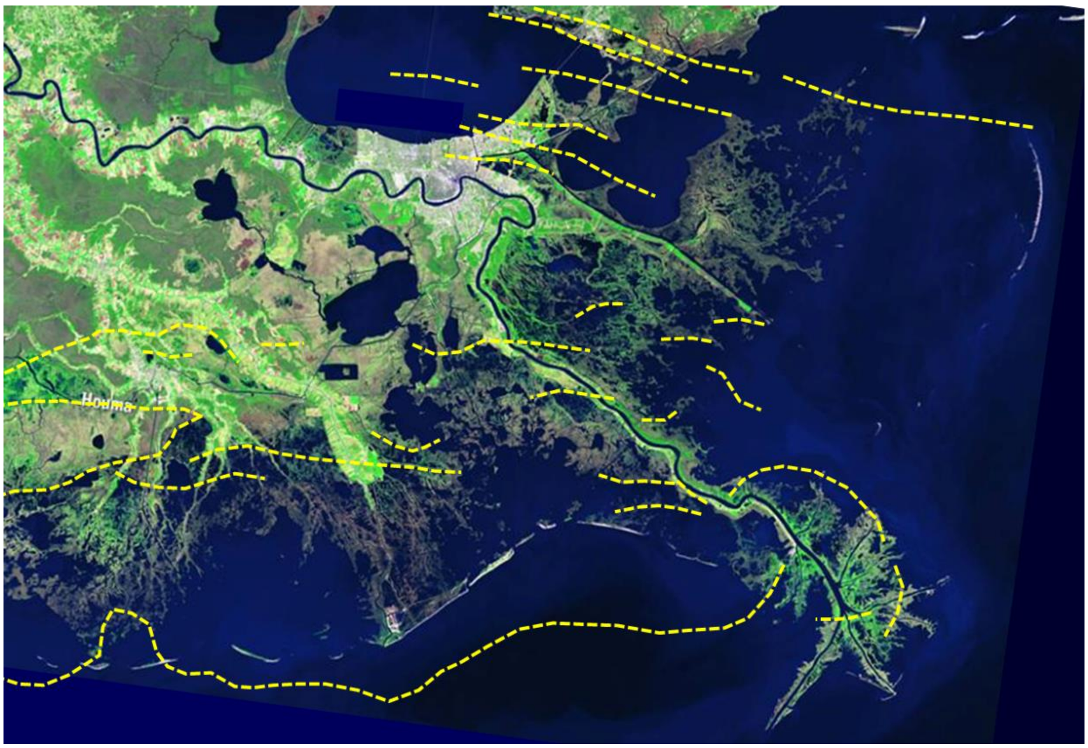
# A Proposal to Create an Atlas of Surface Fault Traces in South Louisiana



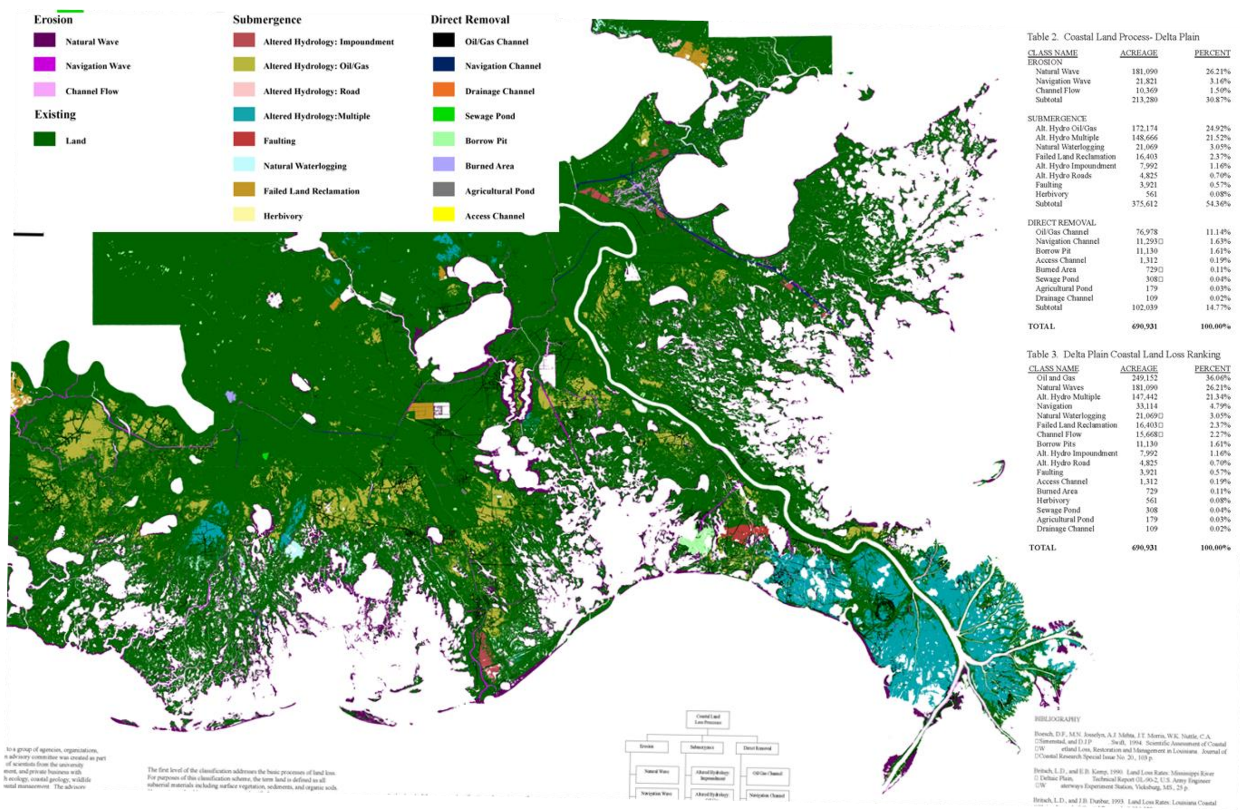

**Executive Summary**

The common conception of land loss in the south Louisiana wetlands is that is has been caused by the dredging of oil and gas canals. A scientific investigation of an example area representative of the coastal wetlands shows that land loss is actually the result of natural subsidence of the marsh surface caused primarily by the downward movement of faults. The first step to correcting the misinterpretation of cause and to lay the foundation for more research on the issue of land loss is to generate an accurate map of the fault traces that cross the coastal plain of south Louisiana.

This is a proposal for oil and gas companies to participate in the generation and publication of an Atlas of Surface Fault Traces. Publication of this atlas would be coordinated by the New Orleans Geological Society, and would be made available to all parties interested in coastal research, wetlands loss and restoration.

## The Original Mis-Interpretation

Few topics of public discourse are simultaneously so widely discussed and so poorly understood as wetlands loss in coastal Louisiana. The common conception, which is routinely reinforced by unresearched media coverage, holds that wetlands loss is due to coastal erosion, which is in turn due to saltwater intrusion caused by oil and gas canals. The foundational study that underlies this conception is entitled “Process Classification of Coastal Land Loss Between 1932 and 1990 in the Mississippi River Delta Plain, Southeastern Louisiana” by a group led by Shea Penland at the University of New Orleans.

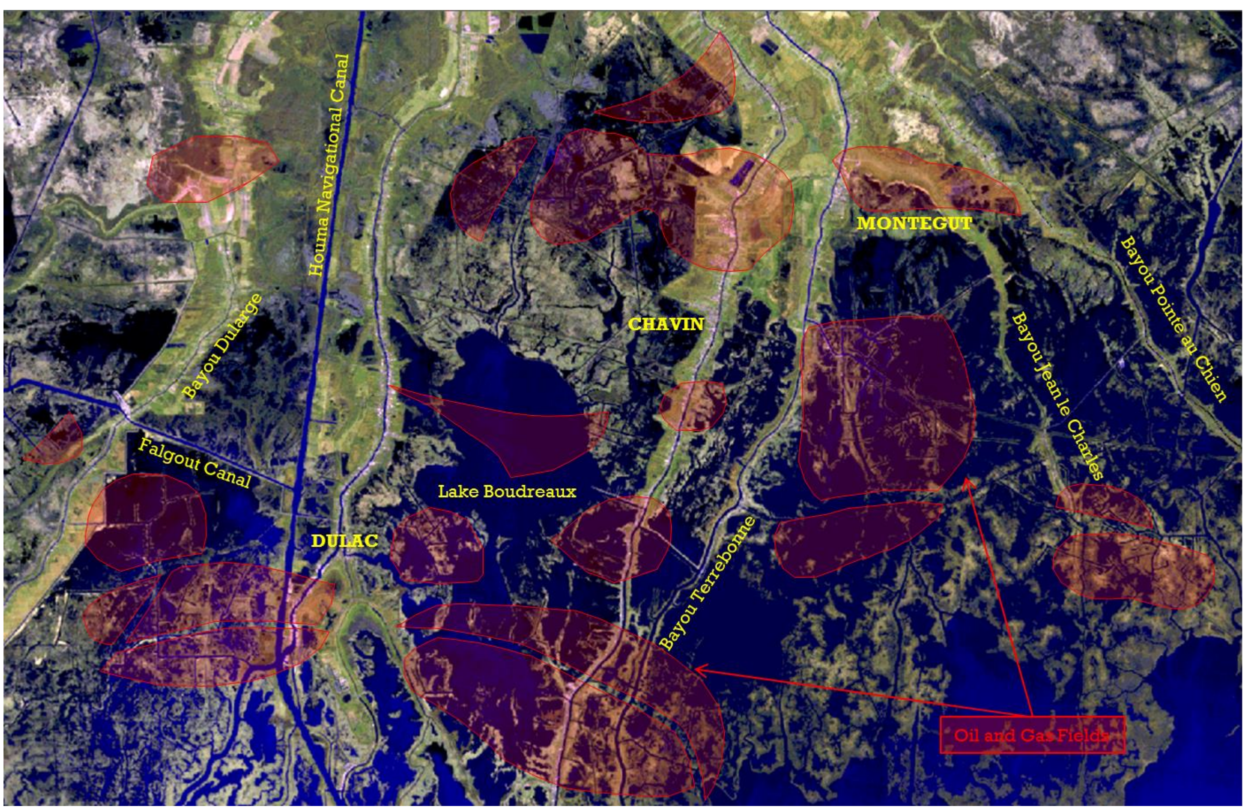


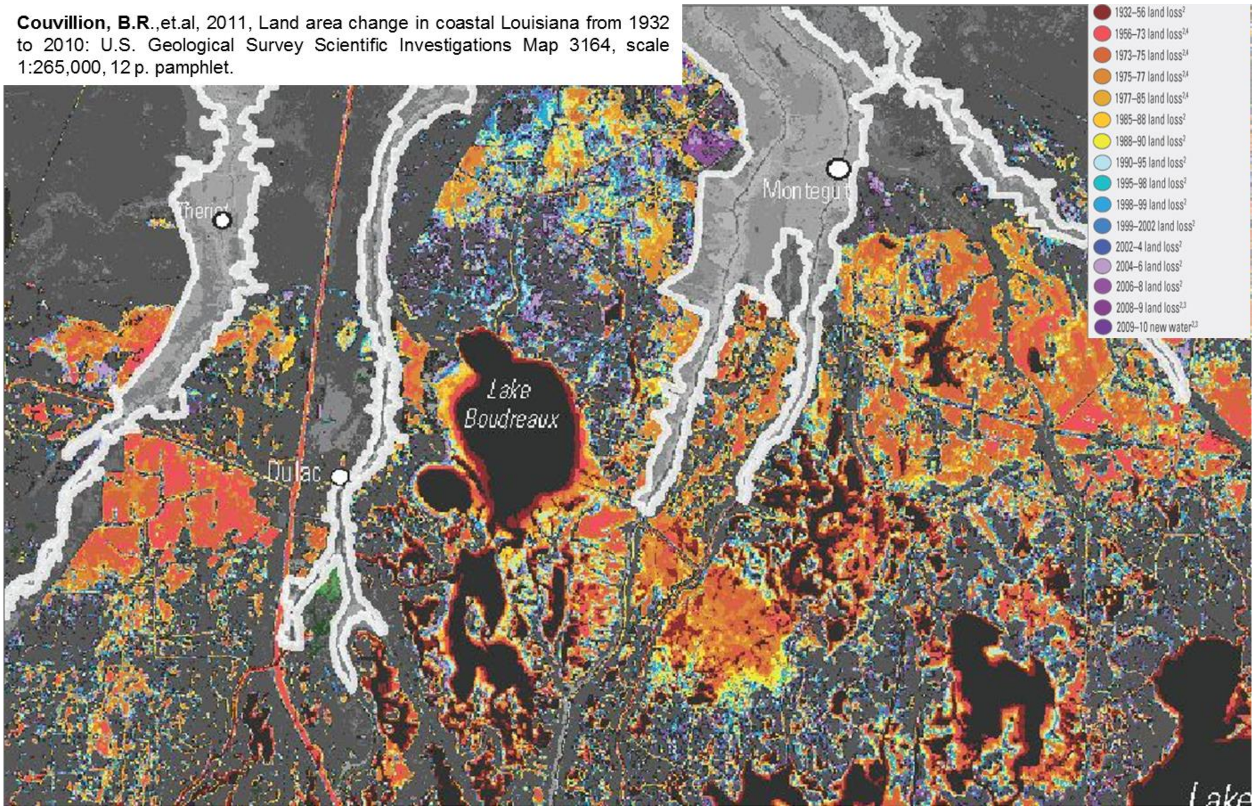

Penland categorized wetlands loss into several groups to which he assigned an underlying cause. These categories included wetlands loss due to the oil and gas canal dredging as “Direct Removal”, to which he assigned a value of 11.14% of the total loss, “Altered Hydrology due to oil and gas activity” to which he assigned a value of 24.92% and “Altered Hydrology due to multiple causes” assigned a value of 21.52%. Close examination of his processes reveals that Penland’s total for Direct Removal includes many navigational canals that either pre-dated the oil exploration era in the marsh, or would have been dredged regardless of oil exploration, and therefore overestimates the total. Penland himself revised the percentage attributable to direct removal to 9% in a later, more detailed study of a smaller but representative area of the marsh. Both of the categories of altered hydrology are found in areas proximal to oil and gas fields where dredging occurred, and several subsequent authors assumed that both categories were attributable to oil and gas activity. This explains why there is general conception that oil and gas activity is responsible for somewhere between 20% and 60% of the wetlands loss that has occurred in coastal Louisiana since 1932. In extreme cases authors have contended that up to 90% of wetlands loss can be attributed to oil and gas activity.

The premise of these conclusions is that the altered hydrology, which in most cases simply means that areas of marsh have converted to open bodies of water, has been caused by erosion of the marsh due to salt water intrusion, and that intrusion was in turn caused by the oil and gas canals. This model fails to fully explain the patterns of wetlands loss that are found across the coastal plain. Some areas that have been subjected to dredging have experienced wetlands loss, and there would appear to be a correlation. Some areas of wetlands loss are not directly associated with any significant dredging, and it is difficult to envision how the erosion model would account for the conversion of marsh to open water. Some areas that have been subjected to significant dredging have not experienced any significant wetlands loss. It is clear that the erosion model is inadequate to fully account for the loss of wetlands in the coastal plain, and there is a necessity for a more robust explanation of the patterns of loss. It is the contention of this proposal that the conversion of marsh into open water in the Louisiana coastal plain is primarily due to natural subsidence caused by the vertical motion of faults, and that accurately mapping the traces of faults that reach the surface will provide a valid and robust model for the causes of wetlands loss.

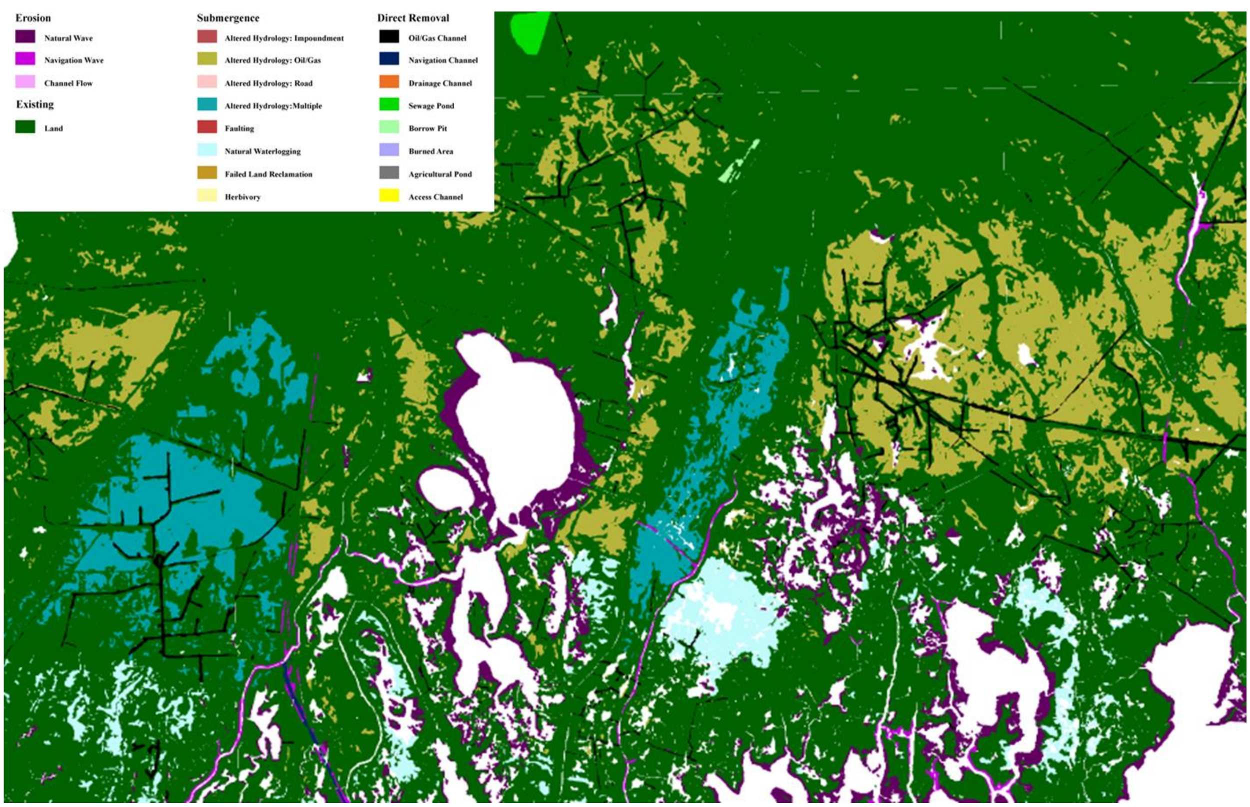
## The Process of Mapping Surface Fault Traces

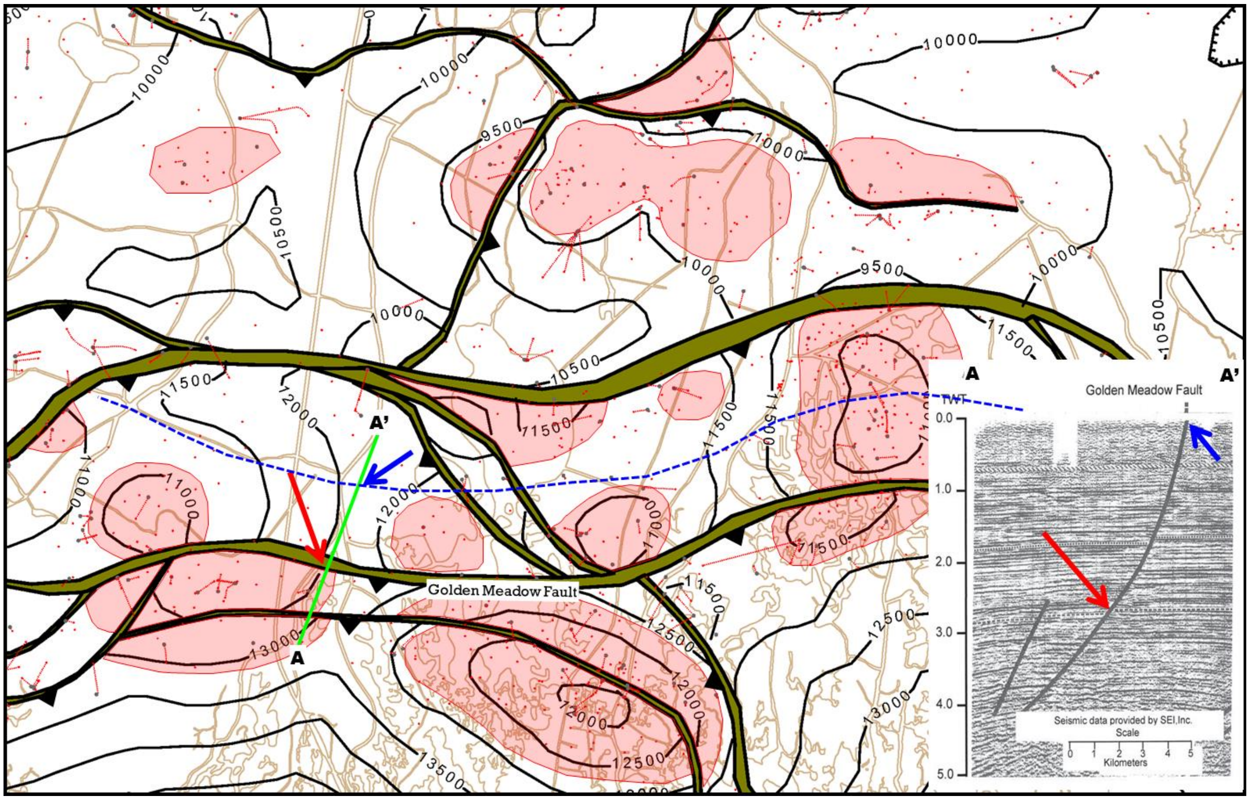
The process of mapping the surface fault traces, and the impact an accurate mapping can have on properly interpreting the causes of wetlands loss can best be investigated by the review of an example area. This area south of Houma, Louisiana is of particular interest because there has been significant drilling activity, significant land loss, and it is the site of a proposed coastal restoration project.






Patterns of land loss as mapped by the U.S.G.S above, and how they were categorized by Penland below

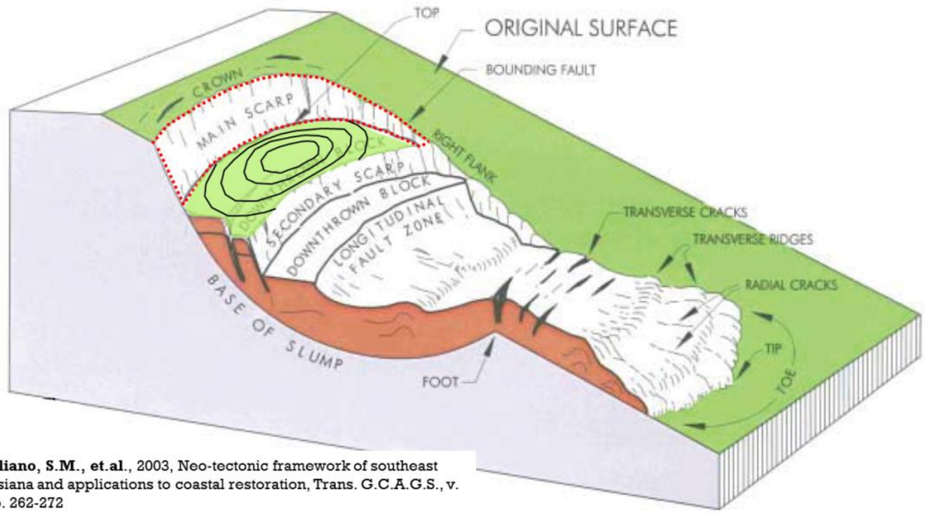





A generalized geological map shows the subsurface structure on a middle Miocene horizon for the investigation area. The contours values are in depth below the surface. A seismic line extending from A to A' on the map is shown in the lower right corner. The mapped horizon is approximated by the black dashed segments on the seismic line, and it can be seen that horizon is cut by two faults that are indicated by the heavy black lines. The faults vertically offset the horizon on the seismic line, and the elevation of the horizon is clearly deeper on the "downthrown" side of the fault on the map. The traces of these faults are shown as the light brown polygons on the map with the black triangles indicating the downward direction of the fault. The red arrows indicate the point of intersection where the mapped horizon intersects the large Golden Meadow Fault on both the seismic line and the map. Of the two faults that cut the middle Miocene horizon one is "buried" just above the mapped horizon, and the other, the large Golden Meadow Fault, extends all the way to the surface. The blue arrows indicate where the Golden Meadow fault intersects the surface on the seismic line and on the map. A dashed blue line shows the interpreted trace of the fault across the area based on a projection from the seismic line and a generally parallel alignment with the trace of the fault as it is mapped at depth. This dashed blue line is trace of the fault along the surface. It is these major faults that cut to the surface that are considered critical to understanding subsidence and land loss patterns in coastal Louisiana.

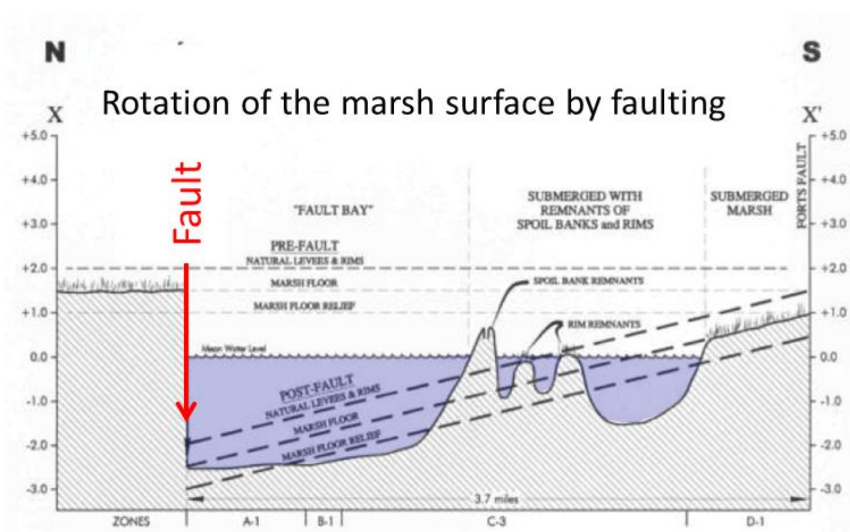
Faults are essentially slide surfaces that are a part of group of geomorphic features that also includes landslides. A three-dimensional block diagram published by Gagliano, which could be used to represent either a landslide or a fault, more clearly shows the fault slide surface. In this example if the green surface on the block diagram were equivalent to the middle Miocene mapped horizon, then the vertical offset of the horizon, which is seen on the seismic line and can be interpreted from the elevation contours of the map, is obvious. The width of the fault scarp in the block diagram is equal to the width of the fault trace on the structure map. Concentric contours are diagrammatically overlain on the "downthrown fault block" to represent the slightly domal structure created by the rotational movement of the fault, commonly called a "fault rollover". It is this domal structure that creates the trap within which the oil and gas accumulate. This in part explains the genetic relationship between faults and oil and gas fields.

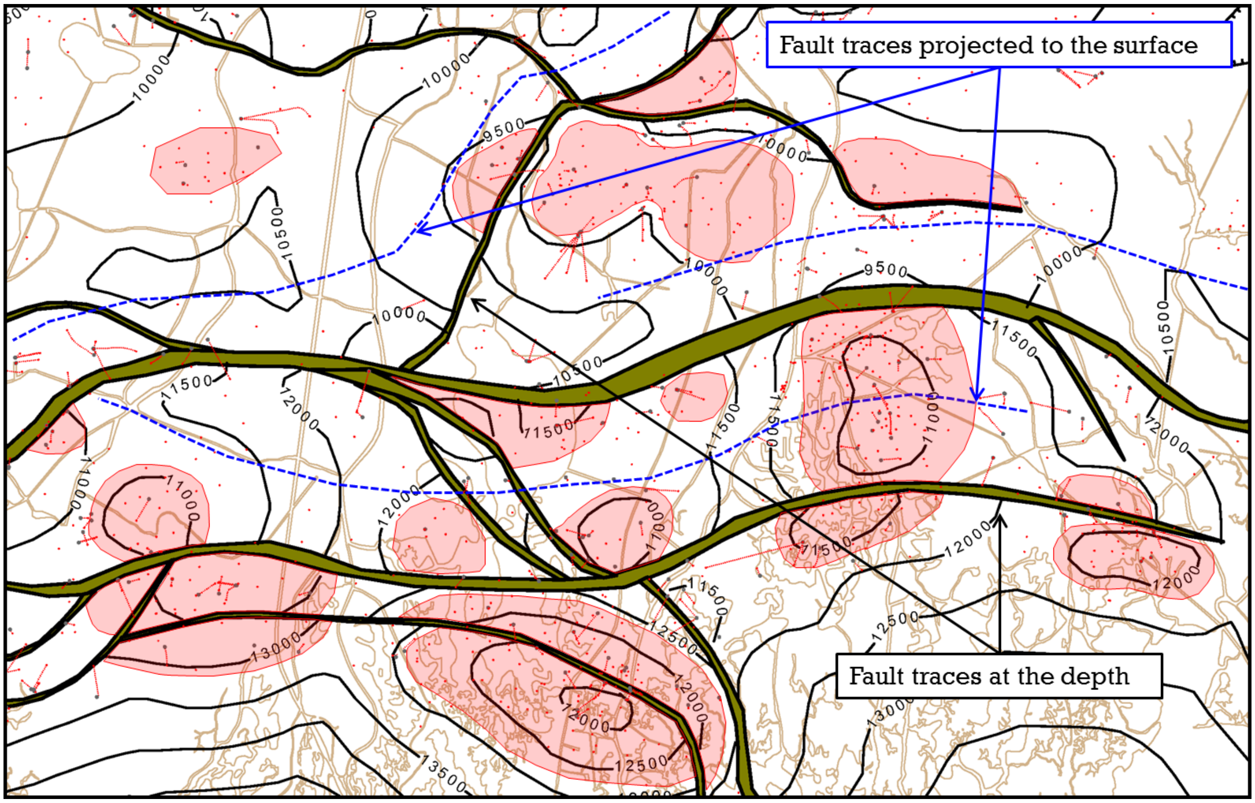
The concept of the fault scarp is also applicable to the intersection of the fault with the marsh surface. The downward movement of these major faults is generally continuous through time, and as will be seen, the expression of this movement and the associated fault scarp is evident at the surface.



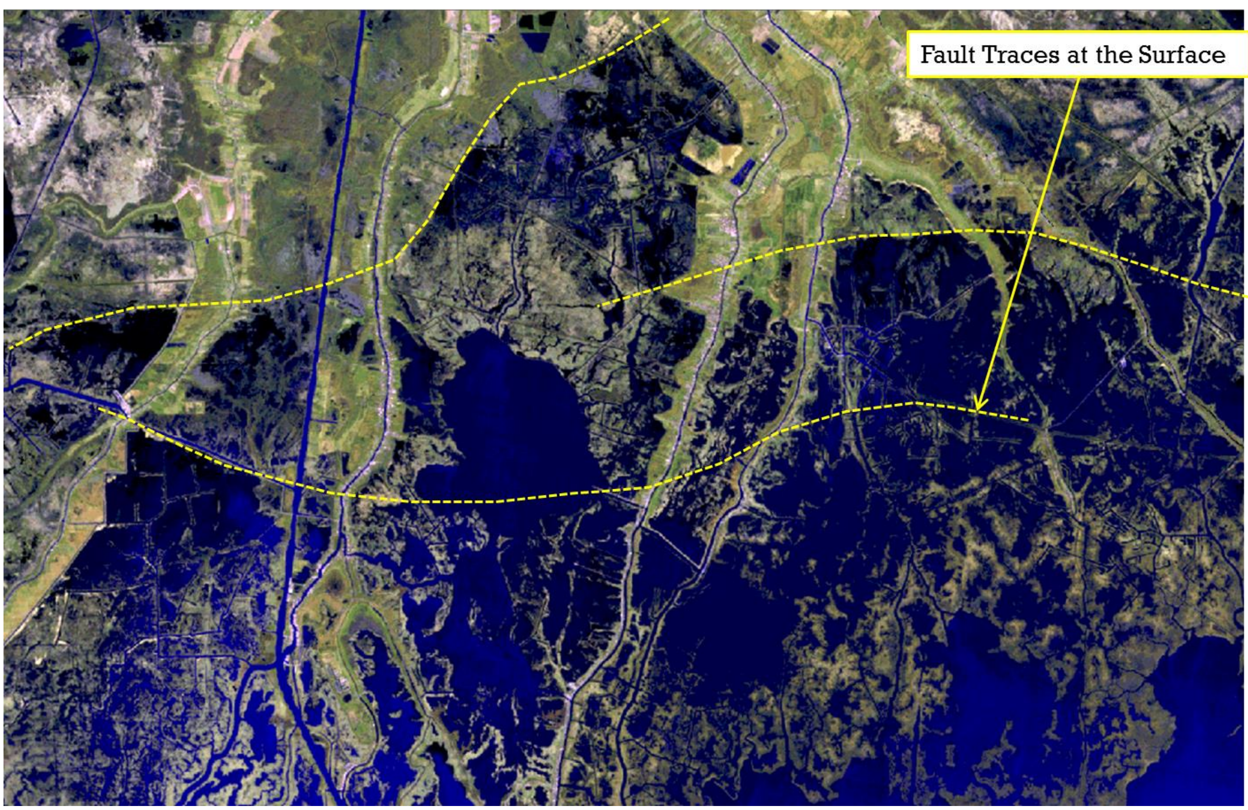

**Gagliano, S.M., et.al.**, 2003, Neo-tectonic framework of southeast Louisiana and applications to coastal restoration, Trans. G.C.A.G.S., v. 53, p. 262-272

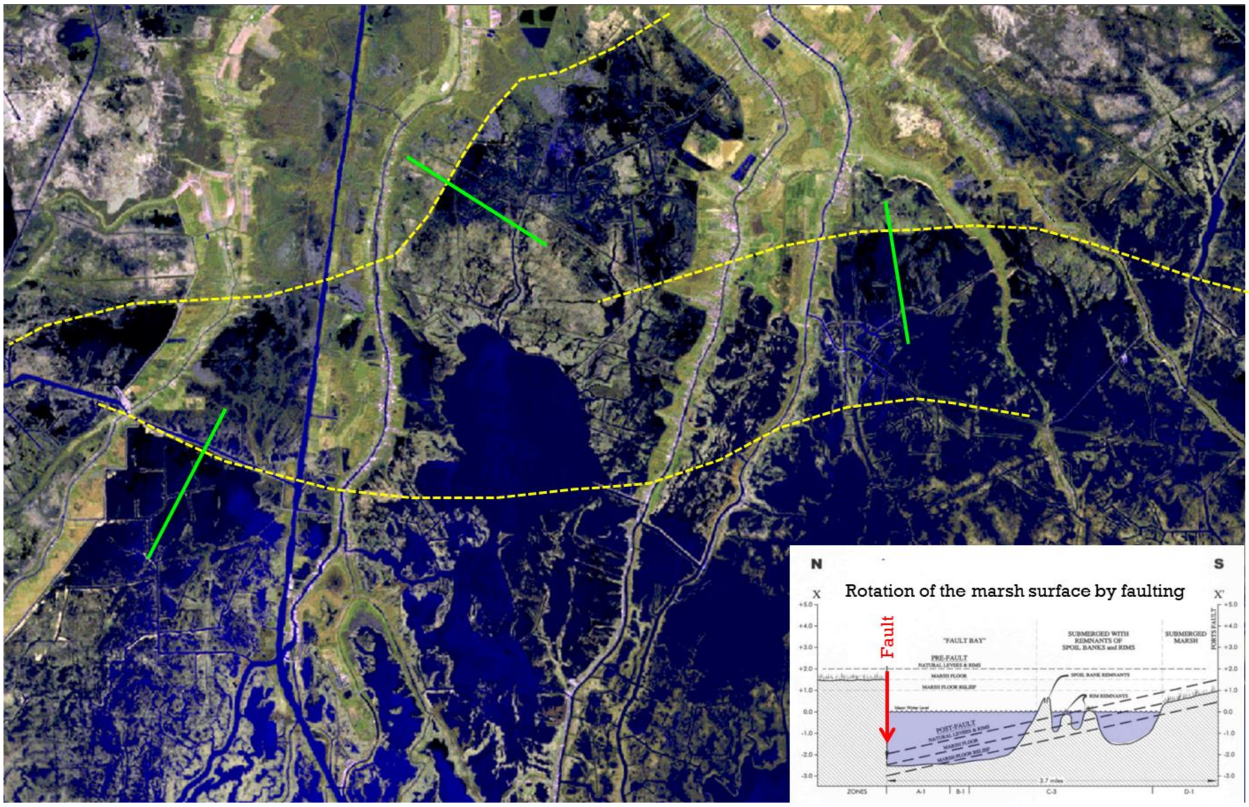
Gagliano also published a diagram of a fault scarp at the surface formed by the rotational movement of the fault. The surface of the marsh slopes inward toward the fault scarp forming an open body of water he called a "fault bay". The "upthrown" side of the fault is not subsided and is generally well preserved.



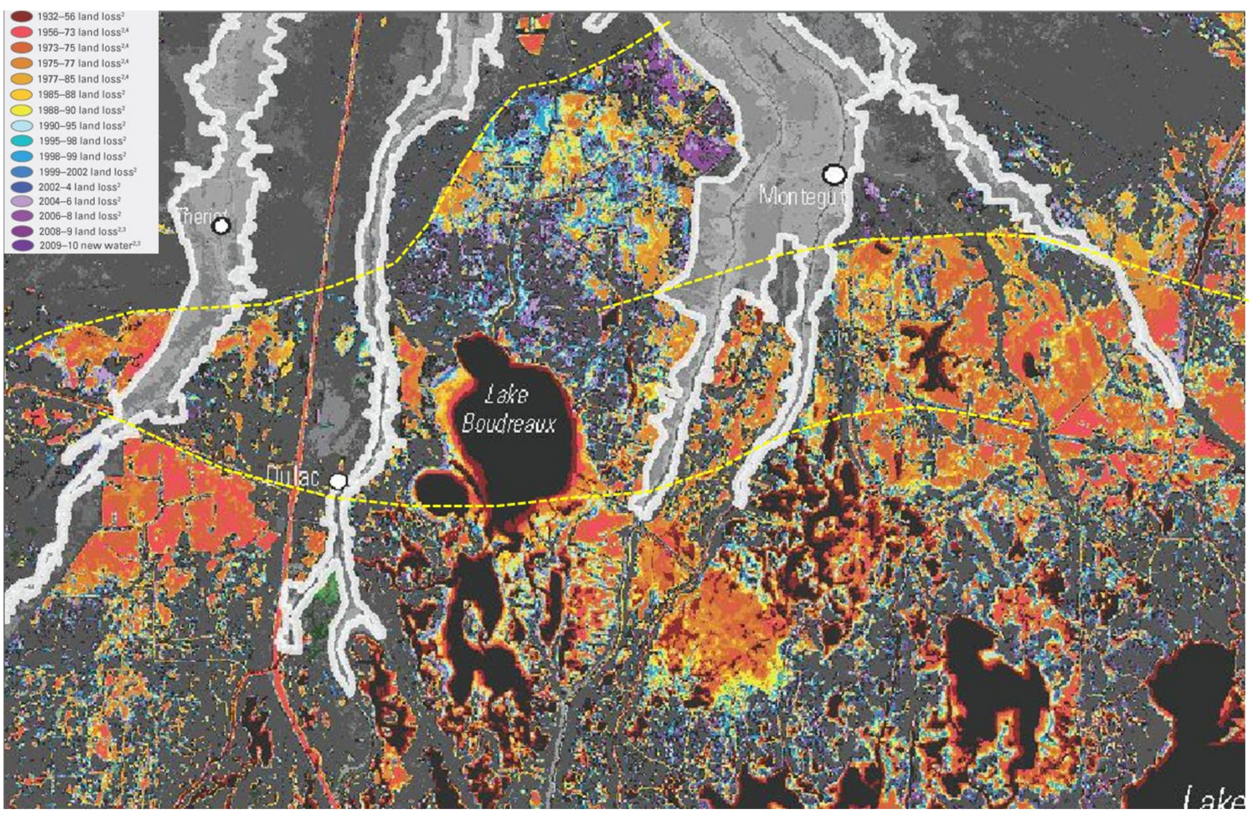


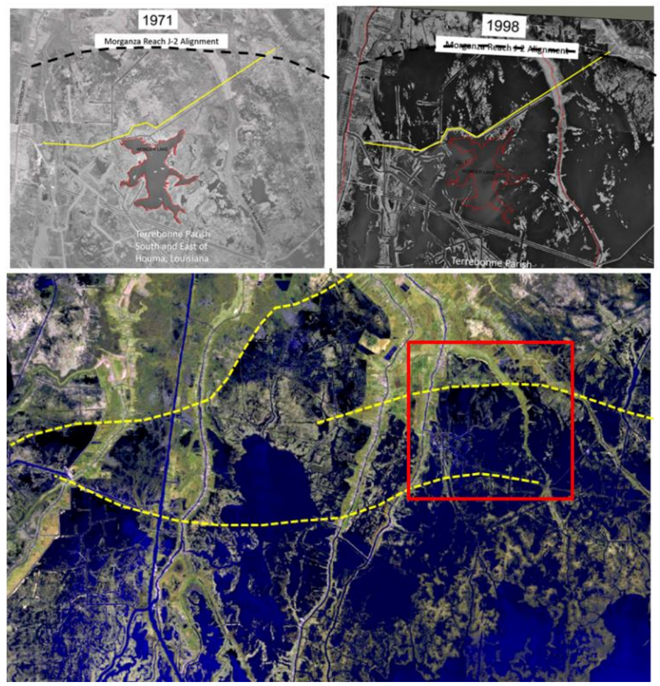

The projection of the traces of the faults on the marsh surface reveals their obvious expression.



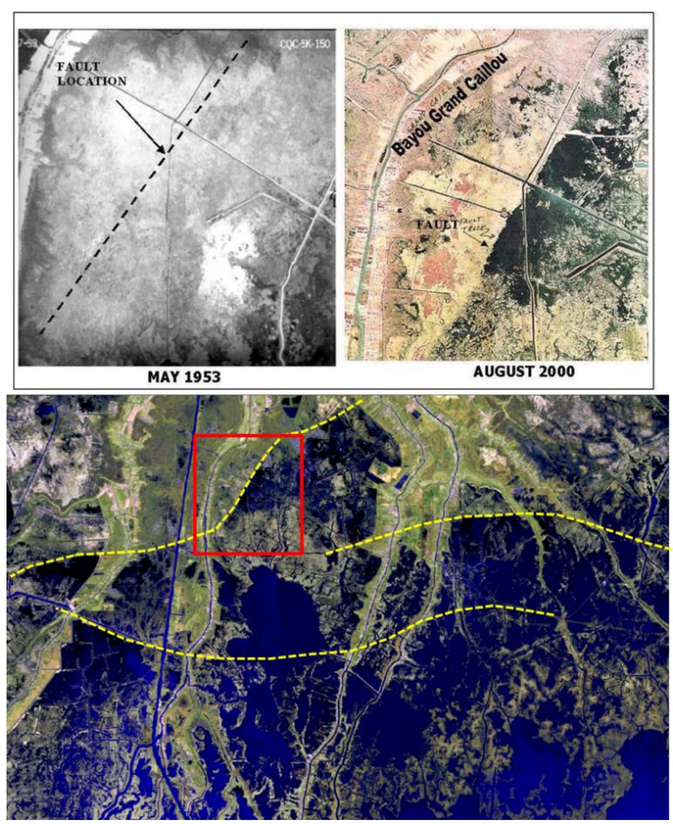



The green lines are locations of Gagliano's diagram, which explains the land loss at each hot spot.



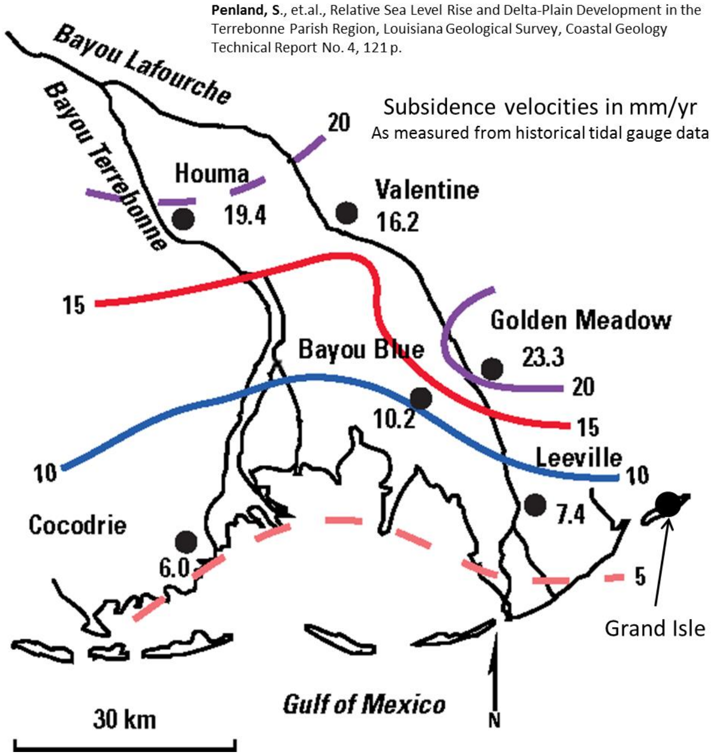



These sets of aerial photographs show the development of the fault bays along the surface trace. The upthrown sides of the fault remain relatively unchanged, and show no land loss on the U.S.G.S. map.

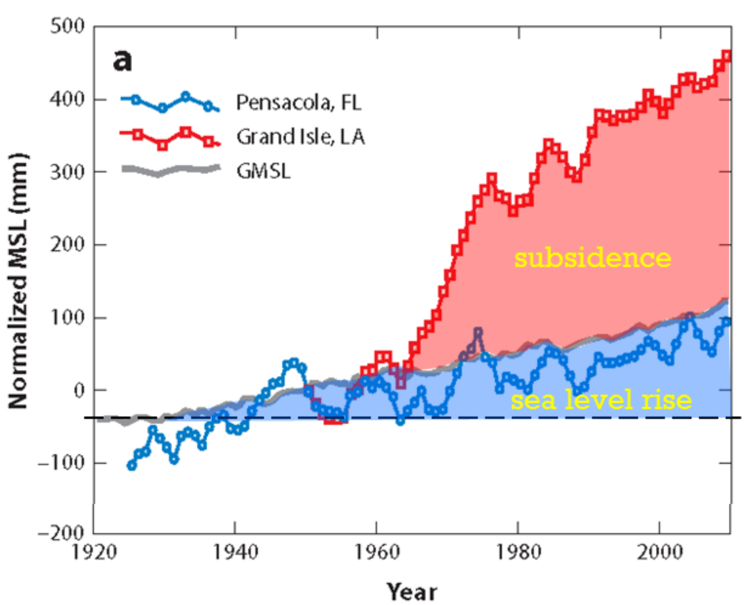


## Measuring Subsidence

Penland, S., et.al., Relative Sea Level Rise and Delta-Plain Development in the Terrebonne Parish Region, Louisiana Geological Survey, Coastal Geology Technical Report No. 4, 121 p.




Subsidence velocities in the area of investigation can be measured by historical tidal gauge data.

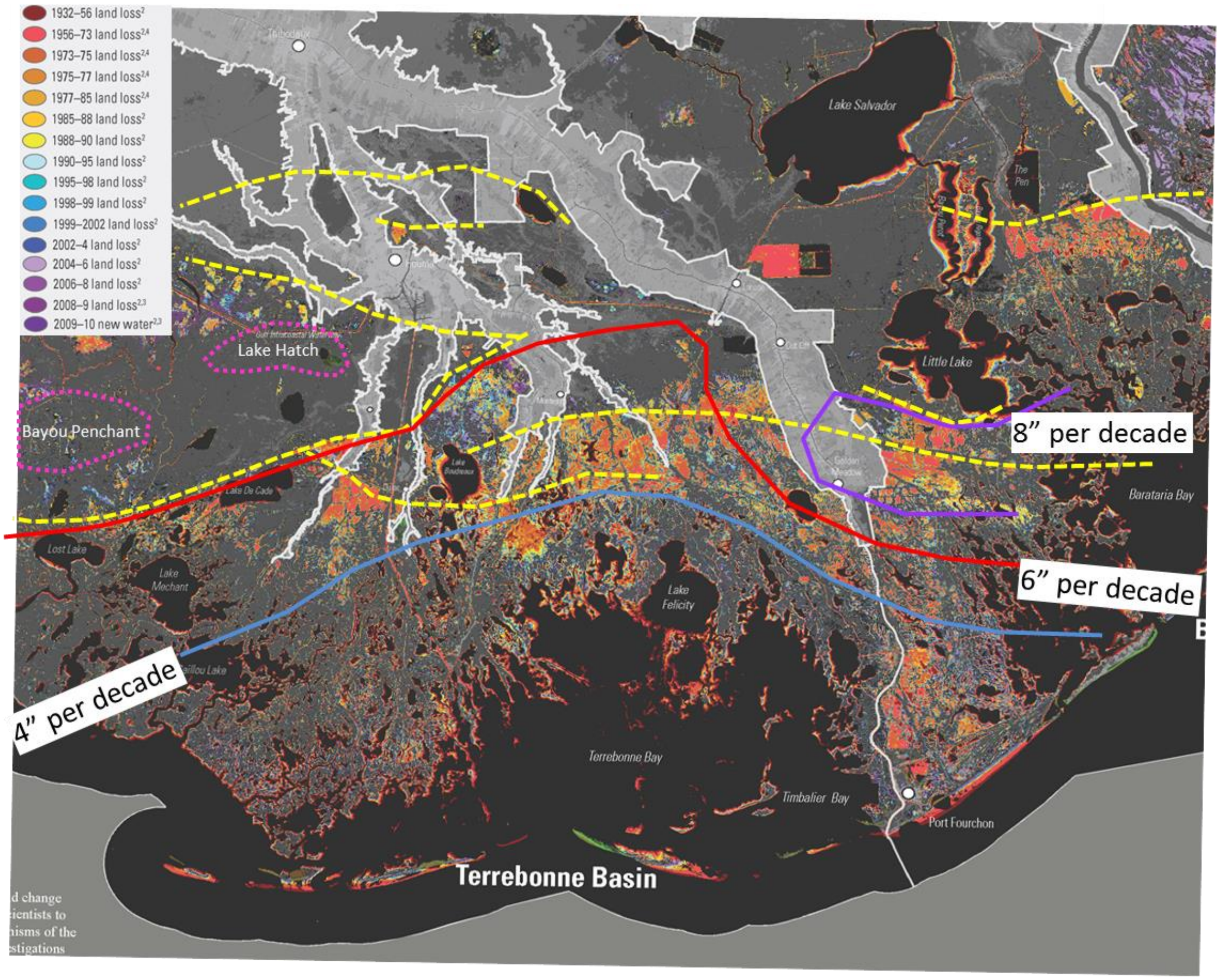



**Blum, M.D. and Roberts, H.H.**, 2012, The Mississippi Delta Region: Past, Present, and Future, Annual Review of Earth and Planetary Sciences, v. 40, p. 655-683

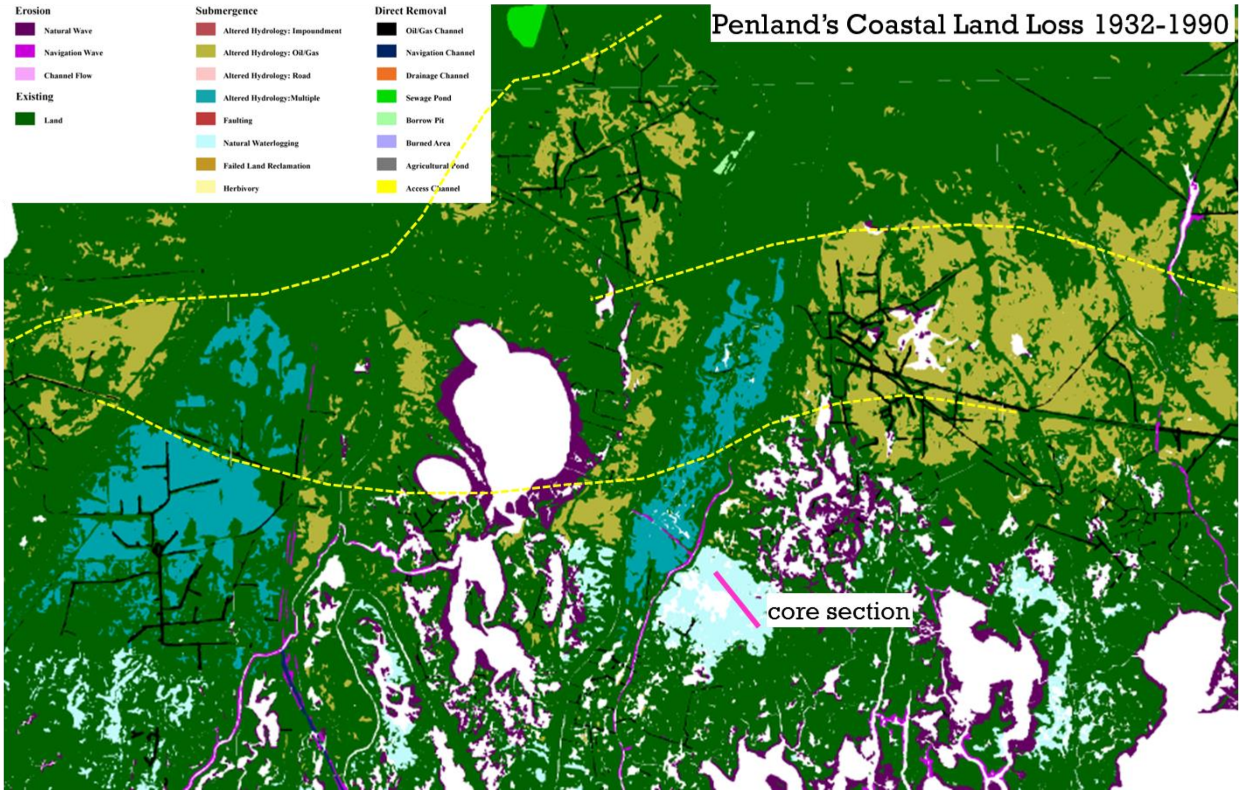
The use of historical tidal gauge data is well established as a means of estimating subsidence velocities during the time span in which data was recorded. The premise is that the values for high and low tide of each recorded interval are effectively a measurements of elevation. Over a period of time it can be seen that these values plot as a curve that has an obvious slope, but the slopes may differ for each tidal gauge. The slope of the curve of historical data for any given gauge is the relative sea level rise that has been experienced at that point during the period of measurement. The apparent relative sea level rise for each gauge is composed of the combination of the effects of global “eustatic” sea level rise and the local apparent sea level rise due to subsidence. The graph on the previous page, to which annotation has been added, shows historical tidal gauge data for the Pensacola and Grand Isle gauges. The accepted curve for global mean sea level is also plotted for reference. Pensacola is located on a stable ridge that crosses the Florida Panhandle, and it experiences virtually no subsidence. Its historical tidal gauge curve therefore closely approximates the global curve. The curve for the Grand Isle gauge has a significantly greater slope, and the difference in slopes is accounted for by subsidence, which makes it appear that sea level is rising faster at Grand Isle than at Pensacola.

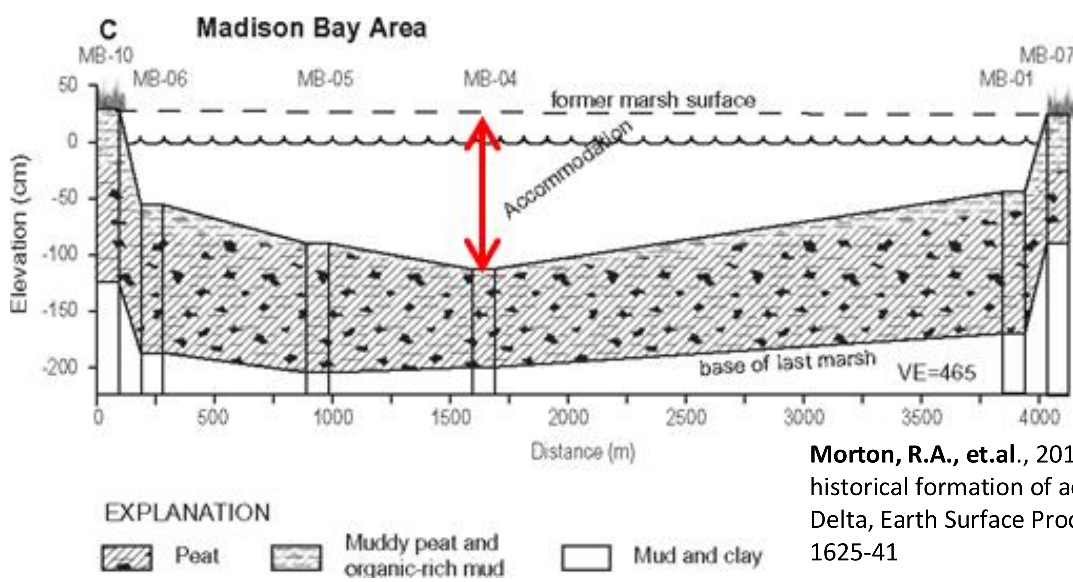
Penland used historical tidal gauge data to estimate subsidence velocities for the gauges shown on the map on the previous page. Unfortunately, Penland did not use the Grand Isle gauge data, and it is uncertain what his exact methodology was, so an exact value for the Grand Isle gauge data shown on the graph is not represented on the map. It can be reasonably approximated that the Grand Isle data represents a value of estimated subsidence of about 5 mm/yr, which would fit into the contours on the Penland map. The map on the next page is constructed by superimposing (and slightly modifying) Penland’s subsidence velocity contours and the surface fault traces onto the U.S.G.S. land loss map. The values of the subsidence velocity contours have also been converted to inches per decade. This combination of data and interpretation makes it fairly obvious that land loss that has occurred since 1932 across central Terrebonne and Lafourche Parishes is the result of subsidence due to faulting.

There have been several academic studies (most notably by Robert Morton of the U.S.G.S and Mark Zoback of Stanford University) that have concluded that subsidence in these areas has been caused by the extraction of oil and gas from fields associated with areas of land loss. Aside from the lack of any rational model that would provide for the translation of the compaction of reservoir at depth through two miles of plastic overburden with perfect rigidity back to the surface, there is no correlation between subsidence and the location of the fields across a broad area. Both Morton and Zoback have selected fields for evaluation that are downthrown to major faults that cut to the surface. Other fields in the area that have had as much or more hydrocarbons extracted as any field examined by these authors have experienced no land loss associated with subsidence. Two examples outlined on the map are Bayou Penchant Field and Lake Hatch Field. Lake Hatch is a field primarily comprised of hydro-pressured reservoirs that produced oil and gas with an aquifer expansion or “water drive”, and Bayou Penchant is comprised of both hydro-pressured and geo-pressured gas reservoirs that primarily produced by depletion drive. This field is exceptional because one of the large geo-pressured gas reservoirs was drawn down to a super-subnormal pressure using compressors. If there were ever a case in which extraction should have caused subsidence at the surface Bayou Penchant should have been this field. A recent publication by Dixon (Nature, 2006, v.441 p.587) measured subsidence velocities using G.P.S. in areas downthrown to faults on the New Orleans East Land Bridge where there has been no hydrocarbon extraction. The values of subsidence velocity measured by Dixon are very comparable to the values derived from tidal gauge data by Penland.




Penland’s Coastal Land Loss Map across the area of investigation is shown on the next page with the surface fault traces superimposed on it. A re-examination of this map shows that all of the areas for which land loss was attributed to “altered hydrology” are in fact fault bays. It is the downward vertical movement of the faults that caused the marsh surface to subside inward toward the fault scarp. The hydrology was altered because the marsh subsided below the surface. The induced slope of the marsh by the fault would logically allow for the gravity flow of saltwater into the subsided areas. It is this induced slope of the marsh surface that is the actual mechanism for saltwater intrusion into the interior marshes. Morton’s 2010 study examined how subsidence has provided accommodation capacity for the accumulation of sediments in historical deltas across the coastal plain. The cross section of shallow cores taken across Madison Bay in the area of investigation provides a strong visual representation of the subsidence of the marsh surface. The cores penetrate a layer of marsh deposit which has subsided up to 100 cm. If the land loss in this area had been caused by erosion, the cross section would have shown a pattern in which the layer of marsh sediment was cut into by the agents of erosion. Instead the layer is consistent across the section, and it has clearly subsided to form the open body of water called Madison Bay.

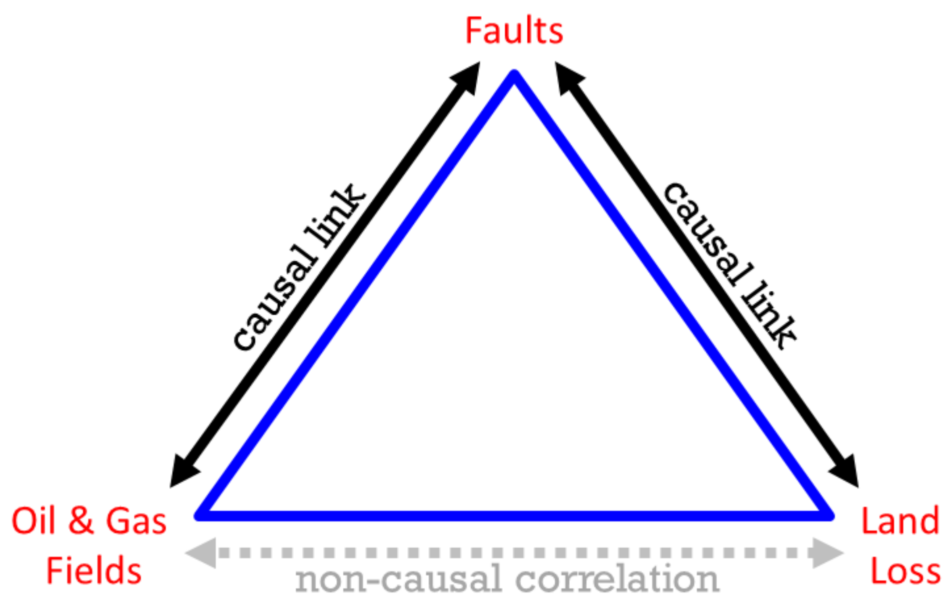



**Morton, R.A., et.al**., 2010, Quantifying large-scale historical formation of accommodation in the Mississippi Delta, Earth Surface Processes and Landforms., v. 35, p. 1625-41

## A Proper Re-interpretation of Land Loss

Without the proper integration of geological data one could be forgiven for drawing the conclusions that Penland, and so many subsequent authors, did – that the apparent relationship between the areas of direct removal and the areas of land loss due to altered hydrology was the result of a causal relationship between the dredging of the canals and the loss of the wetlands. With the proper integration of geological data it is clear that this apparent relationship is in fact a non-causal correlation.

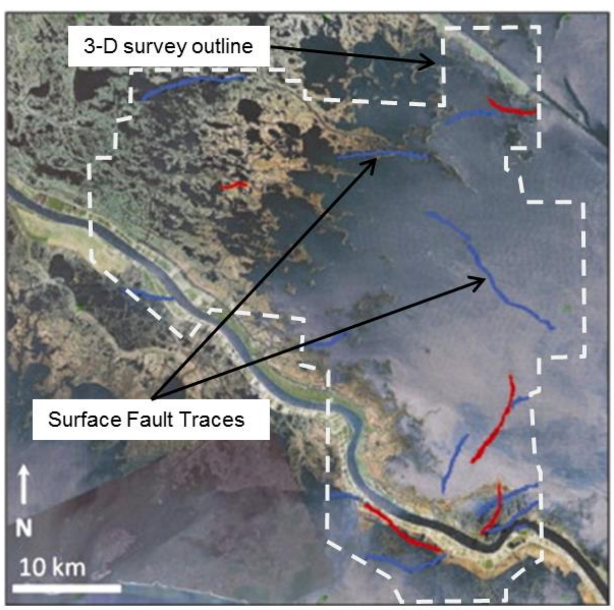



What the examination and comparison of the set of fields and their relative relationships to faulting and land loss in this area of investigation dramatically underscores is the correlative relationships between faulting, oil fields and land loss. There is a strong causal relationship between faults and the location of oil and gas fields. Nearly all major faults have oil and gas fields associated with them. It is the vertical movement of faults that provided the accommodation space within which the sand layers that make up the reservoirs were deposited. The faults also commonly act as a trapping mechanism for accumulations of oil and gas, and are likely to be the conduits by which hydrocarbons migrated into the reservoirs from greater depths. Faults are also primarily responsible for subsidence and loss of wetlands at the surface. As is shown on the map on page 16, the relationship of the surface fault traces to areas of land loss shown in the example area can be extrapolated to every major hot spot of land loss across the southeast Louisiana coastal plain. Because the faults control the location of the fields and faults control where wetlands loss is occurring, there is an apparent, but non-causal, correlation between where canals were dredged to drill the fields and where land loss is occurring.

This observation does not mean that direct removal did not result in some measure of land loss, it obviously did. What is does say is the magnitude of the land loss attributable to direct removal appears to be limited to the original value of about 10% as measured by the average of Penland's two studies. More importantly, what this examination has shown is that the erosion model for wetlands loss is incorrect. The entire concept of the changes that have occurred on the coast, and the changes that are likely to occur in the future needs to be re-examined using the more viable and robust model of land loss due to fault-driven subsidence. The foundation of such a re-examination must be built on an accurate map of the surface fault traces across the coastal plain of south Louisiana.

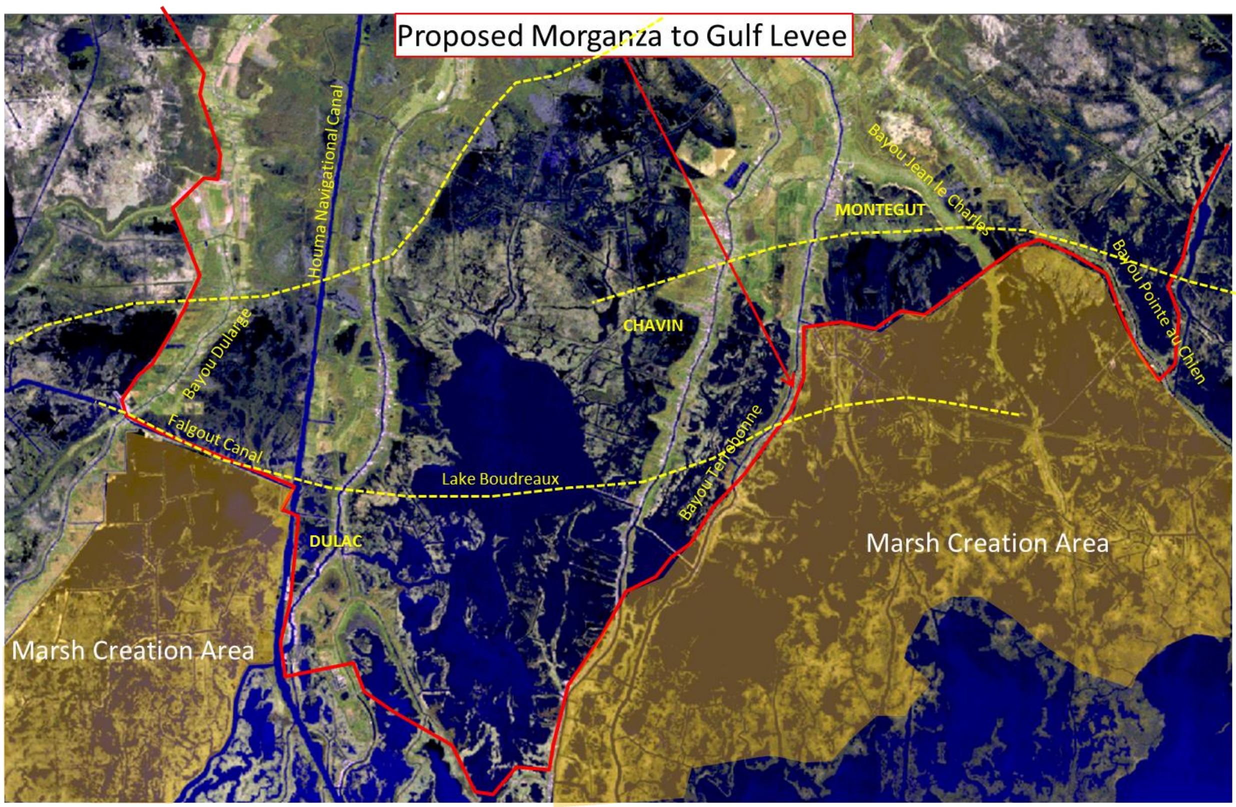
## The Proposal to Create an Atlas

This proposal specifically recommends that there should be a cooperative effort within the oil and gas industry to produce an Atlas of Surface Fault Traces in South Louisiana. This atlas should be published by the New Orleans Geological Society, and the process of its publication should follow the basic format of the several atlases of oil and gas fields that have been published by the Society. In those cases companies volunteered to provide interpretations of oil and gas fields based on data they had in their possession and done by employees of the company. In much the same way this proposal would seek to have companies with significant areas of 3-D seismic coverage to volunteer to produce detailed and accurate maps of the traces of faults that cut to the surface. Those maps would be assembled into an atlas that would include sets of maps across the area covered (which would hopefully be most of southeast Louisiana) as well as example seismic sections extracted from the 3-D data volumes. Each company that owned a license to the data used in the interpretation would seek approval from the licensing geophysical company to publish the seismic sections. This proposal also recommends that Kathy Haggar would act as editor for the atlas publication. Kathy is both a coauthor of the Gagliano, et. al. 2003 study on faulting and land loss referenced here, and is the sole author of a paper to be presented at the 2014 G.C.A.G.S. Convention on land loss due to fault-driven subsidence at Goose Point on the north shore of Lake Pontchartrain.

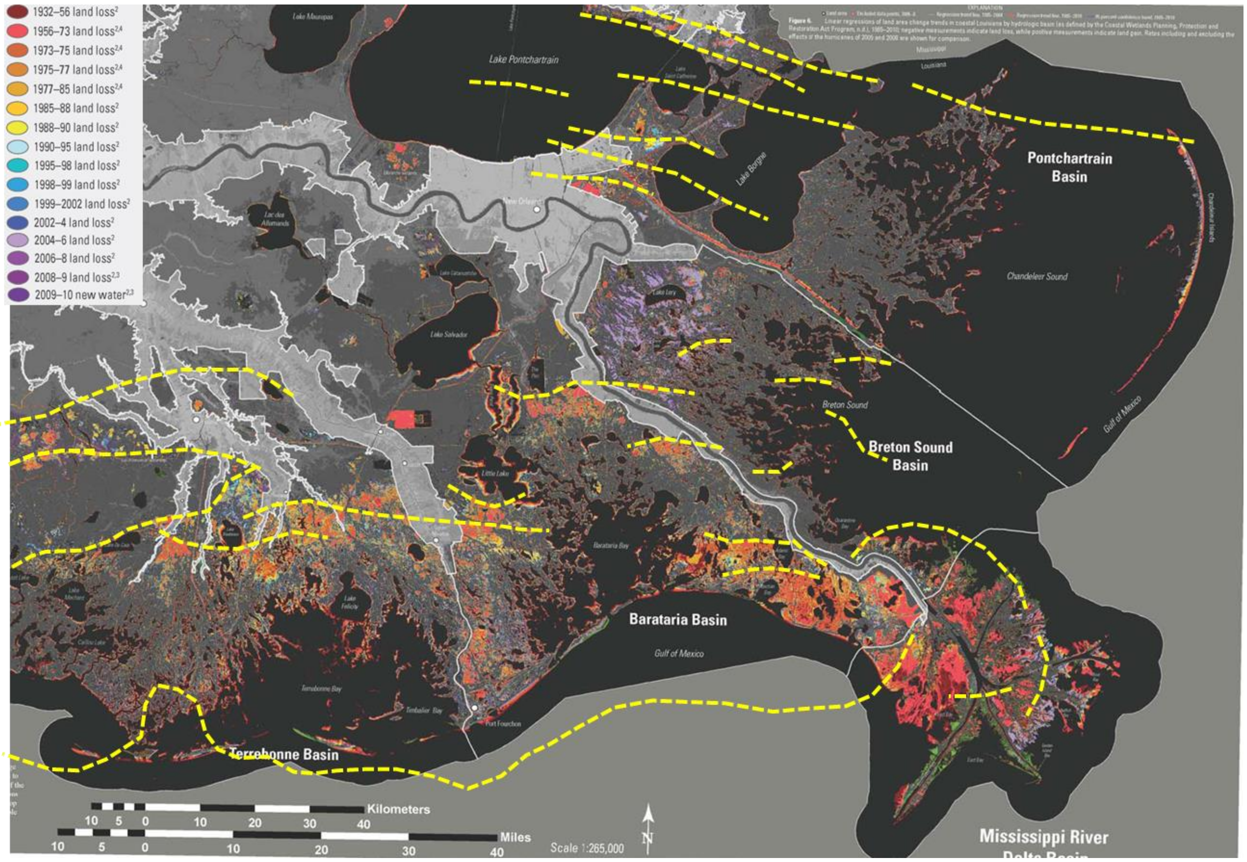



**Armstrong, C, et.al.**., 2014, Influence of growth faults on coastal fluvial systems: Examples from the late Miocene to Recent Mississippi River Delta, Sedimentary Geology, v 301, p. 120-132

The reality of coastal land loss due to subsidence is one that impacts all inhabitants and industries across the coastal plain. The oil and gas industry has major infrastructure investments in port facilities across the coast, and the management of these facilities will require an accurate forecasting of the effects of subsidence. To this end the industry should support research into the accurate measurement of subsidence, such as that being conducted at the L.S.U. Center for GeoInformatics, and into the underlying geological factors that are causing subsidence, such as faulting. A study published in 2014 by the University of Texas began the process of mapping surface fault traces in portions of Plaquemines and St. Bernard Parishes using 3-D seismic data volume that was presumably donated to the University by Schlumberger through its subsidiary WesternGeco. A map of surface fault traces interpreted in this study is shown on the previous page. This type of cooperative relationship between the industry and academia should be encouraged and expanded to provide research for all interested parties across the coastal plain. Chief among those would be the coastal restoration and protection industry.




This map shows the outline of the proposed Morganza-to-the-Gulf levee system and two marsh creation projects that are parts of the proposed sediment pipeline project. This is the same area of investigation considered in this proposal, and the traces of the surface faults are superimposed on the project outlines. Given the subsidence velocities that have been measured by tidal gauge data, and direct association of that subsidence with the faults shown on this map, the proponents of these projects would obviously benefit from an accurate mapping of the surface fault traces, an interpretation of relationship between those fault and subsidence, and a prediction of the effects of fault-driven subsidence on the projects.  Every other proposed coastal restoration or protection project across the coast is potentially affected by fault-driven subsidence and would also benefit greatly from this type of research.




The oil and gas industry is uniquely positioned to take a leadership role in engaging in, promoting, and financially supporting research into the causes and effects of subsidence in coastal Louisiana.  The proposed Atlas of Surface Fault Traces in South Louisiana would have both an immediate utility in all forms research and evaluation relating to existing and proposed projects and infrastructure on the coastal plain, and would provide a foundation for future expanded research projects.

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