OIL AND GAS INDUSTRY INFRASTRUCTURE IN COASTAL LOUISIANA

A proposal to assess the impacts of relative sea level rise due to subsidence using industry knowledge base, data and technology

The New Orleans Geological Society
November 2015

EXECUTIVE SUMMARY

Some of the most vital infrastructure of the oil and gas industry is located in the major port facilities along the southeast Louisiana coast, and it is very likely to be impacted by the progression of subsidence and rising sea level in the coming decades.

The New Orleans Geological Society (NOGS) proposes the oil and gas industry assess its coastal infrastructure in southeast Louisiana by commissioning a set of academic research projects that make use of industry seismic data, knowledge base, and computer processing technology. Each research project will study a specific area of the Louisiana coast covered by 3-D seismic survey or surveys. Each academic institution participating in the project would return an interpretation of near-surface geologic structures that may be impacting surface processes including geologic faults and buried channels. Additionally, each institution would attempt to estimate rates of subsidence using available data to make predictive models of the rates of relative sea level rise due to subsidence and its potential impacts on the land surface and nearby infrastructure.

Initially, NOGS will bring together a coalition of industry partners to fund these academic research projects, seek out 3-D seismic surveys available for academic research, and connect interested academic institutions with project data and funding. The objective is to construct an atlas of surface faults and predictive patterns of subsidence that can be used for infrastructure assessment by the oil and gas industry. The atlas and its supporting academic research could also be available to other academic institutions for research as well as to governmental and non-governmental entities that are interested in conducting their own infrastructure assessments.

The New Orleans Geological Society was organized on October 3, 1941, as a non-profit organization for the purpose of facilitating the development of the profession and science of geology, with specific emphasis to exploration and production of petroleum and natural gas. Secondary related objectives include the dissemination of pertinent geological and environmental technological data, and the maintenance of a high standard of professional conduct of its members.

INTRODUCTION

This proposal from the New Orleans Geological Society was born from the observations of its members. Geoscientists working on interpretations of the subsurface of south Louisiana seismic surveys were the first to notice that many geologic faults extended to the surface. Several members of the Society also recognized strong correlations between many of these faults that reached the surface and distinct patterns of change in the land surface. Presentations of these findings to the Society have shown that the vertical displacement of geologic faults at the surface is very likely to be a significant factor in controlling rates of subsidence and land area change across the southeast Louisiana coastal plain.

Some of the most vital infrastructure of the oil and gas industry is located in the major port facilities along the southeast Louisiana coast, and will be impacted if the progression of subsidence and rising sea level continues in the coming decades. This proposal will lay out a plan of action for the industry to deal with these changes. It will examine in detail the relationship between subsidence and relative sea level rise, the tools for measuring subsidence, and the natural mechanisms that cause subsidence. The essential finding of this proposal is that the oil and gas industry is uniquely positioned to employ its own data, knowledge base and technology to derive a set of maps and predictive models that will best allow for infrastructure planning and management.

We will describe research projects to be commissioned and funded by oil and gas industry partners and implemented by academic research institutions. The first such project is now underway at the Coastal Sciences Laboratory at the University of New Orleans. This project will serve as a model for testing

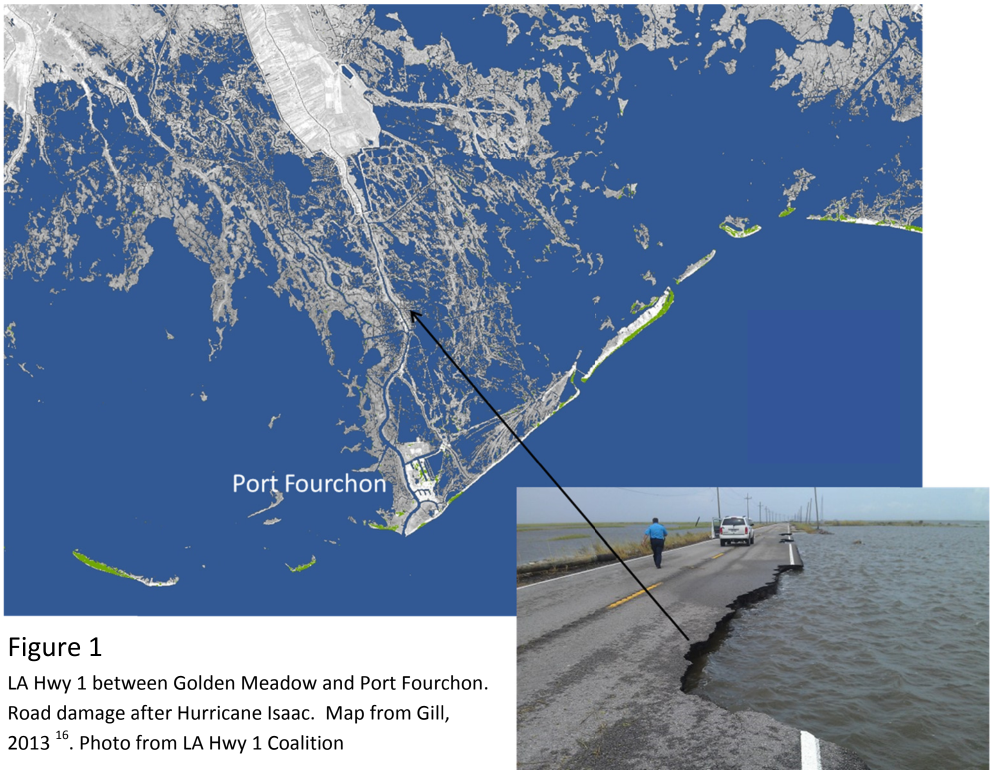


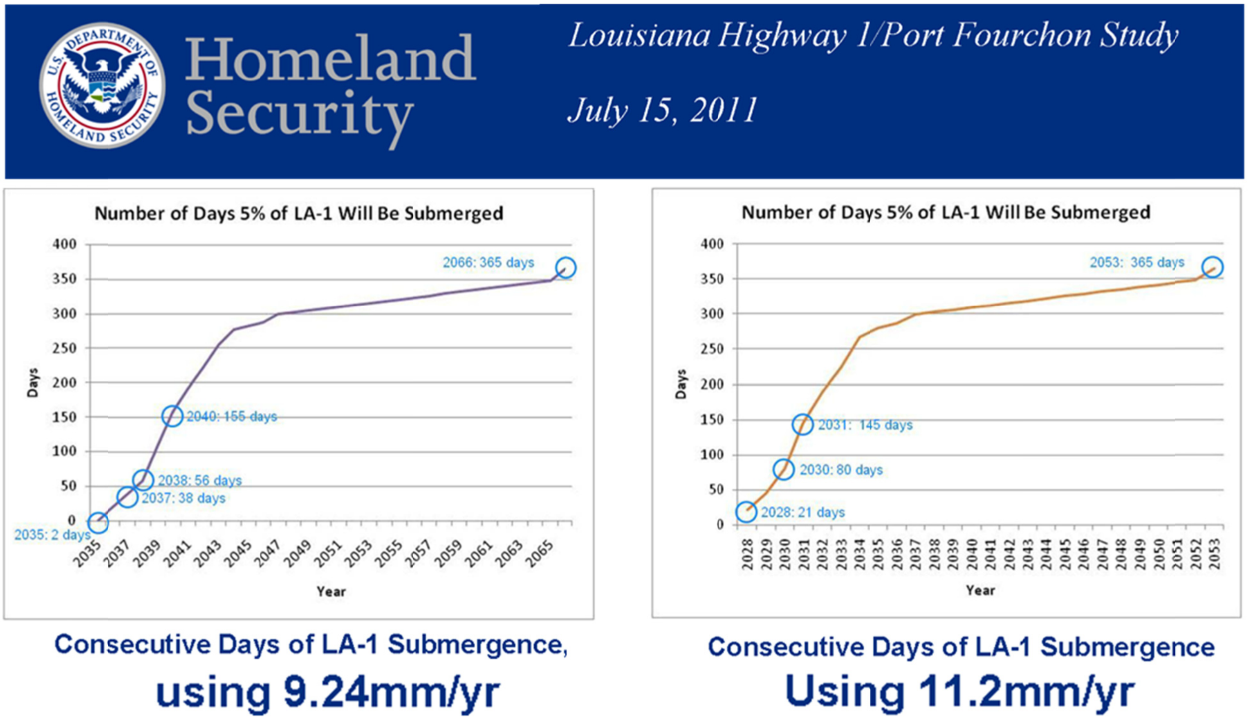
Figure 1

LA Hwy 1 between Golden Meadow and Port Fourchon. Road damage after Hurricane Isaac. Map from Gill, 2013 [16]. Photo from LA Hwy 1 Coalition industry technology in the effort, and an example for funding these projects. The success of this proposal will result in an evaluation of industry infrastructure, and offer a model to assess coastal infrastructure across the Louisiana coast. It will serve to invigorate science research institutions challenged for funding.

THE IMPORTANCE OF THIS PROPOSAL

The Department of Homeland Security's Infrastructure Threat and Risk Analysis Center characterized Port Fourchon, Louisiana in their 2011 Study[37]:

"Port Fourchon is located at the southern tip of Lafourche Parish, Louisiana, along the coast of the Gulf of Mexico. The port is the southernmost port in Louisiana and centrally located in a large area of the Gulf that is rich in oil and natural gas drilling fields. Shallow water operations are serviced out of many ports along the Gulf Coast, but servicing for deepwater operations is located at select ports due to the use of larger vessels that are required to support deepwater operations. Due to its central location, deep channels, favorable weather conditions, and size, the oil and gas industry has chosen to concentrate its infrastructure for deepwater oil and gas operations support at Port Fourchon. Roughly


Homeland Security

Louisiana Highway 1/Port Fourchon Study

July 15, 2011

Consecutive Days of LA-1 Submergence, using 9.24mm/yr

Consecutive Days of LA-1 Submergence Using 11.2mm/yr

Figure 2

Projections of the number of days LA Hwy 1 will be closed due to high water under two different subsidence secnarios. Homeland Security Study[37]

270 large supply vessels traverse the channels of Port Fourchon each day. Normally, about 75 percent of these vessels are servicing drilling rigs. Even though there are many more production platforms that require servicing than there are operating drilling rigs, drilling operations require much more material than production requires. The supplies and materials sent to rigs and platforms from Port Fourchon are brought into the port by the roughly 600 18-wheel trucks that travel on Louisiana Highway 1 (LA-1) each day. There is no alternative road access to transport supplies to Fourchon from inland locations. Consequently, a closure of this road effectively closes the port itself."

Scott (2014)[45] evaluated the economic implications of a disruption of access to Port Fourchon. Using a model that included the experience gained from hurricanes Katrina and Rita, he estimated that a three-week loss in services from Port Fourchon would lead to:

- ***A loss of $11.23 billion in sales at U.S. firms;***
- ***A loss of $3.16 billion in household earnings in the U.S., and;***
- ***A loss of approximately 65,502 jobs in the nation***

One scenario for disrupting Port Fourchon in the next two decades would be the closure of LA 1 due to the catastrophic effects of a major hurricane. The Homeland Security Study also considered that LA 1 could be inundated by the progressive rise of relative sea level over a period of several decades. They integrated relative sea level rise data collected by the National Oceanic and Atmospheric Administration (NOAA) with 2002 elevation data for the most critical portion of LA 1. The Louisiana Department of Transportation and Development (LDOTD) will close this section of LA 1 whenever 5% of the road has been inundated. The Homeland Security Study determined that with an average rate of relative sea level rise of 9.24 millimeters per year (mm/yr.) – measured at the Grand Isle tidal gauge – this portion of the highway would be closed 2 days in 2035, 38 days in 2037, 56 days in 2038, 155 days in 2040 and 365 days a year by 2066. The importance of LA 1, on Port Fourchon underscores the understanding, mapping and predicting the impacts of relative sea level rise in coastal Louisiana.

Elevating critical portions of LA 1 may seem the immediate solution for Port Fouchon, but the implications for the oil and gas industry infrastructure across coastal Louisiana are broader and far-reaching. The study reveals that relative sea level rise will impact the infrastructure of the oil and gas industry across coastal Louisiana within the next few decades. It shows that some areas may experience rates of relative sea level rise that are as much as two to three times greater than the 9.23 mm/yr. value used in the Homeland Security Study. Our proposal has a plan of action for the oil and gas industry to begin to address the issue of relative sea level rise, and we will need to look at the science of relative sea level rise and how it is measured.

Our proposal has two components: one, a long term, extending several years, the other, short-term, that will begin in the very near future. Both use oil and gas industry data and knowledge as a foundation for university-based research on relative sea level rise. We will describe an initial research project in detail with and how it may be expanded to broader applications. Finally, we propose a coalition of oil and gas industry partners to promote the effort and to fund each of the component research projects.

UNDERSTANDING RELATIVE SEA LEVEL RISE

Sea level rise is critical for developed coastal areas; nowhere more true than in Louisiana. Sea level rise has two components. The first, ***global*** sea level rise is the progressive increase of an average elevation of the earth's oceans. It is measured by coastal tidal gauges over the past several decades, is about 3 mm/yr.; it is generally accepted as the average rate of sea level rise since the beginning of the 20th century. Coastal tidal gauges also measure the second component, ***relative*** sea level rise. Subsidence, a drop in elevation of the tidal gauge causes relative sea level rise. Subsidence, where tidal gauge is set in the ground, has the same effect as a global rise in sea level. The individual effects of these two components may be determined by subtracting the rate of global sea level rise over total tidal record from the total values measured by that record. When applied to many tidal gauges across coastal Louisiana, relative sea level rise is as high as 20 mm/yr., nearly seven times greater than the global sea level rise component.

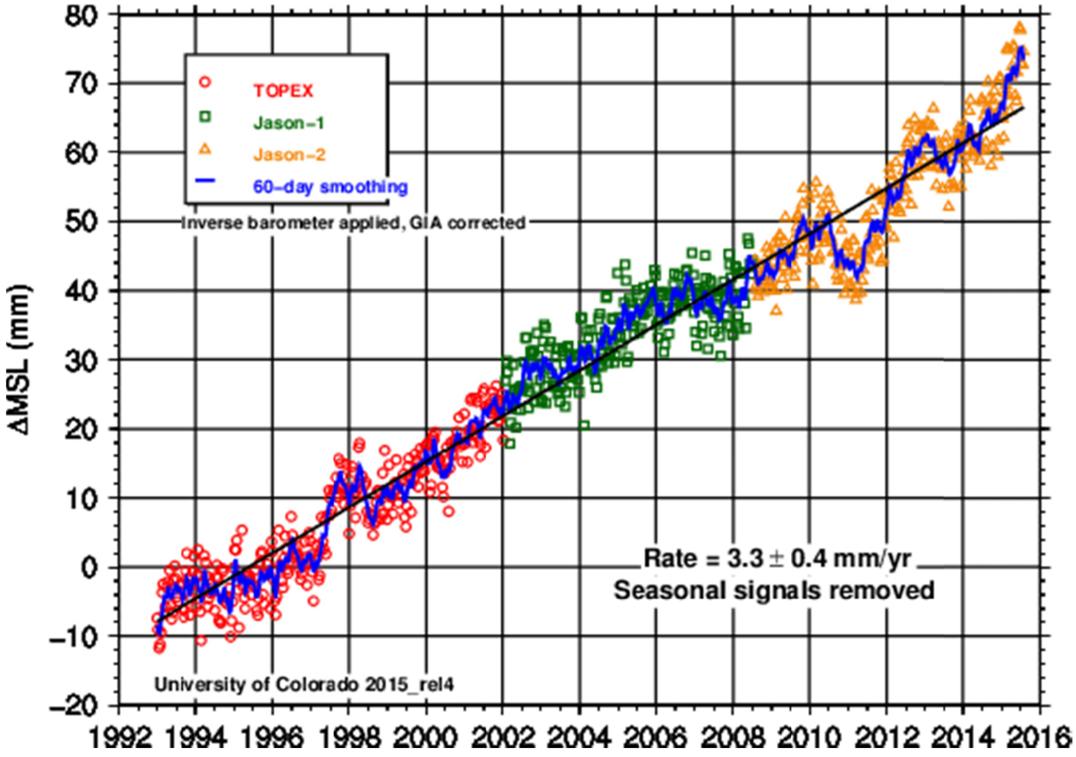


Figure 3

Global mean sea level, Nerem et al (2010) [39]

The measurement of subsidence for coastal Louisiana, indicated by the historical tidal gauge data, has been verified by two other methods: geodetic leveling surveys and Interferometric Synthetic Aperture Radar (InSAR) satellite surveys. Both estimate subsidence rates in a range between 3 and 30 mm/yr. A third method, using GPS satellite data to measure vertical movement of the surface of the earth has measured values between 2 and 6 mm/yr. Included in these measuring devices is the network of Continuously Operating Reference Stations (CORS). These stations were designed to be deeply anchored, away from of the influence of geologic faults and compaction of marsh sediment. CORS data reads a lower range of values, pointing to a broader down warping of the earth's surface across coastal Louisiana. Therefore, subsidence rates measured by the other methods are probably affected by geologic faulting and near surface compaction.

MODELS FOR MANAGING RELATIVE SEA LEVEL RISE

The US government perceives sea level rise as a real threat. In 2008, the Bureau of Reclamation, U.S. Army Corps of Engineers (USACE), U.S. Geological Survey (USGS) and National Oceanographic and Atmospheric Administration (NOAA) formed the Climate Change and Water Working Group (CCAWWG); other agencies, including EPA, FEMA and NASA joined later. CCAWWG emphasizes the interplay between science and the water management aspects of climate change. Measuring, predicting and preparing for sea level rise are critical components of water management. One of its missions is to "engage academia, non-federal, and other federal water resources management and science organizations to understand our shared research priorities." In addition to research initiatives of CCAWWG, several federal organizations are evaluating structures and installations that may be affected

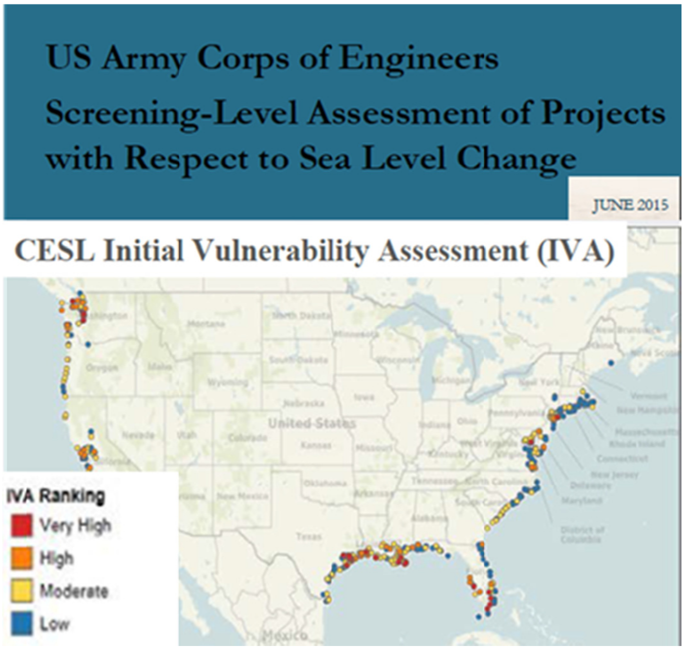


Figure 4

USACE Initial Vulmerability Assessment of Projects with Respect to Sea Level Rise [50] found a concentration ranked Very High in the Gulf Coast Region by sea level rise over the next several decades. These include the USACE, the National Park Service (NPS) and the U.S. Department of Defense (DoD). The DoD published the 2014 *Climate Change Adaptation Roadmap* [7], which outlines the "threat multipliers" that climate change presents to national security. These include the vulnerability of coastal installations due to rising sea level and increased flooding. They are planning for the challenges of relative sea level rise by identifying the effects "using the best available science." The USACE published a fact sheet for their *Comprehensive Evaluation of Projects with Respect to Sea Level Change*[50.] They identified about 500 projects that were likely to be impacted by sea level rise, and ranked them by "Initial Vulnerability Assessment" (IVA) at 50- and 100-year horizons. The greatest concentration ranked "very high" is on the Texas and Louisiana coasts (Figure 4).

Bob Marshall reported in *The Lens*[26] that new data from NOAA indicated that the subsidence at Grand Isle was "about four times faster than any other coastline in the lower 48 states, and one of the highest on the planet."

For two reasons, the Louisiana oil and gas industry is uniquely positioned for an assessment of the potential impacts of coastal subsidence. First, its vital assets are in coastal areas, where the most significant impacts of sea level rise are most critical. Second, the oil and gas industry has seismic surveys essential to understanding processes that control subsidence. We propose that the industry should engage in a cooperative assessment, and strive for results using the best available science.

MEASURING SUBSIDENCE

Subsidence is the downward movement of the earth's surface. Recent advances in geodesy have led to the development of a more accurate datum called the "geoid," which is calculated from the gravitational field and is variable across the surface of the planet. Sea level, relative to the geoid, is in flux. The global mean sea level curve has varied in elevation by as much as 120 meters over the past 20,000 years, and the average rate of change over the past century is about 3-mm/yr.

All of the methods of measuring subsidence will conclude that subsidence is occurring at variable rates across the Louisiana coastal plain, and there is good reason to believe that subsidence of the earth's surface has been continuous, but generally episodic, throughout a significant portion of the geologic history in this area.

Geohistory Analysis

Geohistory analysis is the use of quantitative stratigraphic techniques to unravel and portray geologic history. Quantification of stratigraphic well information is the result of advances in microbiostratigraphy that allow paleontologists to determine geologic ages in terms of millions of years and to express depositional environments in terms of water depth. Geohistory diagrams allow the calculation of rates of sediment accumulation and subsidence. Knowledge of rates and timing of vertical movements is of local importance in distinguishing between different kinds of movements (Van Hinte (1978)[51]).

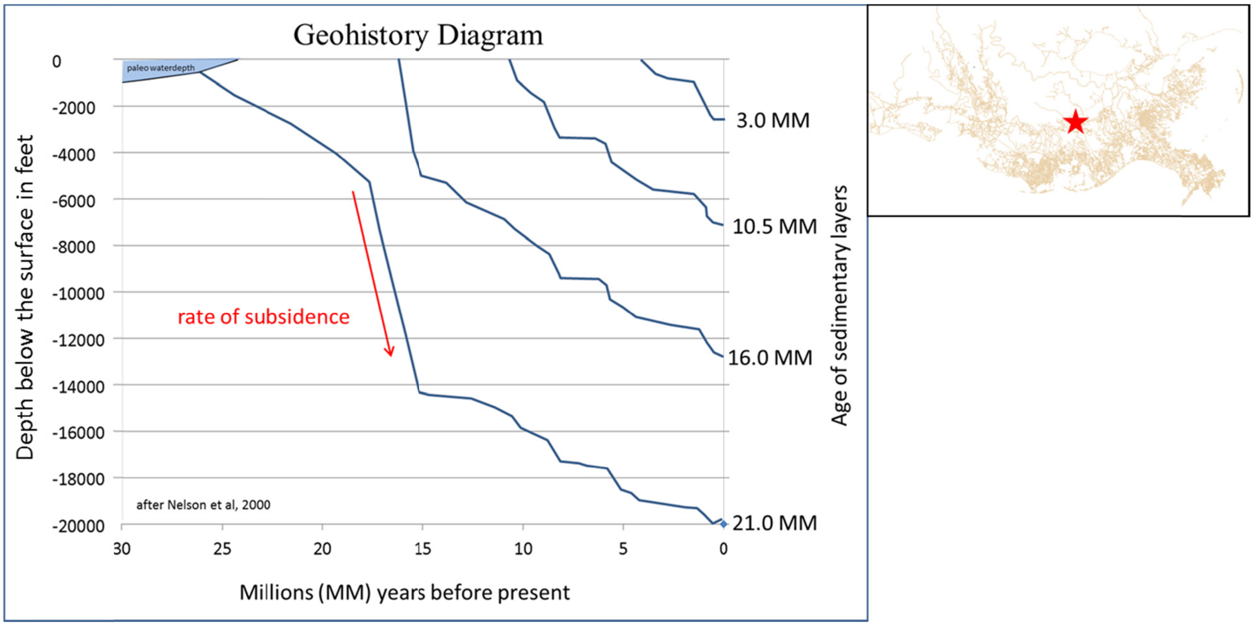


Figure 5

A geohistory diagram constructed with subsurface data from the location indicated by the star on the map. The vertical scale on the right shows the ages of the sedimentary layers below the surface. The vertical scale on the left shows the depth below the surface, and the horizontal scale shows time in millions of years. The history of any sedimentary layer may be traced backwards through time to determine its depth of burial at any point in the past. The slopes of the interior lines indicate the rate of subsidence that was experienced by a sedimentary layer at various points in time. The steeply sloped lines indicate intervals of rapid subsidence that are likely to be related to geologic mechanisms causing subsidence. Nelson, et al.(2000)[37]

It is important to note that this point in south Louisiana has been continuously subsiding for over 30 million years.

To derive the geohistory diagram in Figure 5 Nelson et al. (2000)[38] constructed a 600 km cross section of the northern Gulf of Mexico province. They used a time series of reconstructions of the probable configuration along this profile, which crossed south Louisiana, from the time of the deposition of the Jurassic Louann salt layer early in the history of the opening of the Gulf of Mexico. A comparison of a similar set of reconstructed profiles to the geohistory diagram clearly illustrates that geologic history of south Louisiana over the past 100 million years is a history of subsidence. In simplest terms the diagram is a graph of time (geologic age) versus distance (depth below the surface). Any line within the graph traces the history of a given sedimentary layer from the time of its deposition at the surface to its current depth. The depth of that layer may be determined for any point in time in the past, and these authors used this analysis to estimate when the organic-rich layers of the Jurassic and Cretaceous sedimentary interval passed through a depth and temperature range that would have initiated the generation of hydrocarbons. The lines of the graph may also be used to show that the relationship between time and distance is an estimate of the rate of subsidence that was occurring at that location at any point in the geologic past. The graph shows there been a measurable rate of subsidence (the slope of the line) at the location of this analysis throughout time, and the rate of subsidence has varied through time. The higher rates of subsidence will be discussed in the next section.

The concept of geohistory analysis may be extended to any form of subsurface profile in which there is reliable depth and age data for discrete points on the profile. Several authors employing this concept with shallow cores and borings have conducted the investigation of the recent past of the southeast Louisiana coastal plain. Morton[31-36] and Törnqvist [48, 49, 55] have used depths and radiocarbon age dates of peat layers in the shallow subsurface to derive estimates of subsidence. The work of Törnqvist, using this methodology, is generally accepted to represent the low end of subsidence rate estimates for the coastal plain. Frazier (1967)[14] used shallow core and boring data to reconstruct the most detailed history of the Holocene lobes of the Mississippi Delta system. He used radiocarbon age dates from several hundred cores across the coastal plain in combination with interpretations of depositional environments of the shallow sedimentary layers to assign ages and "lifespans" to each of sixteen delta lobes that built up the coastal plain over the last 6,000 years. Lost in the discussion of the delta building process of the coastal plain is that the majority of these deltas have subsided below the surface since their deposition. One of the profiles constructed by Frazier is shown in Figure 6, which runs from New Orleans eastward to Breton Sound. Figure 6 shows that while Frazier's deltas number 3, 5, 8 and 9 may be considered to have contributed to the construction of the coastal plain, on this profile they are all entirely below the surface.

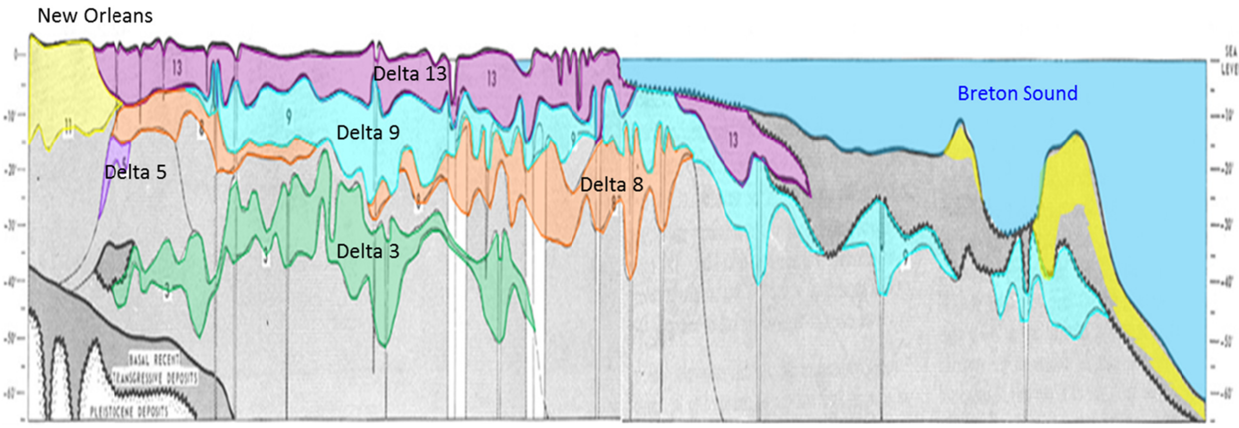


Figure 6

A subsurface profile taken from Frazier, 1967 [14] was constructed from cores and borings from New Orleans into Breton Sound shows the subsided Holocene deltas that have been deposited by the Mississippi River over the past 6,000 years. It is a commonly overlooked fact that the majority of the deltas that contributed to building the wetlands of southeast Louisiana have subsided below the surface. For the most part the substrate of the wetlands at the surface is made of sediments of the most recent deltas.

Delta 3 is about 30 feet below the surface. Radiocarbon age dates from the sediments of these delta lobes and their burial depth may be used to derive an estimate of the average subsidence rate for that sedimentary layer. Figure 7 shows details of the profile in Figure 6 with the annotation of an in situ cypress stump that was encountered in one of the cores in Breton Sound. The wood of the stump was age-dated to 2,100 years B.P.; it can be used to derive an average rate of subsidence associated with the submergence of that delta. The stump was encountered at a depth of 33 feet below sea level. It was clearly at the surface at the time that it died, drowning in saltwater as it subsided. The average rate of subsidence deduced from the current depth of the stump is about 5 mm/yr. The work done by Frazier and other authors including Kolb and van Lopik[21] provided a foundation for the "delta cycle" in which the life cycle of each delta lobe of the Holocene coastal plain is seen as progression from the accretion of new land by the active delta to the submergence of that land below the surface driven by the forces of subsidence.

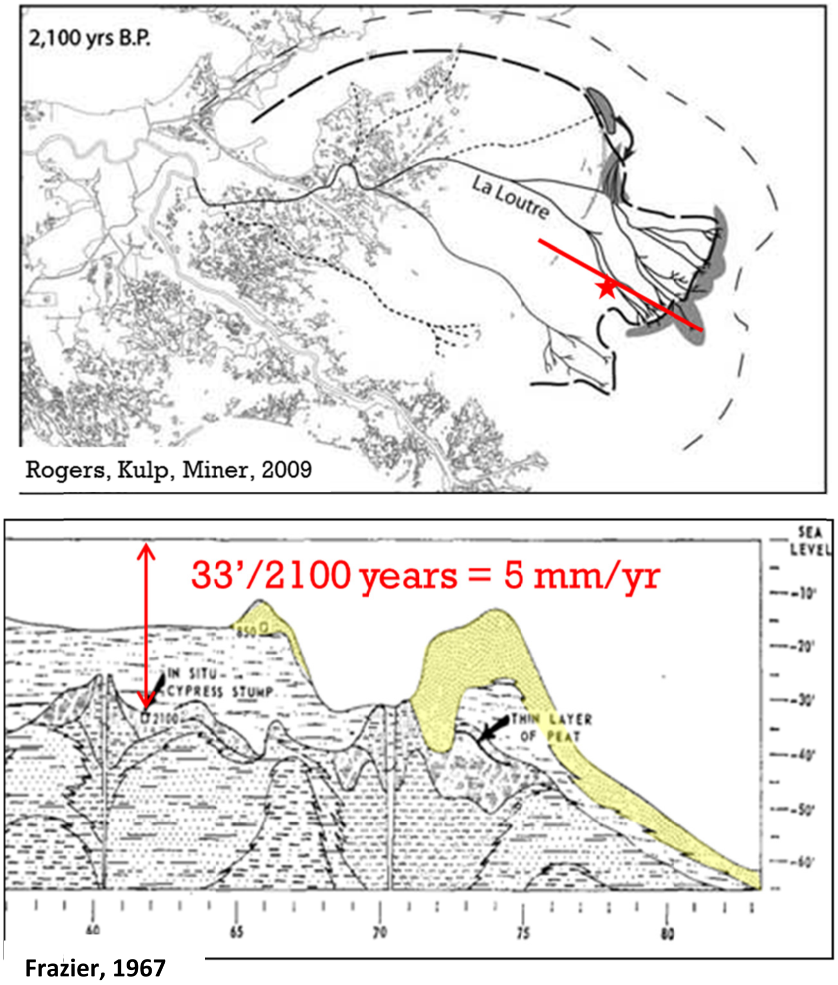


Figure 7

A detail from the same profile shown in Figure 6 from Frazier (1967)[14] shows the location of an in situ cypress stump encountered by one of the cores collected in Breton Sound and used in Frazier's study. The stump was age-dated to be 2,100 years old. It obviously was once at the surface and subsided to its current depth of 33 feet below sea level with an average rate of 5 mm/yr. The location of the profile and stump are shown on the Rogers et al (2009)[43] reconstruction of the distributary channels of the St. Bernard Delta.

Historical Tidal Gauge Data

The recognition of global sea level rise likely came from the historical records of tidal gauges around the world's coastlines. The U.S. Government has maintained tidal gauges along the coastlines of the United States for over a century. Presently, NOAA Tides and Currents website[40] provides access to historical data from hundreds of tidal gauges from around the country. Each tidal gauge, linked to a geodetic elevation benchmark, records the elevation of the high and low tides at that station. Graphing this tide data over several decades reveals a linear trend. The slope of this linear trend is the relative sea level rise (or fall) measured at that tidal gauge station over the period of record keeping for a particular tidal gauge. A comparison of tidal gauge records from around the coast reveals that each gauge station appears to measure a different value of sea level rise.

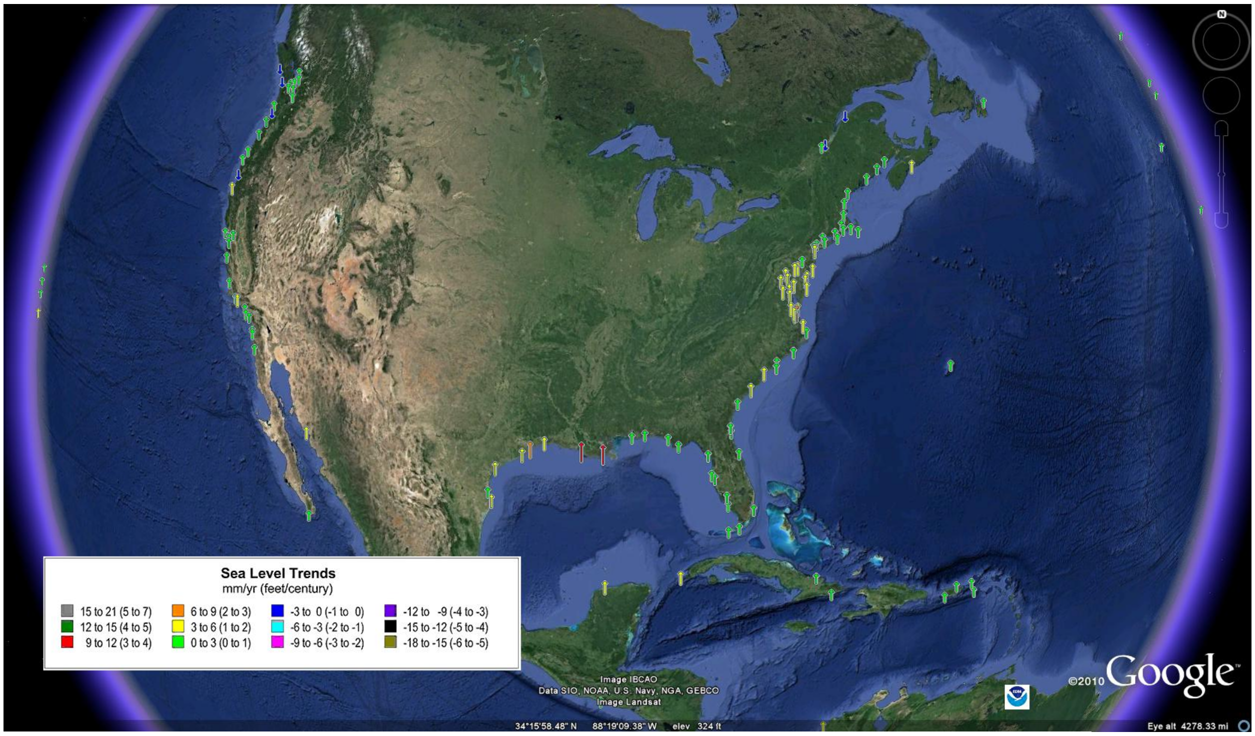


Figure 8

Tidal gauges operated by NOAA[40] around the coast show rates of relative sea level rise that range up to 9.24 mm/yr

Differences in rates of relative sea level rise measured at different tidal gauges are due to the subsidence of the land surface on which each gauge was constructed. The variation of any gauge's rate of relative sea level rise from the accepted rate of mean global sea level rise may be used to derive a rate of subsidence surface at the site of the tidal gauge.

Utilizing historical tidal gauge data from three of the longest running gauges on the Gulf Coast at Pensacola, Galveston, and Grand Isle, Blum and Roberts, produced the graphical evaluation in Figure 10, which incorporates the global mean sea level curve. The rates of relative sea level rise measured by these gauges were approximately 2.15 mm/yr. for Pensacola, 6.38 mm/yr. for Galveston, and 9.27 mm/yr. for Grand Isle. The variation in relative sea level rise among these three gauges is greater than anywhere else on the U.S. coastline, and it underscores the impact of subsidence on tidal records along the Gulf Coast. Kolker et al. (2011)[22] removed inter-annual variability of the gauge data due to meteorological factors, such as sustained periods of high or low atmospheric pressure or sustained periods of a wind direction, which may have affected the gauge's non-uniformly. They recognized that the Pensacola gauge was positioned on a stable carbonate platform, and was not likely to have been affected tectonic forces or glacial isostatic adjustments. Thus, the rate of relative sea level rise measured at the Pensacola gauge record closely approximated the rate of absolute global sea level rise. As can be seen in Figure 10, the historical curve of the Pensacola gauge (in blue) does not exhibit any major variances from the global mean sea level curve (in gray). Kolker et al. isolated subsidence rates at the Grand Isle station by subtracting the Pensacola record. The long-term average rate of subsidence at the Grand Isle station was approximately 7.59 mm/yr., but they found the rate to be variable over time. Averaging rates over six year intervals they determined that the maximum rate of subsidence revealed by the historical gauge data was 15.83 mm/yr. between 1965 and 1970. This period of maximum subsidence coincides with the time period of maximum land area change in the Barataria Basin measured by Couvillion et al. (2011)[6].

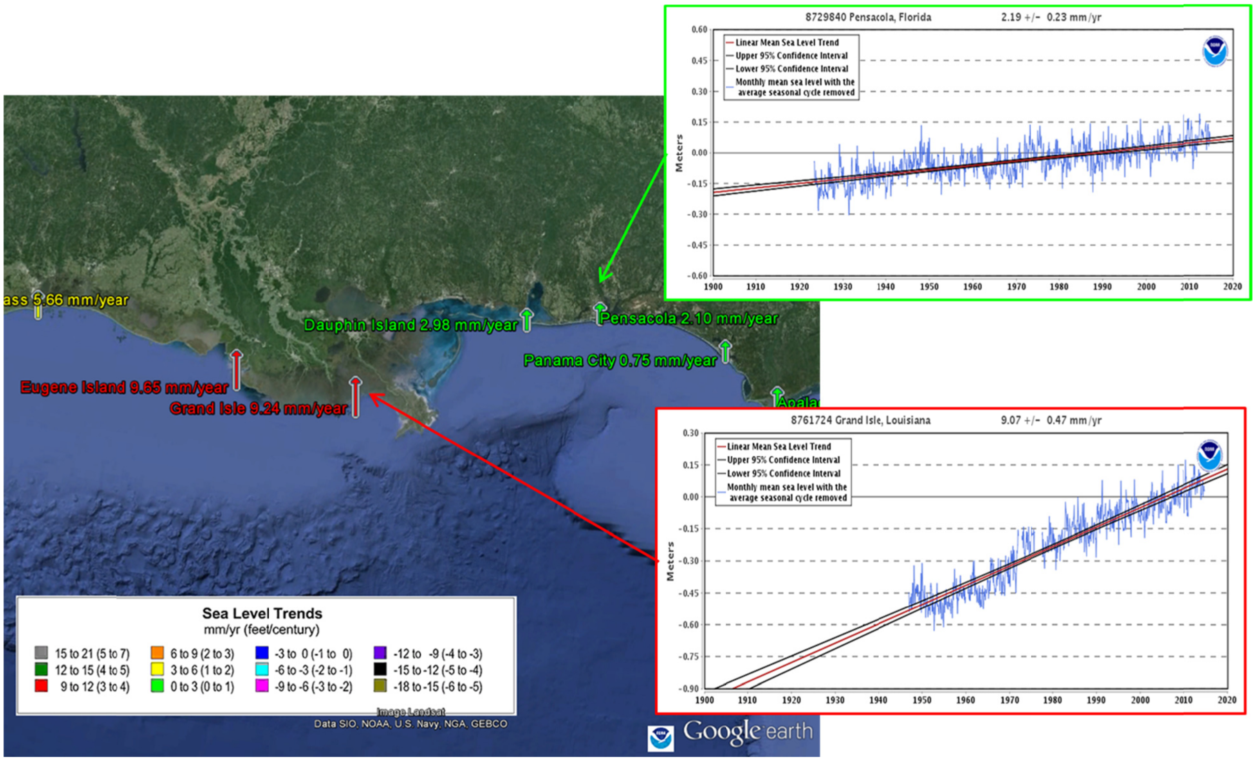


Figure 9

Historical tidal gauge records from Pensacola and Grand Isle from NOAA's Tides and Currents website [40] appear to indicate dramatically different rates of relative sea level rise. The Pensacola gauge has recorded a rate very close to the accepted rate of global mean sea level

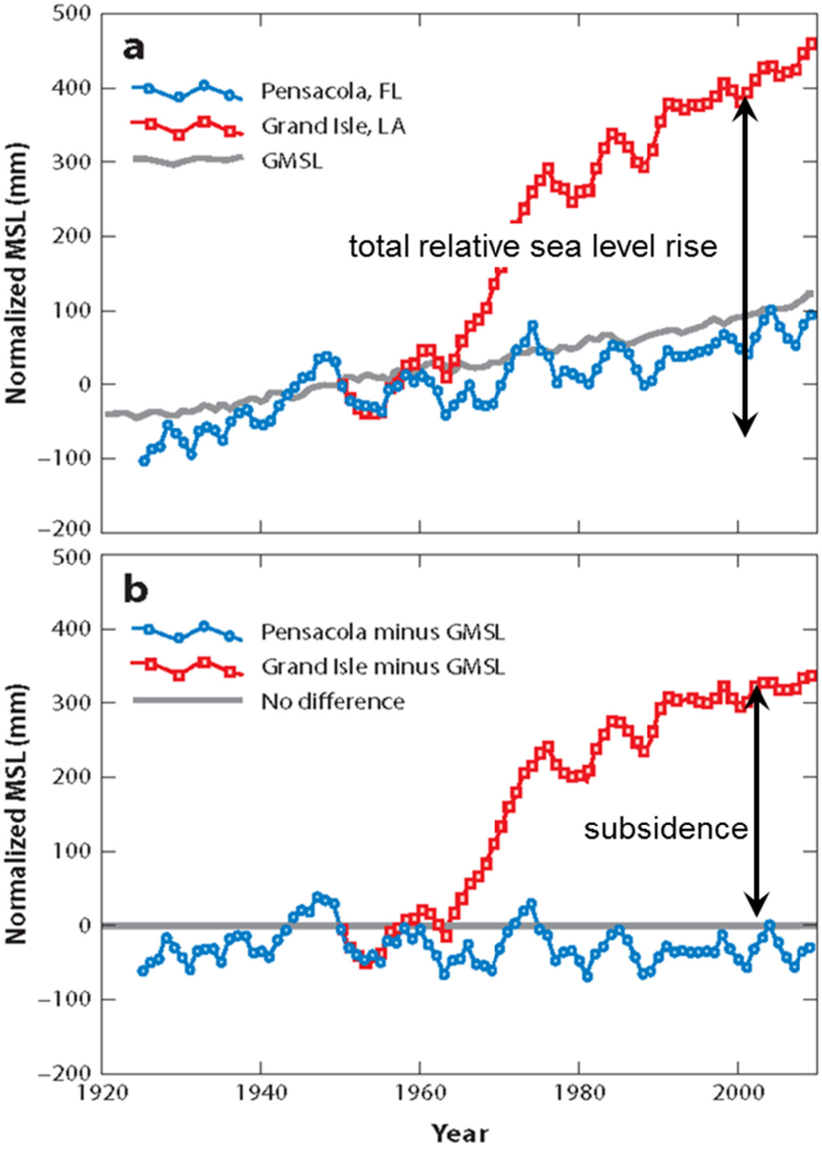


Figure 10

Blum and Roberts (2011)[3] used the historical records from the Pensacola and Grand Isle tidal gauges to show the relationship between relative sea level rise, global mean sea level rise, and subsidence. 10b shows that by removing the change due to global sea level (flattening the curve) a value of subsidence can be derived from the tidal gauge data at the location of the Grand Isle gauge.

Geodetic Leveling Surveys

Figure 11 illustrates the relationship between two gauges and the geodetic elevation benchmarks to which they are tied. In one case the elevation of the benchmark remains constant, and the gauge measures only the value of absolute sea level rise; this is a schematic of the Pensacola gauge. In the other case the elevation of the geodetic benchmark changes due to subsidence. The total relative sea level rise measured by this gauge includes both a component of absolute sea level rise and a component of apparent sea level rise due to subsidence; this is a schematic of the Grand Isle gauge. Note that the elevation of the geodetic benchmark, determined at its installation is no longer valid, but the relative value of subsidence that may be measured by subtracting the rate of absolute sea level rise from the relative sea level rise measured at the gauge is not dependent on a valid elevation reference, and is still accurate. In recent decades it became obvious that geodetic elevation benchmarks across the southern U.S. had been moving relative to their original elevations, and efforts have been made to determine the magnitude of elevation change at each station. The most comprehensive effort of this type was undertaken by Shinkle and Dokka (2004)[46] who published subsidence rates, for 2710 benchmarks in the southeastern United States. Figure 12 shows the location and derived subsidence values for the benchmarks that they evaluated in southern Louisiana. Shinkle and Dokka found variable rates of subsidence across the south Louisiana coastal plain with this method ranging between 5 and 30 mm/yr.

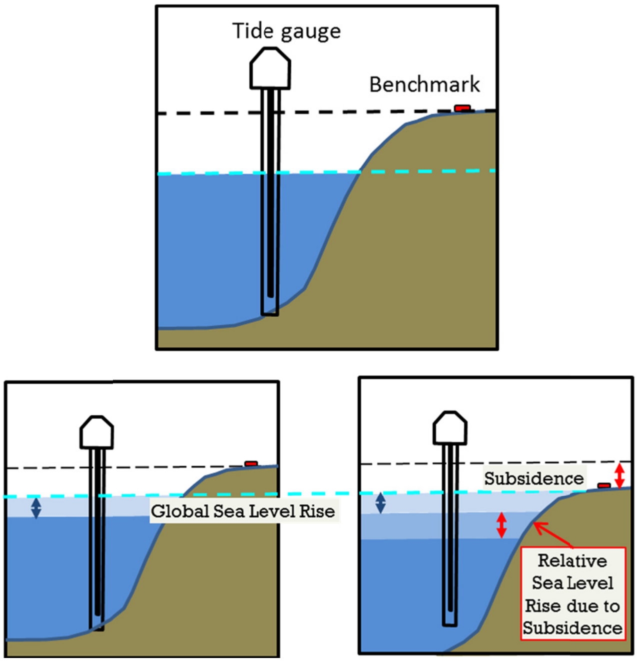


Figure 11

A diagrammatic illustration of two tidal gauges that record changes from a common original condition at the top. One shows global sea level rise only, and the other shows the additional apparent sea level rise due to subsidence

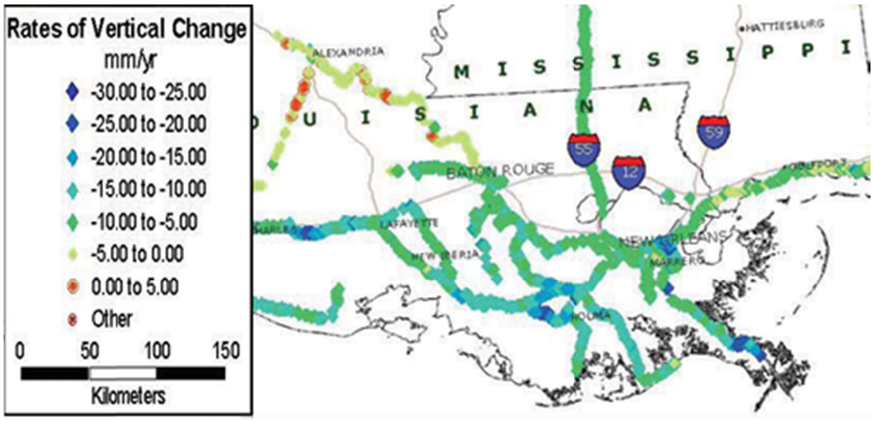


Figure 12

A graphical representation of subsidence rates determined by geodetic leveling surveys by Shinkle and Dokka, 2004 [46]

At the time of their study it was recognized that these values of subsidence were several times greater than the generally accepted range of values for south Louisiana. A comprehensive review of subsidence in coastal Louisiana by Blom et al. (2009)[2] concluded that the 2004 study by Shinkle and Dokka demonstrated:

"that modern subsidence has occurred at substantially higher rates than previously thought and occurs well beyond the wetlands of the Mississippi River Delta (MRD) suggesting crustal-scale processes such as sediment loading contributes to subsidence and land loss"

GPS and CORS

Most applications of Global Positioning System (GPS) technology in surveying and mapping have accuracy requirements that necessitate the use of a relative positioning technique. Many organizations have established GPS continuously operating reference stations (CORS) in support of these activities. CORS facilities collect and record, in an automated manner, the GPS data at a known location that are required for relative positioning. The National Geodetic Survey (NGS), an office of NOAA's National Ocean Service, manages a network of CORS that provide Global Navigation Satellite System (GNSS) data consisting of carrier phase and code range measurements in support of three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States. While two-dimensional positioning by GPS is as commonplace as a smartphone application, the measurement in the vertical dimension is rarely considered. The CORS facilities along the Gulf Coast have been used to derive variations in vertical position due to subsidence at the site of the facilities. Ivins, Blom and Dokka

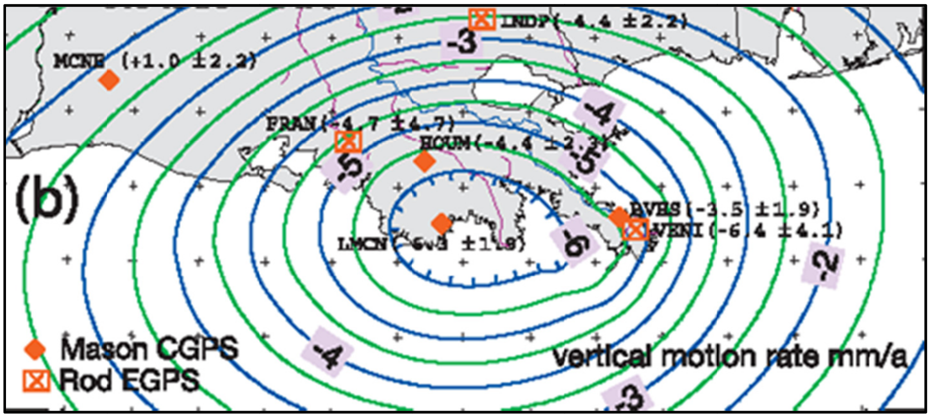


Figure 13

Values of subsidence shown in mm/yr measured at GPS facilities that were selected to insure that the data was not contaminated by shallow surface compaction or fault movement. These values are used in a later evaluation to show the broad pattern of "background" subsidence. Ivins et al (2007)[19] published a 2007 study[19] of subsidence utilizing rates of vertical change from a selected set of CORS and other GPS stations that are deeply anchored and away from any faults or wells. By selecting these stations they insured that the measurements were not contaminated by any effects of shallow compaction or faulting. Their results (Figure 13) are discussed in more detail in the next section on mechanisms of subsidence. The values on the map in Figure 13 are interpreted to represent the subsidence velocities that are due to the lithospheric flexure of the earth's crust under the load of sediments deposited by the Mississippi Delta system since the end of the last ice in the middle Holocene Epoch.

InSAR Satellite Imagery

Interferometric Synthetic Aperture Radar (InSAR) is a technique that enables geographically comprehensive mapping of surface deformation at centimeter scales with spatial resolutions in the millimeter-scale range over spans of days to years by forming interferograms of sequential synthetic aperture radar observations. In other areas around the world InSAR has produced images showing surface displacement due to earthquakes and volcanic activity. The most significant use of InSAR in the Louisiana coastal zone to date is the 2006 study[8] by Dixon et al. on the greater New Orleans area. Using imagery from Canada's RADARSAT satellite they measured subsidence rates in the New Orleans area of between 2 and 29 mm/yr. Figure 14 shows the distribution of subsidence values determined by this study. Dokka used patterns of subsidence from this 2006 study in a later publication 11 to interpret that sharp boundaries in the patterns of subsidence seen in Figure 14 were due to faults. The authors of the 2006 study noted a correlation between areas of high subsidence and breach points of the levees during Hurricane Katrina. They concluded that localized high rates of subsidence may be due to faulting or weak easily-compacted substrate that may have promoted levee failure.

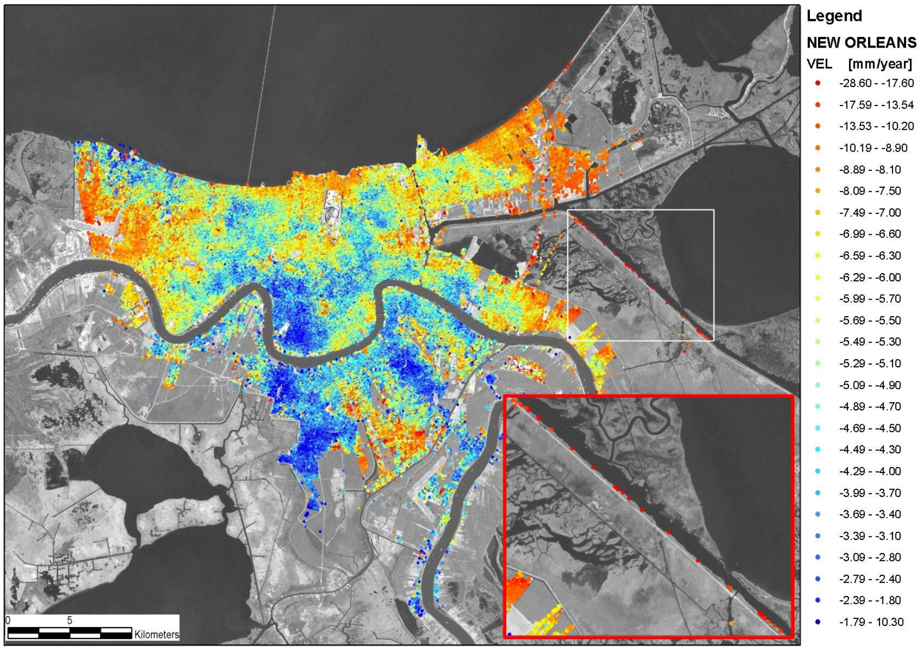


Figure 14

Values of subsidence shown in mm/yr measured InSAR satellite data from Dixon, et.al., 2006[8].

These methods have added to the fundamental understanding of subsidence in the south Louisiana coastal plain, but they do not form a clear picture the actual values of vertical movement of the earth's surface nor the relationship between these values and the range of possible mechanisms of subsidence. Meckle (2008)[29] noted discrepancies among the methods for measuring subsidence, and pointed to an inverse relationship between the rate of subsidence measured by a given methodology and the span of time over which the measurement is made. The mechanisms of rapid subsidence may be episodic, i.e., high rates may be measured over short time periods, but there is a tendency in any given area for the average rate to reduce over more extended periods of time. Meckle concluded that the vertical movement along faults was a likely cause of locally episodic high subsidence rates.

MECHANISMS OF SUBSIDENCE

Meckle's summary of the variability of subsidence rates derived by different methodologies across different time scales underscores the inherent variability in the mechanisms that are likely to be causing the subsidence that is being measured at the surface. The accepted set of processes that may be causing subsidence in the Louisiana coastal plain include both natural and anthropogenic elements.

Natural Causes of Subsidence

Natural causes of subsidence include lithospheric flexure of the attenuated (stretched) continental crust and underlying asthenosphere, the lateral and discordant movement of the Jurassic salt overlying the crust beneath and across younger sedimentary layers, the compaction of the accumulated sediments overlying the salt, the translational movement of lystic faults that displace the sedimentary layers, and a forces associated with glacial isostatic adjustments which have been active over North America over approximately the last 8,000 years.

Anthropogenic Causes of Subsidence

Documented anthropogenic causes of subsidence across the Gulf Coast include the compaction of groundwater aquifers due to extraction, and localized cases of subsidence due to the desiccation and oxidation of organic peat layers beneath the city of New Orleans. A few authors have also introduced the concept that subsidence may be caused by the extraction of oil, gas and water from reservoirs much deeper below the surface than the groundwater aquifers; however, these claims need more documentation. This concept is in the very early stages of development, and is in need of much more detailed evaluation to determine its viability. The studies that have addressed this issue in Louisiana to date have established that some oil and gas fields are located in areas where subsidence has occurred, but no study has established a process-based causal link between deep extraction and surface subsidence. The documented cases of subsidence caused by deep oil and gas extraction in other parts of the world are not directly applicable to south Louisiana. To establish a processed-based causal link by a valid scientific methodology a study would have to establish first that compaction of the reservoir at depth has taken place as a result of fluid extraction, and second that this compaction is propagated to and expressed at the surface. Neither of these processes has been established for oil and gas reservoirs beneath coastal Louisiana. A comprehensive evaluation of the concept would also have to address the large volumes of production that have come from an oil and gas field where there is no apparent subsidence at the surface. The documented mechanisms of anthropogentically-induced subsidence are exclusive to metropolitan areas, which are outside the scope of our proposal.

It is impossible to separate the mechanisms contributing to subsidence in any given area. More likely, subsidence rates are due to the combination of several mechanisms, and the relative significance of each mechanism may be dependent of the time span from which a rate of subsidence measurement is derived. Some mechanisms are associated with lower rates of broad-based, long-period "background" subsidence; other mechanisms are associated with higher rate, localized short-period "hot spot" subsidence.

MECHANISMS OF BACKGROUND SUBSIDENCE

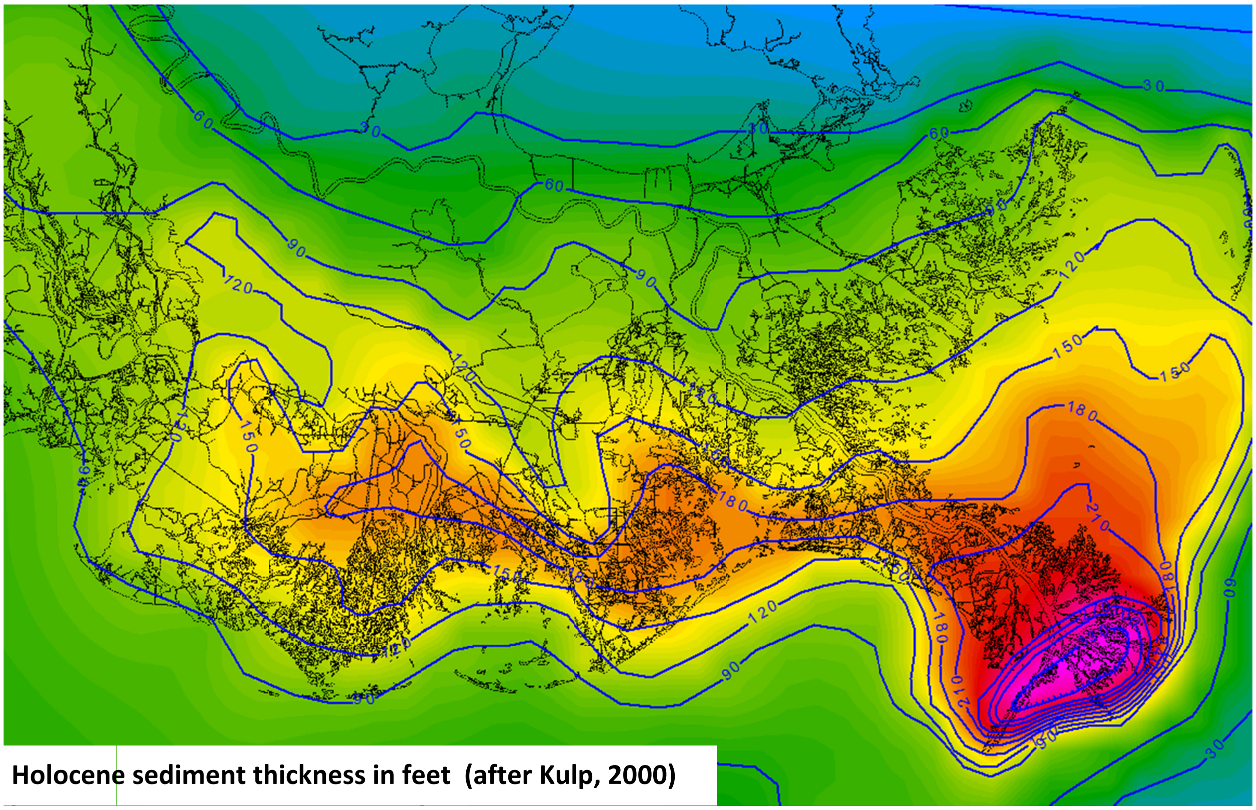
Glacial Isostatic Adjustment (GIA)

This mechanism, also referred to as "glacial forebulge", is generally accepted to be the primary mechanism of subsidence measured along the East Coast of the U.S. as was documented by the 2010 Virginia Institute of Marine Science study[4]. The basic concept is that the surface of the earth responded isostatically to the massive weight of the ice sheet on the North American Continent during the last ice age. The areas that were uplifted by the forebulge effect are now subsiding. This could include portions of the Gulf Coast, and it is possible that there may be some GIA effect in coastal Louisiana. If there is such an effect, it should be almost completely uniform across the coastal area, any contribution that this mechanism would be making to the subsidence rates measured across coastal Louisiana would be essentially equal at every location.

Lithospheric Flexure

The delta deposits that support the Louisiana coastal plain are best understood as a thin veneer of sediment representing the latest in a sequence of delta deposits that goes back at least 50 million years in time. The magnitude of sediment deposited by the Mississippi River system during that 50 million year time interval rivals the Himalaya Range in volume. This accumulated mass can be imagined as an inverted mountain range of sediment stretching across the Gulf Coast of Louisiana and eastern Texas, and downward to depths of up to ten miles. The relationship between the Mississippi as the major drainage system of North America, and the Gulf of Mexico sedimentary basin is subsidence. The river has continued to flow into the Gulf of Mexico and the basin has provided the accommodation for its sedimentary load. The basin has the capacity to accept the massive sedimentary load because of isostasy, the adjustment and deformation of the underlying continental crust to the weight of the sediments. The Gulf of Mexico Basin formed during the opening of the Atlantic Basin. The otherwise rigid crust of the continental plates was stretched and thinned during this process resulting in early rift basins that filled with a thick layer of salt before the basins had access to open ocean circulation.

Ivins, Dokka and Blom, 2007 modelled the most recent episode of lithospheric flexure due to the sedimentary load of sediments deposited by the Mississippi River. The subsidence velocities predicted by their model shown in Figure 13 were found to be in reasonably good agreement with GPS measurements of vertical movement. The total volume of the Holocene sedimentary load that is causing the most recent episode of subsidence due to lithospheric flexure was mapped by Mark Kulp in 2000, as shown in Figure 15. There is an obvious correlation between the pattern of Holocene sediment thickness and the pattern of subsidence in Fgure 13.



Holocene sediment thickness in feet (after Kulp, 2000)

Figure 15

The isopach (thickness) maps of Mississippi Delta sediments from the Holocene Epoch in southeastern Louisiana (Kulp, 2000)[24] shows a central axis of thickening running roughly parallel to the coast. The pattern of thickness of sedimentary layers is reflective of the patterns of subsidence measured at the surface by GPS and shown in Figure 13. The outline of thick Holocene sediments corresponds with the structural limits of the Terrebonne Trough.

Sediment compaction

The "inverted mountain range" volume of sediment that has accumulated in the northern Gulf of Mexico Basin over the past 50 million years was all delivered to the basin by ancestral elements of the Mississippi River system. The northern Gulf of Mexico sediments accumulated in an array of depositional environments across the basin margin, where deposition took place below the surface of the water. When deposited, sediments at the surface are loosely compacted. Recently deposited sediments may have water-filled pore spaces up to 40% of the total volume of the sand layers and up to 80% of the volume of the muds. As deposition progresses, sediments are buried by successive layers of material. The cumulative weight of the overlying sediments contributes to the compaction of the underlying layers, and is called the “overburden stress.” The response of sediments is a reduction in the pore space by dewatering and compaction, reducing of the total thickness of each sedimentary layer. The cumulative reduction of the thickness of all sedimentary layers over time will result in subsidence expressed at the surface equivalent to the total change in thickness of the underlying sedimentary layers.

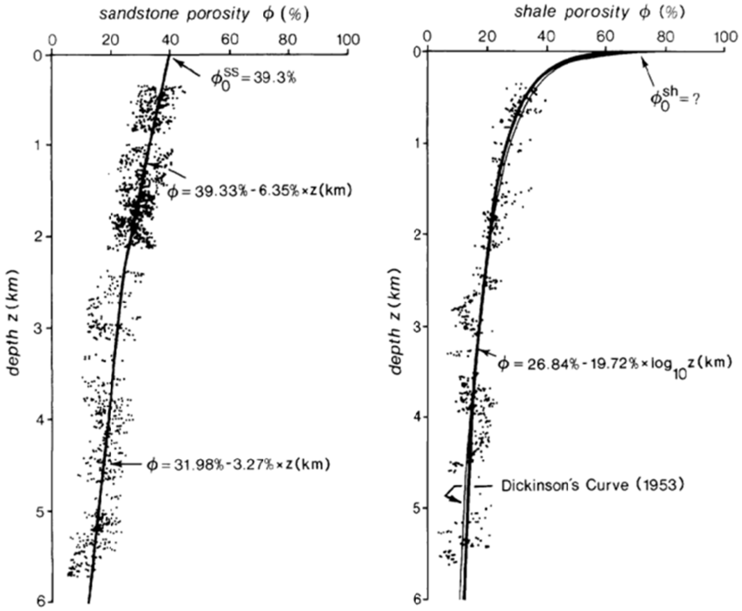


Figure 16

Compaction curve for sand and clay layers in south Louisiana from Xiao and Suppe (1989)[49]

Figure 16 shows the progressive reduction in porosity of sands and shales (compressed and dewatered muds) in an area of south Louisiana. The muds lose about 75% of their pore volume by compaction in the first 3,000 feet of burial, and areas of rapidly compacting and dewatering muds are the most likely to cause subsidence with significant surface expression. Sands have a more linear reduction of porosity with burial and generally experience between 5 and 15% total reduction in pore volume before cementation between the sand grains begins to halt further compaction with depth. It is clear from these figures that the progression of sediment compaction continues to significant depths, and therefore for very long periods of time. Subsidence due to compaction is a long-term and cumulative phenomenon. Based on a comparison of the compaction curves (Figure 16) and the geohistory diagram (Figure 5) values of subsidence due to compaction being measured at the surface today may be receiving contribution from the compaction of sedimentary layers that were deposited 20 million years ago, now 15,000 feet below the surface.

Lateral Movement of Salt

The mechanism of subsidence due to the lateral movement of deca-kilometer-sized salt bodies is one of the most important elements essential to understanding the history of the Gulf of Mexico Basin. The profiles in Figure 17 show that the salt that once formed across the Gulf of Mexico Basin has been gravitationally deformed and folded from the overburden stress. Simply, the salt acts like cookie dough to the action of a roller pin (overburden). Over the history of a sedimentary sub-basin, such as the Terrebonne Trough, the mobile salt bodies progress from laterally moving sheets and swells into elongate domes and spires that appear to have pierced vertically upward through the sedimentary layers. Throughout the history of a now-mature sub-basin, such as the Terrebonne Trough, the initial lateral movement of the salt is translated into vertical subsidence at the surface. Its salt bodies have formed into salt domes, reaching equilibrium with the surrounding sediments. However, there may be a broader regional effect of lateral salt movement that is affecting subsidence at the surface of the coastal plain.

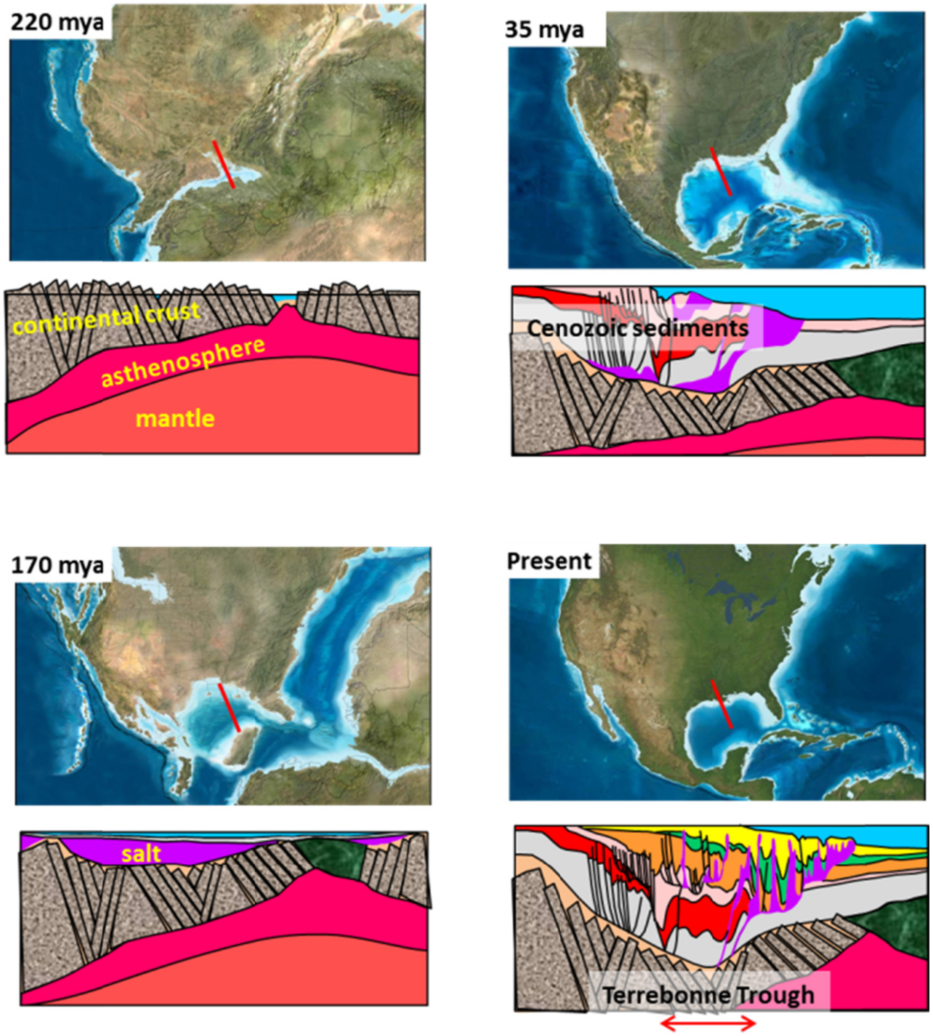


Figure 17

A panel of four time periods during the formation of the Gulf of Mexico. Each time period is denoted by an age in millions of years ago (mya) in the upper left. Maps are paleogeographic reconstructions done by Ron Blakey, Colorado Plateau Geosystems, Arizona USA, 2011. The red line on each map denotes the location of the cross section profile shown below the map. Profiles are after Stephens, 2009 [46]. The progression from the onset of rifting that opened the Gulf about 220 mya shows the formation of a thick layer of salt during the period in which the Gulf was separated from open ocean circulation, and the thick accumulations of terrigenous sediments over the last 50 million years. The later profiles show the relationship between the accumulation of sediments and down-warping of the continental crust and the lateral movement of the salt. The Terrebonne Trough is the central area of down-warping that underlies coastal Louisiana.

Karegar et al. (2015)[20] showed that the velocities of movement recorded by CORS facilities in south Louisiana include a component of horizontal movement. Dokka et al. (2006)[10] attributed this horizontal vector of movement to a large scale, low-angle detachment zone which is rooted in low strength salt and shale. As seen in Figure 18, they envisioned a tectonic block, which they called the "South Louisiana Allochthon" in which lateral movement along a horizontal surface of salt and shale has been expressed both as horizontal and vertical movement across the Louisiana coastal plain. This interpretation of the value of horizontal movement being measured by CORS would relate some portion of the vertical subsidence values being measured by CORS to the lateral movement of salt in the deep Gulf of Mexico. As is the case with the values of subsidence that may be attributed to sediment compaction, any approximated values of subsidence occurring in the coastal zone that may theoretically be attributed to this lateral movement of salt in the deep Gulf of Mexico would be best treated as a component of the overall value of background subsidence that affects the coastal plain in a broad regional context.

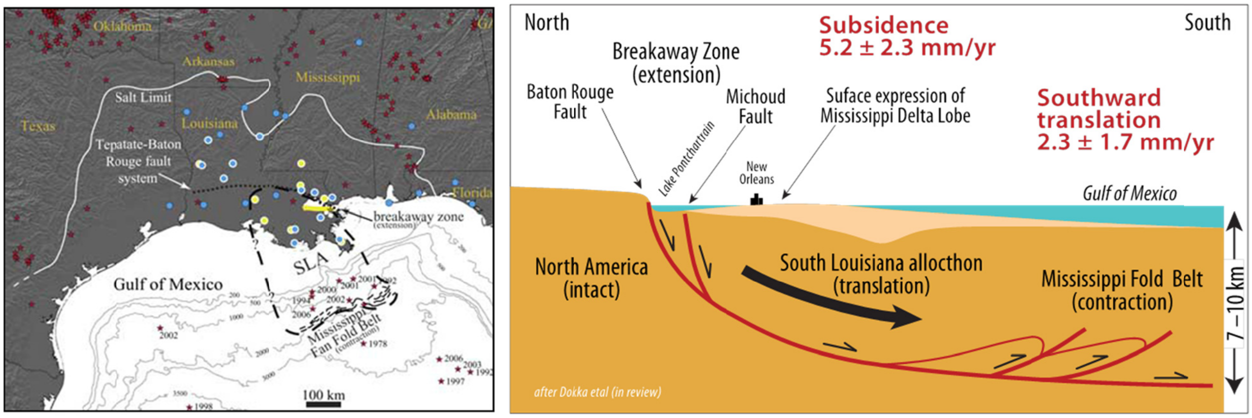


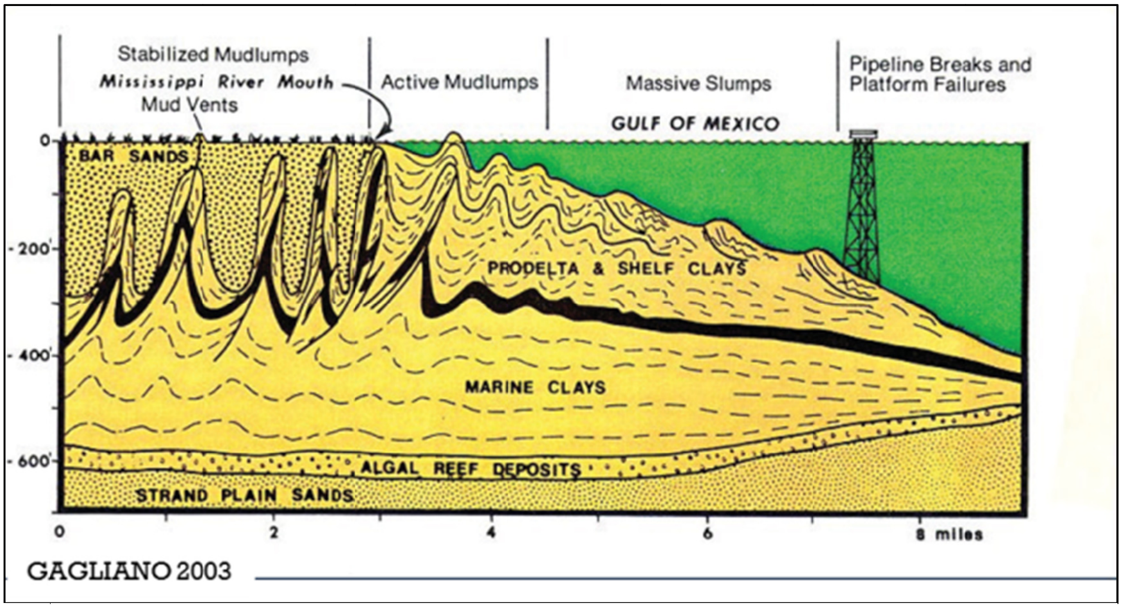
Figure 18

The South Louisiana Allochthon postulated by Dokka et al (2006)[10]. This represents the upper end of the size spectrum for both lateral salt movement and fault features. The east and west boundaries are roughly coincident with Stephens (2009)[47] transfer faults.

MECHANISMS OF HOT SPOT SUBSIDENCE

Lateral Movement of Ductile Muds and Clays

Subsidence due to the ductile muds and clays is 1-2 orders of magnitude smaller and more localized than the lateral movement of salt. It is also probably closely linked to the subsidence due to the dewatering and compaction of those same muds and clays. Morgan, Coleman and Gagliano[30] identified the classic example of subsidence due to the lateral movement of clays in the birdfoot delta of the Mississippi River in their study of mudlumps. Mudlumps are the surface of the diapiric intrusion of older marine clay layers into and through overlying bar sands deposited by the delta. Figure 19 shows that like lateral salt movement, the movement of the clay layers creates subsidence at the surface in the form of accommodation space for the accumulating sand deposits of the delta.



GAGLIANO 2003

Figure 19

Mudlumps at the birdfoot delta. The lateral movement of the clays under the weight of the delta bar sands provides a mechanism of hot spot subsidence. Image from Gagliano et al (2003)[15]

Faulting

Faults are fundamental structural elements of the Gulf of Mexico Province. They may be envisioned as slide surfaces similar to those of a landslide, though at a much larger scale. As seen in Figure 22 the essential components of a fault are the slip surface along which the failure occurs, an escarpment at the "head" of the failure, and a compressive bunching of material at the "toe" of the feature. These faults exist across a scale, from small landslides deca-meters in size to tectonic masses hundreds of kilometers in size. The South Louisiana Allochthon of Dixon, Sella and Dokka[10] represents the latter (Figure 18), a mega-slide structure in which the horizontal movement is linked to the lateral movement of salt in its compressive "toe" region. In scale, the average south Louisiana growth fault is somewhere between these two end members. In a single growth fault, the plane of slippage may extend for three or four miles below the surface, its compressive toe may be fifteen to twenty miles toward the center of the Gulf of Mexico from its head escarpment, and the length of the surface escarpment may be ten to twenty miles. These growth faults translate horizontal slippage along the slide surface to vertical subsidence at the surface escarpment, as suggested by the diagrams in Figures 21-24. The escarpments of the faults that extend to the surface are often expressed as sharp lineations on the topography of the land. Fault movement is driven by gravity, and strain is continually released as a slow and steady creep. Periodic episodes of more rapid movement have been noted.

Researchers including Morton, Roberts, Dokka, Kulp, Gagliano and Lopez have studied and published on subsidence and its impact on the Louisiana coastal plain over the past few decades. All recognized the importance of faults as mechanisms of subsidence at the surface. Mapping these faults in the subsurface has been a principal part of oil and gas exploration in south Louisiana for many decades, and most of the major faults have been named and recognized by many geologists as natural features of south Louisiana. Some of the major faults and salt domes of southeast Louisiana are also the primary structural elements of the Terrebonne Trough. The outline of the Terrebonne Trough has been recognized by the patterns of sediment thickness mapped by Combellas-Bigott et al. (2006)[5] and Kulp (2000)[24] (Figure 15). The Trough can be defined by a system of large faults that gently arc across its northern boundary, and an inter-related set of large faults and salt domes that sharply define its southern boundary. As seen in Figure 20, the faults to the north have arrows indicating a down-dropped direction to the south, or their direction of vertical movement is down toward the center of the trough. The faults to the south have arrows indicating their down-dropped direction is to the north so that their direction of vertical movement is also toward the center axis of the basin. The relation between the structure of the Terrebonne Trough and the patterns of sediment thickness in both the Middle Miocene and Holocene epochs indicates that the vertical displacement of these faults systems has played an integral role in defining the patterns of subsidence over many millions of years, as expressed by the sediment thickness maps. Mapping many of the same faults where they reach the surface is a relatively new development, and there has not been a widespread effort to document the location of faults at the surface.

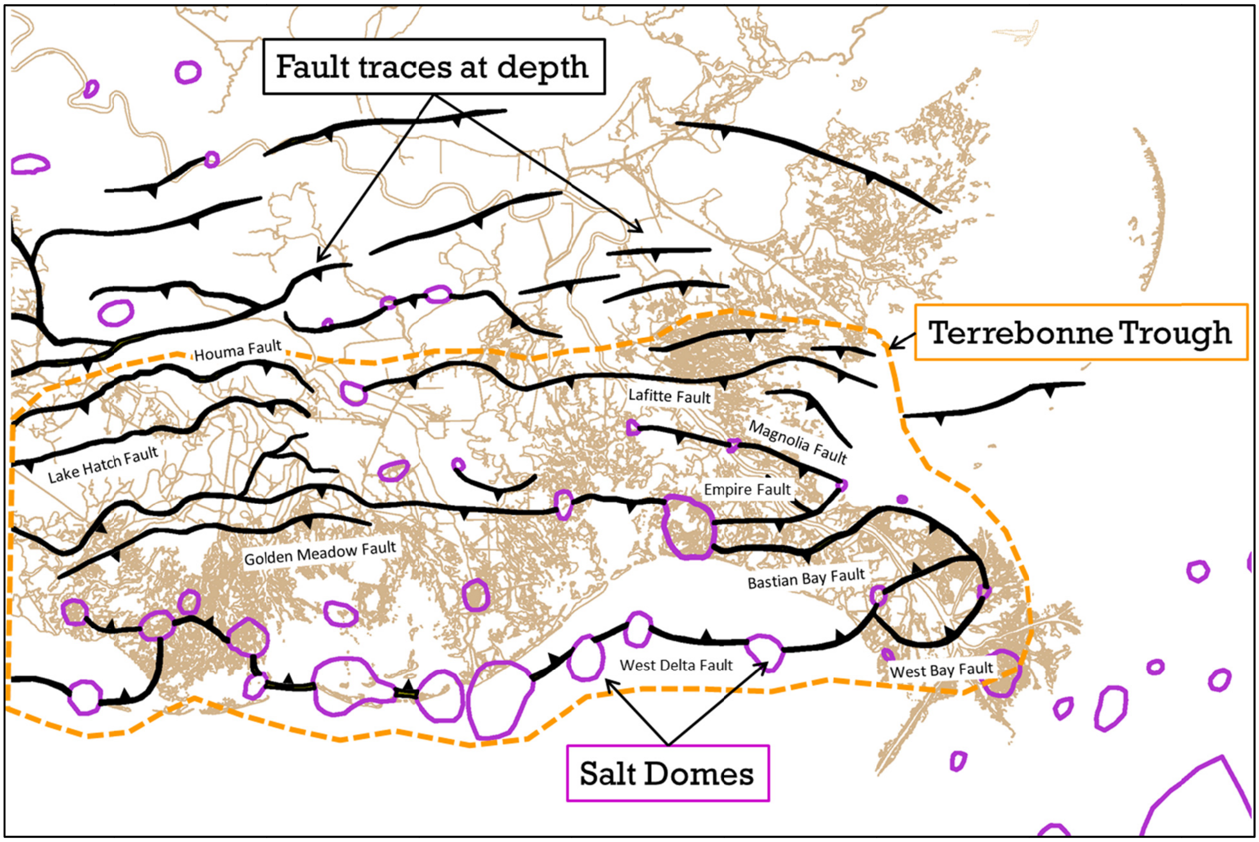


Figure 20

Generalized map of the major fault traces at depth. Arrows indicate the down-dropped direction of each fault. Salt domes are outlined in purple, and the outline of the Terrebonne Trough is shown as a dashed orange line. The faults and salt domes are the structural elements of the Trough. Sediments thicken toward the center of the trough, as can be seen in Figure 15.

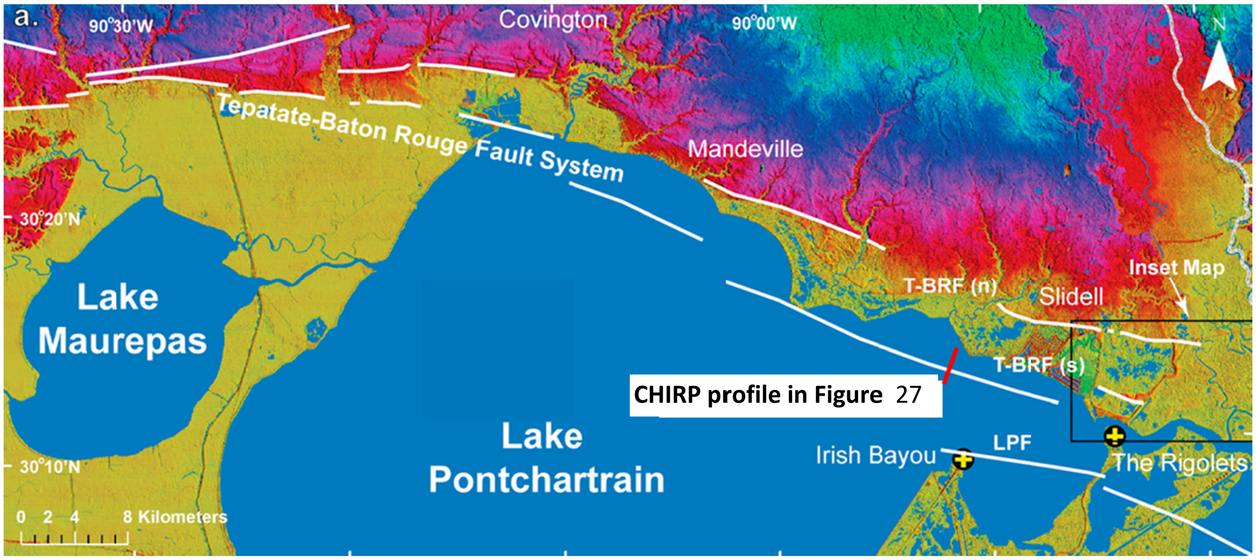


Figure 21

Surface fault traces mapped by Dokka, 2011[11]. Along the north shore of Lake Pontchartrain vertical displacement due to faulting is evident as distinct elevation changes on LIDAR data. The location of the CHIRP profile in Figure 27 is shown as a red line

The most obvious expressions of fault escarpments in south Louisiana are the distinct and sometimes subtle changes in surface elevation along the major components of the Baton Rouge – Tepatate Fault system. McCulloh[23&24] and Heinrich[18] used digital elevation models (DEMs) generated from LIDAR (light detection and ranging) data to delineate the expression of fault escarpments. The surface expression of these faults can be imaged with LIDAR data because they well above sea level where there is enough vertical relief to see the displacement at the surface. Dokka (2006) also used LIDAR DEMs to illustrate where the surface escarpments of this fault system crossed the north shore of Lake Pontchartrain (Figure 21). Haggar (2014)[17] evaluated landscape level changes in the plant communities at Goose Point on the north shore of Lake Pontchartrain, and concluded the subsidence due to vertical movement of a portion of this fault system was the only viable explanation for those changes. Haggar found that this portion of the fault system, called the Lacombe Fault segment, defined a sharp boundary in both elevation change and plant community change. The Baton Rouge – Tepatate Fault system is coincident with Dixon and Dokka's "breakaway zone" that defines the northern extent of their South Louisiana Allochthon. Figure 18 shows the vertical expression of these escarpments along the Baton Rouge – Tepatate Fault system in profile view. This profile also shows a general representation of other growth faults within the basin that reach the surface to the south of the Baton Rouge – Tepatate system. The expression of these faults at the surface in coastal Louisiana cannot be imaged with LIDAR because they generally cross the marshes of south Louisiana where there is essentially no vertical relief. Instead there is simply a cumulative subsidence of the marsh surface on the "downthrown" side of the fault escarpment that results in the formation of an open body of water within the marsh.

Figure 22 illustrates the basic mechanics of faulting and the development of complex faults systems like those found in the subsurface of coastal Louisiana. These are "listric" faults, which are essentially

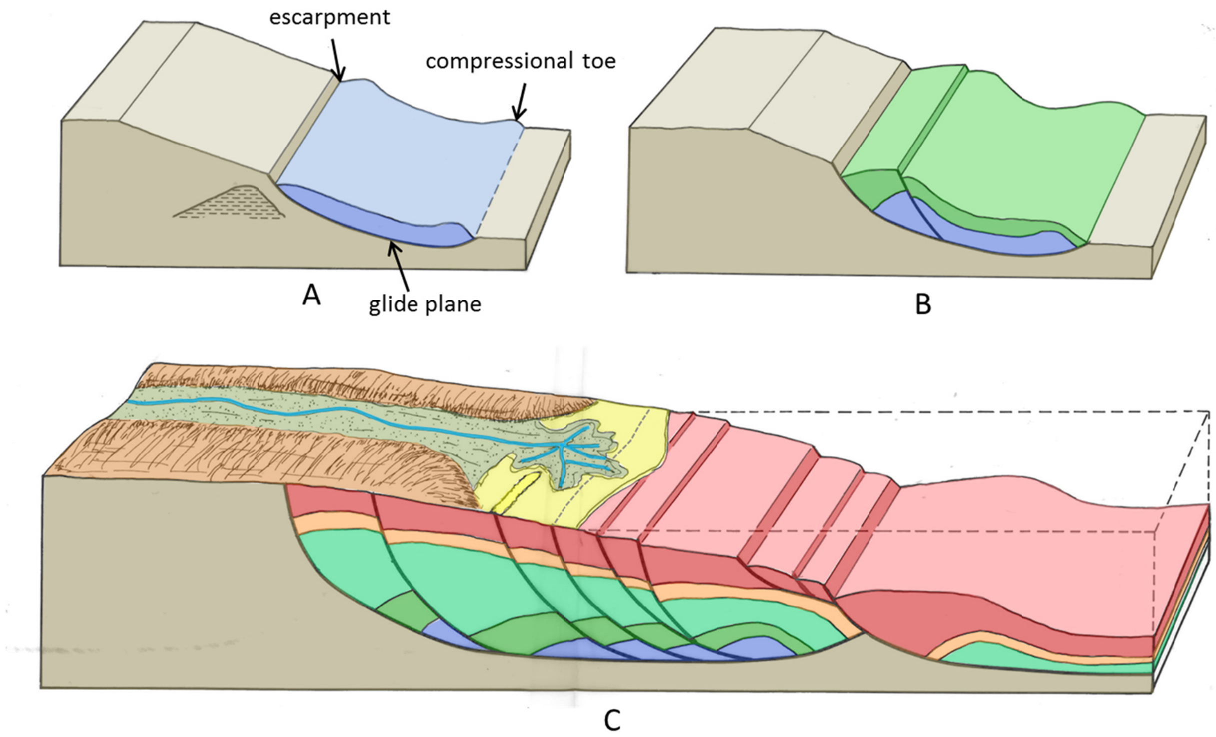


Figure 22

Sequential block diagrams show the development of a fault system. The initial slope failure in A has the essential elements of the glide plane, the head escarpment, and the compressional toe. As sedimentary layers are added in B and C the system becomes more complex with additional faults merging into the glide plane. Active sediment deposition by a delta is likely to be accompanied by episodic fault movement causing subsidence at the surface.

failures of the earth surface along a sloping slide (or glide) surface. Three fundamental elements of the listric fault are defined at the time of formation – the glide plane, an escarpment at the head of the fault, and a compressional "toe". As sedimentary layers are added, the fault system becomes more complex. Listric faults in south Louisiana are commonly called "growth faults" because the sedimentary layers thicken or grow due to the movement of the faults. Active faults that extend to the surface of the coastal wetlands generally have surface expression, and they cause local subsidence of the marsh surface. Gagliano described the development of "D-shaped" lakes in the marsh on the downthrown sides of surface faults where the fault escarpment is the linear stroke of the "D" and the lake is formed by the submergence of the marsh surface within the arc-stroke of the "D". Sharp lineations associated with faults may also be seen in wetlands adjacent to hardwood forests where the submergence of the downthrown side of the fault has killed off trees creating a distinct tree line adjacent to wetlands. Figures 23 and 24 illustrate these types of surface lineations associated with faults in south Louisiana.

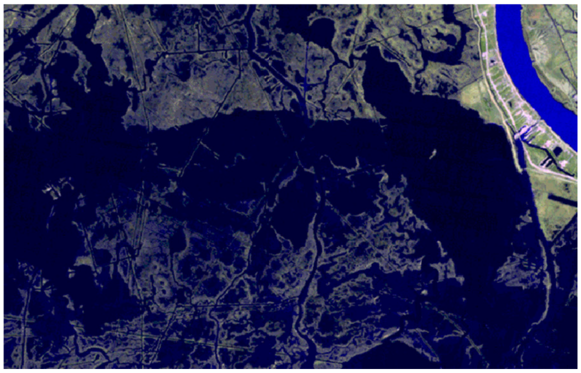


Figure 23

Sharp lineation in the marsh surface caused by the expression of the Empire Fault just west of the Mississippi River. 1992 Landsat Imagery

Figure 24

Lineation of the St. Rose Fault expressed as a tree line in the hardwood swamps near the I-310/Airline Hwy intersection west of New Orleans. Google Earth Imagery

Localized subsidence associated with faulting coupled with the compaction and lateral movement of clays distinguishes them from all of the previously discussed mechanisms of background subsidence. The elements of glacial isostatic adjustment, lithospheric flexure, sediment compaction and lateral salt movement are characterized by having a broad affect across the coastal plain that is not associated with any discrete manifestation of subsidence, such as the formation of a lake. Their effects may generally be grouped together in estimates of a combined value of the background subsidence, which can be measured as a relatively uniform rate over longer periods of time. It is quite probable that the estimates of subsidence derived from CORS measurements and attributed solely to the mechanism of lithospheric flexure by Dixon and Dokka, should be more correctly attributed to a general measurement of background subsidence attributable to some contribution from all of these background mechanisms. Conversely, subsidence caused by faulting and the lateral movement of clays usually has a very direct association with discrete manifestations of subsidence at the surface, and these may be grouped into the category of "hot spot" subsidence. It is also quite probable that higher values of subsidence measured over shorter periods of time by historical tidal gauge records, geodetic leveling surveys and InSAR data are indicative of hot spot mechanisms of subsidence. The association of higher rates of subsidence with the hot spot mechanisms will be discussed in more detail in the section on predictive modeling of subsidence. The most direct evidence of the association of the surface lineations that have been interpreted to be the expressions of faults and the fault planes that displace sedimentary layers at depth is from the vertical profile of the subsurface provided by seismic imaging technology. We propose that seismic imaging can be used to map faults that are impacting the surface of coastal Louisiana and causing hot spot subsidence.

REFLECTION SEISMIC IMAGING TECHNOLOGY

Reflection seismic is a subsurface imaging technology analogous to a sonogram in medicine. Both employ vibrational energy emitted form a source, which reflects off a surfaces where there is a change in density, and is recorded by an imaging device. In the sonogram, surfaces are differences in tissue density; in the case of seismic imaging, subsurface boundaries between sediment layers with different density. Reflection seismic has been an integral part of the oil and gas exploration in coastal Louisiana almost since its inception. Reflection seismic has also been adapted to geotechnical evaluation for major construction projects and offshore "shallow hazard" surveys. Research applications for interpreting shallow subsurface geology with high resolution seismic imaging have proven to be very effective, and are a primary focus of this proposal. The various types of utility for seismic data are primarily determined by the frequency of the acoustic signal emitted from the source. Standard oil and gas industry seismic data is generally intended to resolve images at depths between 3,000 and 20,000 feet. Onshore seismic wavelet frequencies are between 5 and 65 hertz (cycles per second). Shallow investigating seismic are at the other end of the spectrum. Compressed High Intensity Radar Pulse (CHIRP) sub-bottom profilers are intended to resolve images up to 100 feet below the surface. This type of seismic uses an acoustic FM pulse generated by computer in the equipment. The wavelet generated from these pulses can have frequencies between 2,000 and 16,000 hertz. Between these end members are imaging tools including "sparker" and "boomer" surveys. The deeper the focus of investigation that a seismic survey targets, the lower the frequency of the energy source that it will utilize and the lower the vertical resolution of its imaging will be. Oil and gas seismic surveys can normally resolve individual subsurface features no more than 20 feet in thickness. CHIRP surveys are capable of resolving subsurface features on a scale of 2 to 3 feet, but they can only image down to about 100 feet. Faults affecting the surface of the Louisiana wetlands have been imaged with both standard industry exploration seismic data and with high resolution CHIRP data being used in research efforts. We propose an integration of these technologies will most effectively gain a more complete understanding of faulting and its implications for subsidence and relative sea level rise.

CHIRP Sub-Bottom Profiler

Figure 25

CHIRP seismic equipment similar to that owned by UNO and discussed in the initial project proposal

Figure 25 shows a picture of the Edgetech SB-216 CHIRP seismic acquisition equipment. This is the equipment owned by the Coastal Research Laboratory at the Pontchartrain Institute for Environmental Sciences in the University of New Orleans that will be discussed in the specific project details of this proposal. CHIRP has been used in coastal research for several decades. Flocks et al. (2006)[12] used CHIRP profiles to study historical deltas of the Mississippi River now buried beneath the surface of Barataria Bay and the near offshore area. Figure 26 shows a CHIRP profile of an incised channel from one of those delta systems. The CHIRP data can be used to map out the configuration of these submerged delta lobes in more detail so that we may better understand the patterns of the delta cycle that formed the coastal wetlands. Similar incised channels were mapped by Rogers, Kulp, and Miner (2009)[43] in the ancestral St. Bernard Delta lobe that was active about 2,000 years ago and is now submerged below Chandeleur and Breton sounds. This is the same delta system in which Frazier documented a 2,100 year-old cypress stump on the banks of one of its distributary channels, as shown in Figure 7. Combining CHIRP profiling with age-date data is the most effective way to reconstruct the history of the coastal plain. Yeager et al. (2013)[52] used CHIRP data in the Pearl River Delta to map faults that extended to the surface of the delta wetlands. By combining the structural interpretation of the faults with radiocarbon and optically stimulated luminescence age-dating of sedimentary cores they were able to estimate rates of subsidence due to fault movement. They concluded that:

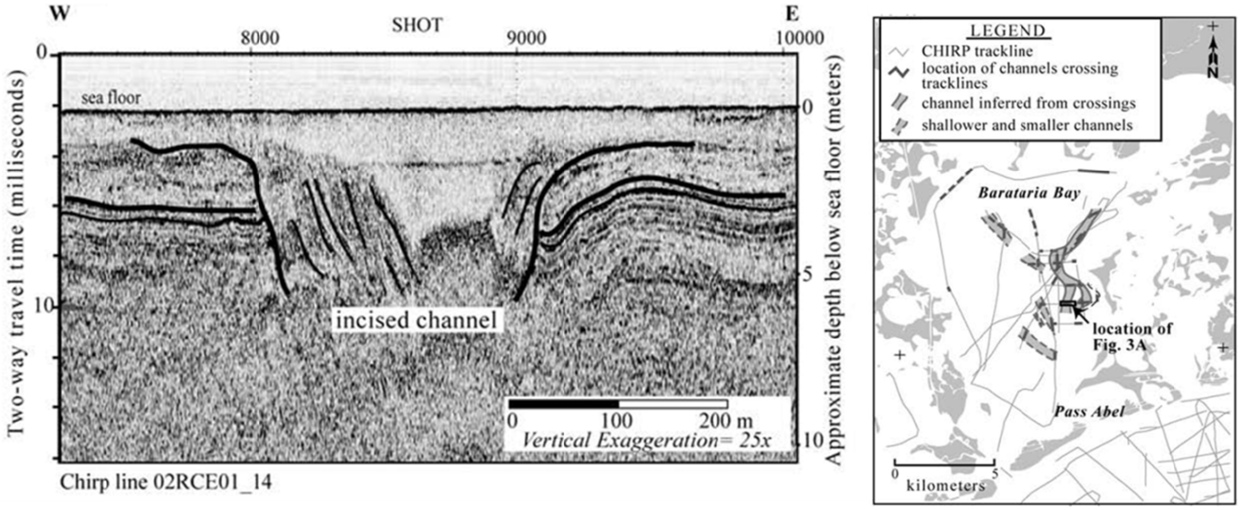


Figure 26

CHIRP seismic image of an incised channel from a submerged delta beneath Barataria Bay from Flocks, et.al., 2006 [12]

"Given the similarities in the geological structure and surface landscapes of, and human impacts on Holocene-age delta systems globally, we expect that these kinds of fault systems and their influences are prolific and represent a critically important but poorly characterized component of marsh sustainability."

While this study was effective in imaging shallow fault displacements on individual profiles, the interpretation was limited by the fact that the CHIRP data was acquired only within the channels of the delta, and the authors were only able to infer the trace of the faults across the surface by extrapolation.

Other authors have also used CHIRP data to map shallow faults in southeast Louisiana. Lopez et al. (1997)[25] documented faults reaching the surface of the bottom of the Lake Pontchartrain. Figure 27 illustrates the ability of the technology to allow for the accurate interpretation of the location of the fault, the timing and rate of its vertical movement, and therefore an estimation of the rate of subsidence caused by that vertical movement. This fault extends the bottom Lake Pontchartrain (at the location shown in Figure 21) vertically offsets the sedimentary layers below the lake bottom and causes a thickening of the sedimentary layers in the downthrown fault block to the left of the fault line on the profile. Lopez et al. concluded sedimentary layers accumulated contemporaneously with the vertical movement of the fault. If the sedimentary layers can be dated, then a rate of subsidence can be estimated for the time period. Using Figure 27 for example, if the sedimentary layer between B and C on this profile is 27 feet thick on the upthrown side of the fault and 38 feet thick on the downthrown side of the fault, then the fault caused 11 feet of thickening (and by inference approximately 11 feet of subsidence) during the period of deposition. If it could be determined that horizon C is 1550 years and horizon B is 1220 years then the subsidence of 11 feet took place over 330 years, or it had an average rate of motion of 0.4 inches (or 10 mm) per year. The quality the U.S.G.S. high-resolution seismic survey is impressive, however, the grid of data was not dense enough nor in the proper orientation to map the traces of faults across the bottom surface of the lake.

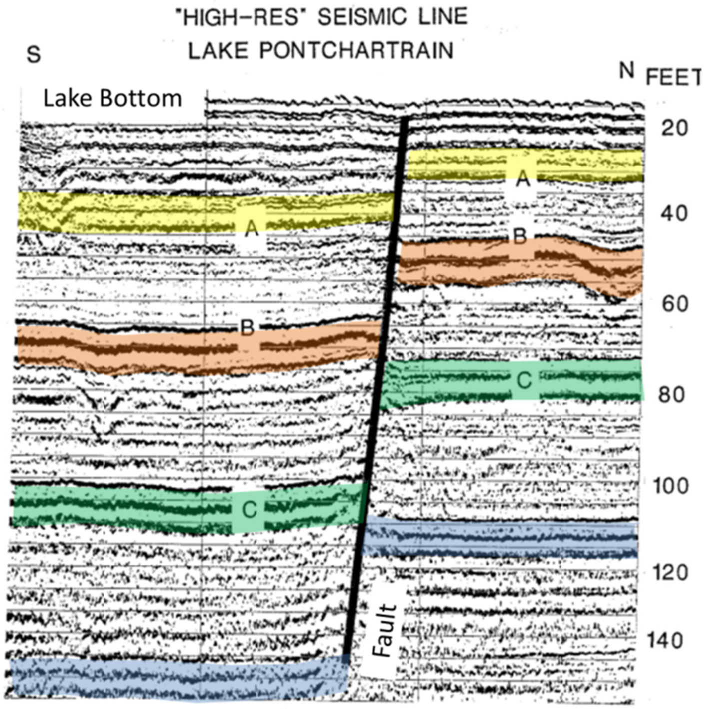


Figure 27

Fault imaged by a high resolution CHIRP seismic line from Lopez, et.al., 1997 [25]. Line location is shown on Figure 21

The Limitations of CHIRP

Roberts, Morton and Freeman (2008)[42] recorded the image (Figure 28) of a fault reaching the surface at the bottom of Lake Mechant in Terrebonne Parish. This image is also an excellent display of the relative thickening of the sedimentary layers (and therefore an inferred rate of subsidence) caused by an actively moving fault. The findings of this study actually had more negative implications for the use of CHIRP in coastal research than would be suggested by the imaging of this fault. The researchers utilized substantial volumes of seismic data that had been acquired over a three-year period. The image of the fault in Figure 28 was the only clear image of a fault that was captured in the entire data volume, and this points to the most significant limitation of CHIRP data in studying the shallow subsurface of coastal Louisiana. CHIRP seismic data must be acquired by towing equipment behind a boat. The minimum water depth necessary for effectively recording sub-bottom profiles with this equipment is about 6 feet. Roberts et al. were limited to acquiring data within the boundaries of lakes in the marsh that were at least this deep. This is the significant limitation to the ability of CHIRP to effectively image the shallow subsurface of coastal Louisiana. Open bodies of water in south Louisiana, deep enough to acquire CHIRP seismic data, are spatially inadequate to regionally map at the scales needed to assess faulting, subsidence and the submergence of the coastal plain by relative sea level rise.

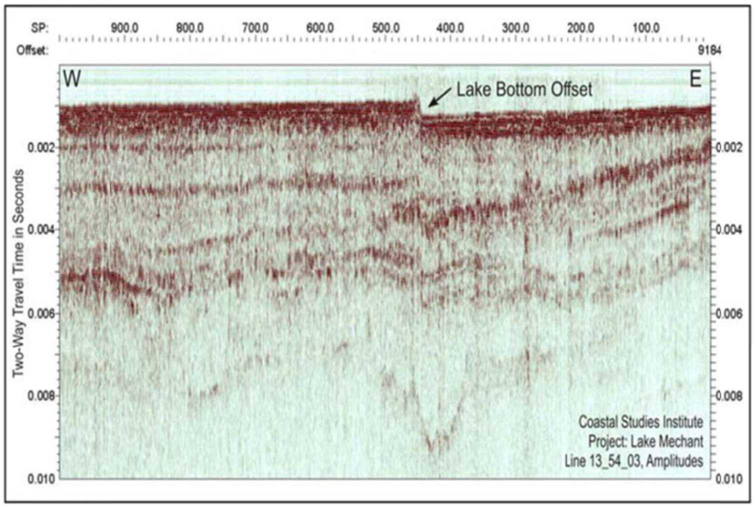
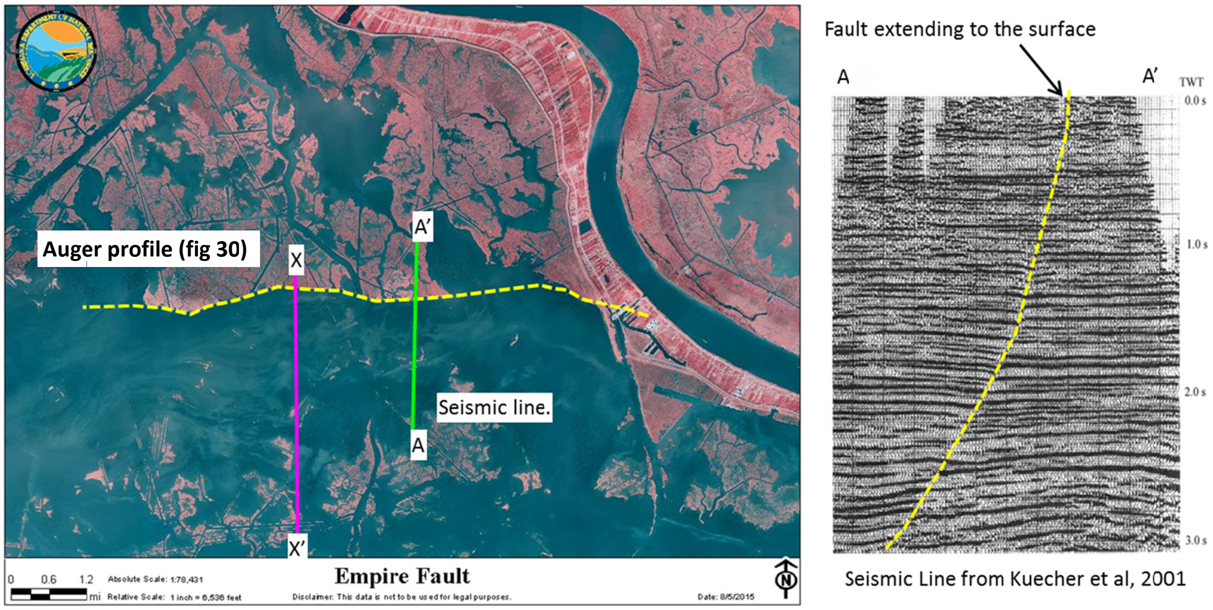


Figure 28

Fault offsetting the bottom of Lake Mechant imaged by a high resolution CHIRP seismic line from Roberts, et.al., 2008 [41]

Oil and Gas Industry Seismic Data in Mapping Shallow Faults

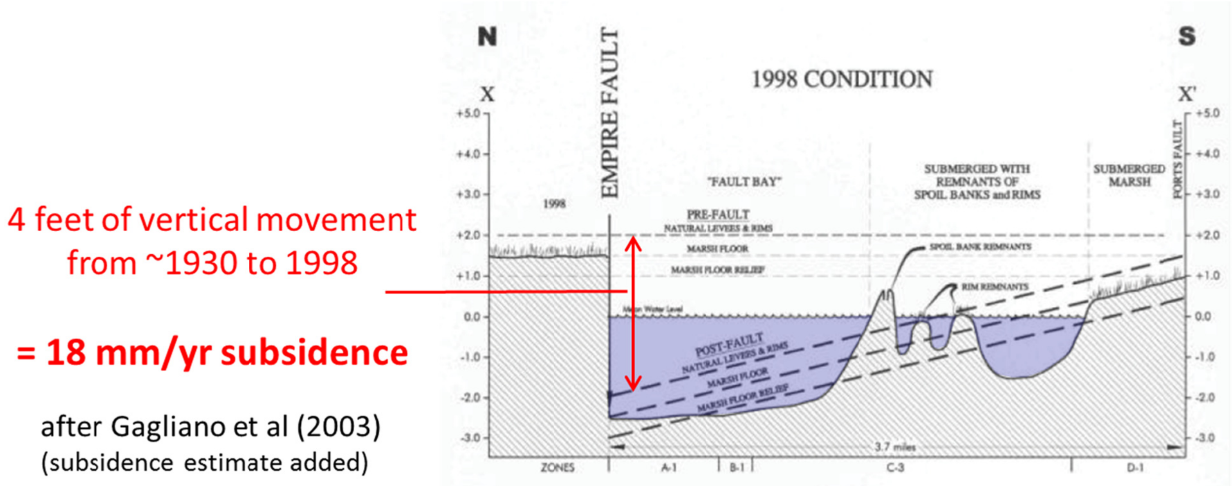
Kuecher et al. (2001)[23] were the first to use oil and gas industry seismic data to identify and map faults extending to and showing obvious expression in the surface of the wetlands. As shown in Figure 29, the faults may be imaged with seismic data because of the discontinuity is evident in the sedimentary layers across the fault. They mapped three well-established faults by the oil and gas industry – the Empire, Lake Hatch and Golden Meadow faults. These faults also offer excellent examples of surface expression by the sharp lineations and the formation of "D-shaped" lakes on their downthrown sides.



Seismic Line from Kuecher et al, 2001

Figure 29

Exploration seismic 2-D profile showing the Empire Fault as a yellow dashed line. The location of the line is shown as A-A'
The fault reaches the surface at the sharp lineaton in the marsh surface. From Kuecher et al. (2001)[23]



after Gagliano et al (2003)
(subsidence estimate added)

Figure 30

McCauley auger profile across the Empire Fault showing the rotational submergence of the original marsh surface by vertical movement on the fault, from Gagliano, et al. (2003)[15]. The location of the profile is shown as line X-X' on Fig 29. Subsidence estimates caused by vertical fault movement have been added to Gagliano's original diagram.

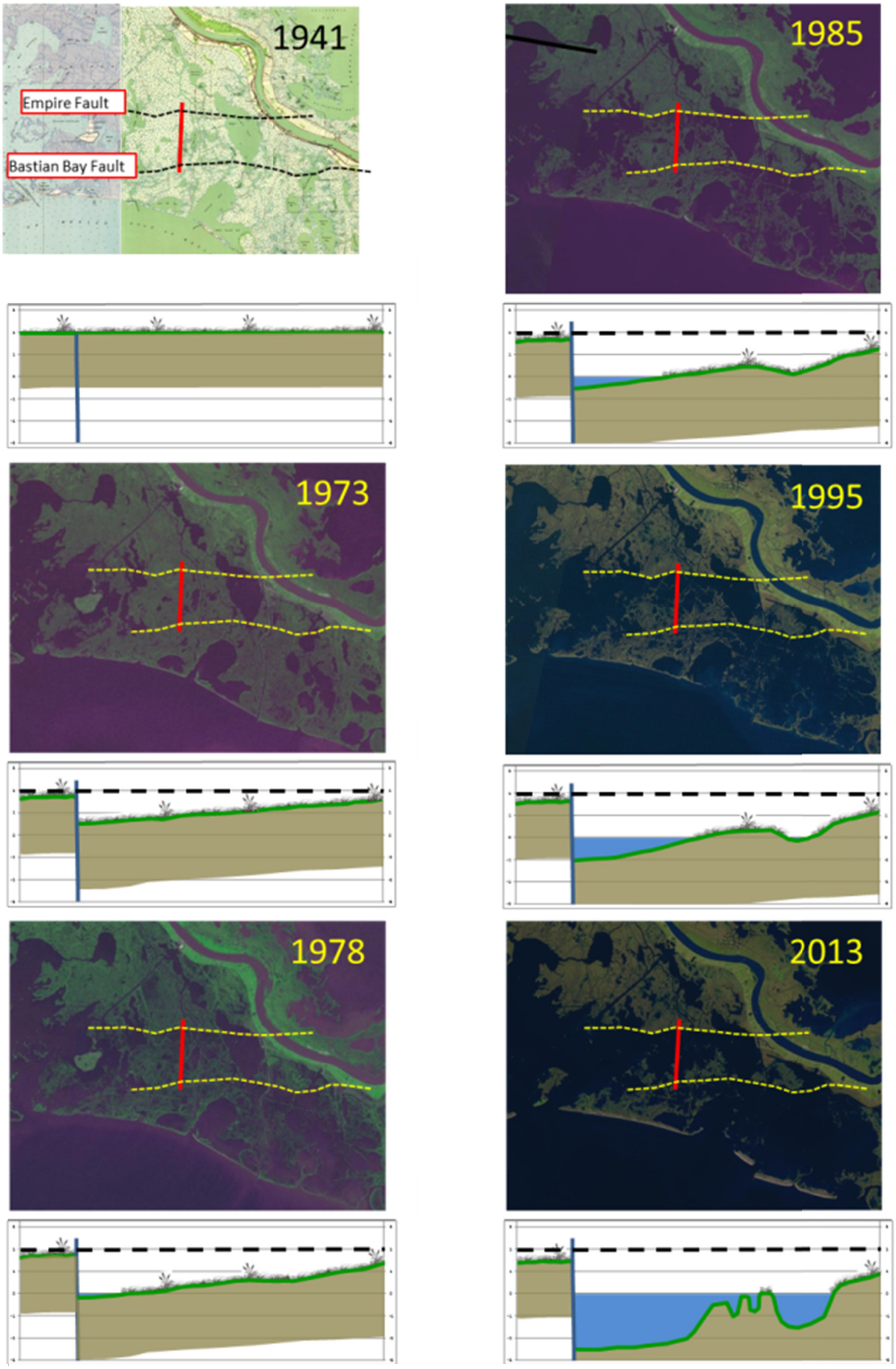


Figure 31

A time sequence of images showing the formation of the open body of water along the downthrown side of the Empire Fault. Each image corresponds to an underlying reconstruction of Gaglino's auger boring profile to the same point in time. The vertical movement of the Empire Fault causes the formation of the open body of water when the marsh surface reaches sea level, which progressively deepens as subsidence advances.

Following on Kuecher's study, Gagliano et al., using auger samples created a profile across the Empire Fault scarp, and demonstrated that the original marsh surface on the downthrown side of the fault had subsided about four feet from its original elevation by the time the cores were collected in 1998 (Figure 30). Gagliano compared aerial photography from 1971 to satellite imagery from 1998 to show that the lake along the downthrown side of the fault trace had been formed in 27 years. By using a more complete set of sequential imagery and assuming that the subsidence rate caused by the fault movement was consistent throughout the period in which the lake was formed, it is possible to reconstruct the profile to its likely configuration at a time coincident with each image in the sequence. Figure 31 shows the reconstruction of the original marsh surface back to a uniform elevation in 1941, the earliest available image for this evaluation. It is more probable that the elevation of the original marsh surface was maintained until the early 1930s, the time at which a complete levee system along the west bank of the Mississippi River would have effectively cut off the sediment supply to marsh. Prior to this time the distributary channels crossing this portion of the delta plain and the annual overbank flooding of the main river channel would have delivered a regular supply of sediment to the marsh allowing it to maintain a consistent elevation. In this situation even if the fault were actively subsiding, the sediment being delivered from the river would have filled in any depression that might be formed by subsidence due to fault movement. After the completion of the levees, and the cessation of regular sediment delivery, subsidence caused by vertical movement along the slide plane of the fault would have created a change in elevation across the marsh surface that was not filled in with sediment. What this sequence of images shows, however is that from a starting elevation of two feet above sea level it would have taken 40 years for the marsh surface to reach sea level. The 1973 satellite image therefore shows no apparent development of open water along the fault. From above it still looks like a uniform marsh surface across the fault plane. The fact that open water does appear on the 1978 imagery indicates that it only required a brief time interval after 1973 to submerge the marsh below sea level, and therefore the elevation of the marsh was probably very close to sea level in 1973. The same uniform rate of subsidence that brought the marsh surface from 2 feet above sea level in 1930 to just below sea level in 1978 continued to submerge the marsh until an open body of water with a depth of about 2 feet below sea level was formed by 1998. An average subsidence rate of 17 mm/yr can be estimated from these elevation changes.

The area south of Houma, Louisiana where Kuecher et al. mapped the Lake Hatch and Golden Meadow faults was coincident with an area investigated by Morton, Buster and Krohn (2002)[31]. Morton et al. used relative sea level rise values that had been interpreted from the historical records of several inland tidal gauges by Penland et al. (1989)[41]. The evaluation by Penland et al. was exactly the same as that used to evaluate subsidence using the record of the Grand Isle tidal gauge by Blum and Roberts in the construction of Figure 10 as discussed earlier. Neither the Penland nor the Morton group derived subsidence values from the relative sea level rise values estimated for these gauges, but a reasonable estimate can be made by simply subtracting an average global sea level rise rate of 3 mm/yr from the total relative sea level rise rate estimated for each gauge. The most important aspect of the Morton et al. evaluation is that they showed that relative sea level rise rates, and therefore implicitly subsidence rates can be represented a by a contour map of subsidence values across a portion of the coastal plain.

Figure 32 shows a side-by-side comparison of the map of surface fault traces generated by Kuecher et al. and the subsidence rate contour map generated by Morton et al. Kuecher et al. determined that the faults they had mapped using subsurface seismic images could be shown to:

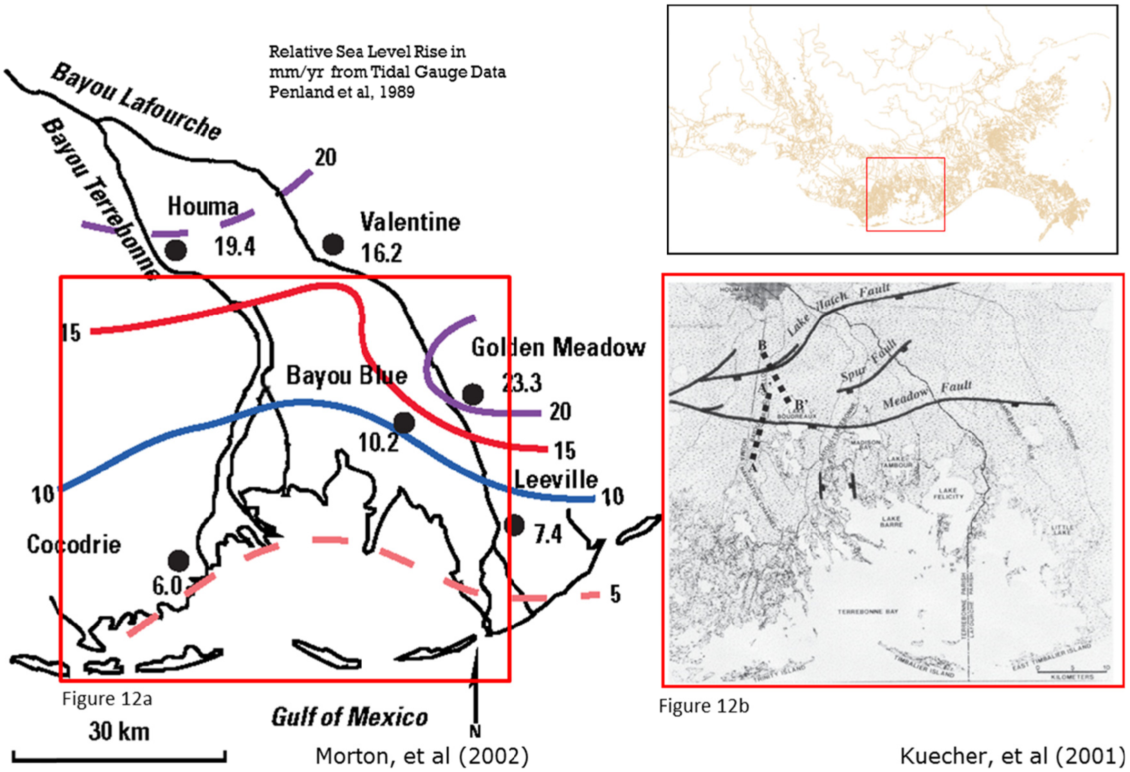


Figure 12a

Morton, et al (2002)

Figure 12b

Kuecher, et al (2001)

Figure 32

A side-by-side comparison of the contour map of relative sea level rise by Morton, et.al., 2002 [31] (using data from Penland, et.al., 1989 [41]) with the surface fault trace map from Kuecher, et.al., 2001 shows a strong correlation between the pattern of faults and subsidence

"identify major vegetation biozones, new areas of wetlands loss, and the position of transgressive lakes" (these would be coincident with Gagliano's "D-shaped" lakes).

They further determined that these surface expressions were the result of "active fault-induced subsidence in the downthrown block (of the fault)". The pattern of relative sea level rise contours mapped by Morton et al. is highly conformable with the pattern of the faults mapped by Kuecher et al., and it may be reasonably inferred that the values of relative sea level rise determined from historical tidal gauge data in this area is due to subsidence induced by the active movement on these faults. These areas are classic examples of hot spots of subsidence caused by fault movement.

3-D Seismic Surveys

All of the examples of both lower and higher resolution seismic data that have been discussed so far were acquired and displayed as linear profiles. These two-dimensional or "2-D" seismic lines are generally laid out in some form of a grid-like arrangement of lines so that individual lines can be "tied" at the points of intersection and interpretations of the subsurface can be carried throughout the grid. Each line in a 2-D grid is acquired, processed and imaged independently. Interpretations across areas covered by 2-D seismic grids require interpolation across areas between the lines, and such interpretations are inherently incomplete. Advancements in acquisition technology and computational capacity by the 1990s allowed for the acquisition of exploration seismic data in three-dimensional grids, in which shot holes and recording devices were laid out in orderly arrangements, and all of the data was combined into a data volume prior to processing and display. The obvious advantages of 3-D seismic surveys are that the data volume generally provides an nearly complete and unbroken image of the subsurface under the area covered by the grid, and images of the data can be displayed in a wide range of orientations including any vertical azimuth, as a horizontal slice, or in a variety of three-dimensional cube-like images. A significant majority of the subsurface underlying coastal Louisiana has been imaged by 3-D seismic data over the past three decades (figure 34). To date the utilization of 3-D seismic data to aid in the mapping of shallow faults has been virtually nonexistent.

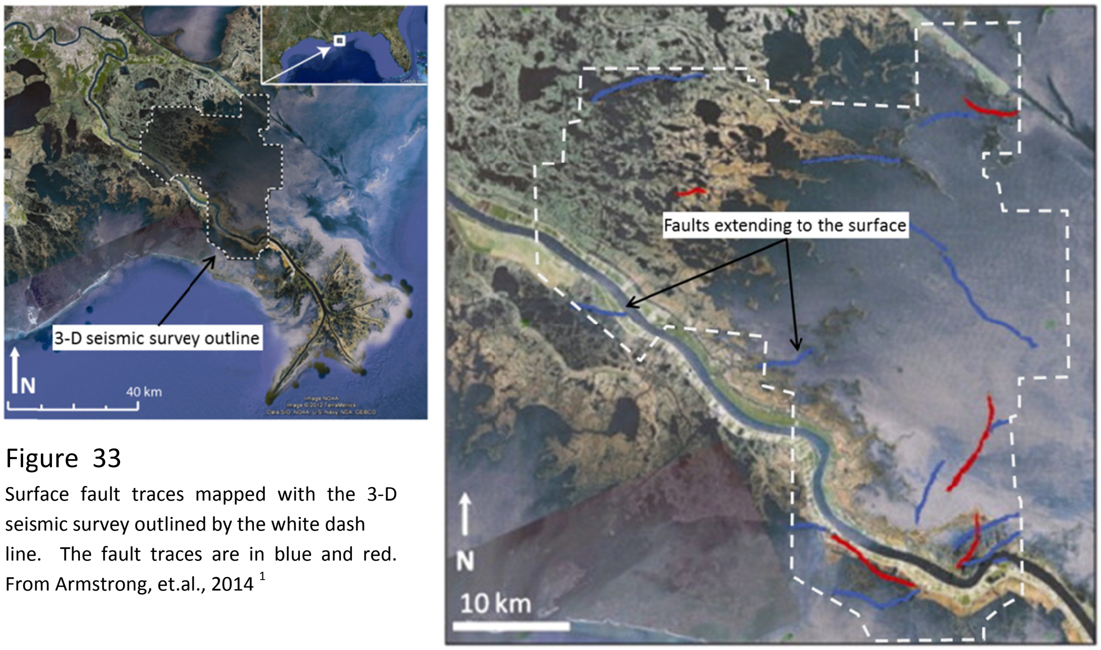


Figure 33

Surface fault traces mapped with the 3-D seismic survey outlined by the white dash line. The fault traces are in blue and red. From Armstrong, et.al., 2014 [1]

The first case of a 3-D seismic survey to be used in the mapping of shallow faults for academic research purposes resulted in a 2014 publication from Armstrong et al.[1] to study the interplay between the morphology of ancestral channels of the Mississippi River and the active growth faults that they crossed. They utilized a 530 square-mile 3-D survey donated to the universities by Western-Geco, now a division of Schlumberger. The survey had originally been acquired in the delta wetlands of St. Bernard and Plaquemines parishes for oil and gas exploration. These researchers were able to map river channel deposits and shallow faults within the data volume. They mapped twenty-eight individual faults, and found that most of the faults imaged appeared to extend to the surface. As illustrated in Figure 33, taken from their publication, they found that:

"several of these faults correspond to abrupt shifts from emergent wetlands to fully submerged areas of open water on the delta surface."

In other words, they found that the surface traces of the faults defined sharp boundaries between marsh surface and open bodies of water, as envisioned in Gagliano's description of a "D-shaped" lake. It is obvious from this interpretation that 3-D seismic surveys can be used to map faults that extend to the surface of the wetlands, and that in many cases the traces of those faults may explain the formation of open bodies of water in the marsh due to subsidence. If this capability to map faults could be expanded to the ability to map the rate of subsidence being caused by fault movement, then significant progress could be made in assessing the impacts of relative sea level rise in coastal Louisiana due to subsidence.

USING OIL AND GAS INDUSTRY 3-D SEISMIC DATA TO MAP SHALLOW FAULTS

There is clear evidence that the vertical movement of faults which extend to the surface in coastal Louisiana is a primary cause of the patterns of hot spot subsidence. These patterns of subsidence have been recognized by several of the most important methods of measurement, and short-term rates are estimated to be as high as 29 mm/yr., or about 11 inches per decade. Peer-reviewed scientific studies have shown that these shallow-cutting faults can be imaged with both lower frequency, lower resolution oil and gas industry seismic data and with higher frequency, higher resolution CHIRP research data. Each of these subsurface imaging technologies offers specific desirable attributes of interpretation, and taken together it would appear that they could be used as complimentary data sets that each provide attributes that the other does not. Keucher et al. (2001)[23] were able to show that the faults they interpreted to be affecting patterns of vegetation and land loss at the surface were the same faults that had been mapped at depth in previous oil and gas exploration efforts. The deep imaging capabilities of the lower frequency data allows for this type of interpretation of the geologic history of a fault. It is likely that detailed studies of faults like those mapped by Keucher's group will reveal patterns of episodic movement that have resulted in variable rates of subsidence through time. Kulp, Roberts, Lopez and their coauthors were able to image the shallow portions of other faults with striking accuracy and resolution. By using CHIRP data, it appears to be possible to interpret detailed patterns of fault movement in the recent past that could provide for reasonable estimates of rates of subsidence. While the acquisition of CHIRP data has limitations, the acquisition of industry seismic data has not been limited by surface geography or topography, and 3-D surveys are widely available across the coastal plain.

The premise of this proposal is that in order to properly assess the likely future impacts of relative sea level rise on the most important infrastructure of the oil and gas industry in south Louisiana it will be necessary to define the relationship between shallow faulting and the subsidence component of relative sea level rise. The essential first step in this assessment will be an accurate mapping of the location of shallow faults across the coastal plain. Oil and gas industry seismic data has been shown to be the most reliable means of achieving a general mapping of shallow faults across broad areas of southeast Louisiana, but the shallow resolution of the readily available data is inadequate for detailed mapping and subsidence rate estimation. This proposal will describe a general methodology by which the existing 3-D seismic surveys covering south Louisiana could be utilized to accomplish the objective of effectively mapping faults and estimating associated subsidence through a set of inter-related research projects. The initial project conceived under this proposal will be described in some detail, and will be used as a model test case that will serve as a basis to develop other projects.

South Louisiana 3-D seismic surveys

The ownership of 3-D seismic data in south Louisiana varies on a survey-by-survey basis, but generally falls into one of two categories – proprietary and speculative surveys. Speculative 3-D surveys have been acquired by geophysical companies for the purpose of licensing the data to third parties. Geophysical companies such as Western-Geco, Seismic Exchange, Seitel and Geophysical Pursuit usually have the technological capability to oversee the field acquisition and processing of the data, and they prepare a user-ready seismic survey for delivery to the licensing third party. The third parties to which the data is licensed are generally oil and gas companies that intend to utilize the data for exploration or oil and gas field evaluation. Proprietary 3-D surveys have generally been acquired by a single entity or a consortium of entities for the purposes of evaluating a specific area with the intention of retaining exclusive ownership of the data. There has been a tendency over time for proprietary surveys to be purchased by the geophysical companies and integrated into the data libraries that they make available for license. A significant proportion of south Louisiana is now covered with 3-D seismic surveys that are owned by the four principal geophysical companies listed, as shown in Figure 34. The essential connection between the geophysical companies and the third parties is the license agreement document. This document defines an intellectual property license to use the data for specific purposes. In executing the license agreement the third party agrees to the terms and conditions under which the data may be used, who may have access to the data, and how it may be shared with others. The utilization of 3-D seismic data for academic research purposes, as will be proposed here, is also covered by a license agreement that defines the same type of terms and conditions for its use. The volume of 3-D seismic data that is necessary for the type of research being proposed here could be limited to a depth of 5,000 or less. The objective of this research is initially to interpret the shallowest portions of the data volumes in an attempt to map faults and potentially estimate subsidence rates. In nearly every case the shallower portions of the subsurface that have been imaged by 3-D seismic surveys in south Louisiana have very little, if any, exploration potential. Limiting the data volumes that are licensed to research institutions to a shallow depth range in the projects envisioned by this proposal should help to facilitate the academic licensing process.

Seismic reprocessing for shallow interpretation

Advances in computing technology brought about the advent of 3-D seismic surveys for oil and gas exploration. Processing of the raw data is as significant as the acquisition of the data itself, and the manner in which a survey is processed can fundamentally determine what the final product is capable of imaging. In south Louisiana the primary objective of acquiring oil and gas exploration surveys is to provide for optimal resolution at depths between 5,000 and 20,000 feet where the exploration targets are likely to occur. In order to most effectively use exploration seismic surveys to map shallow faulting it

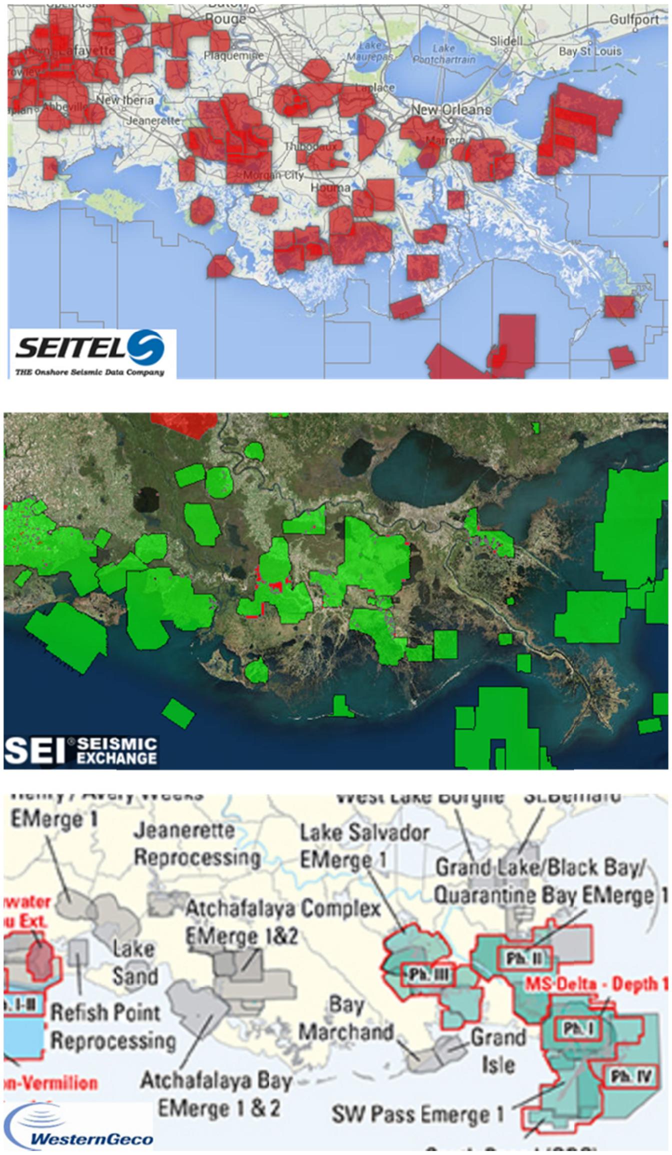


Figure 34

Coverage of southeast Louisiana with 3-D seismic surveys owned by three major geophysical companies – Western-Geco (division of Schlumberger), Seismic Exchange, Inc. and Seitel

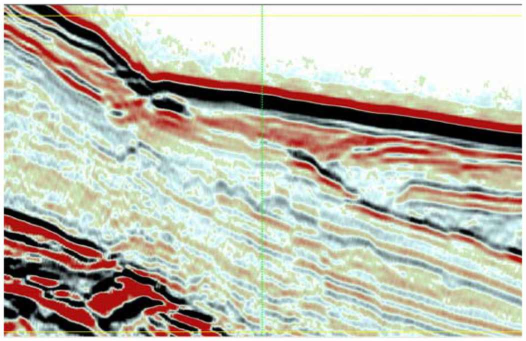


Figure 2: 3D seismic cross section with conventional processing (2000-2500 ms)

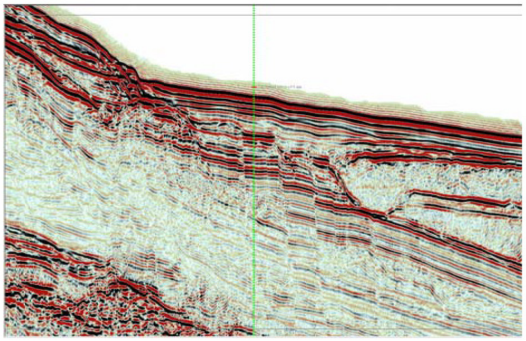


Figure 3: High resolution 2D seismic cross section

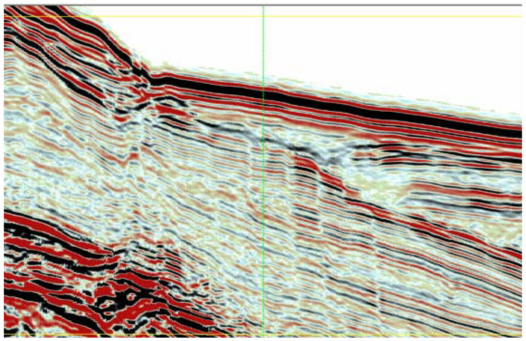


Figure 4: 3D seismic with high resolution reprocessing

Figure 35

Panel from Rollins, et.al.,2010 [44] showing conventional processing of 3-D seismic at the top, a standard high resolution 2-D seismic line in the middle, and a reprocessed version of the 3-D data on the bottom. The enhancement of resolution and frequency content rivals the 2-D line

may be necessary to re-process the data to optimize shallow resolution. There is substantial precedent for the successful employment of this type of reprocessing.

The Bureau of Ocean Energy Management (BOEM) and its predecessor the Minerals Management Service (MMS) have required the submission of a shallow hazard survey report covering the location of each proposed well, facility or pipeline in the Federal outer continental shelf (OCS) waters. Until the relatively recent past shallow hazard surveys included shallow-imaging high resolution seismic profiles that were acquired separately from exploration seismic surveys. In 2008 the MMS changed its regulations to allow for operators to substitute the high-resolution subbottom profiler and medium penetration seismic profiler information with existing 3-D seismic surveys that had been reprocessed to allow for adequate shallow resolution. An example of the effectiveness of reprocessing in improving the shallow resolution of 3-D seismic data to allow for utilization in a shallow hazard survey was presented by authors from BP and TGS at the 2010 Society of Exploration Geophysicists convention (Rollins et al. (2010)43)). The panel of seismic images in Figure 35 shows the conventional 3-D seismic processing on the top, a standard high-resolution subbottom profile in the middle and the reprocessed 3-D seismic data on the bottom. There is an obvious dramatic improvement in the resolution and frequency content in the reprocessed 3-D that closely approximates the high-resolution subbottom profile. These authors noted that the reprocessed data had the added benefit of being a 3-D data volume as opposed to the 2-D grid of profiles in the shallow hazard survey.

Many of the same reprocessing algorithms that have been effective in improving the shallow resolution of seismic data in the OCS can be applied to 3-D surveys that were acquired in coastal Louisiana. The principal objective in reprocessing these surveys is to allow for the accurate mapping of shallow faults, and the possibility in some cases of being able to estimate historical rates of fault movement and associated subsidence. Given this well-defined set of objectives the reprocessing algorithms can be specifically designed to optimize imaging of the upper 5,000 feet of the subsurface. This can be best achieved through four fundamental elements of reprocessing that may be different from the standard algorithms for exploration data.

1. **5-D Interpolation** – this standard component of seismic processing is used to attempt to fill in deficits in spatial sampling along five seismic data dimensions (inline, crossline, offset, azimuth, and frequency). In shallow onshore data 5-D interpolation is most likely to be used to fill in shallow data gaps that have been caused by surfaces obstacles in the acquisition of the data. These shallow gaps are less important in standard deep interpretation, and filling them in with interpolation can be a significant enhancement to shallow resolution.

2. **Frequency filtering** – a broad range of frequencies is very significant in attempting to optimize shallow resolution relative to standard processing. The “high-cut” filter applied in standard data processing may filter out frequency content that is valuable in shallow imaging. The proper low-cut filter is also critical to preserving signal while reducing ground roll and surface noise.

3. **Refraction statics** – surface conditions in coastal Louisiana often require the application of refraction statics to correct differences in arrival times of the seismic data. These are essential to both standard processing and shallow high resolution processing in determining subsurface structure and faulting.

4. **Velocity analysis** – this is likely to be the processing component that offers the greatest opportunity for enhanced shallow resolution. The density of velocity “picks” that control the

outcome of processing is generally focused around the interval in primary interest for a given processing flow. Simply increasing the density of picks in the shallow data can dramatically improve the resolution of the data.

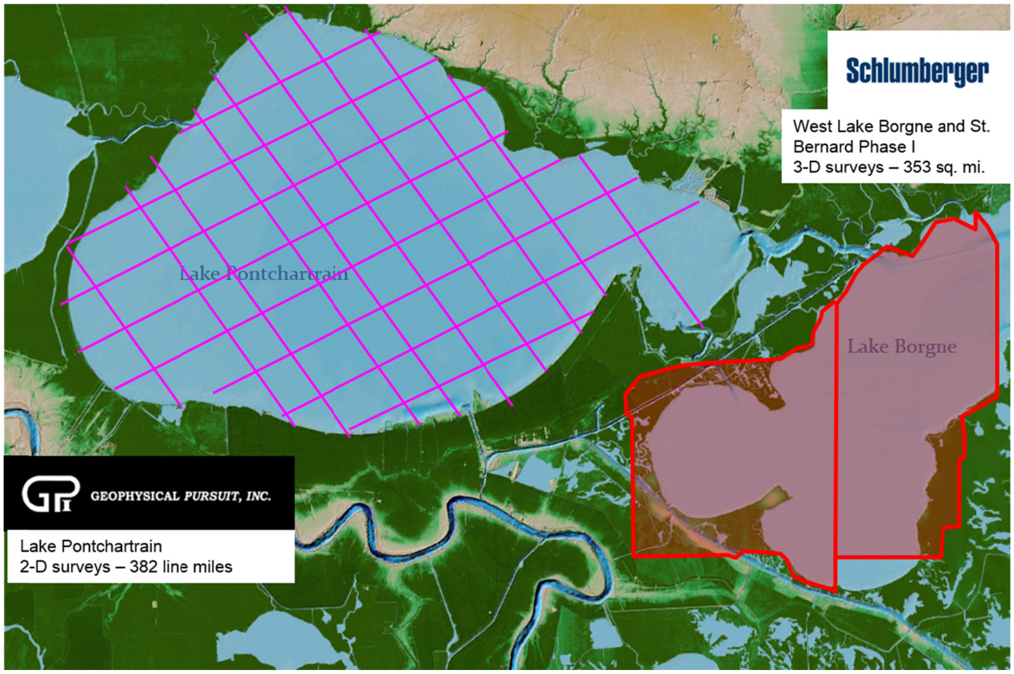
Improving the shallow resolution of 3-D seismic data in coastal Louisiana is by far the most effective means by which to do an assessment of hot spot subsidence due to faulting and its potential impacts on coastal infrastructure. Reprocessing of the 3-D survey that will be discussed in the initial project proposal is by far the most expensive component of the proposal. This initial project is intended to serve as a test case on which to judge the relative merits of a larger scale reprocessing program. If a larger scale program were to come to fruition, it would not only allow for the detailed mapping of faults, it would bring about a new paradigm in coastal research. The ability of get high resolution images of the near subsurface would have wide-ranging applications in earth and environmental science research as well as geo-tech engineering and infrastructure planning.

INTITIAL PROJECT – NEW ORLEANS EAST LAND BRIDGE

We have initiated the New Orleans East Land Bridge Project. The two seismic surveys (Figure 36) have been donated to the Coastal Research Laboratory of the Pontchartrain Institute for Environmental Sciences at the University of New Orleans (UNO). Western-Geco, a division of Schlumberger, donated its St. Bernard Phase I and West Lake Borgne 3-D seismic surveys. This data volume is limited to 1500 milliseconds 2-way travel time (about 5,000 feet) and intended for shallow subsurface research.

Figure 36

A 2-D seismic grid donated by Geophysical Pursuit and two 3-D seismic surveys donated by Schlumberger will provide the basis for the Land Bridge Project. Base imagery from the NOAA Louisiana Coastal DEM



New Orleans Digital Elevation Model

Geophysical Pursuit, Inc. donated its 2-D exploration seismic grid in Lake Pontchartrain. This grid is the latest vintage and highest quality seismic data available in the Lake. Under the direction of Dr. Mark

Kulp, the Land Bridge Project will consist of four primary research components. The essential first step of this proposal is to bring together a consortium of oil and gas industry partners to fund these components. A budget and funding estimates for each component are presented in Table 1.

Component 1 – **Subsurface mapping with exploration seismic data**

Thesis research projects for two M.S. degree candidates and one Ph.D. degree candidate that will include subsurface mapping and fault interpretation utilizing the seismic surveys in Lake Pontchartrain and Lake Borgne. Funding for this component will include stipends and tuition for each student, salary contribution for faculty, university administrative cost, and payment to research partner the Lake Pontchartrain Basin Foundation for GIS mapping support.

Component 2 – **CHIRP seismic acquisition and interpretation**

Each of the three thesis research projects may include acquisition of high resolution CHIRP seismic data. The CHIRP data will be acquired at various points throughout the span of the project. Primary acquisition will utilize equipment and technology owned by the UNO Coastal Research Laboratory. Additional equipment may be leased for data acquisition requirements specific to each thesis project. We want to acquire sufficient CHIRP coverage in the Project Area to enhance faults mapped with exploration seismic data, estimate subsidence rates on the faults, and compare CHIRP with the high resolution reprocessing of the exploration seismic data. Funding for this component will include the cost of operating the UNO equipment and the potential cost of leasing additional equipment to be used on those deployments.

Component 3 – **High resolution reprocessing of exploration seismic data**

This component will advance independently of the thesis research projects, but will contribute to each of them upon completion. The reprocessing will be bid out to third party contractors. This will be the most expensive component of the project, but essential for the integration of the reprocessed data into the individual thesis research projects. The assessment of the reprocessed data relative to the results of the acquired CHIRP seismic data will determine the future utility of high resolution reprocessing as a tool for coastal research. Funding for this component is represented in table 1 as an initial cost estimate.

Component 4 – **Sedimentary core collection and analysis**

Accurate interpretation of the subsurface with seismic data fundamentally relies on a determination of the lithostratigraphy, biostratigraphy, sedimentology, radiochemistry and age-dating of the sedimentary layers that have been imaged by the seismic data. Each thesis project may include the collection and analysis of cores, collected in shallow water, marsh or dry land within the Project Area. Funding for this component is represented in table 1 as an intermittent series of collection and analysis efforts.

The “Project Area” for the initial test project of this proposal is shown in Figure 36. This area surrounding the New Orleans East Land Bridge was chosen for several important reasons:

1. The peer-reviewed literature has established multiple instances of faults expressed at the surface, estimated rates of subsidence caused by fault movement, and documented direct impacts on infrastructure by fault-driven subsidence within the Project Area.

2. The surface geography in the Project Area provides a unique opportunity to study patterns of faulting. Lakes Pontchartrain and Borgne are optimal for acquiring CHIRP data, and straddle the Land Bridge. The established faults appear to run perpendicularly across the Land Bridge and extend out into both bodies of water.

3. Oil and gas industry exploration seismic surveys exist in lakes Pontchartrain and Borgne. This will allow for a complementary interpretation of the faulting with both exploration seismic data and CHIRP data. It will also provide the perfect scenario to evaluate the effectiveness of reprocessing the exploration seismic data because it can be directly compared to the CHIRP data.

4. The Project Area is immediately adjacent to the city of New Orleans, and it includes some of its most critical flood protection and transportation infrastructure. While the principal objective of this proposal is to assess the impacts of relative sea level rise on oil and gas industry infrastructure across the coast, this initial project can immediately achieve the broader goal of providing assessments that are applicable to multiple entities across the coast.

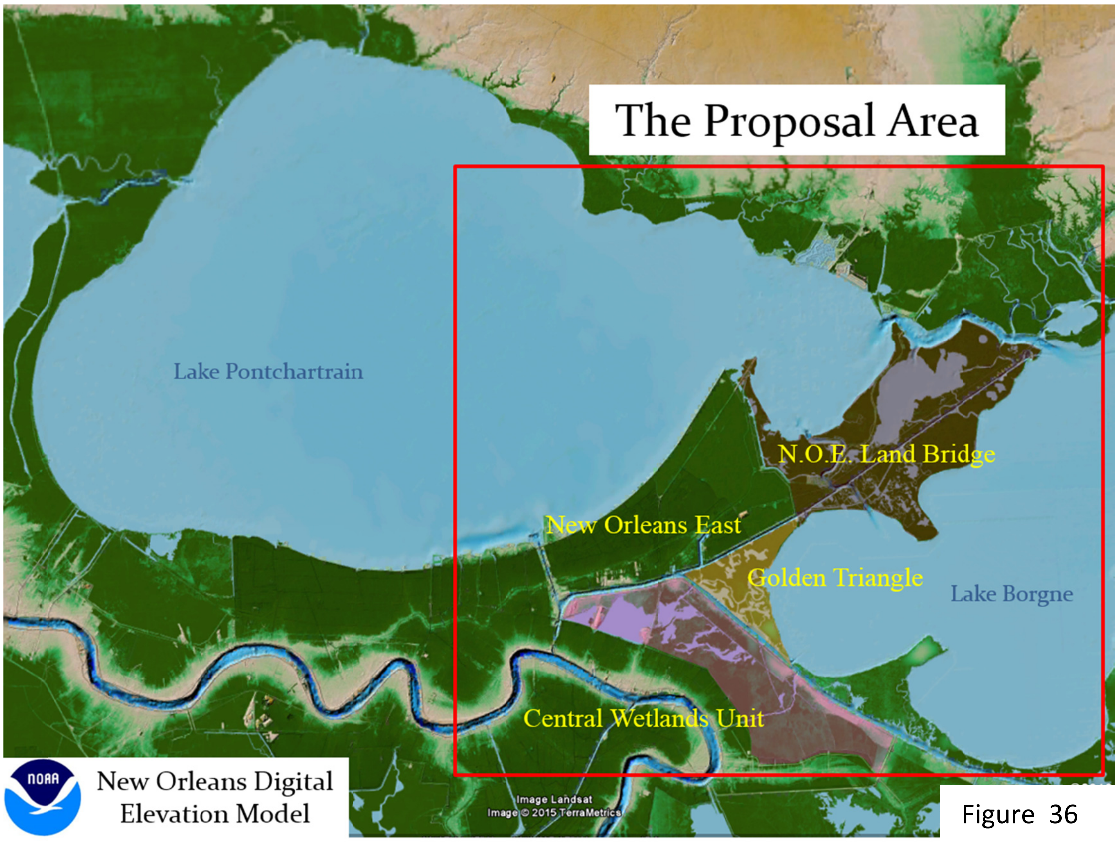


Figure 36

Previous Research

Figure 37 shows the general outlines of the areas studied by Haggar, Kulp, Lopez, Dokka and their coauthors. Each of these studies examined the relationship between faults that could be imaged at the surface and the subsidence that they were interpreted to be causing. Figure 37 suggests a pattern of "en echelon" faults that parallel to the Baton Rouge – Tepatate Fault System, north of Lake Pontchartrain. The patterns of subsidence measured with InSAR data by Dixon et al. (Figure 14) covered the western portion of the Land Bridge, and were used by Dokka in his 2011 study to interpret two of these faults. Kulp, Lopez and their coauthors used CHIRP seismic data to map faults. They estimated rates of subsidence due to fault movement between 0.16 mm/yr. and 2.5 mm/yr. The subsidence rates measured by InSAR along the faults mapped by Dokka were between 6 and 12 mm/yr. These studies provide a solid foundation on which to expand research of faulting and fault-driven subsidence.

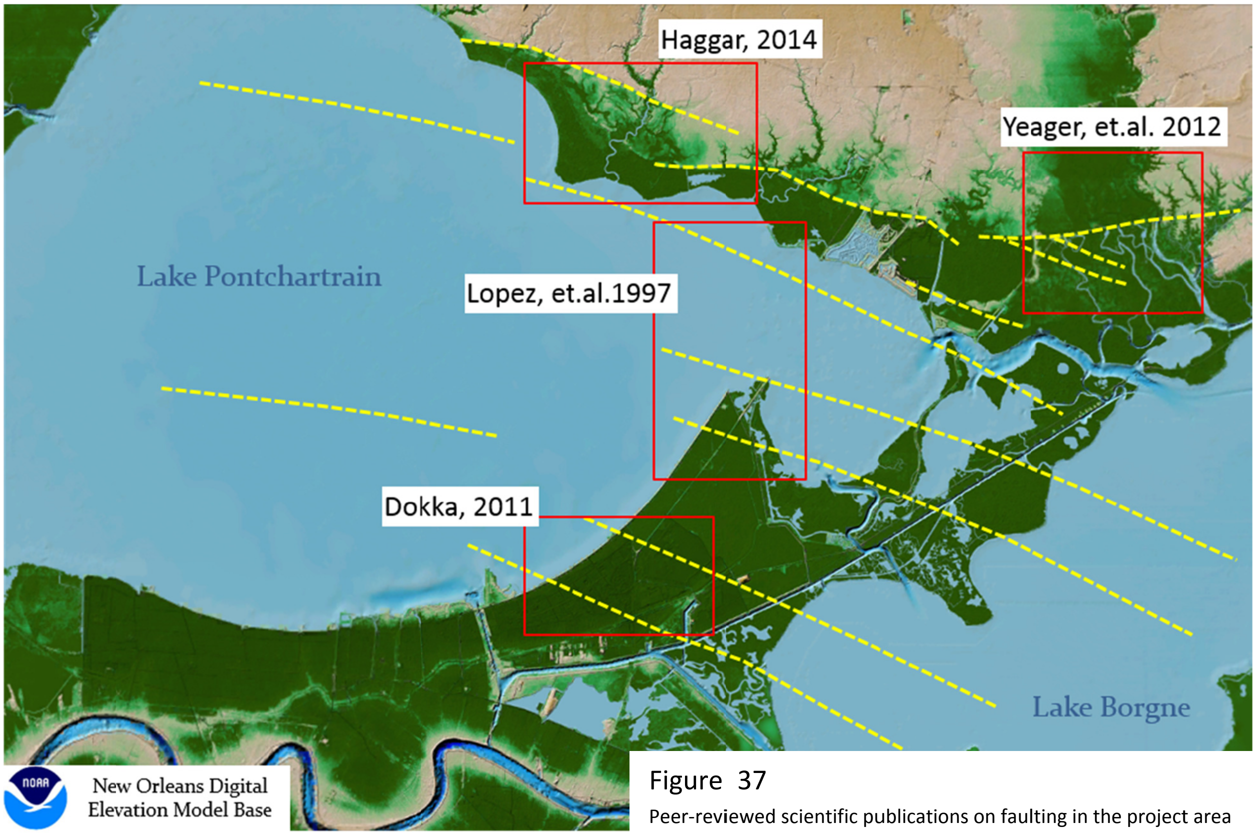


Figure 37
Peer-reviewed scientific publications on faulting in the project area

PREDICTIVE MODELLING OF SUBSIDENCE AND ITS IMPACT ON COASTAL INFRASTRUCTURE

Thus far, our proposal has utilized peer-reviewed literature. However, there are no published peer-reviewed studies that combine the interpretation of faults extending to the surface with measured rates of subsidence at the surface on a regional scale. Furthermore, we find no studies that attempt to use measured rates of subsidence to predict the impact of subsidence on the landscapes of the future. Therefore, we offer a set of interpretations that are a first order approximation of what a regional fault atlas and a subsidence predictive model may look like. These are visual predictive models that could be developed as a result of the academic research in our proposal. They are not actual regional maps or predictive models, but offer the possibility that these visual representations will make it easier to discuss the importance of attempting to develop real predictive models with which to assess coastal infrastructure.

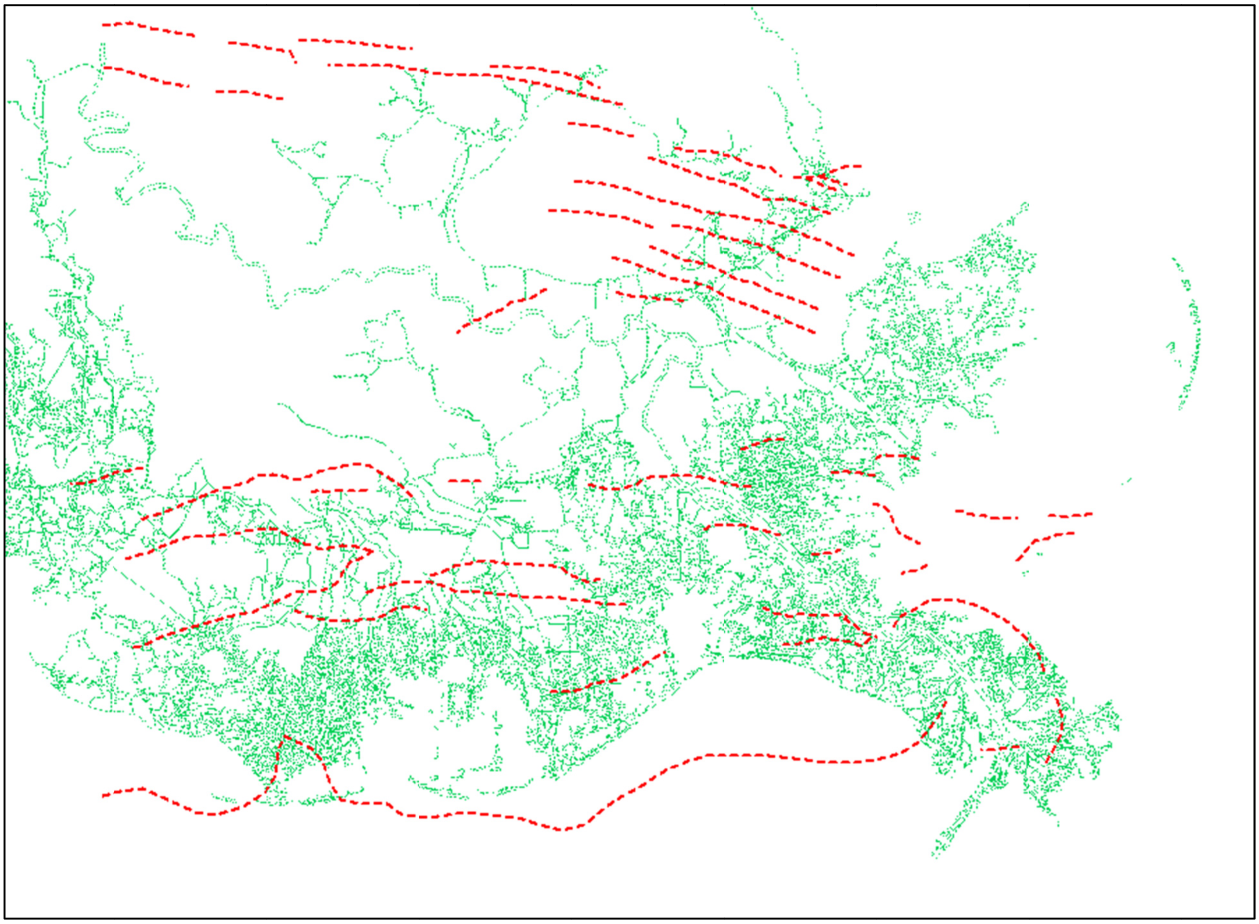


Figure 38

First-order approximation of what a surface fault atlas may look like. Surface fault traces are shown as dashed red lines

Regional Surface Fault Trace Map

Constructed from a combination of sources, Figure 38 is a first order approximation of how a regional surface fault trace map in the proposed atlas might look. Once a “critical mass” of interpretation derived from academic research projects conceived and funded under this proposal has been reached, they can be published in a regional atlas and used widely for further academic research and infrastructure planning.

1. All of the surface fault traces from published peer-reviewed scientific studies with some contribution from unpublished maps from academic study.

2. Surface fault traces that have been recognized by NOGS geoscientists, but have not been published as peer-reviewed scientific studies

3. Extrapolations and extensions of the surface fault traces published in peer-reviewed studies beyond the limits of the study based on some indication of a continuation of the surface lineation associated with the fault

4. Extrapolations of deeper subsurface fault interpretations either from peer-reviewed scientific studies or unpublished subsurface interpretations that are a part of the general oil and gas industry knowledge base of the subsurface of south Louisiana. In general these extrapolations of faults to the surface have been made because of a proximal relation between the orientation of the fault in the subsurface and some form of linear expression at the surface. The most common of these linear expressions are the northern linear shorelines of lakes in the marsh that were generally described by Gagliano's examples of "D-shaped" lakes.

5. The inference of the existence of a surface fault trace by a linear surface feature that is highly correlative to other linear surface features that have been associated with surface fault traces by other scientific study or interpretation.

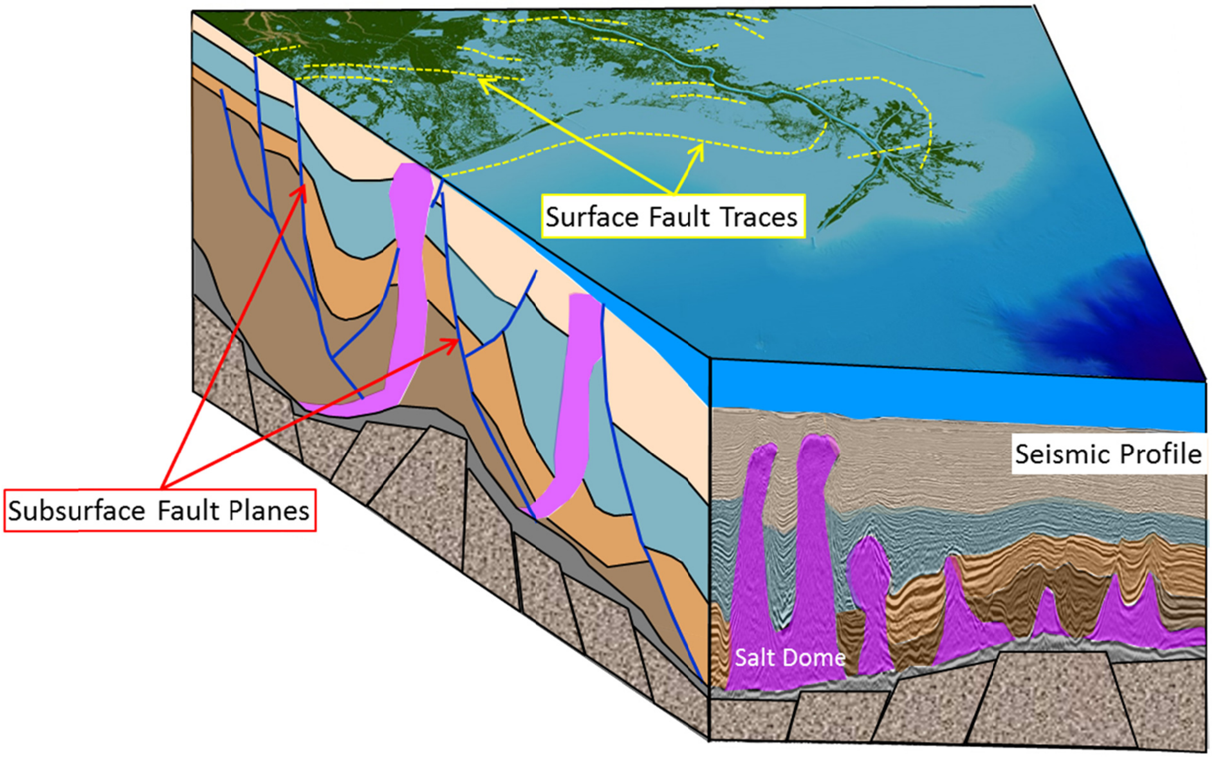


Figure 39

Perspective diagram of south Louisiana and offshore showing fault planes in the subsurface and fault traces on the surface

NOAA Perspective image of coastal Louisiana:

http://www.ngdc.noaa.gov/dem/squareCellGrid/download/680

The relationship between fault planes displayed on a vertical plane, as they would look on a seismic profile imaging the subsurface, and fault traces traversing the surface of coastal Louisiana is shown in Figure 39. The front face of the block diagram shows the image of a seismic profile that would be used to interpret the outline of the salt domes, shown in purple, and the sedimentary layers, shown as variously colored packages of seismic reflectors. The other vertical face shows how the sedimentary layers in the subsurface are offset by the vertical movement of the faults. In general the faults down drop the sedimentary layers into the basins, such as the Terrebonne Trough. It is the down dropped sides of these same faults that define the hot spots of subsidence at the surface.

The ultimate objective of this proposal is to assemble an atlas of surface fault traces that are the cumulative result of many research projects similar to the Land Bridge Project described here. The surface fault atlas will be a valuable resource for academic study and infrastructure planning on its own. Any road, bridge, levee or construction project that is crossed by one of the fault traces mapped as a result of this proposal should be flagged for monitoring for the potential impacts of fault movement. Dixon and Dokka (2006) stated:

> ***"Parts of St. Bernard and Orleans parishes west of Lake Borgne are experiencing subsidence rates of more than 20 mm/yr., including the levee system along the Mississippi River Gulf Outlet (MRGO) canal. Parts of this levee system were breached during the flooding associated with Hurricane Katrina, and this could be explained by the location of breach points and the high rate of subsidence beneath these levee sections. Considered over the lifetime of the levees, our subsidence estimates are probably minimum values, given that subsidence was most rapid in the first years after their construction in the 1960s. Levee failure may have resulted from overtopping because the levees were too low — data collected after the storm indicate that water levels exceeded those expected by 0.9–1.7m. Alternatively, the high subsidence rates we observe might reflect active faulting or a weak, easily compacted substrate, promoting failure at or near the levee base."***

Their observation underscores the critical importance of attempting to interpret and map the location of surface faults across coastal Louisiana. Integrating known subsidence rates across the surface of this area with a map of the fault traces would provide an invaluable tool for infrastructure assessment.

Predictive Modeling of Subsidence

Figure 40 is an example of an integrated surface fault – subsidence map constructed using interpreted data. The surface fault traces are in blue with contours of estimated rates of average subsidence associated with the faults. The map is based on the determination of a temporal relationship between the subsidence measured by the Grand Isle tidal gauge as shown in Figure 41 made by Kolker et al. (2011)[22] and land loss also mapped in the spatial domain in the Barataria Basin by Couvillion et al. (2011)[6]. Figure 41, shows the "tight coupling" between the rate of subsidence derived from the Grand Isle tidal gauge and the rate of land loss within the Barataria Basin, which surrounds Grand Isle. The rate of land loss for the Barataria Basin can be inferred from Figure 42. The histogram shows land loss in

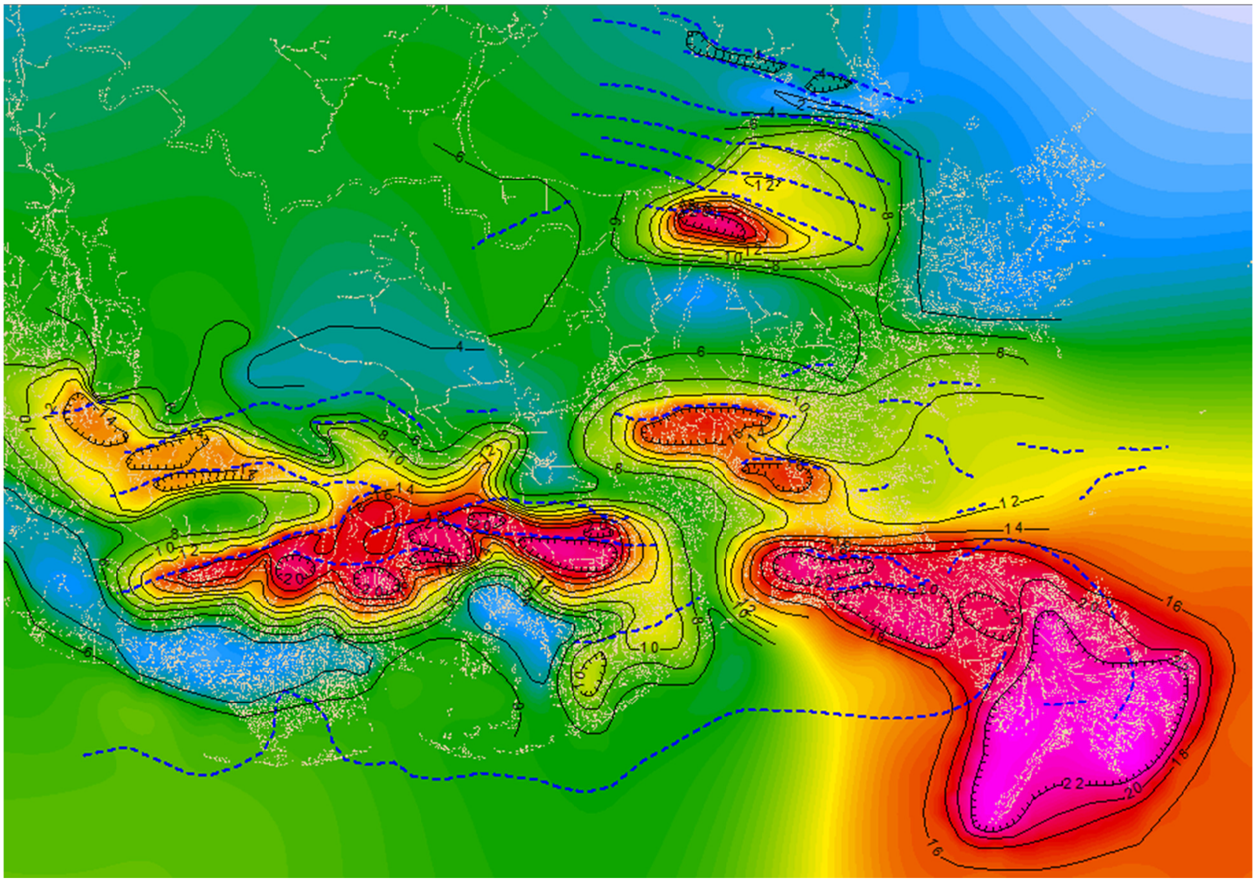


Figure 40

A visualization of what an integrated surface fault trace / subsidence map may look like given adequate academic research to create it. Surface fault traces are show as dashed blue lines. Subsidence contours with values in mm/yr are shown as black lines. Hot spots of high rate subsidence along fault traces indicate active vertical movement of the faults

irregular time intervals, which are identified on the color code legend at the left of the figure. These intervals are determined by the vintages of aerial photography or satellite imagery that were available for land area change measurements. The first aerial photographic survey to cover south Louisiana was acquired in 1932; the next one was in 1956. By 1973 Landsat satellite imagery was available over the coast. Figure 42 shows that about 57 square miles of wetlands were lost in the Barataria Basin between 1932 and 1956, and about 70 square miles between 1956 and 1973. These values are also represented on Figure 41 from Kolker et al., and this figure shows that this period of maximum land loss closely coincides with the period of maximum subsidence that can be inferred from the historical records of the Grand Isle tidal gauge. Kolker et al. interpreted from this relationship that:

“Subsidence, coupled with reduced sediment loads and global sea level rise, leads to an elevation deficit, leading to submergence of marshes and conversion of land into open water.”

In other words subsidence was the primary cause of land loss in the Barataria Basin.

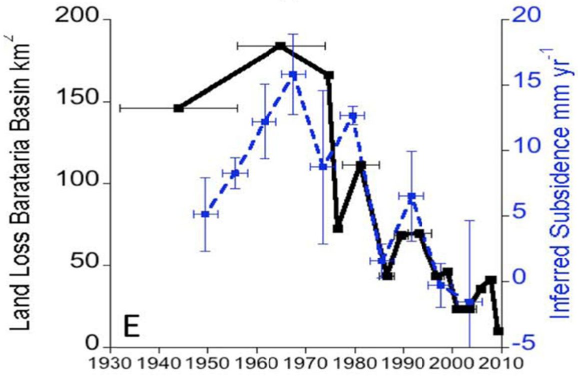


Figure 41

"Tight coupling" in the relationship between subsidence measured at the Grand Isle tidal gauge by Kolker, et.al., 2011[21] and land loss in the Barataria Basin by Couvillion, et.al., 2011. Graph from Kolker, et.al.

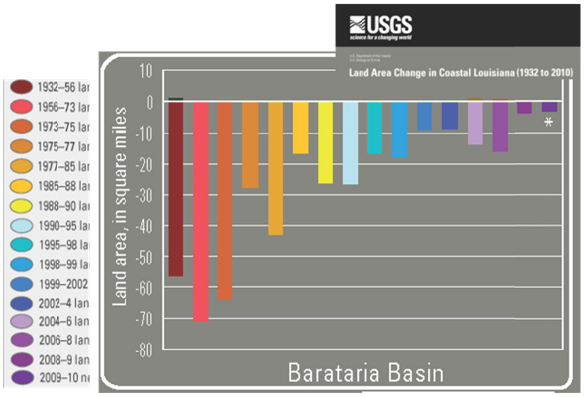


Figure 42

Rates of land loss in the Barataria Basin measured by Couvillion, et.al., 2011 [6] using aerial photography and satellite imagery. Values of land loss measured between vintages of imagery are displayed in Figure 45 at the centerpoint of the time interval. Color codes correspond to those in Figure 47

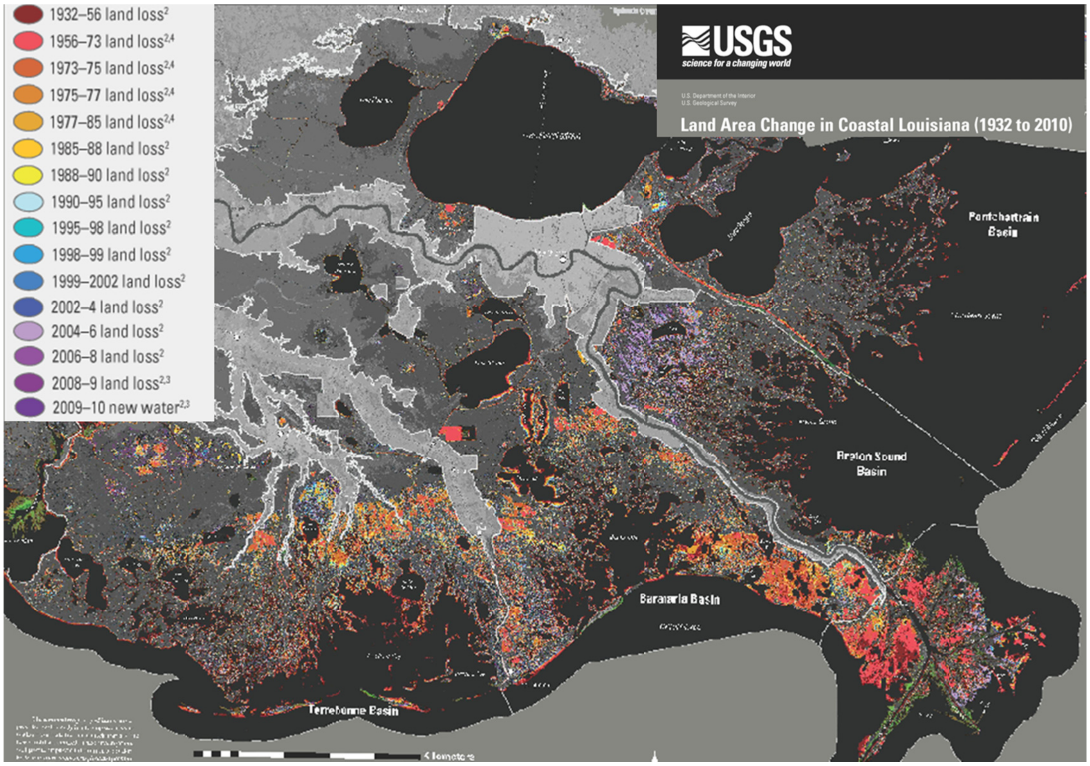


Figure 43

Land loss measured by Couvillion, et.al., 2011 [6] displayed in the spatial domain. The same values represented in the temporal domain in Figure 42 for the Barataria Basin are displayed in map view here. The visualization of what a subsidence map may look like shown is Figure 41 was constructed on the premise that this land loss map may be used to create a subsidence map by contouring values of subsidence measured by various sources using the patterns of land loss in the spatial domain as a guide.

In order to construct the visualization of a predictive map to estimate rates of subsidence across coastal Louisiana, as shown in Figure 40, the relationship between subsidence and land loss that Kolker et al.

made in the temporal domain was extended to the spatial domain. The graph from Couvillion et al. (2011)[6] showing land loss over time in Figure 42 is displayed in map form in Figure 43 from their same study. If the dark red colors of the histogram in Figure 42 are intervals of high subsidence, then the dark red colors on the map in Figure 43 can be related to areas of high subsidence. Hot spots of land loss are, for the most part, hot spots of subsidence, and they can be logically related to the underlying mechanisms of subsidence – faulting and the lateral movement of ductile clays.

Kolker et al. linked this temporal relationship between land loss and subsidence to the temporal pattern of fluid extraction from oil and gas fields, and based on production graphs from Morton et al. (2005)[33]. These graphical representations of the rate and timing of fluid extraction were based on a dataset that was never intended to be utilized in such a broad temporal analysis. Morton, et al. used oil and gas production data from IHS Energy, Inc., which publishes the data commercially. The IHS Energy website indicates that the south Louisiana production data is only valid after 1965. The apparent spike in production volumes between the 1960 and the mid-1970s that Morton et al. and Kolker et al. use to draw a temporal relationship between fluid extraction and subsidence is merely an artifact of the limitations of the dataset. A complete dataset of the production history of south Louisiana does not exist in a digital form that would allow for graphical representation, and if it did, it would be unlikely to support the relationships that were drawn from the partial dataset. Regardless of the attempt to establish a relationship with fluid extraction, the temporal relationship of subsidence to land loss established by Kolker et al. still stands. The Couvillion et al. Land Area Change Map makes a clear implication by displaying the temporal changes in land area as spatial patterns in map view that the relationship between subsidence and land loss may be extended to the spatial domain. Morton et al. (2002)[31] took the first step toward establishing this spatial relationship by publishing the contour map of rates of relative sea level rise which had been derived by Penland et al. (1989)[41] as shown in Figure 32.

By drawing on the correlation of patterns of land loss on the Couvillion et al. Land Area Change Map and the “tight coupling” of subsidence and land loss established by Kolker et al., it may be possible to use the spatial patterns of land loss to derive a spatial pattern of subsidence in map view. An estimation of the values of subsidence derived from this spatial analysis should logically incorporate any available estimates of the rate of subsidence in that area. The combination of tidal gauge records, GPS stations, geodetic leveling surveys and radar satellite imagery analysis discussed in this proposal offers a broad base of subsidence values that may be integrated into an effort to map patterns of subsidence across the Louisiana coastal plain using the patterns of land loss mapped by Couvillion et al. as a basis. Figure 44 shows the location of point sources of published subsidence data to be utilized in this manner for a portion of southeast Louisiana. The tidal gauge values show in this figure were published by Penland et al. (1989)[41] and include those used by Morton et al. (2002) to make the contour map in Figure 32. The tidal gauge record estimates of subsidence are derived by subtracting an average value of 3 mm/yr. for global sea level rise from the relative sea level rise estimates published by Penland, et.al. The geodetic leveling survey values are also from Penland et al. (1989). The CORS values are from Ivins et al. (2007). Figure 45 shows the positioning of the subsidence values upon the Couvillion et al. Land Area Change Map.

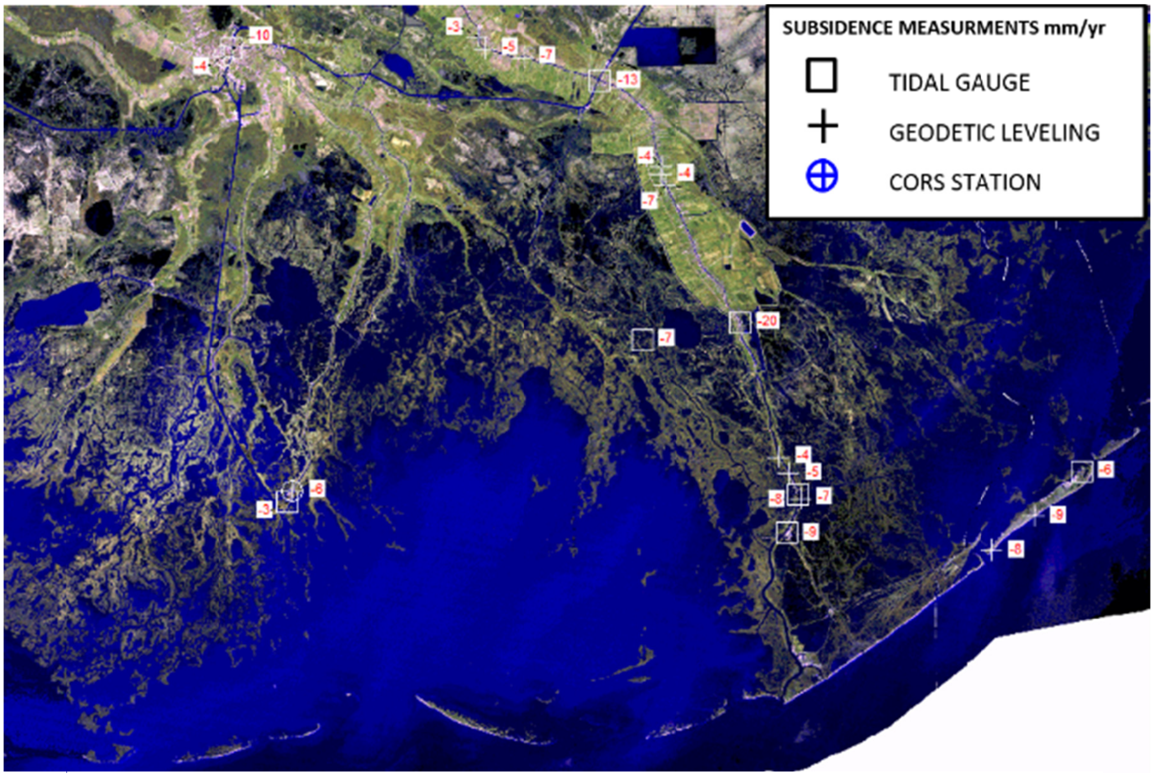


Figure 44

Available subsidence values published in peer-reviewed scientific literature for this area of southeast Louisiana

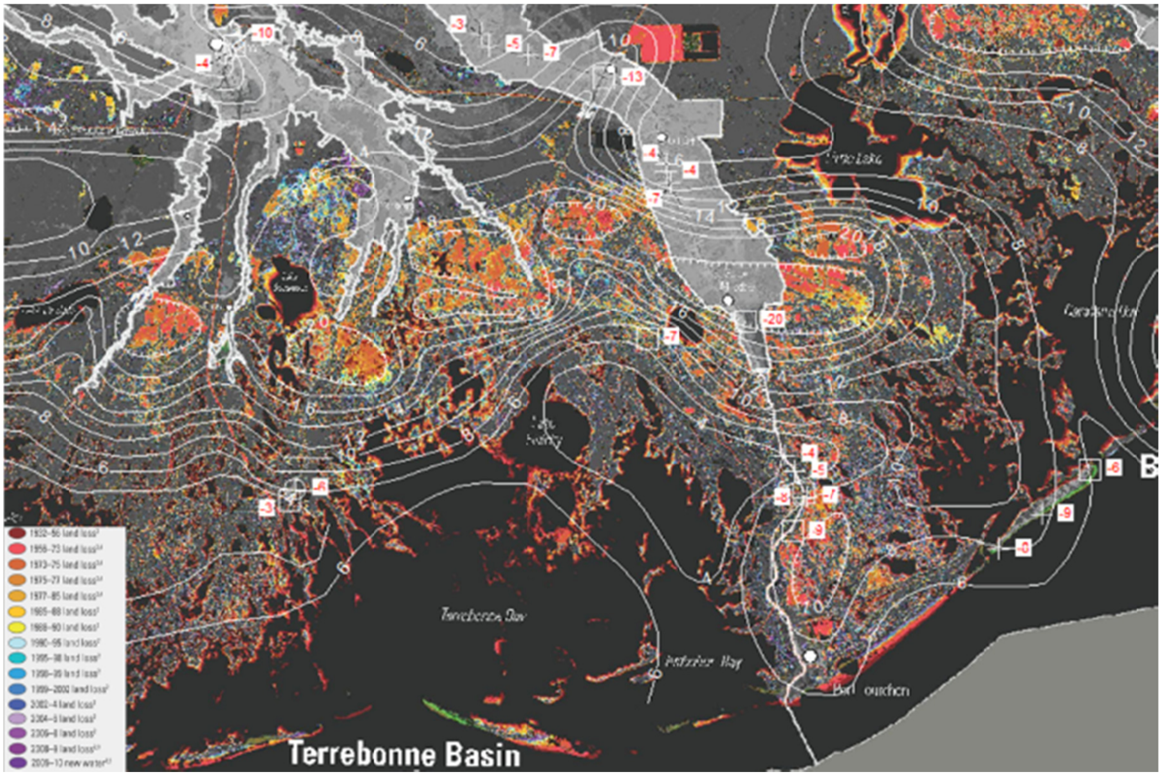


Figure 45

Contours of the subsidence map shown in Figure 44 were drawn using available values of subsidence rate and the patterns of land loss from Couvillion, et.al., 2011 as a guide

Building on the relationship between subsidence and land loss established by Kolker et al. contours are drawn that tie the largest values of subsidence to the areas of maximum land loss. For example the average value of 20 mm/yr. of subsidence that can be estimated from the Golden Meadow tidal gauge record is within the outline of a hot spot of land loss expressed by the bright orange and red color codes stretching across the marsh just outside the levee system from Golden Meadow. These color codes correspond to the highest rates of land loss in the Barataria Basin, as can be seen by comparing the color code legend to the graph in Figure 42. These highest rates of land loss tie directly to the time interval in which the maximum rates of subsidence were being recorded by the Grand Isle tidal gauge. By extension it may be concluded that the pattern of hot spots of maximum land loss extending across the area west of Golden Meadow also represent hot spots of subsidence, and areas of equivalent color code may be assigned values of subsidence equivalent to that measured by the Golden Meadow tidal gauge. Using the pattern of land loss as a guide, subsidence contours can be drawn across this area to incorporate all of the available values of measured or estimated subsidence into a first order approximation of a subsidence surface for the lower Barataria area. The general configuration of these contours can be favorably compared to those published by Morton, et.al. in their 2002 study, as shown in Figure 32.

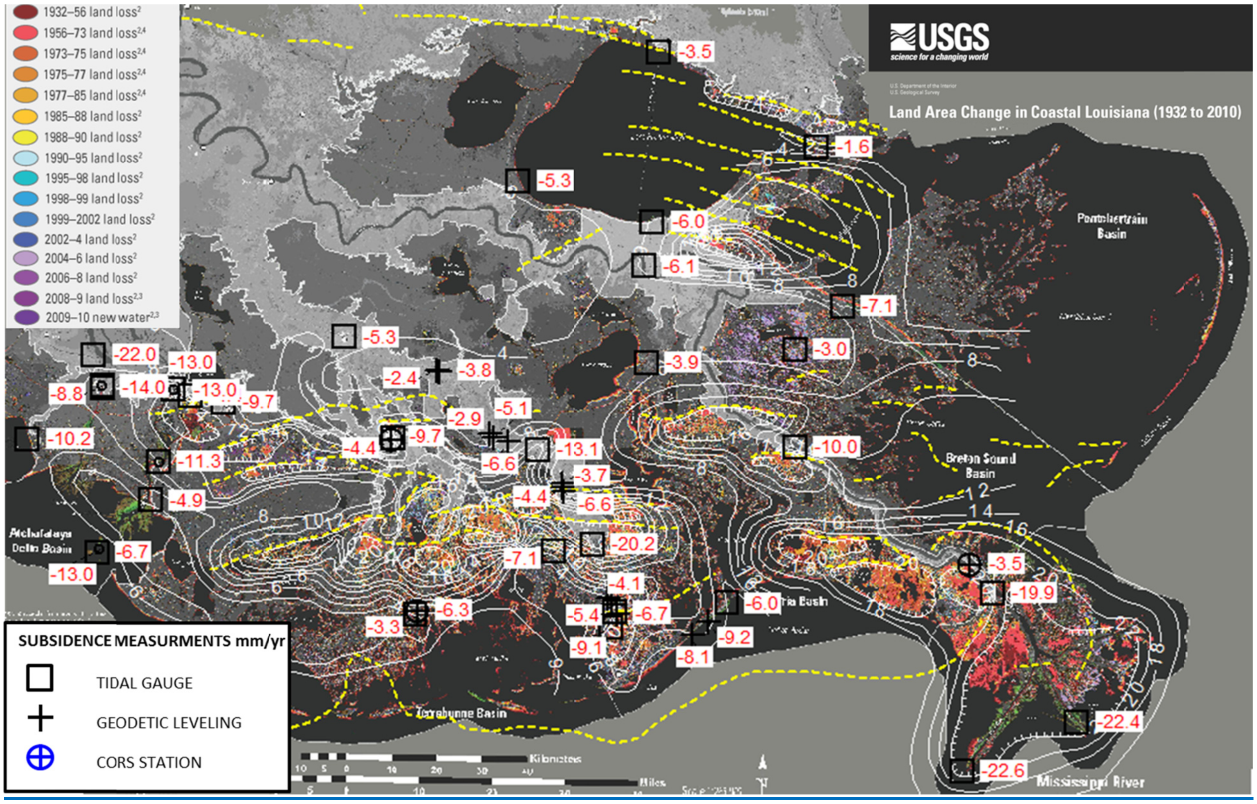


Figure 46

The method of mapping subsidence contours from land loss data may be extended across the southeast Louisiana coastal plain. Integration of the first order approximation of surface fault traces from Figure 42 shows that the hot spots of land loss mapped by Couvillion, et al. (2011)[6] are logically explained as hot spots of subsidence that can be directly tied to the hot spot mechanisms for subsidence – faulting and the lateral movement of ductile clays in the birdfoot delta.

The maps in Figures 45 and 46 illustrate an extrapolation of the process of mapping subsidence using The Land Area Change Map across the southeast Louisiana coastal plain. The first order approximation of surface fault traces from Figure 39 are superimposed onto the subsidence contour map in Figure 44 and the Land Area Change Map in Figure 50. A comparison of these figures shows that the conformance of the patterns of subsidence and faulting that was apparent in Figure 32 is consistent across the coastal plain. The surface fault traces shown on the maps in figures 39, 45 and 46 are the surface expressions of many of the major faults shown in Figure 20 that represent the boundaries of the Terrebonne Trough at depth. It is obvious that vertical displacement along these faults has been a mechanism of subsidence that has controlled the configuration of the Terrebonne Trough throughout its history, and is still active today. The thickness patterns seen in the isopach map for the Holocene epoch in Figure 15 evidences the contribution of vertical displacement along these faults to subsidence within the Terrebonne Trough over the last 6,000 years. It is a logical conclusion that vertical movement on these faults where they reach the surface would have significant impact on patterns of subsidence at the surface that can be measured today, and that conclusion offers the best explanation for the apparent correlation between hot spots of subsidence and surface fault traces seen in Figure 46. Again, the premise of this proposal is that mapping surface fault traces should be the foundation to any effort to map and predictively model the impacts of relative sea level rise due to subsidence across southeast Louisiana.

CONCLUSION

Some of the most critically important infrastructure that supports oil and gas operations in the Outer Continental Shelf and Deepwater provinces is necessarily located in the coastal wetlands of southeast Louisiana. The Department of Homeland Security’s Infrastructure Threat and Risk Analysis Center in 2011 underscored the need for a more expansive evaluation of coastal infrastructure in the near future.

This proposal by the New Orleans Geological Society (NOGS) offers a well-defined process by which the oil and gas industry can make a cooperative effort to create a foundation for a broad assessment of the impacts of relative sea level rise due to subsidence on its coastal infrastructure. The most basic component of this foundation is mapping the surface traces of faults across the coastal plain and attempting to estimate rates of subsidence being caused by their vertical movement. This can best be accomplished by utilizing the 3-D seismic surveys that cover much of southeast Louisiana.

The initial project of this proposal to be carried out at the Coastal Research Laboratory at the University of New Orleans has already secured the donation of two 3-D seismic surveys and one 2-D seismic grid. This project will serve as a model for all future projects, and it is the objective of this proposal to work toward a broad base of coverage of southeast Louisiana with projects of this type. The ultimate objective of the proposal is to assemble and publish a regional atlas of surface fault traces and a predictive model of the impacts of subsidence across the area.

The implementation of research projects conceived by this proposal on a larger scale will have broad implications. The funding of research by academic institutions will come at a critical time for supporting coastal studies. The products of these research projects will be widely applicable to both expanded research efforts and similar infrastructure assessments being carried out by a range of governmental and non-governmental entities. This proposal offers a means to get the vital scientific interpretations that can only be derived from 3-D seismic surveys into the hands of those that will find them to be essential components of infrastructure assessment, but to which they would not otherwise have access.

Going forward NOGS will be acting in a coordinating capacity to facilitate the creation of a centralized entity through which funding for the research projects may be collected and distributed. NOGS will also act to connect academic institutions interested in pursuing research projects similar to the Land Bridge Project described here with available 3-D seismic surveys and funding.

For more information on this proposal or to discuss any aspect of the content of this document or the concept of the proposal in general please contact NOGS members listed here:

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New Orleans Geological Society

Table 1 Land Bridge Project - Proposed Budget

	Fall 2015	Spring 2016	Summer 2016	Fall 2016	Spring 2017	Summer 2017	Fall 2017	Spring 2018	Summer 2018	Fall 2018
MS candidate 1										
tuition	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00			
stipend	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00			
admin cost	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00			
MS candidate 2										
tuition		$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00		
stipend		$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00		
admin cost		$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00		
PhD candidate 1										
tuition				$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00	$ 7,000.00
stipend				$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00	$ 14,000.00
admin cost				$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00	$ 6,440.00
Faculty salary		$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00
LPBF GIS support		$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00
CHIRP acquistion	$ 10,000.00		$ 10,000.00		$ 10,000.00		$ 10,000.00		$ 10,000.00	
Core acquistion				$ 20,000.00				$ 20,000.00		
Seismic reprocess		$ 350,000.00								
	$ 37,440.00	$ 424,880.00	$ 84,880.00	$ 122,320.00	$ 112,320.00	$ 102,320.00	$ 112,320.00	$ 94,880.00	$ 57,440.00	$ 47,440.00
									TOTAL:	$ 1,196,240.00

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