2023 Coastal Master Plan
Project Concept Proposal

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Introduction

This proposal is presented in response to the public solicitation by the Louisiana Coastal Protection and Restoration Authority (CPRA) for project concepts “that continue to provide benefits in the face of sea level rise and subsidence without continued maintenance, those that contribute to maintaining estuarine gradients in future decades, and those that provide risk reduction at the community or regional scale”. The final section of this proposal will outline the concepts for a set of projects. The conceptual framework for these project proposals is based on the natural processes of sediment accretion and subsidence in the intermediate to saline marshes of the Mississippi River delta plain. There appear to be significant portions of these marshes where rates of natural sediment accretion and subsidence are favorable to sustainability. This proposal will suggest that by delineating areas where accretion rates are high compared to rates of relative sea level rise and supplementing the supply of sediment that is feeding natural accretion, long-term sustainability of these marshes can be attained. It will be proposed that accretion in the intermediate to tidal marshes is occurring mostly by transportation by tidal flux, and supplementing these processes with sediment from outside of the estuaries will enhance accretion. In order to present these project concepts in the proper context it will be necessary to establish the scientific framework on which they are based. Prior to the discussion of project concepts this proposal will lay out a framework for the scientific concepts and how they factor into the conception, design and planning of the projects. This framework will rely in large part on the body of research and investigation that has been produced either directly by or in collaboration with the Louisiana Geological Survey (LGS). It is an implicit corollary recommendation of this proposal that there should be a direct engagement between CPRA and LGS in the implementation of the recommendations of this proposal.

Premise

Scientific investigation of the Mississippi River delta plain has been advancing at a rapid pace. Twelve of the technical papers, presentations or poster sessions referenced here have been published in the last two years. This research has established four essential areas of investigation that to date have either not been adequately defined or that have lacked adequate data to be incorporated into the conception and design of coastal sustainability projects:

- Measurement of Subsidence Rates
- Measurement and Mapping of the Thickness of Holocene Deltaic Sediments
- Measurement and Mapping of the Composition of Holocene Deltaic Sediments
- Identification and Mapping of Faults and Salt Domes

Each of these areas of investigation have been historical functions of the Louisiana Geological Survey in the past. The viability of these functions at LGS have been diminished or lost due to finance and resource constraints over the past few decades. A principal premise of this proposal is that integrating these essential areas of investigation into coastal sustainability planning should come primarily from the re-establishment of some of these functions within LGS and a re-vitalization of the LGS budget. Specific examples of how these functions can be re-established and how these functions of LGS can contribute directly to the conception, design and implementation of the set of project proposed here will be presented throughout this proposal.

Proposal Outline

Features and Processes

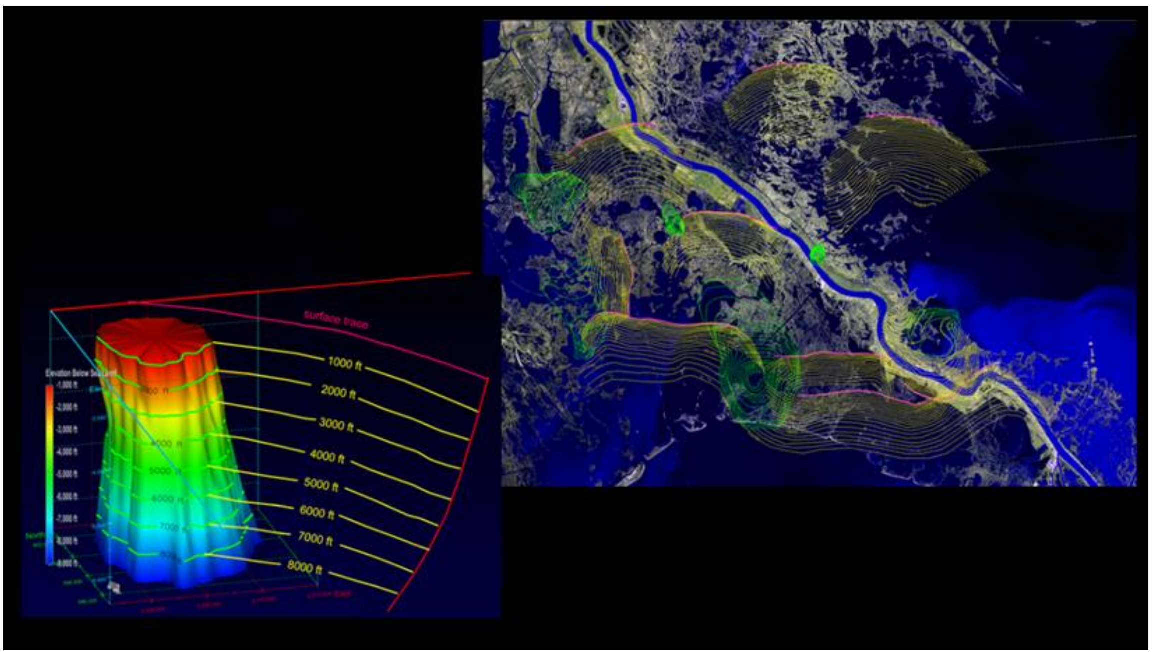
- **Neo-tectonic Framework**
  - Faults
  - Salt Domes
  - Pre-Quaternary Geologic Structure
- **Sediments of the Holocene Epoch**
  - Age
  - Composition
  - Thickness
- **Recent Processes**
  - Subsidence
  - Accretion
  - Surface Elevation Change
  - Land Area Change

Evaluation Procedures

- **Data Collection**
  - Subsidence Rate Measurement
  - Sediment Core and Boring Collection
  - High Resolution Seismic Acquisition
- **Data Integration and Mapping**
  - Pre-Quaternary Subsurface Mapping
  - Quaternary Subsurface Mapping
  - Holocene Subsurface Mapping
  - Map, Data & Cross-Disciplinary Integration
- **Predictive Modeling**
  - Subsidence from Thickness and Composition of the Holocene
  - Sediment Accretion
  - Surface Elevation Change
  - Land Area Change
- **Combining Features and Processes with Predictive Model Inputs**
  - Neo-tectonic Framework and Holocene Thickness
  - Neo-tecontic Framework and Holocene Composition
  - Neo-tectonic Framework Subsidence, Accretion and Land Area Change

Features and Processes

1. **Neo-Tectonic Framework –** The phrase "neo-tectonic framework" in reference to coastal Louisiana was coined by Dr. Sherwood Gagliano in the publication NEO-TECTONIC FRAMEWORK OF SOUTHEAST LOUISIANA AND APPLICATIONS TO COASTAL RESTORATION, which was published in the Transactions of the 53rd Annual Convention of the Gulf Coast Association of Geological Societies held in Baton Rouge, Louisiana in 2003. This publication was contemporaneous with the report ACTIVE GEOLOGICAL FAULTS AND LAND CHANGE IN SOUTHEASTERN LOUISIANA - A Study of the Contribution of Faulting to Relative Subsidence Rates, Land Loss, and Resulting Effects on Flood Control, Navigation, Hurricane Protection and Coastal Restoration Projects, U. S. Army Corps of Engineers, New Orleans District, Contract No. DACW 29-00-C-0034, Gagliano et al., 2003.



Salt dome and fault contours McLindon, 2017 Figure 1

The Corps of Engineers report reaches five fundamental conclusions:

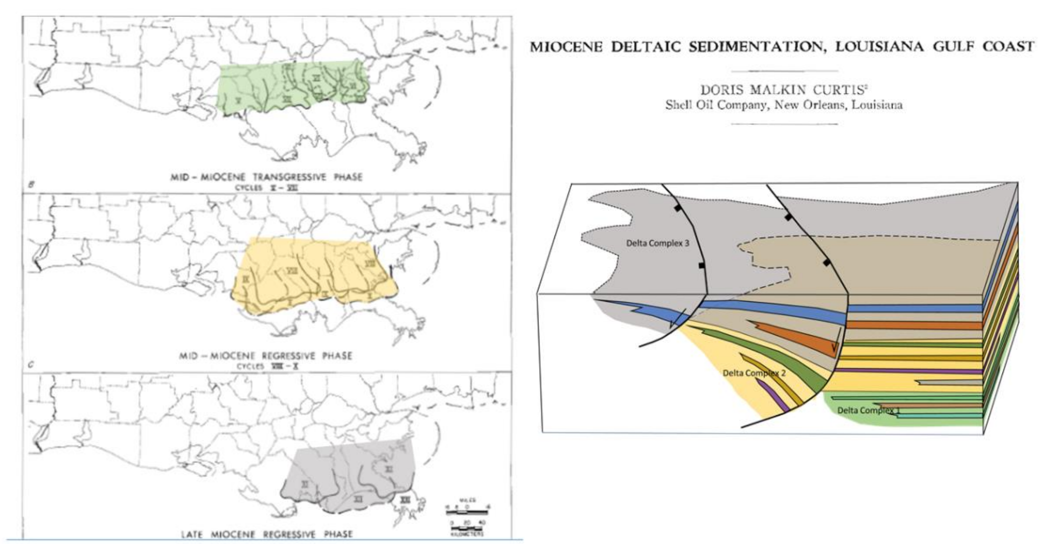
- Submergence of coastal wetlands due to a combination of compaction, sea level rise and fault slip has been the major cause of land loss in the delta plain during the 20th century.
- Fault movement in the area of the modern delta plain has been continual and episodic for millions of years. Episodes of active fault movement are separated by dormant periods when movement persists as slow creep. An episode of fault slip between 1964 and 1980 appears to be associated with significant land loss on downthrown sides of faults.
- There is a relationship between faults and salt structures. Ductile, incompressible, low density salt moves relative to surrounding compacting sediments; and this movement of salt interacts with faults associated with the salt structures.
- Continual episodic and slow creep fault slip may cause preferentially thicker accumulations of compactible organic clays and peats on the downthrown side of the

faults, thereby delineating areas where subsidence rates may be higher due to the greater compactibility of the soil column.

- Faulting poses a natural hazard in southeastern Louisiana, and the findings of the report have direct applications to the planning and design of coastal restoration efforts, including infrastructure elements.

It is the relationship between faults and salt domes that defines the overall structure of the framework, and it is the evidence of recent movement relative to the Earth's surface that makes it neo-tectonic. The framework nature of the faults and salt domes can be seen in the network of fault plane and salt dome subsurface depth contours on Figure 1. The salt dome contours are shown in green and the fault plane contours are shown in yellow.

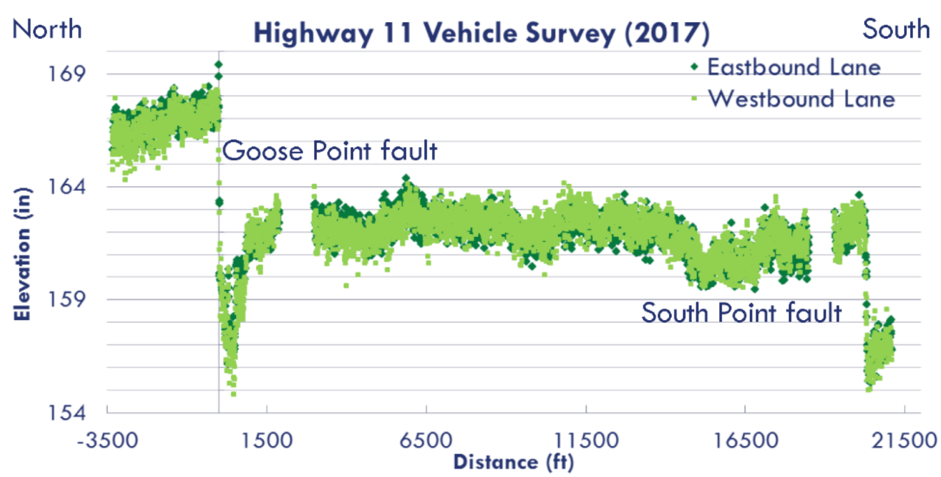
a. **Faults -** Since at least the middle of the Miocene Epoch 15 million years ago faults have been an integral part of the geological evolution of southern Louisiana. Throughout that time span there has been a very strong genetic relationship between faults and the delta systems of the ancestral Mississippi River. Figure 2 from Curtis, 1970 shows the interaction between the Miocene deltas and the faults crossing the coastal plain. The sediments of each successive delta complex are stacked vertically, and each of the delta complexes interacted with a new major fault complex as the system prograded basinward. In simplest terms the delta complexes tended to seek out the accommodation capacity provided by the faults to deposit the sedimentary load of the river. This degree of interaction makes it clear that faults have historically been as much a part of the delta complexes as channels, bars and crevasses. The mapping and measurement of fault slip and associated subsidence will be addressed in this proposal in relation to each component of the Data Collection, Data Integration and Mapping, and Predictive Modeling in the Evaluation Procedures section.



Miocene deltas and fault model Curtis, 1970 Figure 2

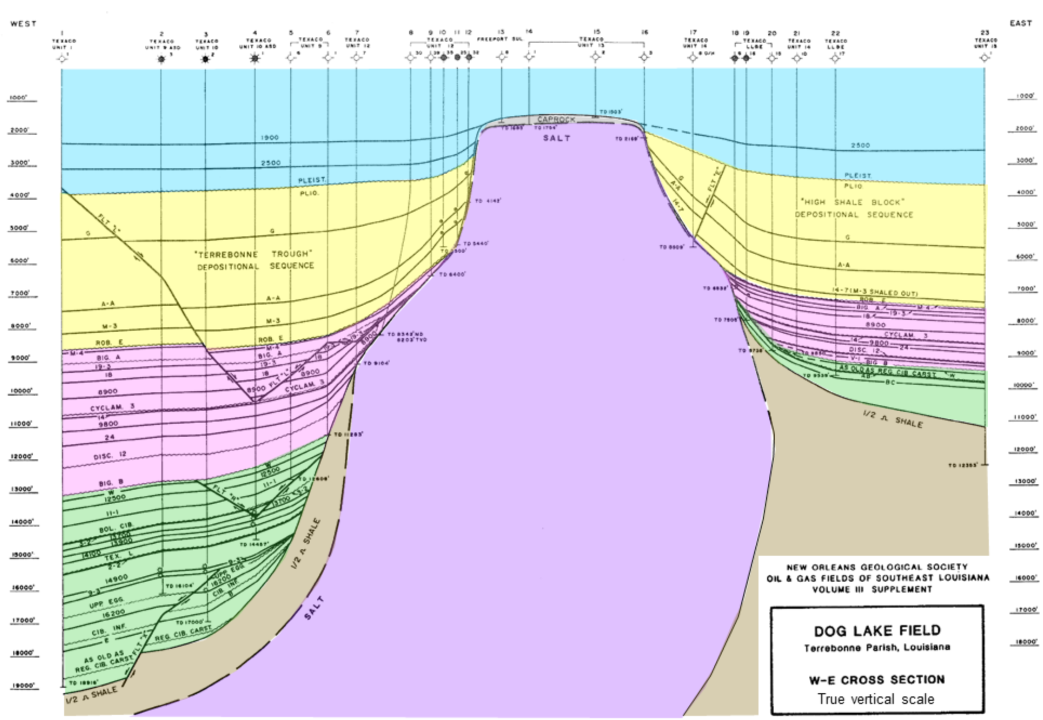
LGS has been at the forefront of fault mapping and research in south Louisiana for several decades. This includes the publication of several LGS Open-File Reports on faulting and several other peer-reviewed technical publications by LGS geologists. LGS has most recently published the Louisiana Landforms Map, which documents the surface expression of faults mapped by LGS geologists and others. LGS is currently engaged in the development of the Louisiana Coastal Geohazards Atlas, which is intended in part to document the surface expression of faults across the coastal zone. It is anticipated that the faults mapped in the LGS Coastal Geohazards Atlas will eventually play a critical role in coastal sustainability planning, design and implementation.

i. **Footwall uplift** – Figure 3 is an elevation profile of the Highway 11 Bridge crossing Lake Pontchartrain. This figure is from a presentation given by the Lake Pontchartrain Basin Foundation at the 2018 Louisiana State of the Coast Conference (Hopkins et al, 2018). The profile shows three interesting characteristics of the faults crossing the bridge at the two locations indicated. 1) The downthrown or hanging wall fault block has its lowest elevation immediately adjacent to the fault. 2) The entire span of the hanging wall fault block of the Goose Point fault is down-dropped relative to the upthrown or footwall side of the fault. This means that movement on the fault has caused subsidence of the entire hanging wall block, an area potentially covering 30 to 40 square miles. 3) The footwall block of both faults increases in elevation toward the fault. This latter characteristic appears to relate to the geological phenomenon called "footwall uplift" in which the downward movement of the hanging wall side of the fault is mirrored by an upward movement on the footwall. There are very few, if any, other elevation profiles of this resolution across other faults in south Louisiana. It is not know the extent to which footwall uplift is expressed on other faults. It is an assumption of this proposal that the footwall uplift apparently expressed in Figure 3 is more likely than not to be associated with other faults,



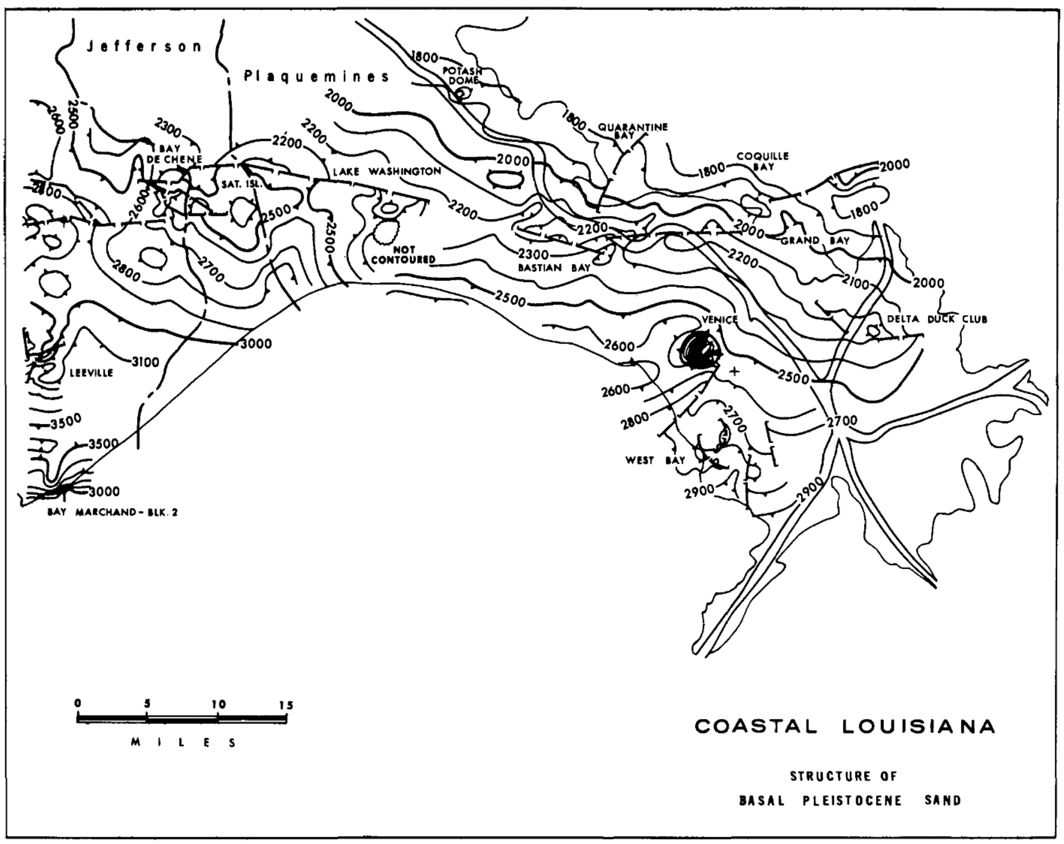
Elevation profile Hopkins et al, 2018 Figure 3 and perhaps many other faults in south Louisiana. The implications for this phenomenon in coastal sustainability planning will be discussed further in the Predictive Modeling section.

b. **Salt domes** – Salt domes have generally dictated the structural evolution of south Louisiana since the deposition of the original salt layer in the middle Jurassic Period. Salt domes interacted with faults and deltas throughout the Miocene Epoch. Active salt movement throughout most of the Cenozoic Era is evidenced by thinning of sedimentary strata onto the domes. The LGS report INVESTIGATION AND GIS DEVELOPMENT OF THE BURIED HOLOCENE-PLEISTOCENE SURFACE IN THE LOUISIANA COASTAL PLAIN, Heinrich et al, 2015 examined the relationships between salt domes and the thickness of Holocene sediments in the coastal plain. The report listed thirty salt domes in the coastal zone that are indicated to have had diapiric movement during the Holocene Epoch. It is also important to note that Attachment C-2 "Subsidence" to the 2017 Master Plan included five of those salt domes in subsidence polygon 16 which was assigned an estimated subsidence rate of -2 to -3 millimeters per year. Negative subsidence rates indicate uplift of the Earth's surface, and many salt domes across the coastal plain may be providing support against subsidence through passive diapirism. This role of salt domes in affecting Holocene sediments and recent processes will be considered in the Evaluation Procedures section. Figure 3 from the New Orleans Geological Society (Vodicka, 1987) shows the thinning of sedimentary layers onto the Dog Lake salt dome in Terrebonne Parish. Thinning extends into the Quaternary indicating relative uplift of the dome by passive diapirism.



Salt dome profile Vodicka, 1987 Figure 4

c. **Geologic structure of the pre-Quaternary** – In order to properly establish the Neo-Tectonic Framework it is necessary to map faults and salt domes at depths below the base of the Quaternary. To fully understand the relationships between the neo-tectonic framework, the sediments of the Holocene, and recent coastal processes, it is helpful to map the geologic structure of the pre-Quaternary. In most areas of southeastern Louisiana highly correlative sand layers in the lower Pleistocene or upper Pliocene can be used to map the structure of the pre-Quaternary. Figure 5 from Sabate, 1968 shows a subsurface structure map on one of the lower Pleistocene sands. This interpretation reveals that the lower Quaternary is offset by faults and impacted by the passive diapirism of salt domes. The subsurface depth contours for many of the faults and salt domes that are represented in Figure 5 can also be seen in Figure 1. This type of subsurface structural interpretation using oil and gas industry seismic data and well logs is a foundational component of the LGS Coastal Geohazards Atlas. The process of mapping is discussed in more detail in the Data Integration and Mapping section of the Evaluation Procedures.



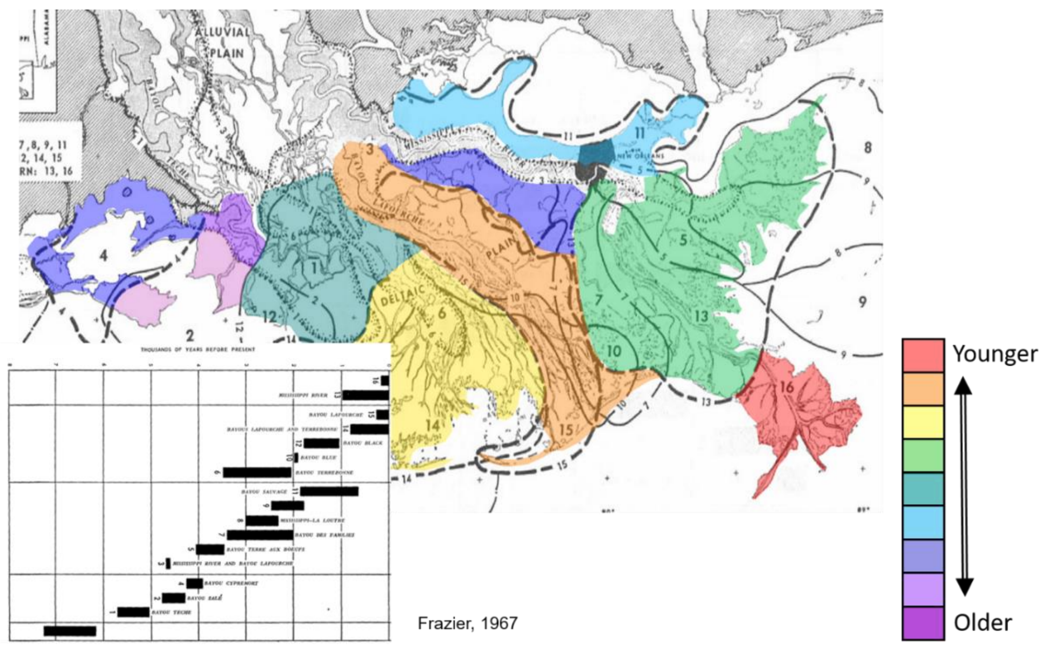
Lower Quaternary subsurface structure map Sabate, 1968 Figure 5

Features and Processes

2. **Sediments of the Holocene**

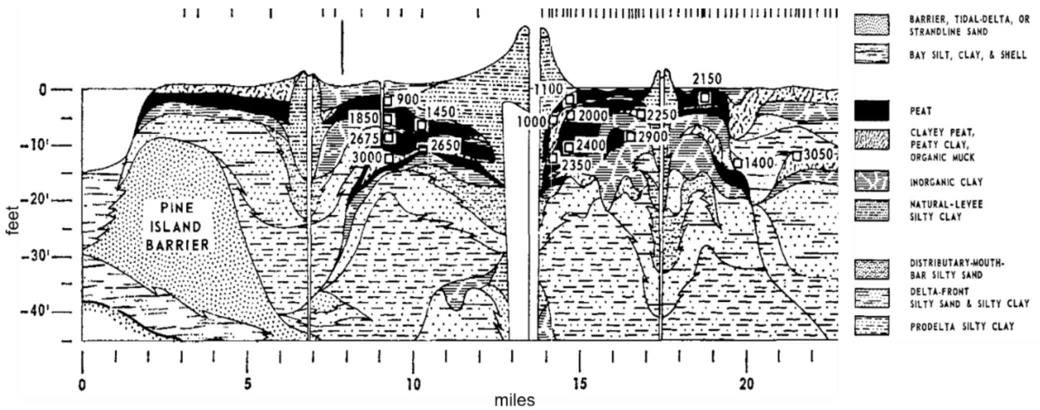
The importance of understanding the age, thickness and composition of the Holocene sediments of the coastal plain is documented by the publication RECENT SUBSIDENCE RATES FOR THE BARATARIA BASIN, LOUISIANA, Byrnes et al, 2019. This study found that "Spatial variability in subsidence indicates a compelling relationship between subsidence rates and the age, composition, and thickness of Holocene deltaic deposits." Measuring and mapping the age, composition and thickness of the Holocene have been historical functions of LGS. Much of that functionality has been diminished in recent decades.

a. **Age of the Holocene –** Byrnes et al, 2019 states: "Consolidation of Holocene deposits is considered the principal contributor to subsidence the Louisiana coastal zone … Primary consolidation occurs as soil volume is reduced due to dewatering under the weight of overlying sediment. Oxidation of organic matter through chemical reactions also reduces soil volume. Fine-grained deposits with high water content characterize the Louisiana coastal zone. Thicker sediment deposits contain more interstitial water available for removal, which leads to high rates of subsidence as they consolidate. Older deltaic deposits have undergone primary consolidation for a longer period and therefore should exhibit lower subsidence rates that recently deposited sediments"



Age of marsh deposits, underlying map from Frazier, 1967 Figure 6

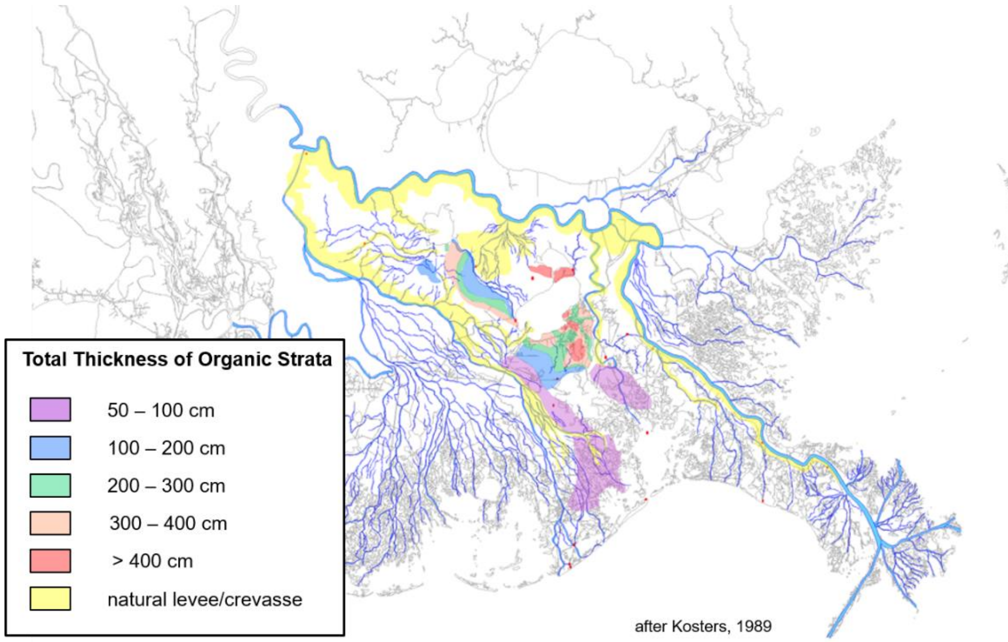
The age of the Holocene deltaic sediments can be considered in two dimensions. Figure 6 shows the areal dimension as an approximation of the relative age of the most recently deposited sediments in the southeastern Louisiana coastal plain based on the last time there was an active delta in that area. Historical maps and navigation charts show that sediments of the Balize or "birdfoot" delta have been deposited over the most recent three centuries. These are almost certainly the most recent deposits in the coastal plain and are likely to be experiencing the highest rates of subsidence due to shallow consolidation and dewatering. By contrast, the marshes bordering the eastern shore of Atchafalaya Bay are made of sediments that were deposited during the active phase of the Teche delta about 4,500 years ago. These sediments are likely to have significantly compacted and dewatered during that time, and the magnitude of subsidence that could be attributed to these processes is likely to be significantly lower in this area than it is in the birdfoot delta.



Sediment boring profile Frazier, 1967 Figure 7

Figure 7 is a boring profile across the city of New Orleans from Frazier, 1967 in which the vertical dimension of the age of Holocene sediments can be considered. The numerical values are radiocarbon measurements of the age of organic material within the sediments (usually rangia clam shells or peat). Younger sediments are generally found at shallower depths than older sediments. The age and depth of burial must both be considered in assessing the degree to which the sediments have consolidated and dewatered. It would be exceedingly difficult, if not impossible, to make a definitive determination of the degree to which the magnitude of subsidence varies across the coastal plain due to variations in age of the sediment. It should be anticipated in general that the younger marsh deposits should have a higher current subsidence rate than the older marsh deposits if all other factors were held equal.

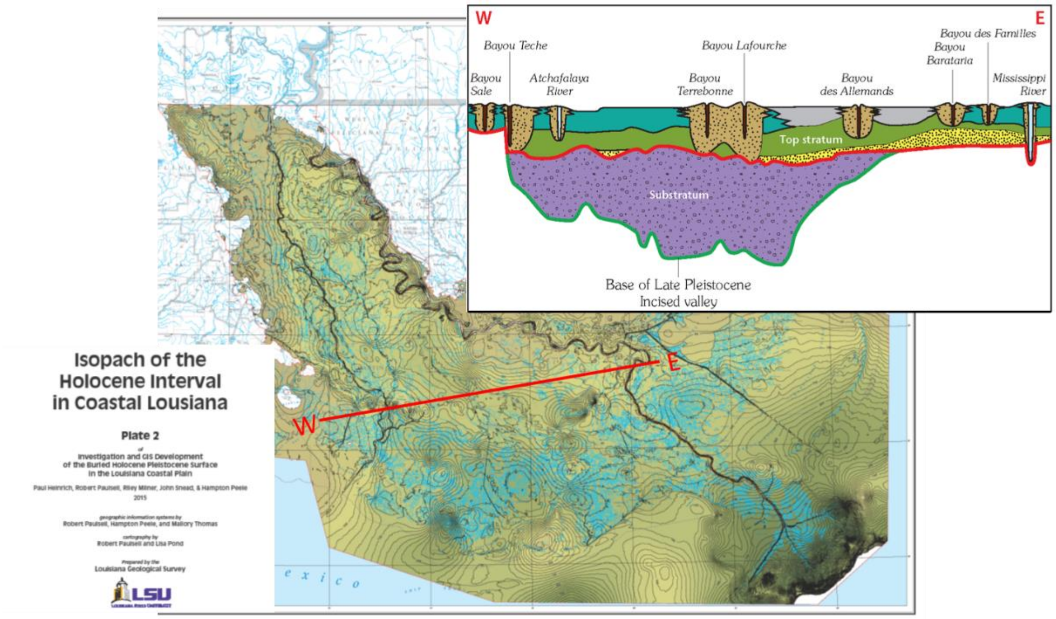
b. **Composition of the Holocene** – Figure 7 also shows the variation in the composition of the Holocene deltaic sediments. The organic-rich clays and peats that accumulate in the interdistributary swamp and marsh environments have considerably higher water content and more compactable matrix than the sands and silts of the natural levee and crevasse splay deposits. Figure 8 is a map of the thickness of organic strata taken from the report ORGANIC-CLASTIC FACIES RELATIONSHIPS AND CHRONOSTRATIGRAPHY OF THE BARATARIA INTERLOBE BASIN, MISSISSIPPI RIVER DELTA PLAIN published by LGS geologist Dr. Elisabeth Kosters in 1989. The areas of thick accumulations of highly organic soils can be expected to have higher subsidence rates than the natural levees that bound them. This map was constructed by LGS with 115 vibracore and McAuley auger borings. There would be significant value in extending this type of mapping across the coastal plain, and LGS could play an important role in achieving that objective. As will be discussed in the Data Collection and Data Integration and Mapping sections of the evaluation procedures recommended in this proposal, there are tens of thousands of cores and borings scattered across the coastal plain which could provide valuable data to construct maps of the composition of Holocene deltaic sediments.



Thickness of organic strata after Kosters, 1989 Figure 8

c. **Thickness of the Holocene** – The most direct and mappable relationship between subsidence and the sediments of the Holocene in coastal Louisiana appears to be with sediment thickness. Byrnes et al, 2019 states "… areas of the deltaic plain overlying thick Holocene deposits within the entrenched Mississippi River valley are expected to subside at higher rates than areas outside the valley where Holocene sediment thickness is less". The most comprehensive attempt to map the thickness of Holocene sediments in the coastal plain was undertaken by LGS in the Heinrich et al, 2015 report. Their report included the isopach map and profile shown in Figure 9. LGS investigated over 15,000 published and unpublished public sources of boring data to create this report. These were still a fraction of the total estimated number of cores and borings that have been collected by private companies and are generally not accessible for contribution to this type of project. This will be discussed in more detail in the Evaluation Procedures section.

It is important to understand that the thickness of the Holocene sediments has both a cause and effect relationship with historical and current rates of subsidence. The concentric closed contours in the areas of Barataria and Terrebonne Bays on the LGS isopach map conform to the axis of the Terrebonne Trough, a fundament structural feature of the geology of the coastal plain. The Terrebonne Trough is bounded by faults and salt domes. The sedimentary layers of the Miocene, Pliocene and Pleistocene Epochs are all thicker within those bounds. Sediments within the trough are denser and more compacted, and the differential weight of this thick, dense accumulation of sediment drives the continual subsidence of the trough. Subsidence rates are higher where Holocene deltaic sediment thicknesses are greater, but Holocene thicknesses are greater along the axis of the Terrebonne Trough where existing higher subsidence rates allowed thicker deposits of the Holocene to accumulate. This is why it is important to integrate mapping pre-Quaternary Geology into an understanding of current subsidence rates.



Holocene isopach map Heinrich et al, 2015 Figure 9

Features and Processes

3. **Recent Processes**

The cumulative effects of the interaction between the neo-tectonic framework and the sediments of the Holocene Epoch are manifest in the recent processes of subsidence, accretion, surface elevation change, and land area change. These processes are in turn the essential metrics of coastal sustainability. The ability to effectively understand, measure, map and model these recent processes will ultimately determine the success of any coastal sustainability effort.

a. **Subsidence** – Byrnes et al, 2019 defines subsidence as “downward movement of the earth’s surface relative to a datum such as sea level”. Subsidence is expressed and measured at the earth’s surface. Unnecessary complication has been introduced into the understanding of subsidence by the use of the phrases “deep subsidence” and “shallow subsidence”. Byrnes et al, 2019 enumerates a list of processes that may contribute to the magnitude of the rate of subsidence measured at the earth’s surface. These include natural causes such as the consolidation of Holocene, Pleistocene, and Tertiary age sediments, fault-induced elevation changes due to basin tectonics, and down-warping of the underlying lithosphere due to sediment loading. They also include human-induced causes such as lowering the groundwater table, overburden associated with flood protection levees, and marsh settling due to altered hydrology. Some of these processes may be rooted in geological processes that are happening deep within the earth, such as down-warping of the lithosphere, and some may be rooted in very shallow processes, such as near-surface consolidation. While the processes contributing to the vertical velocity of the surface may vary with depth, subsidence itself cannot be divided into “deep subsidence” and “shallow subsidence” in any meaningful way.

In Byrnes et al, 2019 campaign-style geodetic GPS (global positioning system) elevation measurements (8- to 24-h continuous measurements for a minimum of two separate days) were evaluated for CPRA/National Geodetic Survey secondary benchmarks and Continuously Operating Reference Station (CORS) elevations (primary survey markers). USACE, USGS, and NOAA water-level gauge measurements were also evaluated for documenting subsidence relative to eustatic sea-level rise estimates for the northern Gulf of Mexico. Some of the earliest work in estimating relative sea level rise and subsidence rates from water-level gauge measurements in Louisiana was conducted by LGS. The basic methodology used by Byrnes et al, 2019 was employed in LGS Coastal Geology Technical Report No. 3 RELATIVE SEA LEVEL RISE AND SUBSIDENCE IN LOUISIANA AND THE GULF OF MEXICO, Penland et al, 1988, and Report No. 4 “RELATIVE SEA LEVEL RISE AND DELTA-PLAIN DEVELOPMENT IN THE TERREBONNE PARISH REGION, Penland et al, 1988. The interpretation of relative sea level rise from water-level gauge measurement by LGS is shown in the graphs of the right of Figure 10. These data were used by Morton et al, 2002 to make the first published map of subsidence rates in coastal Louisiana. It is important to note that the magnitude of relative sea level rise in these evaluations peaked in the 1970s, and the values on the map represent the maximum rates of relative sea level rise over several decades. It appears that the variation of subsidence rates over time are best understood as an event that peaked in the 1970s.

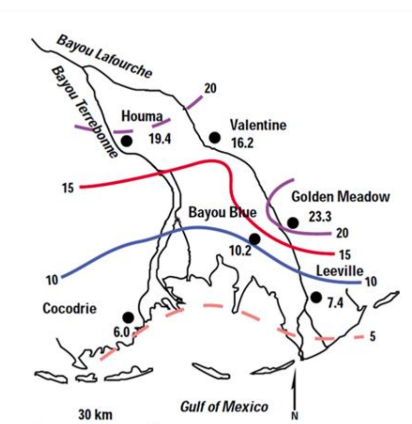
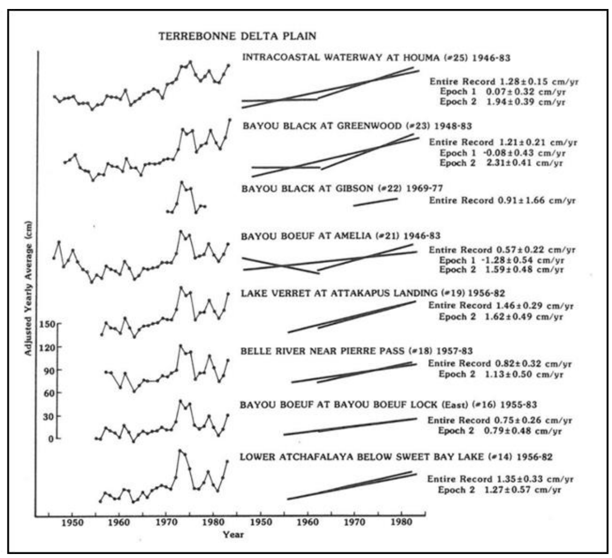


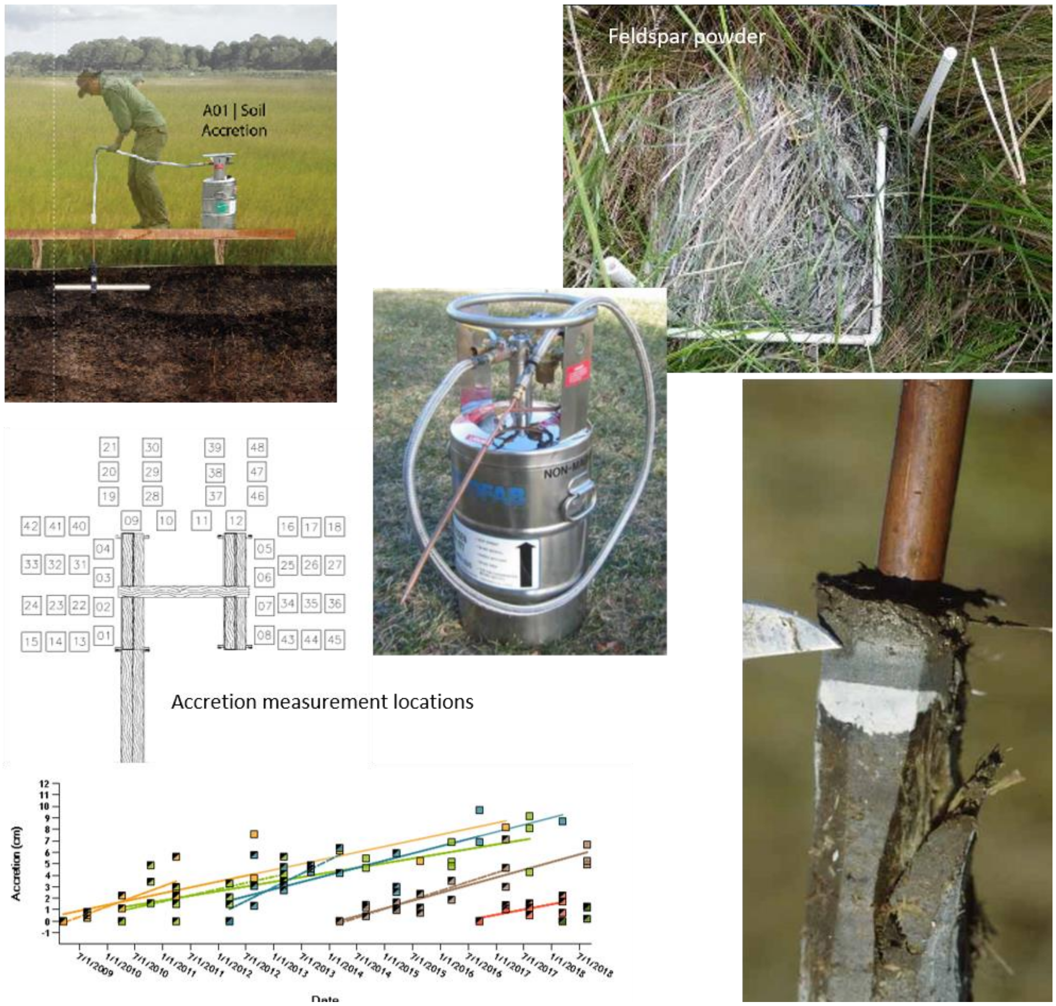
Figure 14. Historical rates of delta plain submergence recorded at interior tide gauges operated by the U.S. Army Corps of Engineers in Terrebonne and Lafourche Parishes. Rates of submergence (mm/yr) are from Penland et al. (1988).



Relative sea level rise Morton et al, 2002 (left) Penland et al, 1988 (right) Figure 10

Recommendations for expanding the scope of subsidence rate measurement will be considered in the Data Collection section of Evaluation Procedures. The recent process of subsidence will be considered in relationship to the Neotectonic Framework and the Sediments of the Holocene in the Predictive Modeling section of Evaluation Procedures.

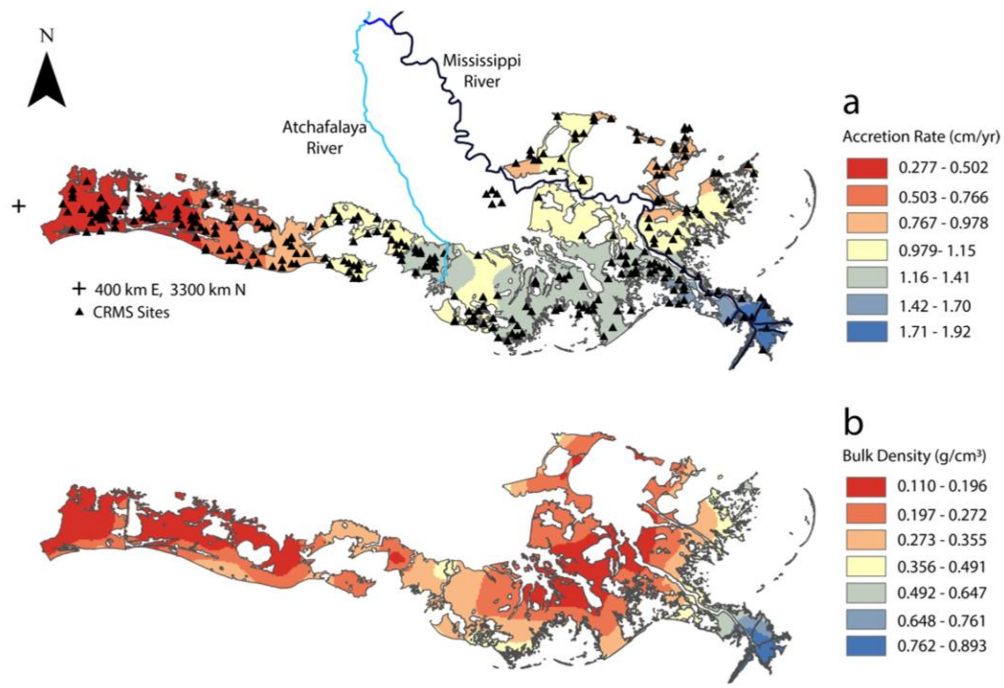
b. **Accretion** – Some important work on sediment accretion in the Louisiana marshes was done at LGS in the late 1980s. The results of some of this research was published in 1994 in the report STORM DEPOSTION AND ^{137}Cs ACCUMULATION IN FINE-GRAINED SEDIMENTS OF THE MISSISSIPPI RIVER DELTA PLAIN, Chumra and Kosters, 1994. This study was able to relate anomalies in sediment accretion in the marsh to tropical storms.



CRMS accretion

Figure 11

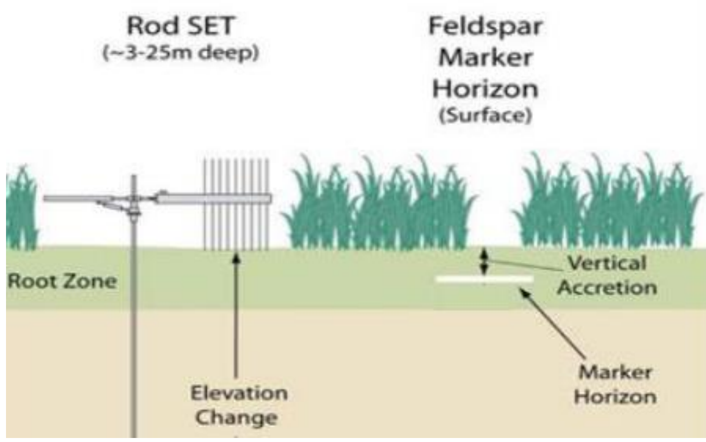
The Coastwide Reference Monitoring System (CRMS) was establish under the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA), which passed in 1990. Significant data from CRMS has accumulated within the past two decades, and is now allowing for detailed evaluation of accretion and other important processes. Data from CRMS was used by Bianchette et al, 2015 to measure sediment accretion rates in the marshes associated with Hurricane Isaac in 2012. Many of the nearly 400 CRMS stations have been measuring accretion data for a decade or more. A typical CRMS marsh location includes elevated boardwalks in an H-shaped configuration. Accretion data is measured by a set of procedures in which a white feldspar powder is spread on the surface of the marsh at designated locations around the boardwalks. At regular intervals sediment samples are recovered by inserting a tipped slim copper tube into the soil column and filling it with liquid nitrogen. This process freezes the sediment around the tube and allows for the extraction of an undisturbed core-like sample. The surface created by the feldspar powder is obvious as a white layer within the core. The thickness of sediment accreted at the site can be measured above the white layer. Over time multiple feldspar markers at multiple locations around each site provide enough data to allow for accurate estimates of long and short term accretion rates through statistical analysis. Figure 11 illustrates the essential elements of accretion measurement process and a typical graphical representation of the data from one site, shown at the lower left.



Accretion and bulk density from CRMS Sanks et al, 2019 Figure 12

This body of data shows that sediment accretion is a significant recent process across the coastal plain. Accretion appears to be happening in freshwater, intermediate, brackish and saline marshes. Sediment sources are likely to be some combination of river-borne suspended load and sediment carried in from estuaries by tidal flux. Accretion in most of the saline marshes in the Terrebonne, Barataria and Breton Basins appears to be primarily sourced by the latter of these processes. Figure 12 is a map of average long-term accretion rates and sediment bulk densities from Sanks et al, 2019. The recent process of accretion will be considered in relationship to subsidence, surface elevation change, and land area change, as well as the neotectonic framework and the sediments of the Holocene in the Predictive Modeling section of Evaluation Procedures.

c. **Surface Elevation Change** – The methodology for measuring surface elevation change was established by Cahoon et al, 2000. This methodology has been employed by CRMS to record data over the past two decades. As shown in Figure 13, a rod surface elevation table (R-SET) is established by driving the rod to refusal and surveying its elevation. A set of fiberglass rods are suspended from an arm with is perpendicular to the rod. This allows for the direct measurement of the elevation of the surface of the marsh relative to the R-SET. Changes in surface elevation are not measurements of positive or negative velocities relative to a fixed datum such as sea level, but only to the surveyed elevation of the R-SET. In order to relate changes in surface elevation measured at a CRMS site to subsidence it would be necessary to survey the site on a repeated basis to determine changes in elevation relative to the fixed datum, or the site would have to be equipped with a GPS device.

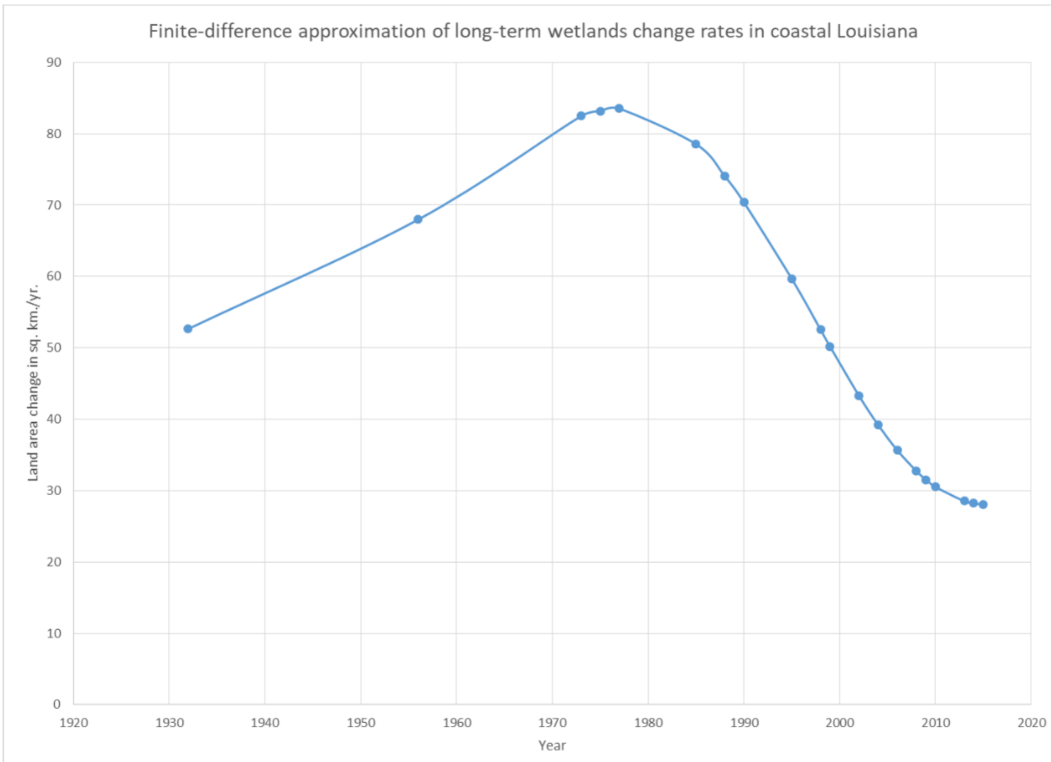


CRMS surface elevation change Figure 13

An evaluation of CRMS surface elevation change data was presented by Leigh Anne Sharp and Camille Stagg at the 2018 State of the Coast Conference. They found "… 332 [CRMS] sites have surface elevation data that can be assessed along with land change data to infer which processes are influencing recent land change … In the Deltaic Plain land loss, in general, is not associated with elevation loss, suggesting that erosion, not subsidence, may be responsible for continuing land loss there. Over the last decade, wetland surface elevation trajectories have been positive at 75% of sites, including those in coastal areas near the Mississippi River delta that have seen the most historic land loss. Land change data reveal continuing land loss at just 14% of CRMS sites and land gain at 10% of CRMS sites including those in the birdsfoot delta and in the upper Mermentau basin. Furthermore, at least eight sites that were classified as floating marsh at project inception are now attached, including sites downstream from diversions and near the Atchafalaya delta. In general, CRMS data reveal that the coast of Louisiana is dynamic, that much of it has been stable in recent years, and that restoration efforts in concert with natural processes have increased stability in some areas".

d. **Land Area Change** – The dynamic nature of the coastal deltaic plain has meant that the total wetlands area that could be measured at any one point in time has been in a constant state of flux throughout the natural history of the area. The ability to accurately measure wetlands area began with the publication of the U.S. Coast and Geodetic Survey

Air Photo Compilation Sheets (T-Sheets) in 1932-33. The ability to measure land area change began with the publication of Tobin Surveys from black and white aerial mosaics in 1956-58 because change could be measured by a comparison of the two data sets. The advent of NASA Landsat Color IR satellite imagery in 1973 meant that highly accurate measurements of land area and land area change could potentially be measured on an annual basis from that point forward. Several investigators including Gagliano, Meyer-Arendt and Wicker, 1981; Turner and Cahoon, 1988; May and Britsch, 1987; and Dunbar, Britsch and Kemp, 1992 have used a comparative methodology among these data sets to measure land area change. The current definitive study is U.S.G.S. Scientific Investigations



Land area change - data from Couvillion et al, 2017 pamphlet Figure 14

Map 3381 LAND AREA CHANGE IN COASTAL LOUISIANA 1932 TO 2016, Couvillion et al, 2017. This study does very careful analysis of the data to insure the alignment of the various vintages of the imagery, and very careful statistical analysis to get the best fit to a curve that provides a meaningful representation of the data. Figure 14 shows the rate of change in coastal wetlands area over time calculated from fitted models using finite difference approximation (positive values indicating rates of land loss). This graph suggests that land area change in coastal Louisiana can best be understood as an event that peaked in the mid-1970s. Estimates of the rate of change of land area have been decreasing since then. SIM 3381 notes that a “coastwide net ‘stability’ in land area has been observed over the past 6-8 years [prior to 2016]”.

There is a very strong interdependency among the features and processes considered here. The neo-tectonic framework has significant control over the patterns of age, composition and thickness of the Holocene deltaic sediments. Any evidence for neo-tectonic activity in the Holocene Epoch is likely to be manifest in within the record of the age, composition and thickness of the Holocene sediments. The interplay between those features of the delta plain has significant control over the processes of subsidence, accretion, surface elevation change, and land area change. In order to properly evaluate the relationships among these features and processes it is necessary to collect, integrate and map an appropriate set of evaluation data. The proposal for data collection, integration and mapping are detailed in the next section. Given an appropriate data set, effective predictive models can be made to assess the likely impacts of each of the recent processes on coastal sustainability. The final section of this proposal will describe the conceptual framework and specific detail for a set of projects borne out of the anticipated results of the set of predictive models.

Evaluation Procedures

4. **Data Collection** – there are three principal areas of proposed data collection:

    a. **Direct Measurement of Short Term (Current) Rates of Subsidence** – Recent studies such as Byrnes et al, 2019 indicate that high resolution GPS elevation surveys should be relied upon more frequently for determining subsidence rates throughout coastal Louisiana. Primary and secondary benchmark coverage in south Louisiana is extensive but requires substantial effort to reoccupy benchmarks and post-process ellipsoid heights to derive accurate velocities. Repetitive elevation surveys at selected benchmarks should maintain a frequency of 3 years or less, and benchmark surveys should be expanded. The measurement of current subsidence rates is essential to any effort to map or model patterns of subsidence for the planning and design of coastal sustainability projects. In addition to using short-term GPS elevation surveys and reoccupying benchmarks direct subsidence measurements may be obtained by the installation of new permanent CORS stations in the coastal zone. It may also be possible that permanent reflectors capable of being imaged by InSAR satellite technology could be installed at strategic locations in the coastal zone to provide subsidence measurements. It is a recommendation of this proposal that the collection of direct subsidence measurements should be funded to a level necessary to provide data to adequately map and model subsidence at project-level detail. Equipping CRMS sites with the ability to directly measure subsidence rates with GPS or InSAR technology would significantly enhance the value of the accretion and surface elevation change data.

    b. **Sediment Core and Boring Collection and Compilation** – Sediment cores and borings have primarily been used in the coastal zone to measure and evaluate geotechnical parameters in association with project engineering and design. The subsurface stratigraphic information contained in borings has significant application in measuring and mapping the age, composition and thickness of the Holocene deltaic sediments that Byrnes et al, 2019 relates to current subsidence rates. There would be significant value in collecting new boring data to evaluate these parameters, but there is also substantial data to be gained from existing borings. As discussed in the Geological Features and

Processes section, LGS has published reports on the composition and thickness of the Holocene sediments. Heinrich et al, 2015 investigated over 15,000 published and unpublished public sources of boring data. It is estimated that there are several tens of thousands more borings across coastal Louisiana that were not accessed in the publication of this report. Given the value of the data in these borings to the ability to measure, map and model the thickness and composition of the Holocene sediments and the relationships with current subsidence rates, it is recommended that CPRA should contract with LGS to identify and catalog the location and ownership of the privately held boring data. Once identified and cataloged it is recommended that CPRA and LGS work to develop data-sharing arrangements with the owners of the boring data to allow for the interpretation and measurement of the critical thickness and composition values necessary to properly map and model subsidence.

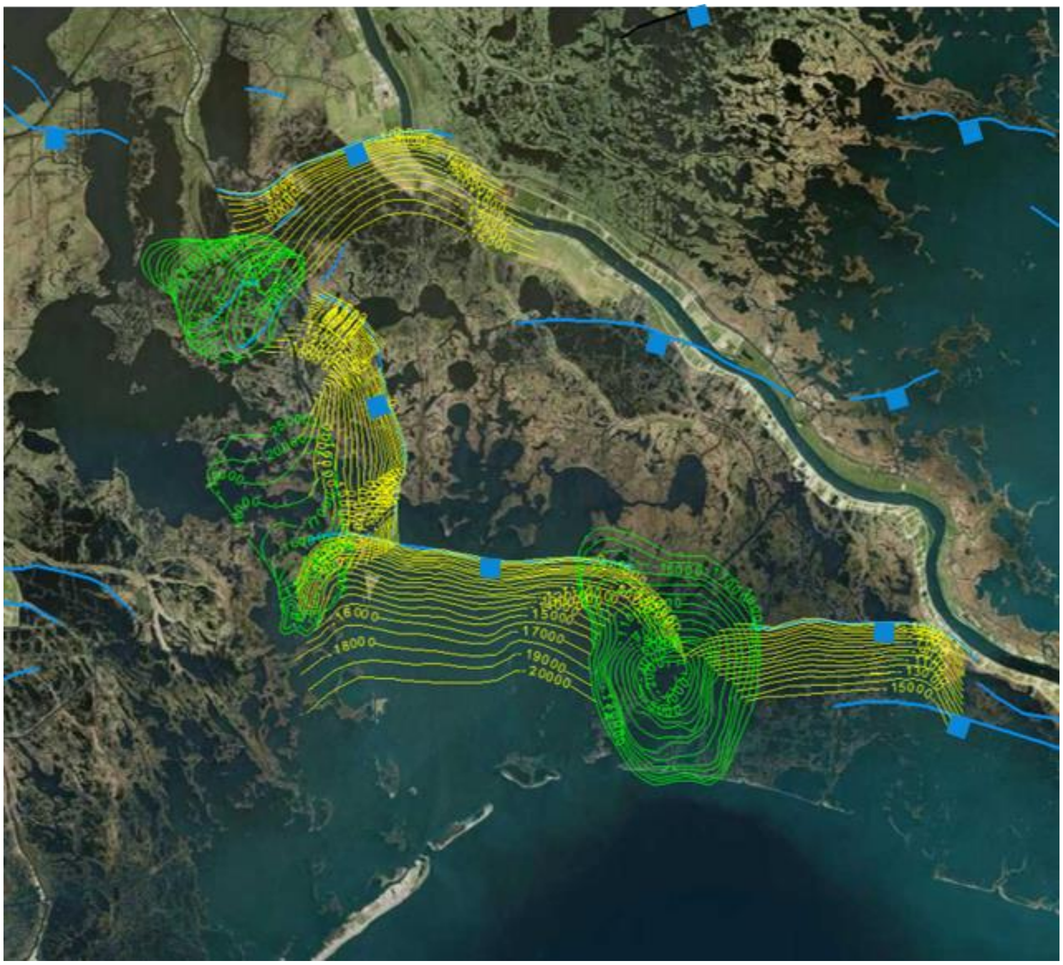
c. **High Resolution Seismic Data Acquisition** – The mapping of faults and Quaternary sedimentary layers with oil and gas industry data, as described in the next section, can be significantly enhanced and supplemented by the acquisition of new high-resolution seismic data in specific areas. Oil and gas industry data allows for subsurface geological mapping in the lower Quaternary across large portions of the coast, but the data lacks the resolution to make definitive determinations about the Holocene. High resolution seismic data targeted at areas where faults can be reasonably extrapolated to the surface can be used to measure the offset of seismic reflectors in the Holocene. If combined with chronostratigraphic age determination from sediment cores, high-resolution seismic data can be used to estimate rates of sediment accumulation, rates of historical subsidence, and differential rates of subsidence across faults. The speculative acquisition of high-resolution seismic data grids across all major engineering projects in the coastal zone, and selected areas where faults appear to extend to the surface based on the interpretation of oil and gas industry data should be considered for funding. The ultimate longer-term objective of high resolution seismic data collection should be the imaging of all major fault systems that extend to the surface.

<u>**Evaluation Procedures**</u>

5. **Data Integration and Mapping –** The value of data collected by the means described above is dependent on the degree to which it can be integrated and presented in map form with other existing data. This includes oil and gas industry data and knowledge base. The LGS Coastal Geohazards Atlas has laid a foundation for the process of using industry data in university research projects to provide the basis for mapping the neo-tectonic framework of the delta plain. This is a process that will need to be continued until a critical mass of interpretation has been accumulated. A fully-funded LGS Atlas project is an essential component of this proposal. Integrating the neo-tectonic framework with existing and collected data to understand the recent processes of subsidence, accretion and land area change is the basis for constructing accurate predictive models on which to base sustainability planning.

   a. **Pre-Quaternary Subsurface Mapping –** Oil and gas industry seismic data and well data can be used to map salt domes and faults that appear to extend to the surface. Figure 15 is a map of some of the faults and salt domes in southern Plaquemines and Jefferson

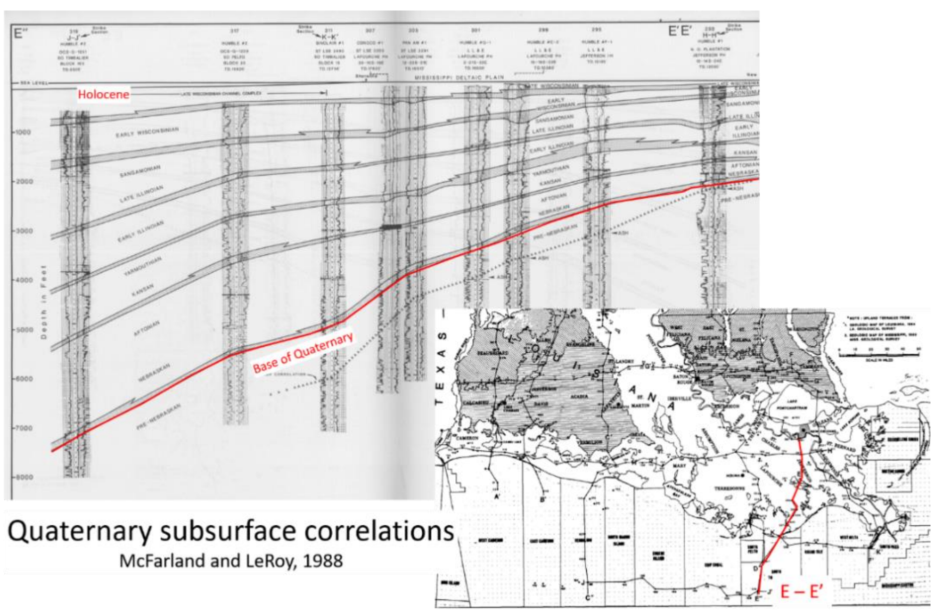
Parishes. Faults are represented by yellow contours and salt domes are presented by green contours, each indicating depth below the surface (McLindon, 2017). The blue lines indicate the “surface trace” of each fault, which is coincident with the zero depth contour of the fault plane map. The blue squares attached to each surface trace indicate the dip of the fault plane neo-tectonic framework for the delta plain. It is necessary to do some interpretation of pre-Quaternary stratigraphic intervals in order to produce the fault



Salt dome and fault contours McLindon, 2017 Figure 15

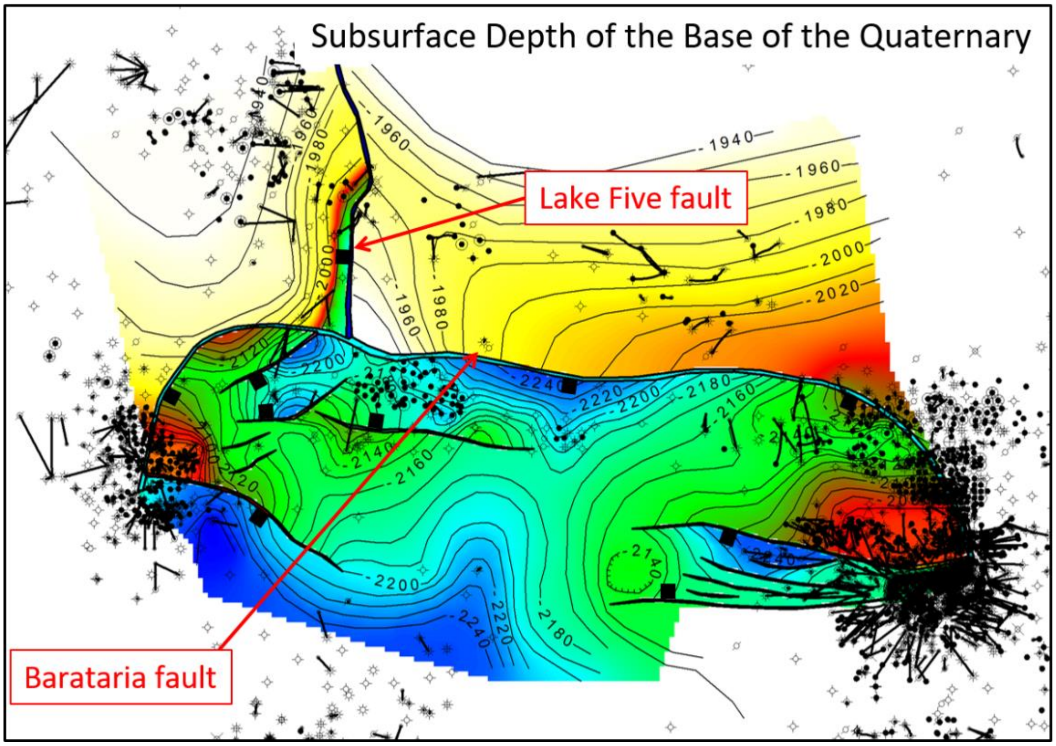
plane and salt dome maps, but in general interpretation of the structural and stratigraphy below the base of the Quaternary is not necessary to provide a subsurface structural foundation. Some investigation of the patterns of movement of faults and salt domes evidenced in the pre-Quaternary will have value in assessing possible patterns of movement in the Holocene. The tendency for faults to interconnect the salt domes is the basis for the conception of the neo-tectonic framework. A long-term objective of the LGS Coastal Geohazards Atlas is to assemble contour maps on all of the major faults and salt domes in coastal Louisiana.

a. **Quaternary Subsurface Mapping –** The base of the Quaternary can be reliably mapped with oil and gas industry data across most of coastal Louisiana. A network of subsurface well log correlations has been published by McFarlan and LeRoy (1988) (Figure 16). From this network detailed maps of the base of the Quaternary surface can be mapped across most areas of coastal Louisiana. Subsurface structure maps in the lower Quaternary have two principal purposes in coastal research. First, a subsurface structure map on a lower Quaternary stratigraphic horizon provides a detailed structural framework within which to interpret the Holocene interval and to establish the neo-tectonic framework of the coastal plain. As will be seen in a subsequent section, there are strong indications that the neo-tectonic framework of coastal Louisiana has had an interdependency with patterns of delta deposition and ecosystem evolution throughout the late Holocene. The structural framework created by the Barataria fault and the Lake Washington and Bay de Chene salt domes will be used as an example. Second, subsurface structure maps of the lower Quaternary can be used to determine total thickness of the Quaternary. Variations in thickness of the Quaternary stratigraphic interval may be indicative of patterns of long-term subsidence and differential subsidence due to fault slip. Figure 17 is a subsurface depth map on the base of the Quaternary generated from the interpretation of oil and



Quaternary subsurface profile McFarland and LeRoy, 1988 Figure 16

gas industry 3-D seismic and well log data (McLindon, 2017). Oil and gas wells are indicated on the map by the circular symbols. Straight lines connecting symbols indicate directional wellbores. Because this map also illustrates the thickness of the Quaternary, it can be used to show that the Barataria and the Lake Five faults were active during the Quaternary. The interval thickness of area immediately downthrown to the Barataria fault is over 200 feet greater than the upthrown side of the fault. There is similar thickening across the Lake Five fault. There are also indications of thickening in the grabens adjacent to the Lake Washington and Bay de Chene salt domes. The domes also indicate interval thinning toward the crests of the domes, which may be indicative of active haloekenisis (salt movement) during the Quaternary. These indications of fault activity in the Quaternary are significant because they may allow for the inclusion of these faults in the U.S.G.S. Quaternary Fault and Fold Database. Currently, the U.S.G.S. Database is restricted to the inclusion of faults that show evidence of having been



Base of Quaternary subsurface structure map McLindon, 2017 Figure 17

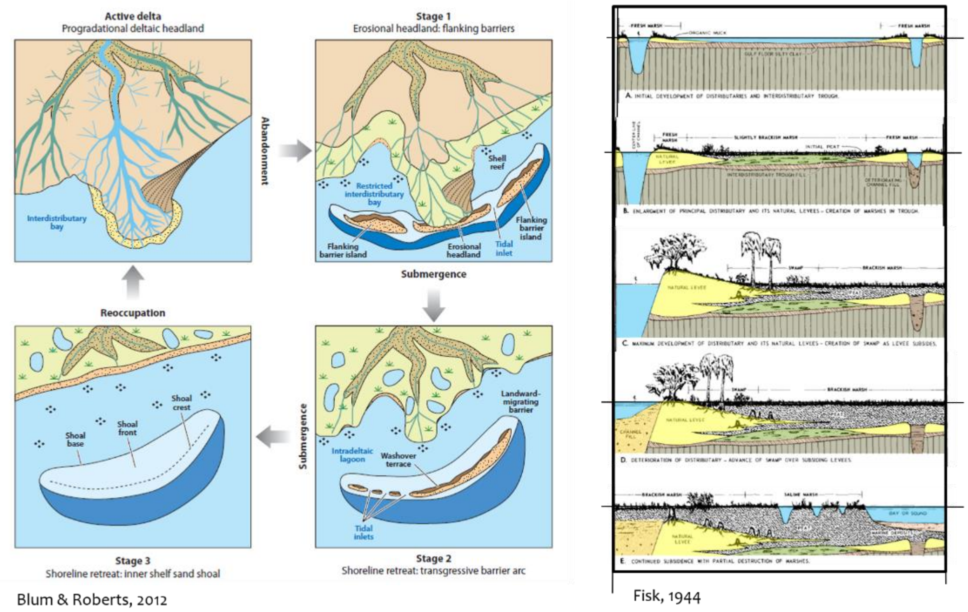
seismically active during the Quaternary. It is likely that the movement of faults in coastal Louisiana, as indicated by this thickness map, is aseismic, or slow-slip, fault movement. If it can be demonstrated that slow slip fault movement continued to occur episodically throughout the Quaternary, then the inclusion of the faults in the U.S.G.S. Quaternary Fault and Fold Database could bring greater focus and resources to the study of these faults.

b. **Holocene Subsurface Mapping –** Subsurface geological interpretation of the Holocene interval is one of the most underutilized research components in the coastal zone. Thousands of cores and borings have been collected across the area over the past several decades, but they tend to be scattered among innumerable individual, and generally isolated, research and engineering projects. Many of these cores and boring penetrated the entire Holocene interval, but were used only to evaluate geotechnical parameters of the sedimentary layers. There are three primary research objectives for Holocene subsurface mapping. LGS has played an important historical role in the use of boring data for geological interpretation. A re-invigoration of that role as it relates to coastal sustainability planning is an important part of this proposal.

i. **Thickness of the Holocene –** (or depth to the top of the Pleistocene). A compilation of all direct measurements of the depth of the top of the Pleistocene from cores, borings, cone penetrometers and geophysical logs would be a very valuable component to an overall subsurface geological evaluation. As discussed in the Features and Processes section, a preliminary compilation map was published by LGS (Heinrich et al, 2015). There are many more direct measurement values from cores, borings and cone penetrometers taken for the evaluation of infrastructure projects by CPRA and DOTD that could be incorporated into mapping the depth to the top of Pleistocene. The process of mapping Holocene thickness can make use of these direct measurements plus Quaternary thickness maps and high resolution seismic. As will be discussed in the section of Predictive Modeling, the relationship between current subsidence rates and the thickness of the Holocene established by Byrnes et al, 2019 in the Barataria Basin indicates that Holocene thickness maps may be used as an essential component in mapping and modeling subsidence in the coastal zone.

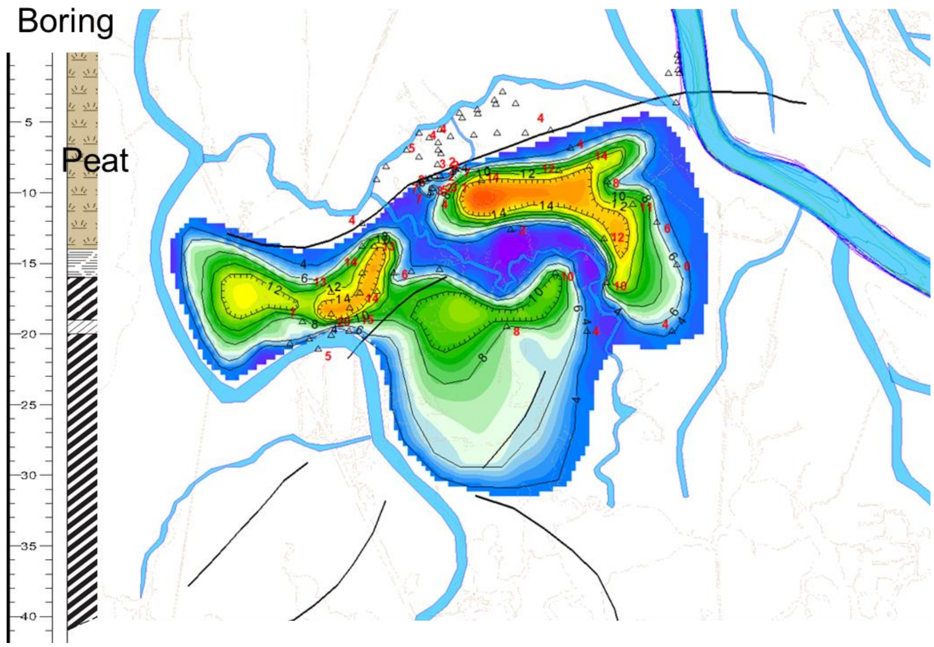
ii. **Holocene Depositional Environments and Sediment Composition** – The interpretation of depositional environments of the Holocene from cores and borings by David Frazier (1967) provided the foundation for our understanding of the construction of the coastal wetlands by a succession of Holocene delta lobes of the Mississippi River. Fraizer's work also provided the basis for understanding the delta cycle that drove the progression of ecosystem evolution throughout the Holocene. Many more cores and borings of the Holocene have been collected since Frazier's initial work, and they should be incorporated into expanding and refining his interpretations. Some researchers have suggested that it may be possible to delineate sub-lobes to each of Frazier's principal delta lobes. An improved understanding of stratigraphy and depositional environments of the Holocene through the integration of existing and newly-acquired cores and borings would improve our understanding of historical rates and patterns of land-building and land-loss in the delta environment. A better understanding of the stratigraphy and depositional environments could also be incorporated with interval thickness maps, fault maps, and sediment composition maps to examine their interdependencies. The relationships between current subsidence rates and the composition of the Holocene deltaic sediments established by Byrnes et al, 2019 indicate that accurate depositional environment and sediment composition maps may be used as an essential component in mapping and modeling subsidence in the coastal zone.

iii. **Thickness of Organic Clays and Peats** – Harold Fisk (1944) provided the basic model for the accumulation of highly organic soils in a coastal delta environment (right panel - Figure 18). This model is closely tied to the delta cycle model, as defined by Penland and Blum and Roberts, 2012 (left panel – Figure 18), and it defines the succession of ecosystem evolution through the progression of both



The delta cycle and peat accumulation Blum and Roberts, 2012 (left) Fisk, 1944 (right) Figure 18

models. The progression of the delta cycle, the succession of ecosystem evolution throughout that cycle and the accumulated thickness of peats are all driven by subsidence. The measurement of the accumulated thickness of organic clays and peats from cores and borings as a part of interpreting the depositional environments and sediment composition is an essential component to understanding patterns of subsidence and its relationship to ecosystem evolution. Mapping peat thickness may also provide insights into patterns of wetlands submergence. As shown in Figure 8, LGS has played an important historical role in mapping organic content. Areas of thick peat accumulations are not only predisposed to subsidence as indicated by the accumulation, the highly compactable nature of the soils means that these areas may be susceptible to current and future subsidence. The ability to evaluate subsurface geological parameters such as interval thickness and peat thickness is primarily dependent on data density. In the area of the Bayou Dupont Marsh Creation Project and the proposed Mid-Barataria Sediment Diversion there is an adequate data density from cores and borings to attempt a peat thickness map. Figure 19 is a contour map of peat thickness values measured in cores and borings taken for these projects. As Fisk's model would predict, thicker peat accumulations are found in the interdistributary areas between the natural levees of the distributary channels. Detailed maps of peat thickness can be used to better understand and predict patterns of subsidence across the delta plain.



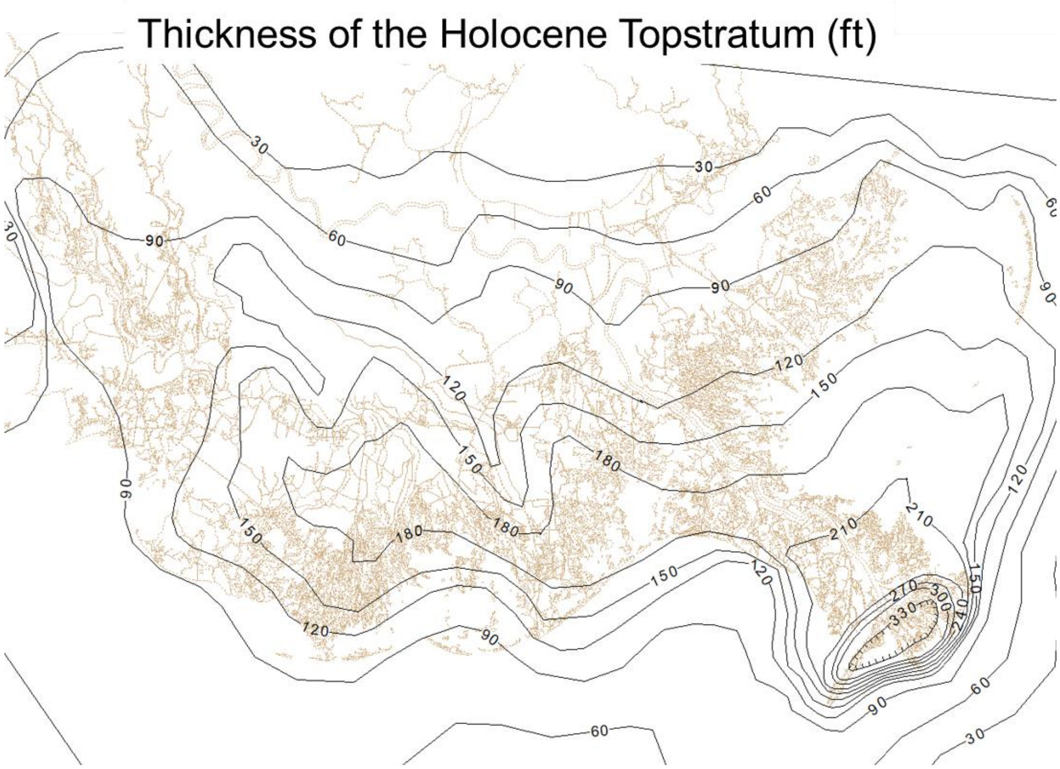
Peat thickness map Figure 19

c. **Map, Data, and Cross-Disciplinary Integration –** The real value of data collection, mapping of faults and salt domes, mapping Quaternary structure and thickness, and mapping Holocene thickness and composition comes from integration. Quaternary thickness maps can be integrated with Holocene thickness maps to study long term patterns of subsidence and deposition. Fault and salt dome maps can be integrated with Holocene thickness and composition maps to study their interdependencies. Short-term rates of subsidence can be mapped and integrated with Holocene thickness and compostion maps and surface fault trace maps.

Evaluation Procedures

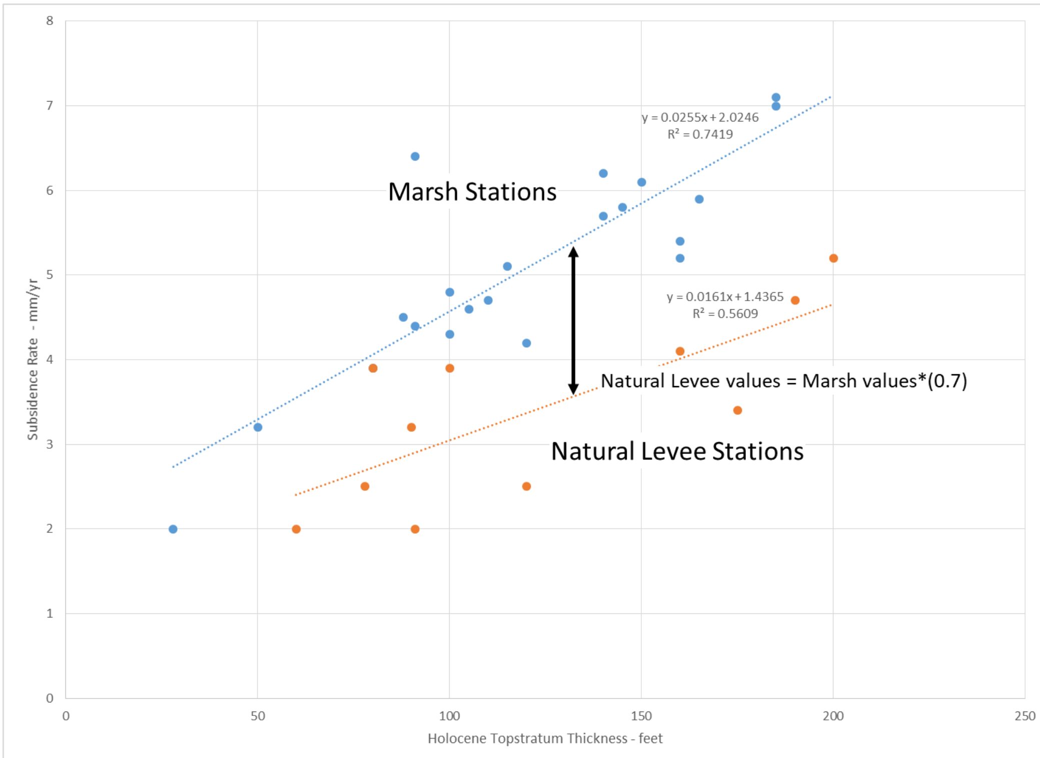
6. **Predictive Modeling –** Data collection, mapping and integration all provide the necessary foundation for accurate predictive modeling. It is a recommendation of this proposal that the collection of new data, the cataloging and organization of existing data, data integration and mapping should all be ongoing activities of the Master Plan. LGS can play an essential role in continuing to develop this foundation. In the interest of discussing the applications of predictive modeling for the data collection and integration recommended by this proposal some rudimentary models will be considered here. These models have been constructed with existing data and very basic analytical techniques, but they offer some insights into the utility of predictive models, and how these models are used as a basis for the set of project concepts presented in the next section.

   a. **Thickness and Composition of the Holocene** – The map in Figure 20 represents the thickness of the Holocene Topstratum of deltaic sediments from Kulp, 2000 converted to depth in feet. Kulp used data from approximately 400 cores and borings to construct this map, and it is generally the most widely cited resource in the investigation of the Holocene in coastal Louisiana. It is important to recognize that the scope of the input data limits this to a generalized representation. The Kulp map was used in this exercise



Holocene isopach map – modified from Kulp, 2000 Figure 20

instead of the LGS 2015 Holocene Isopach map because Kulp's is more widely recognized, and because the smoother and more generalized representation is probably a better representation at this scale. The integration of data from the thousands of potentially available borings could significantly improve the detail and resolution of this map, and allow for more accurate modelling of subsidence using the methodology employed here. While Byrnes et al, 2019 found that the spatial variability in subsidence has a "compelling relationship" with the thickness of Holocene deltaic deposits, a graph of the data indicates a linear mathematical relationship. Figure 21 shows all the values of subsidence from Byrnes et al, 2019 and the value of Holocene thickness at the location of each subsidence measurement. In addition to the overall relationship between greater thicknesses and higher subsidence rates, the data tends to cluster into two trends. Subsidence rates measured at stations in the marsh are shown in blue, while natural levee sites are shown in orange. The linear regression trends can be used to calculate an expected value of subsidence rate for any given thickness of Holocene sediments, and also to differentiate the anticipated rate based on the composition of the sediments. This provides the basis for a rudimentary model of subsidence rates based on the thickness and composition of the Holocene. The basis of this methodology is that the equation for the slope of the linear regression can be applied to a gridded surface of the thickness of the Holocene to derive a map grid of the subsidence rate in marsh environments. A correction factor can then be applied to that grid to account for the variations between the subsidence measurements in the marsh and subsidence measurements on the natural levees.



Subsidence rate versus Holocene thickness – data from Byrnes et al, 2019 Figure 21

i. **Current Marsh Subsidence Rates from Holocene Thickness** – Figure 22 is a map of subsidence rates generated by the methodology described above. In theory the value of Holocene thickness from any point on the map in Figure 20 is used to calculate subsidence by the equation of the blue trend line in Figure 21 [subsidence rate = 0.0255*(Holocene thickness) + 2.0246] to yield the value of subsidence at the same point on the map in Figure 22. The detail and resolution of this gridded surface is dependent on the resolution of the Holocene map and the number of values that went into establishing the linear relationship shown in Figure 21. The subsidence rate values and the overall shape of the map in Figure 22 are generally consistent with the subsidence rate map published by Ivins et al, 2007 and shown in Figure 23. The Ivins et al map is calibrated to GPS subsidence rate measurements. In order to take into account the differences in subsidence rates measured at marsh stations and natural levee stations by Byrnes et al, 2019 it is necessary to apply a correction factor to the grid in Figure 22.

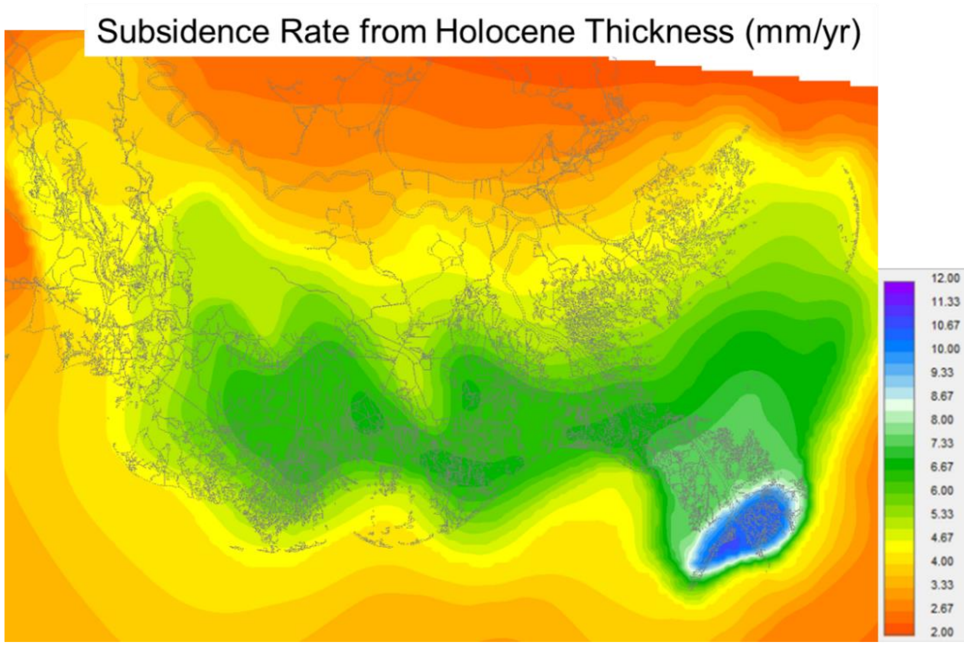
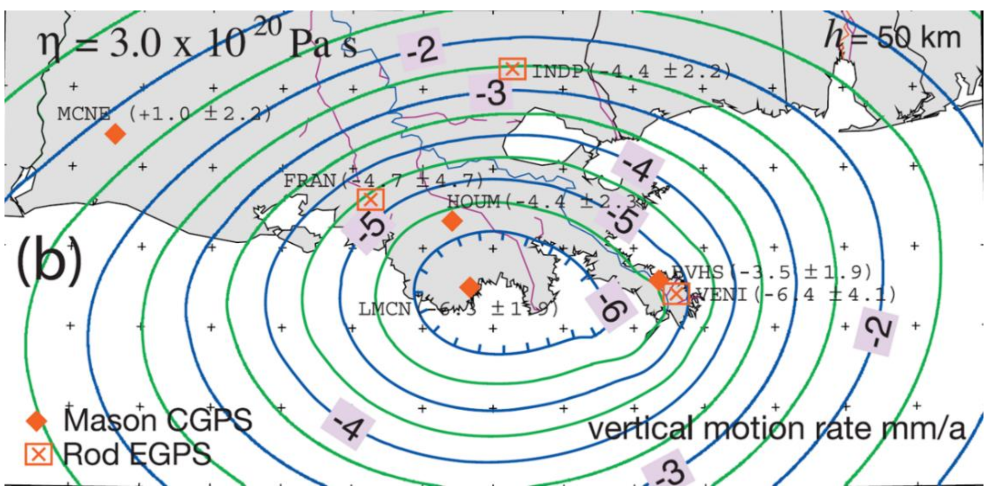


Figure 22



Current subsidence rate Ivins et al, 2007

Figure 23

ii. **Subsidence Rate Correction Factor from Holocene Composition** – the Louisiana State Planning office published the map in Figure 24 in 1976 to establish the variation in subsidence potential in Louisiana's coastal wetlands. The zones established by this map range from the green areas in which there is no anticipated subsidence potential due to organic content to the vermilion areas that represent areas that have greater than 51 inches of accumulated organic layers by this evaluation, and are expected to have the highest subsidence rate potential. The green areas are coincident with the natural levees of the historical distributary channels of the Mississippi River system, and they generally contain little or no organic content. The vermilion areas are generally coincident with freshwater marshes where organics have been accumulating for thousands of years. The orange zones are coincident with the intermediate to saline marsh,

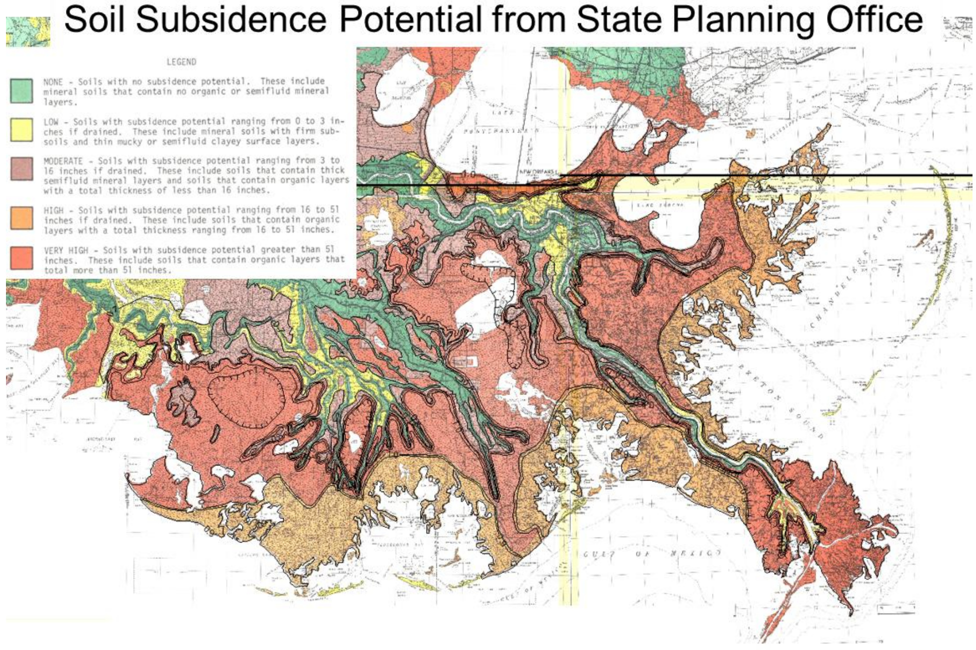


Figure 24

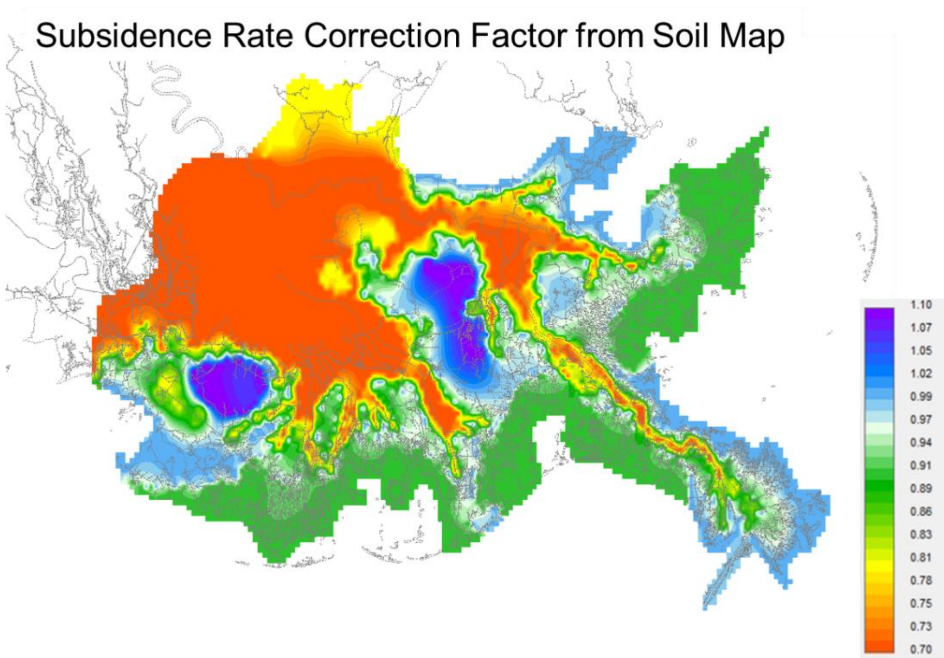


Figure 25

which generally correspond to the settings of the marsh stations measured by Byrnes et al, 2019 and represented on the graph in Figure 21. The relationship between the subsidence rate values from the marsh stations and the subsidence rate values from the natural levee stations for a given value of thickness on the graph in Figure 21 is presented by the equation [natural levee value = marsh value*(0.7)]. This equation sets the correction value for subsidence in the orange zone on the map in Figure 24 at 1.0 and the correction factor in the green zone at 0.7. The black contour lines overlain on the map in Figure 24 show the subsidence correction factor values that are intermediate between orange and green. The vermilion zones are assigned a correction factor value of 1.1 meaning that it is estimated that anticipated subsidence rates for a given thickness of Holocene sediment in the vermilion zones will be 1.1 times the value for an equal thickness in the orange zone. These correction factor values are used to generate the subsidence correction factor grid surface shown in Figure 25. This process of determining a correction factor for subsidence rate based on the organic content of the Holocene sediments is considered to be the most effective way to account for differences in organic content using available data in a rudimentary model.

iii. **Rate of Relative Sea Level Rise** - the subsidence correction factor grid surface can be applied to the subsidence rate map shown in Figure 22 to generate a subsidence rate map based on both the thickness and composition of the Holocene deltaic sediments. A map of the rates of relative sea level rise for the Louisiana coastal plain can be generated by adding a value for eustatic or global sea level rise to the corrected subsidence grid. The map in Figure 26 shows the

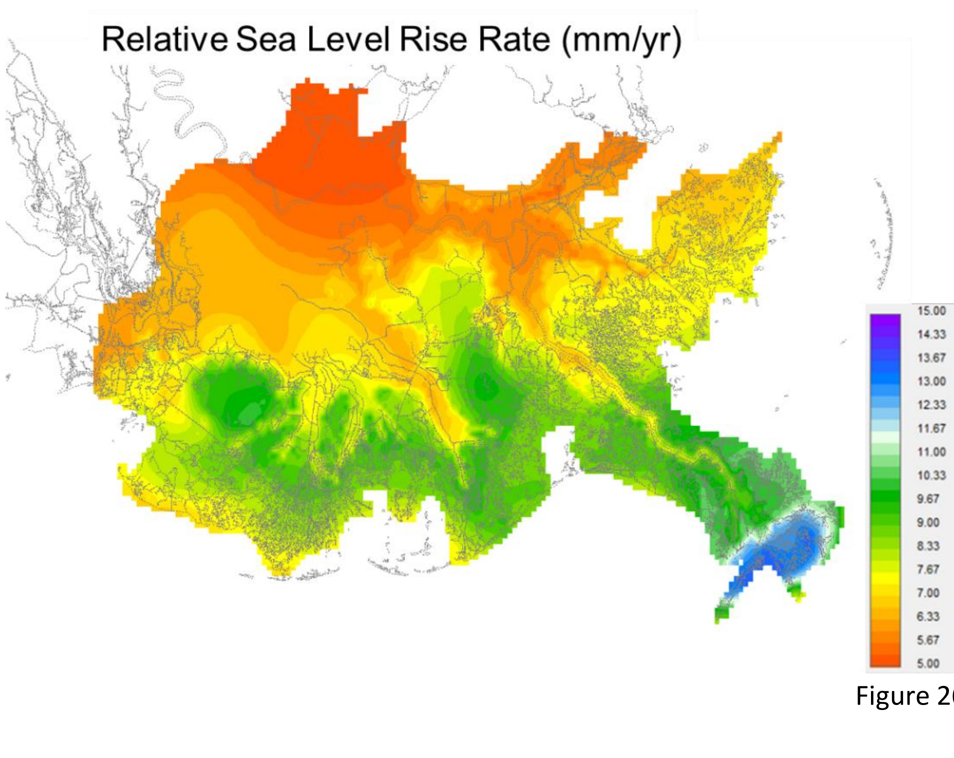


Figure 26

surface grid values for rate of relative sea level rise using this methodology and a rate of global sea level rise of 3.0 mm/yr. This is a generally accepted average rate. Byrnes et al, 2019 established that the rate of sea level rise for the Gulf of Mexico is 2.0 mm/yr, so the map in Figure 26 has a built-in accounting for some amount to future sea level rise. Any value of anticipated future sea level rise could be added to the corrected subsidence grid to generate a future rate of relative sea level rise across coastal Louisiana. There is currently not a clear methodology to predict or model the magnitudes or variations of future subsidence rates across the coast. Any advancements in the ability for predictive modeling of future subsidence rates would significantly enhance the entire process of predictive modeling. In order to fully appreciate the impacts of rates of relative sea level rise it is necessary to account for the impacts of accretion and surface elevation change measured by CRMS.

b. **Sediment Accretion** - the body of data produced by CRMS over the past two decades, as described in the Recent Processes of the Features and Processes section of this proposal, is sufficient to evaluate long-term trends of accretion. The plot of accretion data from a single CRMS site is shown in the lower left of Figure 10. The vertically stacked points represent multiple accretion measurements on a given date. Each of these measurements represents the accretion above one of multiple feldspar markers. The gold points represent accretion values measured from the oldest (and deepest) feldspar marker. The gold trend line on the graph is a linear regression of those points, and is the best representation of the long-term rate of accretion at that CRMS site.

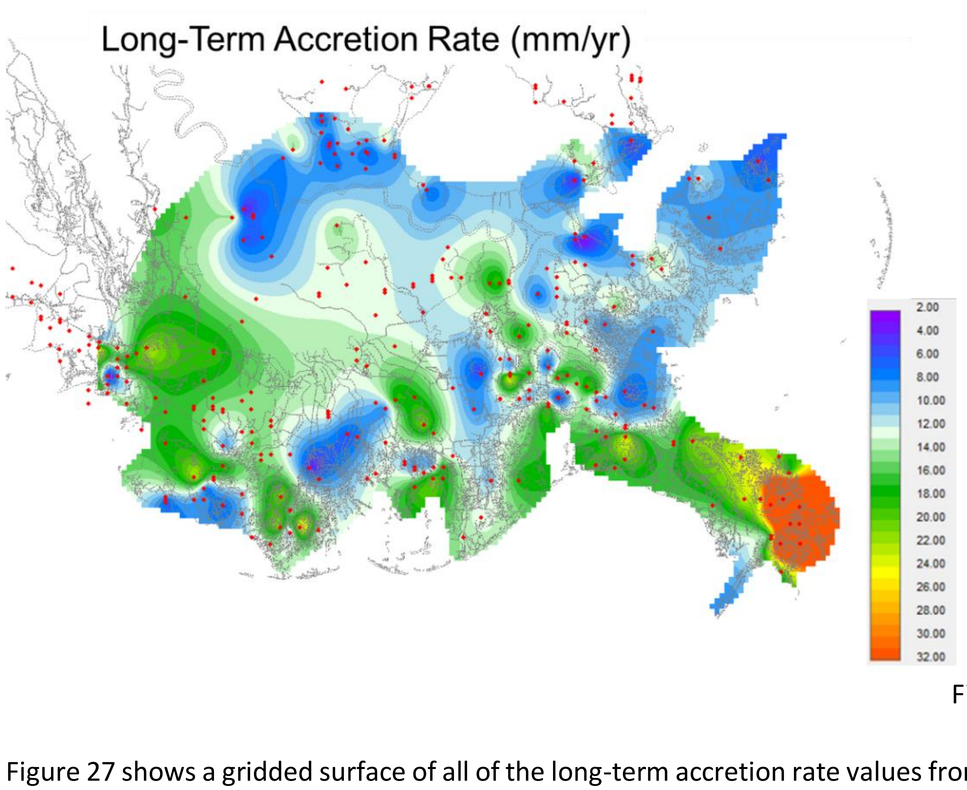


Figure 27

Figure 27 shows a gridded surface of all of the long-term accretion rate values from CRMS sites represented as red dots. A comparison of Figures 26 and 27 reveals that the highest rate of relative sea level rise for most of the Louisiana coastal plain is about 10 mm/yr.

Across much of the area long-term accretion rates are greater than 10 mm/yr. A significant percentage of the areas experiencing accretion rates greater than relative sea level rise rates are in the intermediate to saline marshes around the outer perimeter of the coast. These marshes are generally not receiving sediment from freshwater or river-borne sources. Accretion in these areas is likely coming from sediment carried into the marsh by tidal flux, and the data suggest that the rates of accretion associated with this process is capable of keeping up with near-term rates of relative sea level rise. Figure 28 shows a representation of the values of the relative sea level rate grid subtracted from the values of the accretion rate grid. Values greater than zero (light blue through red) in Figure 28 represent areas where the accretion rate is greater than the rate of relative sea level rise. These areas appear to be naturally accreting and they are presented here as potential sites for the sediment supplementation projects that are presented in conceptual form in the final section of this proposal. Prior to a discussion of the project concepts it is instructive to consider the recent processes of surface elevation change and land area change.

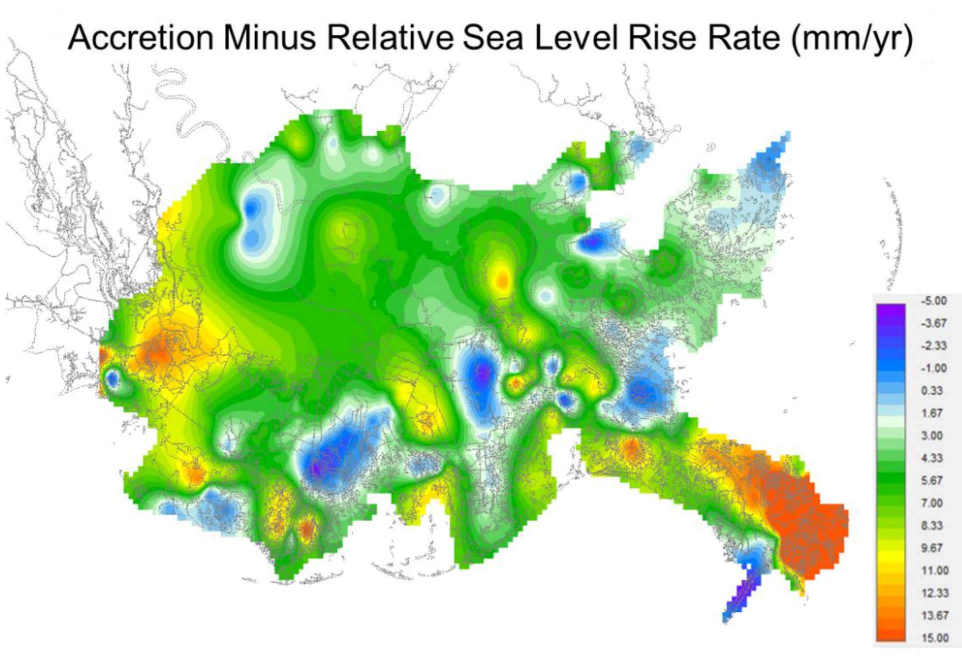


Figure 28

c. **Surface Elevation Change** – long-term surface elevation change from CRMS can be extracted and represented as a gridded surface in a process identical to that used for long-term accretion data. Figure 29 shows the gridded surface for long-term surface elevation change measured at the CRMS sites shown as red dots. Surface elevation change is relative to the fixed (R-SET) rod in the apparatus, and is not representative of the subsidence rate at that location. The positive values for surface elevation change that cover most of the Louisiana coastal plain do appear to indicate that accretion is causing the elevation of the surface to be raised. In areas where the long-term accretion rate is greater than the rate of relative sea level rise, this should indicate a change is surface elevation that is greater than relative sea level rise (or an effective negative subsidence rate). The ability to directly measure subsidence rates at the CRMS sites, as discussed in the Direct Measurement of Short Term (Current) Rates of Subsidence of the Evaluation Procedures section, would significantly enhance the value of surface elevation change data. It is a recommendation of this proposal to initiate a program to directly measure subsidence rates at CRMS sites.

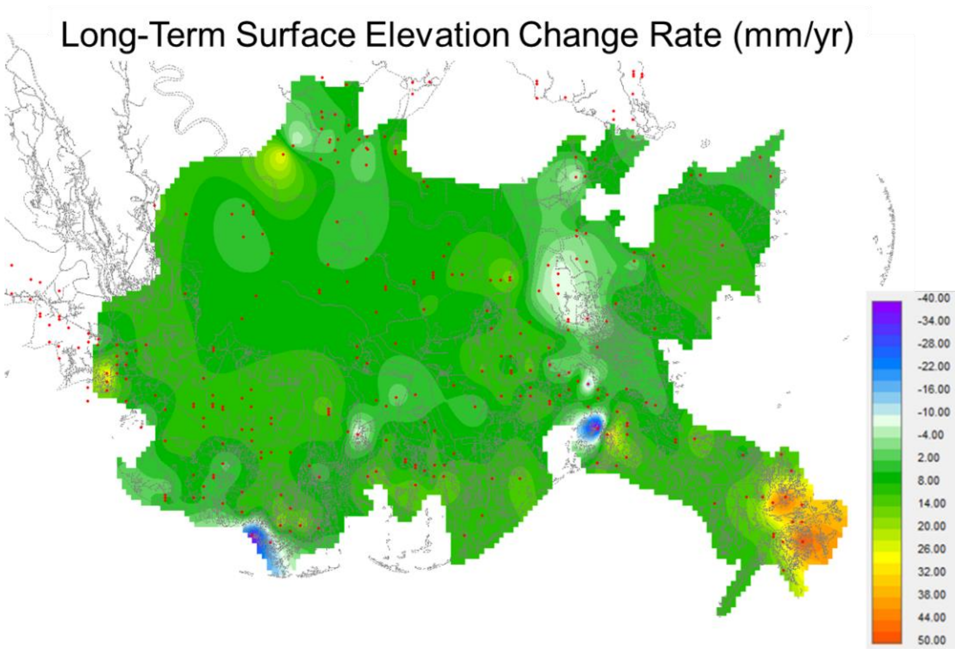
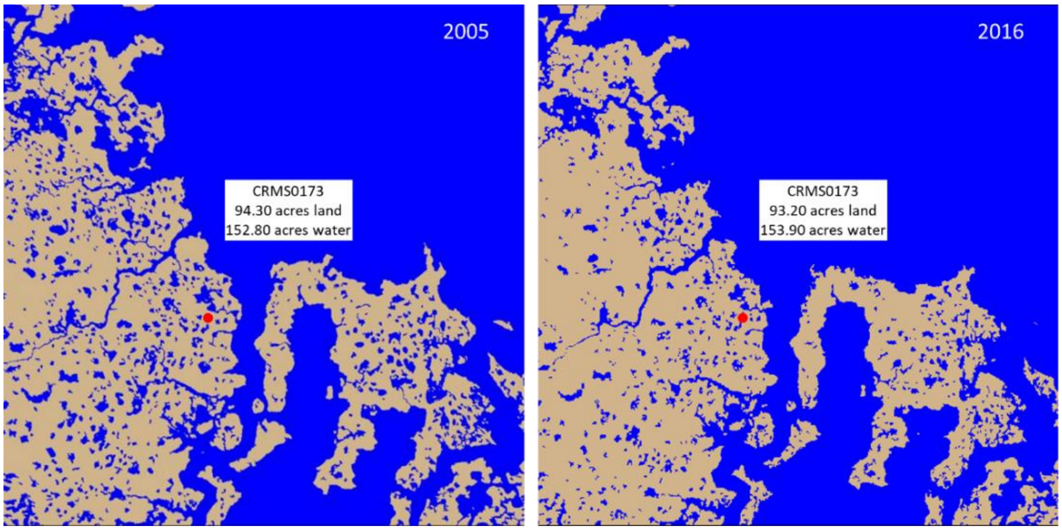


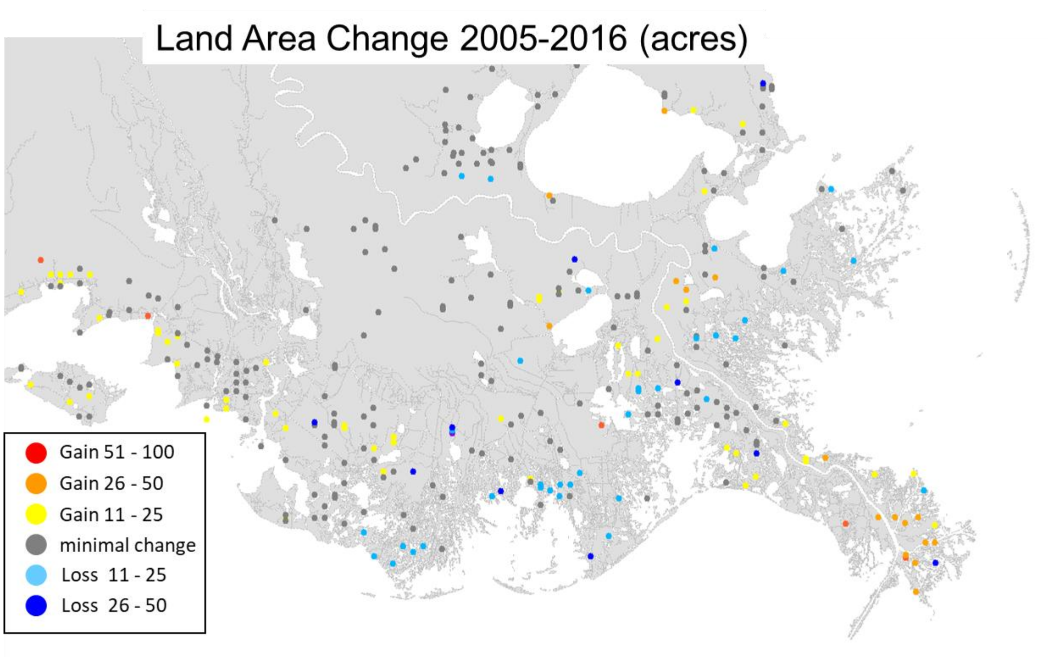
Figure 29

d. **Land Area Change** – land area change is the most accurately and consistently measured attribute of the Louisiana coastal plain that can be incorporated into predictive models. The methodology described in USGS SIM 3381 (Couvillion et al, 2017) provides measurements of the area of land and water on a regular basis at a range of scales. Each CRMS site is apportioned a 1-square kilometer area within which measurements have been made at four time intervals over the last eleven years. Figure 30 shows an example of two such measurements at CRMS site 0173. This is an example of an area that experienced relative stability over past decade, having lost 1.1 acres in 11 years. CRMS0173 is one of many CRMS sites that have experienced little or no change during that time span. These sites are colored gray in Figure 31. There are two observable patterns apparent in Figures 30 and 31. First, a careful comparison of the 2005 and 2016 land-water areas in Figure 30 reveals that the minimal change is a net change that combines losses in some areas and gains in others. The land area losses appear to be happening around the edges of the marsh platform, while the gains appear to be happening by infilling of interior ponds. Second, with the exception of land area gains in the birdfoot delta, the distribution of CRMS sites in Figure 31 experiencing losses appears to be generally seaward of sites experiencing minimal change or net gains in land area.

Both of these patterns are consistent with accretion caused by sediments carried into the marsh by tidal flux. This would suggest that the source of the sediments is edge erosion, and that those sediments are generally being transported in a landward direction, and they are being retained in the interior of the stable marsh platforms. This process of edge erosion and subsequent accretion was described by Wilson and Allison, 2008, as shown in Figure 32. It is interesting to note that they invoke a mechanism of differential

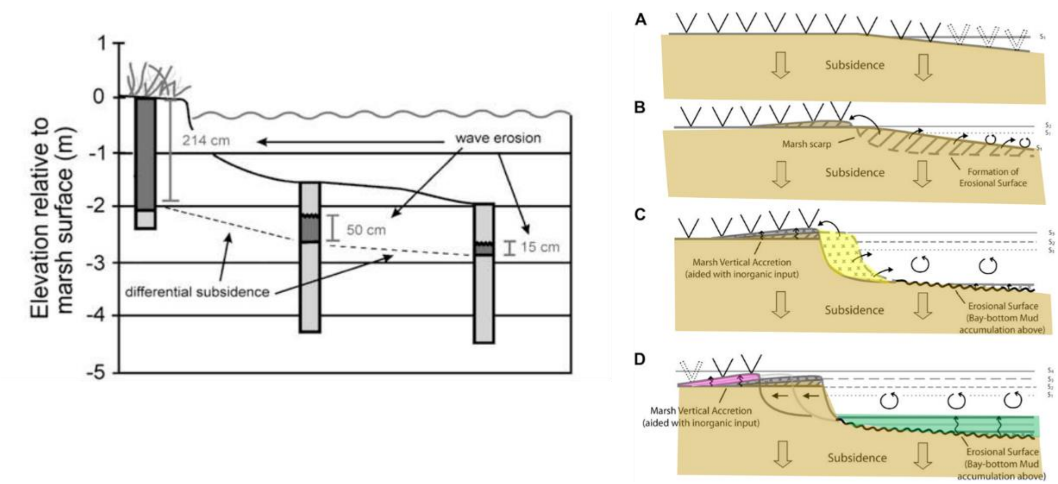


CRMS land area change Figure 30



CRMS land area change Figure 31

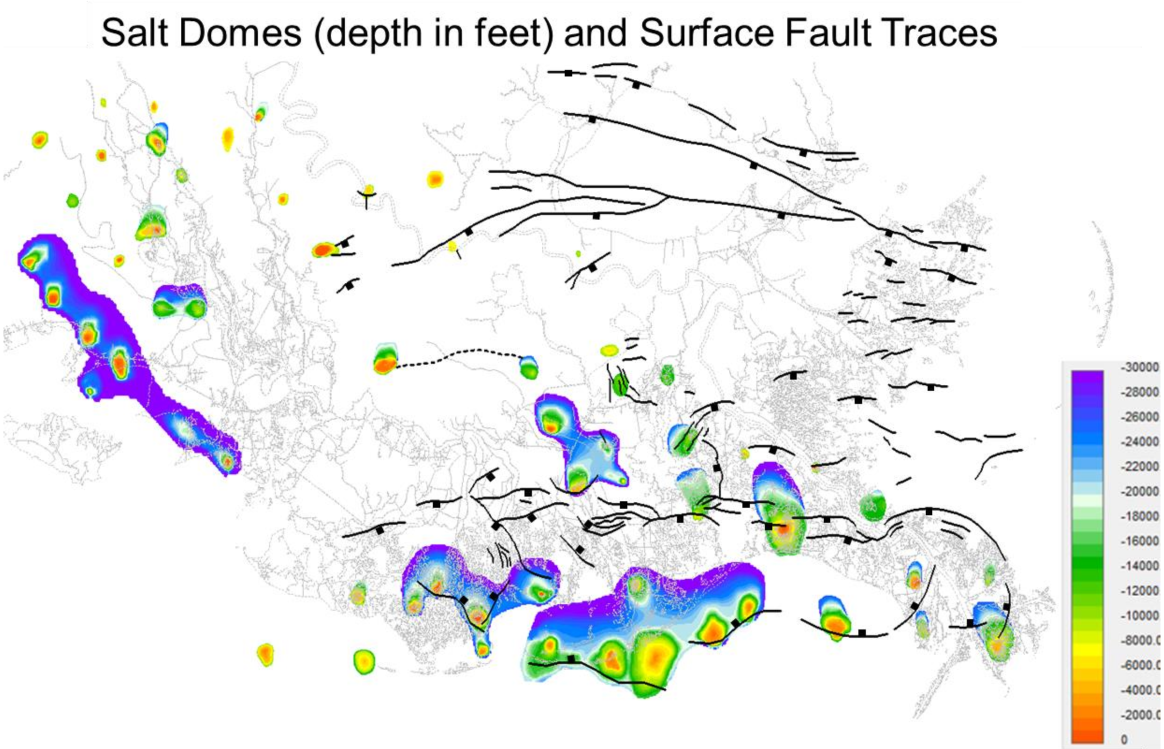
subsidence along the edge of the marsh platform. In their model submergence prior to erosion and redistribution of the sediments is an essential part of the process. As will be discussed in the next section, the most probable mechanism for differential subsidence along a linear boundary such as a marsh platform edge is fault slip.



Marsh edge erosion and accretion Wilson and Allison, 2008 Figure 32

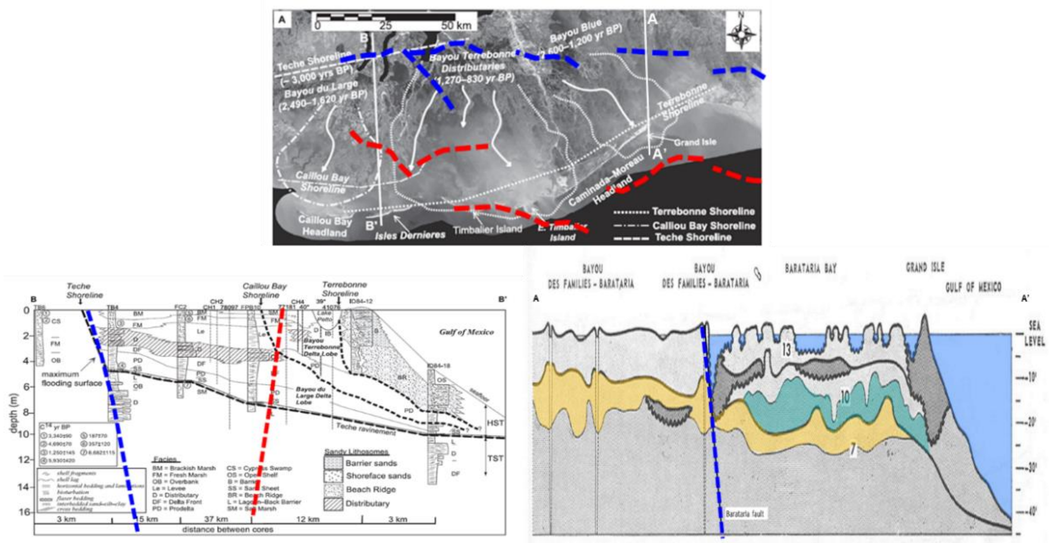
Evaluation Procedures

7. **Combining Features and Processes with Predictive Model Inputs** – Figure 33 is a representation of the neo-tectonic framework of the Mississippi River delta plain. The color code indicates the depth to the top of salt domes. As discussed in the Features and Processes section, domes that penetrate to relatively shallow depths may be providing some measure of stability against subsidence. Surface fault traces are shown in black with squares indicting the downthrown direction of the main faults. These traces represent the current state of a compilation of published works (Armstrong et al, 2014; Gagliano et al, 2003; Kuecher et al. 2001) and an active, on-going interpretative process involving research at UNO, Tulane and ULL (Akintomide et al, 2019; Bullock et al, 2018; Frank, 2017; Johnston et al, 2017; Levesh et al, 2019). The map also reflects compilations of research funded by the RESTORE Act Centers of Excellence, the TranSET transportation consortium and the Louisiana Department of Transportation and Development. Access to the oil and gas industry seismic data used in the university research has been coordinated through the LGS Coastal Geohazards Atlas project. The publication of a complete and accurate map of surface fault traces is one of primary objectives of the LGS Coastal Geohazards Atlas project. In order to achieve this objective, it will be necessary to adequately fund the Atlas project and to negotiate a more comprehensive data-sharing arrangement with the oil and gas industry. It is a recommendation of this proposal that CPRA should either provide direct funding to LGS for the construction of the Atlas, or support funding from another source and to support a cooperative data-sharing arrangement with the oil and gas industry. Prior to a consideration of a combination with Predictive Modeling, the interrelationships between the neo-tectonic framework and other geologic features and processes will be considered.



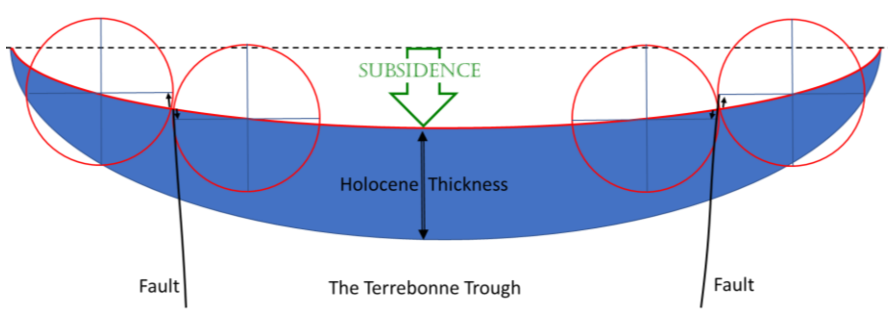
Salt domes and surface fault traces Figure 33

a. **Neo-tecontic framework and Holocene thickness** – The line of salt domes running from southern Terrebonne Parish to southern Plaquemines Parish coincides with a trend of faults that are downthrown to the north. Another trend of faults to the north of this trend are primarily downthrown to the south. Together these faults and salt domes define the neo-tectonic expression of the Terrebonne Trough, which is a fundamental component of the geologic structure of the Mississippi River delta plain. The interaction of the faults and the Miocene deltas shown in Figure 2 is representative of a long history of interaction between the faults that delineate the Terrebonne Trough and the deltas of the Mississippi River. As discussed in the Holocene thickness section of Features and Processes, the concentric contours of the LGS Isopach map of the Holocene shown in Figure 9 conform to the axis of the Terrebonne Trough. The disproportionate accumulation of denser sediments within the trough has helped to drive subsidence throughout the geological history of the area, but as the diagram in Figure 2 indicates, movement of the faults has also played an integral role as a mechanism of subsidence throughout that history. There is limited direct evidence of that fault movement has affected the thickness of the deltaic sediments Holocene, but it is considered to be a reasonable expectation based on the long history of interaction between faults and deltaic sediments. Figure 34 represents examples where the faults that have been mapped in the past few years through the Coastal Geohazards Atlas Project can be seamlessly integrated into older studies of Holocene deltaic sediments to suggest a relationship between the faults and the thickness of the sediments. The map at the top of Figure 34 and the profile in the lower left are from Kulp, Fitzgerald & Penland, 2005. The profile in the lower right is from Frazier, 1967. The surface traces of the major faults bounding the Terrebonne Trough have been added to the map and to the profiles as blue and red dashed lines indicating down to the south and down to the north faults respectively. Kulp et al used boring data collected by LGS to define the “Teche Shoreline” as a revinement surface that bounded the historical delta complexes. Frazier also used boring data to delineate deltas that he numbered 7, 10 and 13. Delta 10 is the same as the Bayou Blue delta shown on the map. In both of these cases thicker Holocene deltaic sediments can be seen on the downthrown sides of the faults once they are superimposed on the profiles.



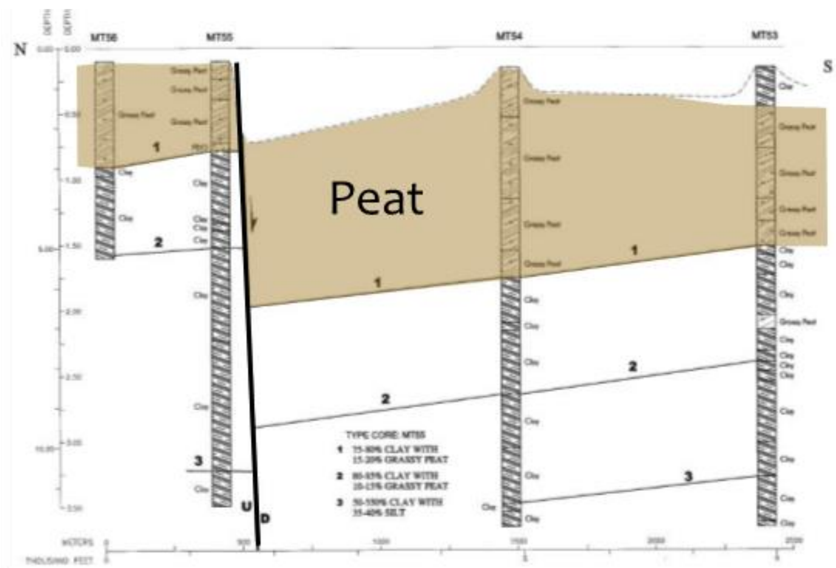
Faults and Holocene – modified from Kulp et al, 2005 (top and left) and Frazier, 1967 (right) Figure 34

Figure 35 suggests that the interaction between the thickness of the Holocene sediments and subsidence being measured at the surface should result in a stress field across the surface of the marsh. Disproportionate stresses toward the center of the Terrebonne Trough could be relieved by fault slip where the major faults extend to the surface. The diagram indicates that the resultant fault slip would include both hanging wall subsidence and footwall uplift



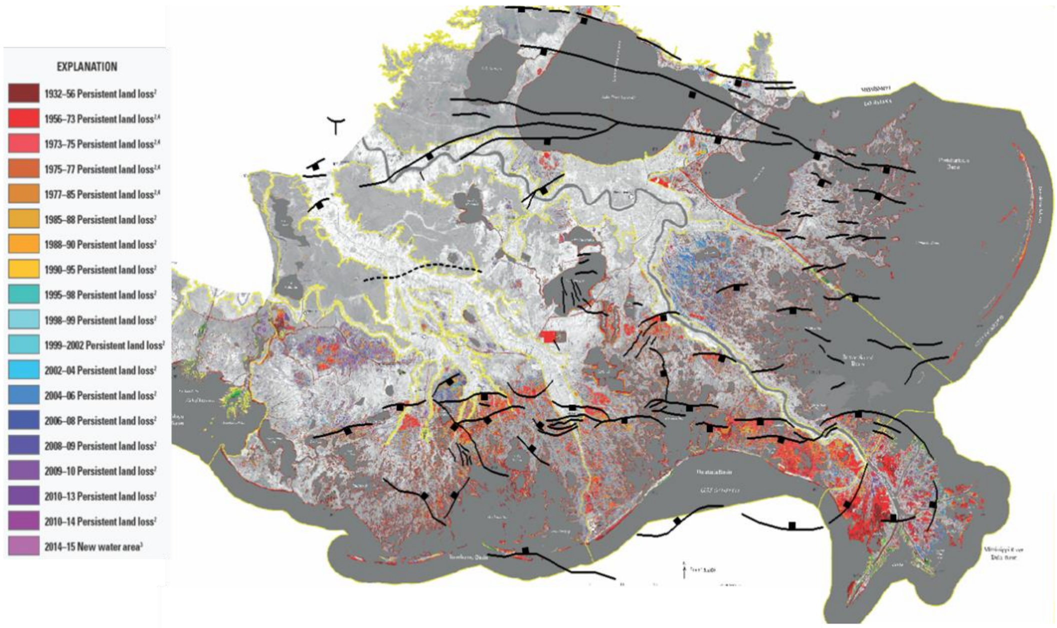
Subsidence, Holocene thickness and fault slip Figure 35

b. **Neo-tectonic framework and Holocene composition** – Figure 36 from Gagliano et al, 2003 shows the relationship between faults and peat thickness. In this interpretation of the Montegut fault in Terrebonne Parish it appears that slow, progressive fault slip has allowed for a greater accumulation of peat on the hanging wall side of the fault than on the footwall. There may also be a subtle suggestion of footwall uplift. There are few other published examples of this phenomenon and it is an area that needs more investigation and study. As will be discussed in the next section, there is good reason to think that understanding the relationships between the neo-tectonic framework, ecosystem evolution and peat accumulation will be very valuable understanding long-term sustainability of the marshes of the delta plain.



Faults and peat thickness Gagliano et al, 2003 Figure 36

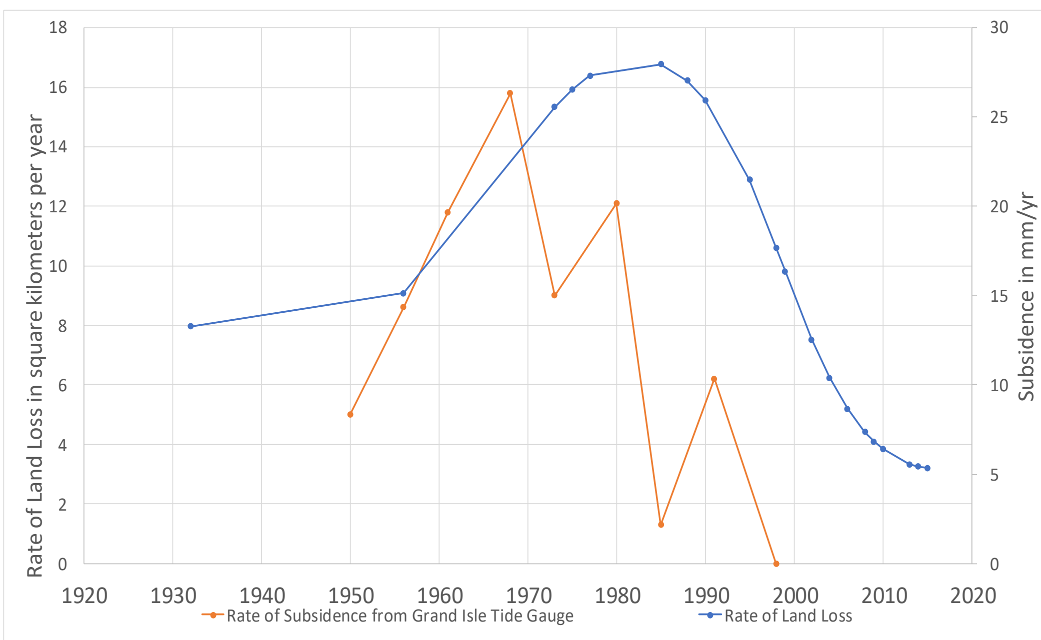
c. **Neo-tectonic framework, subsidence, accretion and land area change** – the interplay between the neo-tectonic framework and the recent processes of subsidence, accretion and land area change is best considered together. Figure 37 shows the superimposition of the surface traces of faults from the neo-tectonic framework onto the USGS SIM 3381 Land Area Change Map (Couvillion et al, 2017). There appears to be a strong relationship between hotspots of wetlands loss in the 1970s and the downthrown sides of the faults. Figure 38 shows the relationship between the rate of subsidence calculated from the Grand Isle tide gauge by Kolker et al, 2011 and the rate of wetlands loss in the Barataria Basin from Couvillion et al, 2017. Together these figures suggest that wetlands loss is closely related to subsidence, and both are closely related to the neo-tectonic framework of the delta plain. As discussed previously, the coast-wide graph of rates of land loss shown in Figure 14 indicates that it is best understood as a land loss event that peaked in the 1970s; the graph of relative sea level rise rates measured by LGS in Figure 10 indicates that subsidence is also best understood as an event that peaked in the 1970s. Figures 10 and 14 strongly suggest that the land loss event was related to the subsidence event, and both were related to the neo-tectonic framework. This does not necessarily have to mean that fault slip was the principal cause of subsidence. The relationships between faults and the thickness and composition of the Holocene deltaic sediments may account for a significant portion of the subsidence event.



Land area change and surface fault traces – modified from Couvillion et al, 2017 Figure 37

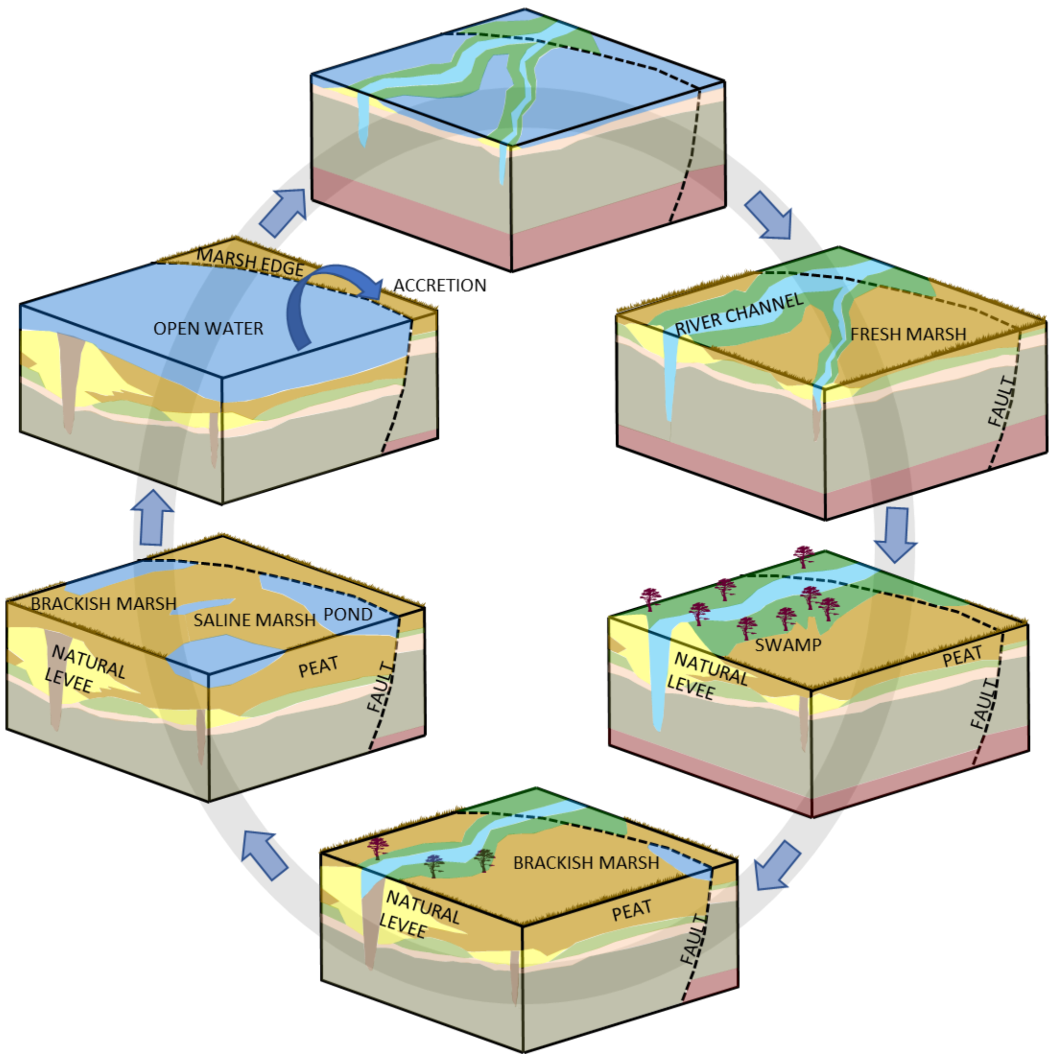
One of the implications of submergence of a significant area of coastal marsh during the land loss event is that the sedimentary substrate of those marshes was subjected to the processes of subaqueous erosion. At the same time that a significant area of wetlands area was lost to submergence, a lot of sediment was put into the aqueous component of the system. This sediment would have been available for movement and redistribution by aqueous processes including tidal flux. Figure 39 is a three-dimensional representation of the patterns of ecosystem evolution defined by Fisk, 1994 shown in Figure 18 and the pattern of peak accumulation on the hanging wall side of a fault defined by Gagliano et al, 2003 shown in Figure 36. The front panel of the blocks in Figure 39 is taken directly from Figure 18. This sequence shows the succession of marsh ecosystems from fresh to saline over time. The sediments supporting new freshwater marsh are deposited in an active delta lobe. When the primary river channel abandons that lobe, the marsh surface begins to subside. The succession to progressively more saline environments is coupled with a progressive accumulation of peat, which is how these marshes maintain elevation in the face of subsidence. The cycle ends with the eventual submergence of the saline marshes on the hanging wall of the fault. The submerged marsh sediments including much of the accumulated peat is subjected to subaqueous erosion after submergence. Some portion of that sediment is transported onto the remaining marsh platform on the footwall side of the fault. At some point in the future the open body of water formed by the submergence of the marsh on the hanging wall may be re-occupied by a new delta system allowing the cycle to repeat, but marsh on the footwall may remain relatively stable throughout that time by the accretion of sediment supplied by the submerged hanging wall. This pattern is suggested in the boring profile from Frazier, 1967 in the lower right of Figure 34. Three successive deltas are stacked one on top of the other on the hanging wall side of the Barataria fault. The gray interval between deltas 10 and 13 indicate the complete submergence and erosional reworking of delta 10 on the hanging wall side. There is no commensurate reworking interval on the footwall, and boring studies from the LGS work presented in Figure 8 (Kosters et al, 1987) indicate a continual and progressive accretion of marsh sediments for about the past 3,000 years.

Figure 40 reveals a striking relationship between the Teche Shoreline boundary from Kulp et al, 2005 and a line of surface fault traces. As shown by the dashed lines in Figure 40, the same boundary separates most of the emergent land and freshwater marsh north of the boundary from the intermediate, brackish and saline marshes south of the boundary. This figure shows that the primarily freshwater marsh along the footwall side of the faults that define the Teche Shoreline have much higher organic content than the more saline marshes to their south (the map in the lower left from Tweel and Turner, 2012). The best explanation for the coincidence of these factors is that delta cycles represented in Figure 39 are primarily played out south of the Teche Shoreline. The outline of the most recent delta lobes show that the historical deltas tend to fan out their distributary channels south of the Teche Shoreline. Each of these delta lobes, with the exception of the modern birdfoot delta, has followed a succession of ecosystems so that their remnant deposits



Land area change and subsidence – data from Kolker et al, 2011 and Covillion et al, 2017 Figure 38

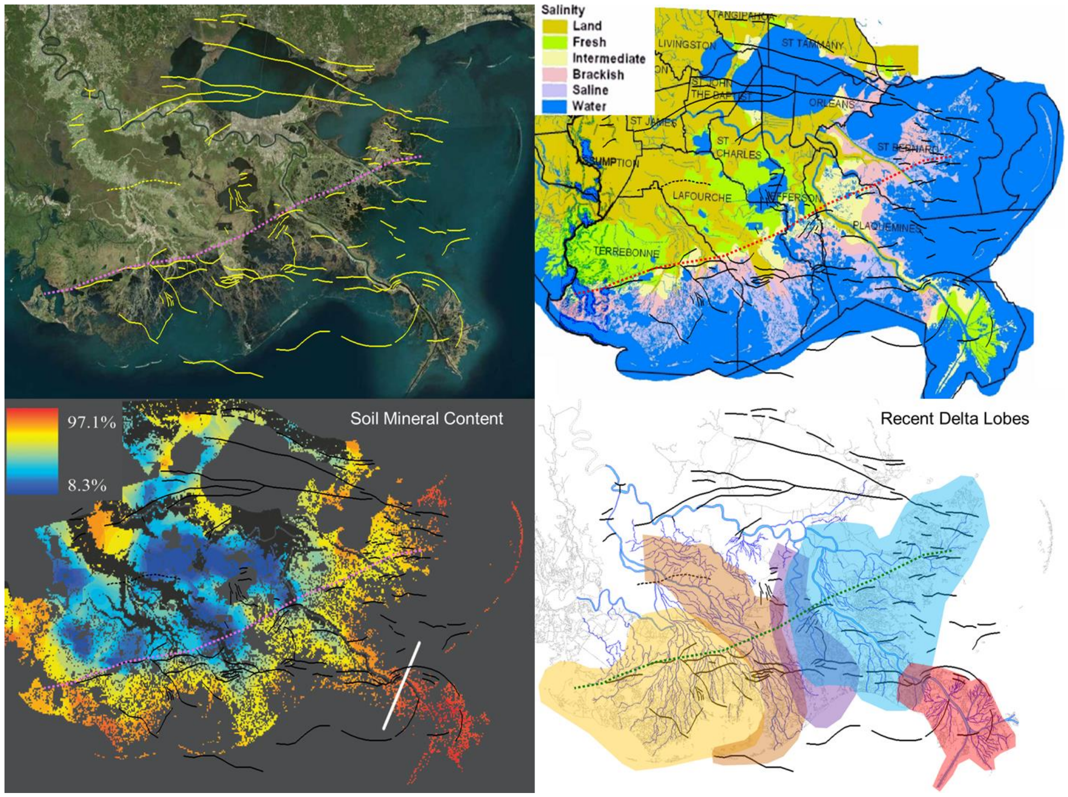
delineate the distribution of saline marshes across the delta plain. The ultimate submergence of these delta deposits along the hanging walls of the faults can be seen as hotspots of land loss on Figure 38. Although peat may preferentially accumulate on the hanging wall side of the fault during most of the delta cycle, much of the accumulated peak is lost to erosion after submergence of the saline marshes. Although peat accumulates more slowly on the north side of the Teche Shoreline the ultimate retention is much greater. This accounts for the relative depletion of total organic content in marshes south of the boundary relative to marshes to the north. It may also be possible that some degree of footwall uplift on the faults may be providing added stability to the marsh platform edges along the fault trends.



Delta cycle Figure 39

The relationships between the neo-tectonic framework and the recent processes of subsidence, accretion and land area change account for the distribution patterns of various marsh ecosystems types in the delta plain and the distribution patterns of the organic content of the marshes. The natural processes discussed previously in the Predictive Modeling sections on accretion, surface elevation change and land area change are also consistent with these relationships. The patterns of these processes seen in

Figures 27 – 31 are best explained as sediment accreting on more stable marsh platforms having been transported by tidal flux. Figure 32 indicates that the source of these sediments is edge erosion along linear marsh edges experiencing differential subsidence.



Teche shoreline from Kulp et al, 2005 - soil content from Tweel & Turner, 2012 Figure 40

The relationship of the surface fault traces relative to areas of recent marsh submergence seen in Figure 37 indicates that faults may be directly associated with the mechanism of differential subsidence invoked by Wilson and Allison in Figure 32. There is very little direct evidence of footwall uplift on any of the faults represented by the traces in Figure 37. It is however, worth considering the possibility of the phenomenon occurring. It may be possible that both footwall uplift and passive diapirism on the salt domes may be providing a relative upward vector against the forces of subsidence. The expansion of capabilities to directly measure current rates of subsidence, as described in the Data Collection section of Evaluation Procedures, would eventually provide data adequate to determine if footwall uplift and/or passive diapirism is occurring. This would allow for the integration of these phenomenon into predictive models and into project planning.

It is important to note that the process of accretion described here comes with the expense of edge erosion. In effect the marsh platform is "cannibalizing" itself in order to maintain elevation. Because only a portion of the mass of eroded sediment is recaptured by accretion the total net change in land area will always be negative. Without sediment supplementation the intermediate to saline marshes of the delta plain will continue to lose land area. It is reasonable to believe, however, that given the introduction of new sediment from outside of the estuary, the processes of accretion could potentially allow the marshes to maintain elevation in the face of relative sea level rise for some time into the future.

Project Concept Proposal

To this point this proposal has attempted to provide a review the scientific basis on which the following set of project concept proposals is based. The critical elements of the preceding scientific review that will factor into the development of the project proposals are:

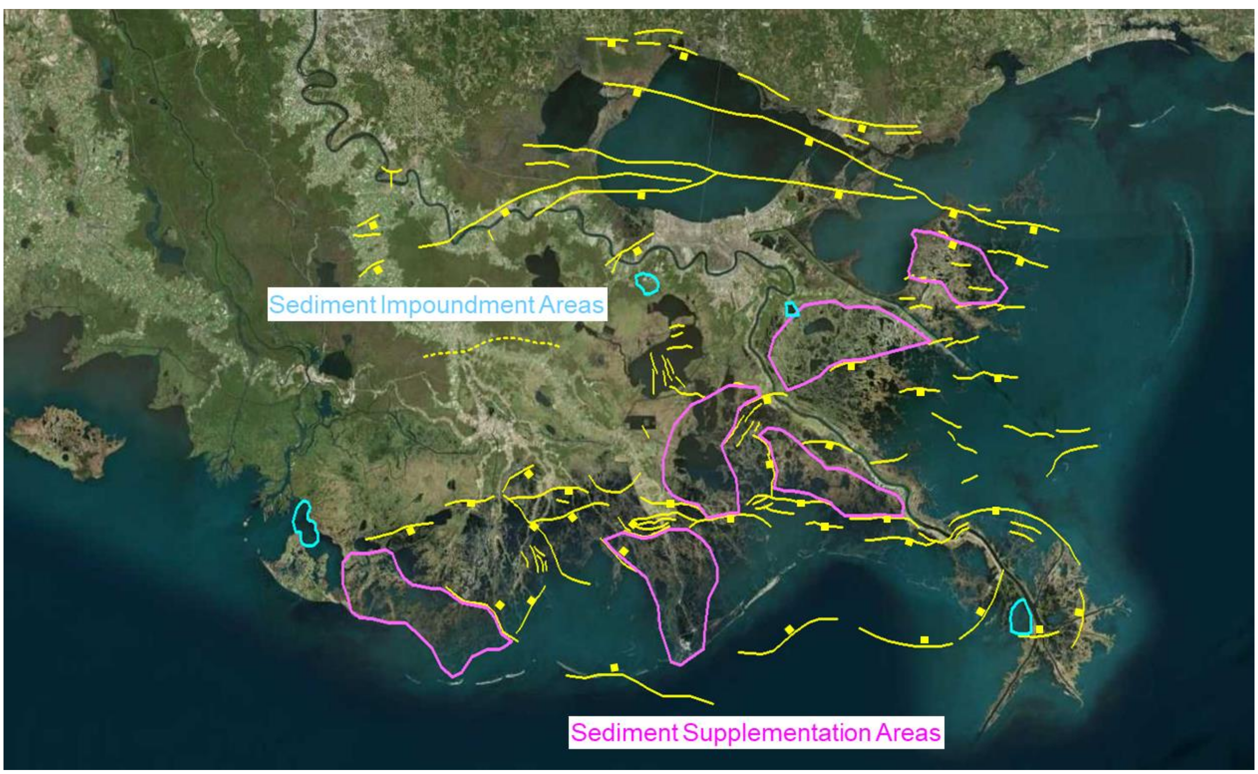
- Subsidence in the Mississippi River delta plain is driven primarily by the consolidation of Holocene deltaic sediments

- Reasonable rudimentary predictive models of rates of subsidence across the delta plain can be constructed using recent subsidence measurements and maps of the thickness and composition of the Holocene deltaic sediments

- Accretion, surface elevation change and land area change data being measured by CRMS sites indicates that many areas of the delta plain are experiencing positive accretion rates, positive surface elevation trajectories, and relative stability in land area change rates.

- Some areas of the intermediate to saline marshes across the delta plain are experiencing natural sediment accretion at rates capable of keeping up with relative sea level rise.

- The natural supply of sediment to the intermediate to saline marshes appears to be derived from submerged marsh material that is subjected by subaqueous erosion and carried onto the marsh surface by tidal flux.



Sediment impoundment areas and supplementation areas with surface fault traces Figure 41

The fundamental concept of the project proposals made here is that the natural sediment supply feeding accretion in the marsh can be supplemented with sediment transported into the estuaries. Six proposed “Sediment Supplementation Areas” are outlined in Figure 41. The basic premise of this project proposal is that sediment captured by dredging of the channels of the Mississippi River and the Atchafalaya River would be retained in “Sediment Impoundment Areas” and then redistributed to the Sediment Supplementation Areas. A review of Figures 28, 29, 37 and 40 shows that the outlines of these areas are generally within intermediate to saline marsh where natural accretion rates and positive surface elevation trajectories are high compared to rates of relative sea level rise and generally along the footwall sides of faults. These characteristics suggest that these areas should have good prospects for long-term sustainability. The addition of sediment from outside sources should primarily serve to enhance sustainability in these areas by feeding the natural processes of accretion that are already occurring.

The four proposed Sediment Impoundment Areas are located at the sites of the Davis Pond, Caernarvon and West Bay Freshwater Diversion projects, and near the delta of the Atchafalaya River. The proposed concept is to convert the three diversion projects on the Mississippi River to new exclusive functions as sediment impoundment areas. Existing infrastructure and rights-of-way should help to facilitate the development of new infrastructure to collect sediment from vessels carrying dredged material in the Mississippi River and transport it from the channel to impoundment areas at the outfall areas of the diversion projects. Dredged sediment in the impoundment areas would then be loaded into barges for transportation to the sediment supplementation areas or transported to other locations by sediment pipelines.

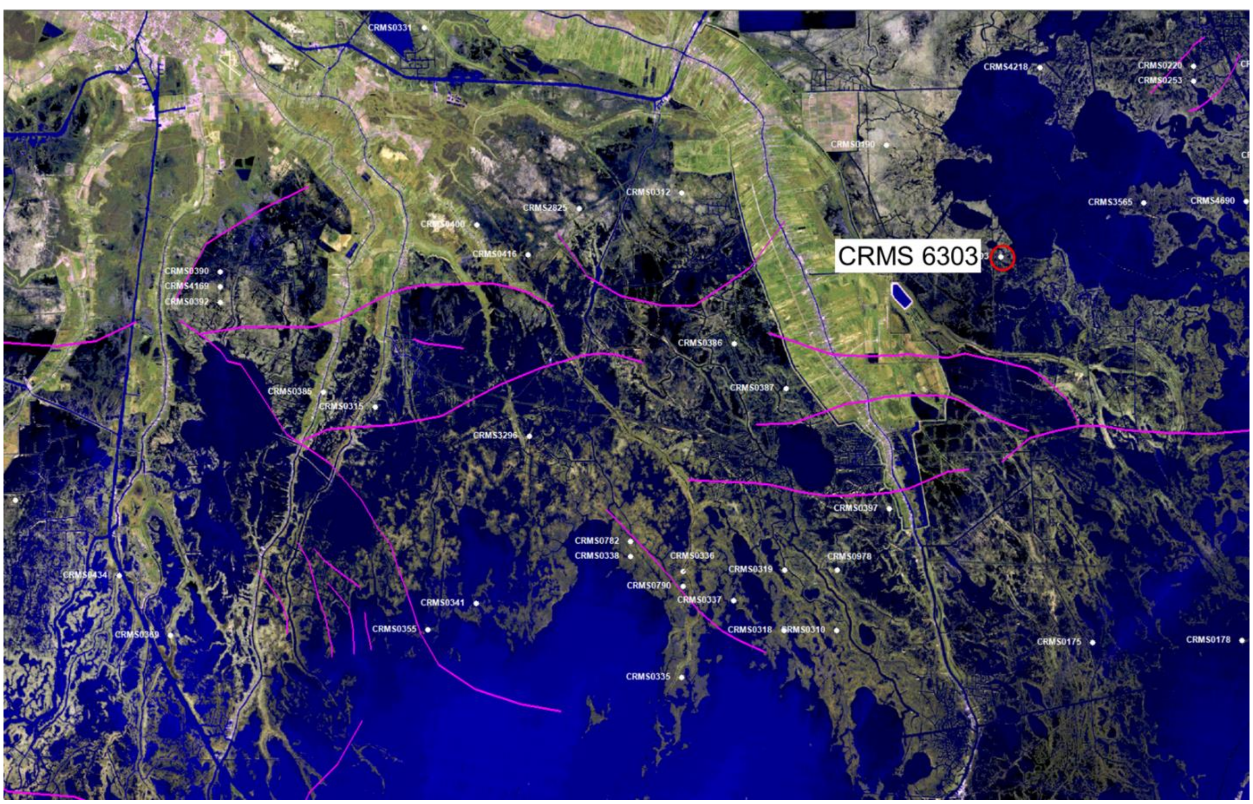


Figure 42

Little Lake Shoreline Protection/Dedicated Dredging Near Round Lake (BA-37) project

A good example of the benefits of pursuing sustainability projects within the naturally accreting intermediate to saline marshes of the delta plain is found at the dedicated dredging project near Round Lake. Sediment dredged from the bottom of Little Lake was pumped into a containment dike surrounding CRMS site 6303 in 2007. The dike was required to retain the slurried sediment to the point that elevations necessary to support new marsh growth could be attained. As seen in Figure 43, after the project was

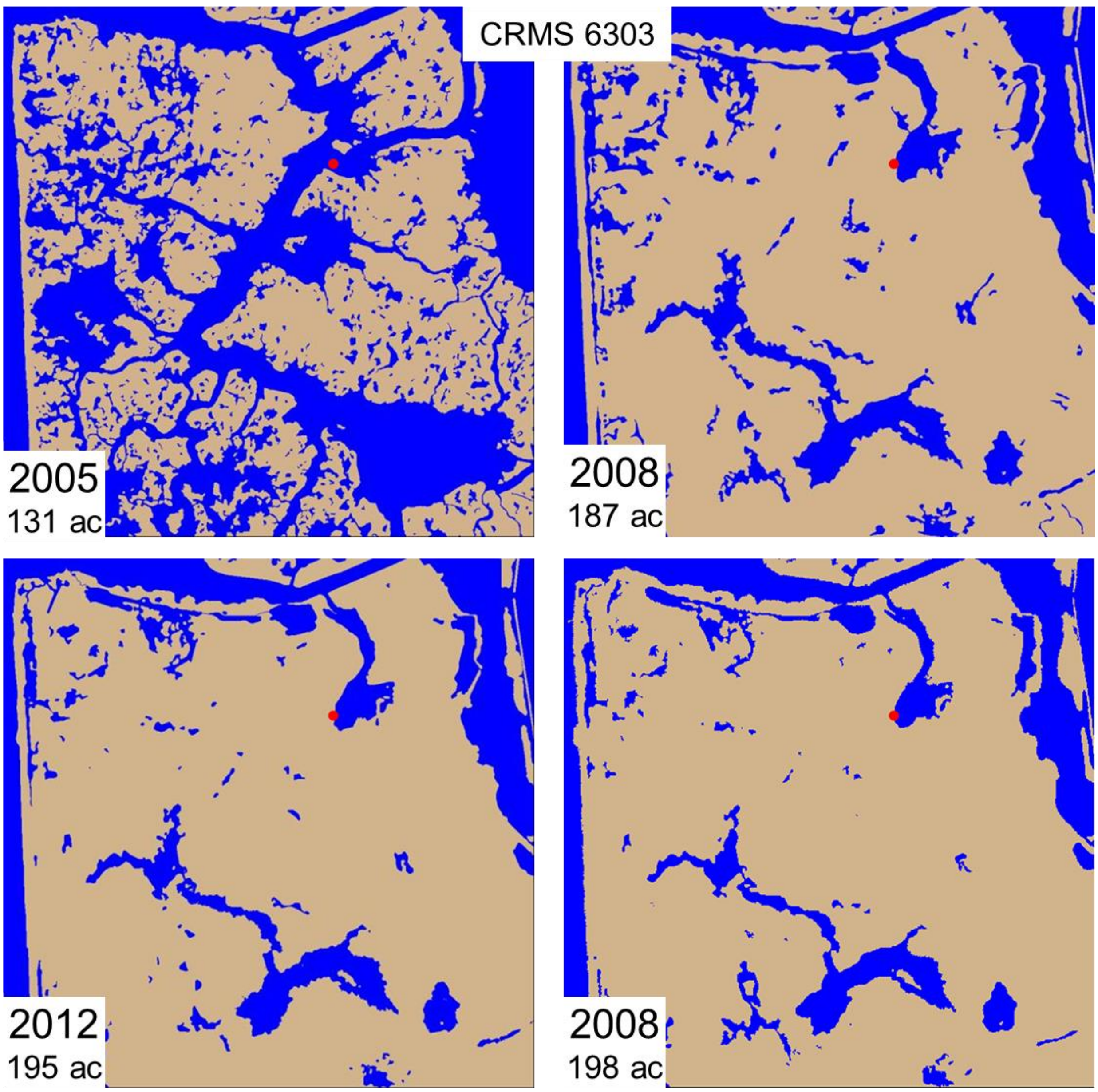


Figure 43

completed in 2007 the area continued to gain land area beyond that provided by the initial introduction of sediment. The net gain of 11 acres of new land area after the completion of the project indicates an ongoing process of accretion. This is a nearly 20% add-on in land area gain to the original 56 acres accomplished by the marsh creation project. The land/water interpretations from CRMS site 6303 show that the additional land area gains occurred by primarily by the infilling of interior ponds within the marsh. There is little doubt that the land area gains measured after the completion of the marsh creation project were due in large part to the additional availability of sediment for the natural processes of accretion. The challenges of Project BA-37 were the use of sediment source from within the estuary, which has a limited capacity on a large scale, and the use of rocks for a containment dike. The containment dike was probably a significant portion of the cost of the project, and the weight of the rocks certainly caused an acceleration of local subsidence rates. These challenges could be addressed by the introduction of sediment from outside of the estuary and the removal of the containment dike from the project design. If sediment dredged from the Mississippi River had been transported to the site of the project by barge and then pumped into the marsh without a containment dike, there would not have been an immediate improvement in the elevation of the marsh surface. Neither would there have been an immediate increase in land area, as measured at CRMS 6303, but it is likely that the benefits of the addition of sediment to the natural processes of accretion would have been manifest in more widely distributed land area gains in marshes around the location of the project. This is the fundamental basis for the project concepts proposed here. A more detailed review of each of the proposed sediment supplementation areas will discuss opportunities for individual projects in each area.

Sediment Supplementation Project Area 1

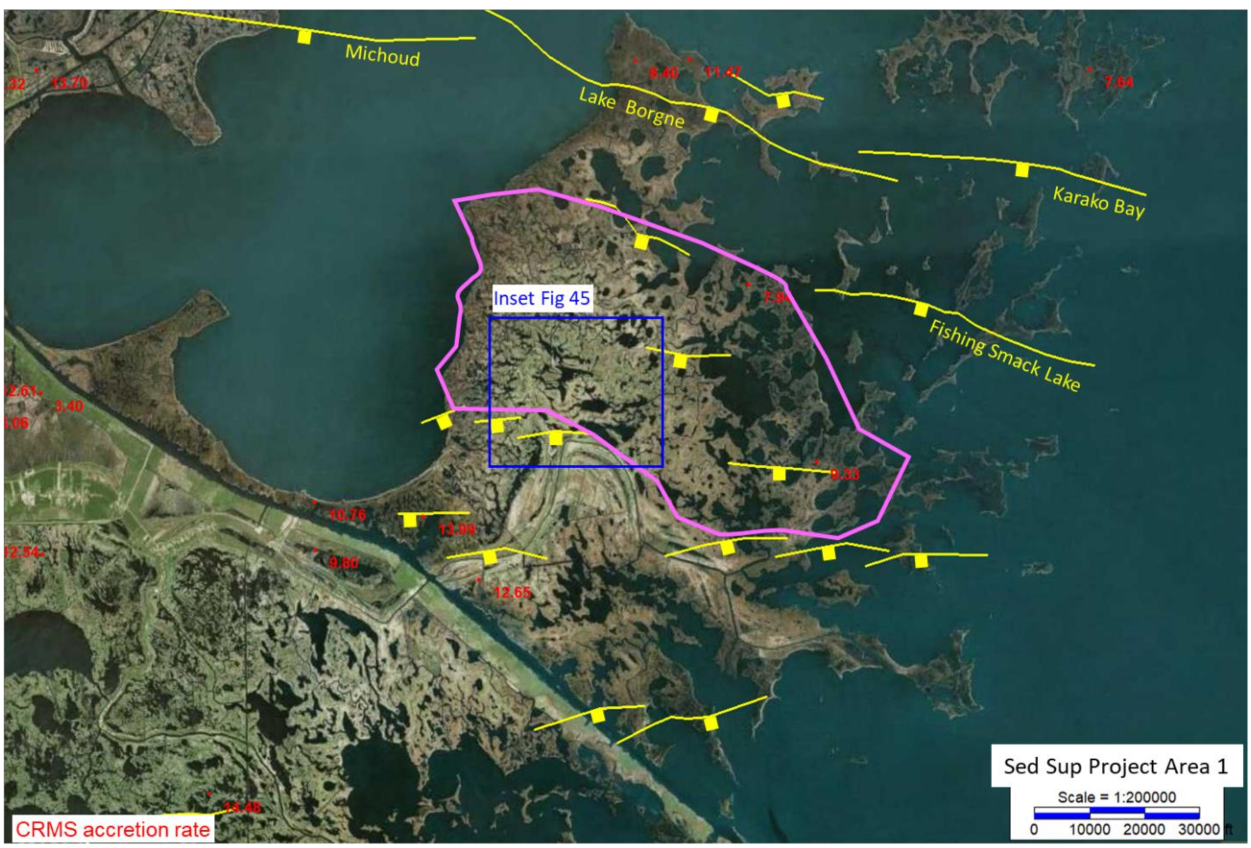


Figure 44

Area 1 covers a significant portion of the brackish and saline marshes in the Biloxi Marsh Complex. The report NEW INFORMATION SUPPORTING THE STABALIZATION & RESTORATION OF THE BILOXI MARSH COMPLEX, Day et al, 2019 provides a fairly comprehensive assessment of the historical causes of wetlands loss and the future sustainability of the marsh complex. This assessment includes a thorough geological evaluation using oil and gas industry seismic data. The potential surface traces extrapolated from faults mapped with the seismic data are shown in 44. The report notes that the Biloxi Marsh Complex lies above an ancient carbonate platform that provides a stable base and has relatively thin underlying deposits of Holocene deltaic sediments. The latter finding is consistent with Figure 20. Figures 22, 27 and 29 indicate that this area is characterized by relatively low subsidence rates and positive rates of accretion and surface elevation change, indicating natural sediment accretion in the marsh.

The Day et al, 2019 report also includes Appendix I - LEVERAGING NATURAL RESILIENCE TO ENSURE LONG-TERM SUSTAINABILITY OF THE BILOXI MARSH COMPLEX : AN INTEGRATED PROJECT. The appendix contains specific project designs for a beach berm along the shore of Lake Borgne, plus numerous marsh creation and marsh nourishment projects. These projects provide perfect examples of the types of sediment supplementation projects envisioned by this proposal, and the appendix to the Day et al, 2019 report provides detailed design specifications. The sole difference between the project proposals of the Day et al report and the conceptual projects of this proposal is the source of the sediment. It may well prove to be more efficient and cost effective to take sediment from within the estuary to build marsh elevation, as proposed by Day et al, but the success of large scale sustainability efforts will ultimately be enhanced by transporting sediment from outside of the estuary.

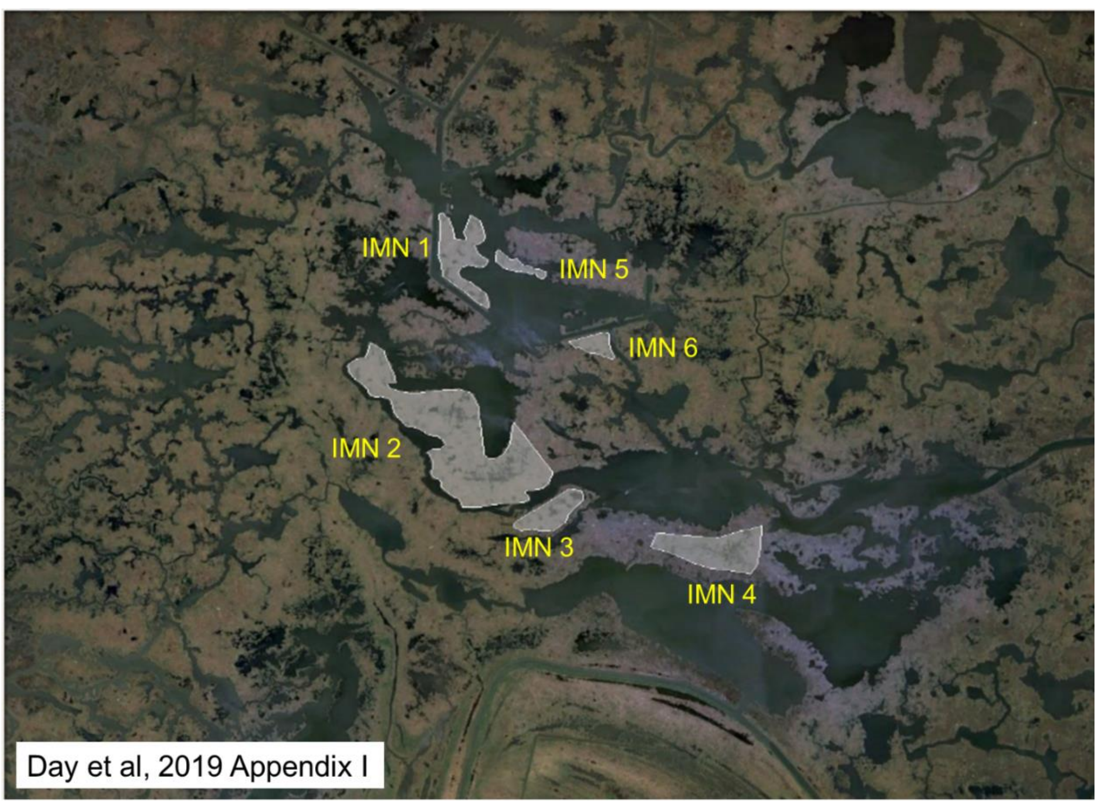


Figure 45

Figure 45 shows the outlines of six Interior Marsh Nourishment (IMN) projects proposed in the Day et al Appendix. These projects are proposed for the transportation of sediment by pipeline in a slurry of sand, silt and water, and the "thin layer addition" of sediment to the marsh by spraying the slurry onto the marsh surface. The appendix notes that thin-layer placement of dredge material in this manner "will be used to increase soil surface elevation, to reduce waterlogging and porewater hydrogen sulfide toxicity, and to increase soil redox potential and vegetation stem density, productivity and nutrient uptake."

Sediment Supplementation Project Area 2

Project Area 2 is unique among the proposed sediment supplementation areas in having suffered significant wetlands loss over the past few decades. The area is underlain by relatively thin Holocene sediments and subsidence rates are correspondingly low. A comparison of Figures 27, 28 and 29 shows that although accretion rates in Area 2 have been high compared to rates of relative sea level rise, the area has generally experienced negative rates of surface elevation change. Several studies including

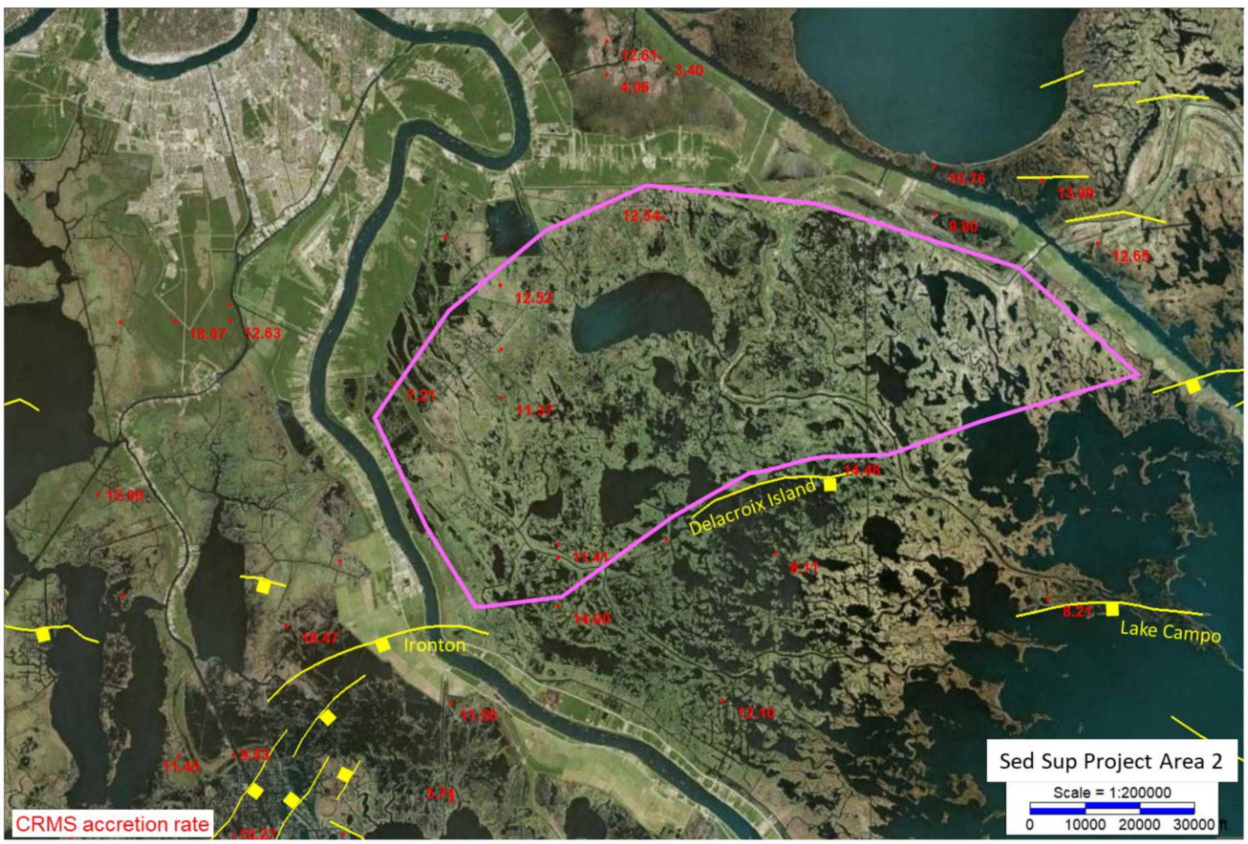
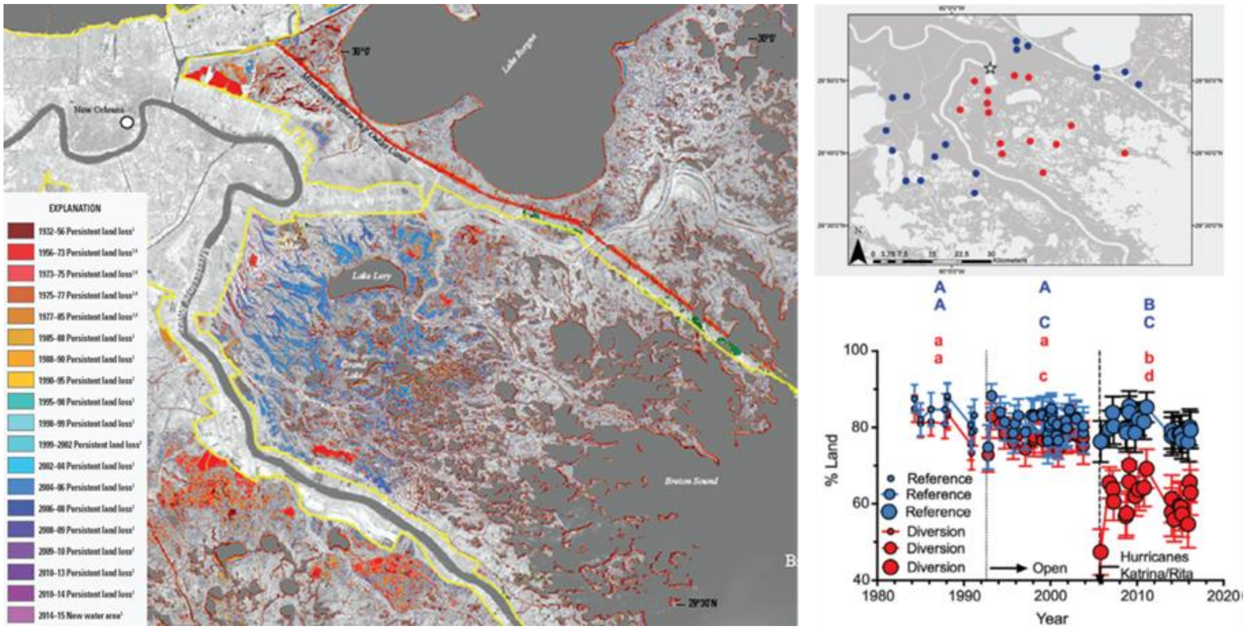


Figure 46

Turner et al, 2019 and Kearney et al, 2011 found that wetlands loss in this area were directly associated with Hurricane Katrina. Areas of land loss shown in blue on the USGS SIM 3381 Map (Couvillion et al, 2017) in Figure 47 delineate the losses that occurred during and after Hurricane Katrina. Turner et al, 2019 evaluated the patterns of wetlands loss over several decades and determined that increased nutrient supply and flooding from the introduction of river water by the Caernarvon Diversion have been negative influences on marsh health. Their graph on the right of Figure 47 shows the accelerated wetlands loss in the receiving basin of the Caernarvon Diversion relative to reference marshes in the area. Kearney et al, 2011 found that “excessive nutrient influx into the Caernarvon diversion marshes is linked to the widespread occurrence of low soil strength (by field shear vane tests), indicating that these marsh sediments are potentially highly erodible”.



Land loss from Katrina Couvillion et al, 2017 (left) Turner et al, 2019 (right) Figure 47

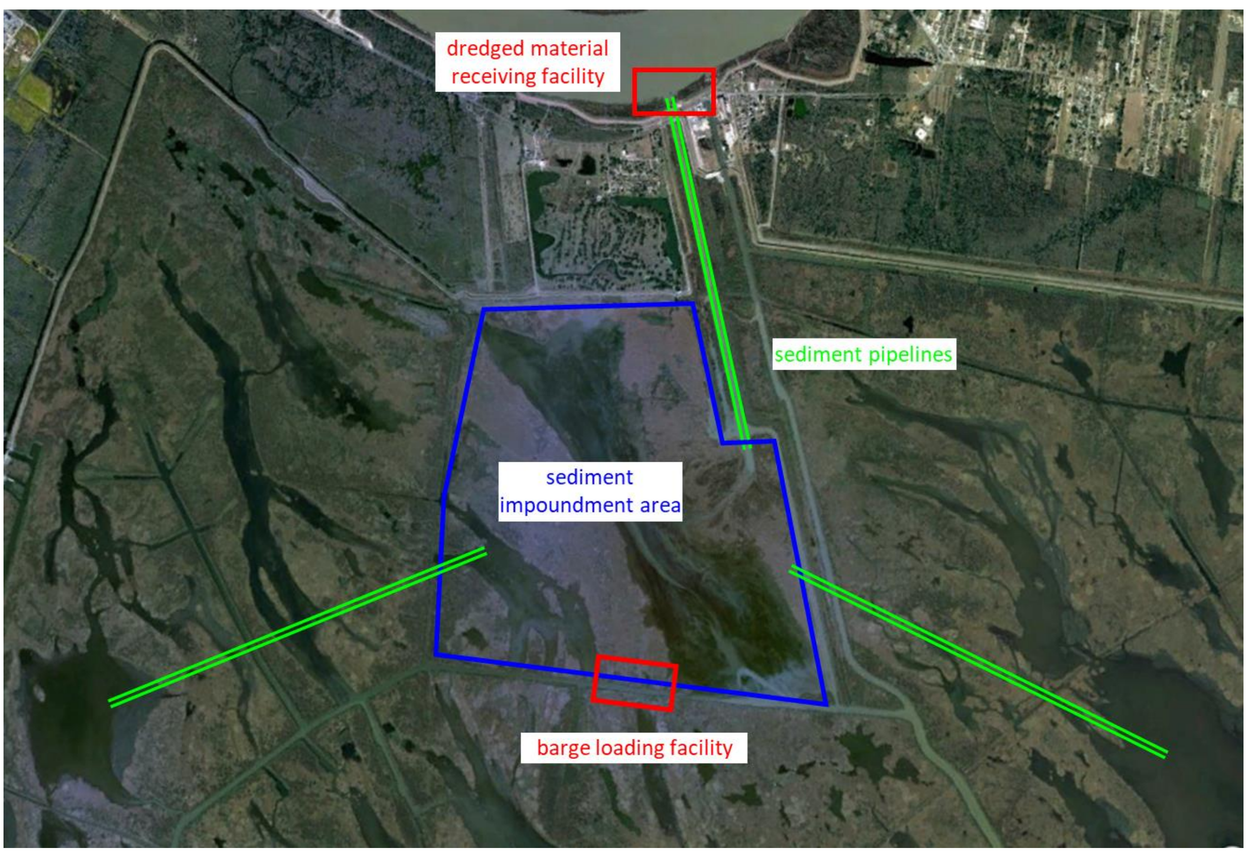


Figure 48

Indications that negative surface elevation change and wetlands loss in Area 2 were primarily attributable to erosion during Hurricane Katrina suggests that sediment supplementation from outside of the estuary combined with a cessation of river water influx from the Caernarvon Diversion could have positive impacts on sustainabililty relative areas with higher subsidence rates. Levesh et al, 2019 showed evidence that wetlands loss on the hanging wall side of the Delacroix Island fault may be associated with recent fault slip. Areas south of the surface fault trace are not recommended for project locations

Figure 48 presents a generalized conception of the Sediment Impoundment Area that is proposed to replace the Caernarvon Diversion. Material received from dredging operations in the channel of the Mississippi River would be transported by a permanent sediment pipeline into the impoundment area. The accumulated sediment could then be redistributed by barge to sediment supplementation projects east of the river. Sediment could also be distributed to projects within Area 2 by temporary sediment pipelines. It is proposed that the primary targets for sediment supplementation in Area 2 would be the open bodies of water formed by erosion during Hurricane Katrina. The object of these projects would be to simply introduce sediment into the lakes and ponds without the use of containment dikes. This would feed the natural systems of sediment redistribution and accretion without attempting to build pre-determined areas of new land.

Sediment Supplementation Project Area 3

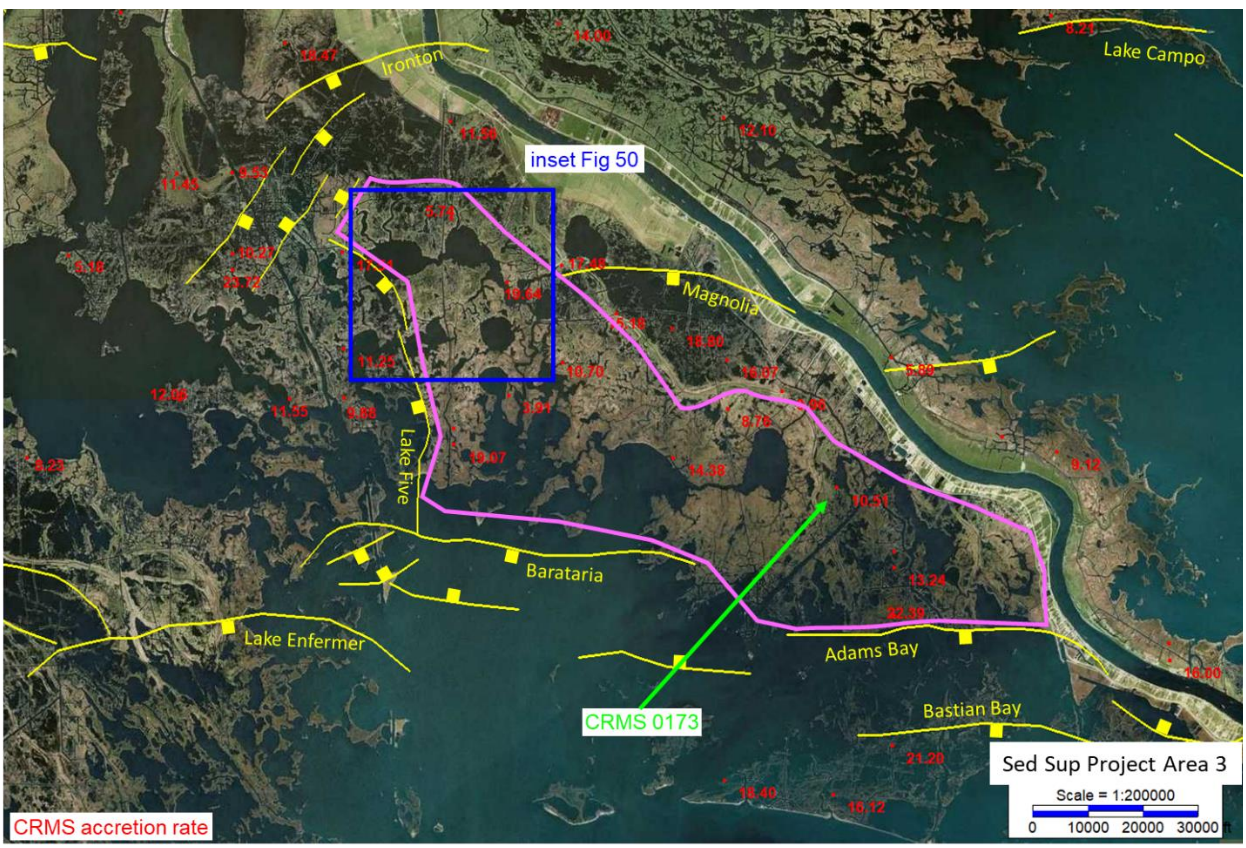


Figure 49

Project Area 3 is bounded by the natural levee of the Mississippi River and the footwall sides of the Adams Bay, Barataria and Lake Five faults. Figures 27, 28, 29 and 37 show that this area has been generally experiencing positive surface elevation change, high rates of accretion compared to rates of relative sea level rise and general stability of land area change over the past several decades. Figure 30 documents that CRMS site 0173, which is in Area 3, has sustained relatively stable land area over the past decade through a balance of edge erosion by the filling of interior ponds by accretion. It is considered likely that CRMS 0173 is representative of much of the marsh platform within Area 3. Supplementing the natural processes of interior pond filling with thin layer addition of sediment by spraying, as described in Day et al, 2019 for their proposed projects in Area 1, should be an effective way to promote sustainability in this area.

Sediment berms placed in open water along the edges of the marsh platforms should also be effective in this area. The concept of these berms would be to introduce new sediment into the system at locations where erosion of sediment is depicted on Figure 32 from Wilson and Allison, 2008. This sediment should be carried onto the adjacent marsh platform in the manner indicated on Figure 32. It may also be possible that the introduction of sediment berms along the edges of the marsh platform could reduce the rate of edge erosion, which appears to be the principal cause of wetlands loss in these marshes.

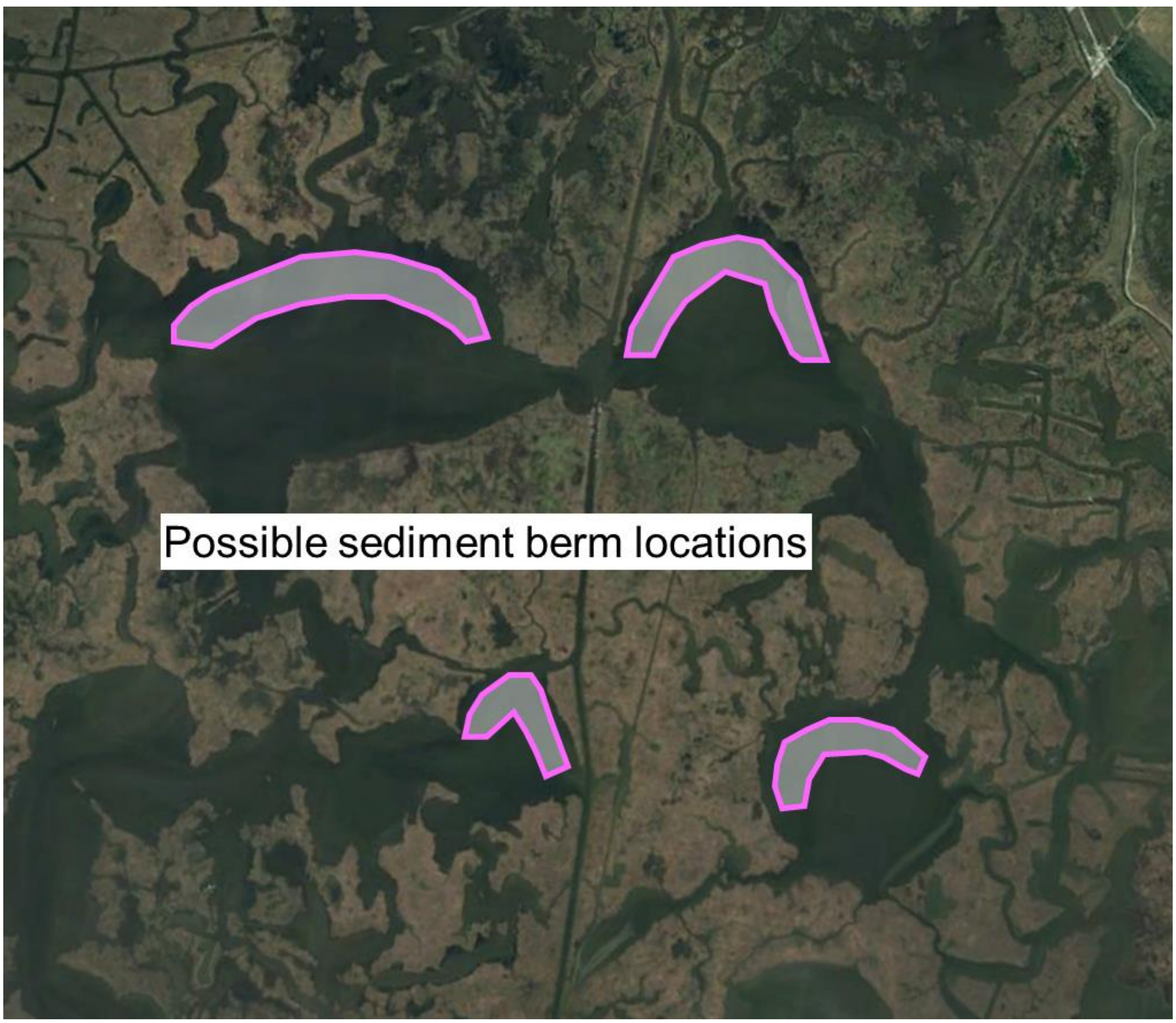


Figure 50

The primary challenge to the introduction of sediment berms along marsh edges in Area 3 is the proliferation of oyster leases. Figure 50 shows a generalized conception of four sediment berm sites at the northern end of Area 3. These sites are not affected by oyster leases. These berms would not require any containment structures, and could emplaced by sediment slurry pipeline from a barge.

<u>Sediment Supplementation Project Area 4</u>

Area 4 appears to be primarily supported by the natural levee of Bayou Lafourche. It is also apparent that there is a relative lack of major faults across the area. The southern end Area 4 includes Port Fourchon. This area may be receiving some support from passive diapirism associated with the massive Bay Marchand salt dome. Figures 27, 28 and 29 show that this area is generally experiencing positive surface elevation change and high rates of accretion compared to rates of relative sea level rise. Area 4 crosses the axis of the Terrebonne Trough and overlies some of the thickest deposits of Holocene deltaic sediments on the delta plain. Correspondingly, subsidence rates have been high in the marshes adjacent to the natural levee. This area experienced significant wetlands loss between the 1930s and 1970s, as evidenced by the graph curves in Figure 38. Rates of subsidence and wetlands loss in this area have steadily decreased over the last three decades however.

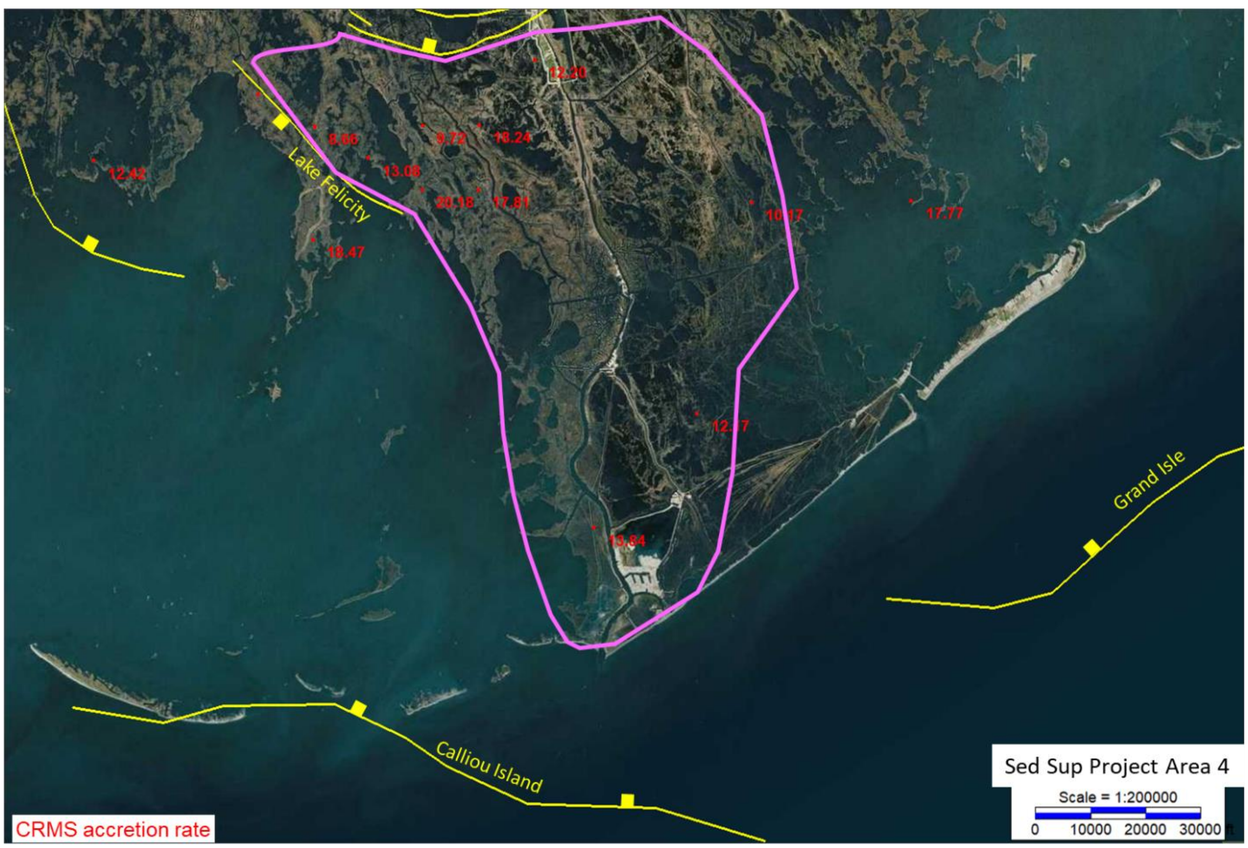


Figure 51

In addition to the high rates of accretion compared to rates of relative sea level rise, Area 4 is considered important for sediment supplementation because of the economic value of Port Fourchon and the LA Highway 1 corridor. Achieving long-term sustainability in this area will help to sustain the economic viability of the area, which in turn will help to provide revenue to support the implementation of sustainability projects. In this regard marsh creation projects around Port Fourchon and along the flanks of the LA Highway 1 corridor are proposed as priority objectives of sediment supplementation in this area.

<u>Sediment Supplementation Project Area 5</u>

Area 5 includes CRMS site 6303 which is located within the Little Lake Shoreline Protection/Dedicated Dredging Near Round Lake (BA-37) project. The continued increase in land area after the completion of this project, which is documented in Figure 43, is used as a model for all of the projects proposed here. Figure 8 shows that work done by LGS indicates that some of the northern portions of Area 5 are underlain by relatively thick accumulations of highly organic soils. These may be challenged by locally higher subsidence rates. Figures 27, 28 and 29 indicate that much of the area has experienced high accretion rates compared to the rate of relative sea level rise and positive surface elevation change rates. Projects similar to BA-37 should be successful around the perimeter of Little Lake. The ability to transport sediment into the area instead of dredging it from the bottom of the lake should allow for a significant expansion of the success achieved by BA-37.

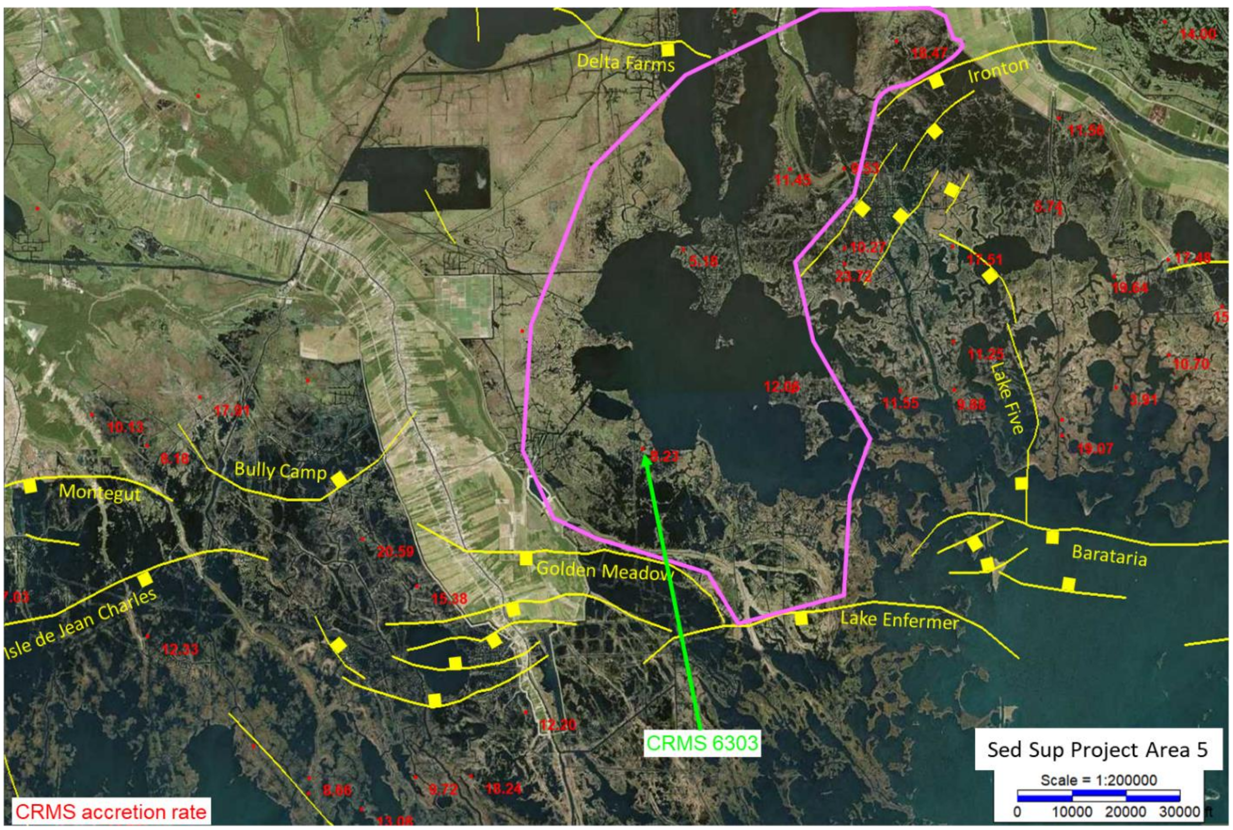


Figure 52

<u>Sediment Supplementation Project Area 6</u>

Area 6 is bounded on its south side by the southern shoreline of Terrebonne Parish. CRMS sites close to the shoreline have measured the significant impacts of shoreline erosion including negative rates of surface elevation change and land area change. CRMS sites within Area 6 that are interior to the shoreline have measured high accretion rates however. It seems likely that some of the marsh that has been lost to shoreline erosion has provided a source of sediment for accretion in the interior marshes. Figures 27,

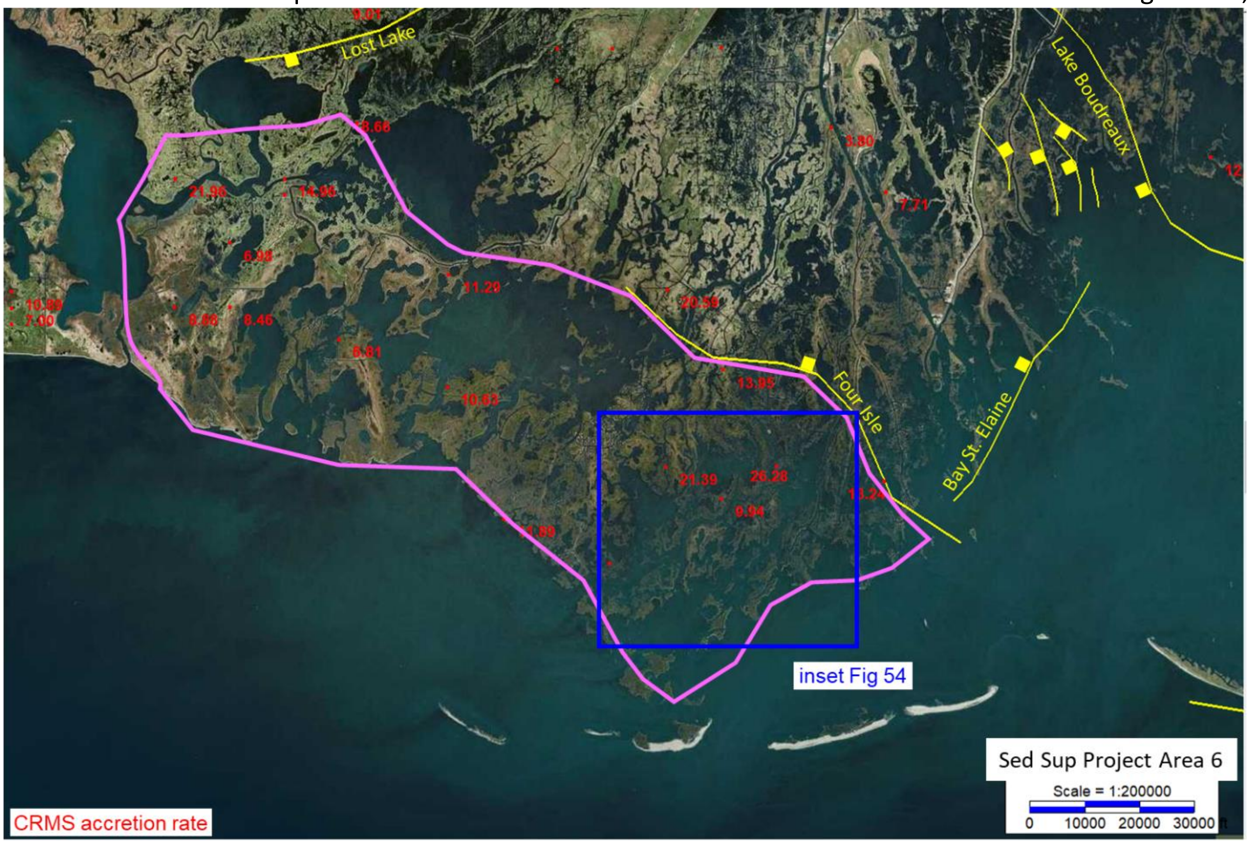


Figure 53

28, and 29 show that much of Area 6 has been experiencing high accretion rates compared to rates of relative sea level rise and positive rates of surface elevation change. Area 6 is on the southern perimeter of the Terrebonne Trough. The thickness of Holocene deltaic sediments is generally thinner under Area 6 than areas to the north. The Dog Lake salt dome shown in profile on Figure 4 is along the northern boundary of Area 6. Figure 4 indicates that the salt dome has affected the thickness of Quaternary sediments by passive diapirism. It may be possible that this salt dome and others along the southern border of the Terrebonne Trough may be providing some measure of support against subsidence. It may also be possible that footwall uplift on the Four Isle fault is having a similar effect.

The exposure of Area 6 to the shoreline means that there is an active flux of sediment in the tidal channels. The movement of sediment within the channels is apparent on Figure 54. If it can be determined that certain channels are preferentially carrying sediment in an inland direction, then there may be a project concept to feed sediment directly into those channels. This could be accomplished by pumping sediment slurry from a barge directly into target channels for transport. Project concepts in Area 6 could also include sediment berms, marsh creation projects and thin-layer addition by spraying sediment onto the marsh surface. The keys to success for each of these project concepts are to stay within the outlined areas of high natural accretion and positive surface elevation change, and to transport sediment into the area from outside sources. The proposed sediment impoundment area in eastern Atchafalaya Bay and Four League Bay shown in Figure 41, which is intended to impound sediment dredged from the Atchafalaya River, is the closest to Area 6.

Figure 54

Summary and Conclusions

The rudimentary predictive models that have been constructed here with available data indicate that there are portions of the intermediate to saline marshes of the Mississippi River delta plain where the rates of natural sediment accretion and surface elevation change are high compared to the rate relative sea level rise. This suggests that supplementing the natural processes of accretion in these areas with sediment from outside of their estuary should enhance the potential for their long-term sustainability. A set of project concepts intended to provide sediment supplementation to these areas is presented here. The accuracy of the predictive models and their utility in guiding the design and implementation of the project concepts is limited by the datasets from which they were constructed. Expanding data collection functions to measure and map current rates of subsidence, the deltaic sediments of the Holocene, and the neo-tectonic framework will dramatically improve the accuracy and utility of predictive modeling. LGS can play an important role in expanding the data collection function. It is recommended that data collection should receive priority for funding in the 2023 Master Plan.

Commentary

The wetlands of the Mississippi River delta plain are in a constant state of flux; so is the state of our collective knowledge about them. Much of the data that has been collected and processed over the past few years and the research that has been performed using that data offer new perspectives on the wetlands. There appears to be good reason to believe that long-term sustainability of the delta plain is achievable. This may even prove to be true for some time into the future in the face of anticipated increases in rates of relative sea level rise.

From the inception of the coastal program in Louisiana it has been primarily implemented with a crisis-management operational approach. The net effective of this approach has been a strong measure of pessimism about the current condition of the wetlands and about the potential for their sustainability. A review of the subject in the popular media would leave the average person believing that long-term sustainability is utterly hopeless. Much of the recent data and research does not support the crisis narrative. They suggest that there is good reason for optimism about the sustainability of the wetlands. Achieving this optimistic outcome will require significant funding however. Replacing the crisis-management approach and its attendant narratives about the condition of the wetlands with a science-based optimistic approach would provide a much stronger basis on which to pursue operational funding for the endeavor.

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