 | 366 | 480 | 543 | 702 | 445 | 829 | 1100 | 786 | 717 | 550 | 414 |

Summary Statistics

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<th>For 1991 Calendar Year</th>
<th>For 1992 Water Year</th>
<th>Water Years 1941 - 1992</th>
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<td>9740138</td>
</tr>
<tr>
<td>ANNUAL MEAN</td>
<td>10970</td>
<td>26620</td>
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<tr>
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<td>LOWEST ANNUAL MEAN</td>
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<tr>
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<td>93400 Dec 31</td>
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<tr>
<td>LOWEST DAILY MEAN</td>
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<td>908 Oct 29</td>
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<td>ANNUAL SEVEN-DAY MINIMUM</td>
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<td>1130 Oct 23</td>
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<td>119000 May 5 1957</td>
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<td>INSTANTANEOUS PEAK STAGE</td>
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6.) Instantaneous peak stage records were set on January 1, 1992 when the Richmond gage recorded stage height at 49.68 feet (15.14 meters).

Flood frequency analysis (Table 5 and accompanying chart) identifies the recurrence interval for floods at particular discharge levels. The maximum daily discharge between December 20 and March 15 was 93,400 cubic feet per second. This has an exceedance probability of 0.10, based on historical records. Thus, for the Brazos River, the 1992 flood was a ten year flood. (Media reports during the flooding reported its annual exceedance near 0.01, but were, in retrospect, exaggerated.)

The annual exceedance probability is not, however, entirely accurate in terms of sediment transport. The overriding factor is the duration of increased flow magnitudes. High instantaneous discharge does not necessarily imply recognizable sedimentary effects. But over longer periods of time, high magnitude events are able to drastically affect the morphology. Put simply, the more time during which the river is above the critical threshold for sediment entrainment, the more pronounced the geomorphic expression will be. Figure 58 shows time versus discharge for numerous floods of similar magnitude that are inferred to have produced appreciable effects on the river and the delta. Note that most floods wane after 10 to 20 days. The 1957 flood is the only equally comparable event to the duration of the 1992 flood. And, this flood waned after 50 or so days, while the 1992 flood was continuing at high discharge levels for greater than 80 days. Thus, although the annual exceedance probability is not so atypical, the duration of increased discharge in the 1992 flood is rare. The issue of duration also addresses the relative impact of the flood on the environment when compared to other instantaneous discharge records. For example, Table 6 lists the ranking order of instantaneous discharge for the period of record at the Richmond Station.
### Table 5 (Chart)

<table>
<thead>
<tr>
<th>Station</th>
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<th>Brazos River at Richmond, TX</th>
<th>1903-1991</th>
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#### PLOT SYMBOL KEY
- WC final frequency curve
- Observed (systematic) peaks
- Systematically adjusted peaks
- Systematic record breaks curve
- When points coincide, only the topmost symbol shown.

#### ANNUAL PEAK FLOW FREQUENCY ANALYSIS
- Preliminary machine computation.
- User is responsible for assessment and interpretation.

#### Peak Flow Frequency Analysis
- Run-date: 3/22/93
- Geo: 1.0001
Table 6

- U.S. GEOLOGICAL SURVEY
- ANNUAL PEAK FLOOD FREQUENCY ANALYSIS
- FOLLOWING INC GUIDELINES BULL. 17-B

- PEAK FLOOD FREQUENCY ANALYSIS
- RUN-DATE 3/23/72 AT 17:24
- SEQ 1,0001

STATION - 08314400 / USGS ONE MILE RIVER AT NICHOLSON, TX 1903-1991

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<td>1958</td>
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</tbody>
</table>

--- CONTINUED ---
Time/Discharge for Most Significant Floods of this Century

Figure 58: Time versus discharge for the Brazos River at the Richmond gaging station. Note that the curve depicting 1992 is above the flood stage for greater than 80 days in 1992.
Although the 1992 flood ranks 6th, the preceding floods waned fairly quickly, and did not occur along the entire drainage basin. Thus, more depositional significance is granted to the 1992 flood. The main point, therefore, is that caution is warranted when instantaneous discharge is used as a gage of significance for geologic impact. Duration coupled with magnitude is much more useful.

Suspended Sediments

Table 7 shows the concentrations of coarse silt (>0.36 microns) and sands (>62.5 microns) in the upper meter of the water column during the initial days of the 1991-1992 flood. Visual observation of sediment remaining on the sieves during collection corroborates the lab analysis. Little, if any, sediment greater in size than coarse silt was being transported in suspension. Furthermore, this data also corresponds to information from the gauging station at Richmond, Texas confirming 80-90 percent of the suspended sediment is finer than 0.063 mm (fine sand). Thus, most of the sediment being delivered to the delta was fine-grained.

Oceanographic Observations

Water column characteristics from immediately offshore of the river mouth during the flood were defined January 3, 1992 (exactly two weeks after the onset of flooding, and three days after peak discharge) with salinity, transmissivity and temperature readings. Figures 59 and 60 illustrate the corresponding water column cross-sections with bottom topography. The water-column cross sections are along depositional strike and reveal the influence of turbid river waters on the Gulf waters. The cross section between B-10 and B-17 indicates a suppression of isotherms directly in front of the river mouth and deepening to the west of the colder river waters. In fact, to the west, the river water is situated between overlying
### Table 7
Water Column Sediment Content
January 1992
Brazos Delta, Freeport, Texas

<table>
<thead>
<tr>
<th>Sample Identification</th>
<th>Relative Water Depth</th>
<th>Sand &amp; Silt Concentration</th>
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</thead>
<tbody>
<tr>
<td>B-6</td>
<td>Surface</td>
<td>0.08</td>
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<tr>
<td>B-4a</td>
<td>Bottom</td>
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<tr>
<td>B-9</td>
<td>Surface</td>
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<tr>
<td>B-13</td>
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<tr>
<td>B-14</td>
<td>Surface</td>
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<td>Bottom</td>
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<tr>
<td>B-29</td>
<td>Surface</td>
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<tr>
<td>B-4</td>
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<tr>
<td>B-15</td>
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<tr>
<td>B-7</td>
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<td>B-5</td>
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<td>Surface</td>
<td>3.7</td>
</tr>
<tr>
<td>B-15</td>
<td>Surface</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Figure 59: Water column profile on strike section. Transect B-17 to B-10 is from water depths of 6 to 8.5 meters.
Figure 60: Water column profiles on strike. Transect B-8 thru B-1 is taken from water depths of 7.6 to 10.5 meters. The data was collected on January 2, 1992, during the flood.
and underlying warmer water masses—an expression of homopycnal equilibration. There is also a distinct turbidity boundary near station B-14, that roughly corresponds to a facies boundary as defined in sediment cores.

The most pronounced stratification of river and Gulf waters is seen in the salinity profile. A 'valley' of fresh river water is obvious near B-13, directly offshore of the river mouth. Moreover, isohaline contours between B-13 and B-17 point to a surficial plume of fresher river water, i.e. hypopycnal jet flow. The intrusive wedge beneath buoy the overlying less dense waters and isolates outflowing river waters to a thin surface plume. Vertical mixing should not occur between these two masses according to Bates (1953), as "evidenced by isohalines remaining parallel to the surface to even rising along centerline profile."

The water column cross-section farther offshore depicts similarly distinct boundaries between river and Gulf water. The jet flow in this zone is, however, more dispersed, with less local concentration of cool river water longitudinally in front of the river mouth. Bottom water stratification is evident as the slightly warmer Gulf waters remain unmixed with overlying, less dense fluvial masses. Also, distinct plumes of turbidity differences are recognized. There is a surface layer of highly turbid waters, with less than 30% transmissivity. Transmissivity gradually increases westward, until there is a sharp increase near B-7. At this location, steeply dipping contour lines define the boundary between sediment-laden fluvial water and less turbid Gulf water.

Surface Sediments

Figure 61 shows the locations of gravity cores collected two weeks after the onset of flooding (January 2, 1992) in order to assess surficial sediment distribution. The sediments deposited during the flood were dominantly fine silt
and clay. The deposits were highly fluidized and distinctively red in color (10YR4/6 to 10YR4/2 to 5YR3/4). Figure 62 represents the typical flood deposit throughout the delta. Flood sediments sharply overlie the preexistent open marine, delta front and prodelta facies. Contacts are sharp. Within the bar and back-bar area, some contacts are erosional. Also, flood related sediments closer to shore are more silty, and sediments on the bar are sandy.

This series of gravity core samples was also analyzed for sand percentages by mass. Seven months later (July 1992), a second series of cores was collected at the same locations. Sand percentages for the flood and post flood deposit are compared in Table 8. No distinct pattern is recognizable. There is no difference in pre- and post-flood sand percentages.

Isopach maps constructed from the gravity core data reveal significant flood deposit accumulation, surpassing 50 centimeters in some locations. The isopach map shown in Figure 63 was constructed from cores taken in the initial stages of flooding (January 1992). Thicknesses for the deposit (in every locality where flood sediments were encountered) ranged from 10 centimeters to 50 centimeters. The gross accumulation rates were 0.71 to 3.57 centimeters per day. This assumes that sediments are immediately deposited and preserved, with no reworking while the river is still at flood stage. After seven months, a second series of gravity cores indicates a new character for the flood deposit (as seen in the isopach of Figure 64). Updated accumulation rates (spread over the 82 days that the river was flooded and inferring minimal post flood accumulation, as indicated by overlying open marine sediment laminations in the tops of cores) were 0.12 to 0.67 centimeters per day. The average preserved thickness for the 1992 flood deposit is 20-25 centimeters based on cores collected in July 1992 after the flood.
PLEASE NOTE

Page(s) not included with original material and unavailable from author or university.
Filmed as received.
Figure 62: Typical water-saturated clay of a Brazos River flood deposit.
### Table 8
Surface Sediment Characteristics
January and July, 1992
Brazos Delta, Freeport, Texas

<table>
<thead>
<tr>
<th>Sample</th>
<th>Percent Water</th>
<th>Percent Sand</th>
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<tr>
<td>B-3</td>
<td>10.5</td>
<td>9.3</td>
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<td>B-5</td>
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<table>
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<th>Sample</th>
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<th>Percent Sand</th>
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<td>BDP 59</td>
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</tbody>
</table>

Refer to Figure 61 for sample location.
The percentages are calculated by total mass.
PLEASE NOTE

Page(s) not included with original material
and unavailable from author or university.
Filmed as received.
Isopach of Flood Deposits
(January, 1992)

Figure 63.
Isopach of Flood Deposits (July, 1992)

Figure 64.
Comparison of Figures 63 and 64 reveals that significant change in the size, shape and thickness of the flood deposits occurred between January and July 1992, including removal of appreciable volumes of sediment in the area. Removal of sediment must have taken place because total thicknesses from January to July 1992 are almost equal; yet we know the river was discharging significant volumes of sediment during this time according to river gage data. The most notable change is reworking onshore and alongshore that is attributed to waves and wind-driven currents (prevailing winds from the southeast).

Total volumes for the flood deposit were roughly calculated, assuming an average thickness across the entire area of the delta of 0.25 meters. This average thickness was chosen not only because it is the average occurring thickness for the contemporary flood deposit, but also because it is representative of sediment thicknesses for other catastrophic floods of this century as recorded in the cores. That is, similar lithologies are noted in several cores, and are inferred to represent previous flood events. Table 9 lists the estimated volume of flood sediments. Also shown on this table is the adjusted volume when water percentages are accounted. As will be seen, these numbers are only applicable to the fine-grained sediments in waters greater than 2.5 meters. Significant accumulation has occurred nearshore, which is also linked to the 1992 flood.

Bar, Back Bar, and Delta Beaches

During and immediately after the flood, field observations indicated that the regions closest to shore had experienced a net addition of sand to the system, but no indications foretold the emergence of a sandy mouth bar. Almost one year after the flood began, aerial photography shows the emergence of an offshore mouth bar, approximately 1.85 kilometers offshore. In this same locality five years before,
<table>
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<th>Date</th>
<th>Total Volume</th>
<th>Total Volume - 35% Water Content</th>
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<tr>
<td>July 1992</td>
<td>9,450,000</td>
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</table>

All values expressed in cubic meters.
the R/V Matagorda collected shallow water seismic profiles in water depths of 2 to 3 meters. Moreover, three months prior to emergence, the bar zone was situated at 1 to 1.5 meters water depth.

Initially, the bar was segmented into several spits emanating from the eastern end of the primary bar and fanning to the west (Figure 65). These bars amalgamated through time into one large bar (Figure 66). Gradually, the bar has migrated onshore and alongshore, in an overall northwesterly direction. Latest reconnaissance indicates that the bar is within 20 meters of the shore at the western end (Figure 67). Whether the bar will completely weld to the shoreline is unknown. There is a tidal channel separating the bar from the shore that is the main conduit for the tidal exchange in the back bar, inland lagoons and marshes.

The local bathymetry changed greatly between pre-emergence and post-emergence (Figure 68). When the bar area was a broad shoal, it was covered by 0.5-1 meters of water and had a steep slope on its seaward margin. Post emergence, the entire area assumed a new profile, with typical shoreface topography offshore of the bar, and a steep slope on the back bar margin.

The bar has complex and numerous (secondary) sedimentological structures. Figures 69, 70 and 71 illustrate sand waves and other features on the bar. Moreover, the bar is undergoing dynamic change daily as winds, waves and tides constantly reshape its topography and morphology.

Bar emergence created a second distinct depositional environment classified as the "back bar". Immediately landward of the bar, a lagoon is encapsulated and protected from the open Gulf. Because wave approach is generally from the southeast, sediment-laden river waters are deflected into this lagoon (with only a minor outlet at the west end), thus rapidly infilling the lagoon.
Figure 65: This photo was taken during the initial emergence of the bar in January 1993. The photo is taken from approximately 1500 meters and is looking to the southwest. The bar was segmented into several smaller bars, and was often breached by incoming waves. Note also the large sand waves on the surface.
Figure 66: This aerial photograph taken from approximately 300 meters illustrates the complex morphology of the offshore bar. The Gulf is to the top of the photo. Note the protection from waves offered to the back bar lagoon by the bar.
Figure 67: These aerial photographs taken from approximately 150 meters (top) and 1500 meters (bottom) illustrate the potential location of welding between the shore and the bar.
Figure 68: Pre- and post-emergence bathymetry.
Figure 69: Aerial Photograph of the Emergent Bar. This photo is taken from approximately 150 meters and illustrates the morphologic character of the offshore emergent bar. Note the numerous bars that compose the bar. Longshore drift is from right to left as shown above, and the Gulf is to the top of the photo.
Figure 70: Aerial Photograph of the Emergent Bar. This photo is taken from approximately 150 meters and illustrates the morphologic character of the offshore emergent bar. The stratigraphic signature resulting from the numerous small bars that make up the overall bar is one of interbedded sand and muddy sand. The sand represents the bars and the muddy sand is reflective of the troughs. The Gulf is to the top of the photo.
Figure 71: Oblique view of the Offshore Emergent Bar. This photo is taken from approximately 150 meters looking southwest. The photo indicates sand waves on the bar. These features were present when the bar was still exposed to tidal submergence.
with fine-grained sediments. In the summer of 1992, the back bar was sufficiently deep (1.5 to 2.5 meters) to allow coring operations from boats. By February 1993, the back bar shallowed to 0.5 to 1 meter water depth. The sediments in this environment are silty clays with washover and eolian sands nearest the shorelines.

Flood-associated deposition also occurred on the main shores of the delta, both east and west. Significant accumulation has occurred on a headland of the west flank. Spit accretion around this headland has accelerated progradation of the shore locally (Figure 72). On the east flank, upper shoreface bars have recently become emergent and significant progradation of the eastern shore has occurred (Figure 73). Prior to the flood, the beach on the eastern shore was approximately 25 meters wide. By February 1993, the beach had widened to nearly 100 meters.

During the flood, a tremendous amount of debris was brought to the delta. The river was nearly non-navigable due to the abundance of floating trees. This debris was piled on the shorelines, and defines boundaries of flood related accumulation. Each major flood results in a new debris zone on the shore, and successive floods can be identified accordingly.

Previous Floods

Brazos delta evolution (Panel 1) correlates precisely with large and extended-period discharge events of the past century (Figure 58). Projecting headlands and offshore bars appeared soon after major floods occurred. Between floods, the Brazos coastline was reshaped, and sediments were redistributed alongshore (to the SW).
Figure 72: Eastern edge of the Brazos River mouth (direct aerial photo from 150 meters) which depicts several offshore bars. These bars have subsequently emerged, and the beach has prograded approximately 0.5 kilometers seaward.
Figure 73: Oblique view photographs looking southwest from approximately 150 to 250 meters altitude. These photos depict the headland on the west flank of the New delta. This location also experienced rapid sedimentation during and after the flood.
DISCUSSION

The following discussion completes the model for the Brazos delta by summarizing the architectural framework of the delta and defining the most significant mechanisms for geomorphic development. The framework develops from a summary of the depositional environments and corresponding lithofacies. Using the primary facies, a three dimensional image of the delta is constructed. The fundamental geomorphic agent is then discussed and succinctly related to the overall facies architecture. In the end, a generalized stratigraphic sequence, within the context of postulated depositional mechanisms, emerges. Throughout the discussion, several questions are addressed pertaining to the utility of the Brazos delta as an analog for ancient systems.

Depositional Environments and Lithofacies

Offshore Environments and Facies

Eight depositional environments and lithologies are identified from modern lithofacies distribution; all of these environments are inferred to have existed during the life of the delta. Figure 74 illustrates the distribution of the offshore depositional environments in the Brazos delta and surrounding areas.

Prodelta

The prodelta of the Brazos delta (Old and New) occurs at -6 to -15 meters water depth, thus placing portions of it below the base of wave erosion situated at between -8 and -10 meters water depth according to Siringan (1993). The offshore extent of the prodelta is variable, but generally occurs between 1.2 km to 7 km
Figure 74: Depositional Environments of the New Brazos Delta.
offshore. The New prodelta generally begins at the base of the closely spaced bathymetric contours near cores sites BDP 6, 19 and 15.

The prodelta is composed of the "reddish brown clay" facies. Recall that these sediments are clay-dominated, with less than 10% sand by mass. Fine-grained organic detritus is abundant throughout the clayey sediments. The organics are most often scattered rather than concentrated in laminations. Bioturbation is noticeably absent in the prodelta clay, and shells are isolated within interbedded storm sands. In the proximal prodelta, sediments are transitional to delta front deposits. In the distal prodelta, sediments are transitional with marine muds, and the "thinly bedded red and gray clay" facies is most typical of the transition zone. This facies illustrates the episodic nature of sedimentation in the area. With each pulse of sediment into the delta, a new layer of the reddish brown clay is deposited. When the fluvial discharge decreases, a layer of marine-looking, olive gray clay is deposited.

Comparison of bathymetric maps that pre- and post-date deltaic input to the area, and sediment cores that penetrated the prodelta, show that approximately five to six meters of prodelta sediment have accumulated since 1929. In all, the prodelta comprises 50-60% of the depositional volume of the delta.

Marine

Marine facies are distinguished from deltaic facies by several characteristics: proportion of organic material, bioturbation, textural maturity (i.e. sorting, roundness), color and mineralogy. Three primary marine facies were observed in this study and are discussed below.

Distal Offshore
Offshore clay deposits are restricted to depths greater than 7.5 meters, and are first seen at the toe of the lower shoreface, approximately 4.5 kilometers offshore. Most of the distal offshore sediments are below wave-base. Sedimentation rates are relatively minimal compared to the adjacent prodelta environment. This is evident in the amount of sediment overlying the Holocene/Pleistocene boundary.

The modern facies of the distal offshore is the "olive gray clay" facies. On the margins of the delta plume, marine clays appear dark yellowish brown (10YR4/2) due to increased Brazos deltaic influence. Increased bioturbation and lack of organics is distinct in the marine "olive gray clay" facies. Also, fully articulated bivalves are often found in the offshore sandy clay deposits.

Coastal and Nearshore

The intent of the following sections is to differentiate interdeltaic sediments from deltaic sediments in the area, and to illustrate the typical character of Gulf Coast nearshore sediments. Based on examination of cores acquired west of the delta, near Cedar Lakes (Figure 1), and offshore of Galveston Island (Siringan and Anderson, in press), the coastal and shallow marine environments of the interdeltaic regions between the Brazos and Colorado Rivers (to the west) and the Brazos and Trinity (to the east) are primarily sandy shorelines and muddy shorefaces. They are composed of muddy sands that are sourced from the adjacent rivers. Sediment supply is highly variable along the coast, but most interdeltaic regions are currently experiencing rapid erosion (Morton, 1980).

The coastal sands observed in core are subdivided into three individual lithologies: (1) shoreface sand, (2) storm sands and (3) offshore muddy sands. All sands of marine facies are texturally mature, and average greater than 95% quartz.
Shoreface sands are gradational from clean sands (<10% mud) ("beach sand" facies or "very fine, clean sand" facies) nearest the shoreline to "muddy sand" facies in the upper shoreface, and to "interbedded /interlaminated muddy sand and sandy mud" facies of the lower shoreface. The muddiness of the upper shoreface is controlled by proximity to river mouths. Sediments tend to be much more muddy on the downcurrent (alongshore) side of the river mouth. Interbeds within the shoreface diminish and sand content decreases offshore.

Sedimentological structures also decrease offshore. Generally, shoreface sands are texturally mature, with rounded to subrounded and well sorted grains. Grain size is typical of Texas shorelines, very fine (3.3 phi) (Anderson, et al. 1986). Bioturbation, infilled burrows and abundant shells are evident. We observe these characteristics in cores west of the river mouth beyond significant influence of delta sediments.

Storm sands ("clean shelly sand " facies) are interbedded with all of the facies identified thus far. Bounding surfaces are highly erosional, and the sands are typically graded (normal and reverse). Recall that grain sizes of the storm sands are highly variable with some sediments within the coarse silt fractions.

These sediments are generally thought to be derived from the shoreface by downwelling (seaward directed) currents of major tropical storms (Siringan and Anderson, in press). Thus, the sediments resemble the shoreface sands.

Offshore muddy sands are described as the "distal very fine sand" facies. They possess a mixture of properties: variable muddiness, high bioturbation, and variegated color. These sands are common throughout the Gulf Coast.

Pleistocene Beaumont Formation
In several cores, a very stiff and variegated clay was penetrated. This clay has been identified from several other studies (Nelson and Bray, 1969) as the Late Pleistocene Beaumont Clay. This formation is irregular on its upper surface due to channel scour and fluvial incision. This irregularity is indicated by differing initial penetration depths in core.

Nearshore Environments and Facies (Deltaic)

Delta Front

The delta front (as defined here) is the area between the mouth bar and the prodelta. It occurs within -3 to -6 meters water depth and is in the zone of wave erosion. The bathymetry of the delta front is highly variable; a change in slope separates the delta front from the prodelta environments.

The delta front is composed of the "highly laminated, muddy sand" facies. Laminations in the upper sections of this facies are frequently convoluted due to either rapid deposition or sediment mass movement (steep depositional slope). Lower in the core sections, laminations are parallel. Silty clays, sandy clays and clayey sands and silts are the dominant sediment types. Thick beds of homogenous clay are common and are interpreted as flood deposits. Bioturbation is absent in this environment. Interbedded storm deposits are easily recognized, and organics are scattered throughout. Laminations often contain high abundance of organic matter.

Bar Front

The bar front is located immediately offshore of the bar. It extends to approximately 3 to 5 meters water depth and approximately 0.9 km offshore of the bar.
Sediments of the bar front are less muddy than delta front sediments, and are rippled or cross laminated. Laminae contain abundant organics and heavy minerals. The heavy minerals and the organics give the appearance of "salt and pepper" laminations. Laminated sections are typically overlain, and in sharp contact with pebble lags. Colors are variable, but general appearance is light brown (5YR6/4). The most representative example of this facies is in the base of core BDB 15.

Bar Crest

The emergent bar is a highly dynamic feature. The emergence of the bar occurred .9 to 1.2 km from the mainland. It is arcuate and is accreting to the west. It is composed of numerous amalgamated bars, especially towards the western end where new spits accrete rapidly. Relief on the bar is nearly 1 meter on the landward facing beach.

Sediments are cleaned by wave and tidal processes, thus making them very sandy. The "bar sand" facies comprises most of the bar sediments. The sand size for the bar is 2.5 to 3.0 phi, with negative skewness values due to shell fragments and heavy minerals. Heavy mineral concentrations are high (15%) in the swash zone. The sands are moderately sorted and contain 5% mica. Thickness of the bar ranges from 1 meter on the west end to 3 meters in the east.

Back Bar

The back bar is divided into two subenvironments—the back bar immediately adjacent to the bar crest and the lagoon. Total width of this zone is gradually diminishing as the bar moves landward. Water depths in the lagoon are 0.5 to 1.5 meters and increase towards the river channel.
Back bar sediments immediately adjacent to the bar are strongly influenced by washover, tidal and eolian processes. Fine-grained muddy sediments are dominant, but interbedded bar sands are common. The sands are often ripple cross-laminated and show isolated ripples. Direct observation reveals that the uppermost layers of sediment are composed of interbeds of rippled sands and sandy/silty clays.

The central lagoon is the site of rapid accumulation of fine-grained, very wet, and very muddy sediments, i.e. "back bar mud" facies. Fluvial sediments are diverted by wave approach into the lagoon and appear to be infilling the lagoon faster than the bar can retreat landward. These sediments show interbeds of clay, clayey sands, muddy sands, sandy silts and silty sands, as discussed for the base of the "back bar mud" facies. The stratigraphy preserves individual flood events as distinct beds, such as homogenous clay beds interbedded with sandy mud. Bioturbation in the back bar is absent, except for minor occurrences in the uppermost layer of the sediment column.

Beach

The mainland beach is very diverse sedimentologically and geomorphologically. The beach contains swash lags, ripples, beach cusps, clay balls, exposed marsh deposits, storm and winter berms, berm erosion scarps, logs, washover channels, and scattered debris of human origin. On a larger scale, the beach is part of the accreting headland on the west flank. And, to the west, the beach includes a series of accreting spits, and tidally exposed bars.

The sediments of this environment are composed of the "beach sand" facies, and are reflective of their proximity to a river mouth, with concentrated micas and heavy minerals in the swash zone. Also, organic debris is present in beach
deposits. Mineral segregation is very distinct in laminae exposed in the wave-cut scarps. Overall, sands are similar to bar crest sands, but slightly less mature texturally.

On the west end, near the site of bar welding, the beach is eroded and underlying marsh deposits are exposed, including clay balls, oyster shells, and marsh grasses (Figure 75). These exposures indicate former shorelines farther seaward, such that lagoon and marsh environments were existent where the beach exists today. Such a scenario was possible during previous offshore bar emergence and lagoon/marsh enclosure.

The beach is currently prograding seaward and facilitating the enclosure of the back bar lagoon. Beach progradation results in coarsening upward units of sand with interbedded back bar mud, as seen in core.

Beach Ridges

Beach ridges are oriented parallel and oblique to the coast within a zone from the modern beach to the pre 1929 coastline. Individually, the beach ridges are fragmented by numerous tidal channels within the marsh. The beach ridges are vegetated, and their crests are above high tides. The sediments are surficially affected by eolian processes, and local morphology shows dune development on some crests.
Figure 75: Exposed marsh deposits within the beach of the west flank of the New Brazos delta.
Beach ridge sediments are very sandy and more mature (texturally and mineralogically) than modern beach materials, as a result of secondary alteration. The beach ridge sediments are represented by the "beach ridge sand" facies. Recall that these sands are fine to medium grained and are poorly sorted. There are also numerous washover fans; deposits of recent storms. Stratigraphically, the beach ridges are unique, for they show how the individual bars become emergent. Sediments are gradational (bottom to top) from pre-emergent shoaling muddy sands with abundant laminations, cross laminations, and ripple laminations, to homogenous, post-emergent fine to medium - grained, clean sands. Core BDBR 01 reflects this sequence from shoaling deposits at the base to emergent sediments in the upper section. Another significant finding is that the beach ridge lithofacies are not amalgamated into larger bedsets. In core BDBR 03, clean sands of the beach ridge sharply overlie clay - rich sediments of the back bar, which are transitionally underlain by "highly laminated muddy sands" of the postulated\(^4\) pre-emergent shoal (or shoreface). Bar sands are not amalgamated one on another, and lagoonal facies are preserved in the stratigraphic record. This has implications for the interplay of waves and fluvial sediment discharge. Whereas, other authors (Psuty, 1970; Coleman and Wright, 1980) contend that wave-dominated systems are composed of flanking strandplains, thereby inferring (by definition) that beach ridges are amalgamated, the Brazos does not follow this model, but is composed of bars (barriers, strictly speaking) separated by shallow

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\(^4\) The postulated origin for these highly laminated, and rippled muddy sands was confirmed during this study with the shoaling and final emergence of the mouth bar. We directly observed the depositional processes in core stratigraphy, and thus are able to compare recent shoal deposits with older sediments, such as in BDBR 03. Also, we penetrated the emergent bar sequence in several cores, and the underlying facies was consistently a muddy sand with abundant parallel and ripple laminations.
lagoons. The lagoons are notable depocenters of previously unrecognized fine-grained sediments.

Interridge Trough

The interridge troughs are the lagoon environments on the flanks of the delta. Water depth in the troughs is less than 0.5 meters and is primarily controlled by tidal range. Relief from the base of trough to bar crest is a primary depositional feature. Tidal flow has created a web of channels between troughs. The back barrier lagoon in the present delta exemplifies the origin of these troughs. Once the bar welds onto the shore and restricts the lagoon from direct wave or fluvial input, the lagoon assumes the character of a marsh, with restricted salinity fauna (i.e. ostrea, and typical salt marsh vegetation). In this stage of development, the lagoon is referred to as an interridge trough instead of back bar lagoon, for the mouth bar has evolved into the new shoreline.

Sediments of the troughs are variable from the margins to the axes but consist mainly of "interridge trough mud" facies. Nearest the ridges, sands are flushed into the trough by washovers, abnormally high tides and eolian transport. These sands are interbedded with very fine - grained suspension deposits. In the centers of the troughs, the sediments are extremely fine grained, with plentiful organic material, and are heavily bioturbated. Also, oysters have colonized the troughs and act as a trap for tidally-swept sediments. In areas where the interridge troughs are tidally exposed, crusty algal mats, bird and crustacean fecal matter, and thin evaporitic laminae are observed.
Facies Architecture

OFFSHORE

Figure 76 displays the facies architecture of the offshore Brazos delta and adjacent shorefaces. In conjunction with the discussion of modern lithofacies, the stratigraphy of the Brazos delta lends new insight to previous wave-dominated delta models.

One of the most striking features of the Brazos delta is its large prodelta. The abundance of prodelta, fine-grained sediments is mostly dependent on proximity to the river mouth. However, this is not the only constraint on prodelta deposition. Longshore currents dramatically affect the depositional patterns, and the resulting architecture is strongly asymmetric to the west. During this study, significant reworking of the 1992 flood deposit was observed, resulting in a more strike-oriented delta geometry. Areas east of the mouth only experience appreciable prodelta deposition during times of increased discharge. Overall, the offshore facies architecture is dominated by fine-grained sediments. The sediments are distinguishable into three facies: prodelta, transitional deltaic/marine, and marine. These are easily distinguished based on lithology, bedding character, abundance of bioturbation, color, and occurrence of organics.

The dominance of prodelta sediments is a fundamental difference between the Brazos facies architecture and other wave-dominated deltas, i.e. Niger delta (Allen, 1965) or Sao Francisco delta (Coleman and Wright, 1980). Most studies attribute more significance to nearshore facies. Moreover, offshore sediments are generally nondistinct, in terms of prodelta or open marine. One explanation for this discrepancy is the type of data for each study. Coleman and Wright (1980) compiled the idealized stratigraphic sequence for the Sao Francisco delta based primarily on surface sediments. For sake of comparison,
a similar approach was taken utilizing the surficial sediment in core sections from this study. Surficial sediments belie the actual significance of fine grained deposits, because very thin beds of sandier deposits overlie thick beds of prodelta clay. While these thin sand beds point to effective marine incursion and reworking, underlying thick deposits of homogenous clay stress the important role of prodelta deposition.

The relative abundance of prodelta fine-grained sediments is also a function of the suspended sediment to bedload sediment ratio. Despite their different architectures, the Brazos, Sao Francisco (Coleman and Wright, 1975) and Niger (Allen, 1965) have relatively high suspended sediment loads (Coleman and Wright, 1975). Bedload transport is active in the latter two systems but much less significant than suspended sediment transport. Therefore, the delta architecture is not strictly a function of sediment supply. Instead, other variables might account for the differences in facies architecture. One such variable is offshore wave energy. Clearly, those systems that deposit into basins with higher wave energy, e.g. Sao Francisco, are going to have different morphologies than deltas on less energetic coasts, e.g. Brazos. Morover, combined with offshore gradient, wave energy can be the dominant factor in coastline morphology.

Finally, earlier studies on wave-dominated deltas focused on nearshore and onshore environments; this study expands the wave-dominated model to include offshore deposits. These deposits are significant to wave-dominated deltas, at least in the Brazos delta, where they make up 60-70% of the total deltaic package. Whereas, early models might have intentionally focused on nearshore eniroments--for purposes of recognizing hydrocarbon reservoirs--offshore deposits should be considered as fundamental and distinct depositional environments.
Figure 76: Offshore Deltaic Facies Architecture
Recognition of Ancient Wave - Dominated Deltas

Numerous authors (Heward, 1981; Wright Dunbar et al., 1992; Chafetz, 1980) discuss the difficulty in distinguishing wave-dominated deltas from shoreface or strandplain deposits. This study, however, is able to identify several distinguishing characteristics.

In general, the entire area shows vast lithologic complexity and stratigraphic differences between the interdeltaic shoreface and the deltaic deposits in the New Brazos delta. Clearly, the abundance of fine-grained, prodelta deposition, as just discussed, is a fundamental distinction. Furthermore, thickness of Holocene sediments varies greatly along strike. In the shoreface, west of the San Bernard river mouth, depth to the Holocene/Pleistocene boundary is approximately 1 meter. Within the delta, the Holocene/Pleistocene boundary was not encountered in cores that penetrated up to 7 meters of sediment.

Lithologic differences are also distinguishable along strike towards the river mouth. The noticeable increase in clay, abundance of organics, decrease in bioturbation, decrease in textural and mineralogical maturity (particularly high concentrations of heavy minerals) and complexity of sedimentological structures are definitively deltaic. Color differences between shoreface and deltaic sediments are most obvious.

Furthermore, subaqueous morphology of the area is greatly enhanced by deltaic deposition. Specifically, isobaths are lobate and deflected seaward in front of the river mouth. Along the coastlines of the interdeltaic shores, isobaths are parallel to the coastline.

Finally, direct comparison of dip sections reveals key differences between shoreface and deltaic sediments. The typical shoreface of the modern
interdeltiac regions of the east Texas coast is a muddy sand deposit that is gradational offshore to interbeds of muddy sand and sandy mud (Figure 77 from Siringan, 1994). In the ancient sequences, blocky sands with larger scale structures, and gradation to finer sediments offshore are typical of shoreface deposits. (Wright Dunbar et al., 1992). Neither one of these descriptions is applicable to deltaic deposits of the Brazos. While there is an overall gradation to fine-grained sediments offshore, this gradation is marked by previously discussed complexities along strike and internal stratigraphic architectures displaying interbedded, distinctly deltaic sediments. In addition, as the next section discusses, the lateral and downcore facies variations are much more complex in the nearshore environments.

NEARSHORE

Figure 78 displays the architecture and facies distribution for the nearshore and onshore environments of the New Brazos delta. Just as the offshore facies analysis indicated the importance of prodelta deposits to wave-dominated deltas, this diagram reveals newly discovered stratigraphic and lithologic complexities in the nearshore and onshore facies.

The diagram indicates several depositional events which created dissimilar stratigraphies, specifically amalgamated versus nonamalgamated beach ridge deposits. In short, the facies architecture is described as (1) isolated beach ridges with interspersed troughs, (2) amalgamated ridges as thick sand bedsets, and (3) shoreface deposits. Underlying facies represent older delta front and prodelta deposits.

Previous studies (Allen, 1965, 1970; Coleman and Wright, 1982) indicated that the nearshore environments of wave-dominated deltas are
Figure 77: Typical Texas Gulf coast shoreface lithofacies profiles from Siringan (1994).
Figure 78: Three dimensional facies architecture of the nearshore and onshore environments.
primarily composed of flanking strandplains. By definition (Reineck and Singh, 1973), strandplains are composed of amalgamated beach ridges. In many deltas, strandplains are manifested as a series of "shoreward-accreting, sub parallel, en echelon sand units" (Fisher, 1969). The Brazos does contain a strandplain section, but this environment is isolated to a small area near the 1930 shoreline and to an intermediate shoreline associated with the 1970-1980 portion of the delta. Most of the subaerial and nearshore delta is composed of numerous ridges which have not amalgamated, but are separated by interridge lagoons (making them barriers, by definition). The "strandplain" models of wave-dominated deltas would predict that cores taken in the interridge areas would initially penetrate a thin cover of muddy sediments but would quickly grade to sandy deposits of the underlying, interfingering ridges. On the contrary, between ridges of the Brazos delta, an average of 2 meters of muddy sediments overlie highly laminated muddy sand facies of the preexistent shoreface. Ridges do not interfinger at depth, but are discrete bodies. Thus, the interridges are preserved as primary depositional features. The significance of this finding is that these zones of fine-grained accumulation have, heretofore, been recognized as secondary tidal features. Primary versus secondary deposition is critical to understanding the evolution of the system, and, as will be discussed, particularly important to depositional mechanisms in the Brazos delta. Also, newly described depositional enviroments should aid the recognition of ancient wave-dominated, nearshore environments.

Why is the Brazos unlike other wave-dominated deltas, with respect to strandplain morphology? Strandplain evolution is tied to the rate of sediment input and the effectiveness of sediment reworking by waves. Put simply, strandplains evolve in systems where sediment input does not keep pace with reworking, and all sediment discharged into the offshore sections are quickly
piled onto the shoreline. The results are amalgamated beach ridge sets. In the case of the strandplain of the Brazos subaerial delta--at the time of river diversion, sediments swept off the Old delta were transported by longshore current, reworked shoreward, and deposited as amalgamated ridges near the mouth of the New delta. Once the source of sediment in the Old delta was depleted, the delta assumed a new morphology, namely a bar and lagoon coastline. A bar/lagoon system evolves when sediment discharge is sufficient to overcome the marine reworking and stabilize a distinct depositional environment offshore (i.e. offshore bar and back bar). In this case, note that the sediment is not coming from alongshore, but is being discharged from the mouth. How the fluvial sediments overcome marine forces is the next subject of discussion.

Depositional Mechanism

With a conceptual notion of the deltaic facies architecture, conclusions are drawn as to the impetus for such sediment distribution. Specifically, what are the most important mechanisms affecting Brazos deltaic stratigraphy and morphology?

Flooding are the most critical elements in the evolution of Brazos deltaic facies. Beach ridge development, primary subenvironment alterations, and sediment volumes are principally controlled by the frequency, magnitude and duration of flood discharge. Major constructional periods of the Brazos delta correlate precisely with drainage basin flooding and corresponding increases in river discharge (discussed below). The recurrence of this type of sedimentation is on a decadal scale. Intervening periods of 6 to 10 years reshape the coastline and mouth bars, but not to the extent that the sediments assume strandplain/shoreface stratigraphies.
Initial sedimentation began with the river diversion and sediments of the Old delta plain. Sediments were reworked from the Old delta and deposited as nearly parallel - to - coast beach ridges within the New delta (as strandplains). A necessary element in this hypothesis is the alongshore current, for it controls the distribution of the sediments. Once the Old delta was depleted, the more "constructive" phases of delta evolution began in the New delta. The first major flood occurred in 1935 and began the constructional phases of bar genesis, bar welding, back bar infilling and abundant prodelta deposition. With each successive flood (major events: 1957, 1965), the delta was able to overcome the receiving basin elements, and construct prominent headlands and offshore bars. Each bar migrated to the west between floods and was welded to the shore. This migration was not sufficiently fast, however, to completely backstep onto back bar facies and abut adjacent bar/ridges. Rather, shallow elongate troughs were preserved and are presently active under tidal influence. During these less constructive phases, the delta was truly wave - dominated, and the projecting thumb-like headlands evolved into lobeate shorelines. Alongshore erosion and deposition was particularly effective during these periods--sweeping bar sands and delta sediments to the west-- creating a definitive strandplain and spit complex near the San Bernard River mouth.

Systematically, the depositional events and lithofacies correspond in the following manner. Floods deposit significant quantities of fine - grained sediment in the prodelta, back bar, and delta front. Sands are isolated to the bar and mainland shores, including the large headland. Normal discharge contributes sediment to the prodelta and delta front, but is inferred to be relatively insignificant to the nearshore zone. Sediments within wave influence are reworked landward during slack times, while sediments below wave base are covered with longshore-
transported marine sediments. Strandplain evolution occurs during interflood periods, while bar/lagoon genesis occurs during flood stages. Figure 78 illustrates that the beach ridges that correspond to flood events are isolated stratigraphic bodies; the ridges that are created during non-flood stages are amalgamated.

Thus, the Brazos delta is more accurately described as a "flood-dominated delta." If the Brazos delta was not so drastically altered by floods, the classic wave-dominated model of strandplain and shoreface stratigraphy would be more applicable. Under separate conditions, the Brazos would not be able to construct prominent headlands and protective bars; around and behind which considerable fine-grained deposits exist. The delta would be the typical highly-destructive type. The discharged sands would be reworked and redeposited onshore in amalgamated beach ridges and overall strandplain. More importantly, offshore profiles would be similar to adjacent interdeltic shorefaces. However, the Brazos is clearly not a classical destructive delta type, in terms of its facies architecture. Flooding, the principal agent of change in the delta, is highly constructive. Moreover, flood discharge is not so rare as to render it insignificant to morphologic development. In fact, floods are the most identifiable genetic mechanism for a majority of the delta's volume and acreage. These assertions were strongly supported by the 1992 flood event.

1992 Flood

The volume of sediments that were deposited during the 1992 flood, and the abundance of flood deposits recovered in cores, indicate the stratigraphic significance of flood deposition. In some places, up to 0.75 meters of fluidized clay is directly attributable the 1992 flood. Moreover, if we accept that the bar evolved in
response to the flood, and timing of emergence is not simply coincidental, then nearly 3 meters of flood borne sand were a result of this single catastrophic event.

During average discharge periods, the Brazos ranks first among Texas rivers for sediment discharge. When at flood stage, this distinction is even more apparent. Flooding in the drainage basin adds considerable discharge and dramatically increases the rivers washload. Silt and clay are the primary suspended load, but sand must also be in transport for the Brazos possesses numerous sandy point bars. The suspended load of fine-grained sediments is obvious in the discharging plume at the mouth of the Brazos--water color disparities are great between basin waters and river waters. Moreover, the viscous forces of the discharging plume dominated inertial forces of receiving basin waters as evinced by dampened waves at the river mouth (Figure 79) during the most recent flood.

Sand and Floods

In the 1992 flood, the flood plume was directly measured for concentrations of suspended sand. Sieving and direct observation consistently revealed less than 1% sand in suspension. The fact that very little observable sand was in suspension suggested (1) that the clay-rich waters had reached carrying capacity with fine-grained sediments, and/or (2) effective fluid flow was dampened by increased coefficients of viscosity, and/or (3) little or no sand was available. The first two explanations are the most feasible, considering the large sandy offshore bar that emerged in the wake of the flood. Thus, the most important question is not "if" but "when and how" sandy sediments were transported.

The lag time of approximately one year for the focused deposition of flood-derived sands necessitates mechanisms of sand storage. The most logical
Figure 79: This photo is taken from approximately 150 meters looking south. The photo was taken on January 3, 1992. The photo illustrates the discharging sediment-laden plume at the mouth of the New Brazos delta. Note that the plume is so viscous that it dampens the incoming 1 to 1.5 meter waves.
explanation of this lag time is that sands were transported via bedload, and these methods of transport operated at relatively slower rates than suspension. The Richmond gaging station indicates that during the flood 90% of the suspended sediments were finer than sand, thus implicating traction or saltation as the transport mechanism for bar sands.

Sand transported during the 1992 flood was most likely stored at the mouth of the river where decreased competence of the discharging plume facilitated mass deposition. During several trips to the area, in the latter stages of flooding (February-March 1992), the river mouth was observed to be aggrading. Immediately seaward of the mouth, the channel became progressively shallower (ramp), and a broad shoal was observed at the terminus of the channel. The shoal remained below sea level (-1 to -2 meters) until approximately one year after initial flooding. Recent observations indicate that the channel has once again deepened, and that the channel has migrated to a more easterly - directed discharge around the offshore bar. This suggests that original nearshore deposition and later reworking was the primary source of bar sands.

Attempts to core the channel facies were not entirely successful, but a clayey sand facies underlies bar sands at the eastern most edge of the bar (core BDC 94-1), on the margins of the river channel. This was the first occurrence of this facies, and it is believed to represent bedload deposits. This substantiates considerable sand deposition at the mouth, but the lack of data is understandably dubious.

It is also conceivable that the bar could have evolved from reworked sands that were originally deposited offshore during the flood. The isopachs for January and July 1992 (Figures 63 and 64) support significant onshore redistribution of flood - deposited sediments. However, reworking of offshore sands, exclusively, as
the source of bar sands is questionable because other variables might account for similar isopach redistribution patterns. For example, rather than being reworked onshore, sediments might have been removed and taken alongshore by longshore currents. The net addition of sediment, between January and July, near the shore (in Figure 64), can be accounted for simply as late flood-stage sedimentation. The deposition of these flood deposits nearer to shore is a function of decreased discharge. That is, as the discharge of the flood waters waned, deposition gradually moved to nearshore locations.

There are other factors that negate offshore redistribution as the principal source of bar sands. First, substantial mud removal would have been necessary to result in the clean sands that compose the bar. Specifically, those sediments offshore, which were 60% (minimum) clay and 40% (maximum) sand and silt, would have had to be reworked into 95-98% sand. This amount of reworking would have also altered the textural and mineralogical maturity of the sediments.¹ Rather than having coarser than normal² and subangular grains (g.s. 2.5-2.75 phi), significant unstable minerals (i.e. micas and heavies), and poor sorting, the sediments would be reworked into very well sorted, very fine, rounded - to - subrounded grains of mineralogically stable minerals (i.e. quartz).

Finally, the volume of sediments in the bar compared to the volume of sands in the offshore flood deposits is not similar. Considerably more sand composes the bar than existed in the offshore flood deposits. Specifically, the volume of the sand in the bar is estimated³ at $1.045 \times 10^6$ m³. The flood deposit is estimated to be

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¹ "Textural maturity is one of the most important keys to the physical nature of the environment of deposition, since it provides a descriptive scale that indicates the effectiveness of the environment in winnowing, sorting and abrading the detritus furnished it" (Folk, 1972).
² Normal grain sizes along Texas beaches is 3.0 to 3.5 phi.
³ The estimate is calculated simplistically by fitting the known (from GPS reading) dimensions of the bar onto a grid, with each subunit of the grid
9.45 \times 10^6 \text{ m}^3, with an average of less than 10% sand. Using the maximum average sand content (10%) and accounting for water content of the mud (i.e. 45%), total sand deposited during the flood is approximately 425 \times 10^3 \text{ m}^3. Therefore, sand must have been contributed from other sources as well. The earlier discussion of river mouth storage is a reasonable explanation.

In the end, "where the bar sands came from" is not entirely clear due to the limited amount of appropriate data. In order to accurately assess the means and timing of sand distribution in the delta during floods, it would be necessary to construct and place sediment traps throughout the delta and river channel, and also to monitor such variables as discharge velocity, and wave energy. Moreover, suspended sediment concentrations would need to be taken throughout the flood rather than during a single day (USGS measurement at Richmond, TX). Finally, pre-flood data is also critical, but is lacking in this study due to the unexpected nature of the 1992 event.

**Generalized Stratigraphic Sequence**

A generalized stratigraphic sequence (Figure 80) is developed from the assemblage of cores and postulated facies distribution. Facies patterns were deduced from cores and amalgamated in a progradational fashion to illustrate the composite deltaic section.

The composite sequence illustrates a repeating pattern of bar/shoreface/trough facies. These recurring units are individual flood events that deposited offshore bars and related facies. The section also illustrates the representing a certain area. This area is multiplied by the number of grid units covered by the bar, and then multiplied by the average thickness of bar sands. In this case bar thickness was 1 meter. This type of estimate yields a minimum value, not accounting for overlap on partial subunits of the grid.
Brazos Delta
Composite Stratigraphic Column

Explanation

I. COASTAL PLAIN: Marsh and flood plain deposits; very fine grained with abundant rootlets and bioturbations.

II. BEACH RIDGES: Wave-formed ridges of sediment mainly derived from the Old delta; ridges consist of sandy (fine) and stacked; sands are mineralogically well sorted, well rounded; complete trees and lots of organic material.

III. BEACH and SHOREFACE: Hummocky and swale-like sands (fine); muddy from local sources; sands are moderately well sorted with <5% unstable minerals; concentrations within laminae of pebbles, shells, and heavy minerals.

IV. BACK BAR/INTERRIDGE: Infilling sandy clay behind mouth bar; sediments are very poorly sorted, contain mineralogically immature sediments, lack bioturbatic stranded ripples at top of unit; various tidal pond strata as the backbar completely fills to shallow subtidal levees; abundant organics; at base of unit are OVERWASH deposits from back side of bar which are interbedded with clay; sand interbeds are rippled.

V. OFFSHORE BAR: very sandy (fine to medium); interbedded thin clayey and muddy units of the tidal channel; abundant interbeds on seaward side due to accretion; shoreface bars and spits.

VI. DELTA FRONT: Highly laminated muddy sands; destratification and convolute bedding; very muddy with interbeds of homogenous clay at base; occasional interbedded marine storm sand; organic-rich laminae.

VII. PRODELTA: Primarily clay with scattered organic transitional to marine clay toward base with abundant variations; colors are highly banded; more frequent storm sands.

VIII. OFFSHORE MARINE: Bioturbated marine clay, is organic; transitional to muddy sands near base.

Figure 80: Generalized Composite Stratigraphic Sequence for the New Brazos Delta.
Explanation

I. COASTAL PLAIN: Marsh and flood plain deposits; very fine grained with abundant rootlets and bioturbation.

II. BEACH RIDGES: Wave formed ridges of sediment mainly derived from the Old delta; ridges are sandy (fine) and stacked; sands are mineralogically mature, well sorted, well rounded; complete trees and lots of organic material.

III. BEACH and SHOREFACE: Hummocky and swaley sands (fine); muddy from local sources; sands are moderately well sorted with <5% unstable minerals; lag concentrations within laminae of pebbles, shells, and heavy minerals.

IV. BACK BAR/INTERRIDGE: Infilling sandy clay behind offshore mouth bar; sediments are very poorly sorted, contain >10% mineralogically immature sediments, lack bioturbation; stranded ripples at top of unit; various tidal pond structures as the backbar completely fills to shallow subtidal level; abundant organics; at base of unit are OVERWASH deposits from back side of bar which are interbedded sand and clay; sand interbeds are rippled.

V. OFFSHORE BAR: very sandy (fine to medium); interbedded thin clayey and muddy units of the tidal flats; abundant interbeds on seaward side due to accreting shoreface bars and spits.

VI. DELTA FRONT: Highly laminated muddy sands; dewatering structures and convolute bedding; very muddy with interbeds of homogenous clay at base; occasional erosionally interbedded marine storm sand; organic-rich laminae.

VII. PRODELTA: Primarily clay with scattered organic material; transitional to marine clay toward base with abundant color variations; colors are highly banded; more frequently preserved storm sands.

VIII. OFFSHORE MARINE: Bioturbated marine clay; lacking organics; transitional to muddy sands near base.
sedimentary signature of intervals between floods, when beach ridges amalgamate due to wave reworking. Note, however, that thickness of the amalgamated ridges is not significantly greater than the isolated ridge sets. This observed feature indicates that non-amalgamated/isolated bars evolve under much higher sediment supply conditions.

The basal units of delta front/prodelta/transitional marine represent various cycles of flood and slack periods that are amalgamated into thick homogenous packages. The distinguishing characteristics of individual flood events and transitional marine sediments are the color bands, organic-rich laminae, non-bioturbated units, and reduced sand percentages. In general, the base of the section is a thick sequence of very fine grained sediments, underlain by pre-delta or fore-delta sediments.

Is the Brazos a good analog?

Understandably, employing the modern Brazos delta as an analog for ancient outcrops assumes that the depositional sequence for the delta is preserved during sea level rise, subsidence or tectonic changes. And, it assumes that the ancient strata have similar sediment and fluvial regimes to the Brazos--most importantly significant fine-grained suspension loads.

Regarding the first assumption, the argument is raised that during transgression, the modern lithofacies and morphologies have little or no preservation potential. Furthermore, transgressed wave-dominated deltaic deposits are inferred to develop morphologies similar to the sand-rich, strandplain environments. Certainly, the sediments above wave-base would be greatly reworked, but this fails to address the previously unrecognized sediments deposited below wave base, i.e. prodelta and delta front deposits. In addition,
transgressions have until recently been assumed to be fairly uniform and continuous--implying thorough reworking of coastal deposits. Thomas and Anderson (1990) postulate that the nature of Holocene sea-level rise is more episodic, and that rapid rises might result in complete drowning and overstepping events, leaving in the wake of transgression many abandoned coastal bodies, i.e. deltas. Abdullah et al. (1994) identified several overstepped paleo Brazos deltas in the offshore Texas region, and attributes their preservation to this episodic nature of eustacy. Thus, complete reworking of deltaic deposits into stranplains is not a foregone conclusion, but is inevitably dependent on the nature of sea level fluctuations.

The argument that modern wave-dominated deltas lack significant preservation potential is certainly true--but only in the context of the presently rising sea level. In the last 10,000 years or so, several episodes of stillstand have occurred which might have allowed sufficient time for wave-dominated deltaic sediments to subside below the wave base. In addition, as discussed earlier, periods of rapid rise might accommodate in situ drowning of the deltaic environments.

The Brazos has also been described as a unique system, in terms of sediment supply and basin dynamics. Wright Dunbar (personal communication, 1994) suggests, however, that the Point Lookout Sandstone of the Cretaceous Western Interior possessed meandering fluvial systems with significant fine-grained loads, much like the Brazos. Furthermore, the rivers of the Cretaceous drained into a basin very similar to the modern northwestern Gulf of Mexico. Within the Point Lookout Sandstone, Wright Dunbar (ibid) identifies deltaic deposits with many of the same characteristics as the Brazos delta. One fundamental observation within the Point Lookout Sandstone is the dramatic increase in
sediment volume (fine grained) from the adjacent strandplain/shoreface to the
delta, identical to the Brazos delta. Thus, there may be several endmembers for
wave-dominated deltas including (1) sandy shorefaces and laterally extensive
strandplains, and (2) finer grained sequences similar to the Brazos. Clearly, the
Brazos River produces a uniquely different wave-dominated architecture than
previously described, and it follows that fluvial systems of the ancient may have
behaved similarly.
CONCLUSIONS

The Brazos delta is frequently referenced as a classical wave-dominated delta. Discussions of ancient wave-dominated deltas often cite the Brazos (and the Niger) as the most appropriate modern analog. In terms of the overall depositional setting, the Brazos region and, in general, the Northwestern Gulf of Mexico is very similar to ancient systems in the Cretaceous Western Interior; the Gulf has similar climate, oceanographic and sedimentological regimes. However, previous comparisons of modern wave-dominated deltaic deposits to ancient sequences is somewhat tenuous due to the lack of thorough and detailed facies analysis in these modern systems. Therefore, this research attempted to add complexities to the previous model through an intensive study of the New Brazos delta, that incorporated assessment of nearshore and offshore deposits, explanation of genetic mechanisms, and implications for preservation potential.

Four primary conclusions are drawn from this study:

(1.) The morphologic pattern of the Brazos wave-dominated delta does not immediately reveal significant internal lithologic complexities;

(2.) The complex facies architecture of the New Brazos delta suggests that generalized depositional models are overly simplistic;

(3.) Catastrophic discharge events drastically alter the morphology, stratigraphy and evolution of the Brazos delta; and

(4.) Preservation potential of Brazos wave-dominated deltaic deposits is not merely as a function of present day sea level trends.
Morphology and Facies Architecture

Galloway (1969) utilized the coastal morphology of deltas as indicators of the relative strengths between waves, tides and fluvial discharge. He correlated strong wave influence with cuspate to lobate shorelines, such as in the Sao Francisco and Brazos deltas. Other authors (Coleman and Wright, 1980; Fisher 1970), similarly utilized coastal outline to decipher the principal depositional mechanisms and related patterns of wave-dominated deltas. Coleman and Wright (1980) studied the Sao Francisco wave-dominated delta and identified cuspate shorelines with expansive strandplains as the principal signature of wave-dominated deltas. Moreover, they incorporated surficial sediments to conclude that the offshore signature for these systems is minimal, and that wave-dominated stratigraphy is most similar to a sandy shoreface.

From this geomorphic perspective, the Brazos delta would be a classical "destructive type" delta, with cuspate to lobate shorelines and buttressed beach ridges (strandplains) on the flanks of the river mouth. Surficial sediments are sandy in the nearshore regions, and waves appear to strongly affect the overall morphology. We might conclude, therefore, that the offshore expression is minimal, lacking prodelta deposits, and that the stratigraphic signature is not dissimilar to a strandplain and/or shoreface.

Figures 76 and Figure 78, however, indicate that the New Brazos delta contains a suite of depositional environments from clayey prodelta to sandy nearshore bars. Sediments are not restricted to nearshore environments, but, in fact, the offshore prodelta comprises nearly 60% of the delta's volume. While surficial sediments throughout the delta are sandy (less than 50% by mass), immediately underlying the surface are muddy and clayey sediments. In several environments, i.e. back bar, prodelta, the sediments are clayey and muddy at the surface. Moreover, the coastline is composed of "apparently"
buttressed beach ridges, but closer examination and sediment cores, reveal that the ridges are separated by distinct back bar, and interridge depositional environments.

Thus, although the coastal outline is similar to the classically - postulated wave - dominated delta, the New Brazos delta has internal complexities that are not immediately recognizable strictly from geomorphology. This not only suggests that the Brazos is unique, but also that the other wave dominated deltas, i.e. Sao Francisco, Niger, Rhone, might contain additional complexities heretofore unrecognized.

Oversimplified Depositional Models

Classifications of wave - dominated systems based on any single factor, i.e. wave - to - discharge - to - tide ratios, are overly simplistic and fail to illustrate true depositional mechanisms and architecture. Often these classification schemes are extrapolated to the specific details of particular deposits and made into broad generalizations. Originally proposed as geomorphologic descriptors, these models evince several implications including sediment types, sediment volumes, and sediment transport mechanisms. One example is the widely - held notion that wave - dominated deltaic shorelines are dominated by bedload materials that rarely are able to escape the zone of wave erosion.

Sediment types, volumes and transport are not foregone conclusions of wave - dominance. In the Brazos delta, contrary to generalized models (i.e. Heward 1980; Fisher 1969), sand is not dominant, sediment volumes are not insignificant, and bedloads are not demonstrably superior. Rather, fine - grained, suspension deposits are voluminous. Yet, Galloway (1969), Fisher (1970) and Coleman and Wright (1980) were not incorrect in their identification
of strong wave - influence in the Brazos delta. The point is that extracting lithologic data from morphologic data is not supported by detailed facies and sedimentological analyses.

*Floods and Depositional Models*

Unless one considers the impact of catastrophic events, i.e. floods, on the Brazos delta, an appropriate model for the evolution and stratigraphy of the delta can not be well understood. Coincidental occurrence of the 1992 flood enabled this study to accurately portray the most important depositional mechanisms in the delta. Floods are the primary constructional agents, adding significant volumes of sediment to the delta in relatively short periods of time. Observations during the 1992 flood revealed that the ridge and lagoon systems evolve entirely as a result of floods. Prodelta flood deposits are also significant, with deposits exceeding 50 centimeters in thickness in some locations. Modification of the nearshore flood sediments, i.e. offshore bar and back bar, are dynamic, with onshore migration of the bar, welding of the bar and eventual encapsulation of the back bar environment. The bar is composed of very fine to fine, clean sands, that exceed 3 meters in some locations, with average thickness of 1.5 to 2 meters. The back bar is dominantly fine - grained with very muddy sands adjacent to the shores, and mud and clay in the central areas.

Aerial photographs and bathymetric charts revealed that previous floods deposited the ridges and interridges now preserved onshore. The orientation of these ridges corresponds to wave refraction around offshore bars and headlands that evolved during high discharge periods. Each ridge and interridge correlates to a specific flood, and non - flood periods are indicated by strandplain - like sections lacking interridge lagoons.
The floods also impact the deltaic facies architecture and stratigraphy. Figure 80 illustrated the generalized sequence that evolves as the Brazos progrades seaward, incorporating several bar and back bar sequences related to floods. Also, the extensive prodelta at the base of the sequence contains several interbeds of red and olive gray clay that correspond to pulsating discharge from the Brazos River.

Based on the stratigraphic importance of floods, and modern depositional significance, the Brazos is more accurately described as a mixed fluvial and wave dominated system, with fluvial dominance during floods, and wave dominance during slack times. That is, floods are the primary depositional agents, and waves are the equilibrium agents.

Preservation Potential

The significance of modern systems is principally related to their preservation potential. That is, those systems with little or no preservation potential are assumed to occupy a less significant role in the stratigraphic record. The preservation potential of the Brazos delta is, therefore, a necessary element, in order to attach importance to its unique facies architecture.

In the Gulf of Mexico, sea level has changed rapidly throughout the Holocene, and these changes are evident in migrating shorelines, and abandoned coastal bodies on the continental shelf. Currently, the Gulf is in a transgressive stage, where coastal systems are assumed to have little or no preservation potential. This assumption is misleading without considering the nature of the transgression. Thomas and Anderson (1990) showed that transgressions throughout the Holocene have been rapid, and have completely drowned some systems--preserving coastal bodies in situ. The Brazos delta was overstepped several times, and numerous abandoned deltaic lobes are
observed on the modern continental shelf (Bartek et al., 1990; Abdullah et al., 1991). Furthermore, this study identified significant preservation (albeit short term) of prodelta deposits of the Old Brazos delta following the 1930 river diversion. Sediments above wave-base were significantly reworked, but prodelta fine-grained sediments are observed beneath a surficial layer of active shoreface sands. Clearly, the Brazos delta sediments above wave-base lack preservation potential, but under separate conditions, i.e. highstands or rapid transgressions, deltaic facies would have higher preservation potential.
PLEASE NOTE

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and unavailable from author or university.
Filmed as received.

UMI


Rice, D.D., and Donald L. Gautier, 1980, Coastal Sediments: Patterns of Sedimentation, Diagenesis, and Hydrocarbon Accumulation in Cretaceous Rocks of the Rocky Mountains, SEPM Short Course No. 11, p. 6-1...6-33.


PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.
Panel 1

Historical Evolution of the Brazos

1930

1957

'New' Delta

1967
PLEASE NOTE:

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FOR THE WEEK OF DECEMBER 29, 1991 THROUGH JANUARY 1, 1992

The transition into the new year was marked by continued downstream flooding in southeastern Texas, welcome heavy rain and snow in California, and a powerful Nor'easter that battered portions of the Atlantic Coast. Up to half a foot of rain, hurricane-force wind gusts, and high surf accompanied the storm system that moved up the Atlantic Seaboard. The storm caused extensive damage to several beach communities, particularly in Delaware. Boardwalks were severely damaged at Bethany Beach and Rehoboth Beach, DE, and to a lesser degree at Ocean City, MD. Coastal flooding was also reported from the Outer Banks in North Carolina to Long Island, NY, with the most serious flooding reported in Maryland and Delaware where evacuations were necessary. Elsewhere, downstream flooding continued to plague southeastern Texas, precipitating further evacuations. According to press reports, 24 counties were declared federal disaster areas after more than two weeks of flooding spawned by torrential rains during late December.

The most extensive flooding occurred along the Trinity, Guadalupe, Brazos, and Colorado Rivers. Up to 500 homes were affected by flood waters in 14 northern Texas counties, and early damage estimates across the state were $75 million.

FEBRUARY 1992

The heavy rains affected much of Texas and the central Gulf Coast for at least the second consecutive month, providing 1992 with the wettest start to a year (Jan – Feb) on record across Texas.

SELECTED STATIONS WITH 3.75 OR MORE INCHES OF PRECIPITATION DURING THE WEEK OF DECEMBER 15 – 21, 1991

<table>
<thead>
<tr>
<th>STATION</th>
<th>TOTAL (INCHES)</th>
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After a tranquil start to the week, a deep, slow-moving storm system crept eastward from the desert Southwest, tapping Gulf moisture and inundating portions of central Texas with as much as 16.2 inches of rain during a five-day deluge. According to press reports, the resultant widespread flooding closed several interstate highways, drowned hundreds of cattle and other livestock, and forced the evacuation of over 200 individuals as the Trinity River flooded portions of southeastern Dallas. Farther south, the Guadalupe River approached record high levels in conjunction with the heaviest rains (over 8 inches), which fell from San Antonio northward to west of Austin. By Sunday evening, eighteen lives had been lost and half a dozen individuals were still missing as the storm finally weakened and moved off to the northeast.
GLOBAL CLIMATE HIGHLIGHTS
MAJOR CLIMATIC EVENTS AND ANOMALIES AS OF JANUARY 25, 1992

Central and Southeastern Texas:
RAIN CONTINUES TO AGGRAVATE FLOODING.
Spotty moderate to heavy rain continued to aggravate existing flooding across southeastern Texas. The Red Cross estimated that 2,500 homes have been damaged by the flooding that began as runoff from heavy rain in north and central Texas poured into the Guadalupe, Trinity, Brazos, and Colorado Rivers. The Brazos River still had not begun to recede at week's end [11 weeks].

Texas

HEAVY RAINS CAUSE SEVERE FLOODING.
During much of December, heavy rains drenched much of the southern Plains. Broad sections of Texas received over 100 mm of rain from the storm within one week, with localized amounts reaching 410 mm north of San Antonio. Rainfall abated but remained above normal at most locations as the year drew to a close, causing prolonged or renewed flooding.

GLOBAL CLIMATE HIGHLIGHTS
Major Climate Events and Anomalies as of March 14, 1992

Southern United States:
STILL WET.
Heavy rain showers drenched parts of the South from northeastern Texas through the Tennessee Valley with 100 to 120 mm of rain. Although lesser amounts fell to the south and west, six-week moisture surpluses of 100-195 mm still covered parts of Texas [22 weeks].

Southern United States and Northern Mexico:
MORE WET WEATHER.
Unusually strong high level winds continued to usher copious amounts of moisture into the region. Parts of the region received over 60 mm of rain last week, with isolated totals reaching 145 mm, according to River Forecast Center reports. The heavy precipitation aggravated existing flooding or caused renewed flooding in a few areas along the Gulf Coast while some rivers remained out of their banks due to previous heavy rain [15 weeks].

The heavy rains affected much of Texas and the central Gulf Coast for at least the second consecutive month, providing 1992 with the wettest start to the year (Jan-Feb) on record across Texas.

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TExAS PRECIPITATION
DECEMBER, 1895–1991

Precipitation in Texas averaged over a half a foot for December 1991, by far the highest amount ever recorded. Numerous individual rainfall totals in excess of a foot for the month were reported.

FIGURE 1. Moderate to heavy rains (up to 7.5 inches) in southeastern Texas aggravated flooding along the lower portions of the Colorado, Brazos, and Trinity Rivers. Heavy rains also occurred...
TH 3.75 OR MORE INCHES OF PRECIPITATION OF DECEMBER 15–21, 1991

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Unusually heavy rains (up to 7.5 inches) in southeastern Texas caused flooding along the lower portions of the Colorado and Brazos Rivers in December 1991, by far the highest amount ever recorded. Numerous deaths were reported.

**FIGURE 1.** Moderate to heavy rains (up to 7.5 inches) in southeastern Texas caused flooding along the lower portions of the Colorado and Brazos Rivers.

**Major Climate**

By Sunday evening, eighteen lives had been lost and half a dozen individuals were still missing as the storm finally weakened and moved off to the northeast.

**TABLE 1.** Precipitation Rankings for the Period 1995 to 1992.

<table>
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<td>MO</td>
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<tr>
<td>IN</td>
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<td>MT</td>
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**RECORD FEW**

**TABLE 2.** Total Precipitation (INCHES)

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<th>STATION</th>
<th>TOTAL (INCHES)</th>
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<tr>
<td>GALVESTON, TX</td>
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<td>AUSTIN, TX</td>
<td>6.55</td>
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<tr>
<td>WACO, TX</td>
<td>6.25</td>
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<tr>
<td>MIDLAND, TX</td>
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<tr>
<td>HARRISBURG, PA</td>
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<td>SHERIDAN, WY</td>
<td>0.02</td>
</tr>
<tr>
<td>COLORADO SPRINGS, CO</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Note: Trace precipitation is considered in these totals.
GLOBAL CLIMATE HIGHLIGHTS
Major Climate Events and Anomalies as of March 14, 1992

2. Southern United States:

STILL WET.

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Precipitation in Texas averaged over a half a foot for December 1991, by far the highest amount ever recorded. Numerous individual rainfall totals in excess of a foot for the month were reported.

FIGURE 1. Moderate to heavy rains (up to 7.5 inches) in southeastern Texas aggravated flooding along the lower portions of the Colorado, Brazos, and Trinity Rivers. Heavy rains also drenched southern Louisiana, generating flash flooding, according to the Office of Hydrology. Wetness across Texas and the lower Mississippi Valley corresponds to anomaly patterns typically found at this time of year during the mature phase of a low-index (warm) ENSO episode (see pages 25 – 26), which favors above normal October – March precipitation in the region.
FIGURE 1. Moderate to heavy rains (up to 7.5 inches) in southeastern Texas aggravated flooding along the lower portions of the Colorado, Brazos, and Trinity Rivers. Heavy rains also drenched southern Louisiana, generating flash flooding, according to the Office of Hydrology. Witness across Texas and the lower Mississippi Valley corresponds to anomaly patterns typically found at this time of year during the mature phase of a low-index (warm) ENSO episode (see pages 25–26), which favors above-normal October–March precipitation in the region.
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**National Climatic Data Center**

**RECORD FEBRUARY PRECIPITATION**

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**RECORD DECEMBER PRECIPITATION**

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**NOTE:** Trace precipitation is considered ZERO precipitation. Stations with no precipitation are only included if normal precipitation is 0.25 inches or more.