CHAPTER 5 – STATE OF THE BAY, THIRD EDITION

Physical Form and Processes

Written by John B. Anderson

[Texas Bays] are a magnificent resource, shallow and brackish and marshy-bordered and rich with life.... The flat land runs to the flat bays, and beyond the flat sand islands is the blue flat Gulf but it is dramatic enough for all that, because of the life that is there . . . . Nearly any memory of that coast has in it a sense of teeming life...

—*John Graves, in* The Water Hustlers *(1971)*

Introduction

Twenty thousand years ago the earth was in the midst of an ice age and ice sheets in both hemispheres were expanding. Expansion of the ice sheets was fed by water from the sea, to the extent that sea level fell an average of 100 meters across the globe. Then, when the ice age ended approximately 17,000 years ago, meltwater from the ice sheets flowed back into the oceans causing sea level to rise to its current level. It was during this rise in sea level that the estuaries of the Gulf Coast were formed, including Galveston Bay. Hence, the very existence of Galveston Bay is attributed to sea level rise.

Setting

The Galveston Estuary includes Galveston Bay (Lower Galveston Bay), San Jacinto Bay (Upper Galveston Bay), Trinity Bay, East Bay, West Bay, and Christmas Bay (Figure 5.1). These estuaries are situated landward of 2 prominent coastal barriers, the Bolivar Peninsula and Galveston Island. The bay averages 2 to 3 meters in depth and astronomical tides average 0.3 meters, but vary seasonally due to variations in wind. Prevailing winds are from the southeast, with occasional strong northerly winds that are associated with passing cold fronts. Wind-driven tides of up to 1 meter above and below mean tide occur during strong winds. Storm tides during a Category 4 or 5 hurricane could be as high as 7 meters above normal water levels.

Sediment supply to Galveston Bay flows primarily from the Trinity and San Jacinto rivers and to a lesser degree the many small streams and bayous that enter the estuary. The Trinity River drains an area of 5,500 km^2 and has an annual discharge of 7.1 billion cubic meters (m^3). The San Jacinto River has an annual discharge of 2.4 billion m^3. Both the San Jacinto and Trinity rivers have been dammed, but sediment delivery to the estuary may not have been significantly reduced (Phillips et al. 2004). The entire Galveston Bay Estuary experiences significant bay-shore erosion, which contributes to the sediment supply of the estuary (Paine et al. 1986).

In addition to the 5 main subbays, the estuary and watershed comprise a number of different environments, each with its own unique set of processes and ecosystems. The following is a brief description of these other environments.

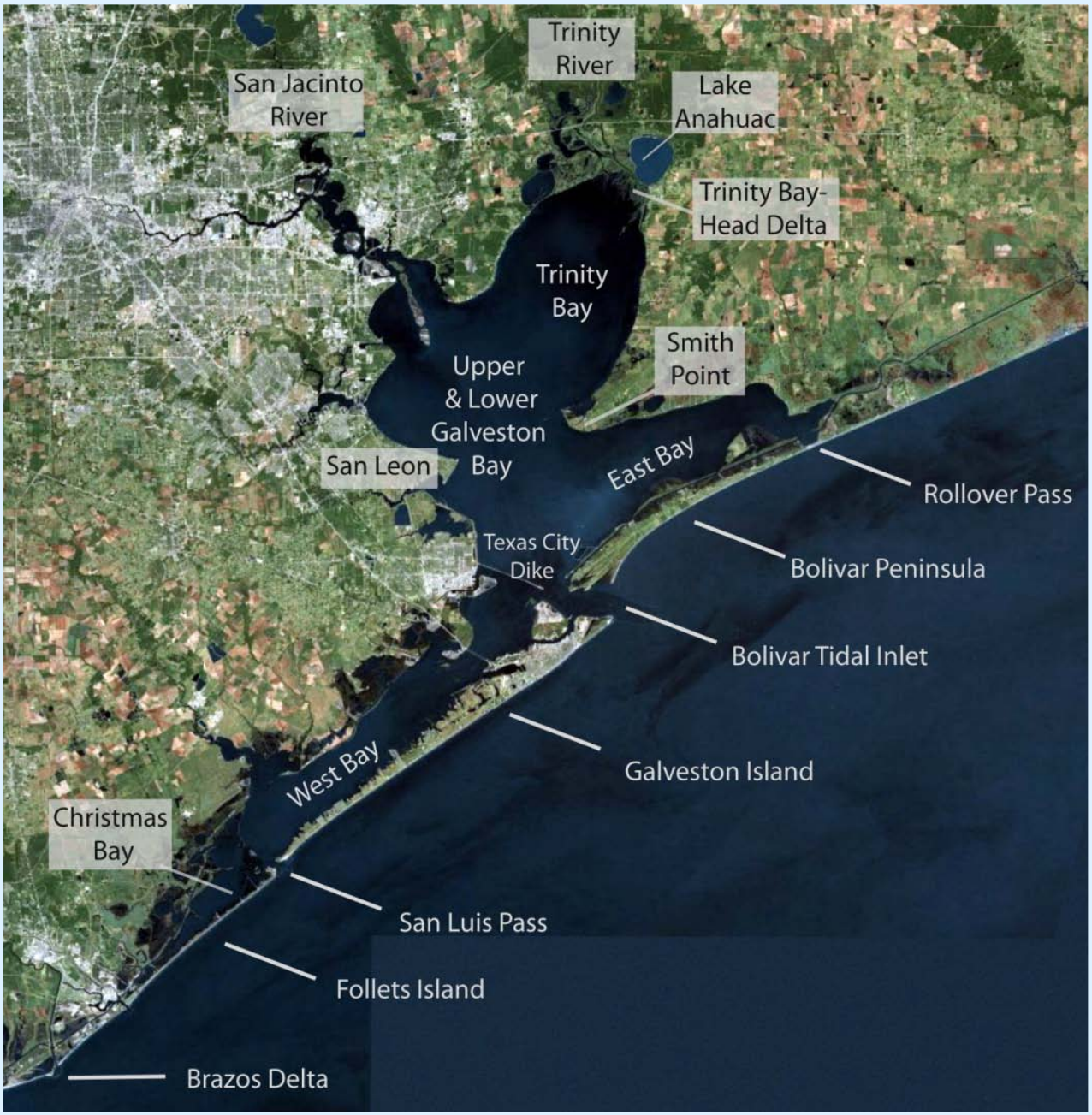

Figure 5.1. The Galveston Bay Estuary.

Wetlands

Wetlands occur along the margins of the Galveston Bay Estuary and are a vital part of the bay ecosystem. Wetlands are also the most rapidly disappearing component of the estuarine complex (see Chapter 7). Salt and brackish wetlands exist within 0.5 meters of mean sea level and are frequently inundated during spring tides and storms; these wetlands are adapted to submergence, but only for brief periods. As sea level rises, wetlands are able to survive only if they are able to grow vertically at a rate equal to that of sea level rise, a process known as aggradation. To aggrade, wetlands require healthy plant growth and a steady supply of sediment to fill the water column created by sea level rise. If the rate of aggradation is less than the rate of sea level rise, the wetlands must migrate inland to higher ground in order to survive.

Approximately half of the natural wetlands of the Galveston Bay Estuary have disappeared in historical time due to a combination of sea level rise, diminished sediment supply and human intervention. Sea level rise, thus far, has been mainly due to subsidence related to withdrawal of subsurface fluid (e.g. water and oil) which peaked in the mid-1970s, when groundwater extraction reached a peak. Groundwater extraction for public, industrial, and agricultural use has decreased since the mid-1970s (Mace et al. 2006) significantly reducing subsidence.

Sediment supply and distribution to the estuary have been altered by construction of the Houston Ship Channel, the Texas City Dike, and coastal highways that block sediment transport across the barriers (e.g. Bolivar Peninsula and Galveston Island) during storms. Adding to the problem, much of the west shore of Galveston Bay has been armored with cement riprap in order to slow the rate of bay-shore erosion (see Figure 5.2). Thus, the wetlands have no place to migrate. The same thing is currently happening along the south shore of West Bay, where bulkheads have been constructed at the edges of the wetlands.

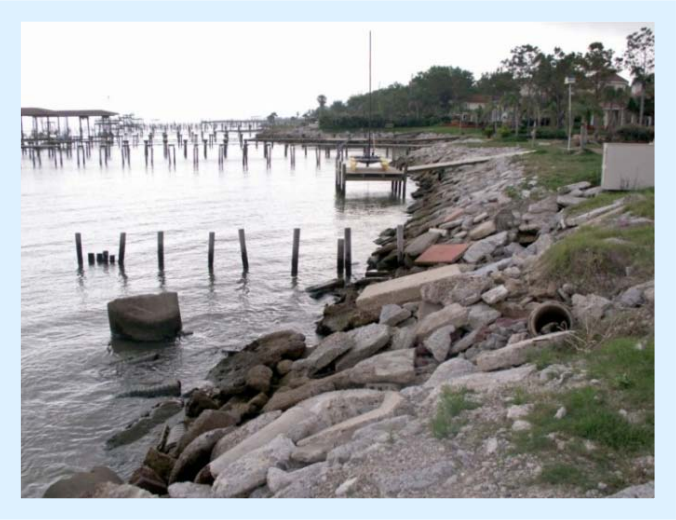

Figure 5.2. Cement riprap along the shore of Galveston Bay.
Image courtesy John Anderson.

Current rates of bay shore retreat along the southwest shore of West Bay average 1 meter per year and are as high as 4 meters per year. In Christmas Bay, which is located west of Galveston Island behind Follets Island (Figure 5.1) and where minimal development has occurred, wetlands are growing. Current laws that are designed to protect wetlands do not take into account their migratory nature. Management of wetland resources will need to address changing conditions.

Trinity Bayhead Delta

Where the Trinity River flows into Trinity Bay, it has formed a large bayhead delta that includes one of the largest single wetland areas in the Galveston Bay Estuary (Figure 5.3). The modern delta plain, that part of the delta that is situated above sea level, covers an area of 16 km^2 and is characterized by smaller distributary channels that actively supply sediment to large bars at their mouths. The Trinity Delta has had a history of growth during the last 2,000 years, which culminated at the end of the past century with the delta extending eastward across the upper part of the bay to form Lake Anahuac (formerly Turtle Bay).

Figure 5.3. The Trinity River Bayhead Delta and associated wetlands.

Sediment cores, collected through the Trinity Delta, sampled a significant amount of sand, which represents the sand delivered to the estuary by the Trinity River. Virtually all of that sand has been encapsulated in the delta, but a small amount of sand is eroded from the western portion of the delta and transported along the west shore of Trinity Bay.

The construction of the Lake Livingston dam has blocked sediment moving down the river to the estuary. Beginning in the early 1900s, the Trinity River mouth was artificially maintained as a navigation channel, resulting in over-extension of the river mouth and significant sediment bypass of the delta. Even though the channel is no longer used for navigation, the river continues to flow through its channel near the town of Anahuac, delivering most of its sediment to the eastern portion of the delta. Only during major floods do the distributary channels along the western portion of the delta deliver sediment to the bay (Figure 5.3). There has not been a significant decrease in the size of the Trinity Delta this century. However, geologists know that the response of deltas to changes in sediment supply is not always instantaneous. In the case of the Trinity Delta, the reduction in sediment supply to the delta was likely offset by increased sediment input to the river resulting from agriculture and land clearing within the drainage basin (Phillips et al. 2004).

Inter-Distributary Bays and Lakes

A number of small bays and lakes, including Lake Anahuac, occur in the upper part of Galveston Bay and along the north shore of East Bay and West Bay (Figure 5.1). These water bodies provide important freshwater habitats and their destiny is closely tied to that of the rest of the estuary.

Lower Estuary and Bolivar Tidal-Delta Complex

The 3 km–wide inlet between the Bolivar Peninsula and Galveston Island is known as the Bolivar Tidal Inlet (Figure 5.1), known to locals as Bolivar Roads. Prior to dredging of the Galveston and Houston ship channel entrance in the early 1900s, this was a natural tidal inlet with a prominent tidal delta that extended both offshore and into Galveston Bay (Siringan et al. 1993). Since the channel was dredged, the tidal delta has shrunk to approximately half its original size, and the inlet has been significantly modified. This is where most of the sand that moved west along Bolivar Peninsula in the longshore transport system was deposited prior to the construction of the north jetty. Now, most of the sand is trapped on the upstream side of the jetty and the tidal delta is no longer being nourished with sand. As a result, the sandy part of the delta has shrunk throughout historical time (Siringan and Anderson 1993).

Coastal Barriers

Bolivar Peninsula

Bolivar Peninsula formed by a process geologists call *spit accretion*, whereby sand is added to the western end of the peninsula by westward flowing longshore currents (Anderson 2007). A detailed study of Bolivar Peninsula by Rodriguez et al. (2004) showed that it is a relatively young barrier, having formed over the last 2,500 years. Its growth was relatively continuous until approximately 800 years ago, when a hurricane destroyed much of the western end of the barrier now located seaward of the current highway. The peninsula seaward of the highway is mostly younger than 800 years old.

As the Bolivar Peninsula grew toward the west, the Bolivar tidal inlet grew narrower. This resulted in gradual alteration of tidal movement in and out of Galveston Bay. The net effect has been a reduction in tidal circulation within the bay, altering its salinity regime. Seismic records from East Bay show that the oyster reefs in the lower part of the bay have migrated through time toward the center of Galveston Bay. This change was likely caused by the change in bay salinity.

The backside of the Bolivar Peninsula is dominated by storm washover deposits that formed during the early phase of barrier evolution (Figure 5.4). The washover deposits provide a framework for the growth of wetlands. They also stand as a reminder of the fact that hurricanes are capable of breaching the peninsula.

Figure 5.4. Storm washover deposits on the Bolivar Peninsula. Image courtesy USGS GlobeXplorer.

Galveston Island

Galveston Island is a typical drumstick-shaped barrier island with prominent beach ridges recording the history of barrier growth since approximately 5,500 years ago (Bernard et al. 1959; Rodriguez et al. 2004). Growth of the island was followed by landward retreat 1,200 years ago, a result of depletion of an offshore source of sand that nourished the island (Anderson 2007). The island is now eroding, both on the Gulf and West Bay sides. Pelican Island, at the east end of Galveston Island, was part of the Bolivar tidal delta in historical time. During the past century it was nourished with sediment dredged from the ship channels, raising its elevation and expanding its area.

Longitudinal Bays

Two subbays—East Bay and West Bay, at either side of Upper and Lower Galveston Bay (Figure 5.1)—were formed as rising sea level inundated the low areas behind Bolivar Peninsula and Galveston Island. The 2 bays differ in that West Bay has a natural tidal inlet (San Luis Pass) at its western end, which results in more vigorous tidal circulation and higher average salinity levels relative to East Bay. Unlike the Bolivar Roads tidal inlet, the San Luis Pass inlet has been unaltered by humans. Hence, sand supply to the delta via the longshore transport system has been unimpeded. Most of the sand eroded from Galveston Island

beaches ultimately ends up in the San Luis tidal delta (Figure 5.5). The sand accumulates in shallow sand bars that provide valuable nesting grounds for birds.

The construction of the Texas City Dike (Figure 5.1) has altered the natural circulation within West Bay by creating a virtual barrier between it and Galveston Bay. The positive effect has been a reduction in sediment transport to West Bay from Galveston Bay, leading to lower sediment concentrations in West Bay. In addition, the construction of the dike likely resulted in a change in the salinity structure of West Bay that reduced the inflow of fresher Galveston Bay water into West Bay, especially during periods of high rainfall and freshwater discharge.

Figure 5.5. The San Luis Pass inlet and tidal delta. Image courtesy USGS GlobeXplorer.

Impact of Sea Level Rise

Sea level has risen over time globally. While the actual rate of rise varies across the globe, the Gulf of Mexico has experienced an increase from 0.4 to 0.6 mm per year for the past 4,000 years to a modern rate of 2.8 mm per year (Milliken et al. 2008) (Figure 5.6a). This is a departure from the long-range trend of decreasing sea level rise over the past 10,000 years (Figure 5.6b).

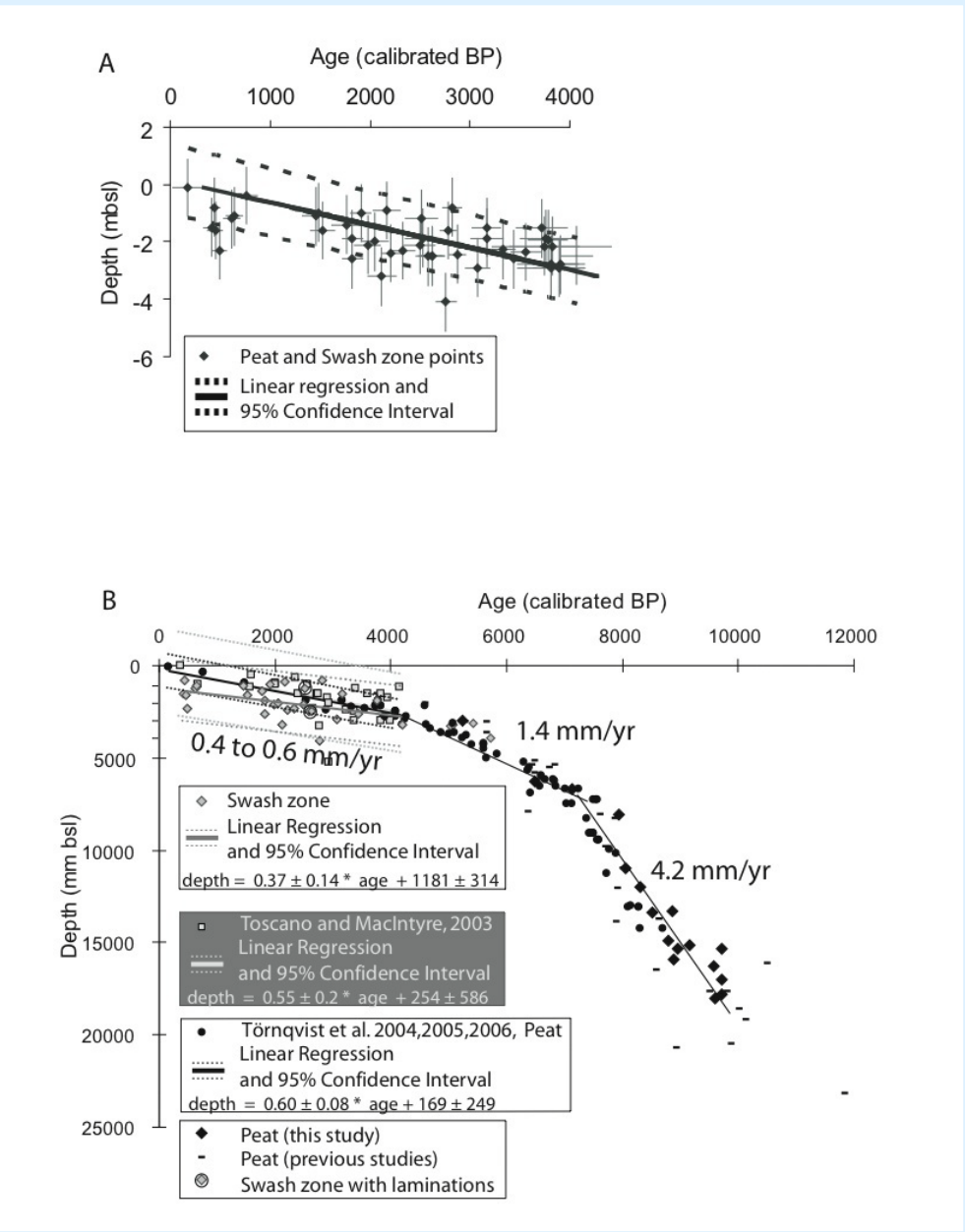

Figure 5.6. Sea level rise in the Gulf of Mexico (a) over the past 4,000 years; (b) over the past 10,000 years. Image from Milliken et al. (2008). Printed with permission from the Geological Society of America.

The relative rate of sea level rise in any given area is due to a combination of *eustasy* (the volume of the ocean based on water quantity and temperature), and *subsidence*. Regional subsidence along the Gulf Coast is the natural response to loading of sediments on the seafloor, which for east Texas is slow (about 0.1 mm per year at the coast). However, subsidence can also be caused through groundwater and hydrocarbon extraction from the shallow subsurface. Within the past century, Galveston Bay and adjacent areas have experienced high rates of subsidence (Figure 4.16) caused by subsurface fluid extraction (Morton et al. 2006), and this has placed considerable stress on wetlands (White et al. 1997; White et al. 2002). Groundwater extraction has slowed, resulting in a significant reduction in the rate of subsidence. Figure 5.7 shows the combination of eustasy and subsidence as observed at Galveston's Pier 21.

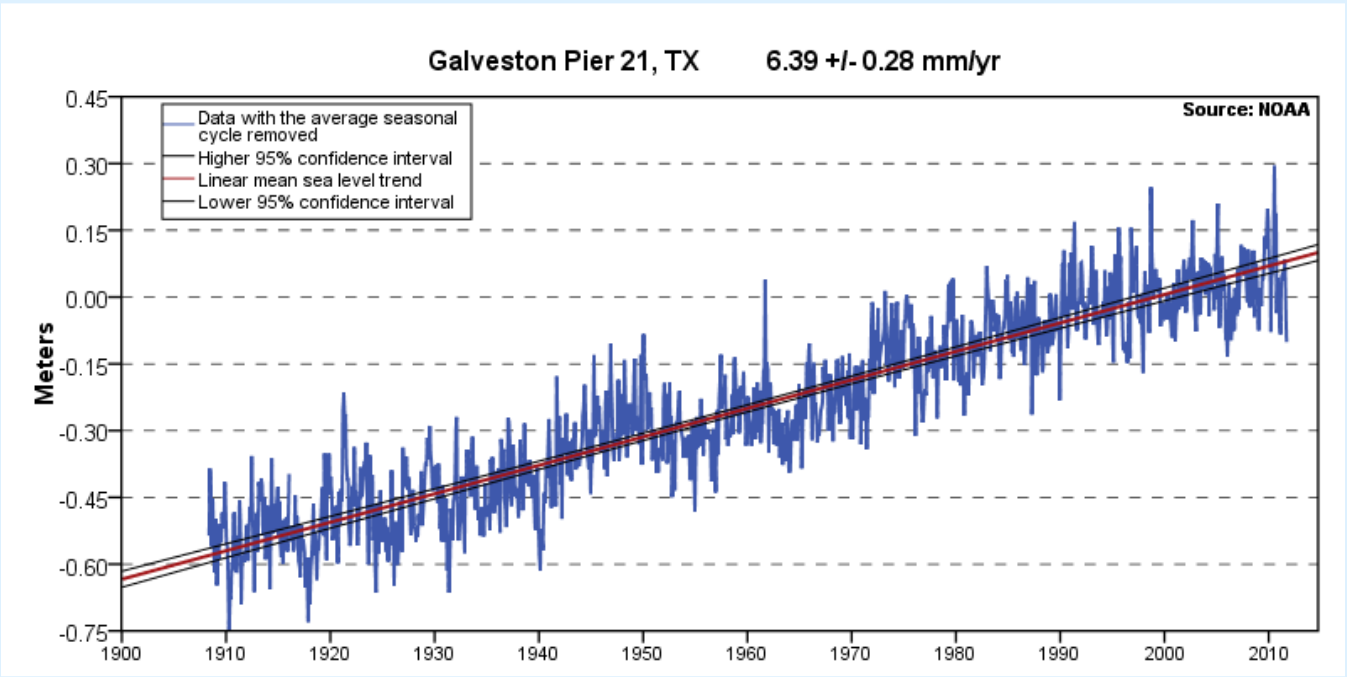

Figure 5.7 . Local relative sea level rise since 1908 based on tide gauge records at Pier 21 in Galveston shows an average rate of 6.39 mm per year from 1908-2006. Data source: (NOAA 2011).

The impact of sea level rise on an estuary is dependent on sediment supply to the estuary. If the rate of sediment supply is great enough to fill the space created by rising sea level, the bay shoreline and wetlands will not be affected. Likewise, even in a stable sea level scenario the bay shoreline and wetlands may experience erosion if the supply of sediment to the estuary decreases. The most important natural factors governing the sediment supply of rivers to estuaries are precipitation, stream discharge, and vegetation cover. Studies have shown that significant changes in sediment supply occur at times when precipitation is changing, especially when the climate changes from more arid to more humid conditions (Fraticelli 2006).

The Galveston Bay Estuary is situated within a part of the Gulf Coast where there is a strong precipitation gradient from east to west (Figure 5.8), so it is highly susceptible to changes in climate. This is supported by the fact that climate varied widely across the region during the past several thousand years as the Earth transitioned out of a glacial period into the current interglacial condition (Toomey et al. 1993). These changes in climate were manifested as changes in precipitation, stream runoff, and the type and density of vegetation along the upper Texas Coast (Nordt et al. 2002). The changes, in turn, led to variations in sediment supply of rivers to the coast.

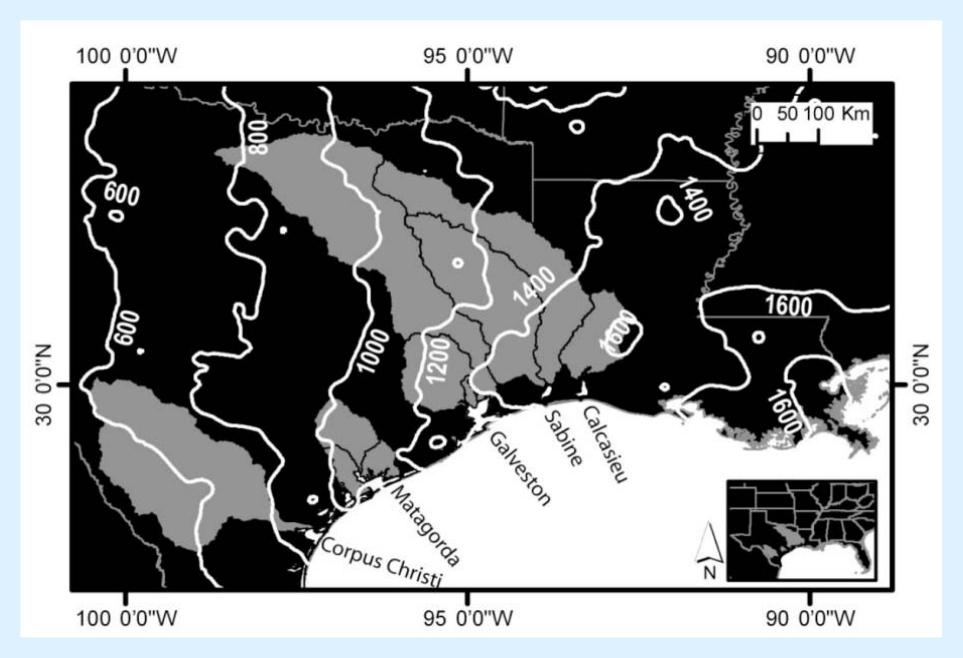

Figure 5.8. The precipitation gradient of the Texas Gulf Coast. Image courtesy of John Anderson.

What will be the impact of relative sea level rise and reduced sediment input to the Galveston Bay Estuary? One way to address this question is to determine how the bay complex responded to past changes in the rate of relative sea level rise and sediment supply.

Let us now examine those changes that occurred in the Galveston Bay Estuary in the past several thousand years as the rate of sea level rise varied from an average of 4.2 mm to 0.4 mm per year (Figure 5.6b). The changes were elucidated through 2 decades of research that initially involved detailed seismic surveys of the bay aimed at mapping the morphology of the Trinity-Sabine incised valley (Smyth et al. 1988). This phase of the research was followed by an examination of the sediments that fill the valley using seismic records and sediment cores. The research led to the discovery that the Galveston Bay Estuary has experienced changes that are far beyond any that have occurred during modern times.

The Evolution of Galveston Bay

We begin our discussion of Galveston Bay's evolution at the last interglacial period, which occurred approximately 120,000 years ago. At that time, the ice sheets were somewhat smaller than today, resulting in a sea level stand approximately 5 meters above present. The shoreline at that time extended from Smith Point across to San Leon (Figure 5.1).

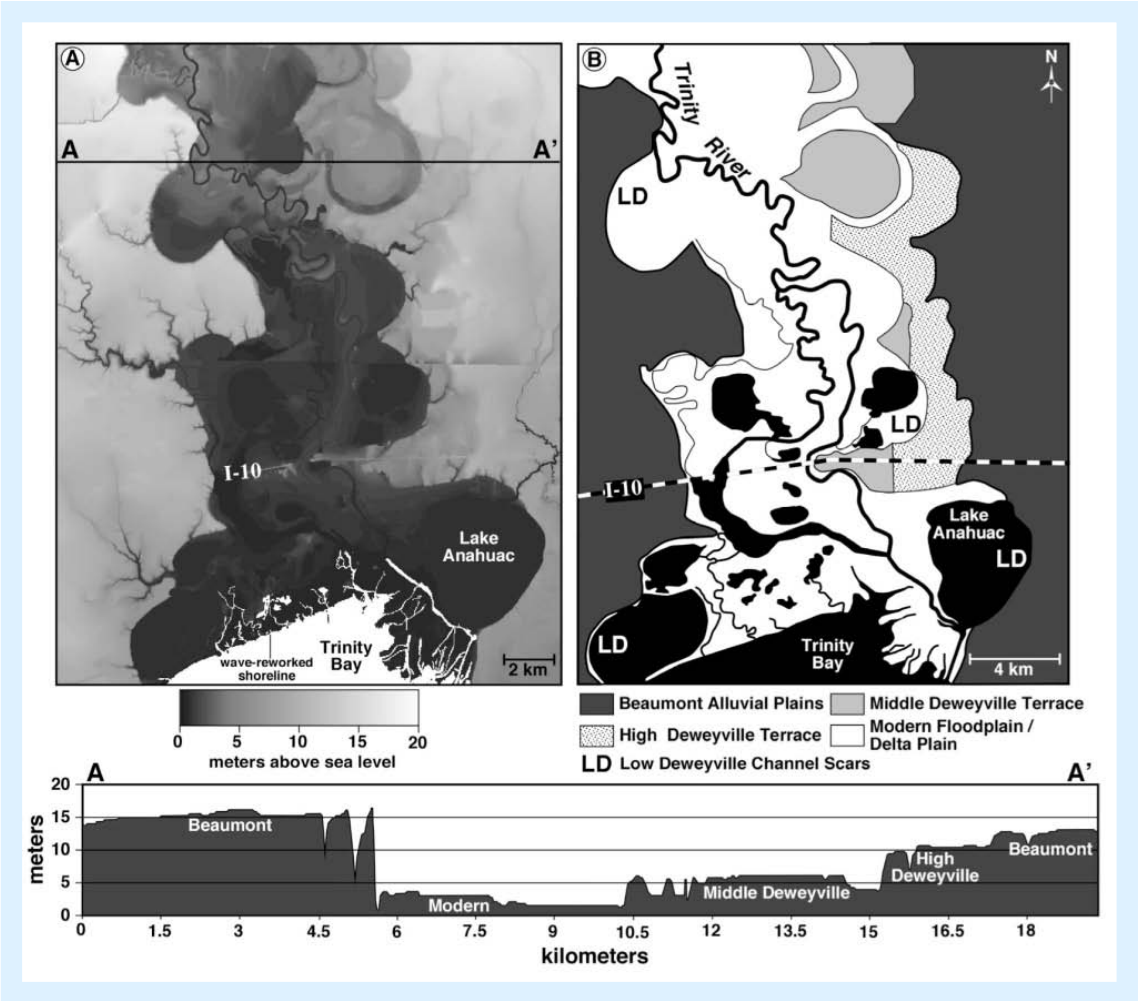

Figure 5.9. The Trinity River formed a broad channel belt that was up to 20 km wide 120,000 years ago. Image from Rodriguez et al. (2005). Printed with permission from the SEPM Society for Sedimentary Geology.

During that time, the Trinity River formed a broad channel belt that was just over 20 kilometers (km) wide, where it is now crossed by Interstate Highway 10 (Figure 5.9). The highstand of sea level was followed by a long period (~120,000 to ~18,000 years ago) during which ice sheets in both hemispheres began to expand, resulting in a gradual fall of sea level. As sea level fell and the shoreline shifted south across the continental shelf, the Trinity and San Jacinto river valleys were incised and the morphology of the valleys changed from that of broad meander belts to narrower and deeper valleys. The fall in sea level was episodic in nature; resulting in the formation of terraces in the upper part of the valleys (Blum et al. 1995; Morton et al. 1996; Rodriguez et al. 2005) (Figure 5.9). The valley extended across the continental shelf and merged with the Sabine River valley approximately 40 km offshore of the current shoreline. The sea level fall culminated at –120 meters, with the shoreline located at the edge of the continental shelf, approximately 150 km south of its current position. During the maximum lowstand, the Trinity River cut a valley that was 35–40 meters deep near the present coast.

Figure 5.10 shows a map of the incised Trinity–San Jacinto river valley, which was flooded by rising sea level during the past 9,500 years to create modern Galveston Bay. Note that the valley is deep and narrow near its center and has a broader, terraced morphology along its margins (Figure 5.9). Again, this morphology reflects the episodic fall of sea level that influenced river down-cutting.

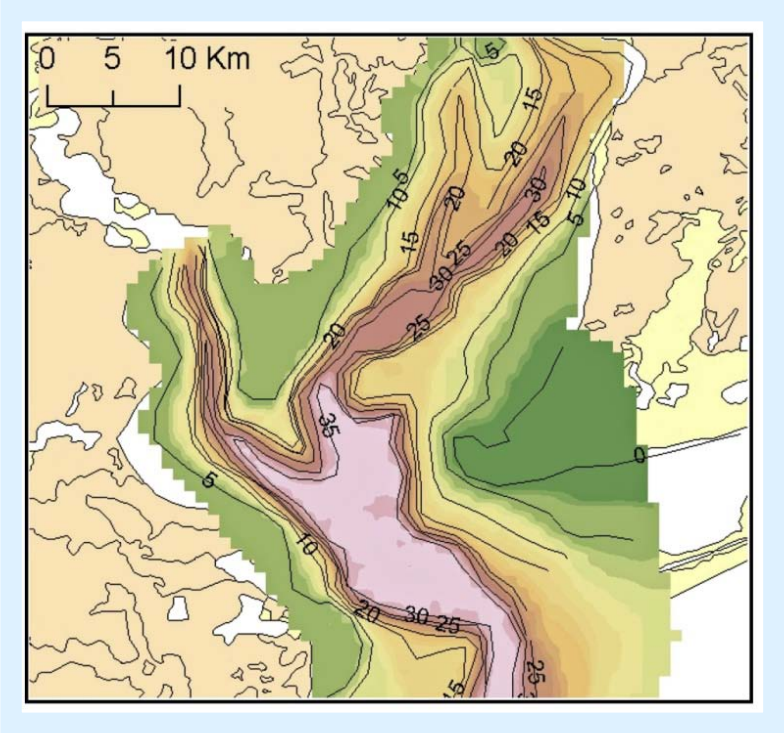

Figure 5.10. The Trinity–San Jacinto river valley was flooded by rising sea level during the past 9,500 years to create modern Galveston Bay. Image courtesy Kristy Milliken.

As sea level began to rise, approximately 17,000 years ago, the Trinity–San Jacinto incised river valley was flooded and filled with sediment. The overall valley-fill succession includes river sands and gravels at the base of the valley that were deposited during the lowstand and initial rise in sea level. These river deposits are overlain by organic-rich mud that represents bayhead delta deposits. These are, in turn, overlain by open bay deposits, which consist mainly of gray mud with oyster shells. Cores collected in the southern part of the bay sampled layers of shell debris and well-sorted sand. These are interpreted as tidal inlet and tidal delta deposits, respectively. This overall succession records the gradual flooding of the valley, or deepening of the water within the bay, and landward shift in estuarine environments.

Knowing the shape of the old river valley that was flooded to create Galveston Bay and given our knowledge of the rate of sea level rise over the past 10,000 years (Figure 5.6), we are able to describe its flooding history. We might envisage that initial flooding of the deep, narrow portion of the valley resulted in a deep, narrow estuary and that the estuary became wider and shallower as the broad shoulders of the valley were flooded. In general, such was the case and ancestral Galveston Bay looked much like modern Chesapeake Bay during its early history. As sea level continued to rise and flood the broad shoulders of the valley, the bay took on its current, more rounded shape, which still bears the outline of old river meanders.

Seismic profiles from Galveston Bay yield images of sediment layers that record changes in the bay setting over time. This is illustrated in Figure 5.11, which shows a seismic record collected in the upper part of the bay. The individual reflections in this seismic record can be thought of as sediment layers. Note that the upper part of the section contains parallel layers, which are indicative of sediments that were deposited in an open estuary setting. The parallel layers rest sharply on a unit containing concave layers that are interpreted as small channels of a bay-head delta. These channels have depth-to-width ratios similar to

modern distributary channels of the Trinity bay-head delta. The observations suggest that the bay setting at this location changed at some point in time, from a subaerial delta plain to an open bay setting. The abrupt nature of the surface separating the 2 seismic units suggests that the change occurred rapidly.

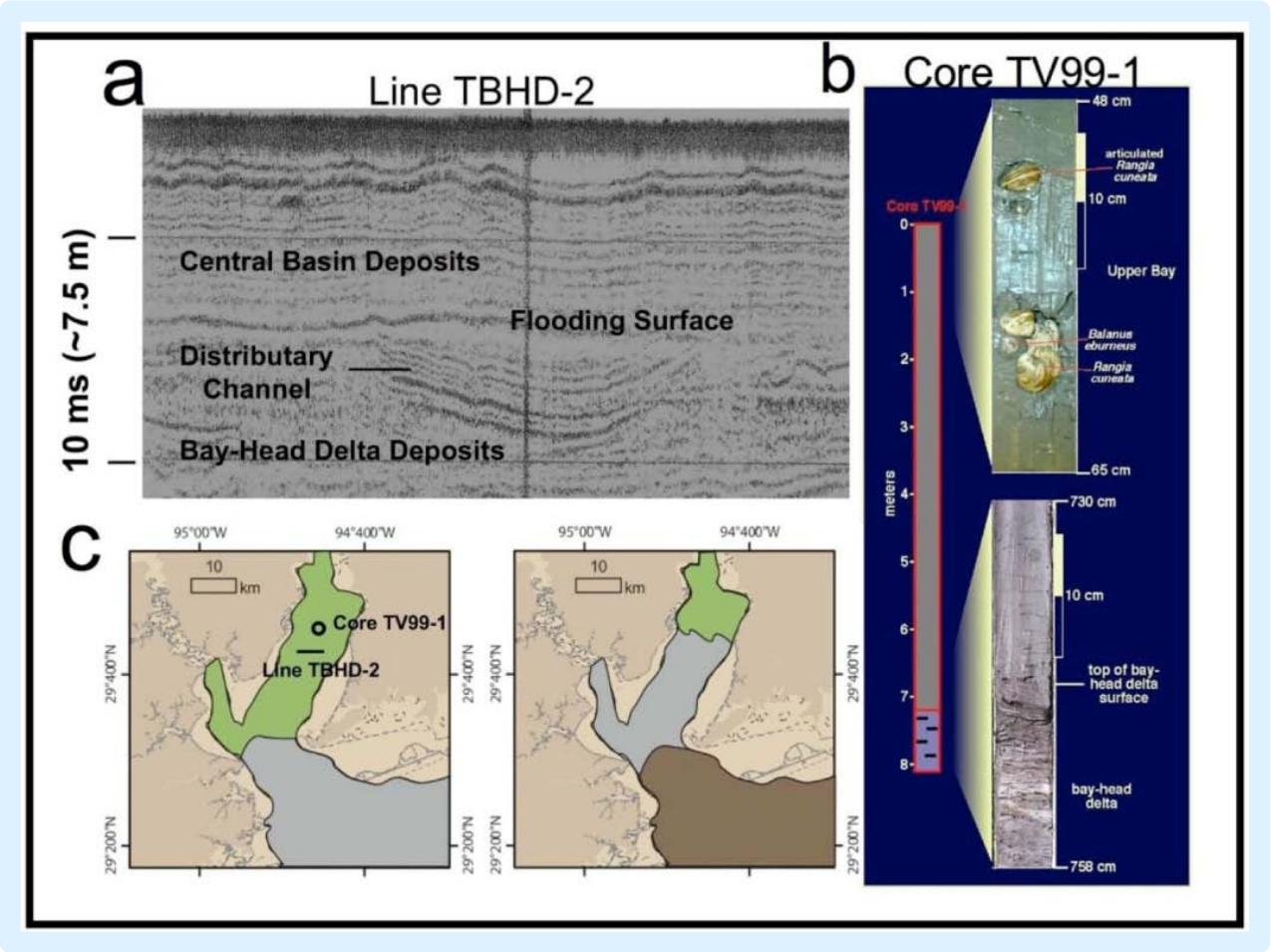

Figure 5.11. (a) Seismic record from upper Trinity Bay. (b) Photograph and core log for core TV99-1 from upper Trinity Bay. (c) Maps show changes in Galveston Bay before and after the flooding event recorded by the seismic record and sediment core. Green is the bayhead delta, gray is open bay, and brown is the lower bay environment. Also shown are the locations of the seismic line and core. Image courtesy John Anderson.

Next, a sediment core was collected from the locality of interest to directly sample the 2 seismic units and allow us to test our interpretations. A small drilling barge (Figure 5.12) was used to acquire sediment core TV99-1 (Figure 5.11). The sample contained greenish mud with oyster and *Rangia* shells in the upper few meters of the core. Below this unit, the core sampled dark gray mud with abundant organic material. The upper unit was interpreted as bay mud; the lower, as a delta plain deposit, based on the similarity of these units to modern sediments and the presence of distributary channels that were imaged in seismic records. Missing in the core were the sandy sediments that are today accumulating in sand lobes around the delta margin.

Figure 5.12. Drilling barge. Image courtesy John Anderson.

The sequence sampled in core TV99-1 and imaged in seismic profile TBHD-2 (Figure 5.11) represents the history of a bayhead delta submerged to create an open bay setting. Geologists refer to a surface that separates landward deposits below, from open bay or marine deposits above, as a flooding surface. Using these results and those from other seismic records and cores, we were able to identify and map a number of flooding surfaces throughout the bay (Figure 5.13). Using these same data, we are able to interpret the changes in estuarine environments marked by these surfaces and to map the extent of these environments before and after each flooding event (Figure 5.13). In the example shown, the bayhead delta shifted up the old river valley nearly 30 km during the flooding event and the area of Galveston Bay expanded by nearly 30 percent. The question is, how fast did this flooding event occur, and what caused it?

We measure the rate of change associated with a flooding event using radiocarbon ages from shells collected above and below flooding surfaces in sediment cores. There is an element of imprecision in this approach because radiocarbon ages may vary depending on the amount of old (reworked) carbon that resides within a particular bay system. For Galveston Bay, we know that the age measured is actually around 500 years older than the actual age, so we have to correct for this effect (Milliken et al. 2008). Having done that, we are able to constrain the age of a shell to within a century or two at most. If we acquire multiple ages from the same surface at a number of different locations within the bay, the range of uncertainty is decreased. Figure 5.13 also shows the ages of the flooding surfaces at different drill sites.

Our results indicate that the evolution of the Galveston Bay Estuary was punctuated by abrupt flooding events that resulted in landward shifts in the bayhead delta and re-organization of estuarine environments within a few centuries. Rates of bayhead delta migration were as high as 150 meters per year. The questions we ultimately want to answer are (1) what caused these events, and (2) what is the probability that similar changes will occur in the next few centuries, given different scenarios for sea level rise and reductions in sediment supply?

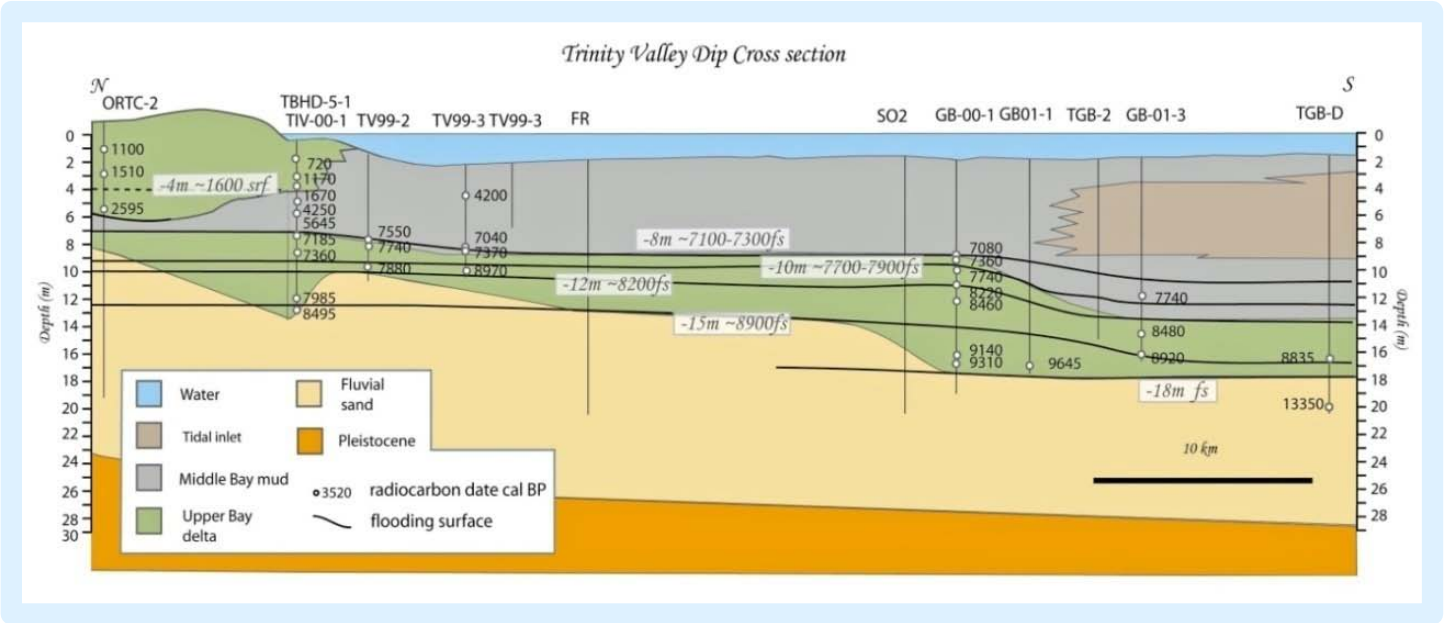

Figure 5.13. This Trinity Valley cross-section was constructed using seismic data and sediment cores collected along the axis of the bay, from Bolivar Inlet to the Trinity Delta. The cross-section depicts the location and ages of past flooding surfaces throughout the bay. Image courtesy John Anderson. Printed with permission from the Geological Society of America.

The initial flooding of the onshore portion of the ancestral Trinity River valley approximately 9,600 years ago occurred when sea level was rising rapidly and perhaps episodically (Figure 5.6b). Likewise, the 8,500-year flooding occurred during rapid sea level rise. The most widespread flooding occurred ~7,900 to ~7,700 calibrated years before the present (cal years B.P.) as the rate of sea level rise was decreasing from an average rate of 4.2 mm per year to 1.4 mm per year (Figure 5.6b), so sediment supply to the bay must have also contributed to this flooding event. While the climate history of east Texas is poorly known, it is generally accepted that the climate was in transition from cool and moist to warm and dry during this time interval (Toomey et al. 1993; Nordt et al. 2002). This suggests that changes in climate and associated vegetation changes within the drainage basin led to decreased sediment supply to the bay.

The Trinity River bayhead delta started to prograde into the upper estuary ~2,600 calibrated (cal) years B.P., well after the rate of sea level rise had decreased to between 0.4 and 0.6 mm per year (Figure 5.6). The rate of growth of the delta increased dramatically after ~1,600 cal years B.P., which indicates an increase in sediment supply. This increase may also mark the beginning of agricultural activity by Native Americans in the drainage basin of the river. Since ~1,600 cal years B.P., the main geological changes within the Galveston Bay Estuary setting were the continued westward growth of the Bolivar Peninsula and associated narrowing of the Bolivar tidal inlet that led to the current circulation and salinity structure of the bay (Figure 5.1).

Summary

The evolution of the Galveston Bay Estuary was punctuated by rapid changes, most of which occurred when sea level was rising at a rate slightly faster than present (average of 4.2 mm per year versus current rate of 2.8 mm per year) and when regional climate was changing. The most important modifications included changes in precipitation and the resultant changes in vegetation and sediment supply to the system. Other Texas estuaries, including Sabine Lake (Milliken et al. 2008); Matagorda Bay (Maddox et al. 2008); and Corpus Christi Bay (Simms et al. 2008) have experienced similar changes.

In the geological record, the Trinity bayhead delta has been shown to be especially vulnerable to rapid sea level rise and variations in sediment supply. In the past, the delta has had a threshold response to these changes that was manifested as virtual destruction of the delta followed by reoccupation of the delta in a more landward location. This, in turn, had impacts on the other estuarine environments. We should begin monitoring changes in the delta and thinking about ways to mitigate impacts.

Figure 5.14. Bolivar Roads at sunrise. Image © Jarrett Woodrow.

Hurricane Ike—Ecological Impacts

By L. James Lester

Hurricanes are a periodic disturbance to the ecology of the Galveston Bay watershed. Since the compilation of U.S. records began in 1851, 7 major hurricanes (Category 3, 4 or 5) have struck the Upper Texas Coast; about one major hurricane every 20 years. The Galveston Bay area experienced direct hits from hurricanes (defined as the eye of the storm making landfall in the lower Galveston Bay watershed) in 1900, 1915, 1932, 1949, 1959, 1983, 1989, and 2008. All of these events must have been associated with qualitatively similar ecological impacts. However, it would have been difficult in 2007 to identify any ecological effects of Hurricane Alicia, which crossed the middle of Galveston Island in 1983 or, in 1982, to identify remaining ecological impacts from Debra, which crossed at San Luis Pass in 1959. Estuarine systems are changing constantly; they respond to many temporal cycles and stresses, including hurricanes.

Figure 5.15. The area in brown below the yellow line represents the extent of vegetation damaged by the storm surge of Hurricane Ike. Only a few isolated patches of vegetation survived, most conspicuously on High Island. False-color satellite image taken Sept. 28, 2008, courtesy NASA/GSFC/METI/ERSDAC/JAROS, and US/Japan ASTER Science Team.

Hurricane Ike was not a major hurricane according to the Saffir-Simpson Hurricane Wind Scale, but it was accompanied by a major storm surge. The storm surge that hit the Galveston Bay region in September 2008 had large ecological impacts, but ecological systems that are adapted to the Texas coast are resilient to such changes. Only those ecological impacts caused by anthropogenic stressors, such as toxic chemical spills, are likely to significantly alter the ecological system on a decadal scale.

The storm surge from Hurricane Ike inundated the wetlands surrounding Galveston Bay, as seen in Figure 5.15. The false-color, infrared image shows the vegetation dying from salinity shock (areas in red depict living vegetation, areas in brown lack living vegetation). The saline water that produced this effect drained out of the marshes soon after the storm passed over the area, but the soil of the area was left with an elevated salinity that can only be reduced by flushing or leaching with freshwater from runoff or precipitation. To the extent that the salinity of soil in an area is permanently increased due to changes in the elevation or topography of an area, the storm will have changed the biological community for a long time. Initial reports suggest that there are areas on the eastern side of the bay where Ike changed freshwater marshes to brackish and brackish to salt (FEMA 2008).

A substantial quantity of sediment was suspended in the storm surge of Ike. Some of that sediment was deposited in the bay and buried benthic communities. It is not clear whether the storm added sediment to the bay, but it certainly redistributed sediment with deleterious impacts on some communities. Much of the area covered by the storm-deposited sediment was populated by a soft sediment biological community before the storm and will be recolonized by a similar biological community in the months and years following the storm. Of greatest significance for the ecological characteristics of the bay is the area of oyster reefs buried by sediment. The Texas Parks and Wildlife Department (TPWD) estimates that Ike buried around 60 percent of the living consolidated oyster reef area in the bay and 80 percent in East Bay. It will take time for the oysters of the bay to build new reefs as large as those that existed in 2007. As noted above, there have been multiple storm surges into Galveston Bay in history, and the oysters had rebuilt to the extent shown in the maps in Chapter 7. Our current concern should be the impact of a depleted oyster population on environmental quality in the bay and the status of the fishery during the rebuilding process.

Figure 5.16. Hurricane Ike flood waters draining near Old River and I-10. Image courtesy Texas Civil Air Patrol.

Whenever there is a major storm surge or flood event that produces a large flow of nutrient-rich water draining from the surrounding marshes, there are fish kills (Figure 5.16). As the flood waters of Ike drained from the marshes, many fish kills were noted (FEMA 2008). Most of the dead fish were likely menhaden and mullet, which have large populations and high reproductive rates. Even if the mortalities were in the millions, these species should recover in a few years.

As the surge moved through areas of human development, it picked up contaminants and solid waste that were carried into the bay. Nearly 200 spills of toxic chemicals were reported (FEMA 2008) and many more unreported small spills occurred when homes, stores and office buildings flooded. Approximately 3,000 acres in the High Island–East Bay area were affected by visible oil sheens, and 500 to 2,000 acres in the Anahuac, McFaddin, and Sabine National Wildlife Refuges suffered spills (FEMA 2008). Despite their common use, household chemicals (e.g. cleaning fluids and pesticides) are often toxic in the environment. The quantity of toxic compounds released from debris and the exact spatial distribution of small releases will never be known. Most synthetic organic compounds can be degraded by physical or biological processes. A few types of pollutants will remain in the sediments for a very long time but are rather quickly buried.

Some monitoring of oil spills occurred after the storm. Spills were documented on the water and in the wetlands surrounding the bay (Figure 5.17). Volatile compounds evaporate, but the heavy compounds can remain in the sediments for a long time until processed by

bacteria. In a subtropical climate, like Southeast Texas, bacterial action is fast, and small volume spills will be digested in a few years. Deeper layers of oil will take much longer.

Solid debris is scattered in and around the bay, including several hundred partially submerged boats and construction materials from hundreds of houses. Debris deposition had obvious local effects on the plants and animals in the area, but recovery of most habitats can occur rather quickly after removal. Some of the materials will not be located in the early aftermath of the hurricane and will be gradually removed over the next 20 years. In some cases the organisms will make use of the debris, e.g., hard substrate for oyster spat to settle on.

Figure 5.17. Spills were documented on water and in wetlands surrounding the bay. The above photos were taken in the days after Hurricane Ike made landfall. Image courtesy NOAA.

Some ecological processes have already recovered; water circulation and tidal flows recovered as soon as the storm passed. The flow of nutrients will be affected longer, as the dead marsh plants contribute much more detritus than normal to the system. Organisms with short life spans that live in the water column and in soft sediments will return to pre-storm dynamics in the next year or two. Organisms that reproduce more slowly or live in the complex ecology of oyster reefs will take much longer. It is likely that most components of the Galveston Bay system have resilience that matches the periodicity of the hurricanes. If that is true, then the ecological services of Galveston Bay should recover from the hurricane in 20 years or less.

Galveston County's waterfront communities have been challenged many times by extreme weather events, but nothing on the magnitude of Hurricane Ike. The storm's devastating surge ripped apart homes, scoured beaches, destroyed landmark businesses and eroded the decades-old character of many coastal neighborhoods. Shortly after the storm, it did not seem possible that Bolivar Peninsula or the sleepy fishing towns lining the shores of Galveston Bay would ever recover, given the extent of destruction. But the residents of these communities are a resilient breed, and they were determined to preserve a peaceful way of life that is so closely tied to the bays and bayous. Friends, neighbors and volunteers from across the country joined with county government and our state and federal partners to clean up debris, remove hundreds of abandoned cars and boats—from both land and water—and restore infrastructure to enable homeowners to rebuild. Our coastal communities survived and are coming back bigger and better than ever. New homes built to better standards are being raised, roadways are being rebuilt and elevated, generators are being installed to keep water and sewer lines flowing properly, and trees are being planted to replace those killed by the salty surge. Disasters bring federal dollars and once-in-a-lifetime opportunities. Galveston County is working to use these dollars in ways that ensure our precious coastal way of life is protected and better able to withstand what Mother Nature sends our way.

—Galveston County Judge Jim Yarbrough, 2009

Literature Cited

Anderson, J. B. 2007. *The Formation and Future of the Upper Texas Coast*. College Station, Texas: Texas A&M Press.

Bernard, H. A., C. F. Major, and B. S. Parrot. 1959. "The Galveston barrier island and environs: a model for predicting reservoir occurrence and trend." *Gulf Coast Association of Geological Society Transactions* no. 9:221-224.

Blum, M. D., R. A. Morton, and J. M. Durbin. 1995. " Deweyville terraces and deposits of the Texas Gulf Coastal Plain." *Gulf Coast Association of Geological Societies Transactions* no. 45:53-60.

FEMA. 2008. Hurricane Ike preliminary recovery assessment: Hurricane Ike impact report.

Fraticelli, C. M. 2006. "Climate forcing in a wave-dominated delta: The effects of drought-flood cycles on delta progradation." *Journal of Sedimentary Research* no. 76 (9-10):1067-1076.

Graves, J. 1971. *The Water Hustlers*, edited by R.H. Boyle, J. Graves and T.H. Watkins, 253. San Francisco, California: Sierra Club.

Mace, R. E., S. C. Davidson, E. S. Angle, and W. F. Mullican II. 2006. Aquifers of the Gulf Coast of Texas, Texas Water Development Board Report 365. edited by Texas Water Development Board. Austin, Texas.

Maddox, J., J. B. Anderson, K. Milliken, A. B. Rodriguez, T. M. Dellapenna, and L. J. B. Giosan. 2008. "The Holocene evolution of Matagorda/Lavaca Bay estuary complex, Texas." In *Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise*, edited by Anderson and A.B. Rodriguez, 105-119. Geological Society of America

Milliken, K. T., J. B. Anderson, and A. B. Rodriguez. 2008. "A new composite Holocene sea-level curve for the northern Gulf of Mexico." In *Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise*, edited by J.B. Anderson and A.B. Rodriguez, 1-12. Geological Society of America Special Paper 443.

Morton, R. A., J. C. Bernier, and J. A. Barras. 2006. "Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA." *Environmental Geology* no. 50 (2):261-274.

Morton, R. A., M. D. Blum, and W.A. White. 1996. "Valley fills of incised coastal plain rivers." *Gulf Coast Association of Geological Society Transactions* no. 46:321-331.

NOAA. *Sea Levels Online, Mean Sea Level Trend 8771450 Galveston Pier 21, Texas*. National Oceanic and Atmospheric Administration (NOAA), Center for Operational Oceanographic Products and Services (CO-OPS) 2011 [cited 29 November 2011. Available from http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8771450.

Nordt, L. C., T. W. Boutton, J. S. Jacob, and R. D. Mandel. 2002. "C4 plant productivity and climate-CO2 variations in south-central Texas during the Late Quaternary." *Quaternary Research* no. 58:182-188.

Paine, J. G., and R. A. Morton. 1986. Historical shoreline changes in Trinity, Galveston, West and East Bays, Texas Gulf Coast. Austin, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geology Circular 86-3.

Phillips, J. D., M. C. Slattery, and Z. A. Musselman. 2004. "Dam-to-delta sediment inputs and storage in the lower Trinity River, Texas." *Geomorphology* no. 62 (1-2):17-34.

Rodriguez, A. B., J. B. Anderson, and A. R. Simms. 2005. "Terrace inundation as an autocyclic mechanism for parasequence formation: Galveston Estuary, Texas, USA." *Journal of Sedimentary Research* no. 75 (4):608-620.

Rodriguez, A. B., J. B. Anderson, F. P. Siringan, and M. Taviani. 2004. "Holocene evolution of the east Texas coast and inner continental shelf: Along-strike variability in coastal retreat rates." *Journal of Sedimentary Research* no. 74 (3):405-421.

Simms, A. R., J. B. Anderson, A. B. Rodriguez, and M. Taviani. 2008. "Mechanisms controlling environmental change within an estuary: Corpus Christi Bay, Texas, USA." In *Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise*, edited by J.B. Anderson and A.B. Rodriguez, 121-146.

Siringan, F. P., and J. B. Anderson. 1993. "Seismic facies, architecture, and evolution of the Bolivar Roads tidal inlet/delta complex, East Texas Gulf Coast." *Journal of Sedimentary Geology* no. 63:794-808.

Smyth, W. C., J. B. Anderson, and M. A. Thomas. 1988. "Seismic facies analysis of entrenched valley-fill: a case study of the Galveston Bay area, Texas." *Gulf Coast Association of Geological Societies Transactions* no. 38:385-394.

Toomey, R. S., M. D. Blum, and S. Valastro Jr. 1993. "Late Quaternary climates and environments of the Edwards Plateau, Texas." *Global and Planetary Change* no. 7:299-320.

White, W. A., and R. A. Morton. 1997. "Wetland losses related to fault movement and hydrocarbon production, southeastern Texas coast." *Journal of Coastal Research* no. 13:1305-1320.

White, W. A., R. A. Morton, and C. W. Holmes. 2002. "A comparison of factors controlling sedimentation rates and wetland loss in fluvial-deltaic systems." *Texas Gulf coast Geomorphology* no. 44:47-66.