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# SUBSIDENCE IN COASTAL LOUISIANA:

## Causes, Rates, and Effects on Wetlands

Fish and Wildlife Service — Louisiana Universities Marine Consortium

U.S. Department of the Interior — State of Louisiana

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# SUBSIDENCE IN COASTAL LOUISIANA: CAUSES, RATES, AND EFFECTS ON WETLANDS

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## PREFACE

The coastal wetlands of Louisiana are being lost at an alarming rate of over 100 $km^2/yr$ due to natural deltaic processes of erosion and subsidence greatly compounded by the effects of human activities. This loss is of particular concern because these wetlands directly or indirectly support the Nation's greatest concentration of coastal fish and wildlife resources.

The Louisiana Universities Marine Consortium (LUMCON), representing the State's public universities, and the U.S. Fish and Wildlife Service (FWS) have entered into a Cooperative Agreement (14-16-0009-81-1016) for joint investigations to analyze land loss and wetland habitat changes in coastal Louisiana. As an objective of these cooperative studies, a geographic model of subsidence is being developed for application with the FWS Geographic Information System (GIS) for predicting wetland habitat changes. GIS is a computer-based mapping and analysis system located at the FWS National Coastal Ecosystem Team in Slidell, LA.

As an intermediate step toward development of applicable subsidence models, this technical report reviews and synthesizes the literature on subsidence in coastal Louisiana.

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## SUMMARY

Coastal wetlands are being lost at a rapid and accelerating rate in Louisiana. Much of this loss is attributable to a relative lowering of the wetland surface below the level adequate to support emergent vegetation. Although global sea level has risen only slowly (about 1.5 mm/yr) during the past century, sea level may rise more rapidly due to warming induced by the buildup of $CO_2$ in the atmosphere. Currently, apparent sea level along coastal Louisiana as reflected in tide gauge records, has risen more than five times faster than global sea level due to subsidence of thick unconsolidated sediments.

Such rapid subsidence is a natural phenomenon related to the progradation and abandonment of distributary lobes of the Mississippi River Deltaic Plain. For a considerable period after abandonment of new sediment sources, wetlands are able to keep pace with subsidence by accreting sediments reworked by marine processes. But inundation of interior wetlands removed from such an active sediment supply, wave exposure, and saltwater intrusion eventually result in deterioration of the wetlands. Human activities may accelerate this process by disrupting sediment supplies for wetland accretion, raising global sea level, causing saltwater intrusion, and withdrawals of subsurface materials.

Present subsidence rates from tide gauge records exceed 40 mm/yr at the modern Mississippi River Delta and approximate 10 mm/yr in wetlands near the gulf coast. Subsidence rates over the last 1,000 years appear to have been half the rates presently observed. This either results from natural variability, inaccuracy of tide gauge records, or human influences. The effect of the high rate of increase in locally apparent sea level on wetlands is difficult to quantitatively predict because of local variations in subsidence and accretion, uncertainty regarding future global sea level, and lack of knowledge of the accretionary limits of wetlands.

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## ACKNOWLEDGMENTS

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## INTRODUCTION

The rapid rate of coastal land loss in Louisiana has recently received wide public attention and concern. Although the rapid changes in coastal wetlands in the Mississippi River deltaic system have long been known (Russell 1936), recent systematic comparisons of habitat changes (conducted for the U.S. Fish and Wildlife Service) based on topographic maps and aerial photographs have surprisingly shown that the net rate of coastal land loss is in excess of 100 $km^2$/yr and apparently is growing geometrically (Gosselink et al. 1979; Wicker 1980; Gagliano et al. 1981). Most of these lands being eroded or inundated are coastal wetlands, including salt, brackish, and fresh marshes and wooded swamps. These habitat changes have potentially enormous consequences to the abundant fish, shellfish, fur and hide-bearing animal, and bird resources as well as to human society in coastal Louisiana (Boesch 1982).

Many natural and man-induced factors are responsible for the current rapid land loss. These include the senescence of the currently active delta, regional and localized subsidence, rising sea level, leveeing of the Mississippi River, and the channelization and draining of wetlands. A particularly pervasive factor is the apparent rapid rise of sea level due primarily to subsidence or sinking of land. Subsidence, coupled with a lack or disruption of the supply of new sedimentary material results in inundation or enhanced erosion. Subsidence in coastal Louisiana is broadly regional, but varies locally depending on sediment type, depositional history and, potentially, human influences.

The purpose of this review is to summarize the known causes of subsidence in coastal Louisiana, to examine the available data on subsidence rates, particularly as they may vary throughout the region, and to review the effects of subsidence on wetlands. Knowledge of the causes and rates of subsidence and its implications to the fate of wetlands is critical to predicting future coastal habitat conditions and in planning appropriate management strategies.

## SEA-LEVEL FLUCTUATIONS

The surface elevation of the sea is continuously changing. It is affected daily by oscillating tides that vary in range depending on the position of the moon in relationship to the earth's equator. The average tide in Louisiana is 32 cm (Baumann 1980). When the moon is in the tropics, the tide range is enhanced to a semi-monthly maximum of 47 cm. When the moon is in the equatorial plain, minimum tides (16 cm) occur. Because the tidal range in Louisiana is so small, meteorologic effects including wind, rain, and runoff can cause sea-level changes more significant than those caused by astronomic (lunar) effects. For example, the passage of cold fronts across Barataria Bay causes average decreases in the mean sea-level elevation in the lower bay at Grand Isle of 15 cm, almost half the mean tide range (Wax 1977).

Sea-level elevations also change seasonally. Locally, spring maximum sea-level elevations may result from increased river discharge (Meade and Emery 1971). Seasonal variations in sea level more broadly result from atmospheric effects of pressure and wind stress and from steric temperature effects (Patullo 1966). Seasonal variations in wind stress and the curl of the wind stress over the Gulf of Mexico result in two sea-level maxima (spring and fall) and two minima (winter and summer). The fall maximum is higher because of thermal expansion and the winter minimum is lower because of contraction resulting from lower temperatures (Chew 1962; Whitaker 1971; Sturges and Blaha 1976).

Longer term changes in sea level, on the order of one year to millions of years, result from processes affecting both eustatic and local sea level (Table 1). Eustatic sea-level changes reflect worldwide raising or lowering of mean sea surface elevations. This variation may occur when ocean basins change their volumes through geologic time because of tectonic movements. If the water volume has remained constant there would be a corresponding change in sea level. Changes in water volumes in the ocean would also result in raising or lowering of sea level. Global temperature trends are closely tied to these types of sea-level fluctuations. Global warming has caused glaciers to melt releasing volumes of water to the ocean and increasing the sea's mean elevation. Cooling trends add to the volume of high latitude glacial ice and remove water from the ocean, lowering its mean elevation. Global temperatures also have steric effects on ocean levels. The recent warming trend experienced worldwide should, theoretically, cause a thermal expansion of the surface waters of the ocean. Gornitz et al. (1982) attributed half of the present rate of eustatic sea-level rise to steric expansion. The rate of eustatic sea-level rise during the past century has been estimated at 1.5 mm/yr (Hicks 1978; Gornitz et al. 1982; Barnett 1983), however, Emery (1980) suggested that sea level has been rising more rapidly at an average rate of 3.0 mm/yr over the past 40 years and may have risen as rapidly as 14 mm/yr over shorter periods. Recently, Barnett (1983) has reexamined sea-level rise patterns and could find no evidence of a more rapid sea-level rise in recent years than was experienced since 1903. He further concluded that it is not possible to assign a cause for the rise (thermal expansion, polar ice cap and glacial melting, or changes in ocean circulation).

Table 1. Major mechanisms of sea-level change and their associated rates, time scales, and magnitudes (data from Nummedal, in press).

| Factor | Time scale (yr) | Typical rates (cm/yr) | Cumulative sea level change (m) |
|---|---|---|---|
| Changes in sea-floor spreading rates | $10^7$ to $10^8$ | $2 \times 10^{-2}$ to $5 \times 10^{-4}$ | 100 to 500 |
| Dessication and filling of marginal ocean basins | $10^6$ | ? | 10 |
| Ocean sedimentation | $10^7$ to $10^8$ | ? | ? |
| Glaciations | $2 \times 10^4$ to $10^6$ | 1 to $2 \times 10^{-2}$ | 100 |
| Holocene and recent climatic fluctuations | 5 to 500 | 1 to 0.1 | 1 to 2.5 |
| Seasonal changes | 1 | 7 cm/mo | 0.2 to 0.3 |
| Storms | hours | 50 cm/hr | 1-5 |

Recent industrialization has caused the release of large quantities of $CO_2$ into the atmosphere (Siegenthaler and Oeschger 1978). This increase in $CO_2$ levels decreases the amount of terrestrial thermal radiation which can escape back to space. The solar energy is trapped more efficiently, and the earth experiences warmer temperatures (Broecker 1975). This phenomenon is widely known as the "greenhouse effect." The consequent global warming would cause both steric expansion and the addition of glacial meltwaters to the ocean volume, thus causing a rise in the sea level. This "greenhouse effect" may be responsible for recent accelerations in rates of sea-level rise (Nummedal 1983) and may result in a sea-level rise of between 48 and 369 cm by 2100 (Hoffman 1983).

Of additional concern in Louisiana are local processes contributing to relative sea-level rise. These are local (regional) variations in sea level caused by sediment compaction, tectonics, or isostatic adjustments of earth's crust (Table 1). Along the western coastline of the United States, tectonic uplift has resulted in a steep coast marked by long stretches of cliffs. Rapid crustal uplift has caused a relative lowering of sea level in that region. On the eastern coastline of the United States, isostatic adjustments have resulted in a downwarping of the continental shelf ever since the glaciers of 18,000 years ago melted and receded (Blackwelder 1980). During the last continental glaciation, the continental shelf was subaerial, with much of water being locked up in the great masses of ice. When global temperatures increased and the ice melted, the sea level rose rapidly and flooded the shelf area (Emiliani et al. 1975). The weight of the water sitting on top of the continental shelf has caused it to depress. According to Blackwelder (1980) approximately 30 m of this "hydro-isostatic" depression has occurred along the middle coast of eastern North America since the most recent glaciation.

Relative local sea-level changes in Louisiana are tied to the geologic framework of the coastal and deltaic sediments. Subsidence in coastal Louisiana has been caused both by loading-induced subsidence of Pleistocene and older sediments, as well as compaction of Holocene sediments due to dewatering (Nummedal, in press).

## PROCESSES RESULTING IN SUBSIDENCE

### REGIONAL GEOLOGIC SETTING

The geology of coastal Louisiana is dominated by the building of the Mississippi River Delta (Figure 1). The delta area, including the alluvial valley and delta plain, covers nearly 26,000 $km^2$ from the Louisiana-Mississippi border to the Louisiana gulf coast (Gould 1970). The delta is bounded to the west by coastal marshlands of the Chenier Plain, and to the north and east by a Pleistocene age terrace on which the Prairie Formation is exposed (Figure 1). The Prairie Formation dips seaward and forms a basement with an overburden of marine transgressive and Holocene Mississippi River sediments. The weight of the deltaic sediments on the Prairie Formation has caused it to downwarp (isostatic deformation) a maximum of 150 m at the tip of the Mississippi delta. A combination of Prairie Formation downwarping and post-Wisconsin eustatic sea-level rise accounts for sediment thicknesses exceeding 300 m (Figure 2; Gould 1970). The Holocene sedimentary wedge thins in a general landward direction and pinches out to the north of Lake Pontchartrain.

The recent depositional history of the Mississippi River Deltaic Plain has been reconstructed through geomorphologic interpretations (Russell 1936), analyses of the historical maps and air photos (Fisk 1955), sediment sampling, coring, archaeological studies (McIntire 1954) and $^{14}C$ dating of recovered organic materials (McFarlan 1961; Frazier 1967). The deltaic plain has been marked by cycles of delta construction and abandonment. Presently, most of the Mississippi River discharge flows into the Gulf of Mexico through the modern Balize or "Birdfoot" Delta (Figure 1). Presently 30 percent of the flow is discharged through the Atchafalaya River. During the past 6,000 years the river has occupied at least four other major river channels to the coast (Figure 3). From oldest to youngest the Mississippi deltas are: (1) the Sale-Cypremort Delta lobe farthest to the west, (2) the Cocodrie, (3) the Teche, (4) the St. Bernard Delta lobe farthest east, (5) the Lafourche which overlaps the older Teche, (6) the Plaquemines Delta lobe which extended to (7) the modern Birdfoot Delta, and (8) the Atchafalaya, which is a newly emerging delta.

The switching of major distributary channels in the Mississippi River Deltaic Plain is related to the efficiency of channel flow. As the distributary channel builds a delta into a receiving basin, the channel extends over it. The longer the channel becomes, the more gentle the gradient of gravity flow becomes and the less efficient the channel is at carrying the river's discharge. To improve the efficiency the flow will seek a shorter, more direct route to the gulf. A case in point is the modern Balize Delta, which has built a lengthy channel extending nearly to the shelf edge (Figure 1). The Atchafalaya River channel presently offers a shorter, more efficient route for the Mississippi River discharge. Without the artificial control structure at the Old River, the Atchafalaya River would capture most of the river flow and become the newest major river channel.

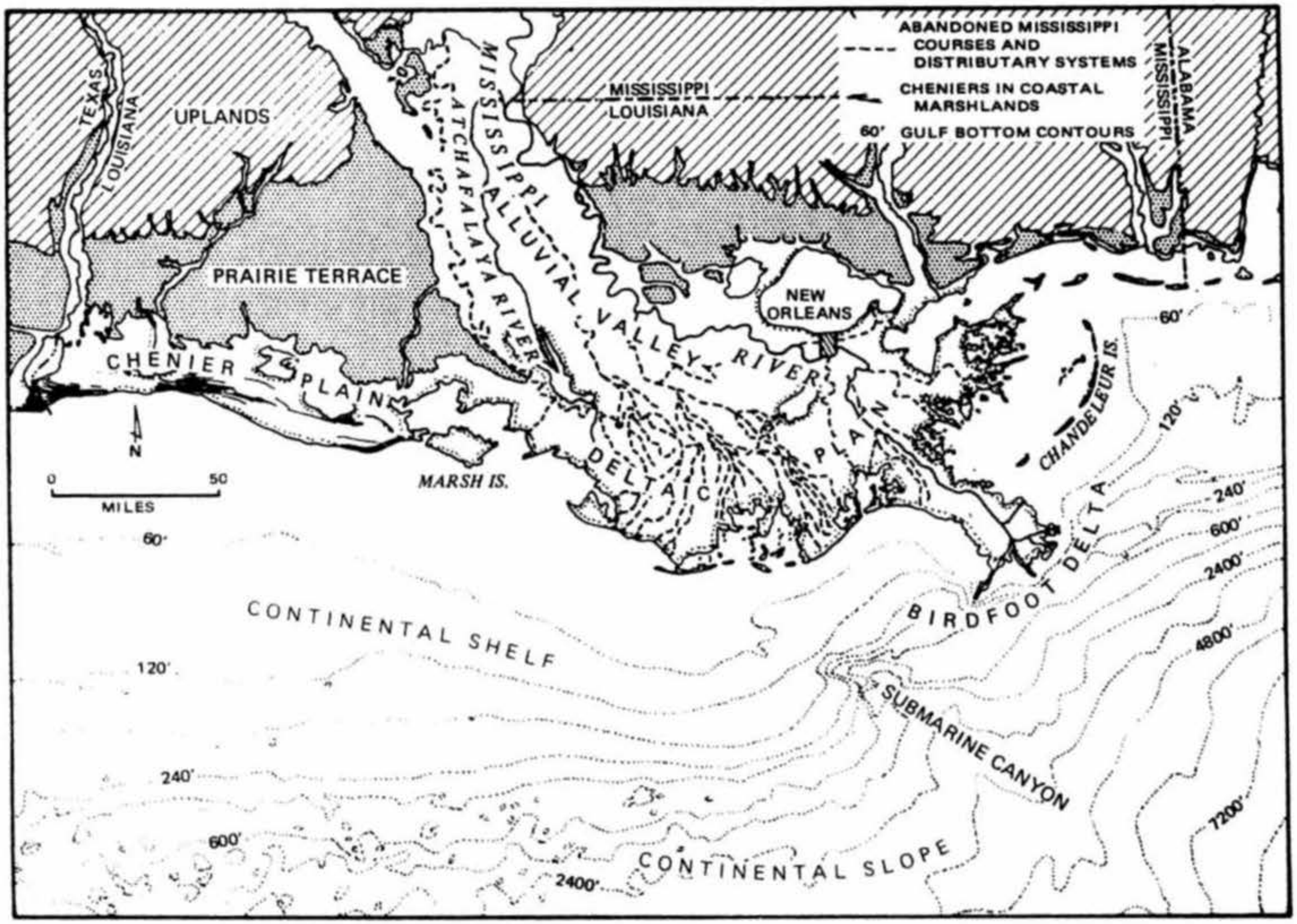


Figure 1. Physiographic features of south Louisiana and adjacent offshore area (from Gould 1970).

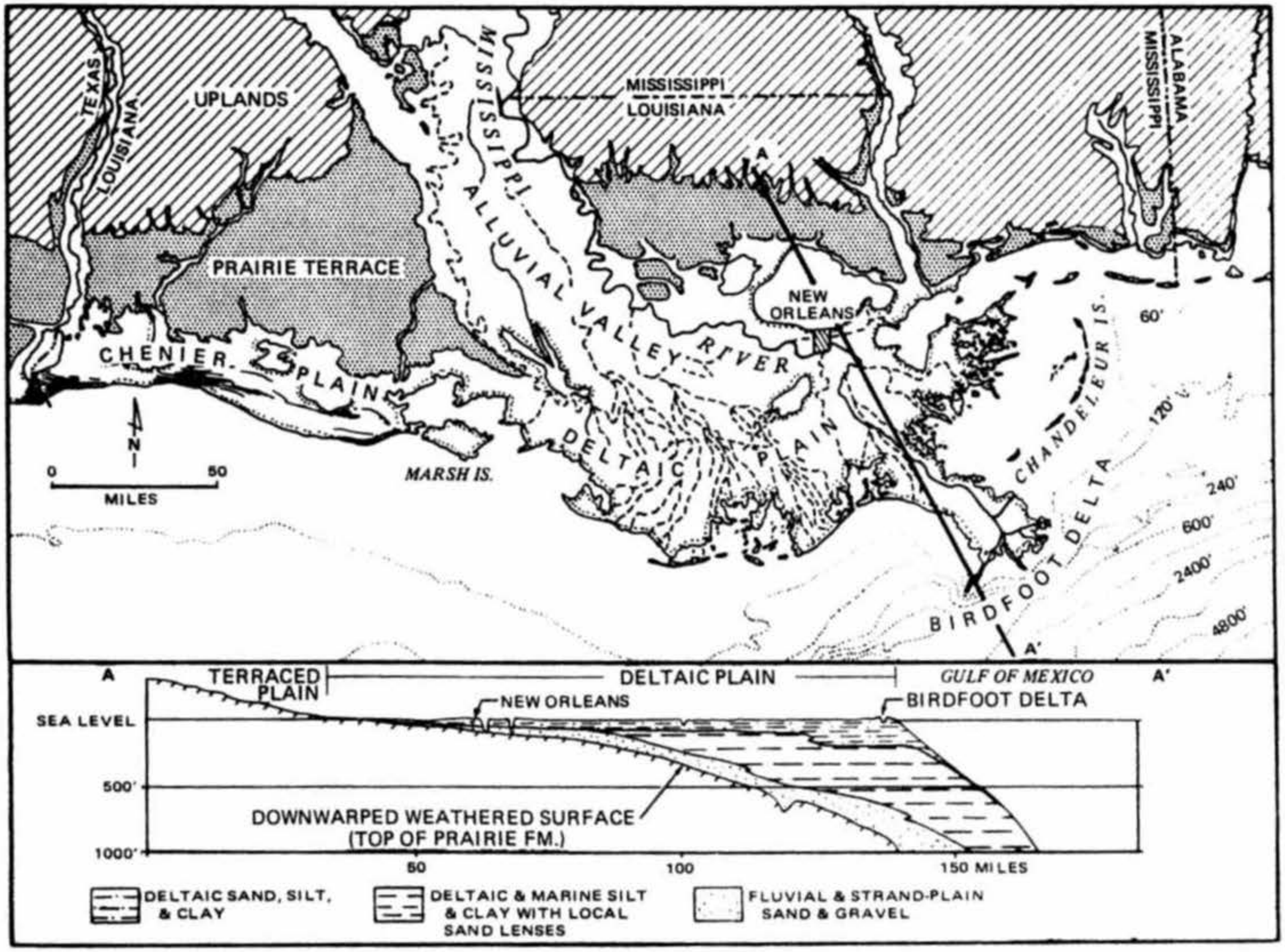


Figure 2. Stratigraphic section of late Quaternary deposits of the Mississippi River Delta (from Gould 1970). Note the increased downwarping of the Prairie Formation surface with distance offshore.

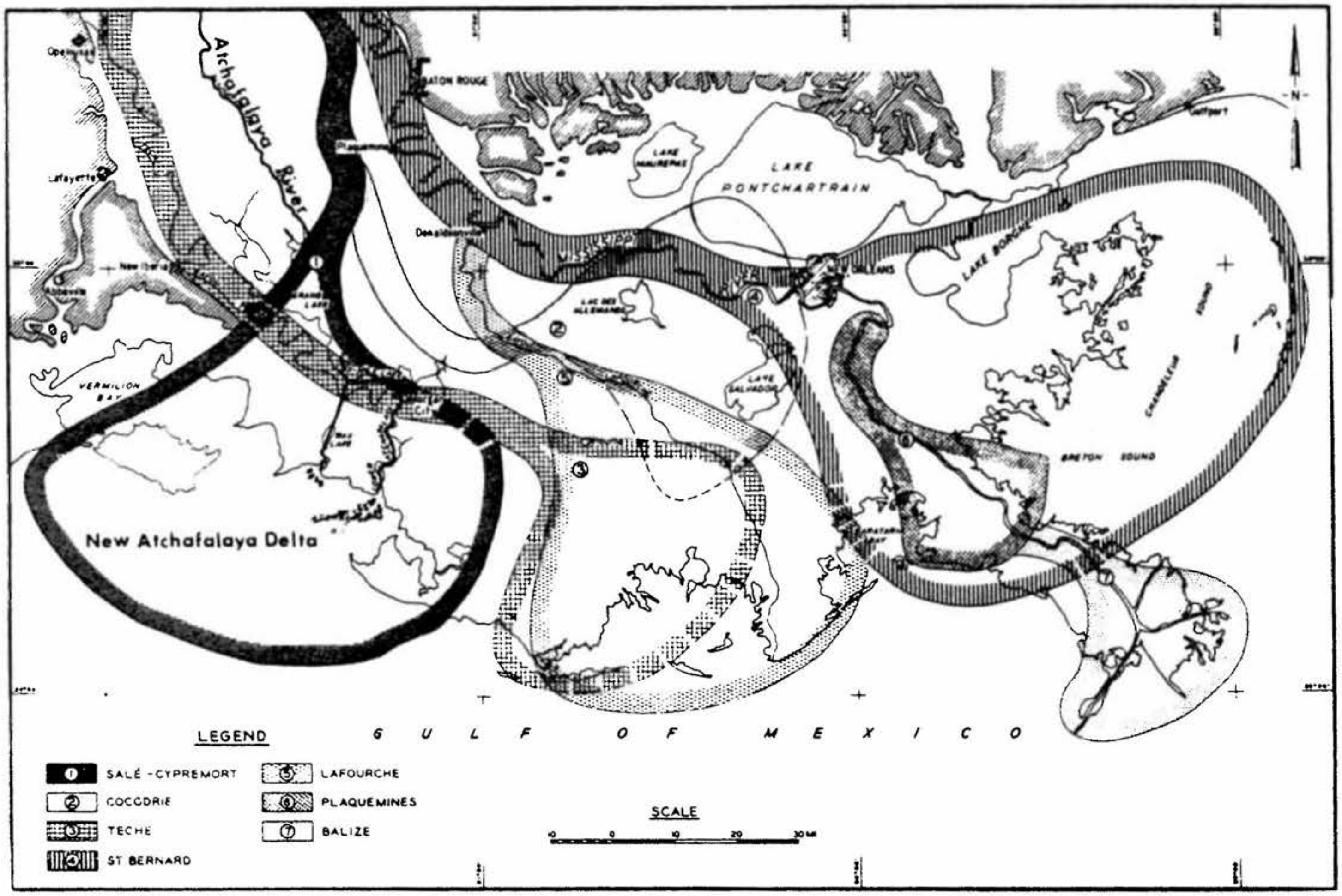


Figure 3. Major delta lobes that have constructed the Holocene Mississippi River Deltaic Plain (modified from Kolb and Van Lopik 1966).

DELTA LOBE CONSTRUCTION AND ABANDONMENT

The cycle of delta lobe building and abandonment begins with a distributary channel discharging its sediment load into an interdistributary area or similar receiving basin. The delta will prograde over the existing bay bottom as a relatively thick wedge-shaped accumulation of sediments (Figure 4). Initially, the sediments deposited by the plume issuing from the distributary channel will be fine-grained, reflecting the most distal influence of the river discharge. These fine-grained prodelta deposits build a platform for further vertical accretion of the delta. As the actual outlet of the distributary channel migrates seaward, delta-front sands will be deposited over the prodelta material. The sands will be covered by finer-grained marsh sediments as the channel outlet pushes farther seaward. The weight of the delta-front sands building over the undercompacted prodelta sediments results in the release of pore waters and consolidation occurs (Jones and Wallace 1974). Consolidation and downwarping of underlying strata allow the delta-front sand bodies to attain thicknesses in excess of the depth of the waterbody into which they are built. The resulting subsidence is, therefore, most pronounced in the vicinity of distributaries (Morgan 1977).

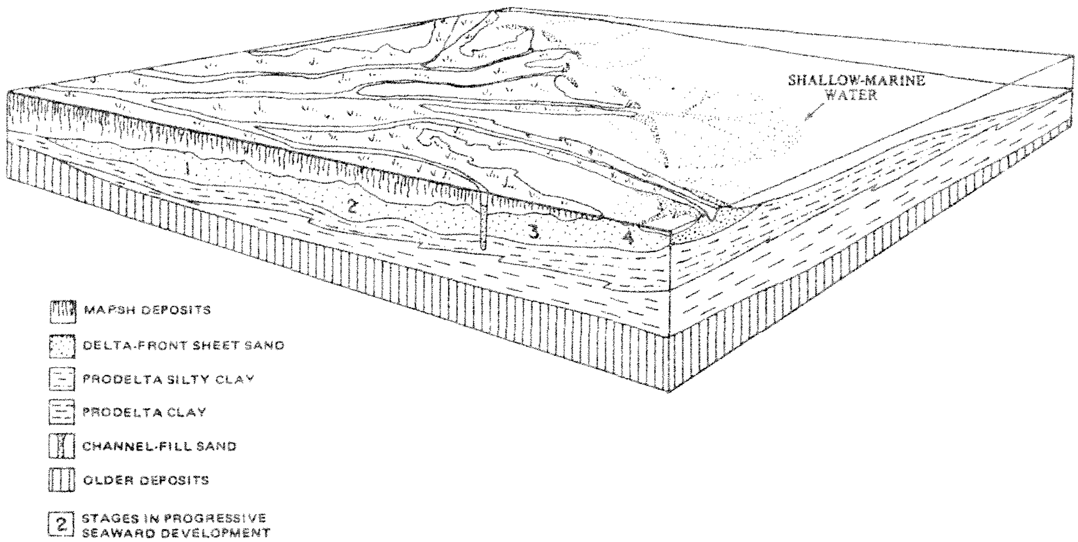


Figure 4. The structure and components of a shallow water delta (from Gould 1970).

Upon abandonment of the distributary channel, the lobe of sediments built by the prograding delta enters its destructive phase. Initially, the distributary mouth bar and delta sands are concentrated along the outer edge of the deltaic body (Morgan 1977). These sandy accumulations may form transgressive beaches and barriers which protect the inner portion of the delta from direct wave attack (Figure 5). Without renewed sediment supply once offered by the active distributary, subsidence of the delta sediments procedes without compensation other than that locally afforded by redistribution of sediments already in the system. Subsidence allows marine incursion to occur and open water area increases; thus an incipient bay is formed. In time, the bay

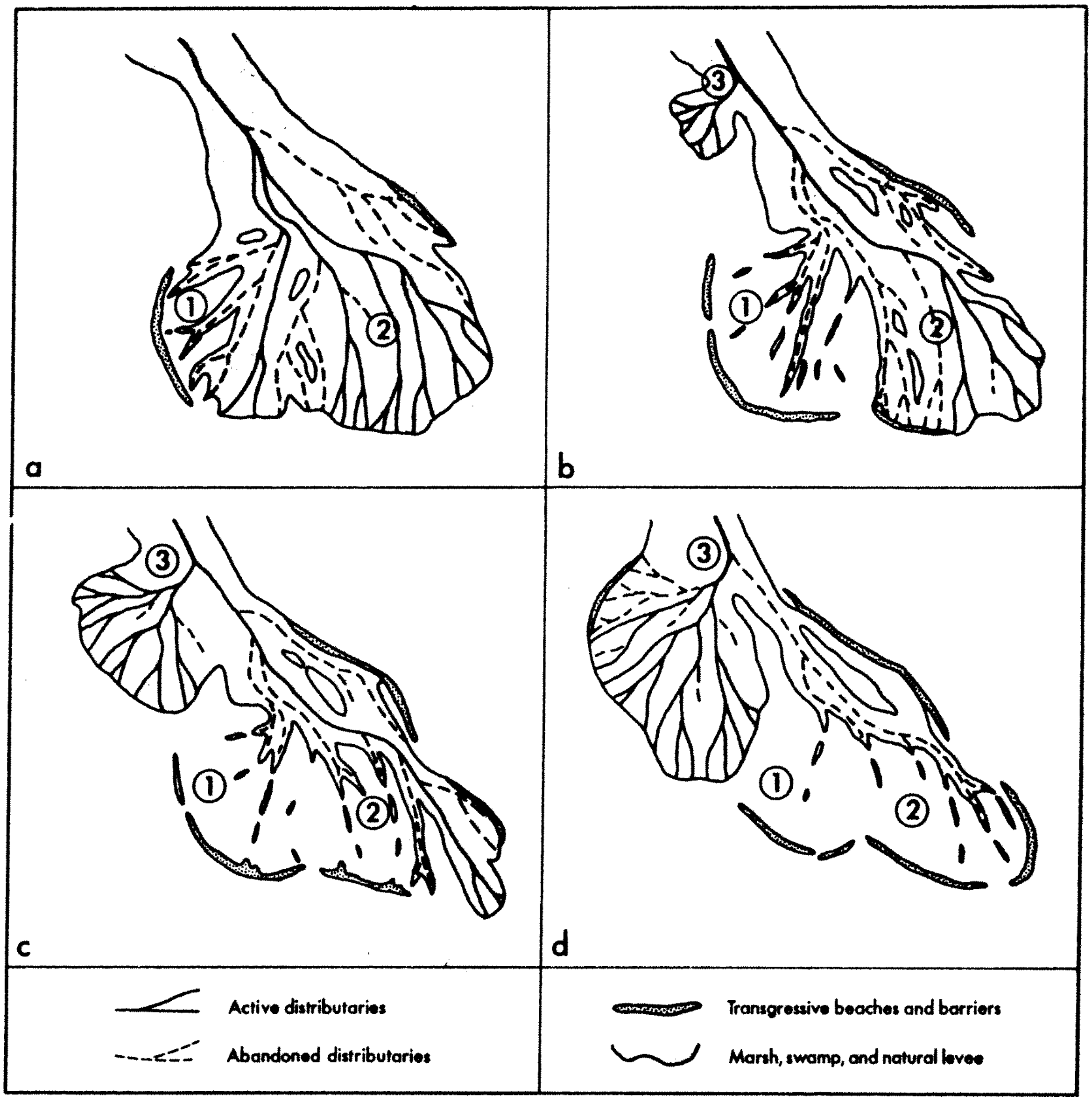


Figure 5. Map view of a general sequence of distributary evolution in the Mississippi River Delta: (a) when the lobe is built and abandoned, sand accumulates at its distal end while (b) the interior subsides becoming (c) a bay floor (from Morgan 1977).

that the delta originally filled will return. The bay is separated from the gulf by sandy transgressive barrier beaches or delta-flank barrier islands (Penland and Boyd 1982). This stage of the delta lobe destruction can be observed on the eastern side of the Mississippi River Deltaic Plain. The Chandeleur Islands (Figure 1) are delta-flank islands formed with sands deposited when the St. Bernard Delta was active (Figure 4; Gould 1970). In the final stage of the abandoned distributary lobe the delta-flank islands may become subaqueous shoals as the islands subside and their sand supply dissipates (Penland and Boyd 1982). Waves will then be able to travel past the shoals, and the highly digitate shore present behind the delta-flank islands will be straightened. The gulf shorelines on either side of the entrance to Atchafalaya Bay may be examples of this final destructive phase. The coastline is straight and unprotected by a barrier island shield. The bathymetry and sediment distribution off that coast indicate the presence of shoals as possible remnants of barrier islands that might have been present following the abandonment of the Sale-Cypremort Delta lobe (Figure 3).

The cycle of distributary lobe construction and abandonment reaches full circle when the river finds the remnant embayment, once again, to be an efficient avenue for discharge. A new delta lobe is then built out over the remnants of the previously abandoned lobe. Repetitions of lobe building, subsidence, and renewed delta progradation at the same site are replete in bore-hole records of the Mississippi River Deltaic Plain (Morgan 1977).

The delta building process results in great variations in sediment particle sizes, both horizontally and vertically. Silts and clays rapidly deposited in the delta front and in interdistributary bays have a very high water content and water is expressed slowly, but continuously, under compaction. The clays which slowly accumulate on the prodelta have lower water content and, consequently, undergo less compaction. Sands initially have even lower water content because the grains are more nearly spherical and better packed. As sediment mass accumulates, pore water pressure increases but little compaction occurs until burial by 100 m or more. Once compaction begins, it proceeds gradually over long periods for clay sediments but more rapidly for sands. An actively prograding delta, therefore, will exhibit extremely high rates of subsidence as recently deposited sands and silts rapidly compress and the compression of prodelta clays is accelerated by the weight of the heavy sand overburden. Older levee ridge deposits subside less rapidly because they are composed of coarser sediments, except where underlain with clays which will compress under the weight of levees. However, the weight of human structures built on levee ridges may accelerate their subsidence. As a consequence of the vertical and horizontal sediment complexity, local subsidence rates would be expected to be highly variable.

## WETLAND DYNAMICS

During active delta building, marshes may be actively built in the interdistributary bays as they become shoal enough to support emergent vegetation. Sediments trapped by the baffling effect of the vegetation enhance the rate of marsh proliferation, filling the interdistributary bay. The accretion of sediments in the marshes is rapid enough to at least keep pace with the rapid subsidence characteristic of the active delta lobe. When the river abandons the delta lobe, however, the source of new sediments to continue marsh accretion is lost. This by no means results in the immediate inundation of the marsh, because of the marsh's ability to trap and accrete remobilized sediments and organic debris (peat). Thus, the marshes continue to grow upward as their sedimentary foundation subsides and may advance over the swamps and subaerial natural levee deposits that subside below sea level due to the lack of continued accretion (Fisk 1960; Figure 6). Eventually, the rate of sediment accretion in the marsh falls behind the rate of subsidence and protective barriers subside exposing the erodable marsh deposits to waves. Rapid destruction of the wetlands results. This is the present state of the St. Bernard, Lafourche, and most of the Teche delta marshes. The rapidity of this wetland deterioration is illustrated by the historical changes in wetlands of the Lafourche Delta (Figure 7).

The rate of loss of wetlands due to subsidence varies in relation to the composition and age of sediments undergoing compaction and the supply of sediments available for continued accretion. Wetland loss rates are greater in newer delta lobes and nearer the coast (Scaife et al. 1983) due to more rapid subsidence resulting from compaction of newer sediments and greater exposure to wave attack.

The processes by which salt marshes accrete sediments and actually increase their size by prograding over tidal flats in response to rising sea level are well known from the classic work of Redfield (1972) in Barnstable Harbor, Massachusetts. Redfield felt that fringing "young marsh" could accrete 18 mm/yr of sediment, while "older marsh" removed from a source of sediments accretes at approximately 2 mm/yr. McCaffrey (1977) using $^{210}Pb$ to date sediment horizons in a Connecticut <u>Spartina patens</u> marsh found an average accretion rate of 30 mm/yr over the last 40 years. Other estimates of marsh accretion rates from U.S. Atlantic coast marshes based on stratigraphic interpretation, particulate marker horizons, historical records or radiometric dating (Table 2) have been compiled by Hatton et al. (1983). These show accretion has been equal to or has exceeded the local apparent rise in sea level, half or more of which has been due to the secular eustatic rise in sea level.

Apparent sea-level rise along the northeastern U.S. coast has, however, recently been 2 to 3 mm/yr (Hicks 1978), considerably below the apparent sea-level rise of 10 to 40 mm/yr characteristic of the seaward portions of the Mississippi Deltaic Plain (Swanson and Thurlow 1973). Consequently, in order to persist, coastal marshes in Louisiana must accrete sediments at a substantially greater rate than those along the Atlantic coast.

Several investigators (DeLaune et al. 1978; Baumann 1980; Baumann and DeLaune 1982; Hatton et al. 1983) have employed radiometric dating and marker horizon techniques to determine sediment accretion rates in Louisiana marshes in both the Mississippi Deltaic Plain and Chenier Plain and under a range of salinity conditions (Table 2). They analyzed profiles of $^{137}Cs$, a bomb-produced radionuclide which first appeared in 1954 and peaked in concentration in 1963. This technique is thus limited to estimation of sediment accumulation rates since 1954. R. DeLaune (Louisiana State University, personal communication) has recently analyzed profiles of $^{210}Pb$, a naturally occuring radionuclide, which has a half-life allowing dating to about 200 years before present.

Accretion rates of Louisiana marshes over the last 10 to 20 years based on $^{137}Cs$ (Table 2) analysis, were higher near drainage streams than in backmarshes more distant from tidal waterbodies. Streamside marshes (within about 10 m of the stream) generally aggraded (vertically accreted) at rates ranging from 10.6 to 14.0 mm/yr, approximating

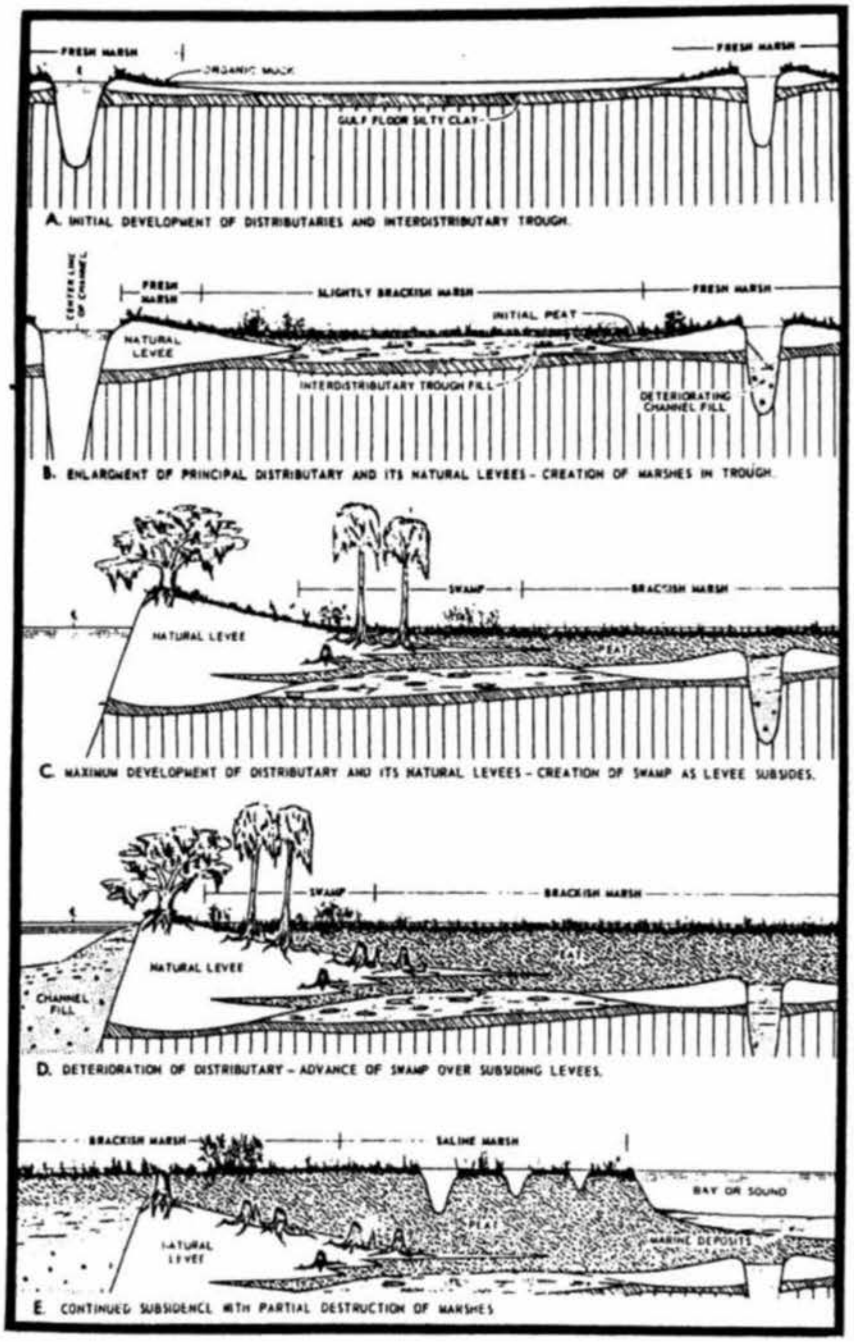


Figure 6. Progressive stages of marsh aggradation and deterioration during deltaic development (from Fisk 1960).

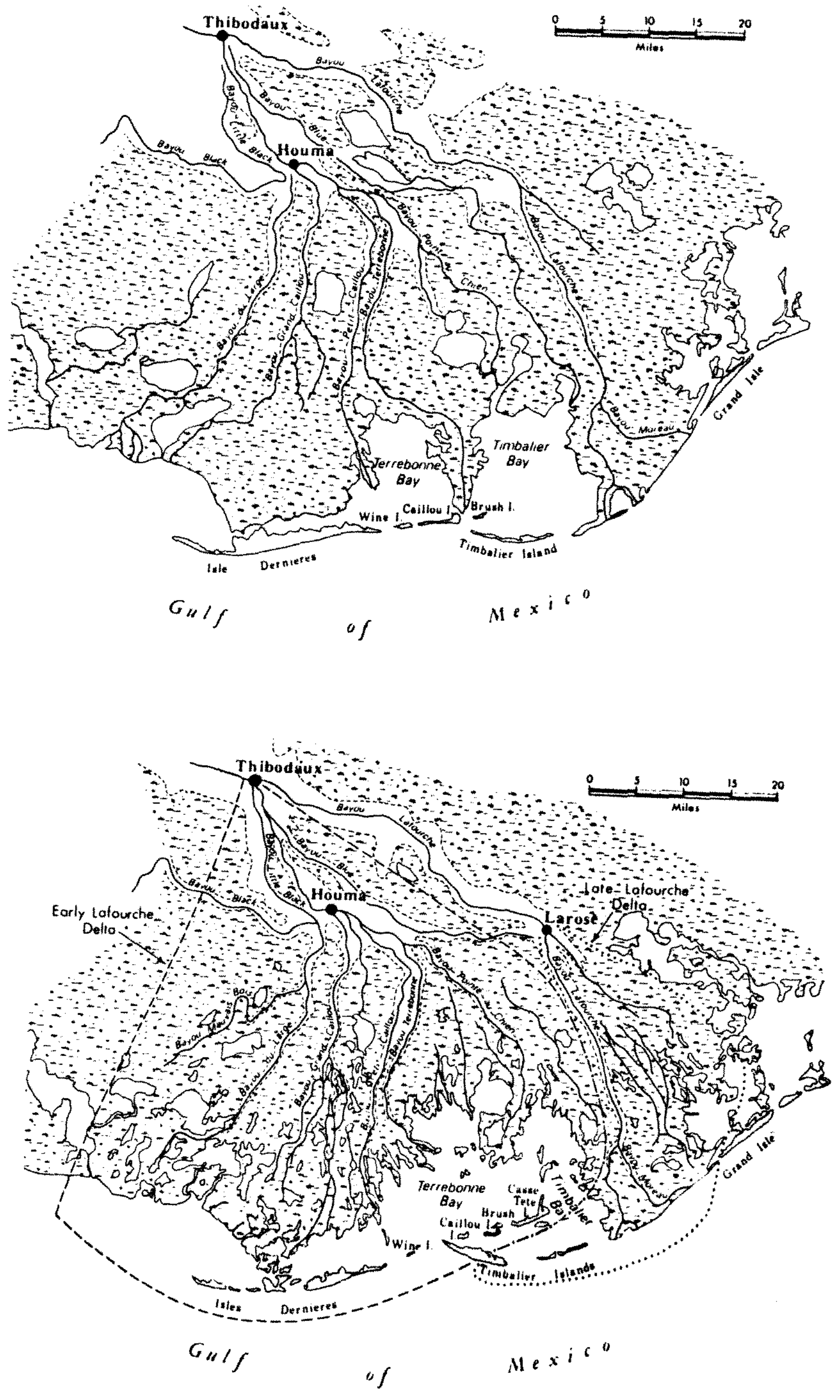


Figure 7. Wetland deterioration in the Lafourche Delta lobe between the mid-nineteenth century (above) and circa 1970 (below) (from Morgan 1974).

Table 2. Summary of marsh accretion rates measured in coastal Louisiana and along the U.S. east coast.

| Location | Marsh type | Marsh accretion rate (mm/yr) | Mean sea-level rise (mm/yr) | Reference |
|---|---|---|---|---|
| Louisiana Deltaic Plain | Freshwater | | 11.0 | Hatton et al. 1983 |
| | streamside | 10.6 | | |
| | backmarsh | 6.5 | | |
| | Intermediate (*Spartina patens*) | | | " " |
| | streamside | 13.5 | | |
| | backmarsh | 6.4 | | |
| | Brackish (*S. patens*) | | | " " |
| | streamside | 14.0 | | |
| | backmarsh | 5.9 | | |
| | Saline (*S. alterniflora*) | | 13.0 | DeLaune et al. 1978; Baumann 1980 |
| | streamside | 13.5 | | |
| | backmarsh | 7.5 | | |
| Chenier Plain | Salt-brackish (*S. patens*) | 7.0 | 12.0 | Baumann and DeLaune 1982 |
| Georgia | *S. alterniflora* | 3 - 5 | | Summarized by Hatton et al. 1983 |
| Delaware | *S. alterniflora* | 5.0 - 6.3 | 3.8 | " " |
| New York | *S. alterniflora* | 2.5 - 6.3 | 2.9 | " " |
| Conn. | *S. alterniflora* | 8 - 10 | 2.5 | " " |
| | *S. patens* | 2 - 5 | | |
| Mass. | *S. alterniflora* | 2 - 18 | 3.4 | Redfield 1972 |

the apparent local sea-level rise measured at nearby tide gauges over the same period. Backmarshes have aggraded at much lower rates (6.4 to 7.5 mm/yr). These differential accretion rates relative to proximity to tidal waters follow Redfield's (1972) observations and reflect the proximity of the streamside marshes to the sediment source, i.e. tidal flooding with suspended sediments. In the case of the Louisiana marshes, however, backmarshes are not aggrading enough to keep pace with the much faster rise in apparent sea-level, as much of 90 percent of which is due to subsidence.

Shorter-term observations of accretion over marker horizons of white clay placed on the surface of a Barataria Bay marsh showed that from 1975 to 1978 most aggradation occurred during the winter (Baumann 1980), however exceptionally great accretion was also observed during the summer of 1979 (Baumann and DeLaune 1982). New accretion was primarily related to storm events. During winter frontal passage, high southeasterly winds preceeding the front raise the water level and resuspend sediments in the bays and other water bodies, and the marshes are inundated with sediment-laden water. Northerly winds, following the front, lower the water level, draining the marsh, but maintain high suspended sediment concentrations (Cruz-Orozoco 1971). The rapid accretion of sediments during the summer of 1979 was probably related to the large scale resuspension of sediments by Tropical Storm Claudette and Hurricane Bob. Sediment accretion in the marsh was notably low during peak discharge of the Mississippi River in spring, even during the high flow year of 1979, indicating that the river is not a direct source of contemporary accretion. Bottom sediments in the estuarine water bodies and shallow continental shelf and marsh shoreline erosion are the available sources of mineral sediments for continued marsh aggradation.

Less saline, inland marshes not receiving significant fluvial sediments are remote from a source of inorganic sediments for accretion. Consequently, inland marshes are increasingly dependent on organic matter for continued vertical growth. Hatton et al. (1983) found a monotonic increase in the organic matter content of streamside marsh deposits of 20 to 41 percent dry weight from salt to fresh marshes in the Barataria Basin and a similar increase of 20 to 52 percent in backmarsh deposits. Accumulation rates of inorganic sediments declined along the same gradient by 74 and 85 percent for streamside and backmarshes, respectively. Organic detritus from vascular plants provides the great bulk of the deposits in inland marshes, however, inorganic sedimentation may provide nutrients critical to the plant growth supplying the organic accumulation (DeLaune et al. 1981).

As the deficiency of sediment accretion compared with the subsidence-induced rise in sea level increases, "die back" of marsh grass results and shallow, open ponds develop (Mendelssohn et al. 1981). In such instances, Spartina alterniflora probably dies from oxygen deficiency of the roots as the more-or-less continuously wet soil becomes anaerobic and highly reducing. As a shallow open pond within the marsh forms, lateral erosion by windwave activity increases the growth of the pond.

## HUMAN ACTIVITIES

Human activities may affect wetland elevations with respect to sea level in several ways: (1) increases in global sea level, (2) subsurface withdrawals, (3) drainage, (4) disruption of sediment supplies for accretion, (5) alteration of tidal exchange enhancing, for example, saltwater intrusion, and (6) placement of dredged material and other overburden on the wetland surface. Most pervasive is the potential cultural effects on atmospheric $CO_2$ levels and the resulting modifications of climate and global (eustatic) sea level (Hansen et al. 1981; Gornitz et al 1982). The rate of global sea-level rise may have doubled since 1940 to about 3 mm/yr (Emery 1980), although more recent analyses have estimated global eustatic sea-level rise is 1.2 mm/yr (Gornitz et al. 1982). A more rapid rate of sea-level rise of 60 cm over the next century has been projected as a result of climatic warming and eustatic rise could be as great as 10 mm/yr over the next 40 years (Nummedal 1982). This would make the eustatic sea-level rise approximately equal to the rate of subsidence and thus increase the rate of apparent sea-level rise by 60 percent or more. Such a dramatic increase in apparent sea level would obviously challenge the wetlands' ability to maintain themselves by aggradation not only in Louisiana but on a global basis.

Another potential human effect on the elevation of wetlands with respect to sea level results from increased subsidence due to withdrawal of subsurface materials, including water, oil, gas, sulphur and salt. The compression of subsurface formations by their overburden is balanced by the pore pressure of trapped fluids. As these fluids are withdrawn, the formations may compress resulting in differential subsidence or faulting at the ground surface. Greatly increased subsidence rates are well-documented as a result of groundwater withdrawals, for example in the Houston-Galveston, Texas, region (Gabrysch 1970) and at Baton Rouge, Louisiana (Davis and Rollo 1970). Oil and gas extraction in southern California (Castle et al. 1970), Venezuela (van der Knaap and van der Vlis 1967) and coastal Texas (Yerkes and Castle 1970) has resulted in land subsidence and tidal inundation. Subsidence rates of up to 50 cm/yr have been observed in the Wilmington Field near Long Beach, California, causing considerable damage to surface structures. As much as 1 m of subsidence was observed over a 7-year period at the Goose Creek Field in upper Galveston Bay, Texas.

Tremendous withdrawals of oil, formation waters, and sulphur have occurred in coastal Louisiana over the last 50 years and it has been suggested that locally high rates of land loss may have resulted in areas of such fluid withdrawals (Gagliano et al. 1981). Detailed documentation of locally increased subsidence in the vicinity of extensive mineral extraction in coastal Louisiana is sorely lacking, however. Most oil and formation water production in coastal Louisiana is from deeper strata (2,000 to 5,000 m) than those strata from which withdrawals resulted in surface subsidence in California, Texas and Venezuela (less than 1,000 m). Because of the high compression these deep formations may already experience, removal of fluids results in relatively little additional compaction. Furthermore, increased compaction of deeper formations should result in relatively less surface subsidence than comparable compaction of shallower formations. Roberts (1970) measured compressibility of clastic sediments (sands and clays) at high pressures and concluded that even at depths of 1,500 m compaction resulting from fluid withdrawal may result in surface subsidence. Differential subsidence of 10 to 90 mm has been observed over Southern California oil fields producing from 2,800 to 3,800 m (Yerkes and Castle 1970).

Many of the early developed oil and gas reservoirs in coastal Louisiana are relatively shallow and increasingly large volumes of formation waters are produced as oil production declines. The effect of these shallow withdrawals on surface subsidence and wetland deterioration should be investigated and the effectiveness of water injection in slowing subsidence (Yerkes and Castle 1970) evaluated.

Forced drainage of wetlands results in lowered water table and oxidation of organic peat. Consequently, subsidence in those areas drained for agriculture, urban, or industrial development may be greatly accelerated by sediment compaction and loss of volume. Subsidence is a serious threat to property, structures, and buried utility lines in the New Orleans area, much of which was naturally fresh and brackish water marshes and swamps with highly organic soils. Subsidence rates of up to 45 mm/yr are found in suburban Jefferson Parish and eastern New Orleans (Earle 1975; Snowden et al. 1977, 1980). This effect is confined to drained wetlands and does not take place as long as tidal exchange is not limited.

Finally, wetland elevation is influenced by human disruptions of the natural source of sediments for accretion necessary to keep pace with rising sea level and subsidence. The general consequences of leveeing the Mississippi River, which prevents normal overbank flooding and sediment supply to the surrounding wetlands, have already been discussed. Baumann and Adams (1982) have documented lower wetland loss rates or even net wetland gain in those areas receiving suspended sediments from the Atchafalaya River discharge compared to nearby wetlands not receiving this subsidy. The proposed extension of the Avoca Island levee at the mouth of the Atchafalaya could interfere with this sediment dispersal.

Perhaps more insidious is the influence of hydrologic modifications to the wetlands themselves. Of particular concern are small levees and spoil banks, which interfere with the tidal inundation that provides sediment nourishment. The result is exaggeration of the sediment deficit of inland marshes as discussed above and documented by Baumann and DeLaune (1982) and Hatton et al. (1983). Turner et al. (1982) and Scaife et al. (1983) have hypothesized that the effects on wetland loss resulting from such levees and spoil banks are greater than the effects of dredged canals per se. They present as evidence the proliferation of small ponds in marsh separated from natural water bodies by spoil banks. These ponds probably result from the deficiency of accretion compared to subsidence wherein the marsh surface sinks to a level at which marsh plant growth is prevented (Mendelssohn et al. 1981). Saltwater intrusion caused in part by channels and canals which cut across the estuarine salinity gradient has resulted in pervasive vegetation changes in fresh and intermediate marshes and swamps (Gagliano et al. 1981). Vegetation changes and die offs alter the effectiveness of the wetlands in trapping inorganic sediments and producing the organic matrix necessary for continued aggradation required to balance subsidence and eustatic sea-level rise.

## SUBSIDENCE RATES

Subsidence is an active process and perhaps the dominant contributor to land loss in coastal Louisiana (Adams et al. 1976). General qualitative discussions indicate increases in rates of subsidence toward the seaward edge of the delta deposits (Kolb and Van Lopik 1966) and slower rates at its flanks. In order to predict future coastal conditions and expected changes in wetlands, it is essential to know the variations in subsidence rates throughout coastal Louisiana. Information relevant to this task comes primarily from two sources: (1) interpretation of the long-term (hundreds of years) sedimentary records based on accumulated sediment thickness and $^{14}C$ dating of organic matter and (2) interpretation of short-term (tens of years) apparent sea-level records.

### LONG-TERM SUBSIDENCE

Long-term subsidence of the continental margin off Louisiana is the most rapid in the United States. Rates of subsidence since the Cenozoic have exceeded 40 cm/1000 yr off Louisiana, but only 1 to 2 cm/1000 yr off the U.S. east coast (Emery and Uchupi 1972). More pertinent, however, is the subsidence of sediments deposited since the Miocene and especially those deposited after the Holocene transgression to the relative still stand of sea level, during which the Mississippi delta system was developed. Subsidence due to compaction of these deposits is far more rapid.

An example of an interpretation of longer-term subsidence rates from radiocarbon measurements is Gerdes' (1982) study of the Caminada-Moreau beach ridge plain in southern Lafourche Parish (Figure 8). Gerdes' data suggest that relative sea level in that region has risen a total of 2.75 m during the past 1,000 years. His results also point out the importance of discounting abberant dates resulting from $^{14}C$ analysis of older shells and organic matter which have been uncovered and redeposited with younger deposits. Because there has probably been no net eustatic sea-level rise over the last 1000 years, the rate of long-term subsidence may be approximately 2.7 mm/yr, substantially lower than the apparent sea-level rise and marsh accretion rates discussed above, i.e. about 12 mm/yr.

A large number of $^{14}C$ datings has been made on peat and other organic matter recovered from borings in coastal Louisiana (Frazier 1967). Gagliano and van Beek (1970) plotted the determined ages of peats versus the depths from which they were recovered in order to develop a long-term subsidence curve based on the assumptions that the peats were formed at sea level, preserved in place, and buried by continued accretion as the land subsided. They determined an average subsidence rate of 1.1 mm/yr over the last 3,500 years. Penland and Boyd (1983) have compiled and interpreted all published $^{14}C$ dates existing for coastal Louisiana, including those of Frazier (1967). Of the more than 250 dates available, only 155 were considered reliable for one or more reasons. Based on these dates an average regional subsidence rate for coastal Louisiana of 5.5 mm/yr was computed for the last 7,000 years and a rate of 3.2 mm/yr for the last 3,500 years. In the areas underlain by the thickest Holocene deposits (approximately 100 m), apparent subsidence rates may be up to 10 mm/yr. Other areas underlain by thinner deposits are subsiding less rapidly. For example, Saucier (1963) reported subsidence rates of 1.2 mm/yr for the Lake Pontchartrain basin.

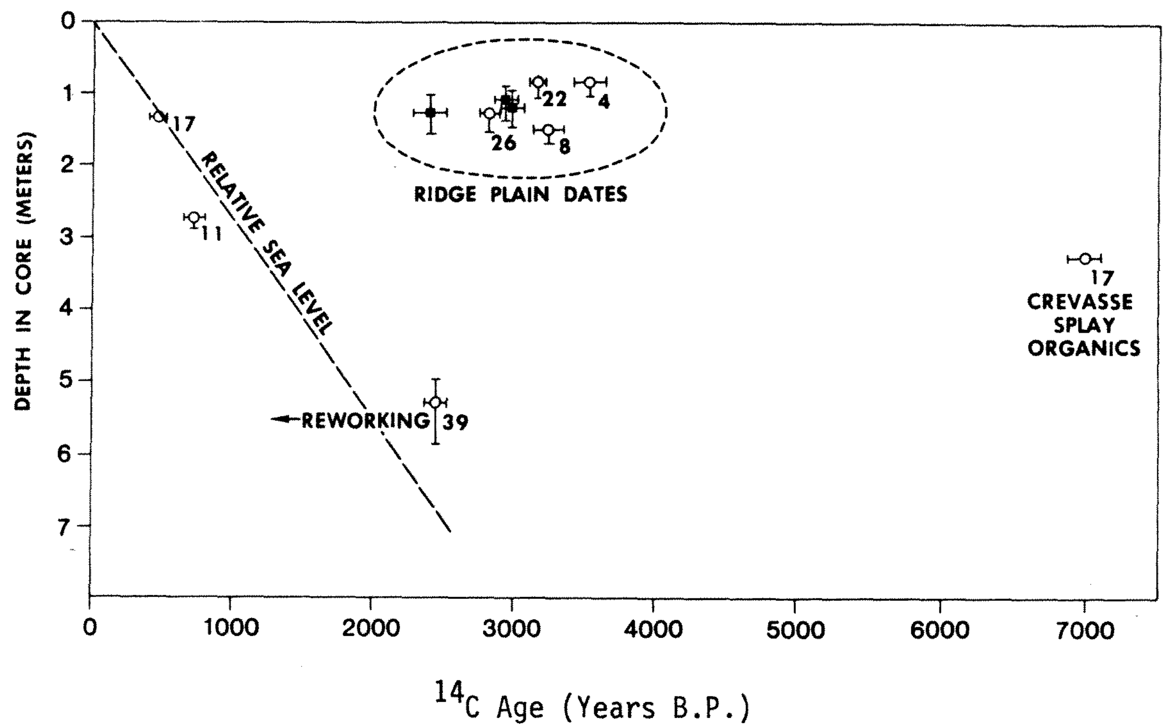


Figure 8. Inferred relative sea-level rise at the Caminada coast of Lafourche Parish (from Gerdes 1982). The curve is based on radiocarbon dated basal peats and in-situ, articulated shells of Crassostrea virginica.

## MODERN SUBSIDENCE

Swanson and Thurlow (1973) analyzed tide gauge data for the Mississippi and Texas coast in an effort to quantify rates of subsidence after subtraction of eustatic sea-level rise. Rates ranged from 43 mm/yr near the modern Birdfoot Delta to 5 mm/yr near Port Isabel, Texas. Port Isabel is out of the influence of the Mississippi Delta system, but illustrates the decrease in subsidence rates moving away from the delta's depositional center. Rates of subsidence along the Po River Delta in Italy also showed a decrease in rates of subsidence toward its flanks, reflecting a lateral thinning of the Holocene sediments (Nelson 1971). Subsidence rates published by Morgan (1967) are of the same magnitude as those reported by Swanson and Thurlow (1973) ranging from 15.2 to 39.6 mm/yr at the modern Mississippi River Delta.

Swanson and Thurlow (1973) suggested that rates of subsidence will vary with location and be strongly dependent on local geologic conditions. The local variation in subsidence is not well-documented because of a lack of long series observational data for the Louisiana coastal region. Gagliano et al. (1981) compared coastal maps and photos from five intervals dating from 1890 to 1978 to determine the amount of land that has changed from subaerial to subaqueous. They determined that the largest loss of land was occurring in the vicinity of the Modern Mississippi River Delta, the area suggested to have the highest rate of subsidence. Correlating land loss directly with subsidence in this instance, although convincing, is not definite in light of the limited data base concerning locally apparent sea-level rise.

Most tide gauge data collected for Louisiana are either too short in duration, discontinuous, or of too poor quality to accurately assess the rate of subsidence or relative sea-level rise. The gauges are not distributed evenly around the state, but are clustered in certain locations (Figure 9). Furthermore, they are located on levee ridges,

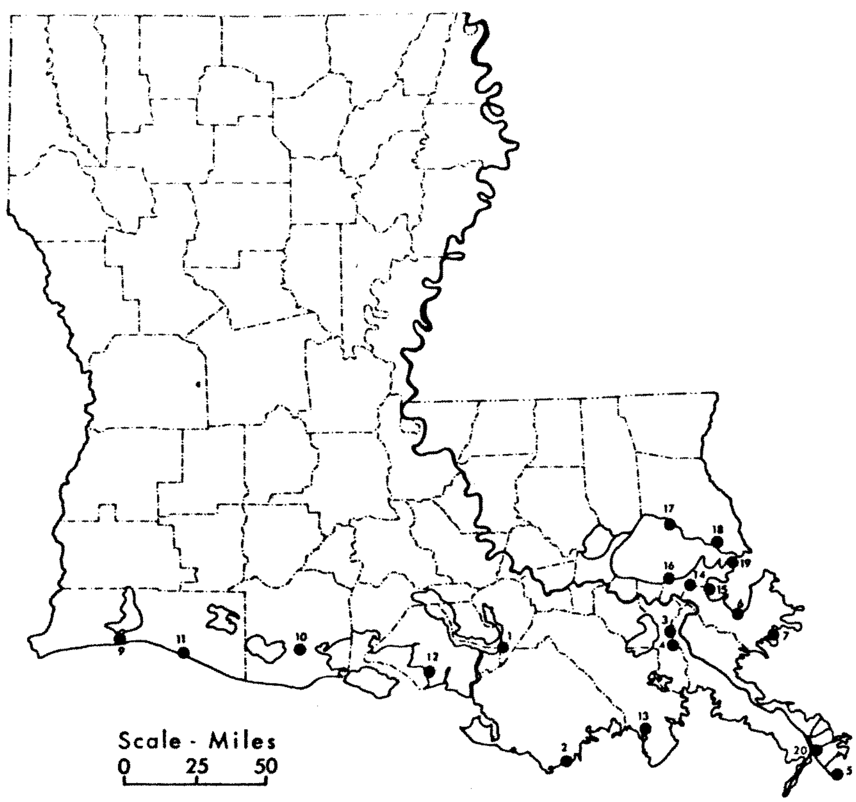


Figure 9. Location of tide gauge stations in coastal Louisiana in addition to those included in Figure 10.

barrier islands or near uplands and generally not in the central marsh-estuarine basins. Discontinuous records are another problem with the local tide gauge data. Only 2 stations, stations 4 and 14, out of 19, have continuous records for 10 years prior to 1980, although a few stations have continuous data running for periods of 7 or 8 years. In most cases data are collected for 4 or 5 years; and a malfunction or maintenance problem causes a 2 or 3 year lapse before the data gathering resumes.

The paucity of good tide data along the Louisiana coast reflects the poor condition of the tide gauge maintenance program. Although the distribution of gauges is sparse, continuous data collection would allow baseline conditions of subsidence to be analyzed. The program requires checking of equipment, gauge recalibration, and elevation checks at reasonable intervals of time. The elevations of each gauge should not be resurveyed from benchmarks in the same vicinity as the tide gauge. If the benchmark was to subside at the same rate as the tide gauge, no apparent change in sea level would be recorded.

In view of a "eustatic" sea-level rise of 1.5 mm/yr, it is clear that most of the local sea-level rise observed on the Louisiana coast is due to subsidence. Figure 10 presents three tide gauge records from the central Louisiana coast as well as a longer tide series from Galveston, Texas, all of which document a history of rapid local relative sea-level rise. These are the best long-term tide data we can identify. The longer Galveston record documents well the temporal changes in observed rates of sea-level rise. For example, if the entire Galveston record is averaged, one finds a rate of rise of 5.5 mm/yr. If one only considers the 20-year time span from 1950 to 1970, the rate then was 2.5 mm/yr. The rapid local change in sea level at Galveston between 1940 and 1945 (Figure 10) might be due to man's activities in the area, although sea-level curves from as far away as Pensacola show a rapid increase during the same period. In view of these rapid temporal changes the subsidence rates estimated below should be considered very tentative.

From the Humble Oil "A" and the Bayou Rigaud tide gauge records (Figure 10) one finds a rate of local sea-level rise of between 10 and 11 mm/yr for the duration of the two records. Analysis of the Bayou Rigaud data since 1954 by Baumann and DeLaune (1982) yielded the slightly higher rate of 13 mm/yr cited in Table 2. By subtracting a rate of 1.5 mm/yr for eustatic rise one arrives at a subsidence rate of about 8.5 mm/yr for the south-central Louisiana coast. Farther west, at Eugene Island, at the entrance to Atchafalaya Bay, one finds a subsidence rate of about 7 mm/yr, although because of gauge leveling problems and water level increases resulting from progradation of the Atchafalaya Delta this figure is open to question (R. Baumann, Louisiana State University, personal communication).

The long-term subsidence rates developed from radiocarbon dates (e.g., Gerdes 1982; Penland and Boyd 1983) are generally lower than the contemporary subsidence rates estimated from tide gauges (e.g. Baumann and DeLaune 1982). This observation has several interpretations: (1) natural processes of subsidence in coastal Louisiana have been highly variable over the history of the delta, (2) the rapid subsidence over the past few decades is largely induced by human activities or (3) tide gauge estimates are biased by differential settlement of the gauges. A linear extrapolation of existing subsidence rates along the coast would predict a cumulative subsidence over the next 100 years of 85 cm (2.8 ft) for the Grand Isle area.

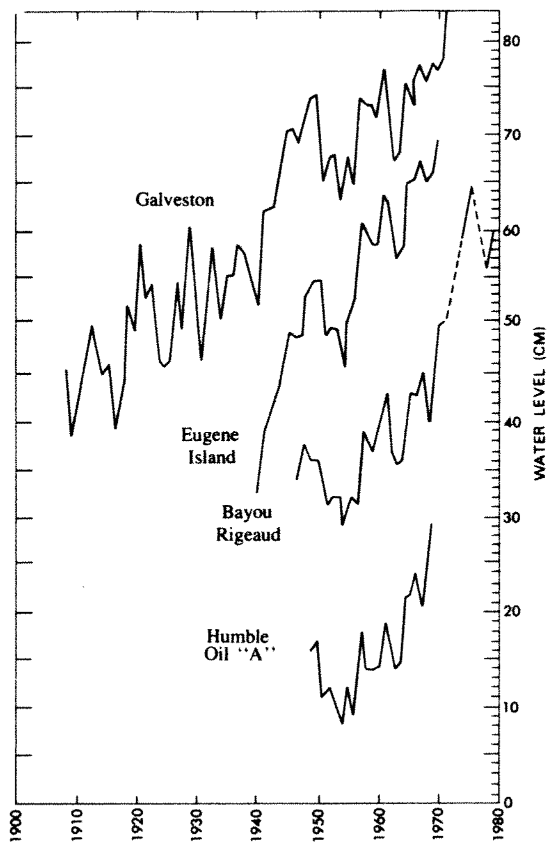


Figure 10. Yearly mean sea-level series for four stations along the north-central Gulf Coast. Data from tide gauges at Galveston, Eugene Island (at the entrance to Atchafalaya Bay), Bayou Rigaud (Grand Isle), and Humble Oil Platform "A" (13 km off Grand Isle). Data from Hicks and Crosby (1974) and Baumann (1980).

## EFFECTS OF SUBSIDENCE ON WETLANDS

Subsidence obviously is, and has been, a dominant factor in the destruction of wetlands in coastal Louisiana. The variation in the extent and nature of wetlands in delta lobes of various ages and comparisons of historical maps make it clear that wetlands eventually deteriorate by succumbing to subsidence when an active source of sediments for accretion is removed. Subsidence would obviously be resulting in substantial wetland loss without the effects of human activities, although these losses may be more nearly offset by accretionary gains if coastal Louisiana were in an entirely natural state.

The loss of coastal wetlands due to subsidence directly results from increased inundation as apparent sea level rises but, the indirect effects of subsidence on wetlands are also significant. Saltwater intrusion increases as the interdistributary basins "flood", causing death of salt-intolerant plants in fresh and intermediate wetlands in the upper basin. As water bodies widen, peripheral wetlands are exposed to increased wave attack and erosion.

The persistence of a wetland removed from the direct infusion of fluvial sediments depends on the delicate "balance" between apparent sea-level rise and accretion of remobilized marine-delta sediments. Little is known of the ability of wetlands to keep pace in aggradation with accelerated apparent sea-level rise, resulting either from increased eustatic sea level or subsidence. Evidence from Louisiana is clear that certain wetlands are incapable of accreting enough sediment to accommodate present sea-level increases. There is also increasingly strong evidence that human activities interfering with suspended sediment nourishment, such as spoil banks, dykes, and levees may be significant factors in wetland loss.

Given the multiple and complex ways subsidence can influence wetland deterioration, it is a difficult task to predict wetland loss from subsidence rates, even if data on the distribution of subsidence rates throughout coastal Louisiana were available, and they are not. At a minimum, knowledge of the distribution of aggradation rates or potential aggradation rates would also be necessary. These rates are much more highly variable at local scales than subsidence rates. Complex effects of vegetation type, proximity to open water bodies and supply of suspended sediments would also have to be understood. It should, however, be possible to employ a reasonable range of estimates of the dominant variables of the rates of apparent sea-level rise and marsh aggradation to develop scenarios for a range of possible conditions in the form of predictive maps.

## CONCLUSIONS

1. The local apparent rise in sea level in coastal Louisiana is dramatic, greater than 1 cm/yr in wetlands near the Gulf Coast.

2. Local apparant sea-level changes are presently dominated by subsidence. The rate of subsidence along the coastline is more than five times as high as the average rate of global, eustatic sea-level rise over the past century.

3. Subsidence is a natural phenomenon related to the progradation and abandonment of distributary lobes of the Mississippi River Deltaic Plain. The distributary lobe builds out into a receiving basin until it becomes less efficient than another course, when it is abandoned. When the river switches to the new preferred channel, the abandoned lobe deteriorates through subsidence and marine processes that rework the sediments.

4. Present rates of subsidence approach 40 mm/yr at the modern Mississippi River Delta and are about 10 mm/yr or more at Grand Isle. Subsidence rates over the last 1,000 years have apparantly been somewhat slower, approximately 3 to 5.5 mm/yr.

5. Localized data regarding recent subsidence rates, as deduced from apparent sea-level rise throughout coastal Louisiana, are sparse. Tide gauge data are either discontinuous, unavailable or of too short a period of record for long-term quantitative trend analysis.

6. Subsidence directly results in wetland destruction when the apparent sea-level rise exceeds the wetland sediment aggradation rate. Subsequently, these effects are amplified by increased saltwater intrusion and shoreline erosion.

7. Human activities may directly accelerate subsidence or indirectly exacerbate the differential between marsh aggradation and apparent sea-level rise in several ways: (1) increases in global sea level due to the "greenhouse effect", (2) withdrawals of water, oil, and minerals from subsurface strata, (3) drainage, (4) disruption of sediment supplies for accretion, (5) alteration of tidal exchange causing saltwater intrusion, and (6) placement of dredged material on the wetland surface.

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**16. Abstract (Limit: 200 words)**
Coastal wetlands are being lost at a rapid and accelerating rate in Louisiana. Much of this loss is attributable to a relative lowering of the wetland surface below the level adequate to support vegetation.

Such rapid subsidence is a natural phenomenon, related to the progradation and abandonment of distributary lobes of the Mississippi River Deltaic Plain. For a considerable period after abandonment of new sediment sources, wetlands are able to keep pace with subsidence by accreting sediments reworked by marine processes. But inundation of interior wetlands removed from such an active sediment supply, wave exposure, and saltwater intrusion eventually result in deterioration of the wetlands. Human activities may accelerate this process by disrupting sediment supplies for wetland accretion, raising global sea level, causing saltwater intrusion, and withdrawals of subsurface materials.

Present subsidence rates from tide gauge records exceed 40 mm/yr at the modern Mississippi River delta and approximate 10 mm/yr in wetlands near the gulf coast. Subsidence rates over the last 1,000 years appear to have been half the rates presently observed. This either results from natural variability, inaccuracy of tide gauge records, or human influences. The effect of the high rate of increase in locally apparent sea level on wetlands is difficult to quantitatively predict because of local variations in subsidence and accretion, uncertainty regarding future global sea level, and lack of knowledge of the accretionary limits of wetlands.

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