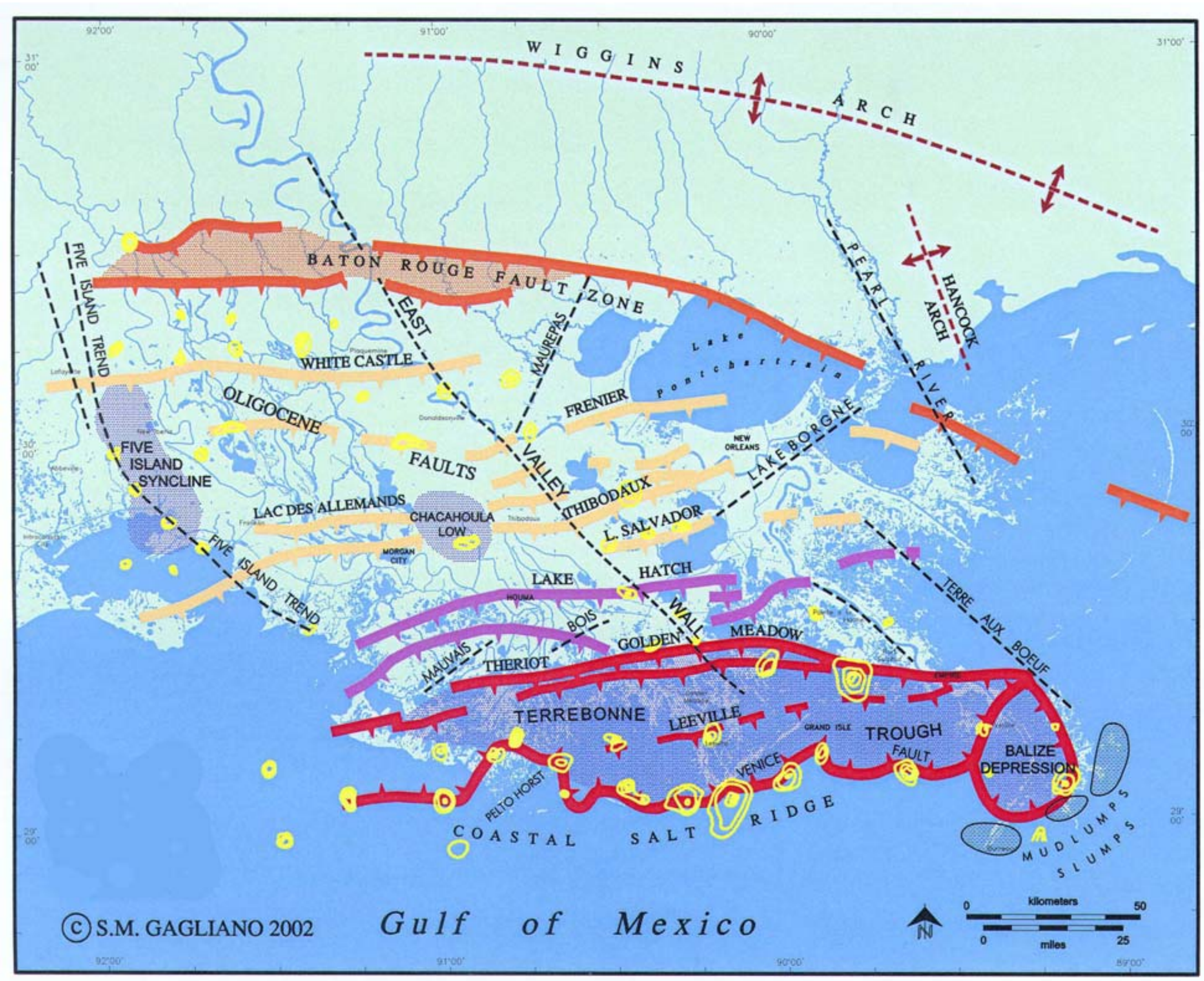
Effects of Earthquakes, Fault Movements, and Subsidence on the South Louisiana Landscape



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About the cover: *The map is of Southeast Louisiana and its coastline. It shows active fault lines and related geological features in the region.*

Journal Editor's Note: *The thesis presented in this article, if generally accepted, would have a significant impact on the practice of geotechnical engineering and the infrastructure decisions in the region, and on the strategy for accomplishing Louisiana's coastal restoration.*

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Effects of Earthquakes, Fault Movements, and Subsidence on the South Louisiana Landscape

By

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Introduction

Recent geological findings change forever our perception of the tectonic stability of south Louisiana. Results of research in several disciplines are converging into a unified model of fault and earthquake activity called the linked tectonic system that explains many previously puzzling aspects of the ever-changing landscape. The findings also indicate that fault-earthquake effects are an underrated hazard that must be considered in planning and design for restoration of the coastal zone, including construction and maintenance of its infrastructure.

Ho hum, here comes Henny Penny again... The sky is falling!.. The earth is cracking!.. The land is sinking!.. Another hazard to worry about...

This article is not about a contrived catastrophe. The facts are compelling and the implications are far reaching, particularly for coastal restoration.

Brief History

One of the milestones in formulating the tectonic model was the recognition and demonstration that modern movement along ancient geological faults, as shown in Figure 1, that underly Louisiana's coastal lowlands are a major cause of the catastrophic twentieth century land loss (Gagliano 1999, Gagliano *et al.* 2003a). We now know that more than half of the land loss is due to submergence and not edge erosion. The primary driving process is fault-induced subsidence and not the eating away of the land along its edges by waves. Fault-bound blocks underlying the coastal zone are sinking and tilting and are being inundated by the Gulf of Mexico.

The people of south Louisiana live on top of a linked tectonic system, part of which extends under the gulf (Peel *et al*. 1995). The system resides within a great trough in the earth's crust, diagramed in Figure 2, that has been opening and sinking for more than 200 million years. And, that process is continuing. The tectonic system is in constant motion. As the bottom of the trough sinks, the resulting depression is filled with sediment brought in by rivers that drain the continent. If the sinking rate exceeds the sediment delivery rate, the land becomes submerged; lakes and bays form and the shoreline moves inland (transgresses).

Ironically, sediment loading may also accelerate subsidence. Thick beds of low-density salt, originally deposited at the base of the 50,000-foot thick sequence of sedimentary deposits, squeeze and shift under the weight of the heavier detrital sediment complicating the internal adjustments to loading. The salt behaves like silly putty working its way upward in the section along faults and fractures to form salt domes and in other places fanning out between bedding layers to form salt canopies. The folds and faults resulting from these movements form the traps that collect the rich deposits of oil and gas underlying both the onshore and offshore areas of south Louisiana.

The constant movement and adjustments within the sediment pile have dramatic effects on the surface. Large depressions develop over salt withdrawal areas. Subsidence and tilting are found at the surface on *down-dropped fault blocks* as depicted in Figure 3. Linear depressions above grabens result from vertical and lateral movement. These holes are called *accommodation*

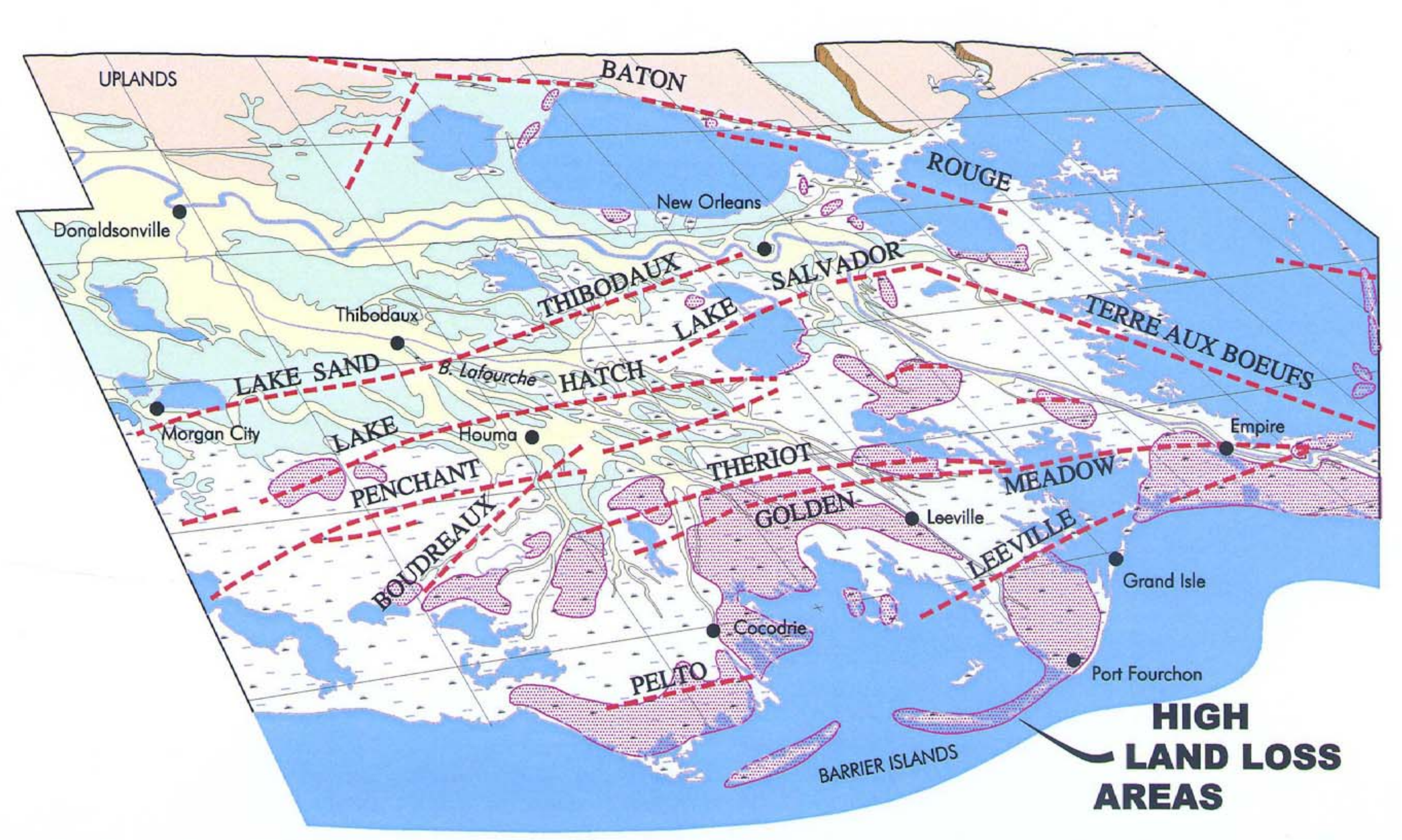

Figure 1. Perspective maps showing relationship between faults and areas of high land loss in southeastern Louisiana. Faults are the major cause of land submergence and loss in the region (modified from Gagliano 1999).

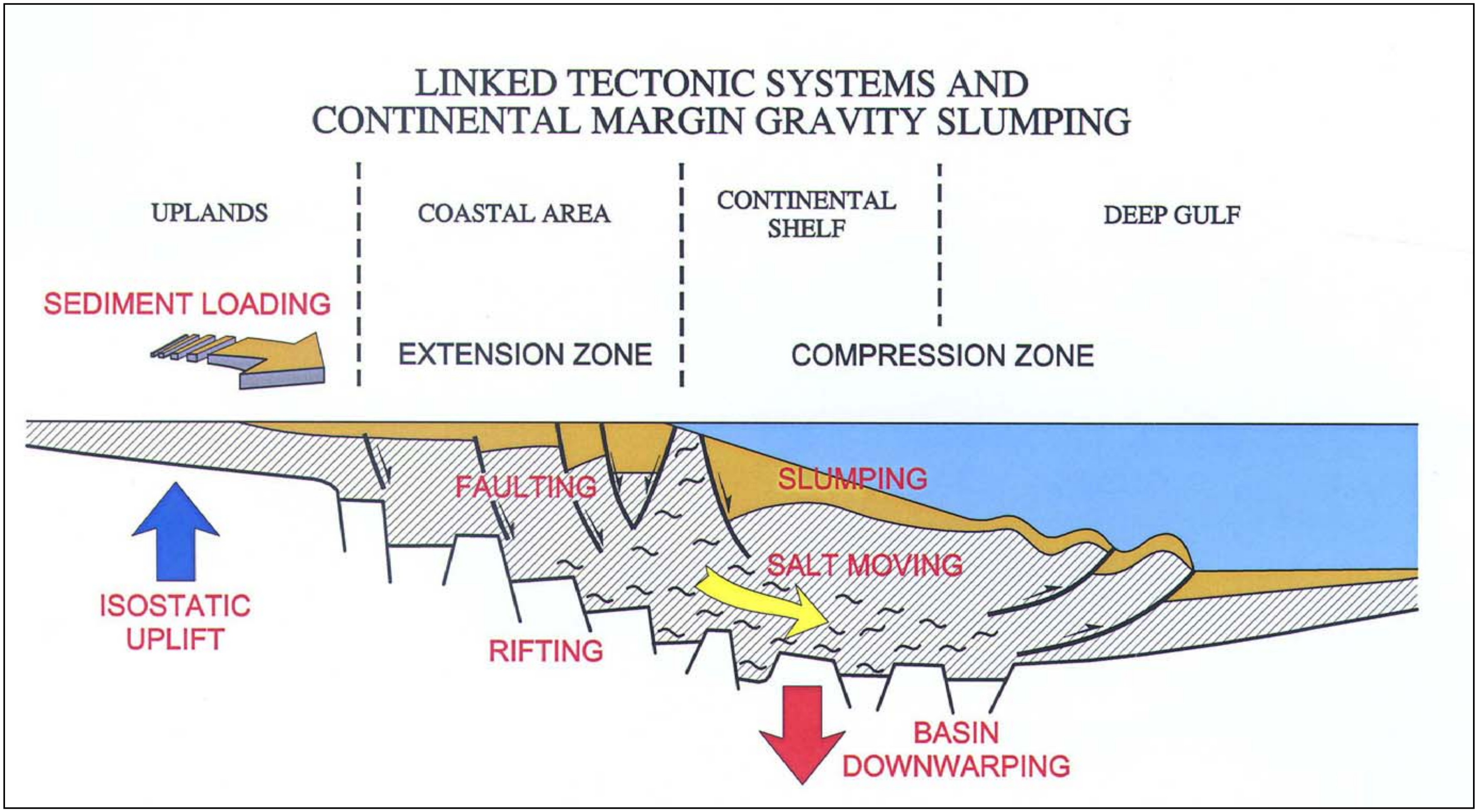

Figure 2. **The linked tectonic system under south Louisiana, part of which extends under the gulf, resides in a great trough in the earth's crust. The trough fill is riddled with faults an penetrated by salt domes, the movement of which in relation to overlying sedimentary deposits affects the surface landscape.**

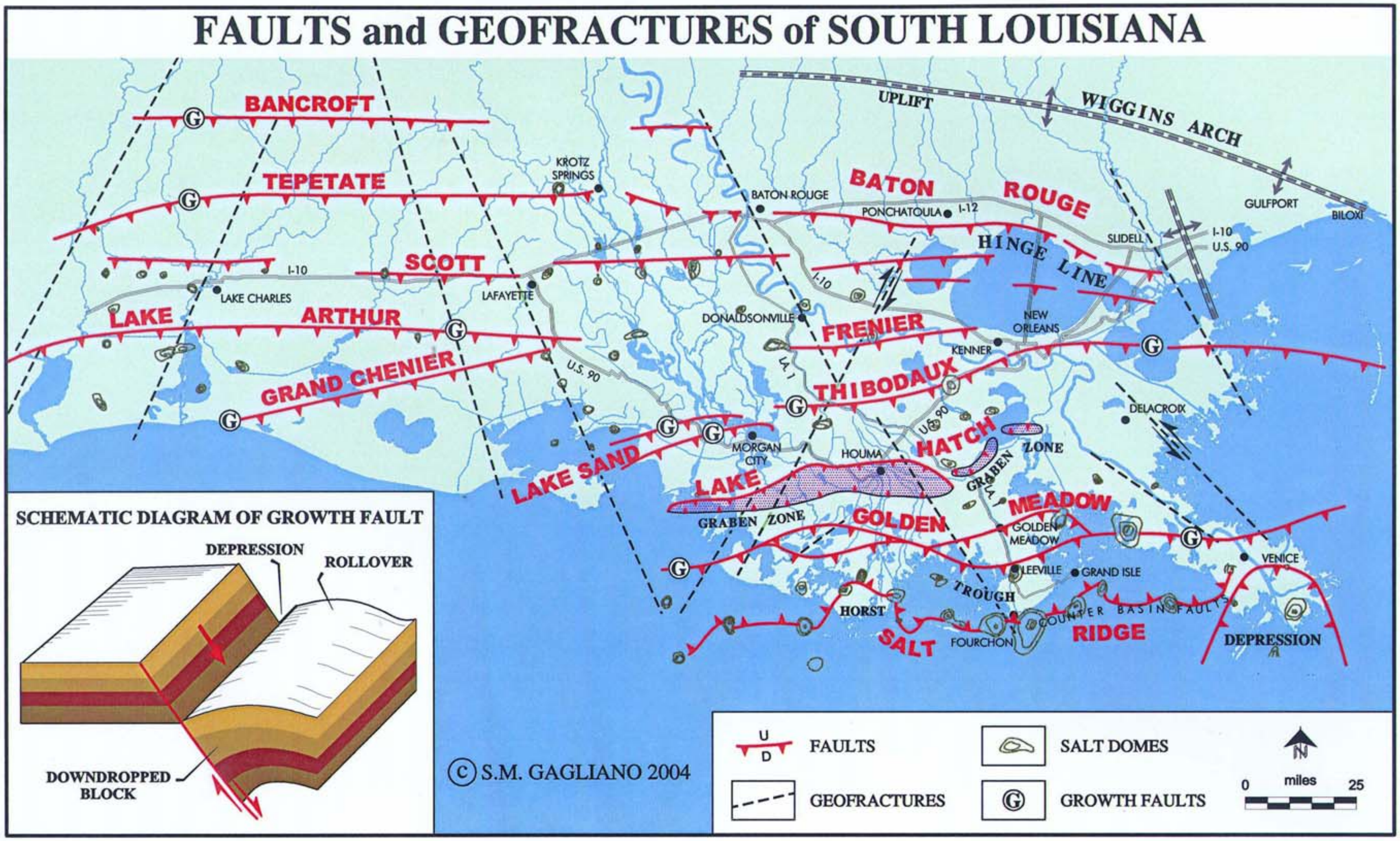

Figure 3. **Map showing major structural features in south Louisiana, known from a century of intensive oil and gas exploration and development.**

space because they make room for new deposition at the top of the upside down mountain of sedimentary deposits.

Vertical adjustment to subsidence occurs along *growth faults* (Figure 3), most of which were established and have remained active for tens of millions of years. The faults are linked, or articulated into a tectonic framework. If one segment of a fault moves, stress may be transferred and released along neighboring faults, initiating a domino effect that continues until all stress is resolved and equilibrium within the framework is restored.

Subsurface Geology

The locations and character of the faults and salt features have been carefully mapped, as shown in Figure 3 (Tectonic Map Committee, Gulf Coast Association of Petroleum Geologists, 1972). The driving processes of fault and salt movement are well understood as the result of a century of intensive oil and gas exploration and development within the *Gulf Salt Basin*, the name given to the sediment-filled trough by geologists (Murray 1961, Fails *et al*. 1995, and others). An important factor in the petroleum industry's success in finding oil and gas in the region has been the development of geological process-response models. The models are fundamental tools in the search for hydrocarbons as they depict the three dimensional relationships and geometry of source beds and hydrocarbon bearing horizons and serve as road maps for finding oil and gas from geophysical and well log data. Models developed as a result of research in the Gulf Salt Basin have been applied to deltaic and shallow marine rock sequences throughout the world and the validity of the models has been proven by the success of the industry.

Remarkably, there has been an information disconnect between the geologists and geophysicists working in the petroleum industry and the community of scientists, engineers and planners engaged in coastal restoration. The restoration community is largely oblivious to the tectonic dynamics of the region. A major goal of the research reported herein is to apply the knowledge gained from the interactive tectonic depositional model, as derived from the rock and landform record, to a better understanding of modern coastal change. This in turn will strength the basis for planning and design of coastal restoration projects.

Active Faults

Fault occurrence and movement is not confined to the coastal wetlands. Some faults that are part of the tectonic framework underlie the terrace uplands. For example, active fault movement occurs along the Baton Rouge - Tepetate Fault zone in urban neighborhoods of Baton Rouge (McCulloh 1991), rural areas of the piney woods in Livingston and Tangipahoa Parishes (Gagliano *et al.* 2003a), as well as in the rice fields in St. Landry, Jefferson Davis and Acadia Parishes (Miller and Heinrich 2003). The prominent fault line scarp of the Baton Rouge Fault in Livingston Parish is shown in Figure 4. Note the influence of the fault on the large bend of the Amite River.

Cracks in streets, building foundations and masonry structures attest to modern fault movement in Baton Rouge (McCulloh 1991). In recent years, two public school buildings that were built on faults in Baton Rouge have been abandoned and demolished. Fault damage is usually less severe, but is still discussed, only in hushed tones, by property owners fearful of property devaluation. Other evidence of movement along the Baton Rouge Fault outside of the urban area includes fault cracks and displacements on all highways, rail bridges and

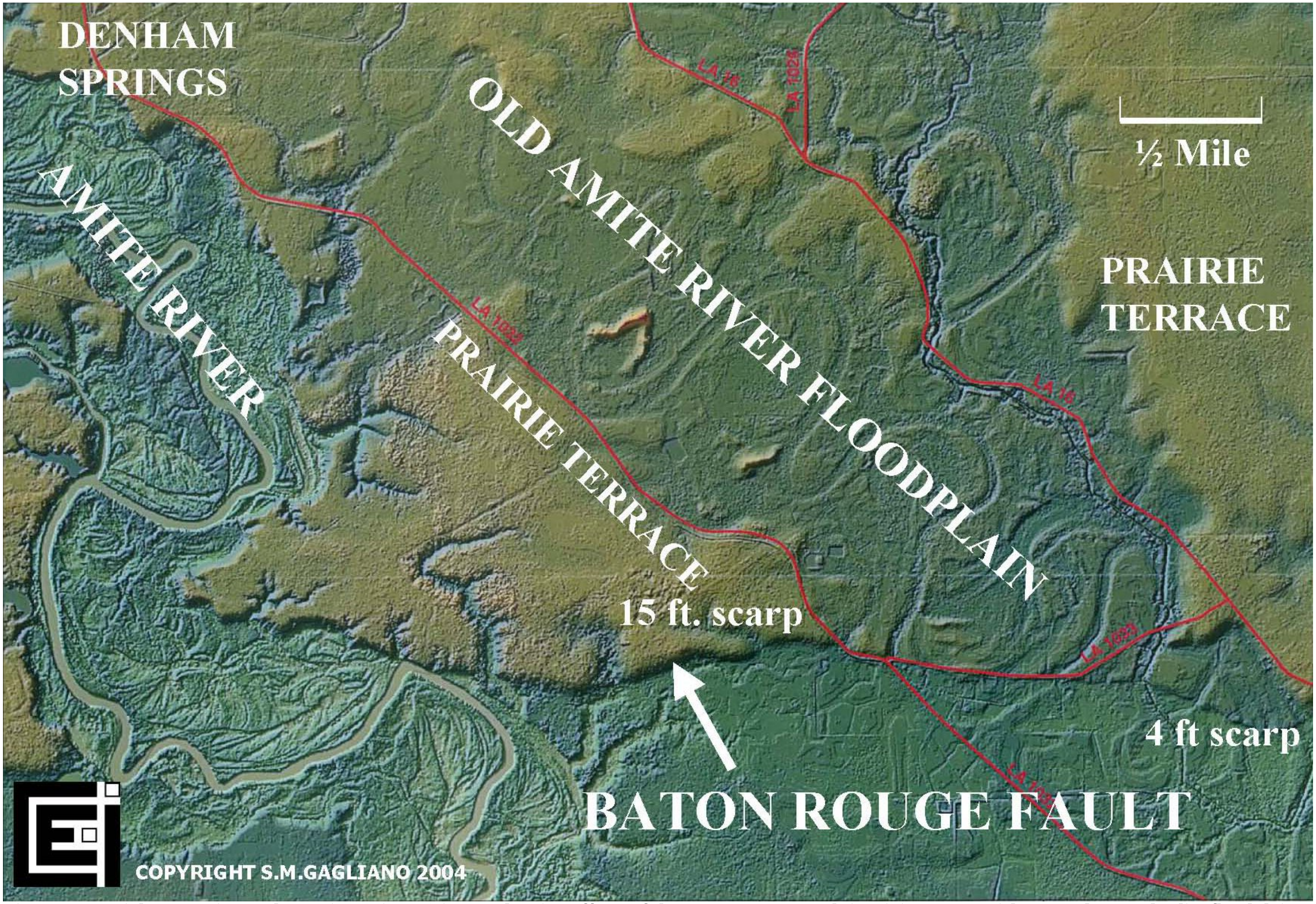

Figure 4. **Light Detection and Ranging (LiDAR) image showing effects of the Baton Rouge Fault in Livingston Parish on modern and relict floodplains of the Amite River.**

causeways that cross Lake Pontchartrain (Lopez *et al*. 1997). Lateral movement of six inches or more during modern decades has also been reported on one of the Mississippi River bridges in New Orleans. The faults are moving!

Faults and Earthquakes

Perhaps the best evidence of fault movement is the occurrence of earthquakes. Louisiana is generally thought of as an area of low seismic activity. It is widely believed that the soft rocks of the region are not conducive to the kind of stress buildup and release that occurs in areas of more brittle rocks, such as along the San Andreas Fault in California. Nevertheless, a number of earthquakes have been recorded in south Louisiana. The best known of these was the Napoleonville Earthquake of October 19, 1930, with a *Richter scale magnitude* of 4.0 (M - 4.0) and a *Modified Mercalli felt intensity* of VI (MMI - VI). The Napoleonville Earthquake was the surface manifestation of spontaneous movement that occurred on a local subsurface fault. That is, the earthquake had a local epicenter.

Other notable historic earthquakes with local epicenters in Louisiana include the Opelousas Earthquakes of 1823 and 1870 (MMI - VI), the New Orleans Earthquake of 1958 (MMI - IV), the Cameron Earthquake of 1959 (MMI - VI), the Lake Charles Earthquake of 1983 (M - 3.8, MMI - IV), and the Irish Bayou Earthquake of July 31, 1987 (M - 3.0, MMI - V). None of these local earthquakes was of high intensity or long-duration. The felt effects, as reported by witnesses, had MMI values of III to VI and lasted from 10 to 15 seconds. There has been no major structural damage nor any known loss of life attributed to any of these historic earthquakes of local origin.

Another category of surface tremors reported from south Louisiana is related to earthquakes with remote epicenters. This category includes seiches and *unusual waves*. The most notable examples occurred during the M - 9.2 Alaskan Earthquake of March 27, 1964. This was the largest historically recorded earthquake in the United States since 1900 and the second largest earthquake ever recorded. The effects of this earthquake in the vicinity of the epicenter near Prince William Sound, Alaska were devastating, including extensive structural damage and landslides in Anchorage.

Newspaper articles and other contemporary reports indicate that shock waves from the 1964 Alaskan event caused unusual water disturbances at numerous locales across the region of south Louisiana and southeast Texas (Figure 5). Re-examination of the musty newspaper reports and plotting of locations of reported effects revealed that the disturbances occurred along known faults (Figure 6) and had MMI values that were as great or greater than those associated with the previously mentioned earthquakes with local epicenters. The evidence suggests that shock waves, after traveling 3200 miles from Alaska, actually triggered a series of secondary earthquakes in Louisiana and Texas (Gagliano *et al*. 2003b, Gagliano 2004). Also shown in Figure 5 are the damage areas of the New Madrid Earthquake of 1811 and the Charleston Earthquake of 1886. Felt effects were reported from both of these earthquakes in the City of New Orleans, suggesting possible effects on local faults.

Effects of the 1964 Alaskan Earthquake

Concurrent with the March 27, 1964 earthquake in Alaska there were a series of five or six waves with peak-to-peak amplitude of up to 4 feet over a period of 30 mintues. Logs were thrown on the banks and small boats broke loose from their moorings - *Opelousas Daily World*,

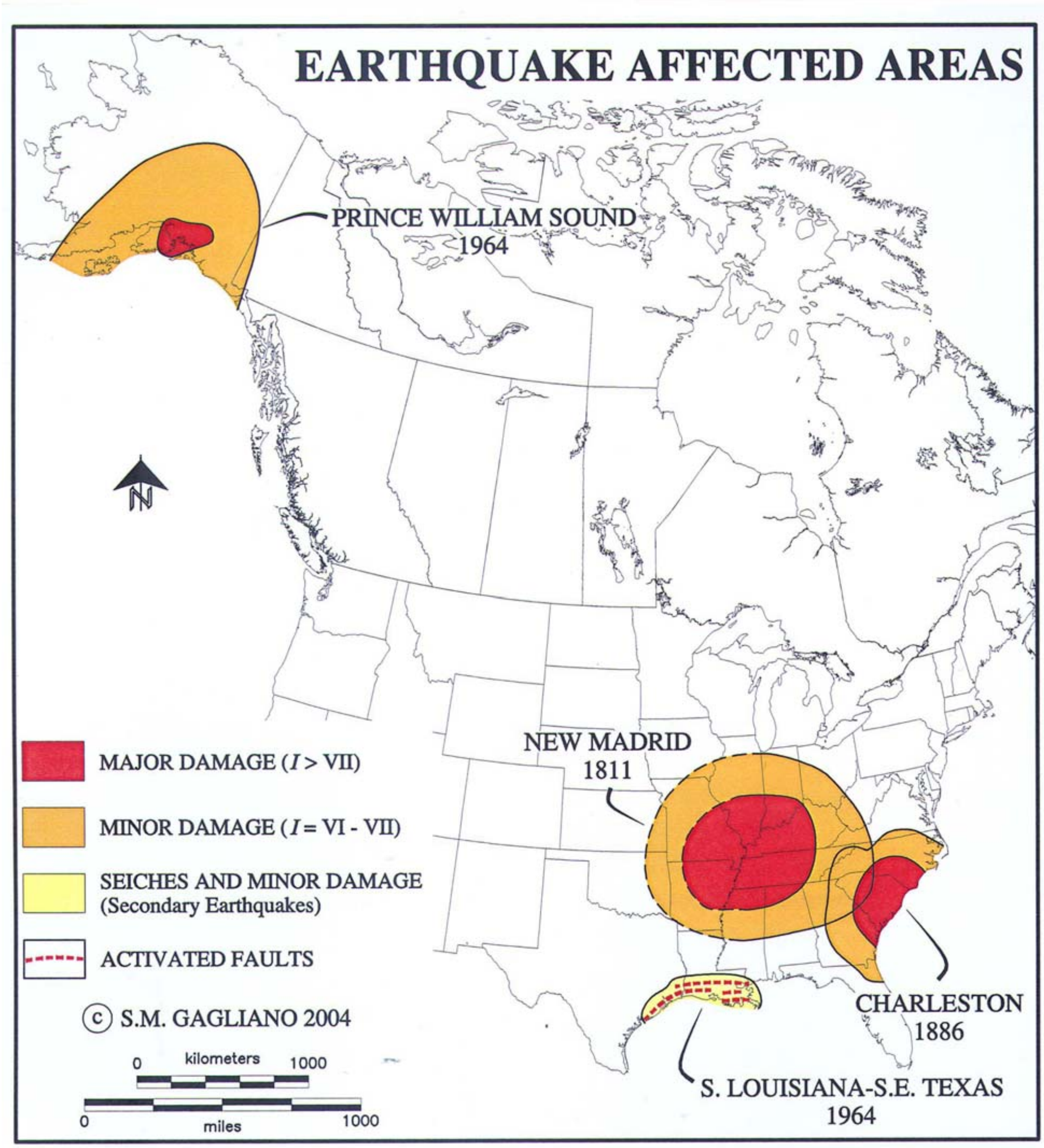

Figure 5. Felt areas of three historic earthquakes that caused tremors in south Louisiana. Locations and intensity of felt effects suggest that the 1964 Alaskan Earthquake triggered secondary earthquakes along faults in the northern Gulf region.

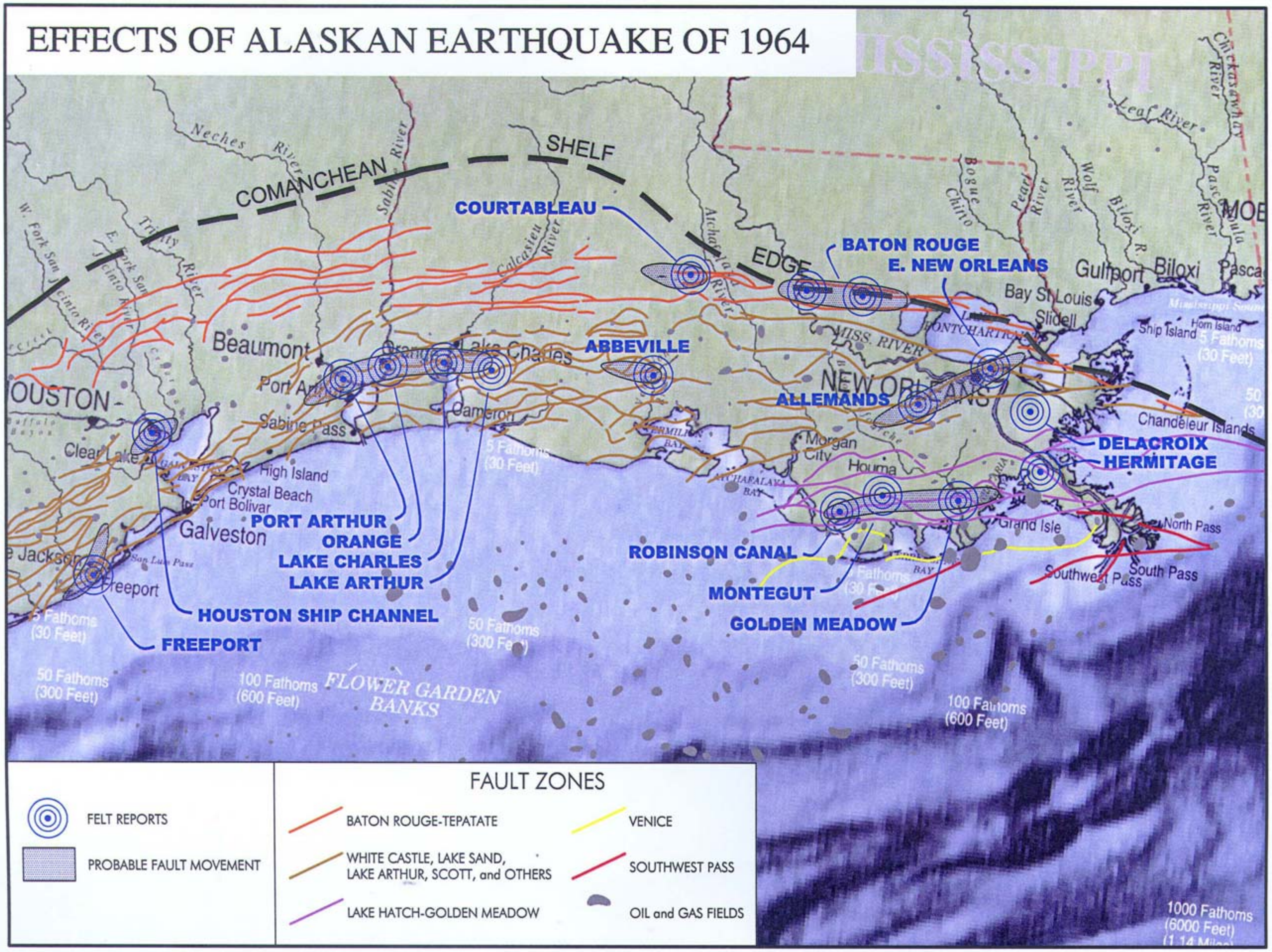

Figure 6. Location of the reported effects of the apparent secondary earthquakes in south Louisiana and southeast Texas triggered by shock waves from the 1964 Alaskan Earthquake.

1964. There was a delay of 10 to 12 minutes between the time of the shocks in Alaska and their arrival in south Louisiana.

Near Port Vincent, east of Baton Rouge, there was a similar series of 3 to 4-foot waves over a period of 20 minutes. The bottom of the 5-foot deep Amite River was exposed for a short period as the water rushed out, and then back in with great force causing damage to boat docks and breaking small boats from their moorings - UPI New Orleans, 1964.

Along Bayou Lafourche, between Galiano and Golden Meadow, a series of five large waves with amplitudes of up to 6 feet swept along the bayou for a distance of 10 miles. Submerged logs and debris were thrown up onto the roads on each side of the bayou and an oyster lugger was tossed into a paint store located along the bank. Customers ran from a barroom located on the bayou, fearful for their lives as the waves swept into the establishment - *New Orleans States - Item* 1964, AP New Orleans 1964a.

In the Calcasieu River and Ship Channel at Lake Charles, a 4-foot high wave jolted a large tanker - *Lake Charles American Press,* 1964.

Numerous effects were reported from the Beaumont-Port Arthur-Neches River area, where ships bobbed up and down six or seven times in response to sudden drops in tide and waves with amplitudes of 6 or 7 feet. Boats and docks were damaged - *Port Arthur News*,1964.

In Houston, a ship captain reported, "...the water was rolling and bubbling up throughout the ship channel as if something was underneath it." - AP New Orleans, 1964b. Dr. J. C. DeBremaecker, a Rice University, Houston, seismologist reported that "...the city was lifted four inches late Friday as a gigantic surface wave from the Alaskan Earthquake passed through..." - AP Houston, as reported in the *Port Arthur News*, 1964.

The evidence suggests that the main difference between the earthquakes reported in Louisiana with local epicenters and those that occurred across the entire region from Chandeleur Island to Freeport in response to the 1964 Alaskan Earthquake is that the latter were *secondary earthquakes* caused by slippage along the local fault lines triggered by the shock waves from the distant epicenter. In 1964, five violent seiches occurred during a 30-minute period in comparison to the tremors of a few seconds duration that are typical for the spontaneous earthquakes of local origin.

There were no immediate reports of streets buckling or structures collapsing in south Louisiana or southeast Texas at the time of the 1964 earthquake, but there was structural damage. Most of the newspaper accounts focused on the "large waves" and the rocking of boats and ships. After-the-fact reports link cracks in a public swimming pool in Baton Rouge and collapse of the concrete walls of a water treatment plant in New Orleans directly to the 1964 earthquake. The local faults moved on March 27, 1964!

On November 3, 2002, an earthquake (M - 7.9) occurred at Denali, Alaska. This earthquake caused seiches at a number of locales along the same faults in south Louisiana and southeast Texas that were affected by the1964 Alaska Earthquake, though the intensities in 2002 were less. Historically, felt effects from both the earthquakes in the New Madrid, Missouri area in 1811-1812 and the Charleston, South Carolina Earthquake of 1886 - the location of both shown on the map in Figure 5 - were reported in New Orleans.

Surface Effects

Major regional fault zones where earthquakes have occurred and that also exhibit signatures of fault movement on the landscape shown in Figure 3 include the following:

- Baton Rouge
- Tepetate
- Lake Arthur
- Lake Sands
- Lake Hatch, and
- Golden Meadow.

Fault movement affects everything on the surface, including all natural landforms and human-made features. Natural levee ridges and barrier islands located on subsiding fault blocks become increasingly submerged as a result of both slow and imperceptible movement and episodic rapid fault slippage of 3 feet or more (Gagliano *et al.* 2003a, Gagliano *et al*. 2003b). Symptoms of active fault movement include cracks in highways and building slabs, and failures along flood protection levees. Fault and earthquake movements pose potential threats to pipelines, bridges, tunnels, refineries, petrochemical plants and power plants, as well as private homes.

Human settlement in the coastal lowlands has been concentrated on the relatively higher and firmer natural levee ridges of relict Mississippi River distributaries and old gulf beaches (cheniers). As a result of subsidence, it has become necessary to protect the communities on many of these natural ridges with flood levees and forced drainage districts. Many of the natural ridges have sunk to elevations below the level of adjacent marshes and water bodies. Some communities and highways now lie below sea level, within the confines of drainage districts, creating a curious reversal of topography. Likewise, as the barrier islands fringing the deltaic coast sink, they become segmented and awash. Because levees and forced drainage are not practical measures for protecting barrier islands, the approach has been to build the surface of the islands up with dredged sand. The sand budget required to keep the barrier islands above gulf level increases geometrically through time. Consequently, it will become more and more difficult to maintain these islands as they continue to sink.

Ecological Change

As ridges sink, the live oak (*Quercus virginiana*) forests on their crests die. In the coastal marshes, lowering of the marsh floor by 1 or 2 feet is enough to cause the grass to drown, as demonstrated in the aerial photograph in Figure 7. The brown-marsh phenomenon of 1999 was, in part, fault-induced subsidence accentuated by drought conditions (Gagliano *et al*. 2003a). Four clear cases have been identified where fault movement caused die-back of *Spartina sp.* (marsh grass) creating the brown marsh condition. This condition is often a stage in the breakup of the tidal marsh resulting from fault movement.

Two notable examples of fault-induced land submergence are found in Plaquemines Parish near Empire and Buras and depicted on the map shown in Figure 8. Movement in 1974-1975, along the Bastian Bay Fault, a 4.6-mile-long segment of the Golden Meadow Fault Zone, created a 23,600-acre bay with water depths of 3 to 4 feet. (Gagliano *et al*. 2003a, Gagliano *et al*. 2003b). A few years later in 1976-1978, similar movement along the neighboring 4.8 mile-long

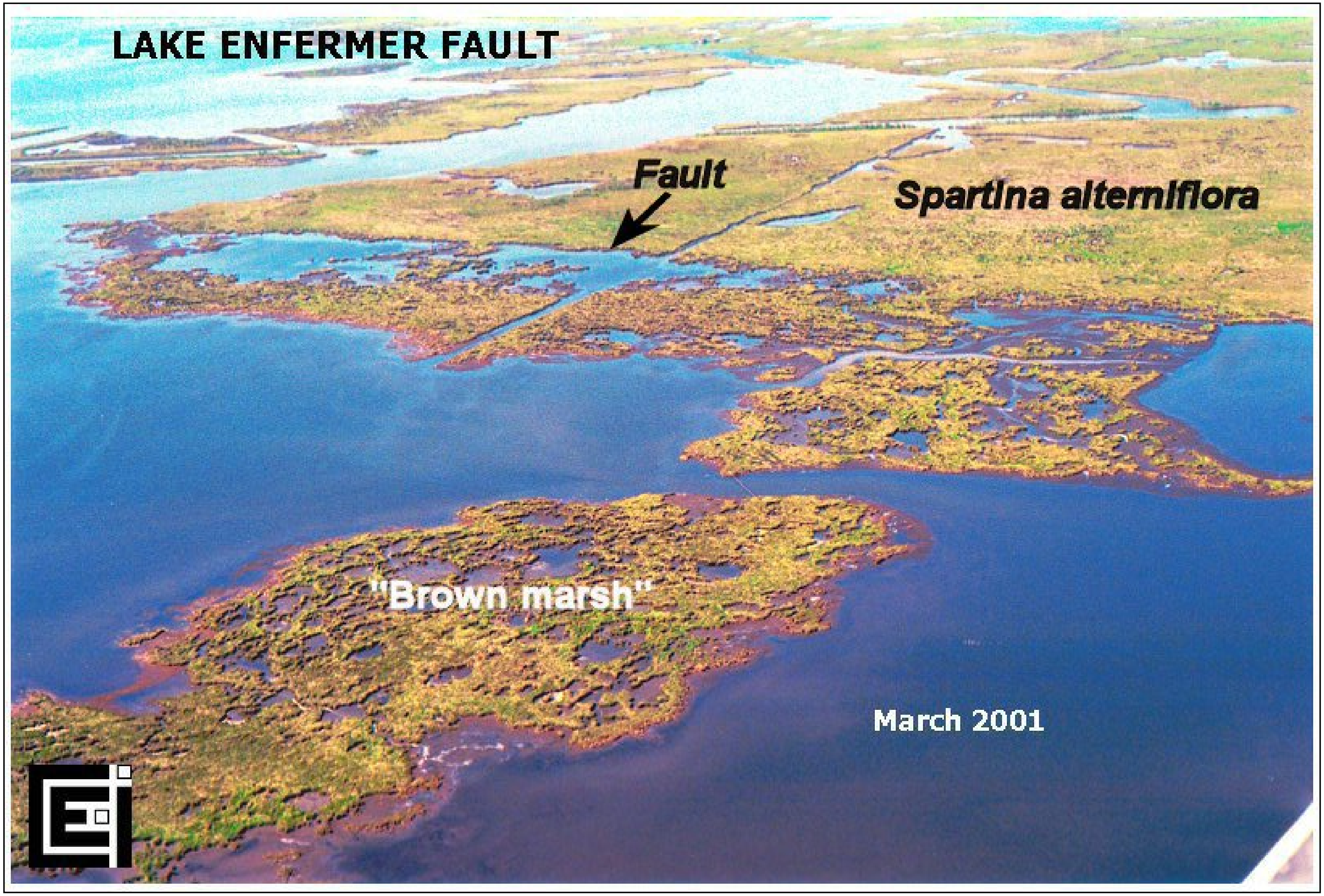

Figure 7. **Brown marsh on the down-dropped block of the Lake Enfermer Fault, a segment within the Golden Meadow Fault Zone (after Gagliano *et al*. 2003). Much of the brown-marsh phenomenon in 1999 was caused by fault-induced subsidence accentuated by drought conditions.**

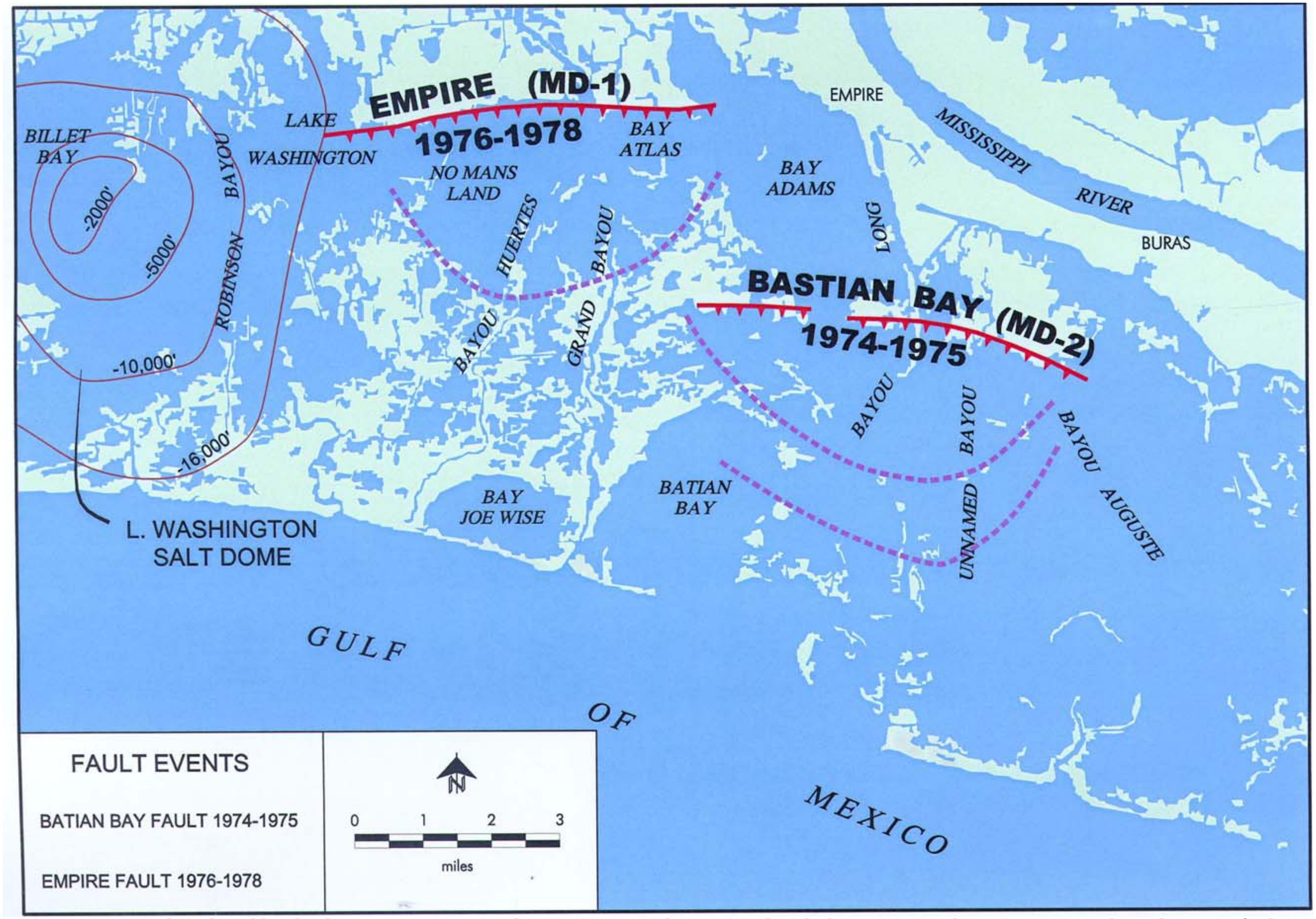

Figure 8. **Fault-induced land submergence areas in Plaquemines Parish associated with the Empire and Bastian Bay Faults. These two fault segments, along with the subsurface Lake Washington Salt Dome, lie within the Golden Meadow Fault Zone.**

Empire Fault added a 12,400-acre bay with water depths of 3.5 to 4.0 feet. Similar fault events have left zones of open water along the major growth faults.

Tremors and Liquefaction

One of the greatest potential dangers identified in this study is the possibility of liquefaction along faults. It now appears that earthquake tremors may separate floating marsh mats from the substrate and otherwise break up marsh mats and other highly organic soils of the coastal marshes and thus, may be a major contributor to coastal land loss. There is also mounting evidence that the long, unexplained pimple mounds that dot the surface of the Prairie and Beaumont Terrace surfaces in a large area in southwest Louisiana and southeast Texas, including the Houston area, are relict sand blows resulting from liquefaction that occurred along faults during late Quaternary times. While this theory will require additional research to verify, if true it would further suggest that the region is not as tectonically stable as previously believed. Friction piling driven in sand deposits support many large structures in south Louisiana. Susceptibility of these sands to liquefaction and compaction from earthquake tremors warrants further investigation.

Measuring and Dating Fault Movement

As in the case of any natural hazard, it is important to forecast the potential danger of fault movement. This can be accomplished by knowing the location and character of the faults, and by measuring the magnitude and speed of movement (vertical and lateral), the frequency of occurrence, and the duration of slippage. A variety of direct and indirect measurement techniques has been applied to the problem. Analysis of tide gauge records has proven to be most useful in determining relative changes in sea level, and in removing the component of change caused by worldwide or eustatic sea level rise from regional and local subsidence. Use of tide gauge records to measure relative sea level rise in south Louisiana was pioneered by Shea Penland and his students. Penland, now with the University of New Orleans, and his team were among the first to report spatial and temporal variations in rates of subsidence in the northern Gulf region (Penland *et al*. 1988).

Modern rates of eustatic change are best measured at tectonically stable places, such as Pensacola, Florida (0.0075 ft/yr during last 40 years) and Port Isabel, Texas (0.011 ft/yr of rise during last 40 years). In contrast, the apparent rates of sea level rise in southeastern Louisiana, as measured from tide gauges stations such as Grand Isle (0.064 ft/yr during last 40 years) and Little Woods (0.116 ft/yr during last 40 years), are among the highest in the world. The difference between rates of relative sea level rise recorded from tide gauges at stable locations and those from gauges at locations that are sinking is a measure of subsidence.

Another excellent data set for measuring vertical change are benchmarks for which change has been measured along highways across the coastal landscape. Recently, the National Geodetic Survey (NGS) in conjunction with the Spatial Data Center at Louisiana State University (LSU) has been re-evaluating this data. Roy Dokka, director of the LSU team, reports that "...loss of elevation ranges from 0.3 to 1.5 inches or 0.03 to 0.13 feet per year across south Louisiana..." and that much of the coastal zone will be below sea level within 70 years (NOAA Magazine 2003). The NGS-LSU findings are generally consistent with those presented herein. The NGS-LSU work focuses on modern rates of movement, with emphasis on the location, character and driving processes of the tectonic structures. In the context of the linked tectonic system model, the highest rates reported by the NGS-LSU team appear to be measures of short duration movement on down-dropped fault blocks at locations near fault planes.

The length of time that both the tide gauge and re-surveyed benchmark records have been kept is relatively short - a few decades to a maximum of 100 years - and therefore, the confidence level for prediction of recurrence is relatively low. A third technique uses geological, geomorphological and archaeological methods to extend the record by dating past fault and earthquake events. The geomorphological approach is based on identification of landform signatures of fault movement. These signatures include shapes of land loss areas, river patterns and submergence of ridges that are distinctive enough to be recognized on modern aerial images as well as historic maps. Thus, first appearance of fault event signatures on images and/or maps of known age date the event. As the name implies, geoarchaeological dating uses archaeological sites and artifacts to date landforms and sedimentary deposits affected by fault movement. This technique can be used to date events that occurred during the 11,500 years or longer period of prehistoric Native American occupation of the region.

Borings and high-resolution seismic lines are also used to identify faults. Radiometric dating of material in the displaced beds provides the basis for calculating subsidence rates and differences in rates across faults is a measure of movement.

Dating fault events and measuring past movement employ geo-forensic methods that draw clues and information from many sources and utilize both empirical and anecdotal data. The use of this combination of techniques has provided the basis for formulating the linked tectonic system model and conducting risk analysis of the fault-earthquake hazard on both a site specific and regional basis.

Debate Over Causes

Within the last few years, following the realization that much, if not most, of the subsidence and resulting land loss in south Louisiana is related to fault movement, several theories have been offered to explain the spatial variation and apparent acceleration in rates of movement that has occurred since the mid-1960s. Gerald Kuecher and Harry Roberts (Kuecher *et al.* 2001) were among the first to link land loss to fault movement. They concluded from studies of data collected from borings in the Terrebonne area that the geographic variation in rates can be partially explained by differential compaction and variation in thickness of poorly consolidated Holocene sediments. Vertical adjustments to differences may occur along old faults.

Kuecher *et al.* (2001) proposed that the mechanism for fault movement involves venting of saline fluid and gas from geopressured shales upward along growth fault planes. This loss of fluid and gas via faults results in *accommodation space* at depth that in turn causes fault induced subsidence above the down-dropped fault block. Movement does not occur simultaneously along the entire growth fault trace, but rather along disconnected segments producing a *key-stepping* pattern, with segments of regional faults alternately being active and dormant.

Soda Straw Theory

Another fault-subsidence theory that has gained some recognition has been proposed by Robert Morton and his U.S. Geological Survey associates. It is based on fluid withdrawal

(Morton *et al*. 2001). It is known that removal of large volumes of ground water from shallow aquifers - generally 1000 feet or less in depth - in urban and industrial areas may cause surface subsidence. In Houston, for example, surface subsidence of 8 feet or more that extends over large areas has been correlated with ground water extraction. Similar correlations between localized subsidence and ground water withdrawal have been made in New Orleans and Baton Rouge. In addition, some old oil fields with shallow production from closely spaced wells have experienced surface subsidence. A classic case is the Goose Creek Field on the edge of Galveston Bay where surface subsidence, fissures, and submergence that began in the 1920s have been attributed to withdrawal of oil and produced water. However, other geologists have found that the subsidence is only partially explained by fluid withdrawal. Faults with surface displacement attributed to *natural tectonic processes* have been mapped and measured throughout the Houston area and appear to be an important factor in the subsidence (Verbeek and Clayton 1981).

Robert Morton and his colleagues have extended the fluid withdrawal theory to Terrebonne Parish in south Louisiana to explain high rates of modern land loss. Morton *et al*. (2003) have cited apparent correlations of changes in land loss rates - as measured from aerial photographs and subsidence rates measured from borings - with volumes of fluid extracted and pressure loss measured from production records, as evidence in support of the fluid withdrawal theory. The land loss rates accelerated and peaked in the mid-1960s at the same time that the oil field records show peak production and pressure loss.

The *soda straw theory* has gained some acceptance from the coastal restoration community who fear that if the massive land submergence is due to natural causes and that the driving processes continue, the problem is hopeless and some of the proposed solutions are not worthy of the expenditure of tax dollars. If the theory posed by Morton *et al*. (2003) is correct, the apparent solution to south Louisiana's subsidence and land loss is to either stop production of oil, gas and produced water or inject the produced water supplemented with surface water to replace the volume that is withdrawn.

The soda straw theory is attractive because it provides a villain and the promise of a possible reduction in rate of subsidence. However, there are several problems with this theory. Unlike the Goose Creek Field, most production from the coastal oil fields is from relatively deep - 2,000 to 15,000 feet and greater - higher pressure deposits where the fluids removed through wells are replaced by salt water and may, thereby, not create *accommodation space*.

Many, if not most, of the subsiding oil fields owe their existence to structural traps on the downthrown blocks of ancient faults. The faults along which Morton and his associates cite evidence for subsidence induced by fluid withdrawal, primarily Golden Meadow, Theriot, and Lake Hatch, have long and nearly continuous, albeit episodic, histories of movement that began tens of millions of years ago and has continued into modern decades. Some segments along the Golden Meadow Fault exhibit more than 2000 feet of cumulative vertical displacement at depth. Using the geo-forensic techniques previously mentioned, movements on segments of the Golden Meadow Fault have been dated and documented and are known to have occurred periodically:

- during ancient geological times (tens of millions of years ago)
- at the base of the Pleistocene Formation (2 million years ago)
- at the top of the Pleistocene (25,000 to 5,000 years ago)
- during prehistoric Native American times (3,500 to 1,200 years ago), and
- during historic and modern times (150 years ago to present).

As discussed previously, movement and shaking effects also occurred along the Golden Meadow Fault during the 1964 Alaskan Earthquake indicating that the fault system is active. To attribute the subsidence and land loss of the last 50 years to anthropomorphic causes flies in the face of the geological record.

Linked Tectonic Systems

Fault induced subsidence is largely driven by ongoing, interacting, natural processes of fault movement within a linked tectonic system. As is shown in Figure 2, the driving processes include:

- sinking and rifting of the earth's crust
- sediment loading
- up-fault venting of fluid and gas from geopressured shales
- salt movement
- isostatic adjustment, and
- gravity slumping.

Vertical and lateral adjustments to these process interactions occur along the fault planes as part of the system expands and other parts contract. South Louisiana overlies the expansion or *pull-apart* portion of the tectonic system, where *accommodation space* develops and is expressed at the surface as cracks and depressions. Because the tectonic components are articulated, and stresses are transferred, movement along one fault may initiate movement along neighboring faults. This domino effect continues until quasi-equilibrium is reached. This interactive movement constitutes a flexing of the linked tectonic system.

Denial

The outcome of what might ordinarily be a not-too-exciting academic debate over the causes of a geological phenomenon - fault related subsidence - has far reaching implications. The outcome will affect the future of a large, economically important area and may determine how vast sums of badly needed tax dollars are spent. The fault-subsidence issue has been on the table for discussion for 5 years. Yet, serious consideration of the issue has had - and continues to have - a low priority on the agenda of the coastal restoration community.

The response to the fault-land loss findings has been denial. Why is this? Reasons given by the restoration community include:

> We'll worry about that later. Let's not delay the program. We can't have an academic debate while a huge block of the state sinks and calves into the gulf. That would be like fiddling while Rome burns. The people of south Louisiana want the land-loss problem fixed. The fault debate will delay approval of the billions of dollars requested from the federal government for coastal restoration. Kill the messenger!

It must be unsettling for the proponents of a restoration program built on ecological models to learn that geological processes drive the landscape changes and that the biological changes are only the responses and not the driving processes.

Denial that the hazard exists has already resulted in bad decisions based on the wrong geological model. Consequently, investments of huge sums of tax dollars have been made in structures that are under-designed or in the wrong location. Continued denial will only result in a flawed restoration plan and project designs that will predictably result in a false sense of security to the communities at risk. Failure to re-evaluate the fault-earthquake hazards posed to older structures and infrastructure not designed to withstand the effects of these hazards may also result in failures. Continued denial can ultimately result in the catastrophic loss of life and property.

Conclusion

We are at a critical juncture in re-structuring our coastal area for the future. Faults and earthquakes present a clear and present danger to south Louisiana. While constructive debate among the geologists engaged in fault research continues, there is a consensus that the problem is urgent and that there is a need to expeditiously address this previously underrated natural hazard. This hazard presents a particular challenge to geologists and geotechnical engineers, because some common and invalid conceptual models must be revised. These models may have served us well but they must be updated and fine-tuned with the new information that is available. This is not a criticism of what we have done in the past or a statement that we cannot stabilize the coast for natural system sustainability and multiple-use. It is rather a plea for objective, science-based land use planning and engineering design. The fault-earthquake hazard can and needs to be mitigated by:

- avoidance
- monitoring, and
- applying good engineering design and land use practices because...

The faults are moving!

Postscript

Less than one month after the preceding article was published in *The Louisiana Civil Engineer* an apparent small earthquake was reported from the south Lafourche area in the vicinity of the Golden Meadow Fault. Katina A. Gaudet reported the event in the following story which appeared in *The Lafourche Gazette* (March 6, 2005, p. 8-A).

Tremors "shake up" So. Laf. community

No one really knows what caused the ground to shake in South Lafourche and elsewhere this week.

The only thing that is certain is that some felt it.

Whether it was a sonic boom or a tremor, it left people talking.

"You're standing up and you're talking and you can feel the ground quiver and you can see in the next door neighbors' yard the swing in the tree rocking," said Lafourche Parish Councilman Brent Callais on describing the experience.

At about 3:50 p.m. Tuesday, Callais was at a parish maintenance barn with parish employees when they felt what some have described as a small earthquake.

Golden Meadow resident Kirk Cheramie was home with his daughter and niece when they, too, felt something.

"We felt the whole house tremble, so I immediately went outside and our neighbors were in the street looking up and down the street to see if anything crashed," said Cheramie, who asked his neighbors if they felt what he did. "They said, 'Yes.' "

After that, Cheramie called Windell Curole, general manager of the South Lafourche Levee District and Lafourche Parish's coastal zone administrator.

On Wednesday, Curole, like many others, was awaiting answers on possible causes of the incident, which was reported from Leeville to Lockport and in southern Terrebonne Parish.

Given the fault lines in South Louisiana, an earthquake is a possible explanation. In fact, Louisiana has been known to experience earthquakes. One of the largest in the state occurred near Donaldsonville in 1930.

In Napoleonville, a church rocked noticeably, with the congregation spilling out into the street. The earthquake was felt in Des Allemands, Donaldsonville, Morgan City, Franklin and White Castle, with evidence manifesting as small overturned objects, cracked plaster and other effects.

A few years ago, many felt tremors along the bayou.

"It's interesting, but we actually have, in years past, seen tremors right down here, so it's not unknown," said Tim Osborn, who heads NOAA's Gulf operations at the agency's Lafayette office.

Although many who felt the movement say it was an earthquake, there are other possibilities.

One is that it was a sonic boom.

A sonic boom occurs when an aircraft breaks the sound barrier. When it flies past, it produces a sonic boom.

As people began to discuss the event Wednesday, some noted aircraft flying at low altitudes, which could have resulted in booms.

"It appears that something did happen," said Curole, who was making calls Wednesday to NOAA and to Louisiana State University's Department of Geology and Geophysics.

Both have access to seismic equipment, with NOAA's National Weather Service receiving earthquake information from the U. S. Geological Survey. But neither had reported any seismic activity in the area as of late Wednesday afternoon.

"There was enough people saying they felt vibrations or heard metal buildings shaking that something took place. Right off the bat, you think of a sonic boom, but nobody heard any noise, but that's always a possibility," Curole said.

It's likely that no cause will be determined.

"Sometimes things happen, and we can't find a definitive cause," Curole said.

Staff Writer Emilie Bahr contributed to this report.

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