

# Wells to Monuments Program

## Phase 1 Proposal Purpose and Justification

May 2020



## Introduction

The underlying concept for the Wells to Monuments Program was conceived by Dr. Elizabeth McDade of Chinn-McDade Associates, LLC. Dr. McDade is also a co-author of the TranSET study referenced here. This proposal is made by the group of collaborators listed below. The intent of the program is to repurpose orphaned oil and gas wells to be used as geodetic monuments equipped with Global Navigation Satellite System (GNSS) equipment in a manner consistent with protocols of the U.S. National Geodetic Survey. The most prevalent GNSS is the Global Positioning System (GPS) is a U.S.-owned utility that provides users with positioning, navigation, and timing (PNT) services. It may also be possible that these monuments could be attached to corner reflectors design to reflect radar signals from an interferometric synthetic aperture radar (InSAR) satellite. Geodetic monuments provide a survey base for the state and support mapping, boundary determination, property delineation, infrastructure development, resource evaluation surveys and scientific applications. In addition, monuments equipped with GPS and/or InSAR reflectors allow for the measurement of vertical and horizontal velocities of the Earth's surface to which the monument is anchored. Orphaned oil and gas wells generally consist of steel casing that is anchored many thousands of feet below the surface. This means that monuments created from repurposed wells will measure velocities that are not impacted by near-surface compaction (e.g., Keogh and Törnqvist, 2019). The ability to compare vertical and horizontal velocities between new deep-anchored, as well as existing shallow-anchored GNSS and tide gauge monuments would provide new insights that both increase the spatial resolution of coastal monitoring, but that also enable separation of shallow and deep contributions to coastal subsidence (vertical velocity) and all forms of infrastructure design and planning, which may be impacted by both vertical and lateral velocities. Spatial patterns in the new data may also enable quantification of slow creep along coastal fault systems.



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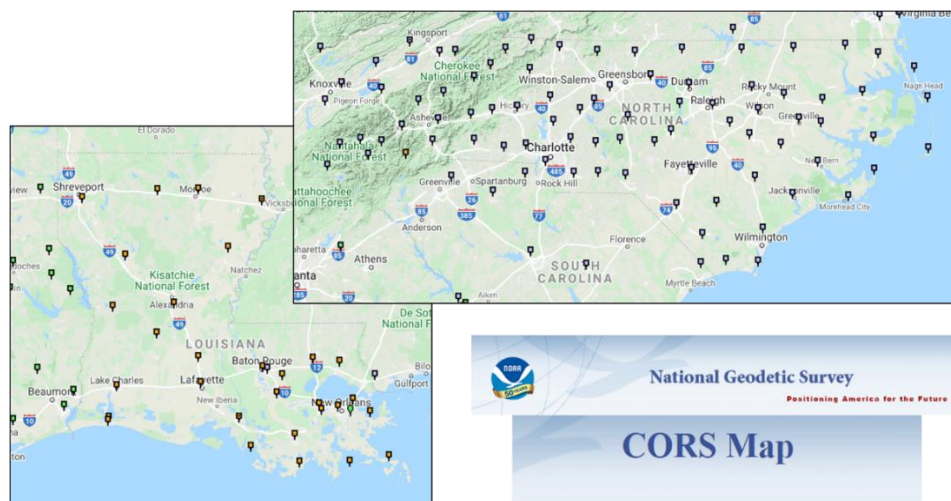
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The Wells to Monuments Program Proposal consists of four phases:

1. Purpose and Justification
2. Engineering Design and Cost Estimation
3. Bureaucratic Procedure
4. Implementation

This document is Phase 1 of the program proposal. It is intended to outline the scientific purpose and justification for the program, and it will be followed by separate documents that define the subsequent phases. Increasing the density of geodetic monuments in Louisiana is considered to have implicit value beyond the scientific purposes discussed here. Louisiana currently has relatively sparse coverage of monuments in the National Geodetic Survey [CORS](#) (Continually Operating Reference Station) program. The State of North Carolina, by comparison, has made a substantial investment in its network of geodetic monuments, and has much more robust coverage. The benefits of the increased density of coverage in Louisiana that would result from the implementation of this proposed program extend to all phases of infrastructure design and planning including transportation, navigation, ports and coastal restoration.



In addition to providing measurements of subsidence and enhancing positioning applications, other useful information can be extracted from the GPS signals. For the wells that are located over open water, reflectometry techniques can be applied to estimate the height of the GPS antenna above the water surface from the GPS receiver's recorded signal to noise ratio, effectively turning the GPS site into a tide gauge (e.g., Larson et al., 2013; Larson et al., 2017; Larson, 2019). In addition, all of the sites may be usable to estimate precipitable water vapor (PWV) from the atmospheric delays on the GPS signals (Bevis et al., 1992; Bevis et al., 1994; Moore et al., 2015; Shuanggen et al., 2015). PWV observations from GPS (e.g., <https://www.suominet.ucar.edu>) have been incorporated in improved weather forecasts, and have been used to study severe weather events and intense rainfall events (e.g., Basivi et al., 2015; Sapucci et al., 2018).

It is the intention of this proposal that the data generated by the monuments created through its implementation should be open access. This offers the opportunity to build on current in-state data collection that is managed by the LSU Center for GeoInformatics.

## Proposed Wells

Six wells were chosen from the Louisiana Department of Natural Resources (DNR) Orphaned Well Program for consideration in the proposal. The selection of these wells was based on three factors: 1) a distribution of locations that would effectively increase the density of geodetic monuments in the coastal zone, 2) locations that are likely to provide a range of velocity signals based on subsurface geology, and 3) the utility of the well in the program based on the conditions of the well and associated infrastructure at the surface. The wells are shown here referenced by their American Petroleum Institute (API) well serial number, which is a unique identifier for each well, and to which all records of the well are referenced. The well locations are shown in context to the existing CORS network.

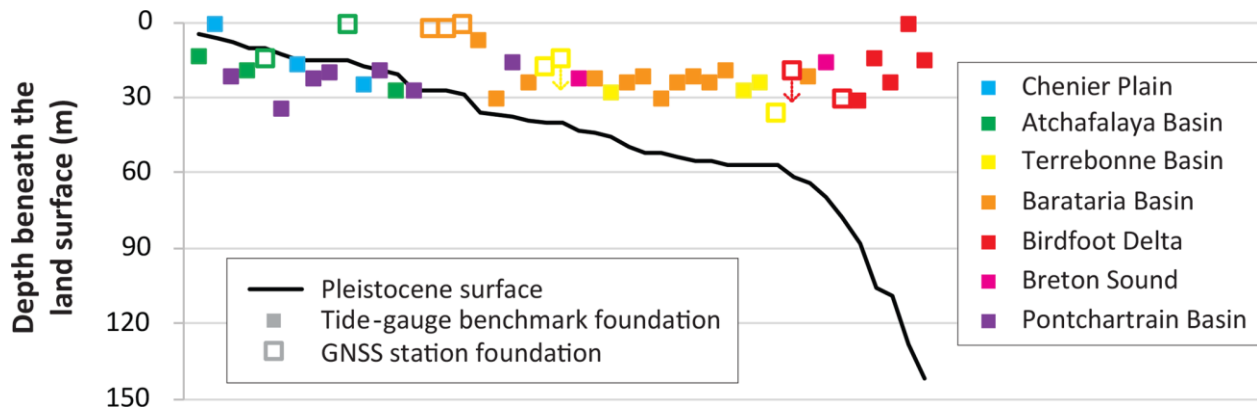
According to the DNR program the term “orphaned” refers to the current status of a particular well site and indicates that the operator of record is no longer a viable responsible party. Following a specific notification procedure, well sites are declared officially orphaned after being sent to the State Register to be published. Wells are removed from the Orphaned Well Program through the Louisiana Oilfield Site Restoration Program, which was created in 1993. The focus of the program is to properly plug and abandon orphaned wells, and to restore the site to approximate pre-well site conditions by cutting well casing below the surface and removing all surface facilities and infrastructure associated with the well. Revenue for the Oilfield Site Restoration Program is generated from a fee on oil and gas production in the state which is paid quarterly by Louisiana oil and gas operators. The fund has collected on average about \$4.5 million each year. The program has plugged and abandoned and restored 2306 wells since 1993 at a cost of \$64 million. There are currently 2833 wells remaining in the program. The intention of this proposal is to use funds from the Oilfield Site Restoration Program to properly plug and abandon each well below the surface but to leave the well head and surface infrastructure in place to be repurposed as a deeply-anchored geodetic monument.

## Subsidence

The primary objective of this proposal is to provide new infrastructure for the direct measurement of subsidence velocities in the Louisiana coastal zone. The National Academies Consensus Study Report (2018) recognized subsidence as an essential research gap in understanding the long-term evolution of the coastal system “The causes, rates, and patterns of subsidence along the Gulf Coast are not sufficiently well understood to allow for accurate prediction at the local to regional scale.” The reasons for this insufficiency are both a paucity of subsidence measurement infrastructure and a poor comprehension of the relative contribution of the various causal processes. According to the most recent study of subsidence published by the Louisiana Coastal Protection and Restoration Authority (Byrnes et al, 2019) “Understanding the causes and rates of subsidence is critical to successful planning and implementation for Louisiana Coastal Master Plan Projects”. The study recognized that subsidence measured at the earth’s surface is the result of 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, and human-induced causes such as lowering the groundwater table, overburden associated with flood protection levees, and marsh settling due to altered hydrology. Other studies have recognized Glacial Isostatic Adjustment (GIA) as a contributing cause of subsidence (Love et al, 2016). Some of these processes are rooted in geological processes that are happening deep within the earth, such as down-warping of the lithosphere, and some are rooted in very

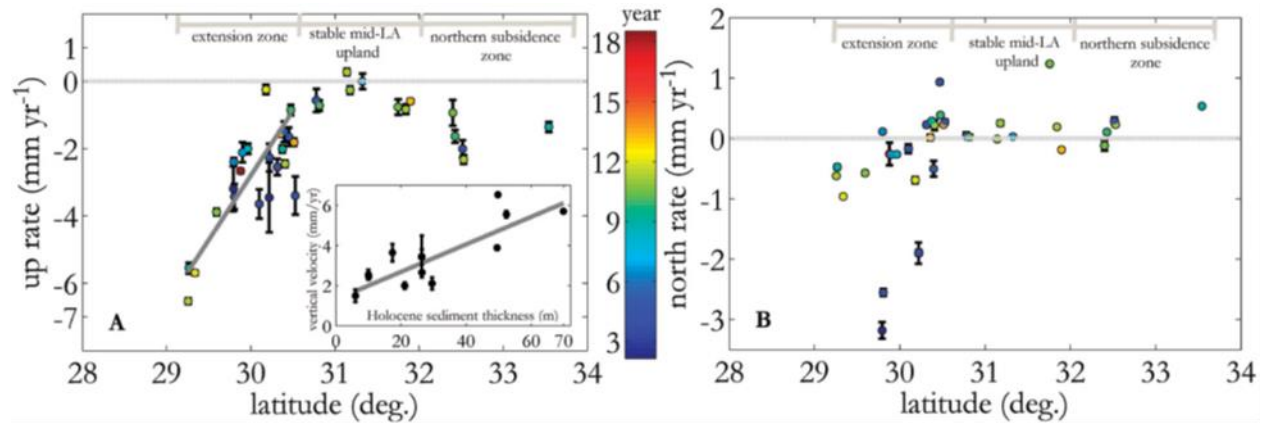
shallow processes, such as near-surface consolidation. The study found that previous attributions of deep-seated geologic processes as the primary mechanisms of subsidence measured at the surface by Dokka (2006,2011) assumed that all measured elevation changes reflected movement deeper than the base of piling or rods. Byrnes et al found that unanchored and/or unsleeved benchmark rods or pilings in Holocene sediment are affected by the downward force exerted by the consolidating deltaic sediment.

Keogh and Törnqvist (2019) highlighted the importance of understanding the depth at which benchmark monuments are anchored. Tide gauges, which have been the primary source of data used to calculate multi-decadal- to century-scale rates of relative sea-level change, are each associated with an elevation benchmark. Keogh and Törnqvist showed that depth at which these monuments are anchored varies substantially across the coast relative to the top of the Pleistocene surface. Holocene sediments above this surface are highly compactable.

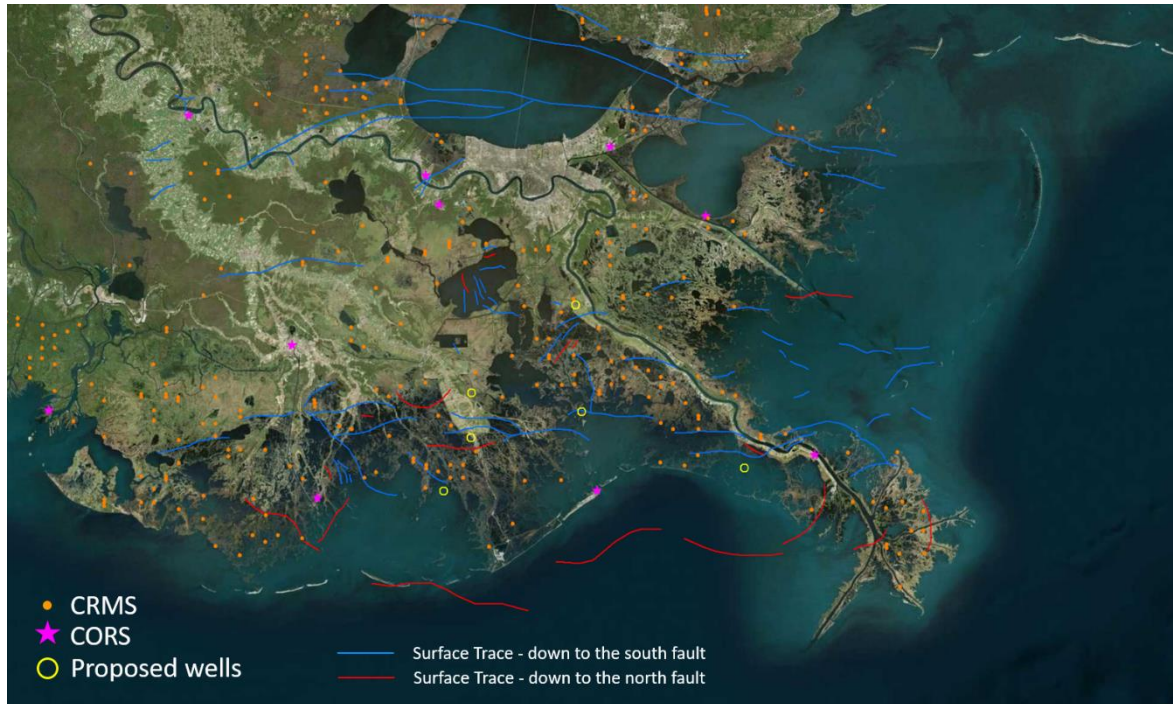


Using deeply anchored wells as monuments would provide a true direct measurement of subsidence velocities that are not affected by the consolidation of Holocene deltaic sediments. This proposal recommends that each deeply-anchored monument created from a repurposed well should be co-located with a shallow-anchored monument. Each of these monuments could be equipped with both a GPS device and an InSAR corner reflector. This configuration would allow for the most accurate assessment of subsidence signals.

Horizontal velocities



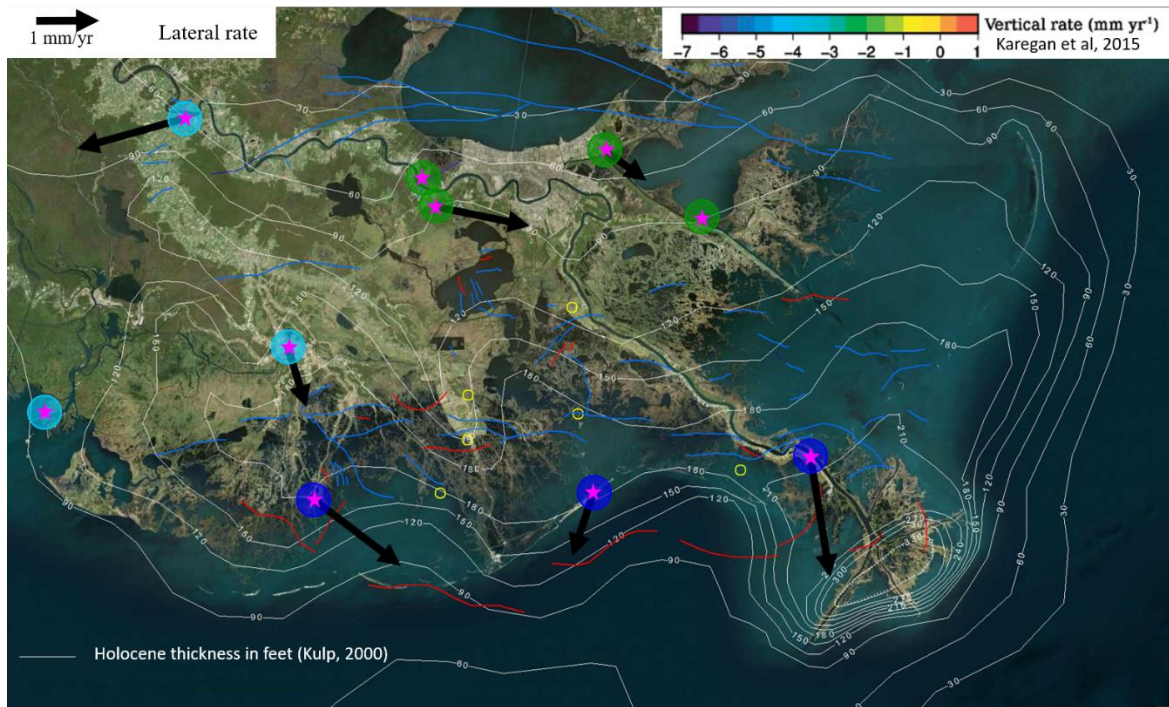
These figures from Karegar et al (2015) show values of vertical and horizontal velocities measured by CORS stations across Louisiana. The inset in the graph on the left shows the relationship between vertical velocities and the thickness of Holocene sediments, as measured by Kulp (2000). Byrnes et al (2019) similarly found that the spatial variability in subsidence has a “compelling relationship” with the thickness of Holocene deltaic deposits. Karegar et al state that the horizontal velocities in the graph on the right “may reflect slow downslope movement on a series of listric normal faults due to gravitational sliding but could also represent the horizontal component of differential compaction”. Velocity data collected from deeply-anchored monuments could provide valuable insights into horizontal motion in coastal Louisiana. This vector of land motion is rarely considered in infrastructure design and planning.



### Subsurface Geology

Every significant recent study of vertical and horizontal land motion in coastal Louisiana (Byrnes et al, 2019; Dokka et al (2006); Jones et al (2016); Karegar et al (2015); Zou et al (2015)) has recognized the potential contribution of fault slip. However, there has been limited access to accurate maps of subsurface fault planes or surface fault traces. The first accurate map of surface fault traces in coastal Louisiana was published by Armstrong et al (2014). Researchers at Tulane and UT-Austin used an oil and gas industry 3-D seismic survey in Plaquemines Parish to project the surface traces of about 20 faults. Since then, on-going work by research groups at Tulane, UNO and ULL have significantly expanded the coverage of surface fault trace interpretation using seismic data. This research has been funded in part by grants from the U.S. Department of Transportation’s University Transportation Centers Program and through the Louisiana CPRA Center of Excellence Research Grants Program (the RESTORE Act) administered by The Water Institute of the Gulf. Preliminary interpretations have been published by the Transportation Consortium of South Central States (Culpepper et al, 2019), and are available in GIS form on the LA Department of Transportation Website. These published interpretations have been integrated here with unpublished interpretations by McLindon Geosciences that are the result of subsurface

geological interpretation in coastal Louisiana utilizing seismic and well log data over the past 40 years. The surface fault trace maps presented here follow the color scheme used by Armstrong et al and are considered to be the most comprehensive and accurate interpretations available.



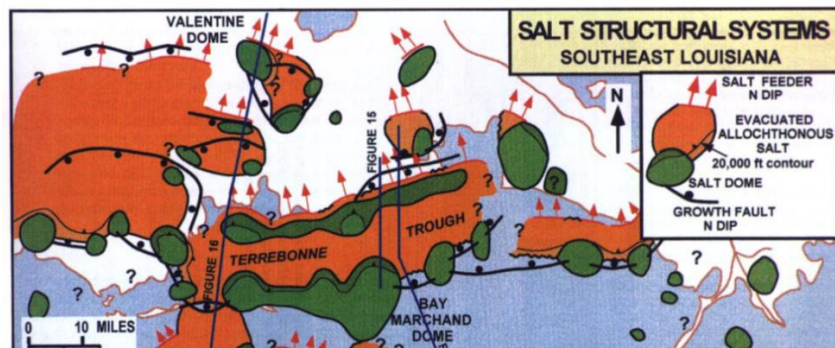
These maps illustrate the strong relationship between vertical velocities measured by existing monuments and the thickness of Holocene deltaic sediments from Kulp (2000) that was noted by Karegar et al (2015) and Byrnes et al (2019). It is important to recognize, however, that the axis of maximum thickness of the Holocene coincides with that of the regional geological feature commonly called the Terrebonne Trough. Maximum Holocene thickness lies between sets of conjugate faults that form the northern and southern boundaries of the trough. Progressive fault slip throughout the Holocene could have contributed to the increased thickness of the Holocene along this axis. Recent fault movement could be contributing to the subsidence velocities that may otherwise appear to be solely dependent on Holocene thickness. Deeply-anchored monuments could provide data that could help to differentiate the relative contributions of these two factors. Lateral velocities of the CORS sites reported by Karegar et al (2015) appear to be consistent with expected fault movement based on these interpretations. If the lateral velocities were entirely due to a horizontal component of compaction, the station at Grand Isle should measure a more northerly vector of motion, toward the center of the compacting basin.

The CORS network and the proposed wells are shown in context to stations in the Coastwide Reference Monitoring System (CRMS), which is operated by CPRA and USGS. CRMS has collected a wealth of valuable data over the past two decades. A typical station measures vertical sediment accretion, surface elevation change, land area change and soil salinity. Currently, the highly accurate surface elevation change data does not record measurements relative to a fixed datum like sea level. Elevation change measurements are made relative to a fixed Rod Surface Elevation Table (RSET), which is probably subsiding at an unknown rate. An increased density of geodetic monuments among the CRMS stations would improve the estimations of subsidence rate at each RSET and would thereby allow for a more accurate estimation of

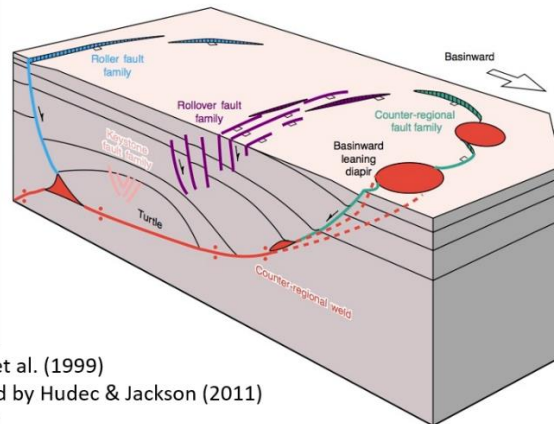


the surface elevation change relative to sea level. Eventually InSAR corner reflectors may be attached to the RSET at CRMS stations and calibrated to nearby geodetic monuments. A direct measurement of subsidence rates at CRMS stations would allow for detailed evaluation of the relationships between accretion, subsidence and land area change. Many CRMS stations that are measuring high sediment accretion rates are also measuring net gains in land area. It is likely that the rate of accretion is greater than the rate of relative sea level rise (subsidence plus eustatic sea level rise) in these areas.

The geological interpretations presented here indicate that the horizontal vectors of land motion in coastal Louisiana are primarily affected by movement associated with the network of faults and salt features including salt domes and salt welds. Hudec and Jackson (2011) modified the genetic block diagram from Rowan (1999), which shows the relationships among these features. Schuster (1995) mapped outlines of the ridges of salt bodies that parallel the coast and the directions of lateral movement along the salt welds (evacuated allochthonous salt). The implied vectors of lateral motion are consistent with those being measured by the existing geodetic monuments. The increased density of monuments provided by the proposed program would allow for a more detailed understanding of these relationships.



Schuster, 1995

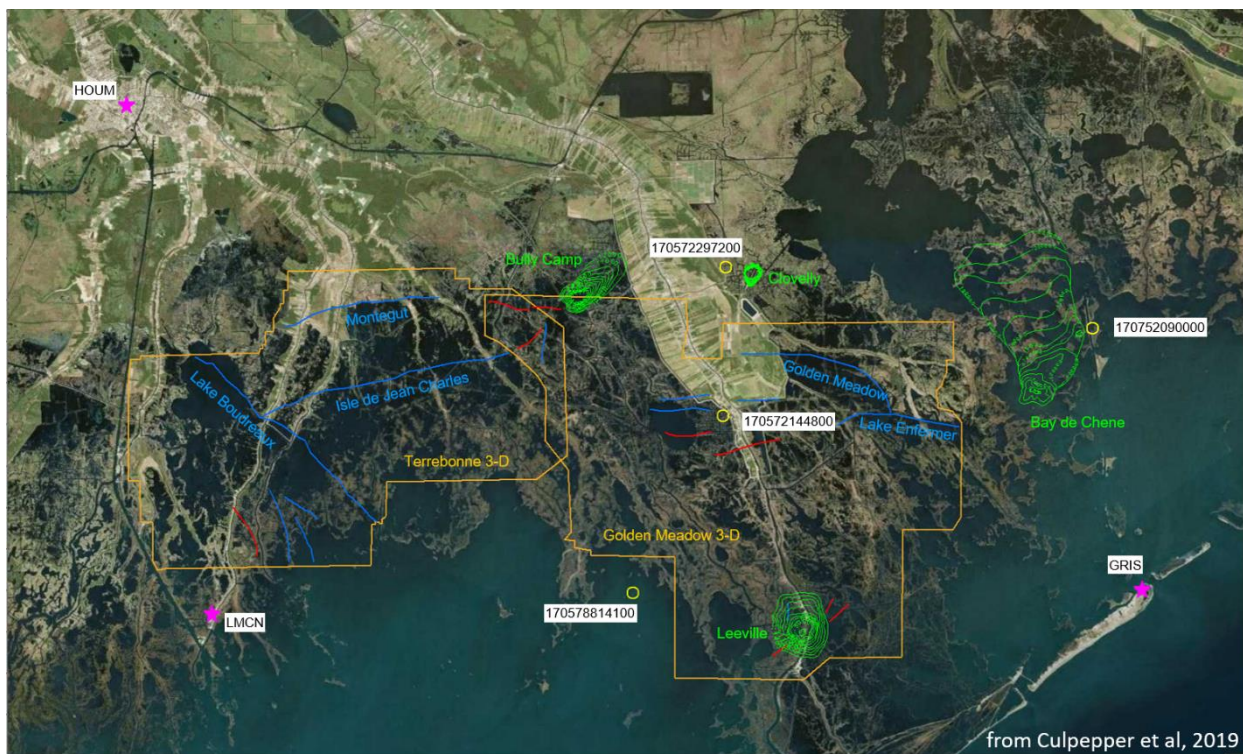


Rowan et al. (1999)  
modified by Hudec & Jackson (2011)

### Geological overview of proposed well locations

Three of the proposed well locations are shown in relationship to the surface fault traces published by Culpepper et al (2019). Subsurface depth contours of the associated salt domes are shown in green. These locations offer a range of settings relative to the subsurface geology that are likely to produce a range of land motion velocity signals. The higher vertical velocities should be expected at wells 170578814100 to the south, which is near the center axis of the Terrebonne Trough and well 170572144800 which is in the Golden Meadow graben. Well 170572297200 is north of the bounding

faults of the trough and adjacent to the Clovelly salt dome. This location should measure lower vertical velocity than those to the south. It may also measure some component of velocity that is influenced by the dome, which rises to less than 400 feet below the surface. Research in this area continues at Tulane with the addition of a 3-D seismic survey to the south. Future publications resulting from this research should significantly expand the scope and detail of geological interpretations in this area. The addition of land motion data from these proposed locations would offer a significant enhancement to understanding the results of the ongoing geological research. The ultimate goal is to better understand relationships between subsurface geological processes and surface morphological and ecological processes.





These three proposed locations are shown in relationship to surface fault traces and salt domes mapped by McLindon Geosciences. A portion of these fault traces are included in the publication by Armstrong et al (2014). The eventual publication of ongoing research at UNO will provide more detailed interpretation of faults in this area. Maximum land motion velocities values would be expected from well 170750164600 to the south, which is anchored on the hanging wall block of the Bastian Bay fault. The lowest values would be expected from well 170752306200 to the north, which is on the footwall block of the Ironton fault. Well 170512090000 in the center is in a complex location involving the Barataria fault, the Lake Five fault and the Bay de Chene salt dome and would be expected to produce intermediate velocity values. Each of these locations will be considered in the context of more detailed geological interpretations in the next section.

### Individual well evaluations

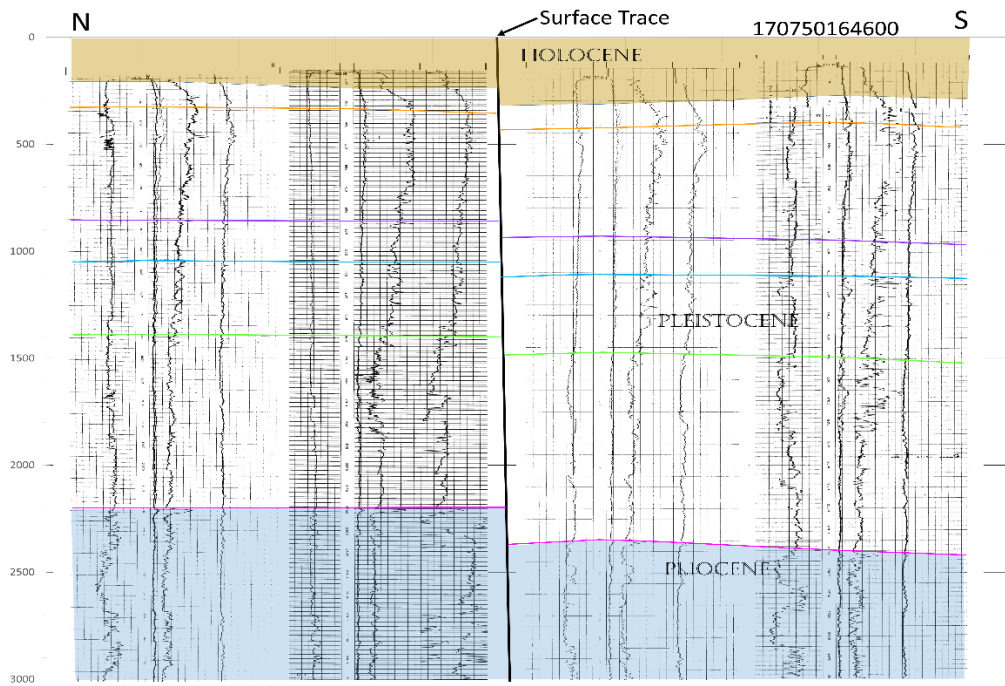
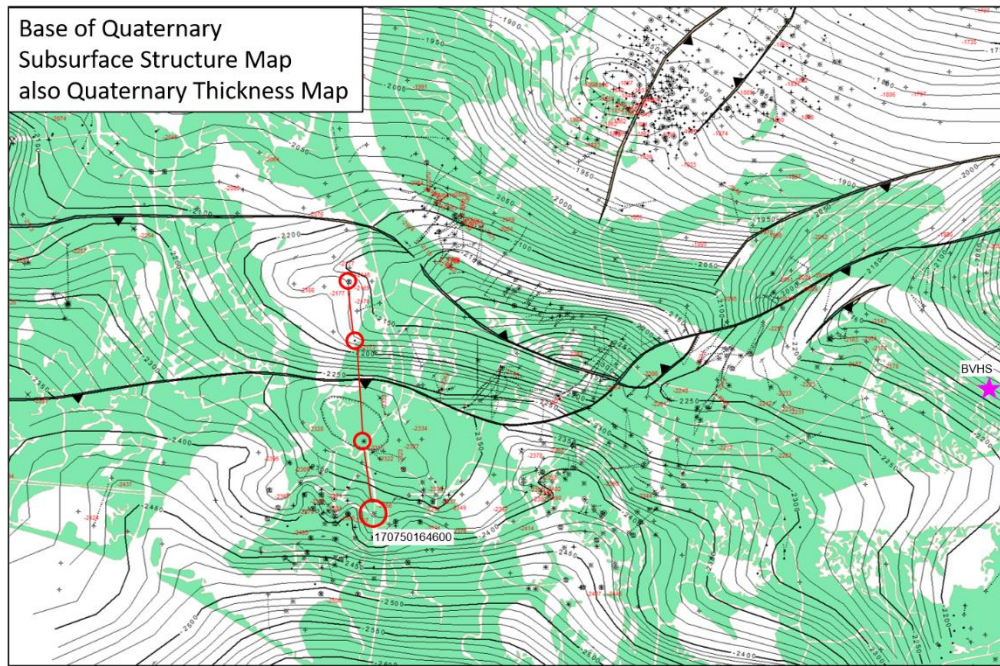
The following section provides a more detailed examination of each well location. Some subsurface geological interpretation is included for individual wells to support the potential value of data measured at that location in the area covered by McLindon Geosciences. Similar interpretations are likely to become available for the wells in the area covered by Culpepper et al in future publications.

Phase 2 of this proposal will determine the exact engineering design and cost analysis necessary to fully repurpose the location as a geodetic monument.

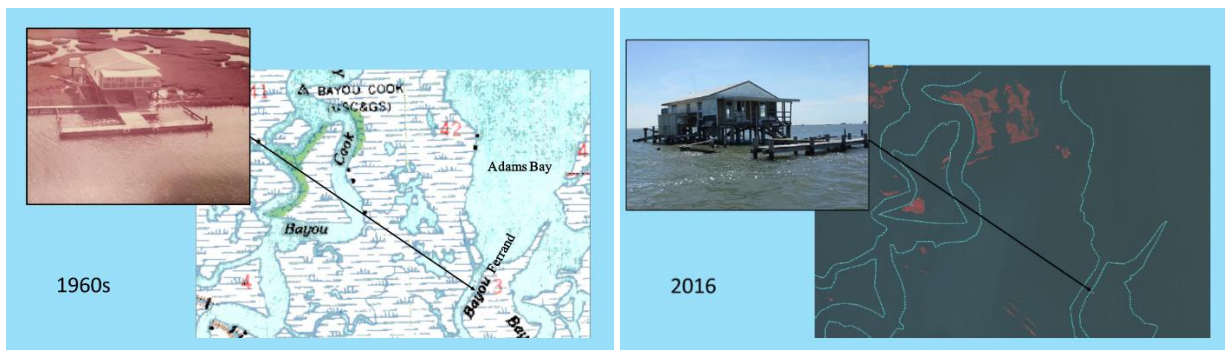


170750164600

This well is located in open water in Barataria Bay southwest of Buras. The pilings and surface decking have presumably survived in this location for several decades and are likely to provide an adequate base to be equipped with GPS and an InSAR reflector. A complete design and cost evaluation will be provided in Phase 2 of this proposal. As long as the decking is not attached to the well casing, it may be possible to co-locate equipment that is attached to the pilings and deck with equipment attached to the well.



The well is anchored with 5-1/2" casing at a depth of 9,229'. The wellbore is entirely on the hanging wall or downthrown block of the Bastian Bay fault. The increased thickness of Pleistocene stratigraphic intervals on the hanging wall side of the fault seen on the well log profile indicates continual fault movement throughout the Quaternary. A structure map on the top of the Pliocene horizon is also a Quaternary thickness map. Increased thicknesses on the hanging walls of several faults indicate activity in the area. Holocene fault activity is implied by the profile, but it cannot be reliably measured. A monument created from this well should measure velocity vectors attributable to fault movement.



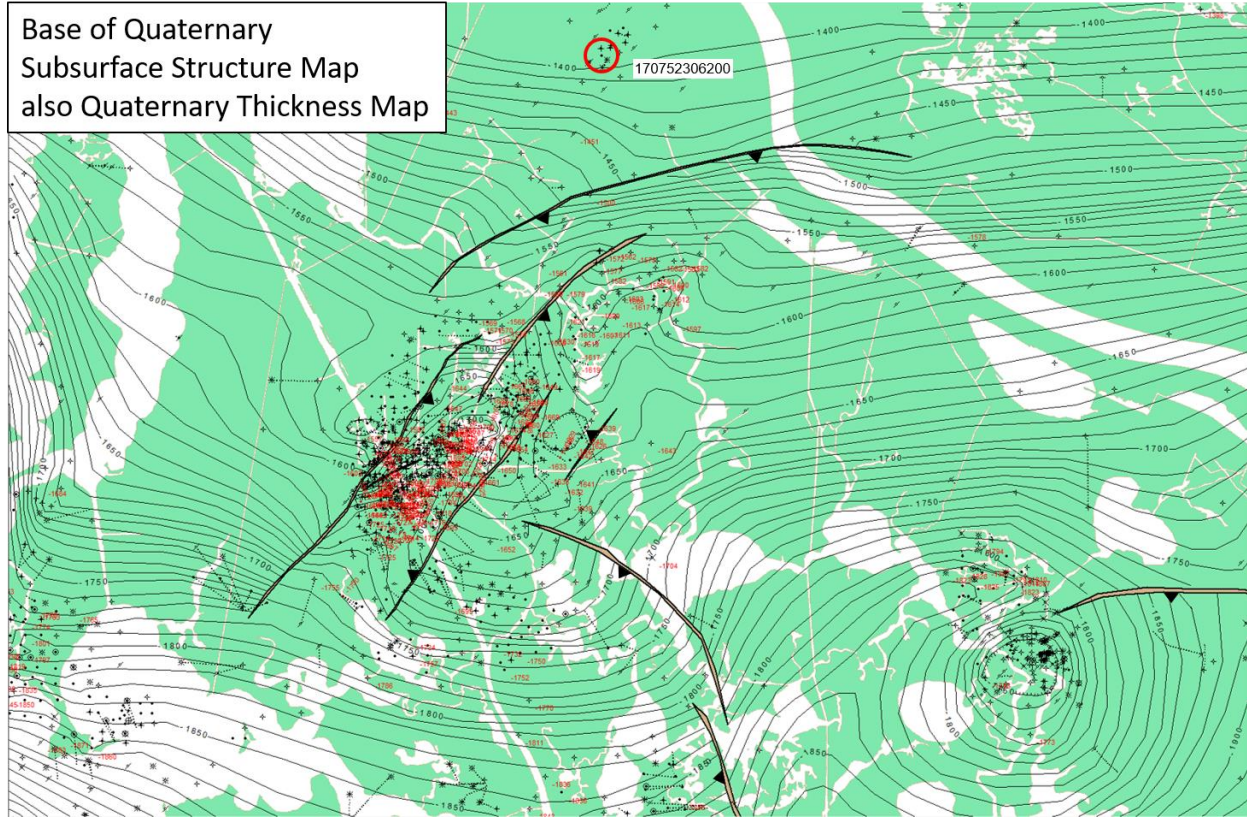
Gagliano et al (2003) collected anecdotal evidence of subsidence from local oyster fishermen and camp owners. Pete Hebert that told Gagliano about his camp built in the 1960s in Plaquemines Parish west of Buras. The camp was located on the banks of Bayou Ferrand, but by the mid-1970s it was standing in open water. Hebert reported that the land surface under the camp sank by 3 to 3 ½ feet over that time span. Gagliano later referred to the Bastian Bay fault as the “Rosetta Stone” for deciphering relationships among fault movement, subsidence and land loss in southeast Louisiana. Subsequent scientific investigations of the Bastian Bay fault using seismic data were conducted by Armstrong et al (2014) and Dawers and Martin (2006). The episode of fault movement implied by the rapid sinking of Pete Hebert’s camp would coincide with the formation of the Fort St. Phillip crevasse during the 1973 flood. It may be the case that the crevasse was caused by the fault movement. Historical crevasses at Darrow, Vacherie and Davis Pond appear to be associated with faults. It may also be the case that movement on the fault during a major flood event was not coincidental. The dilation of shallow aquifers during high river stages is likely to change the stress field across the surface and may contribute to triggering fault slip. Episodic fault movement would be likely to produce variable velocity signals from a monument in this location.



170752306200

This well is located at the fringe of the natural levee of the Mississippi River northwest of Ironton. It appears to be an accessible dry land location

Base of Quaternary  
Subsurface Structure Map  
also Quaternary Thickness Map



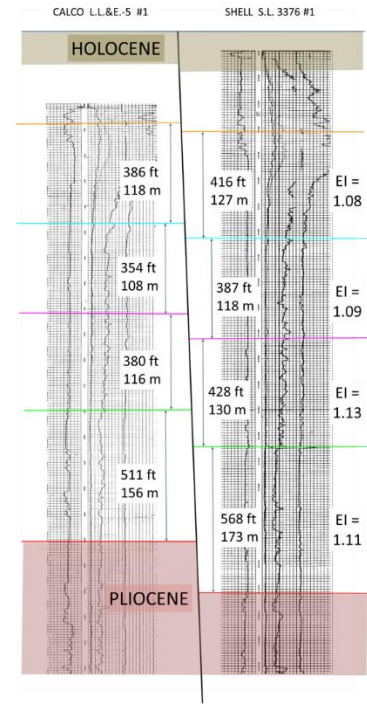
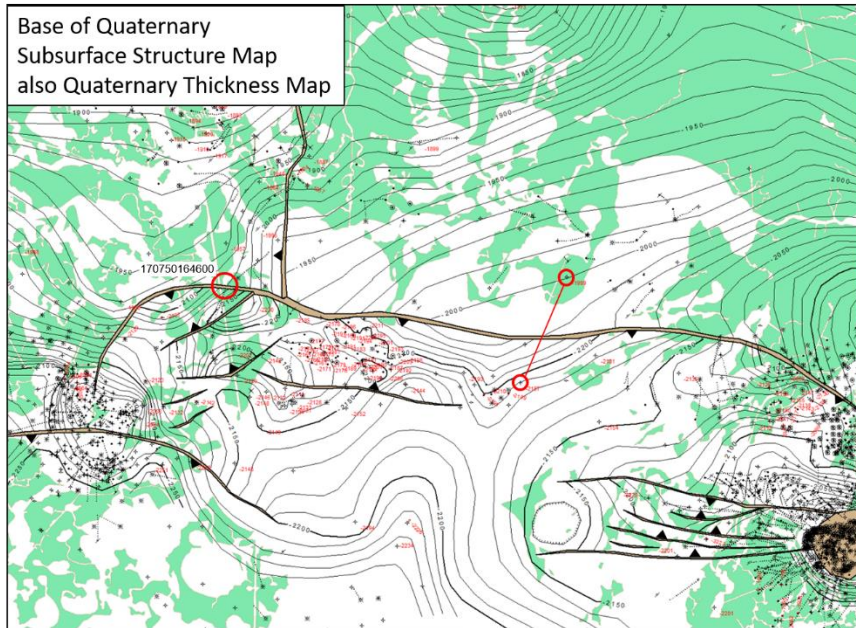
The well is positioned on the footwall side of the Ironton fault, which is in turn north of the crestal graben above the Lafitte salt dome. The Quaternary thickness map indicates that the Ironton fault and the graben faults were active during the Quaternary. A monument at this location should measure lower velocity signals than those to the south. There are several CRMS sites along both sides of the Ironton fault and within the bounds of the graben. Eventually equipping these sites with InSAR reflectors would allow for the potential to measure relative motion across the area. One of the objectives of a detailed evaluation of land motion using an array of measurement sites would be to measure footwall uplift. Detailed elevation surveys have measured the phenomenon on other faults in the area (Hopkins et al, 2018). The existence of footwall uplift on faults in the coastal zone would have significant implications for sustainability.



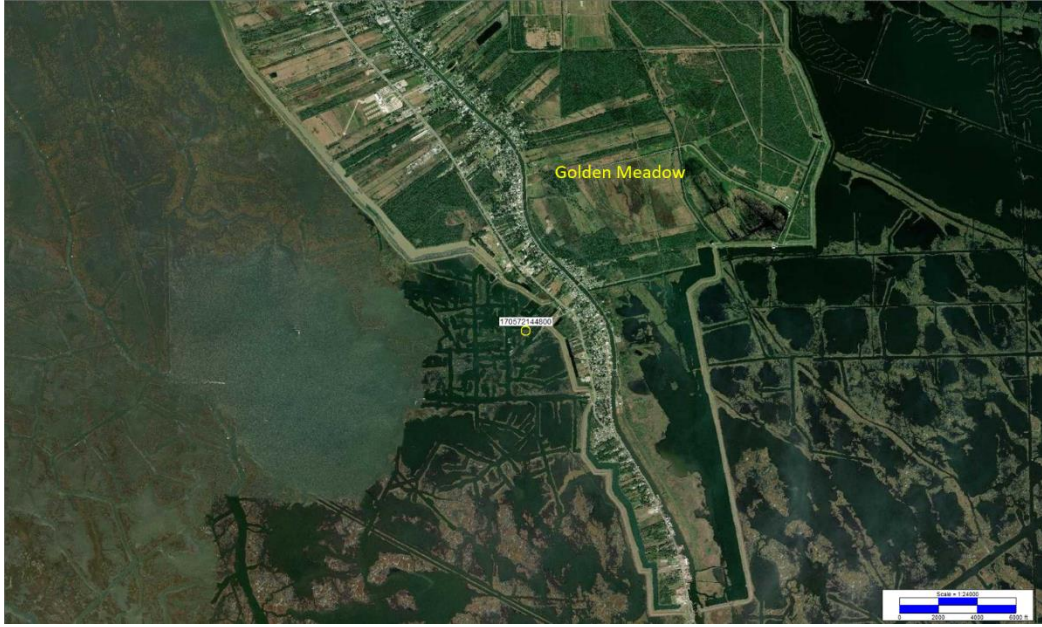


170752306200

This well is located on the remnant spoil banks of the Barataria Bay Waterway on the western side of Barataria Bay. The pilings and decking appear to be in good condition.

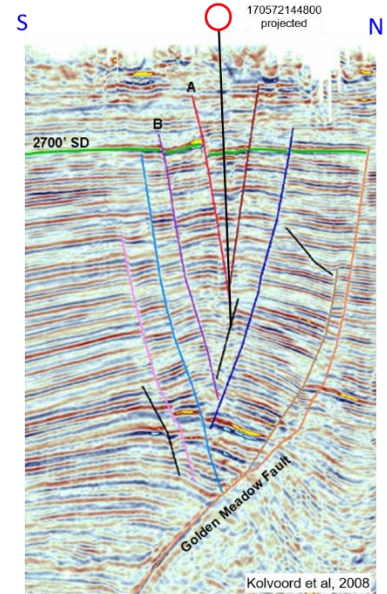
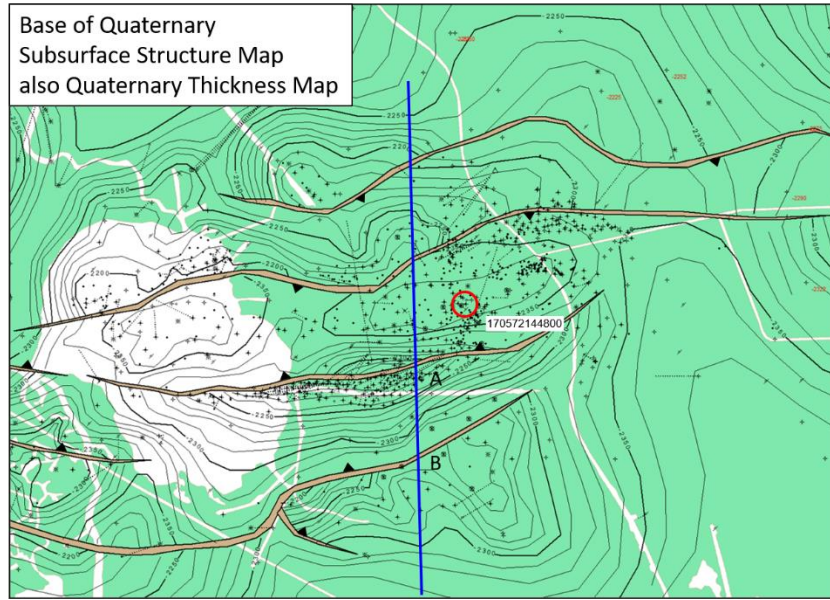


The surface location of this well is immediately downthrown to the surface trace of the Barataria fault. The deeply-anchored portion of the well is on the footwall of the Barataria fault and the hanging wall of the Lake Five fault, which is down to the west. The well is also on the flanks of the Bay de Chene salt dome, which has a genetic relationship with both faults. The well profile and Quaternary thickness map indicate that both faults and the grabens on the flanks of the Bay de Chene and Lake Washington salt domes were active in the Quaternary. A monument at this location is likely to measure velocity signals that may be affected by each of these geological features.

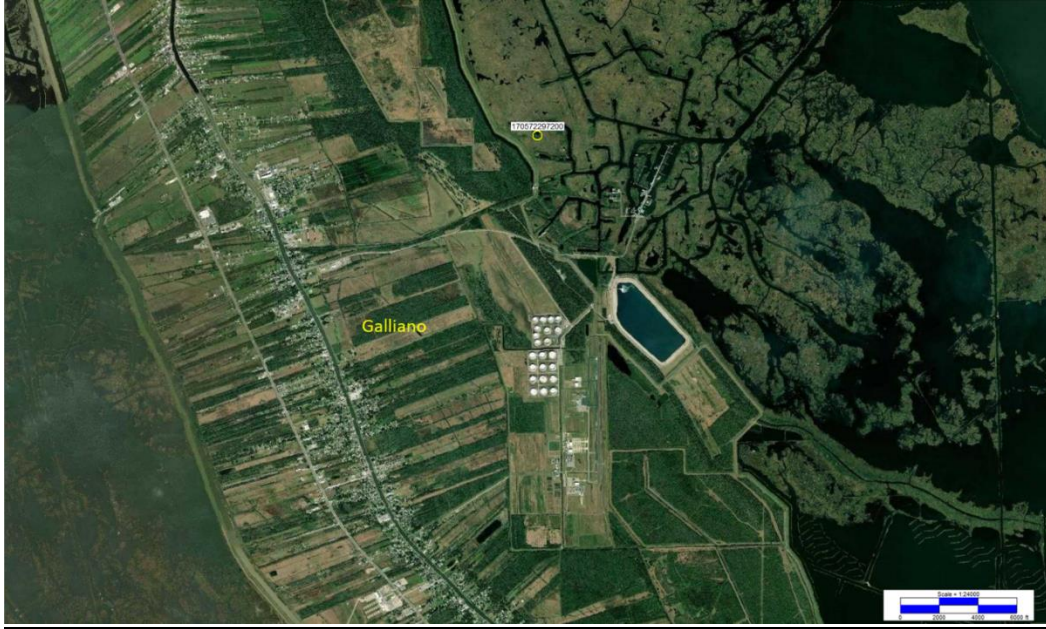


170572144800

This well is located near Catfish Lake south of Golden Meadow and west of Bayou Lafourche. The well and decking appear to be in good shape and may provide for the co-location of deep- and shallow-anchored monuments.

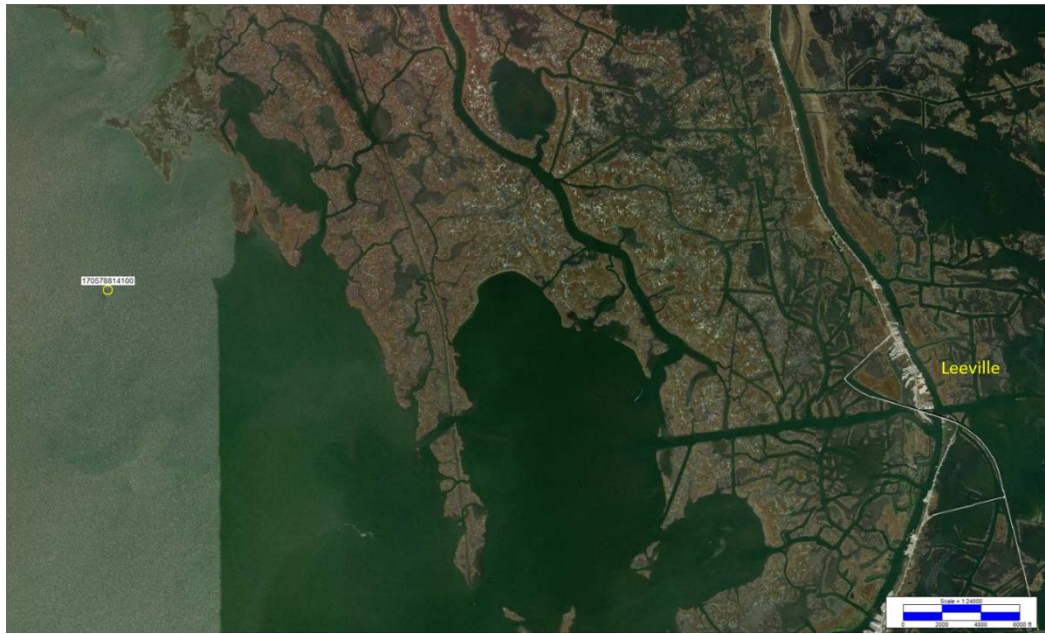


This well is located in the center of the Golden Meadow graben, which is developed on the hanging wall of the large Golden Meadow fault. The Quaternary thickness map indicates Quaternary activity on the graben faults. This is also along the axis of maximum Holocene thickness. A case can be made that the variation in Holocene thickness on a boring profile down the banks of Bayou Lafourche may reflect the impact of fault slip, but it is not definitive. A seismic profile from Kolvoord et al (2008) shows the configuration of the graben. This location should be expected to have the maximum subsidence signals to be measured by this program.



170572297200

This well is located north of Galiano and east of Bayou Lafourche. Available photography is not adequate to fully assess the condition of the well, and accessibility may be an issue. As discussed previously, this wells is north of the bounding faults of the Terrebonne trough and on the flanks of the Clovelly salt dome. It should provide a lower subsidence signal than the wells to the south.



170578814100

This well is in open water in Terrebonne Bay west of Leeville. The well and decking appear to be in good condition and should provide for the co-location of deep- and shallow-anchored monuments. As discussed previously, this location is near the center of the Terrebonne Trough and maximum Holocene thickness. Any component of the subsidence signal attributable to lithospheric flexure should be most easily measured here.

## Summary and Conclusions

The Wells to Monuments Program offers an opportunity to significantly increase the density of geodetic monuments in the Louisiana coastal zone by making use of existing infrastructure that would otherwise incur costs to be removed. The array of proposed well locations offers several sites that appear to be well suited for the co-location of deep- and shallow-anchored monuments that could make use of both GPS and InSAR technologies. Collecting velocity data from locations that were specifically chosen for the geologic setting is the most expedient way to determine the relationships between subsurface geological features and land motion at the surface – and ultimately between subsurface geology and surface coastal processes.

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