EFFECTS OF GEOLOGICAL FAULTS ON LEVEE FAILURES IN SOUTH LOUISIANA

Prepared for Presentation and Discussion

U.S. Senate Committee on Environment & Public Works

Senator James M. Inhofe, *Chairman*
Senator James M. Jeffords, *Ranking Member*

Testimony of

Sherwood Gagliano, Ph.D., *President*

Coastal Environments, Inc.

November 17, 2005
Washington, D.C.

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Executive Summary

During Hurricane Katrina, a number of breaches occurred in hurricane levees and floodwalls in southeastern Louisiana in locations where the structures were built across deep-seated geological faults. Fault related breaches along the 17th Street Canal, the London Avenue Canal, and the Inner Harbor Navigation Canal in the Greater New Orleans area caused flooding in densely populated urban areas resulting in catastrophic loss of life and property. Along the Mississippi River below the City of New Orleans in Plaquemines Parish, flood levees were breached as storm surge moved up the river channel. In addition, levees in the vicinity of Montegut, south of Houma, Louisiana were also breached. At many, if not most, of these locales major regional geological faults are known to underlie the levees.

Recent studies indicate that ancient deep-seated regional faults, long-believed to be dormant, have exhibited surface movement during the past 50 years. Some of these faults extend down 25,000 feet and have been active for 100 million years or more. Fault planes and fault plane zones are deep cracks that result in poor foundation conditions where they reach the surface. The fault planes and zones are conduits of fluid and gas

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movement which contribute to poor foundation conditions. The active faults are part of a linked tectonic system that underlies the region. Most fault movement within this system is driven by natural geological processes. The fault system is an expression of, a massive “continental margin gravity slump” extending from the latitude of New Orleans to the deep waters of the Gulf of Mexico. The faults underlying the levees are elements of the linked tectonic system within this slump.

Fault hazards were not recognized at the time of the levee design and construction, but are now known to pose a significant natural hazard. The fault hazards are not insurmountable obstacles to the restoration and maintenance of a sustainable coastal zone in Louisiana, but must be a primary consideration in planning, and design of all aspects and elements of the restoration effort. All existing and proposed levee alignments in south Louisiana should be evaluated for potential fault hazards.

Introduction

Hurricane Katrina slammed into the northern Gulf of Mexico coast on August 29, 2005, exposing numerous low and weak spots in the levee system surrounding New Orleans and other southeastern Louisiana communities. In some areas the levees were overtopped by elevated water and/or wind-driven surge, but in other places in the Greater New Orleans (GNO) area breaches occurred along navigation and drainage canals causing flood devastation to densely populated inner-city neighborhoods. Some, if not most, of the breaches that occurred are in places where the levees were built across geological faults. This statement focuses on failures where there is an apparent relationship to faulting, a largely overlooked natural hazard. Figure 1 shows the spatial relationship between existing and proposed levee alignments and major geological faults in southeastern Louisiana. Figure 2 shows the locations of the Hurricane Katrina levee and floodwall breaches in the GNO area.

I have conducted field inspections at the breach sites in the GNO area, but have not had an opportunity to conduct detailed site-specific study. However, the findings and interpretations presented in this statement are based on a five-year research effort

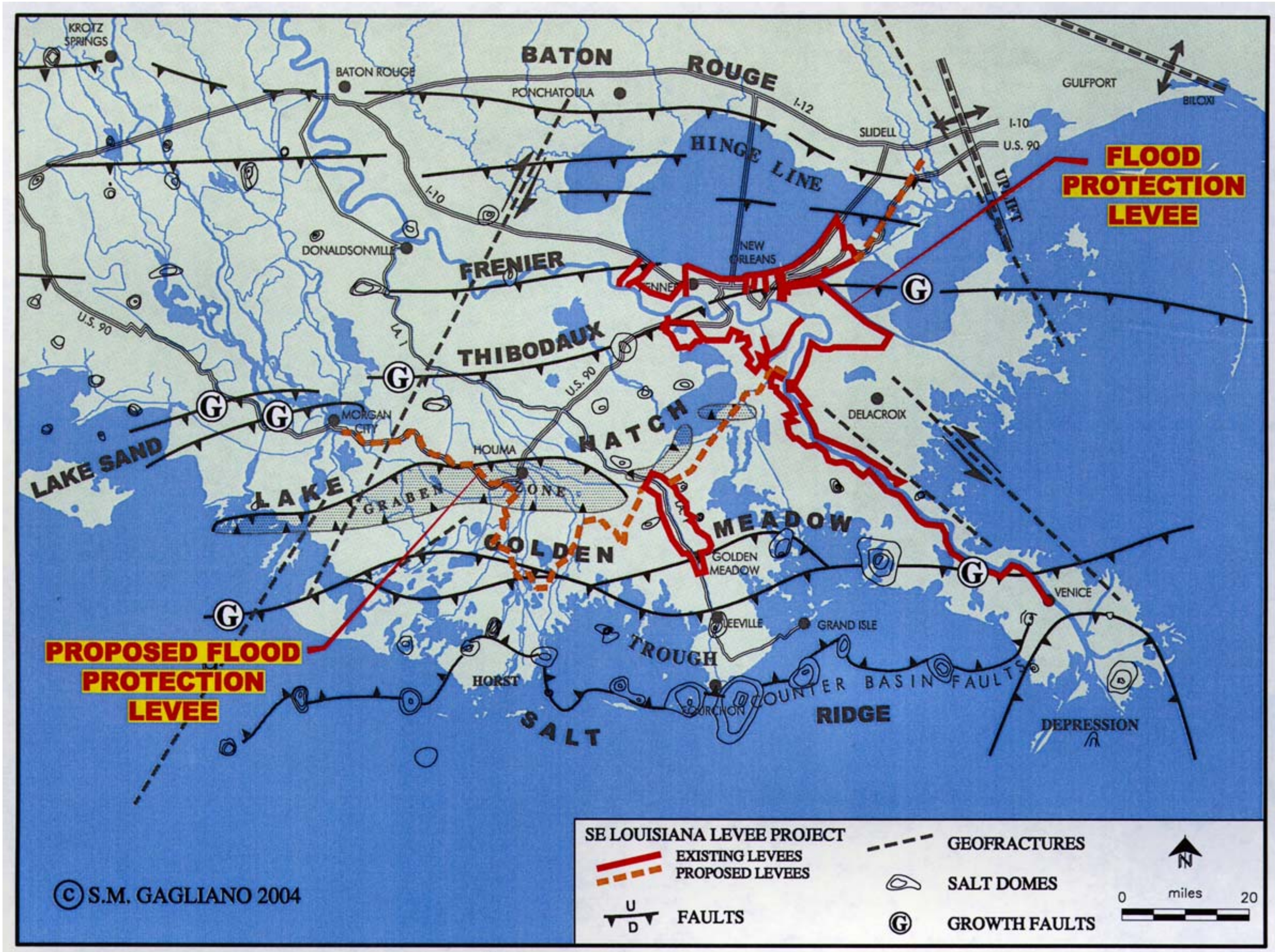


Figure 1. **Map showing the relationship between existing and proposed hurricane protection levee alignments and underlying regional geological faults in southeastern Louisiana.**

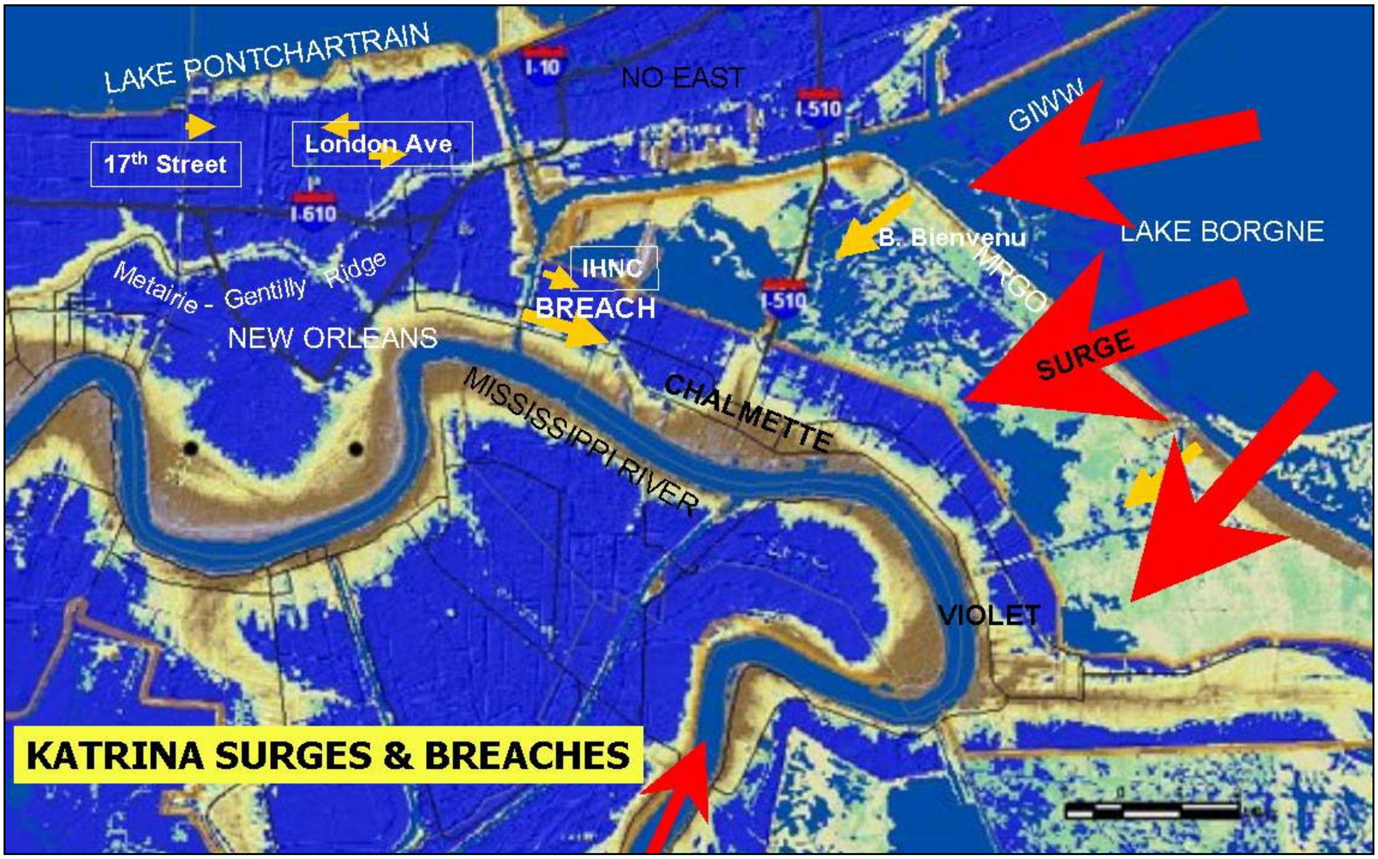


Figure 2. Location of levee and floodwall breaches that occurred during Hurricane Katrina in the Greater New Orleans area. Backdrop is a satellite image showing extent of flooding.

regarding fault movement and resulting landform change in south Louisiana and southeast Texas. Results of the work have been published in geological journals, engineering journals and technical reports and have been presented at numerous meetings of professional associations and public bodies. For additional information on fault hazards see Publications at www.coastalenv.com.

Faults and the Tectonic Framework

South Louisiana is underlain by a maze of faults, which are known primarily from information gathered during a century of exploration for oil and gas. Most of these east-west trending features are classified as growth faults because the sedimentary beds cut by the faults are usually thicker on the down-dropped block, indicating that the faults moved during deposition. The faults are components of a regional linked tectonic framework that has been in motion for more than 100 million years and is still moving. Many subsurface faults within this system have been correlated with surface faults (Figure 3). Characteristics of growth faults are shown in Figure 4, and surface effects of their movement on landforms and near-surface deposits are shown diagrammatically in Figure 5.

Fault-driven submergence is responsible for more than half of the total land loss that has occurred in south Louisiana since the 1930’s (Figure 6). Fault movement affects surface landforms and infrastructure including ridges, barrier islands, wetlands, flood protection levees, highways, and coastal communities. Depressions along faults and fractures, and tilting of fault-bound blocks also strongly influence the alignment and channel-meander configuration of the Mississippi River and its distributaries in the deltaic plain. Barrier island breakup, as well as river bank failure have been linked to fault movement. A cause and effect relationship has been established between modern fault movement and the catastrophic land submergence and loss that has occurred in coastal Louisiana during the last 50 years (Gagliano et al. 2003a, 2003b.)

The GNO area lies along the upper margin of the Eastern Tectonic Province of the Gulf Coast Salt Dome Basin (Figure 7). Movement is occurring on deep-seated faults that are part of the tectonic framework of this province. The Eastern Province is in effect a giant gravity slump block, the toe of which lies in the deep waters of the Gulf of Mexico and the crown fault underlies the GNO area (Figures 7 and 8). The faults within the tectonic framework are moving in response to this massive continental margin slumping, which is driven primarily by basin sinking, sediment loading, gravity, and movement of underlying salt deposits. Onshore components of the linked framework are expanding or pulling apart and thus creating surface depressions and block tilting, while offshore components are contracting into folds and thrust faults that are piling up at the base of the continental slope.

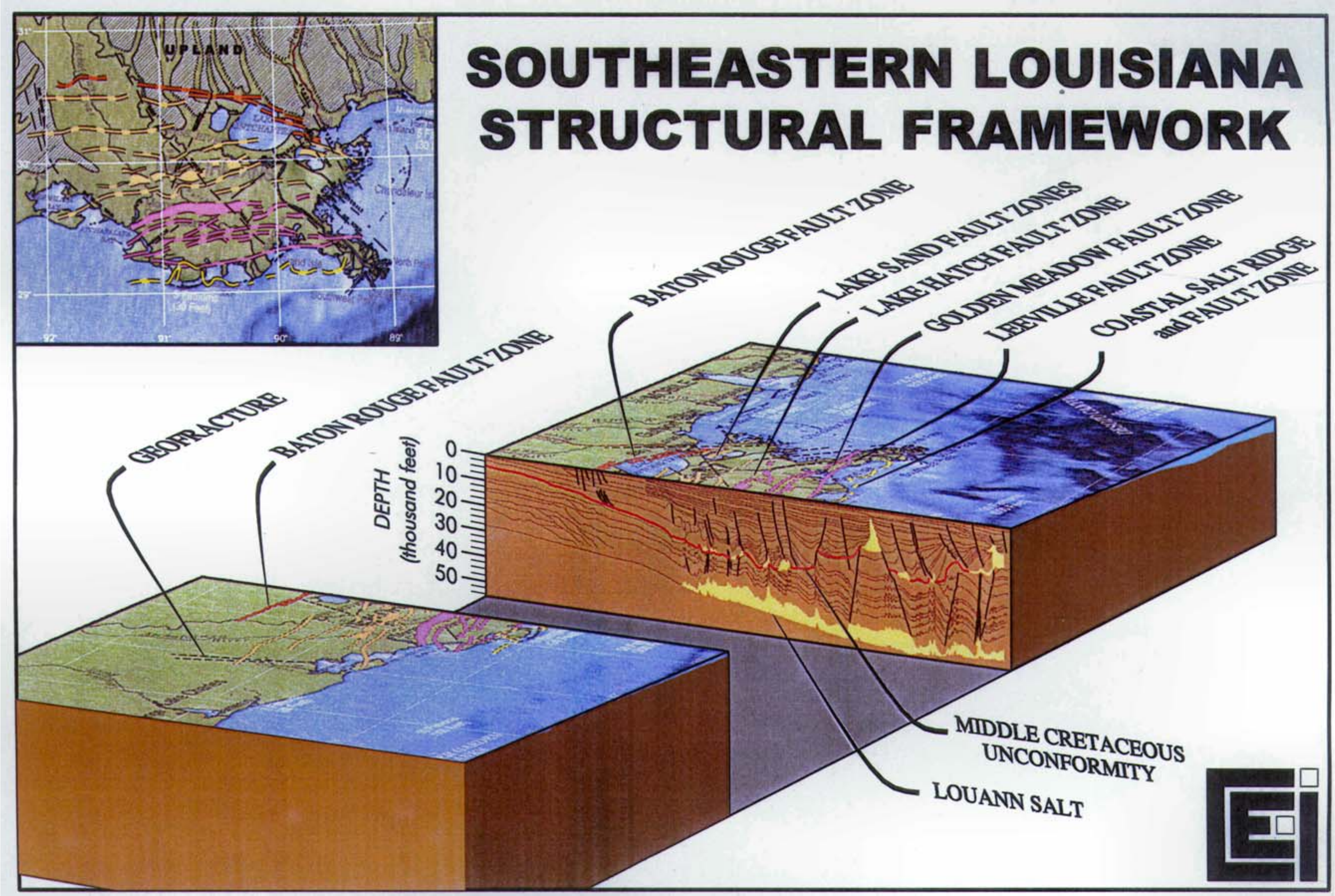


Figure 3. **Active surface faults have been correlated with ancient deep-seated faults. Southeastern Louisiana overlies a deep, sediment filled structural trough, the bottom of which is 35,000 to 50,000 feet below the surface. The bases of active faults in the GNO area are 25,000 to 30,000 feet below the surface.**

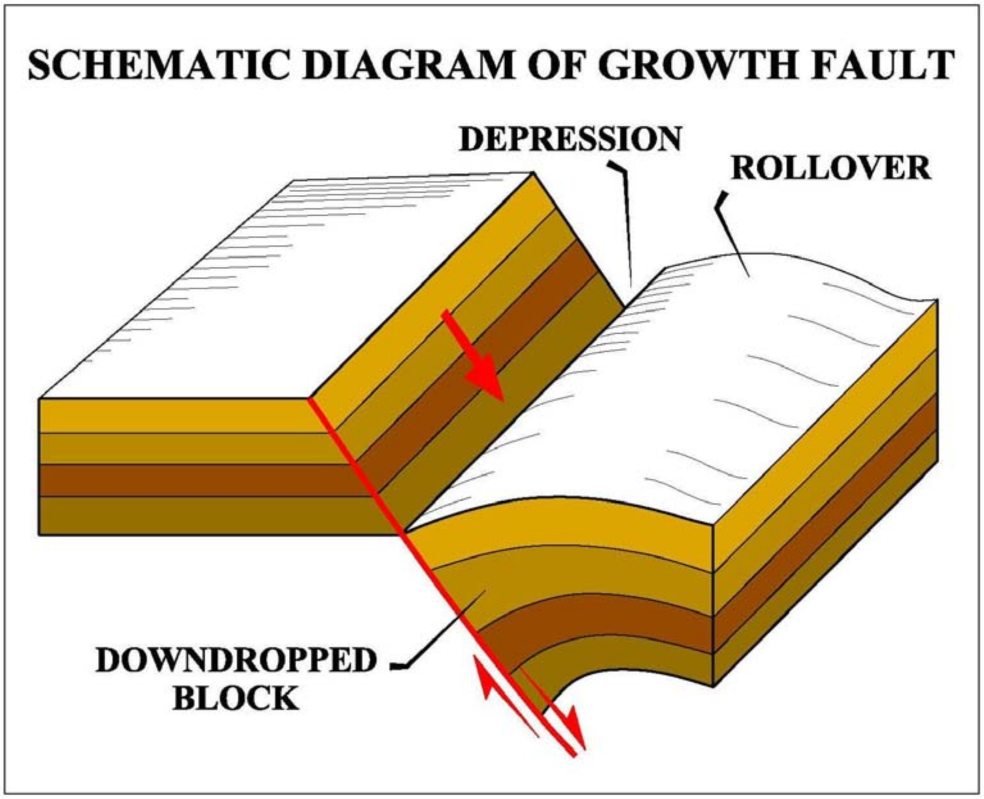


Figure 4. **Growth faults are breaks in beds of rock or sediment where slippage has occurred. Individual beds are characteristically thicker on the downdropped block indicating movement of the fault during deposition of the beds. As the downdropped block slides along the fault plane, it tends to rotate, resulting in a depression aligned along the fault trace and an uplift or rollover structure forms in a down dip direction. Movement along the faults may be at intermittent intervals and, or slow and imperceptible, but continues over long periods of time.**

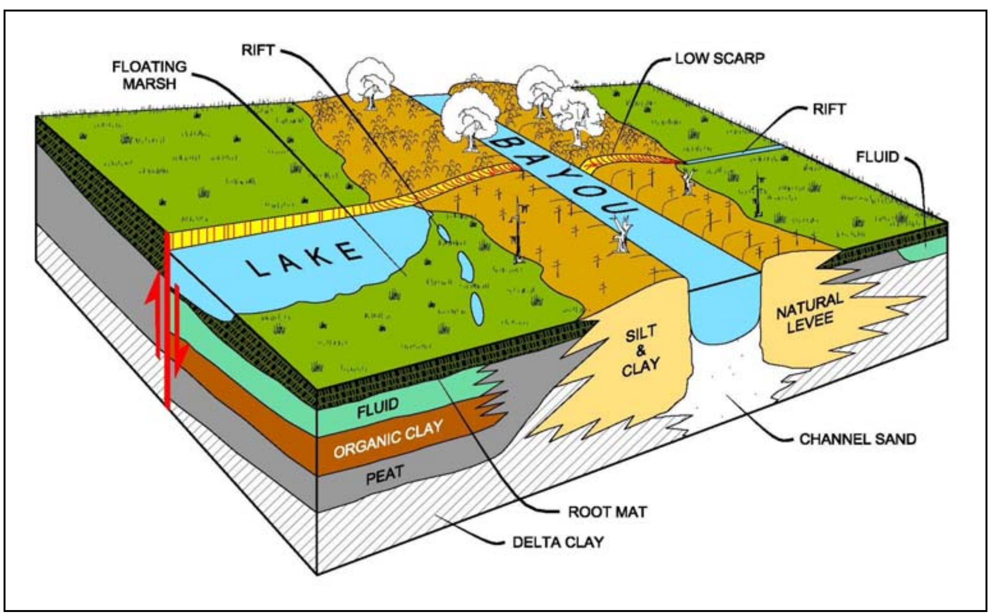


Figure 5. **Diagram showing effects of growth fault movement on different landforms and near-surface deposits in the deltaic plain of southeastern Louisiana. The effects on flood protection levees and floodwalls are similar to those on the natural levee ridges bounding the bayou.**

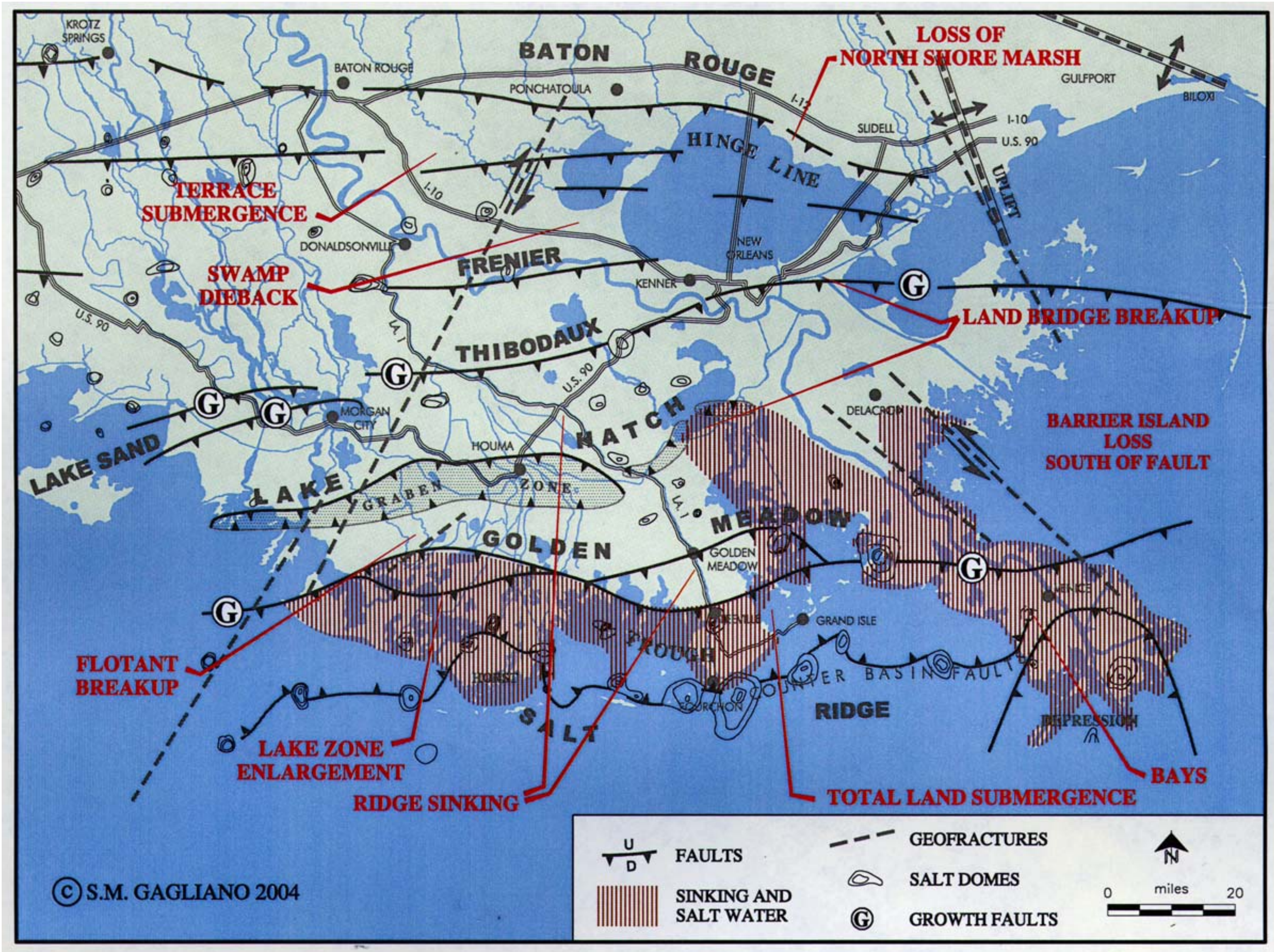


Figure 6. **Map showing areas of land submergence and other environmental deterioration related to fault movement in southeastern Louisiana.**

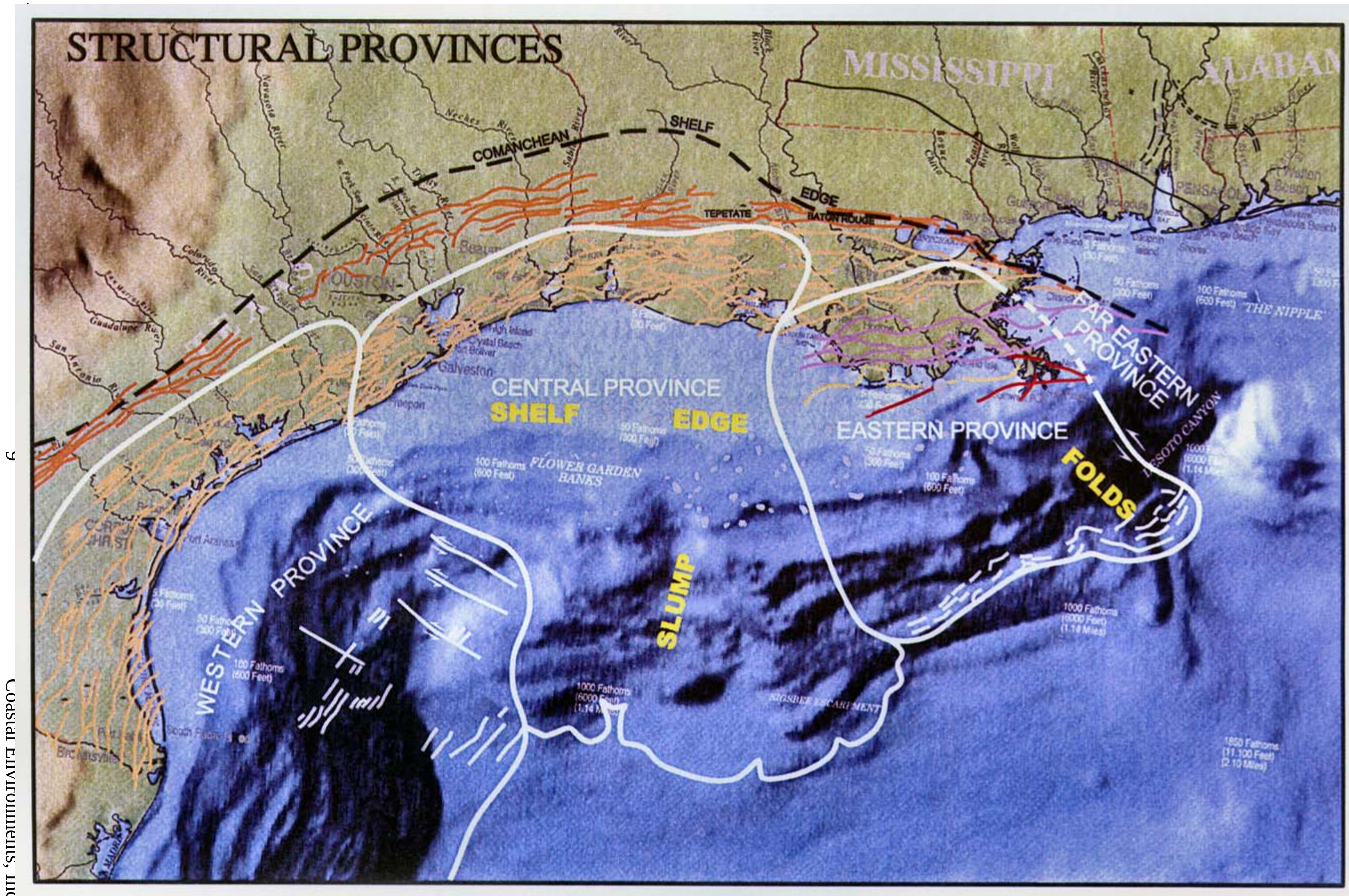


Figure 7. The onshore faults and fractures are parts of linked regional tectonic systems that extend into the deep Gulf. The crown faults of the Eastern Province underlie the Greater New Orleans area (base map with permission of Port Publishing Co., Houston Texas, structural provinces modified from F. J. Peele et al. 1995, faults after GCAGS).

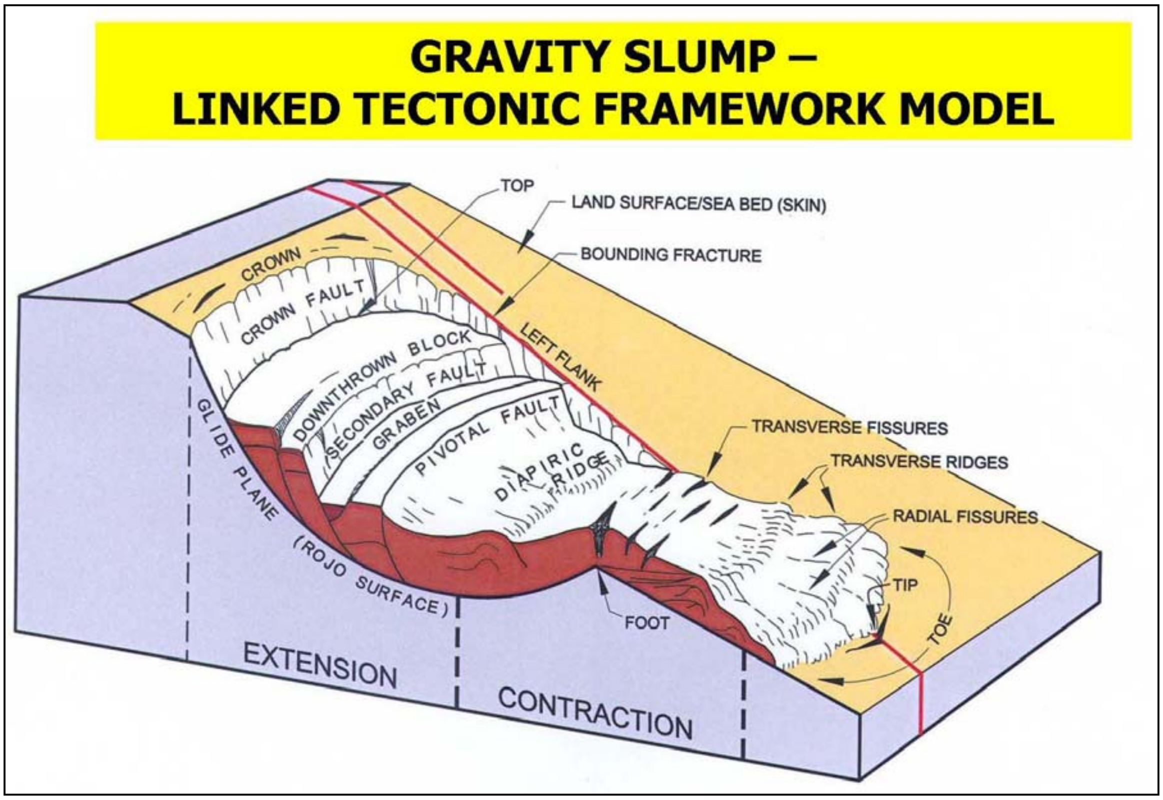


Figure 8. Gravity slump model showing relationships of structural elements of the Eastern Tectonic Province, as shown in Figure 7. The GNO area lies above the crown fault of the slump system.

The crown faults at the head of the Eastern Province slump underlie the GNO area and have controlled the trends of ancient Mississippi River distributaries. For example, the position of the Metairie-Gentilly ridge, which is made up of a pair of natural levee ridges that mark a 3,000 year old course of a now extinct Mississippi River distributary is controlled by the crown faults. In addition, the trends of shallow buried barrier island sands, which underlie parts of the Lakeview, Little Woods and the New Orleans East areas are also controlled by the crown faults. The breaches that occurred on levees along the 17 Street and London Avenue Canals are at places where the levees were built across the crown faults and may be the cause of the floodwall breaches. Secondary processes, yhat may result in localized subsidence include sediment compaction, soil de-watering and fluid withdrawal (ground water, hydrocarbons and produced water).

Figure 9 shows the depth to the weathered surface that marks the top of the Pleistocene formation. The weathered surface is important from the geotechnical standpoint as this is a load-bearing horizon and above it lies poorly consolidated Holocene deposits. Depth to the top of the Pleistocene is less than 100 feet throughout the GNO region. Figure 9 also shows geofractures, subsurface faults, and salt domes. The top of the Pleistocene is displaced by many of these deep-seated structures. In most geotechnical studies, the top of the Pleistocene is considered to be a stable foundation bearing horizon.

The Baton Rouge Fault Zone is a major regional feature that marks the northern boundary of the Gulf Coast Salt Dome Basin. This is a hinge line fault. That is, the land surface north of the fault is rising, and south of the fault the land surface is sinking. This fault zone is marked by a pronounced topographic escarpment that separates Lakes Pontchartrain and Maurepas and their surrounding wetlands from the pine-covered terrace lands of the "North Shore." Segments of this fault zone are known to be active. Highway pavement cracks must be frequently repaired and railroad tracks must be frequently adjusted where they cross this fault zone.

The Lake Sand-Thibodaux Fault, one of a series of Oligocene growth faults that underlie Lake Pontchartrain and the GNO area, is the crown fault of the Eastern Province. Displacement of the top of the Pleistocene Formation has been identified from correlations of boring logs and on sub-bottom acoustical profiles across several of the Oligocene faults under Lake Pontchartrain. Highway and railroad bridges across the lake are also cracked, offset and displaced where they cross these faults. These offsets have been documented in the geological literature (Lopez et el. 1997). It should be noted that salt domes, which are associated with many of the faults of the region, are absent or rare in the GNO area

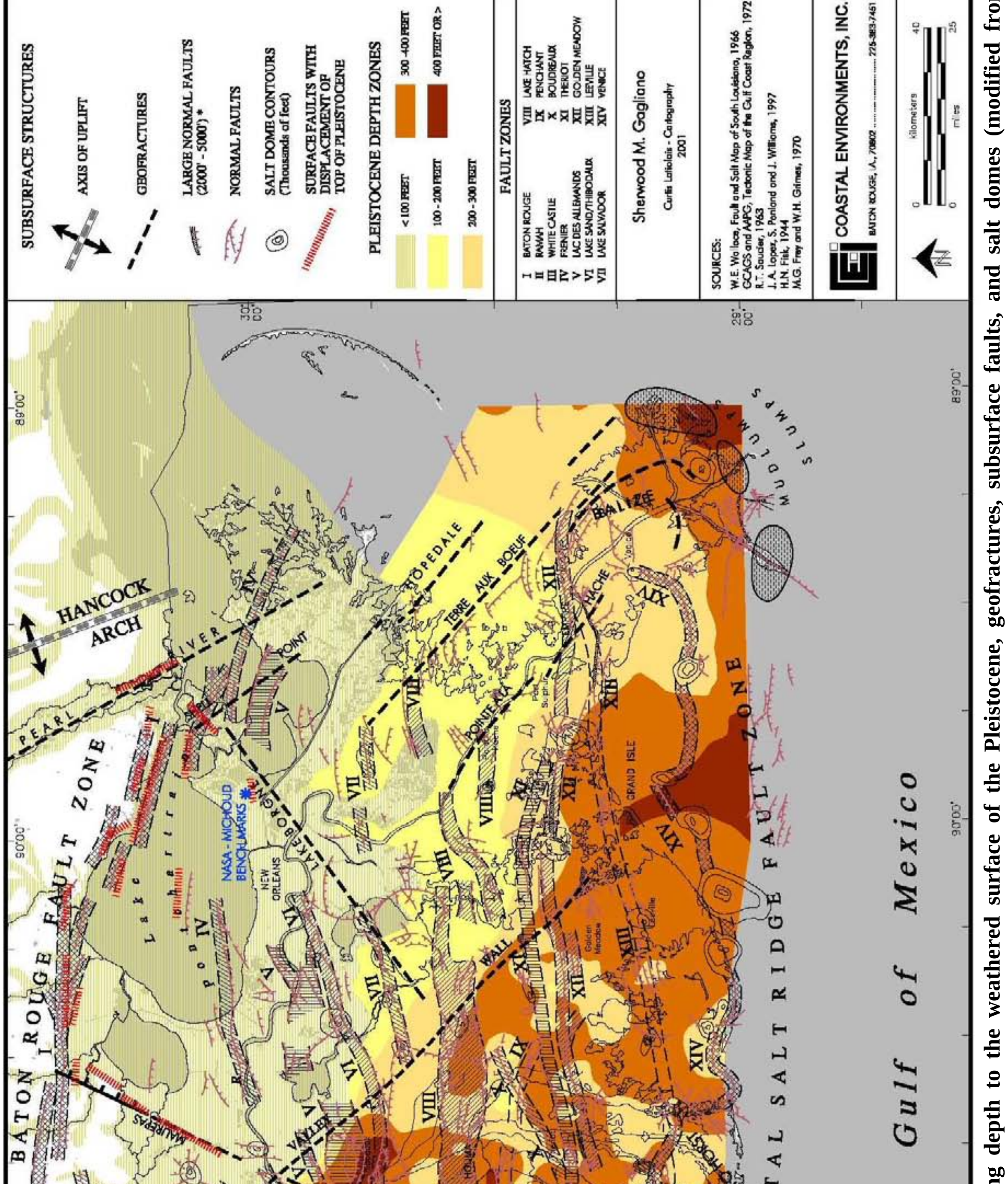


Figure 9. **Map showing depth to the weathered surface of the Pleistocene, geofractures, subsurface faults, and salt domes (modified from Gagliano et al. 2003a, Pleistocene depth data from L.D. Britsch 2001).**

Geofractures constitute another important category of structural features that have surface expression and may affect foundation conditions. An extension of the northwest - southeastern trending Terre aux Boeufs Geofracture cuts through the GNO area (see Figure 9). This feature segments the blocks between some of the regional growth faults.

Many of the east-west trending growth faults terminate at their intersection with this geofracture. The Lake Borgne Geofracture (Fault) Zone strikes northeast - southwest and has played an important role in determining geometry of river courses in the area as well as the formation of lakes and bays. Fault segments in this zone may have contributed to the floodwall breach along the Inner Harbor Navigation Canal (IHNC, also known as the Industrial Canal).

Although some regional faults have been active for millions of years, contrary to common belief, not all movement has occurred during the dim geological past. Some faults have moved during, prehistoric Native American times (the last 12,000 years), historic times (the last 300 years) and modern decades (the last 50 years). Surface effects of fault movement have been reported from numerous locales across south Louisiana (Lopez et al. 1997, Gagliano 1999, Keucher et al. 2001, Morton et al. 2002, Gagliano et al. 2003a Gagliano 2005, and others). Figure 10 shows dates of surface movement of faults in southeastern Louisiana, as determined from comparative studies of aerial images and maps. For example, comparison of aerial photographs taken in 1976 and 1982 show surface displacement along a fault segment at Bayou Long (Gagliano et al. 2003a). Lake Lery is a fault depression that is depicted on the earliest historic maps of the region and is shown in Figure 10 as pre-1803 surface fault movement. Modern fault events occur along fault segments from 1 to 5 miles in length with vertical displacement of a few inches to 5 feet or more. Fault events result in the formation of lakes and bays, submergence and breakup of marsh, submergence of natural levee ridges, and submergence and breakup of barrier islands.

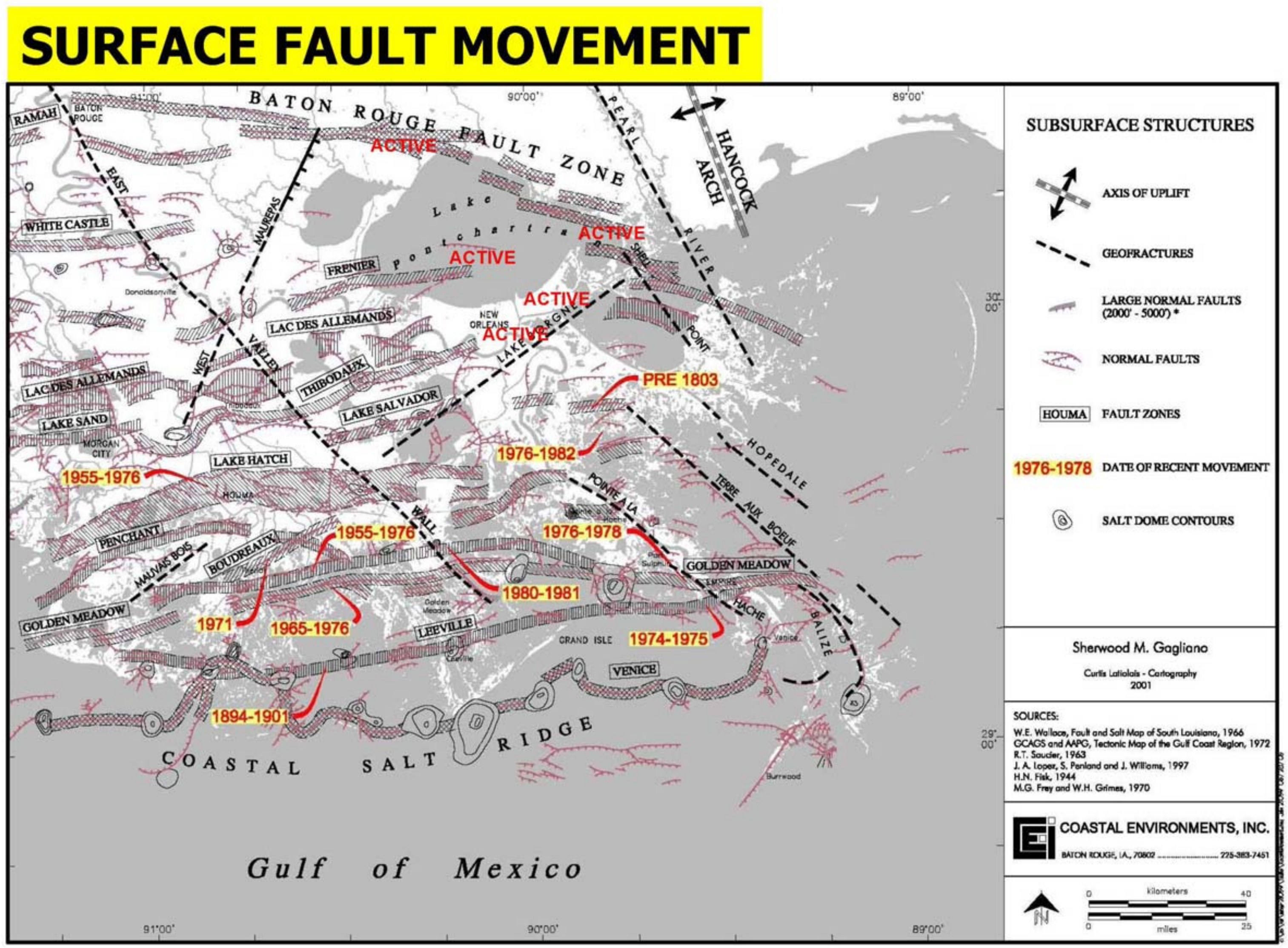


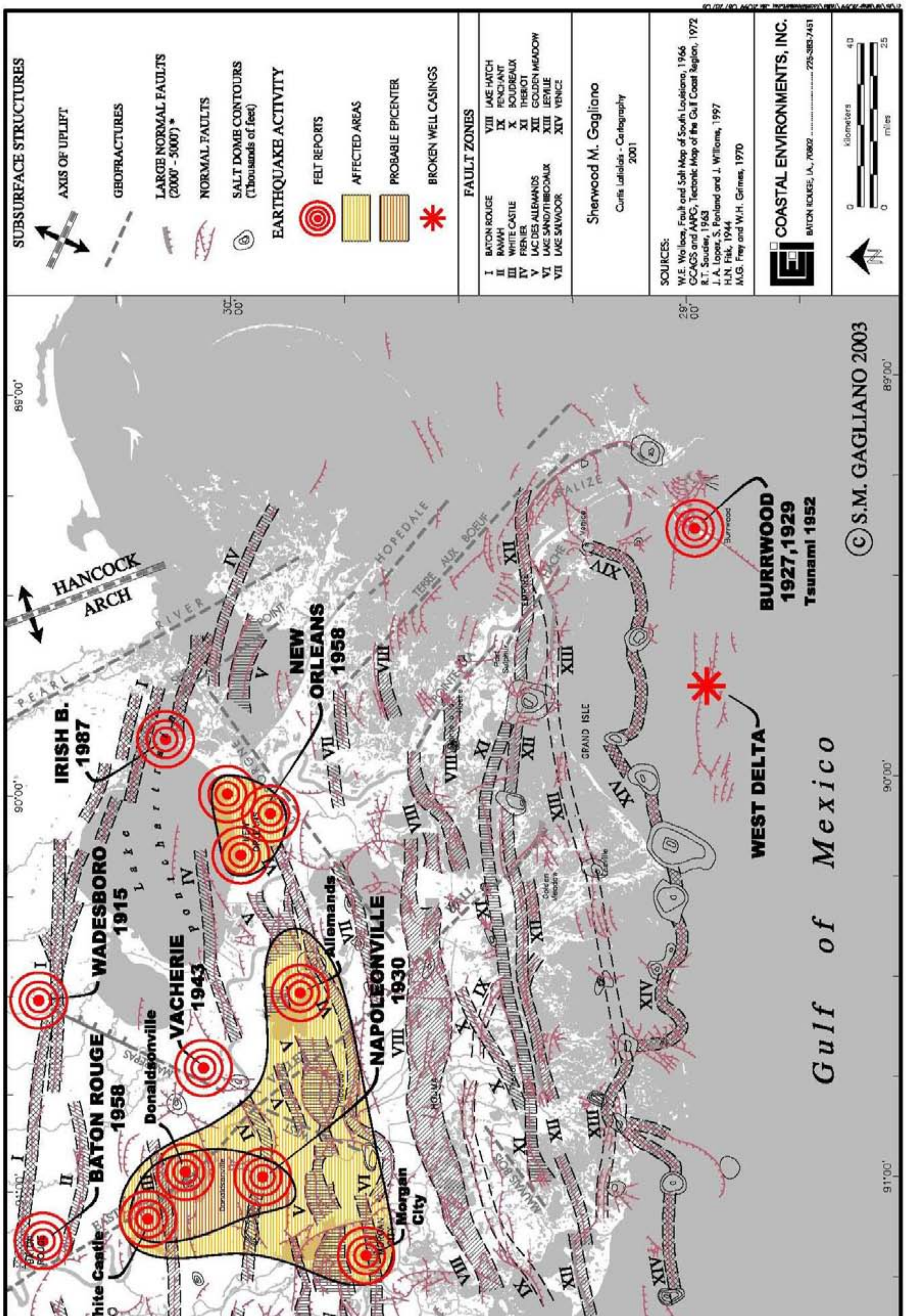
Figure 10. Map showing dates of surface fault movement in reference to known subsurface faults.

Fault movement and earthquakes

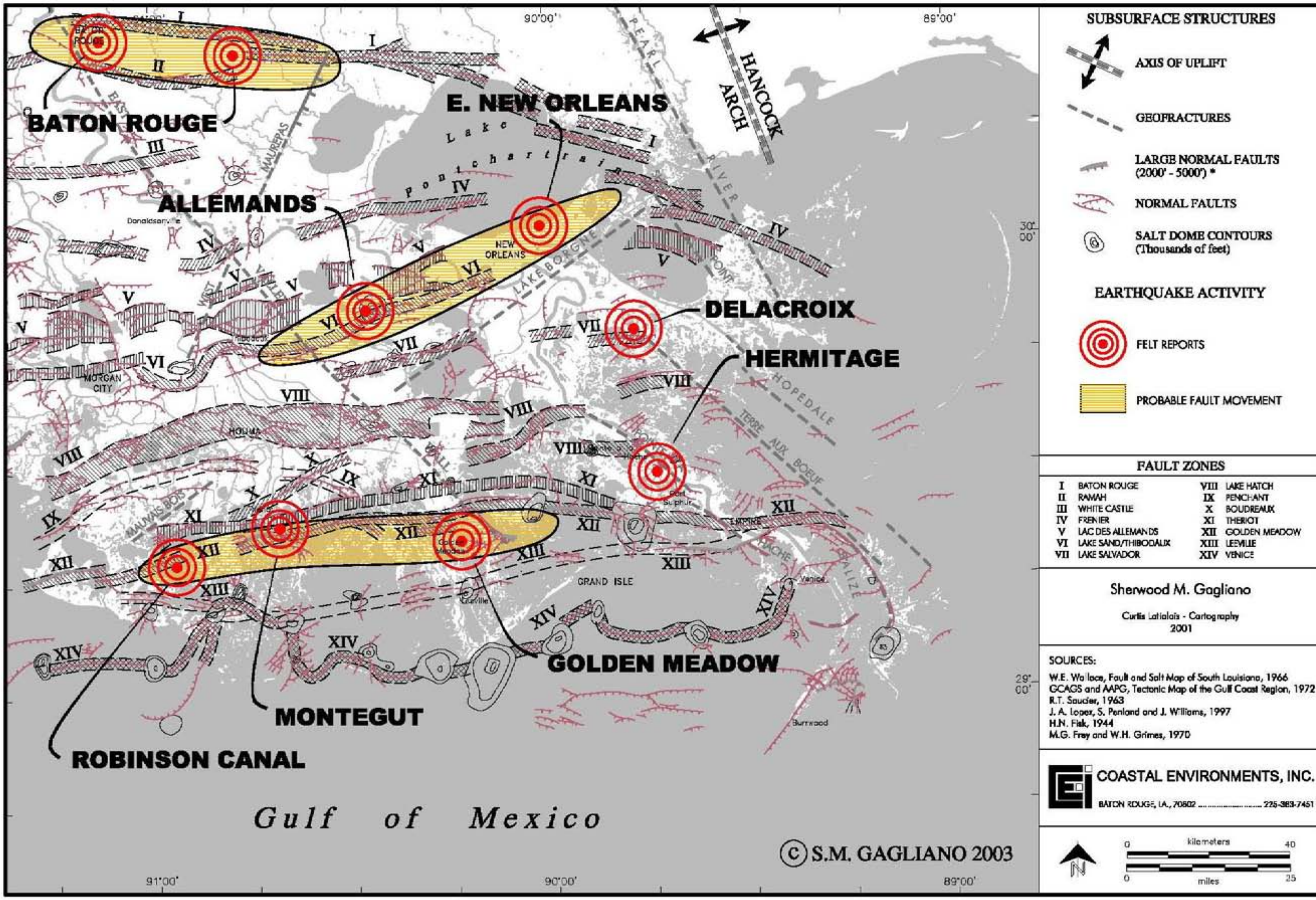
Earthquake occurrences indicate locations of active faults. Two categories of earthquakes have been reported in south Louisiana. The first is caused by random slippage on subsurface faults. Figure 11 shows locations where this type of earthquake has occurred. Those within and near the GNO region are aligned along the Lake Sand - Thibodaux Fault Zone. On November 6, 1958 an Intensity IV earthquake occurred within a five-to seven mile radius of downtown New Orleans. The area where effects of the earthuake were felt extended from Lake Pontchartrain on the north to Gretna on the south and from Harahan on the west to Arabi on the east. The earthquake was recorded on the Loyola University seismograph located in New Orleans as a 15 second vibration. The earthquake caused windows to shake and doors to rattle (Brasseaux and Lock 1992:319, Stevenson and Mc Culloh 2001:6)

The second type of earthquake occurs when shock waves from distant earthquakes trigger slippage along local faults, which in turn may cause a secondary earthquake (Gagliano 2005) (Figure 12). An event particularly relevant to the Hurricane Katrina IHNC floodwall breach occurred on March 27, 1964 at 10:00 PM when "…swells were reported in the Industrial Canal [IHNC] NEAR new Orleans…" *UPI, New Orleans*, 1964. "'It caused our docks and vessels moored in the yards to go crazy-like, bobbing up and down, moving sideways, back and forth.' Said Leon Poche 47, superintendent of Avondale Shipyards." *AP, New Orleans* 1964a. " 'The water rose about six feet above normal all at once,' said O.C. Boxton, night watchman at New Orleans Industrial Canal. 'It was one of the wildest scenes that I've seen in a long time,' he said. The water was rolling, barges began to move in and out and the lines (holding the barges) began to turn and break." *AP, New Orleans*, 1964b. "One marine company at New Orleans said the waves in the Intracoastal Canal were 'at least four or five feet.' Several boats were torn loose, including a line holding an 83-foot Coast Guard vessel." *AP, New Orleans*, 1964.

This Industrial Canal event was apparently triggered by arrival of shallow shock waves from the Alaskan Earthquake of Prince William Sound of the same date and 12 minutes earlier. It took the shallow seismic waves approximately 12 minutes to travel 3200 miles



F Figure 11. Location of reported felt effects of historic earthquakes in southeastern Louisiana and correlation with known subsurface faults.



F Figure 12. Locations of reported effects of apparent secondary earthquakes in southeastern Louisiana triggered by shock waves of the M 9.2 Prince William Sound Earthquake of March 27, 1964.

from the epicenter of the Alaskan earthquake to south Louisiana. The intensive water disturbances indicate the presence of an active fault. During Hurricane Katrina in 2005, the two breaches that occurred in the floodwall along the east bank of the Industrial Canal were in the same location as the 1965 earthquake induced water disturbances. It was these breaches that caused extensive flooding in the Lower 9th Ward of New Orleans and adjacent areas of Arabi and Chalmette in St. Bernard Parish.

Measuring movement

Rates, magnitude and frequency of movement have been determined for some faults. Several data sets have been used to measure vertical movement of land surfaces in south Louisiana, including tide gauge records, differential elevations of re-surveyed topographic bench marks, movement of historic and archaeological features and structures, land loss, habitat change and radiometric dating of buried deposits. These measurements have been related to known faults. Tide gauge records indicate that the Little Woods area along the Lake Pontchartrain shore in New Orleans, in the general vicinity of the London Avenue Canal Breach, has one of the highest rates of subsidence in the state. Records from a tide gauge at Little Woods show a total relative sea level rise (subsidence plus eustatic rise) of 1.84 feet for the period between 1940 and 1976, for a rate of 0.51 feet per year. Further, the record is distinctly "stepped," suggesting episodic fault movement.

Resurveyed bench marks at the NASA - Michoud facility, located near the IHNC breach, likewise show exceptionally high subsidence rates. The NASA-Michoud measurements also indicate accelerated movement during recent decades.

Recently, the National Geodetic Survey (NGS) in conjunction with the Spatial Data Center at Louisiana State University (LSU) has re-evaluated vertical change data from benchmarks. Dr. Roy Dokka, director of the LSU team, reports that "…loss of elevation ranges from 0.3 to 0.13 feet per year across south Louisiana…" (NOAA Magazine 2003). The NGS-LSU findings are generally consistent with those presented herein.

Types of Fault Impacts

There are three categories of fault impacts. The first is subsidence and tilting of the surface near and between faults. This effect is most pronounced on the downthrown block in the immediate vicinity of the fault. On a larger scale, entire fault-bound blocks tilt and subside. Large areas become inundated creating lakes and bays within short time intervals. As stated previously, fault induced land submergence is the primary cause of land loss in southeastern Louisiana (Figure 6).

The second category of impact relates to foundation instability along and within the immediate vicinity of the fault plane or zone. Movement may be instantaneous or slow and imperceptible. Even when slow and imperceptible, fluids and gas may migrate toward the surface along the fault plane (Keucher et al. 2001, Gagliano et al. 2003a). Some fault planes are pencil line thin with surfaces that exhibit slickensides (smoothed and striated surfaces that result from friction along fault planes) and/or clay and mineral films. Other faults exhibit multiple, parallel planes. Another type is characterized by brecciated zones, where clay particles are broken into pellets as a result of movement along the fault zone. Sand and silt dikes that may be several feet wide may also mark fault planes. In all cases, the fault plane or fault plane zone is a deep crack in the earth's surface. Foundation conditions across the crack are poor and if a levee or floodwall is built across the fault, the fault plane may become a conduit for piping or seepage under the levee base or under the bottom of interlocking steel sheet piles. Since the faults are deep-seated, the depth of the cracks may be greater than the bottom of the longest sheet piles.

The third category of instability relates to minor earthquakes and related phenomena such as liquefaction. As previously discussed, earthquakes may result from sudden release of pent-up stress or may be triggered by shock waves from remote earthquakes. When accompanied by earthquakes, fault movement effects may include liquefaction, breakup of floating marsh mats and other damage to landforms and human-made structures (Figure 5). Liquefaction occurs when earthquake vibrations cause buried sand deposits to become more compact and in the process expel pore water. The expelled water may form “sand fountains” in which sand-charged water shoots up above the surface through fault crevices.

Hurricane waves are known to cause slumping along the unstable delta front area offshore from the active outlets of the Mississippi River. It is conceivable, though it has not been proven, that the weight of the elevated water column in the canals combined with the pounding of wind-generated waves during Hurricane Katrina could have caused release of pent-up stress on active faults.

Relationship Between Fault and Floodwall Breaches in the GNO Area

Available data suggests that the breaches along the 17th Street Canal, the London Avenue Canal (2 breaches) and the IHNC (2 breaches) were at least partially caused by underlying faults. The 17th Street Canal and London Avenue breaches appear to be on the same fault zone. This fault controlled the location of a series of southwest-northeast trending barrier islands that formed through what is presently the Metairie-Lakeview area about 5000 years ago. It was sand from one of these barrier islands that was expelled to the surface at the breach on the London Avenue Canal during Hurricane Katrina.

Surface inspection of the larger IHNC breach site revealed evidence of a possible fault (Figure 13). The site was inspected after a long drought. Aligned desiccation cracks and water seeps called attention to what appears to be a silt dike. As shown in the photographs in Figure 13, the feature runs under the emergency levee that was constructed to close the breach and apparently under the base of the failed floodwall.
Could this silt dike have formed as a result of liquefaction during the 1964 earthquake event? While the evidence is not conclusive, it demands further investigation.

Figure 14 is a schematic representation of a canal with floodwalls constructed across a fault. As shown, the stability of the levees and floodwalls could be affected by the poor foundation conditions within the fault plane zone, by piping of water under the levees and sheet pilings along the fault plane or within the fault plane zone, and by sagging of the levee crown.

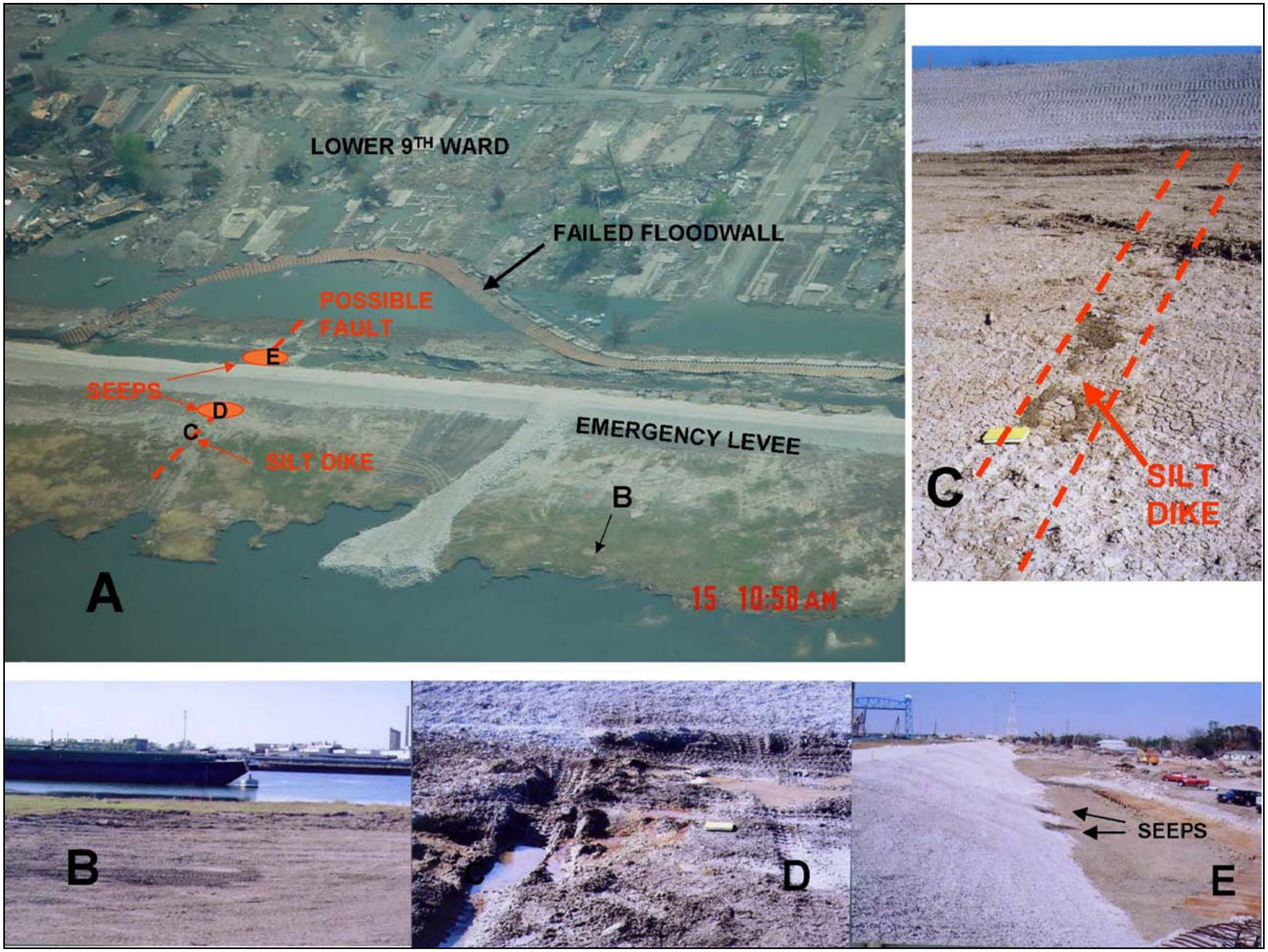


Figure 13. **Floodwall breach on the east side of the Inner Harbor Navigation Canal in New Orleans. A. View looking southeast across area of floodwall failure. Uprooted steel sheet piles capped with concrete are clearly visible. B. View of canal batture looking west. Water level in the canal is approximately 1 to 1.5 feet below batture land level. Except where disturbed by vehicle movement, the batture in this area is grass-covered and not deeply scoured by water flow. C. Water seepage along possible silt dike. D. Seepage through possible silt dike at base of emergency levee, canal side. E. Seepage at base of emergency levee, east side. These seepage patches align with the possible silt dike on the west side of the levee.**

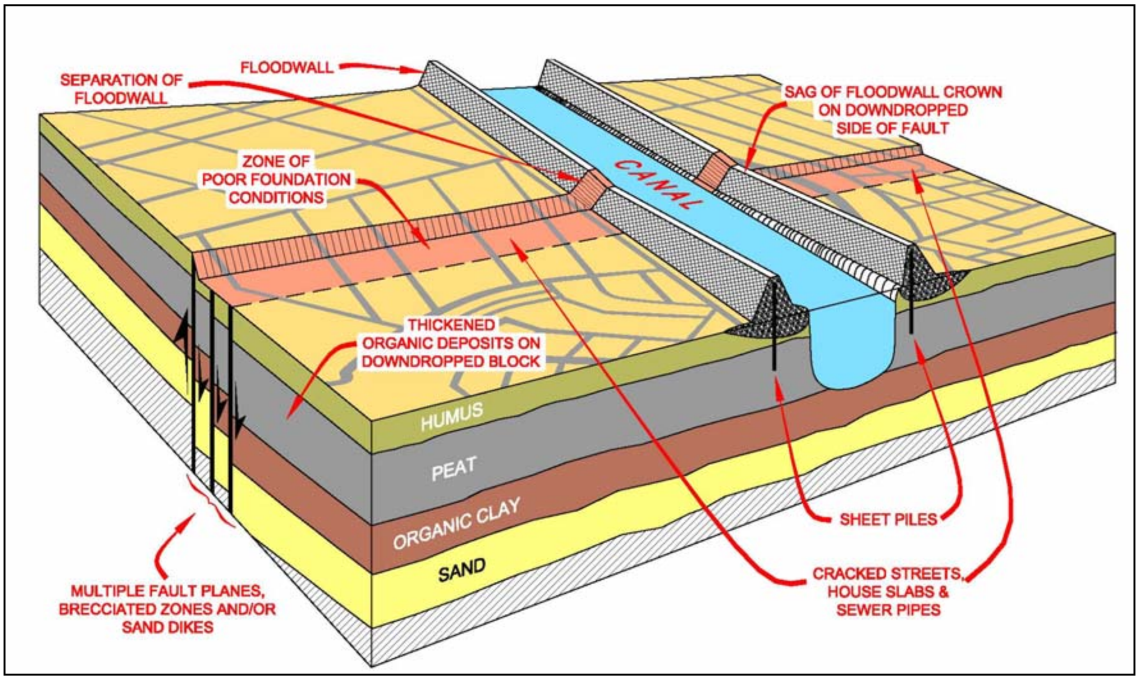


Figure 14. **Diagram showing possible effects of a fault on levees and floodwalls built across the fault plane.**

Breaches along the MRGO hurricane protection levee southwest of Lake Borgne (Figure 2) at the Bayou Bienvenu and Bayou Dupre floodgates are most likely the result of levee overtopping and return surge flow.

Fault Hazards Along Existing and Proposed Levee Alignments

As shown in Figure 1, proposed levee alignments in southeastern Louisiana cross major known faults at a number of locations. Breaches in the flood levees along the Mississippi River in Plaquemines Parish below New Orleans may have been caused by underlying faults. The levees are constructed across several major fault zones including the large and active Lake Hatch and Golden Meadow fault zones. At some of these fault crossings, steel sheet pilings had been installed to reinforce the earth levees prior to Hurricane Katrina because of chronic foundation problems.

Breaches in levees have also occurred during two hurricanes where levees were constructed across known faults in the vicinity of Montegut, south of Houma, Louisiana.

As shown in the photograph in Figure 15, a flood levee was constructed across the Montegut Fault. Surface expression of this fault is distinguished by a marsh-water break.

The surface expression of this fault appeared between 1972 and 1976. Field studies at this location showed 3.3 feet of change in elevation from the marsh surface to the pond bottom and a comparable amount of displacement of near-surface beds as determined from borings.

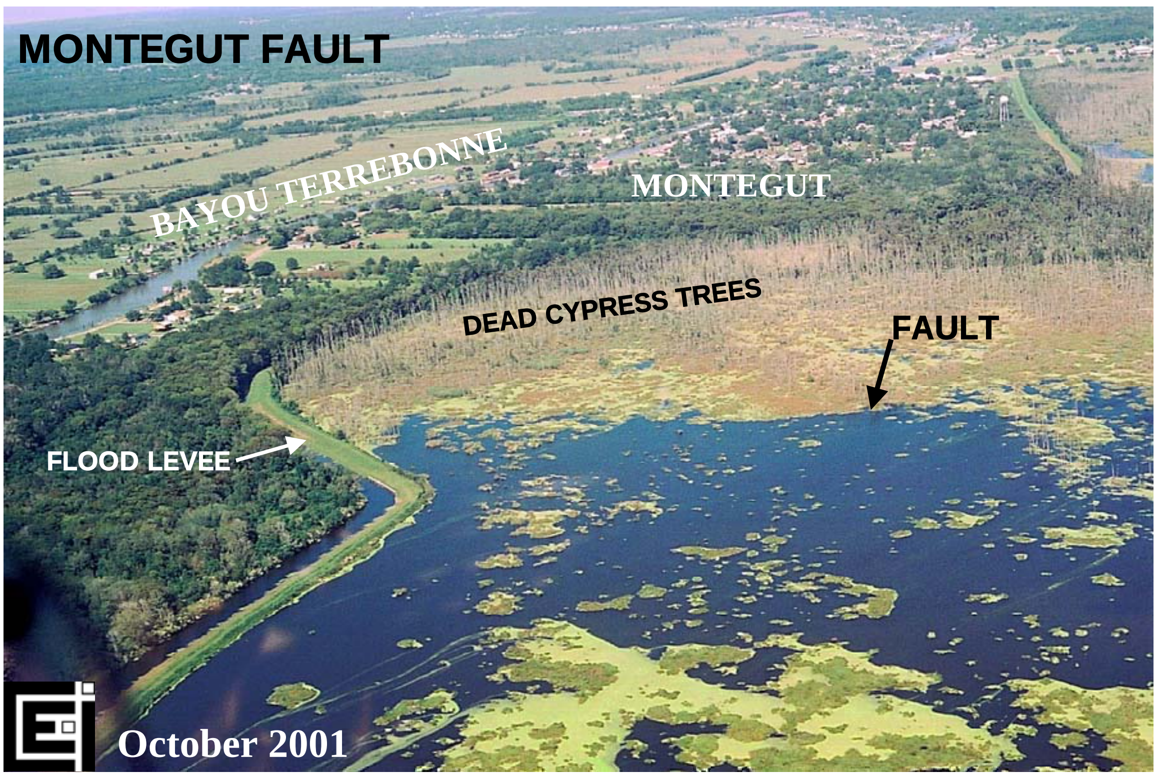


Figure 15. Flood levee constructed across an active fault at Montegut, Louisiana. The levee failed at this location during Hurricanes Isadore and Katrina. The view is looking north across a large pond and broken marsh on the down-dropped block of the fault. Note the dead cypress trees on the up-thrown block. The flood protection/drainage levee is located along the back-slope of the Bayou Terrebonne natural levee ridge. The Montegut community is located on the natural levee. Photography S.M. Gagliano, October 17, 2001.

Summary and Conclusions

Evidence from a number of different data sets indicates that faults in the GNO area and throughout southeastern Louisiana have been active during recent decades. Levees and floodwalls have been built across these active faults. Strikes of known subsurface faults are parallel to lines projected between levee breaches along the London Avenue and 17th Street Canals. Converging lines of evidence suggest that floodwall breaches along the IHNC are fault-related. There are numerous other problem areas where existing and proposed levee alignments cross known, active faults.

Hurricane protection and wetland restoration have been regarded as a battle against the erosive forces of the sea, a horizontal engagement. Findings of the tectonic studies indicate that the dominant processes are geological and the changes are vertical, thus requiring a fundamental shift in battle strategy.

While faults represent serious geological hazards in southeastern Louisiana, they do not present an insurmountable obstacle in our quest for adequate storm and flood protection. However, <u>fault hazards must be taken into consideration in planning and design of protection levees and all other infrastructure (including floodgates), as well as in the coastal restoration program</u>.

The issue that fault driven subsidence is the major cause of land loss and coastal deterioration in south Louisiana has been on the table for more than 5 years and has largely been circumvented by the coastal restoration community and most public officials. This is partially due to the fact that fault processes and effects have only recently been understood. This is new science and it takes time to be absorbed. However the main reason is the difficulty of informing citizens and businesses that their property is on the wrong side of a fault, and therefore, may be impossible to protect and maintain. Fault movement and related land subsidence are natural processes and there is no institutional or corporate villain. We are in denial. (Figure 16).

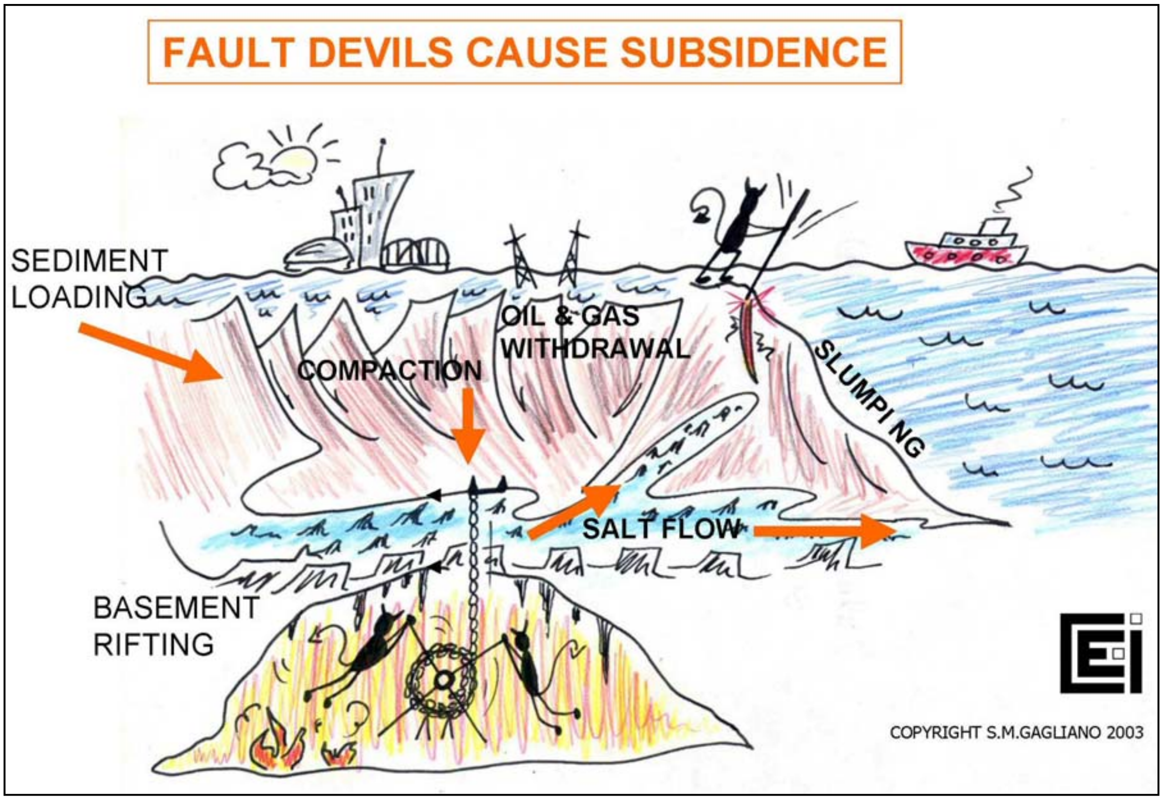


Figure 16. Fault induced subsidence is not a politically correct theory. Most people in Louisiana, including most public officials, do not understand, or will not accept that the southern edge of the state is being submerged as a result of fault movement that has accelerated during the past 50 years.

If our efforts to protect the Louisiana coast are to succeed, we must test each hypothesis and not arbitrarily reject those that predict outcomes that are difficult to resolve or hard for the public to accept. We can't cure the disease if we don't know the cause. This testimony deals with a controversial and sensitive topic and is advanced in the hope of stimulating solutions and not to stifle a program of protection and restoration of coastal Louisiana.

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