Subsidence and the Changing Shoreline
THE EPISODIC EVOLUTION OF GALVESTON BAY: IMPLICATIONS FOR FUTURE RESPONSE TO GLOBAL CHANGE

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Abstract
We report here the preliminary results of a geological investigation into the evolution of Galveston Bay. The information gained from this study is needed to predict the response of the bay and adjacent wetlands to increased rates of sea-level rise and climate change over the next one to two centuries.

The modern Galveston Bay estuary has evolved over the past 11,000 years by flooding of the ancestral Trinity/Sabine river valley. The retreating coastal environments that occupied the valley, which include the river, its bayhead delta, the middle bay environment, and the lower bay tidally influenced environment, have retreated landward in a series of abrupt shifts of many kilometers. Available radiocarbon age data suggests that these dramatic environmental changes occurred over time intervals of decades to a few centuries.

Forecasting coastal change within the Galveston Bay complex over the next two centuries is not possible given our current knowledge of the system. But, its geological record suggests that significant changes will occur within the next two centuries if even modest global change predictions prove valid. The main uncertainties in forecasting the extent of coastal change in the region are: (1) the rate of vertical accretion of various coastal environments, (2) those factors that regulate local subsidence, (3) the impact of climate change on sediment discharge from the Trinity and Sabine rivers, and (4) the impact of increased storm frequency.

Introduction
One of the key questions raised in various global change scenarios concerns the potential impact of global warming on sea level, specifically the magnitude and rate of sea-level rise that will occur over the next century. There is little question that the rate of rise will accelerate. Indeed, the rate has already begun to increase based on long-term tide gauge records (Hicks, 1978; Gornitz and Lefedeff, 1987; Douglas, 1991) and radiocarbon dating of ancient salt marsh deposits (Varekamp and Thomas, 1998), though the cause of this recent increase is problematic. It is also clear that an increased rate of sea-level rise will have a number of adverse impacts on world coasts, such as wetland loss and accelerated coastal erosion.

Modern coasts and estuaries evolved during an interval of relatively slow sea-level rise (15 to 25 cm/century) over the past 4,000 years. Prior to this time, sea level was rising at a much faster rate (average 50 cm/century), in response to ice sheet melting in both hemispheres. Early
coastal inhabitants were conditioned to rapidly advancing shorelines and associated changes in coastal environments. During the past 10,000 years, the east Texas coast has retreated landward approximately 50 kilometers, or at an average rate of 5m/yr. This is five times the current rate of coastal retreat. The Louisiana coast experienced even greater changes during this time, with substantial loss to coastal wetlands (Penland et al., 1988). The U.S. Gulf Coast is one of the most vulnerable coasts to accelerated sea-level rise because the area is characterized by high rates of coastal subsidence (locally in excess of 200 cm/century). This is particularly true for Louisiana and east Texas.

The predicted rates of sea-level rise from global warming by the year 2100 range from 20-23 cm/century to 86-96 cm/century (Warrick et al., 1996), with the main uncertainty in this prediction being the stability of polar ice sheets, particularly the West Antarctic Ice Sheet. A more conservative estimate of 49-55 cm/century (Warrick et al., 1996) is close to the average rate of sea-level rise during the Holocene (10,000 yrs BP to Present). This being the case, we should be able to better predict coastal response to accelerated sea-level rise by examining the geological record of coastal change during the Holocene. Compounding the impact of sea-level rise will be the increased frequency of tropical storms due to warmer atmospheric and surface water temperatures. Here we report preliminary results of an investigation into the geological history of Galveston Bay and document profound changes that have occurred in the bay during the past 8,000 years, roughly the time humans have inhabited its shoreline.

Results
During the last glaciation (22,000 to 16,000 yrs BP), sea level was approximately 120 meters below present levels and the east Texas shoreline was situated about 120 kilometers south of its present location. The Trinity, Sabine and Brazos rivers converged on the continental shelf and cut a deep valley that extended to the edge of the continental shelf (Thomas and Anderson, 1994), (Fig. 1). This former river valley is approximately 40 meters deep beneath Bolivar Roads (Anderson et al., 1996).

The first phase of this project involved the acquisition of high-resolution seismic data to map the incised river valley and the deposits that fill it. This was followed by the acquisition of long sediment cores through the bay strata. In general, the bay stratigraphy consists of river deposits in the base of the valley, overlain by organic-rich restricted bay and bayhead delta deposits and capped by middle and lower (tide-influenced) bay deposits (Smyth et al., 1988; Anderson et al., 1991). We were surprised to observe that these deposits, and the environments they represent, have stepped landward distances of several kilometers and that the flooding surfaces across which these changes occurred are quite sharp (Thomas and Anderson, 1994) (Fig. 2). This implies that landward shifts in coastal environments and their associated ecosystems occurred rapidly. The elevation of these surfaces is controlled, in part, by pre-existing fluvial topography; specifically the occurrence of relatively flat terraces that were inundated by the overall rise. In addition, there may have been times when the rate of sea-level rise was too fast for coastal systems to adjust by upward growth (Anderson et al., 1991).

The modern Galveston Bay estuary was initially flooded about 11,000 yrs BP (Rehkemper, 1969; Smyth et al., 1988). At that time the ancestral Trinity River delta was situated near
Bolivar Roads. By approximately 9,000 yrs BP the river delta had shifted north to a mid-bay location where a pronounced topographic step exists between Smith Point and San Leon. The shoreline at that time was located approximately 50 kilometers south of its present position. Heald Bank and Shepard Bank are remnants of barriers that were situated adjacent to the bay mouth (Rodriguez et al., 1999 (Fig. 1). At approximately 7,600 yrs BP, sea level reached the top of this step and flooded the relatively flat region to the north to create Trinity Bay. At about this time, the shoreline shifted landward to a new location coincident with Sabine Bank (Rodriguez et al., 1999). The ancestral Trinity Bay estuary was quite different from the modern bay. It was a shallow, brackish bay that filled with organic-rich sediments that contain only traces of benthic life. The next phase of bay evolution also appears to have occurred abruptly, as indicated by a prominent flooding surface in seismic records and a sharp contact between brackish bay sediments and overlying bay muds with abundant mollusk shells, including oysters. We are awaiting the results of radiocarbon ages that will help constrain the age of this final flooding event. We do know that sometime prior to 3,500 yrs BP the shoreline rapidly shifted northward to approximately its present location and that the Sabine Bank barrier was drowned in place (Rodriguez et al., 1999).
Figure 1. - Map of the east Texas shelf and coast showing the location of the ancestral Trinity and Sabine river valleys (gray shaded area) that were flooded by the rising sea to create the Galveston Bay and Sabine Lake estuaries. Also shown are the locations of Shepard, Heald and Sabine banks, which are former barrier islands. The location of profile A-A' (Figure 2) along the axis of Galveston Bay is also shown.
Figure 2. Cross section A-A' through Galveston Bay showing flooding surfaces at ~10 and ~14 meters separating river, bayhead delta and open bay deposits. These flooding surfaces represent times when the bay environments shifted landward several kilometers. The rate at which these changes occurred is being investigated.
Since about 3,500 years ago the bay shore has retreated slowly, which is consistent with global sea-level records of generally slow rise during this time interval. The modern Bolivar and Galveston barriers also evolved during this time interval, which resulted in the restriction of Bolivar Roads inlet and associated changes in tidal circulation within the bay.

In summary, the record of shoreline retreat is one of overstepping or in place drowning of barriers (Rodriguez et al., 1999). This is consistent with abrupt backstepping of bay environments (Anderson et al., 1991; Thomas and Anderson, 1994). Thus, the bay setting shifts from one with barriers and a narrow tidal inlet to one that is more open to the Gulf? This implies dramatic changes in tidal circulation and the salinity structure of the bay. Existing data show that Bolivar Roads grew narrower by several kilometers during the last few thousand years and that the Bolivar flood tidal delta shrunk in size (Siringan and Anderson, 1993). But, the full extent of changes in the tidal inlet and associated changes on the bay’s ecosystem remains problematic. These changes should be recorded in the bay deposits. What is clear is that the evolution of the barriers and the bay are closely linked.

The next issue that has to be addressed is how the bay will respond to the predicted increase in the rate of sea-level rise and climate change (e.g. possible increased storm frequency and decreased sediment discharge from Trinity and Sabine rivers) over the next few centuries. Future work must focus on establishing the long-term vertical accretion rate of the wetlands and other coastal environments. We must also determine subsidence rates throughout the Galveston Bay Complex. Indeed, this information is necessary if we are going to understand current wetlands retreat. Measured coastal subsidence rates vary by about an order of magnitude within the region. This reflects differences in the thickness and character of Holocene sediments. It is also important to establish the capacity of the Bolivar and Galveston barriers to withstand an increased rate of sea-level rise and greater storm frequency. The sandbanks that occur offshore of our coasts (Sabine Bank, Shepard Bank and Heald Bank) are gravestones that document in place drowning of past barriers. Abrupt landward shifts in bay environments have occurred in the past and the best prediction is that they will occur again if predictions for sea-level rise are valid.

References


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HISTORICAL SUBSIDENCE IN THE HOUSTON-GALVESTON AREA, TEXAS
The greater Houston area, possibly more than any other metropolitan area in the United States, has been adversely affected by land subsidence. Extensive subsidence, caused mainly by ground-water pumping but also by oil and gas extraction, has increased the frequency of flooding, caused extensive damage to industrial and transportation infrastructure, motivated major investments in levees, reservoirs, and surface-water distribution facilities, and caused substantial loss of wetland habitat.

Land subsidence first occurred in the early 1900s in areas where ground water, oil, and gas were extracted and has continued throughout the 20th century due primarily to ground-water pumpage. The patterns of subsidence in the Houston area closely follow the temporal and spatial patterns of subsurface fluid extraction. Subsidence caused by oil and gas production is largely restricted to the field of production, as contrasted to the regional-scale subsidence typically caused by ground-water pumpage.

A period of rapid growth in the development of ground-water resources was driven by the expansion of the petrochemical industry and other allied industries in the early 1940s through the late 1970s. By 1943 subsidence had begun to affect a large part of the Houston area although the amounts were generally less than 1 foot. By the mid-1970s, 6 or more feet of subsidence had occurred throughout an area along the Ship Channel between Bayport and Houston, as a result of declining ground-water levels associated with the rapid industrial expansion. During this time, subsidence problems took on crisis proportions, prompting the creation of the Harris-Galveston Coastal Subsidence District. By 1979 up to 10 feet of subsidence had occurred, and almost 3,200 square miles had subsided more than 1 foot.

Since the late 1970s subsidence has largely been arrested along the Ship Channel and in the Baytown-LaPorte and Pasadena areas due to a reduction in ground-water pumpage made possible by the conversion from ground-water to surface-water supplies. However, subsidence has accelerated in fast-growing inland areas north and west of Houston, which still rely on ground water and, partly as a result, the Fort Bend Subsidence District was created by the legislature in 1989.

Houston's continuing rapid growth means that subsidence must continue to be vigilantly monitored and managed. However, the region is better-positioned to deal with future problems than many other subsidence-affected areas, for several reasons: a raised public consciousness, the existence of well-established subsidence districts with appropriate regulatory authority, and the knowledge base provided by abundant historical data and ongoing monitoring.
Interferometric synthetic aperture radar (InSAR) is a powerful tool that uses radar signals to measure deformation of the Earth's crust in spatial detail at a high degree of measurement resolution. Interferograms developed from repeat-pass radar imagery of the Houston-Galveston area acquired in 1996–97 from Earth-orbiting satellites reveals subsidence landward of Galveston Bay and some localized uplift near the coast. Historically, land subsidence in the greater Houston area attributed to the withdrawal of subsurface fluids has increased the frequency and intensity of coastal and riverine flooding. Since 1977, management efforts to reduce ground-water pumpage and increase the imported surface-water supply to industries and municipalities along Galveston Bay, especially near the Houston Ship Channel, have largely arrested subsidence in these near-coastal areas. However, during this same period, increased ground-water pumpage resulting in ground-water-level declines and subsidence have occurred landward in the Jersey Village area.

In the Jersey Village area, InSAR detected a maximum of 35 millimeters (mm) of subsidence between January 1996 and December 1996 and revealed nearly 700 square kilometers affected by more than 5 mm of subsidence. The detailed pattern of subsidence defined on the interferogram correlates with the alignment of surface faults and in general with the patterns of ground-water-level declines measured in this area from 1977 to 1996.

In the Galveston Bay area, an interferogram for the period, August 1996 to March 1999 shows some small-magnitude uplift of 5 to 15 mm along the ship channel near Pasadena and Baytown. For this same period, rising ground-water levels and uplift was measured by the Pasadena and Baytown borehole extensometers (approximately 5–12 mm). Inland areas, such as at the NASA and Clear Lake extensometer sites, show small-magnitude subsidence of 5 to 15 mm on the interferogram compared with approximately 4 to 11 mm measured by the extensometers at these sites.

Other areas showing small changes are the developing Kingwood area near Lake Houston (uplift) and Galveston Island (subsidence). The latter area already has an elevation near sea level and any change in land-surface elevation could be critical. The high degree of measurement resolution and spatial detail reinforces the usefulness of InSAR as a tool to identify areas of concern for land- and water-resource managers. InSAR for the Houston-Galveston area works well for areas of urban land use, but is limited by vegetation cover and variations in atmospheric moisture.
In November 1997, the U.S. Geological Survey, in cooperation with the City of Houston's Utilities Planning Section and the City of Houston's Department of Public Works & Engineering began an investigation of the Chicot and Evangeline aquifers in the greater Houston area to better understand the hydrology, flow, and associated land-surface subsidence. As part of the investigation, a numerical model was developed to simulate ground-water flow and land-surface subsidence in the greater Houston area. The study area covers 18,100 square miles. The finite-difference grid used in the numerical model encompasses all of Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, and Waller Counties and parts of Austin, Colorado, Fayette, Grimes, Hardin, Jefferson, Matagorda, Montgomery, Polk, San Jacinto, Walker, Washington, and Wharton Counties. The focus of the study is Harris and Galveston Counties, but the other counties were included to achieve the appropriate boundary conditions. Each grid layer consists of 103 rows and 109 columns. The model was vertically discretized into three layers resulting in a total of 33,681 grid cells. Layer 1 represents the water table using a specified head layer, layer 2 represents the Chicot aquifer, and layer 3 represents the Evangeline aquifer.

Simulations were made under transient conditions for 31 ground-water withdrawal (stress) periods that began January 1, 1891, and ended on December 31, 1996. The finite-difference computer code MODFLOW was used to simulate the Chicot and Evangeline aquifer system.

Simulation of land-surface subsidence and water released from storage in the clay layers was accomplished using the Interbed-Storage Package (IBS). The elastic and inelastic skeletal specific storage coefficients were parameters that were calibrated interactively with heads in the aquifers. The mean values of simulated inelastic skeletal specific storage for the Chicot and Evangeline aquifers were $7.34 \times 10^{-5}$ ft$^{-1}$ and $1.42 \times 10^{-5}$ ft$^{-1}$, respectively. Land-surface subsidence was calibrated by comparing simulated long-term (1891–1995) and shorter-term (1978–1995) land-surface subsidence with published maps of land-surface subsidence for about the same period until a good match was achieved.

The years 1977 and 1996 were chosen as potentiometric-surface calibration periods for the model. Simulated and measured potentiometric surfaces of the Chicot and Evangeline aquifers for 1977 show a good correlation. By 1977, large volumes of ground-water withdrawal in east central and southeast areas of Harris County had caused the potentiometric surfaces to decline as much as 250 feet below sea level in the Chicot aquifer and as much as 350 feet below sea
level in wells in the Evangeline aquifer. Simulated and measured potentiometric surfaces of the Chicot and Evangeline aquifers for 1996 also show a good correlation. The large potentiometric-surface declines in the southeastern Houston area, noted in 1977, show significant rises in 1996, while the new centers of declines are much farther to the northwest. The potentiometric surfaces of the Chicot and Evangeline aquifers were measured and simulated at more than 200 feet and 350 feet below sea level, respectively.

Simulated 1996 Chicot aquifer flow rates indicate that a net flow of 562.6 cubic feet per second (cfs) enters the Chicot aquifer in the outcrop area, and a net flow of 459.5 cfs passes through the Chicot aquifer into the Evangeline aquifer. The remaining 103.1 cfs of flow is withdrawn through well pumpage; about 84.1 cfs is supplied to the wells from storage in the sands and clays. By simulation, about 19-percent of the total water withdrawn from the Chicot aquifer comes from clay storage.

Simulated 1996 Evangeline aquifer flow rates indicate that a net flow of 14.8 cfs enters the Evangeline aquifer in the outcrop area, and a net flow of 459.5 cfs passes through the Chicot aquifer into the Evangeline aquifer for a total inflow of 474.3 cfs. Of the 528.6 cfs of flow withdrawn by wells, about 54.3 cfs comes from storage in the sands and clays. By simulation, about 10-percent of the total water withdrawn from the Evangeline aquifer comes from clay storage.