Transportation Consortium of South Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Synthesis of Fault Traces in SE Louisiana Relative to Infrastructure

Project No. 17GTLSU12

Lead University: Tulane University

Collaborative Universities: University of New Orleans, University of Louisiana at Lafayette

Preserving Existing Transportation Systems

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January 2019

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16. Abstract

Geological faulting has been implicated as a contributor to subsidence, coastal land-loss and submergence of marshlands in southern Louisiana. This report reviews whether fault motion, either by slow creep or more sudden slip, can cause deformation of engineered structures resulting in increased infrastructure maintenance and repair costs. The impact of surface, or near-surface, geologic faulting on critical infrastructure is insufficiently documented in southeastern Louisiana, but the state has a vast amount of energy-sector subsurface data that to date has been under-utilized for transportation and other near-surface engineering applications. Recent and on-going work by research groups at Tulane University, University of New Orleans, and University of Louisiana at Lafayette use energy industry subsurface data, including well data and 2D and 3D seismic reflection data to map and project deep-seated faults that have been in place for millions of years, to create provisional surface fault trace maps. Descriptive criteria for reliability of fault locations were developed and are based on resources used in the interpretation and map scale: Level 1 suspected faults – described in the literature and included here from georeferenced maps; Level 2 identified faults – those observed on 2D or 3D seismic and mapped in a geographic reference system; Level 3 confirmed faults – mapped on seismic and ground-truthed with field methods including age-dated sediment borings and high-resolution seismic. We have compiled data resources in a GIS-based system for simple retrieval and map-based review so that additional work specific to critical infrastructure projects can be prioritized. The intent is to give the public information, so that they may better assess the importance of faulting in any particular project area and as a resource to identify areas that already have energy industry seismic available.

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Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

BRFZ	Baton Rouge Fault Zone
CPT	Cone Penetrometer Test
DTN	Down to North
DTE	Down to East
DTS	Down to South
GPI	Geophysical Pursuit Incorporated
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
SEI	Seismic Exchange, Inc.
UNO	University of New Orleans
ULL	University of Louisiana Lafayette
USGS	United States Geological Survey

EXECUTIVE SUMMARY

Geological faulting has been implicated as a contributor to subsidence, coastal land-loss, and submergence of marshlands in southern Louisiana. Fault motion, either by slow creep or more sudden slip, can cause deformation of engineered structures. In addition, the compaction of thick soils and Holocene sediments on the down-dropped sides of faults contributes to land subsidence that has resulted in increased infrastructure maintenance and repair costs. The impact of surface faulting on critical infrastructure is insufficiently documented in southeastern Louisiana. Accurate mapping of surface faults and an increased knowledge base of the pattern and extent of faults will aid in the design and placement of infrastructure, as well as in determining mitigation methods.

Louisiana has vast amounts of subsurface data that to date has been under-utilized for near-surface engineering applications outside of the energy sector. Recent and on-going work by research groups at Tulane University (Tulane), University of New Orleans (UNO), and University of Louisiana at Lafayette (ULL) use energy industry subsurface data, including well data and state-of-the-art 3D seismic reflection data, to accurately map faults in the near surface. This project has synthesized fault mapping and produced fault trace maps relative to critical infrastructure in areas underlain by existing 3D seismic surveys, and in other areas having a high density of wells and 2D seismic data.

Critical infrastructure projects in the vicinity of Golden Meadow, Leeville, and Lake Borgne were identified with Louisiana Transportation Research Center (LTRC) and Louisiana Department of Transportation and Development (LADOTD) personnel. This project has compiled and cataloged existing published literature and available unpublished reports on faults and their surface expressions. Due to the mobile nature of sedimentary salt in the near-surface, several sources for generalized location of shallow salt structures are also included, although this cannot be considered a comprehensive summary. Using industry datasets already available to the research team, we have produced georeferenced maps that can be utilized in GIS databases.

Descriptive criteria for reliability of fault location were developed and are based on resources used in the interpretation and map scale: Level 1 suspected faults – described in the literature and included here from georeferenced maps; Level 2 identified faults – those observed on 2D or 3D seismic and mapped in a geographic reference system; and Level 3 confirmed faults – mapped on seismic and ground-truthed with field methods including age-dated stratigraphic intervals and high-resolution seismic. We have compiled data resources in a GIS-based system for simple retrieval and map-based review so that additional work specific to critical infrastructure projects can be prioritized. The intent is to give LTRC and LADOTD personnel information so that they may quickly assess the importance of faulting in any particular project area and as a resource to identify areas that already have energy industry seismic available.

IMPLEMENTATION STATEMENT

The research team will meet with professional staff within LADOTD, including civil and geotechnical engineers, to disseminate results and transfer knowledge about how to further study the faults identified. This may be done in Baton Rouge, LA or possibly at field sites where highway infrastructure has or may be impacted, or anywhere requested by LADOTD/LTRC. Anticipated field workshop sites include Golden Meadow and Leeville, along the LA 1 corridor, and near various bridges in the Lake Borgne region.

The research team will also develop material from this project to be utilized in two existing courses at Tulane: Subsurface Geology and Applied Basin Analysis. Additional materials will also be developed for earth structures course at UNO, including field trip guidebooks, which will be developed for a Tectonic Geomorphology and/or Structural Geology course. Data and knowledge obtained may be useful to deep foundations and geotechnical engineering courses, as well as courses in structural design and rehabilitation. Because of recent collaboration with ULL and UNO faculty in geology and geophysics, any presentations or workshops to engineering departments within those institutions will have the added benefit of fostering ties between the geosciences and engineering, in general at those institutions.

1. INTRODUCTION

The surface of the Mississippi River delta plain in Louisiana is influenced by geologic faults that developed long before historical times and are typical of deltaic, passive-margin sedimentary basins *(1, 2)*. Well-known subsurface stratigraphic relationships indicate that fault motion has been a fundamental geologic control on sedimentation patterns and geomorphic evolution along the northern Gulf of Mexico since the basin's inception *(3, 4)*. Deep-seated normal faults have long been known to exist in the subsurface of Louisiana within the hydrocarbon industry, and recent studies document the presence of active faults in southeastern Louisiana at shallow depths *(5–11)*. Where these faults underlie critical infrastructure, deformation by fault slip, as well as compaction of locally thickened sediment along faults, can create added costs related to mitigation and rehabilitation of roadways, levees, and bridges.

Early maps depicting faults that affect the landscape in south Louisiana were constructed on the basis of surface features such as scarps that were evident in aerial imagery, observations of patterns of land loss, and reviews of literature on deep fault locations. Near-surface faults have been implicated in a variety of cases of warping or failure of infrastructure, linear marsh breaks, river channel avulsions, and surface seepage and liquefaction, but the true trend of a fault in young, shallow sediments is deceptively difficult to delineate accurately using only surface evaluation methods *(5, 7)*.

Energy industry data, including 2D and 3D seismic reflection surveys and well data, both of which penetrate thousands of feet below the surface, offers the only truly accurate means of mapping faults in the deep strata and then assessing where these deep features cut upward through more shallow strata and potentially to the surface of coastal Louisiana. When a fault plane is mapped in the subsurface using these types of data, the fault plane extent in three dimensions is captured, and it is a simple matter to extend the plane upward to provide a good estimate of the intersection of the fault with the surface of the earth, thereby creating a surface fault trace.

To date, minimal work using 2D or 3D seismic energy industry data to pinpoint fault locations has been conducted for the purpose of identifying how faults may affect shallow strata and surface environments of south Louisiana. One reason is because energy industry seismic data is expensive to acquire and typically available only through licenses, thus limiting its application outside of the industry. In the last several years, however, the three universities of this project (Tulane, UNO, and ULL) have been granted access to energy industry seismic data through academic licensing agreements.

Faults as geologic hazards can have direct or indirect effects. An earthquake creates direct effects that are related to movement along a fault surface. The force of the movement causes surface displacement or damaging motion. Due to its geologically young age and loosely consolidated sediments at the surface, Louisiana has only a few instances of hazardous conditions due directly to faulting where surface rupture was distinct and rapid. More subtle are indirect effects of faulting, a process usually associated with subsidence on the downthrown side of the fault. Surface scarps (i.e., based on field investigation or in LiDAR models), marsh breaks, development of open water areas through time, slope instability or failure, offset in rigid infrastructure, seepage and liquefaction, brine or HC fluid flow, are all associated with episodic or continuous fault movement. In part, recognizing fault-related deformation at the surface depends on the environment encountered at the surface: uplands, marsh, open water, bay, channel etc. Open water and active sedimentation will mask most any feature that a fault might make, whereas in upland areas along the Northshore to Baton Rouge, LA form distinct fault scarps of several feet or more.

Differentiating the effects of long-lived but slowly moving faults from changes brought about by other surface processes like storm systems, compaction, and sea-level rise will be improved with a good fault map. Once accurate maps are created, appropriate field work will further define the location, rates of movement, and local effects from active faulting. With well-positioned sediment borings, cone penetration tests (CPTs), high-resolution seismic, chronostratigraphy, and aerial or satellite imaging, faulted areas will be better understood, and eventually, predictive models for fault deformation can be devised and used early in project planning.

Highly detailed 3D seismic reflection from the energy sector was donated for use by local universities to map geologic features identified on seismic data to help predict areas of future land loss. It is hypothesized that the locations of geologic features as deep-seated faults and salt domes will prove to be closely related to many areas of coastal land-loss in south Louisiana. As a result of this collaboration, coastal restoration, flood-control and sustainability initiatives that are based upon this knowledge should be optimized to deal with future relative sea-level rise.

1.1. Background: Baton Rouge Fault System

The northernmost fault systems of the south Louisiana growth-fault trends *(24)* comprise the Tepetate-Baton Rouge-Denham Springs-Scotlandville fault systems *(25)*. This network consists of a series of *en echelon*, discrete and semi-continuous faults extending from western Louisiana north of the southern outcrop of pre-Holocene sediments, to the east in a broad arcuate pattern extending slightly beyond Lake Pontchartrain (Figure 1) *(5, 25, 26)*. The entirety of these closely spaced and interrelated fault segments compromises the Baton Rouge Fault System. Sections of the Baton Rouge Fault System are the most well documented for having undergone recent movement of any south Louisiana fault trend *(5, 23, 25, 27)*. On the most recent geologic map of Louisiana *(31)*, the easternmost extension of the system (north of Lake Pontchartrain) is the only fault of southern Louisiana mapped as having a surface expression.

Figure 1. Base map of southern Louisiana showing an oversimplified distribution of major fault trends with Cenozoic strata.

The trend of the Tepetate-Baton Rouge-Denham Springs fault does not show the distribution of splays that have been suggested to exist within Lake Pontchartrain *(5)*. Black arrow denotes the approximate location of the seismic image presented in Figure 2 in the vicinity of the Highway 11 Bridge as well as the photograph of Figure 3. LP = Lake Pontchartrain and LB = Lake Borgne, both of which are separated by the East New Orleans Land Bridge.

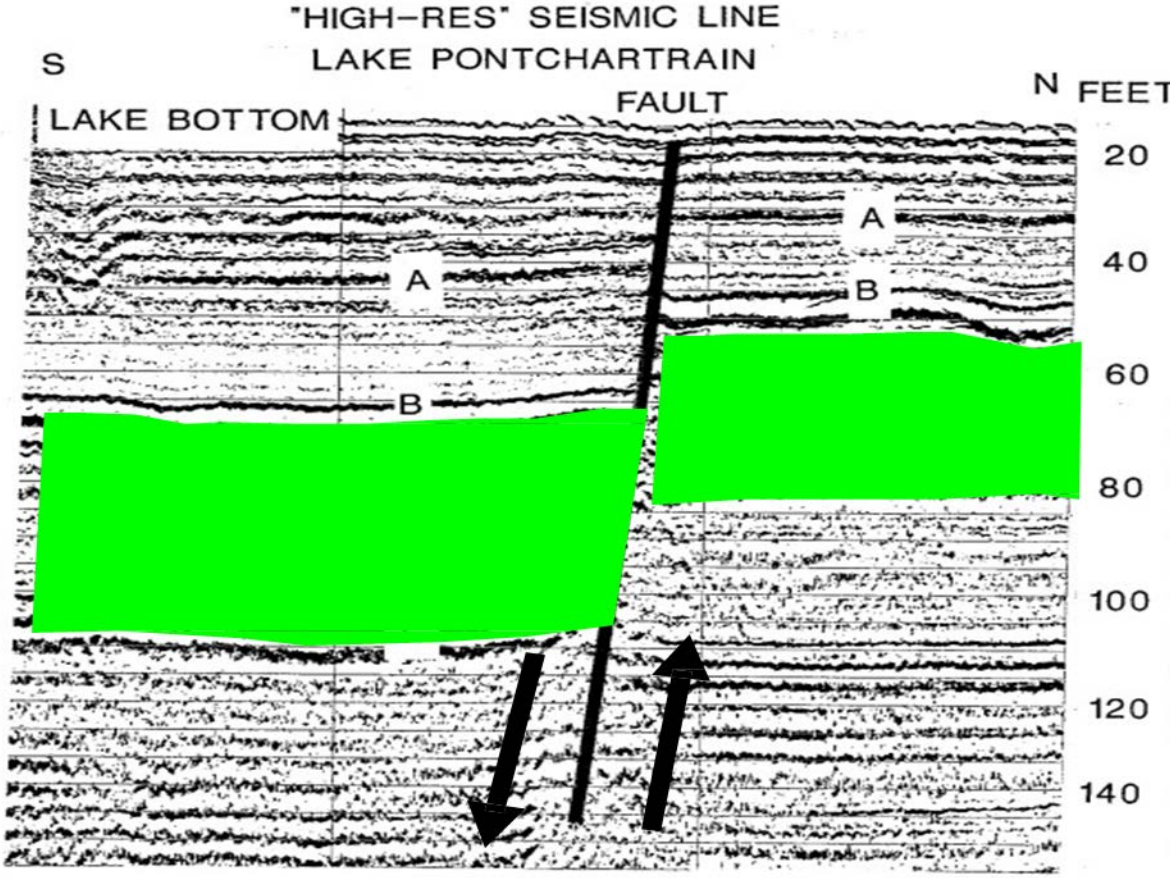


Figure 2. North-trending, high-resolution seismic image of shallow stratigraphy above a deep-seated fault imaged in hydrocarbon industry data *(5)*.

Offset is clearly evident in Pleistocene strata, partially indicated in this image with the green-highlighted interval. The trend of the fault extends upward through Holocene strata that similarly appear to record some degree of deformation but because of the soft, unconsolidated nature of the Holocene sediments is not clearly imaged *(5)*. Approximate location of seismic line in Lake Pontchartrain is depicted in Figure 2 with a black arrow. Heavy black arrows on the Figure indicate the down-to-south sense of fault motion indicated by the non-continuity of the subsurface seismic reflections.

Figure 3. Photograph of fault induced offset in the Highway 11 Bridge that crosses Lake Pontchartrain *(5)*.

This offset approximately corresponds to the location of fault offset documented in deep hydrocarbon industry data. Approximate location of deformation in the picture is shown on Figure 3 with a black arrow. View toward the north from near the end of the Bridge.

1.1.1. Timing and Rates of Motion

Durham and Peeples *(27)* suggested that motion along the eastern segments of the fault trend was post-Miocene in age and that activity has been predominantly during the Pleistocene. Hanor *(25)* similarly presented evidence for Pleistocene movement on the basis of just 12-m offset in sediments at a depth of approximately 1,000 m slightly west of Baton Rouge. Although limited by the availability of shallow data, there was no evidence for penetration of the fault to subsurface depths of less than 70 m.

Recent fault motion in the Baton Rouge area has been documented on the basis of abrupt changes in topography (fault scarps) within semi-consolidated Pleistocene sediments, drainage variations, soil variability, cracking and offset of building foundations, offset in road infrastructure, and chronostratigraphic relationships across the fault *(11, 23, 28)*. Total surface displacement across the faults in the near vicinity of Baton Rouge ranges between 1.5 and 6 m *(23, 29)*, proceeding seismically in recent times. Rates of movement in the area vary according to the time span during which motion is gauged. Ages of offset Pleistocene terraces indicate time-averaged rates of movement near Baton Rouge ranging between 0.001 and 0.008 cm yr^{-1} during an 80,000 year interval *(23)*. However, local displacements of building foundations yield rates of motion along the same fault trend that are as much as 1.0 cm yr^{-1} for this rate the reference time was tens of years *(23)*. Shen et al. *(11)* reported rates of localized motion of 0.02 cm yr^{-1} for the late Holocene.

Local movement along the eastern segment of the Baton Rouge Fault System trending eastward across Lake Pontchartrain and possibly into Chandeleur Sound has been convincingly documented (Figure 2) *(5)*. The presence of “deep seated-faults” in this area has been verified with petroleum industry seismic data examined in a variety of studies *(5, 17, 18)*. Upward-projected fault-surfaces from depths below 300 m correlate to offsets documented in modern railroad and highway bridges crossing Lake Pontchartrain (Figure 3) *(5)*. Moreover, in eastern Lake Pontchartrain high-resolution seismic data clearly indicate approximately 3-m of offset at the Holocene-Pleistocene stratigraphic contact at a depth of approximately 12 m. Elsewhere along fault strike, however, there is no evidence for Holocene stratigraphic offset in either bridges or in shallow strata identified on high-resolution seismic profiles despite the presence of faults at depth. Although not precluding the presence of a Holocene faulted interval, the displacement must be less than the resolving power (~35 cm) of the high-resolution seismic data *(5)*. Rates of movement within Lake Pontchartrain, similar to the results of Roland et al. *(23)*, vary according to the time over which rates are gauged. A post-Miocene, time-averaged rate is approximately 0.0003 cm yr^{-1}, whereas rates derived from modern offsets with a temporal scale of tens of years or less, range between 0.2 and 1.0 cm yr^{-1} *(5)*.

An objective of this research is to demonstrate that a combination of deep industry seismic data, shallow high-resolution seismic data, and vibracore data can be used to identify and map the location of faults that may impact modern surface features and infrastructure such as roads and bridges.

2. OBJECTIVE

The objective of this project is to create an Arc-GIS-based tool to help direct decision-making in the southeastern Louisiana study area where direct or indirect movement at the surface associated with active geologic faults could affect infrastructure during its project life. Available energy industry data resources including seismic data and wells have been compiled into the Arc-GIS tool to aid in assessing data availability in areas of interest where subsurface fault analysis in the project workflow is desired. Locations of geological faults have been input into the Arc-GIS tool through: (1) the compilation of existing reports and literature and, in particular, (2) the synthesis of recent university research on faults mapped using high-quality energy industry datasets. Several of the faults identified in the university research are being examined in further detail to look for offset in near-surface sediments.

Energy industry seismic data available in southeast Louisiana is generally available through license from seismic brokers and are shown as lines (2D data) and polygons (3D seismic volumes). Methods for describing and characterizing the attributes of faults and quality of geological interpretations have also been developed. The synthesis will form a knowledge base of surface fault locations in relation to critical infrastructure in the coastal zone of southeastern Louisiana.

A list of potential mitigation techniques to assist in the preliminary design phase for critical infrastructure projects is provided. However, as the report is implemented in the LADOTD system, we expect this to be an ongoing effort and that in-place infrastructure that may be affected by faults will be identified using the Arc-GIS tool, followed up with near-surface work to further delineate faults, followed by geotechnical work conducted with respect to the fault location. Potential mitigation and rehabilitation techniques specific to faulting near particular critical infrastructure projects will be generated.

This project allows for the identification of critical infrastructure underlain by existing 3D oil and gas industry seismic reflection datasets and also where major gaps in 3D seismic data coverage occur. High densities of other data types such as 2D seismic data, oil and gas wells, and shallow borings are also cataloged from various sources. By utilizing existing licensing agreements in place with energy companies, data owners and seismic brokers, the project team has made an initial synthesis to produce fault trace maps that intersect or are present in the near-surface (ca. upper 1000 meters) and integrate these with other available datasets.

Metadata, including the quality and reliability of the data used to interpret the faults, have been gathered and compiled and a ranking system has been created with levels specific to the confidence level in the interpreted fault position. Surface observations in isolation are less reliable than surface traces underlain by faults from seismic interpretation. The most reliable fault trace locations are identified with seismic and confirmed with offset in age-dated sediment borings taken on each side of the fault trace and/or trace locations are confirmed by imaging with high-resolution 2D seismic surveys conducted perpendicular to the fault trace.

3. SCOPE

The scope of this project is to develop a work flow that includes geologic surface fault mapping with a primary goal to reduce mitigation and maintenance costs to the State of Louisiana by anticipating eventual problems early in the development stages of LADOTD projects. While mapping of fault trends from depth and projecting the fault trace location to surface is an accurate method to predict where a geologically active fault may impinge the surface, in most of the study area, this report does not address whether a fault actually reaches the surface and caused offset in the near-surface.

Metadata, including the quality and reliability of the data used to interpret the faults, have been compiled and a ranking system has been created identifying the confidence level in the interpreted fault position. Fault traces from literature sources included in this report in particular, are considered to be the least reliable for several reasons: (1) limited documentation of methods or data sources, (2) use of georeferenced scans of regional-scale maps, and (3) lack of access to subsurface information. However, these studies are important to include even if somewhat flawed, because prior to this study, the literature maps were all that was available for infrastructure planning. In some areas lacking seismic interpretation, those interpretations remain the sole source for fault interpretations to be considered when starting a project. The most reliable fault trace maps will be created when faults are imaged on 2D or 3D seismic, projected to surface and confirmed with near-surface techniques.

4. METHODOLOGY

The main deliverable of this project is a GIS database that compiles: (1) location of 2D and 3D seismic available for subsurface fault interpretation and (2) the state of knowledge of where geologic faults are suggested to impact the surface from three primary sources: (a) historical literature, (b) projection of seismic traces from seismic interpretation, and (c) field confirmation. Each data source reflects greater resolution and confidence in placement of fault traces at surface.

4.1. Available Seismic Data

Shape files and data collection and processing parameters of 2D and 3D seismic data available for commercial license from four vendors active in south Louisiana were made available to the project team, either downloaded from vendors' websites or by email request. Vertical slices of 2D seismic data are depicted as lines on the map. 2D is available from Geophysical Pursuit, Inc. (GPI), Seismic Exchange, Inc. (SEI) and Seitel. 3D data volumes are multi-square mile volumes of seismic data which offer the best ability to map a fault plane, determine a fault's dip angle and direction, and project the fault to surface. 3D seismic data is shown as polygons and is available from SEI, Seitel, and Schlumberger. A "3D data gap" polygon was also created, so that areas with no 3D data can be quickly identified. If fault investigation is required within the 3D data gap, 2D data may be available. Energy industry seismic data volumes have been donated to Tulane, UNO and ULL for each of the locations identified in Figure 4.

Figure 4 shows the southeast Louisiana study area outline. This area encompasses the urban areas of Baton Rouge, New Orleans, Slidell, and Houma and includes critical transportation arteries including LA 1 to Port Fourchon, Hwy 23 to Venice, and highways that traverse the New Orleans East land bridge area. Yellow outlines are 3D reflection seismic volumes with 110 ft bin spacing between inlines. In Lake Pontchartrain, a 2D seismic dataset was mapped with a variable line spacing of approximately three miles.

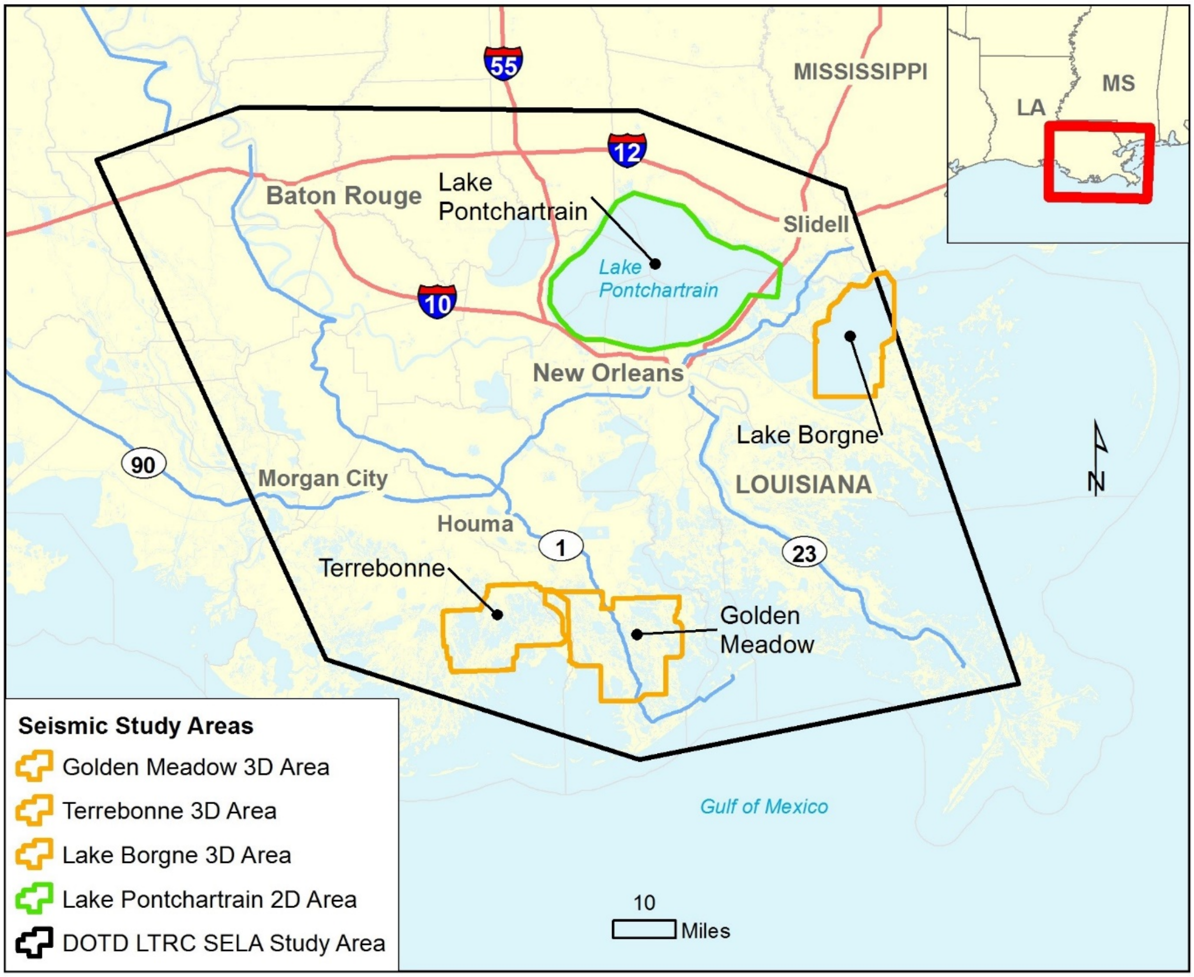


Figure 4. Study area in southeast Louisiana.

4.2. Synthesis of Faults from Literature

Maps of faults from literature have been scanned, georeferenced, and essential location information cataloged. Fault locations in literature sources are based on varied methods of study with a wide range of resolution and accuracy. Table 1 summarizes the reports included in this study and the types of data used to identify faults at the surface. Sources include seismic data, subsurface well data, field methods, and airborne surveys.

Table 1. Data from the literature.

Literature Source	3D	2D	2D HR	O&G	SWD	H_2O	Chronostrat.	Core Descr	CPT	Elev. Diff.	LIDAR	Photos	Other
Armstrong et al. *(10)*	X			X									
Dokka *(8)*											X		X
Gagliano et al. *(7)*		X						X		X		X	
Frank and Kulp *(17)*	X		X										
Keucher and Roberts *(6)*			X					X					
Lopez et al. *(5)*		X	X	X						X			
McCulloh and Heinrich *(12)*											X		
Wallace *(13)*		X		X				X		X			

4.3. 2D and 3D Seismic Interpretation

Faults were mapped using 2D and 3D seismic in four main study areas: Terrebonne, Golden Meadow, Lake Pontchartrain, and Lake Borgne. Students had access to 2D or 3D data loaded on workstations with Kingdom mapping software which facilitates the mapping process using built-in designated tools for mapping faults and horizons in a three-dimensional space. Conventional reflection seismic data is acquired using sound sources and geophones. Seismic is delivered with the vertical axis presented in two-way-time, i.e., the amount of time it takes for the acoustic signal generated by the sound source to travel into the ground, be reflected off a horizon, and return to surface. As the name would imply, 2D seismic data provides a vertical image of the subsurface along a single line at the surface. 3D seismic data is acquired in a much more tightly spaced grid pattern and is processed to create a three-dimensional volume of seismic data. Maximum resolution in a seismic volume is “bin spacing” – which for the areas in this report is 110 ft. 3D data is much preferred for mapping faults, but it is important to note that three-dimensional fault planes are also created when mapped on 2D.

Due to a “mute” placed on the data to minimize the noisy data gathered from near-surface interference, most seismic data on land has little to no good information in the upper 0.5-1.0 seconds of data. This is equivalent to 1,500 ft – 2,500 ft depth in most places. Students were asked to map faults in their study area and to identify those that appear to extend to or near to the surface. Because of the mute, they were asked to follow the slope (dip angle) of the fault to project the fault to surface. In this way, a well-constrained fault plane mapped in three-dimensions is projected to the surface to create a surface trace with x-y points that were then exported, converted to shape files, and metadata compiled into an Arc-Map geodatabase. Faults are named according to geographic location. Related faults are numbered and, where appropriate, “graben” or “salt dome” is included in the name for clarity. Descriptive information for each fault includes survey name and type, interpreter, dip direction, and type (regional, counter-regional or salt-dome, and reliability level).

4.4. Field Confirmation

4.4.1. Energy Sector Seismic Data

The project team from UNO has reported initial measurements of fault movement in this study. The basis for this work was the donation of two hydrocarbon industry seismic datasets to UNO that allow deep-seated faults and other structures to be mapped at depth (1000’s of meters) and projected upward to shallow subsurface or surface locations. One of the donated seismic surveys is a 3D survey that covers a large area of Lake Borgne (Figure 5), representing two individual surveys that were completed across the Lake Borgne area. The western portion of the total surveyed area extends to a two-way travel time of 6s, and the eastern survey extends to 1.5s depth.

The other seismic survey covers the entirety of Lake Pontchartrain and extends down to 6s two-way travel time. Although none of the industry seismic datasets were collected or processed with the intent of imaging the uppermost 300 m of strata, they nonetheless are useful for the identification of faults at depth and, through upward projection, determine the approximate location where they would intersect shallow strata or the Lake bottoms. In order to determine whether deeply imaged faults truly penetrate upward and offset shallow stratigraphic units and/or surface features additional methods of investigation are required such as shallow, high-resolution geophysical data from Chirp seismic systems and vibracores that provide a record of the lithostratigraphic framework in the shallow subsurface.

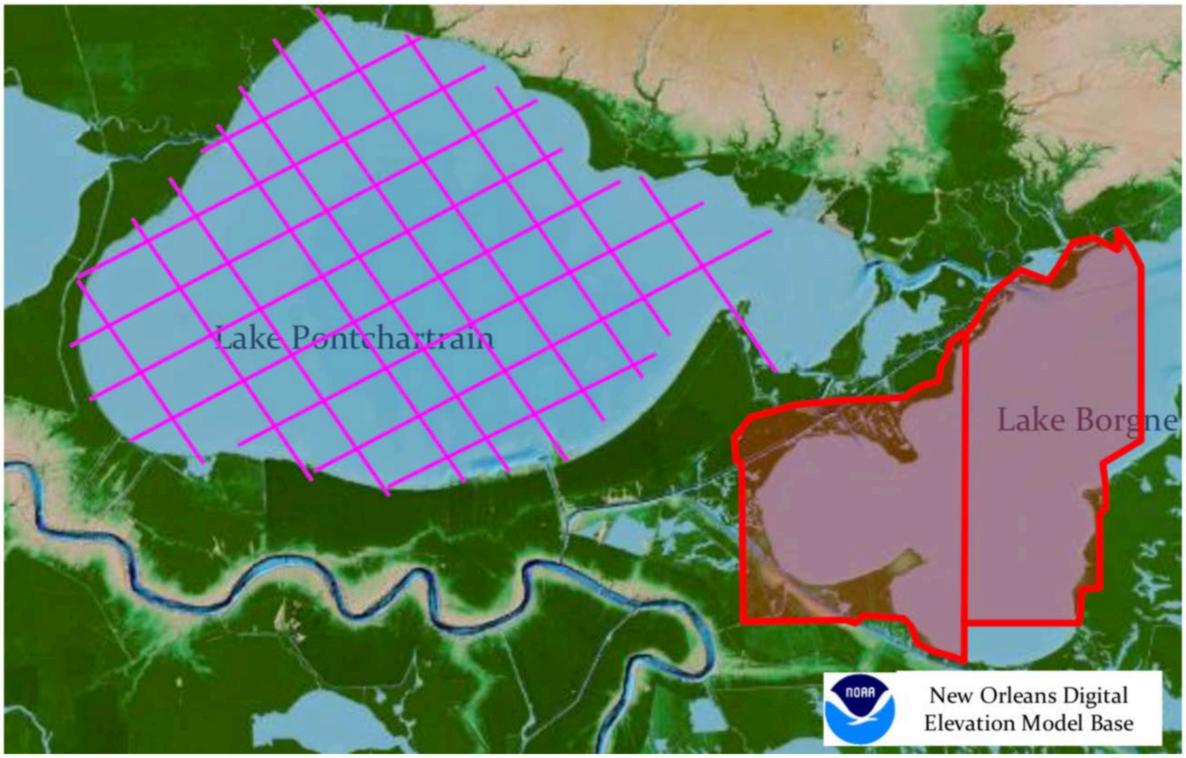


Figure 5. Base map showing the area of coverage for 3D seismic surveys of Lake Borgne and the coverage of the 2D Lake Pontchartrain seismic survey.

4.4.2. Chirp Seismic Data

Chirp seismic has been used in a wide array of studies focused on geologic framework, geohazards, pipeline routes, and marine archaeological investigations because of the ability to image the subsurface with vertical resolution at the scale of centimeters. Depths of penetration for the acoustic signal are variable and dependent upon the lithology of the subsurface strata (e.g., mud versus sandy units). In this study an *Edgetech* SB-216 Chirp system was used to image the subsurface, which consists of a tow fish and a 3100-p topside processor. The *Edgetech* SB-216 tow fish contains a singular transducer for emitting the acoustic signal and two receiver arrays. The system operates in the frequency range of 2-16 kHz providing penetration depths of as much as 91 m depending on the sediment characteristics. Sand-rich strata are likely to be on the shallow end of penetrating depths 6 m (20 ft), whereas mud-rich strata may result in greater penetration depths. The vertical resolution for this system ranges between 5.8 to 9.9 cm, which means this system could capture potential offsets in the Holocene as small as approximately 10 cm. A travel time of 1500 m s^{-1} was used for converting acoustic travel times to depths, which is the acoustic speed in normal salinity marine waters at 25° C and a research standard when using Chirp systems across shallow water environments of coastal Louisiana.

4.4.3. Vibracores

Vibracoring is a standard technique to directly acquire subsurface sediment samples and develop a subsurface lithostratigraphic framework. In this study, vibracore collection relied upon using a portable Honda 5.5 horsepower gas motor, Stow Model G500 vibrator, 3 m attachable vibrator cable with weighted head, 10 m length, and 7 cm interior diameter core barrels. The entire vibracore rig was vessel mounted on a specially designed flat bottom aluminum vessel with a centrally located moon pool through which the vibracoring is undertaken. The core barrels are placed through the moon pool, penetrated into the substrate until refusal and then removed with a winch system. A total of five vibracores were collected in this effort and all vibracores were transported back to Coastal Research Laboratory at UNO, where they were cut open, described in detail, sampled for potentially dateable horizons, and photographed.

4.5. Fault Reliability

Identifying the most likely location of surface faulting in south Louisiana's young and soft surface sediments is difficult without subsurface investigation and connecting a surface feature to a fault in the subsurface. Once the subsurface to surface connection is made, it is appropriate to then conduct field work to confirm a fault's position and effect in the near-subsurface. In south Louisiana where only extensional normal faults are reported, offset of Holocene horizons in the near-subsurface provides the best confirmation of active movement along a fault surface, and with age-dated horizons, rates of past fault movement can be estimated. Figure 6 illustrates key points that may occur in the process of identifying faults at surface and in the subsurface. The figure includes a typical line from a 3D seismic survey oriented S-N west of Golden Meadow *(14)*.

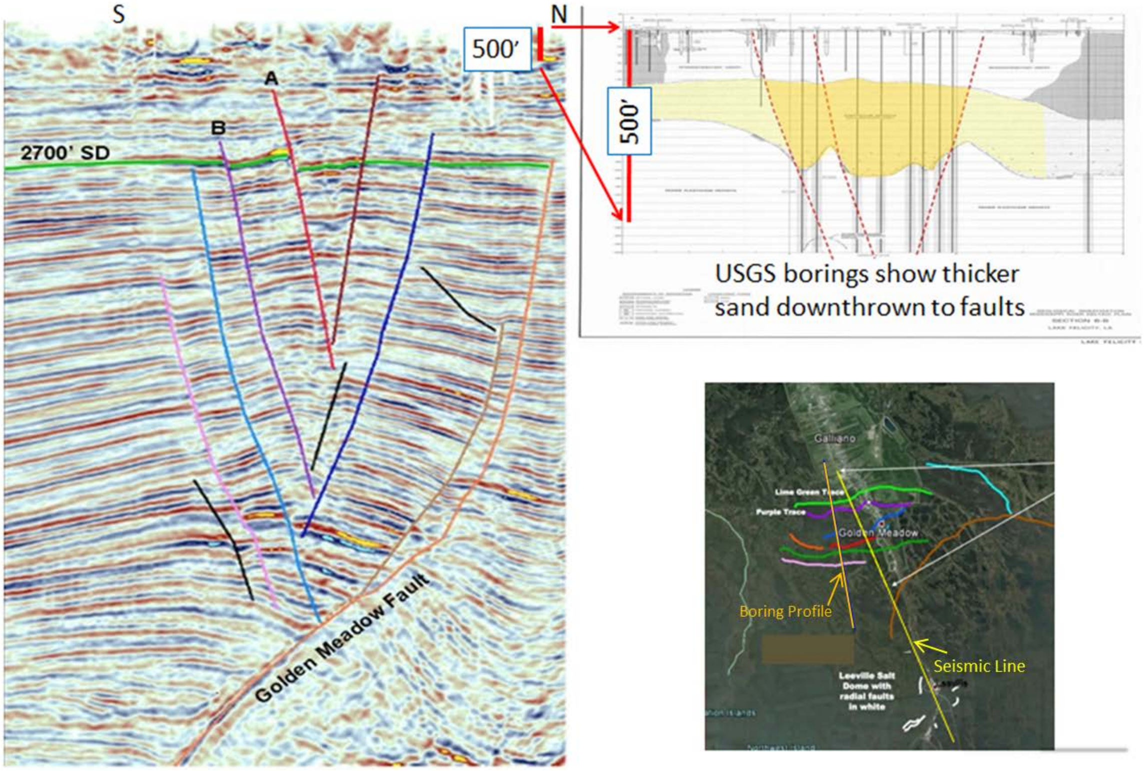


Figure 6. South to North 3D seismic profile *(14)* and USACE sediment boring profile across Golden Meadow graben.

Numerous faults oriented W-E perpendicular to the seismic profile are identified, and the down to north (DTN) and down to south (DTS) orientation of the fault planes toward each other form a geologic structure called a graben where the center between the faults is moving down relative to the sides. Note that although the faults are easily mapped on the seismic (by an experienced practitioner), seismic data nearest the surface has been muted and is of poor quality. Mapping fault traces all the way to the surface is difficult. However, the fault traces are mapped in three-dimensions, and the plane is well-defined because mapping of fault planes on adjacent lines constrain the plane to a well-defined geographic position.

Also included in Figure 6 is a profile of sediment borings conducted by the United States Geological Survey (USGS) to about 500 ft, in which a sand body is observed to thicken in the middle section of the diagram. This section was originally described in 1984 without the benefit of subsurface analysis, but when faults from the study conducted by Kolvoord et al. are projected onto the section *(14)*, it is apparent that slippage along the DTN and DTS faults in the Golden Meadow graben contemporaneous to deposition is likely to be responsible for the thicker sand section. Further work to confirm the position and age of fault movement would include detailed analysis of sediment borings and radiometric age dating of offset horizons.

The USGS has also compiled a GIS-based map depicting geologic faults that have been active in the last 1.6 million years. Two factors describing reliability are included in their main definitions of faults: how well the location is constrained, and the date of last movement based on chronostratigraphy. This descriptive framework is sound, and while surface fault traces in Louisiana will undoubtedly be indistinct due to loose consolidation, reliability levels indicating increased knowledge of location and time were also applied (Figure 7).

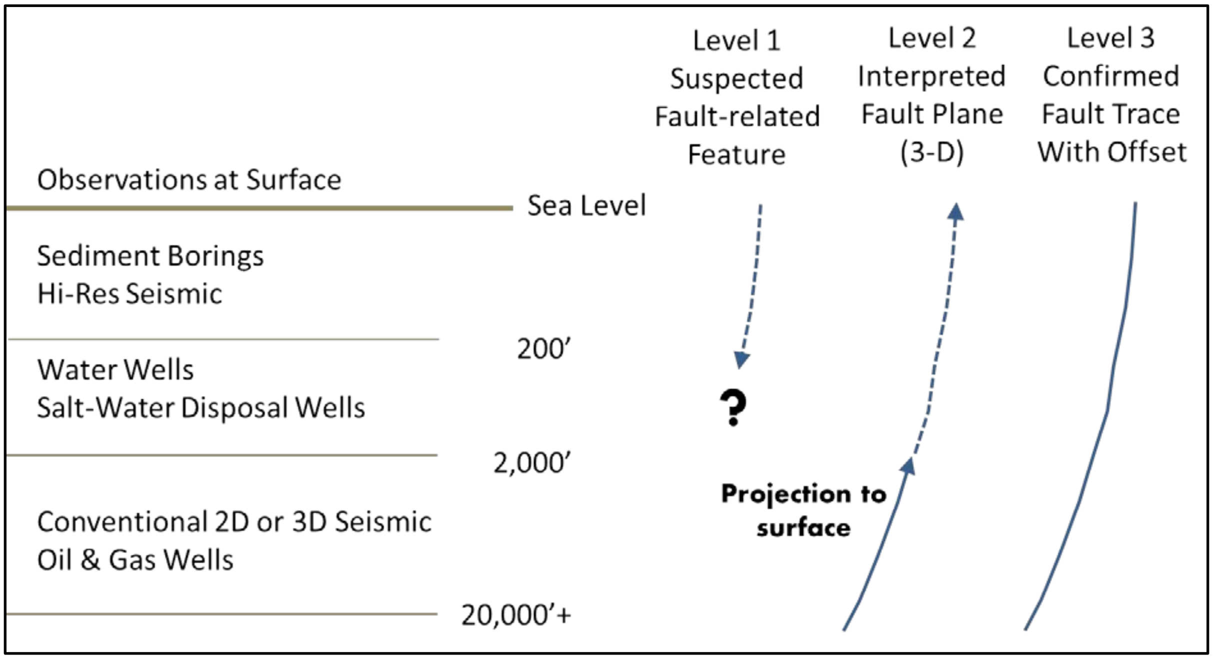


Figure 7. Fault reliability scheme, where reliability levels are based on location accuracy.

4.5.1. Reliability Level Definitions

Level 1: Suspected faults include those that have been interpreted based on surface methods, aerial methods, or are from large scale maps showing regional trends rather than exact fault position.

Level 2: Identified faults use subsurface data, preferably 2D or 3D seismic, to project fault planes for a good estimate of where they meet the surface. Study areas included in this study and other literature sources *(10, 17)* used 2D and 3D data for fault trace position and are considered Level 2.

Level 3: Confirmed fault traces have data that complete the connection from the subsurface to the surface by adding a network of sediment borings, and which have distinct lithostratigraphic or chronostratigraphically age-dated sedimentary horizons that show offset. Level 3 fault traces may also be confirmed when imaged on near-surface 2D high-resolution seismic.

This study adds to the current knowledge of fault locations in southeast Louisiana by cataloging fault locations reported in the literature while, more importantly, providing testable surface traces based on seismic interpretation in four main study areas. As fault offset near-surface is compiled with data from sediment borings, and high-resolution seismic, observations of near-surface effects can be made and a more robust understanding of the varied effects that fault will result. Additional surface observations related to faults, such as the presence of surface scarps (i.e., as seen based on field investigation), marsh breaks, development of open water areas over time, slope instability or failure, offset in rigid infrastructure, seepage and liquefaction, etc., can be cataloged as well and placed on maps as appropriate. It is expected that this mapping tool will help lead to an improved understanding of how faults behave at the surface in the dynamic deltaic system of south Louisiana.

5. FINDINGS

5.1. Seismic Data Availability

2D and 3D seismic data is widely available for license in south Louisiana and underlies critical infrastructure in much of the study area, particularly south and west of Lake Pontchartrain. Figure 8 shows 3D dataset polygons from three vendors: Schlumberger, SEI, and Seitel. Overall, coverage is quite good. However, 3D seismic coverage is poor in many urban areas where critical infrastructure may require review.

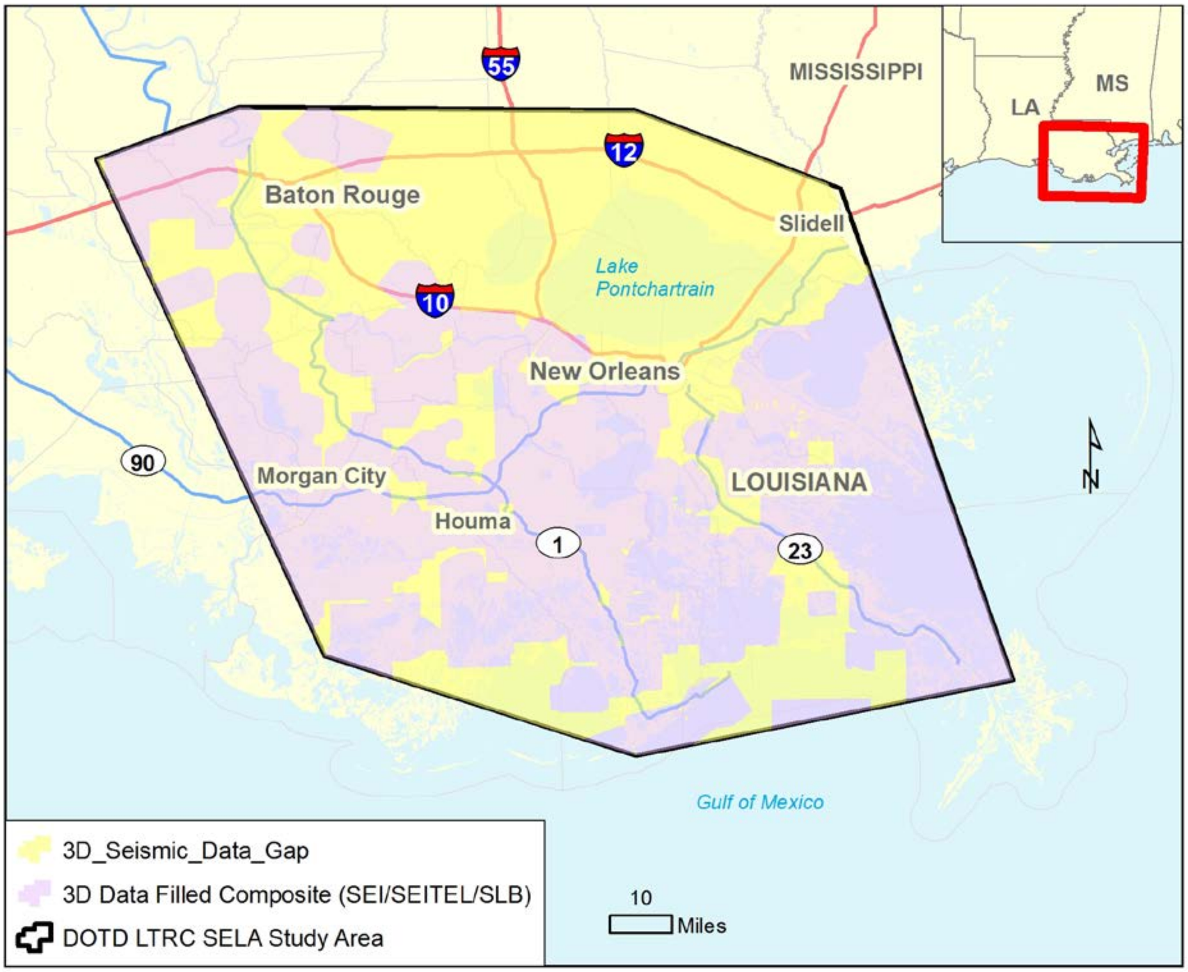


Figure 8. 3D seismic datasets are shown in pink and gaps with no 3D seismic coverage are shown in yellow.

Figure 9 adds the available 2D seismic lines to the Figure. Three vendors handle 2D data, and data is concentrated in areas that also have 3D data, but important areas including Lake Pontchartrain and the Northshore have some coverage that fills in the 3D data gap areas. Areas with exclusively 2D data available are highlighted with the yellow background of the 3D data gap.

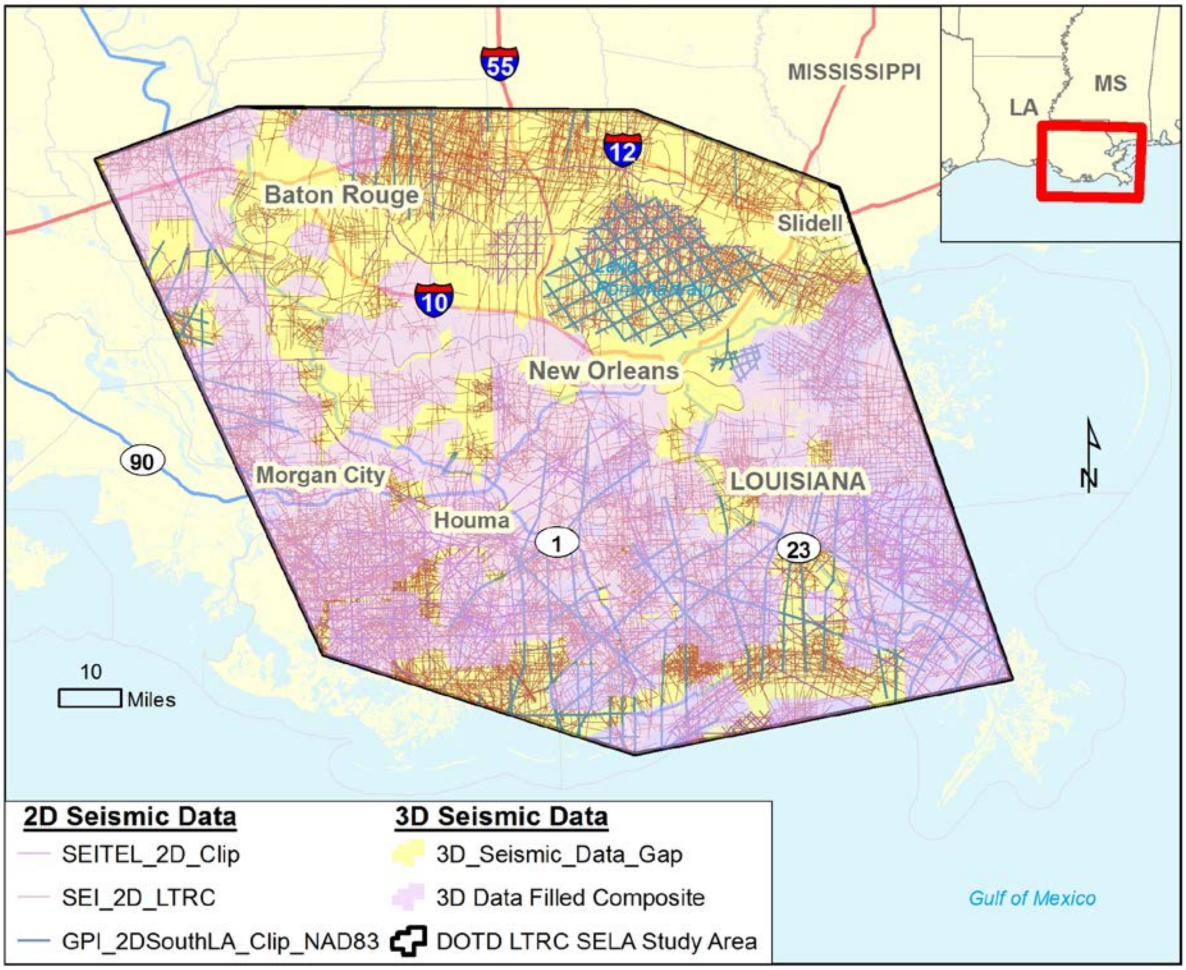


Figure 9. 2D seismic lines from vendors in blue, purple, and dark pink, with 3D data in pink and 3D data gap in transparent yellow.

5.2. Fault Interpretations

The compilation of fault maps from various sources into one GIS project allows for comparison of fault maps made using different interpretive techniques. Gagliano et al. *(7)* includes maps that summarize extensive work over many years by Coastal Environments, Inc. Fault mapping consisted mostly of field work and time-lapse aerial photography, with limited access to seismic data.

The surface fault trace map by Gagliano et al. *(7)* is overlain with that by Armstrong et al. *(10)* in Figure 10. A few key points can be made. First, every segment mapped by Armstrong et al. *(10)* is also represented by part of one or more faults mapped by Gagliano et al. *(7)*. Similar trends are seen in both maps, but Gagliano et al. *(7)* appears to connect the fault segments more extensively and includes many more faults than the 3D seismic interpretation. Also, some segments are connected that should not be according to the 3D interpretation. This may suggest that while south Louisiana is extensively faulted, faults may not be quite as widespread or have as large an effect as the maps by Gagliano et al. *(7)* might suggest. These observations are difficult to test without better knowledge of the data resources Gagliano et al. *(7)* employed; detailed sediment boring and chronostratigraphy would help resolve the issue.

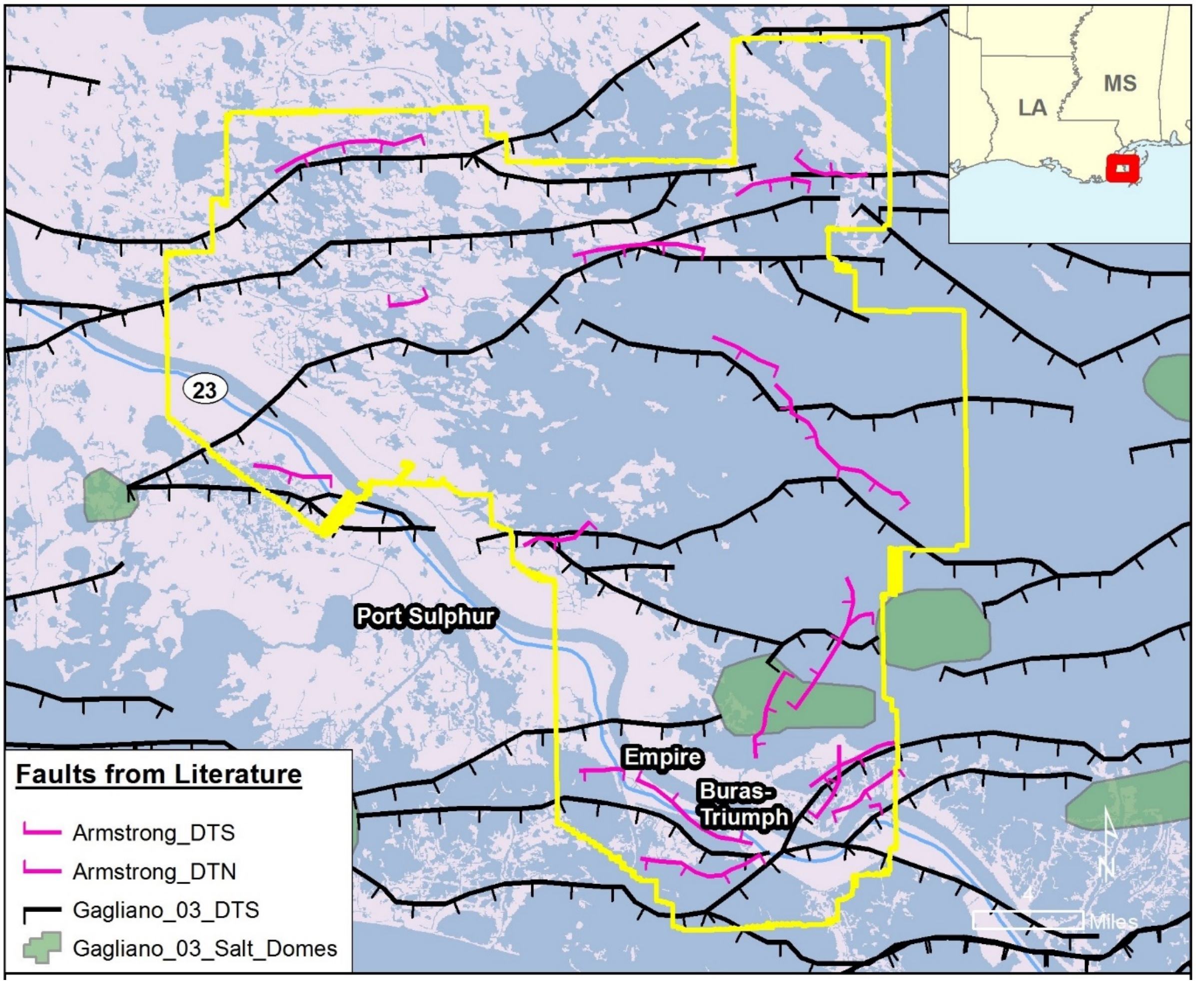


Figure 10. Fault map of Gagliano et al. *(7)* with faults in black and salt domes in green. The outline shows the 3D data mapped by Armstrong et al. *(10)* whose surface fault traces are shown in magenta.

5.2.1. Terrebonne Area

Surface fault traces south of Houma near Montegut, Chauvin, and Isle de Jean Charles were mapped by Akintomide et al. *(15)*. Most faults are DTS except for the salt dome related faults in the vicinity of Bully Camp in the northeast and the graben in the southwest part of the study area.

Modern-day movement is suspected on at least some of the faults in this area. Montegut Fault in particular is coincident with a prominent linear marsh break, south of which is mostly open water. Lake Boudreaux's northeast boundary is parallel to the fault and may represent a marsh edge that has retreated back, parallel to the fault. The position of the Isle de Jean Charles fault is critical for the community of Isle de Jean Charles located on the southern, downthrown side of the fault.

As shown in Figure 11, Bully Camp faults are associated with the top of Bully Camp salt dome. Note that Bully Camp 1 and 3 faults consist of two traces. This is a result of overlap between the surveys mapped in the Terrebonne and Golden Meadow study areas and slightly different map levels used by each student to create the final surface trace maps.

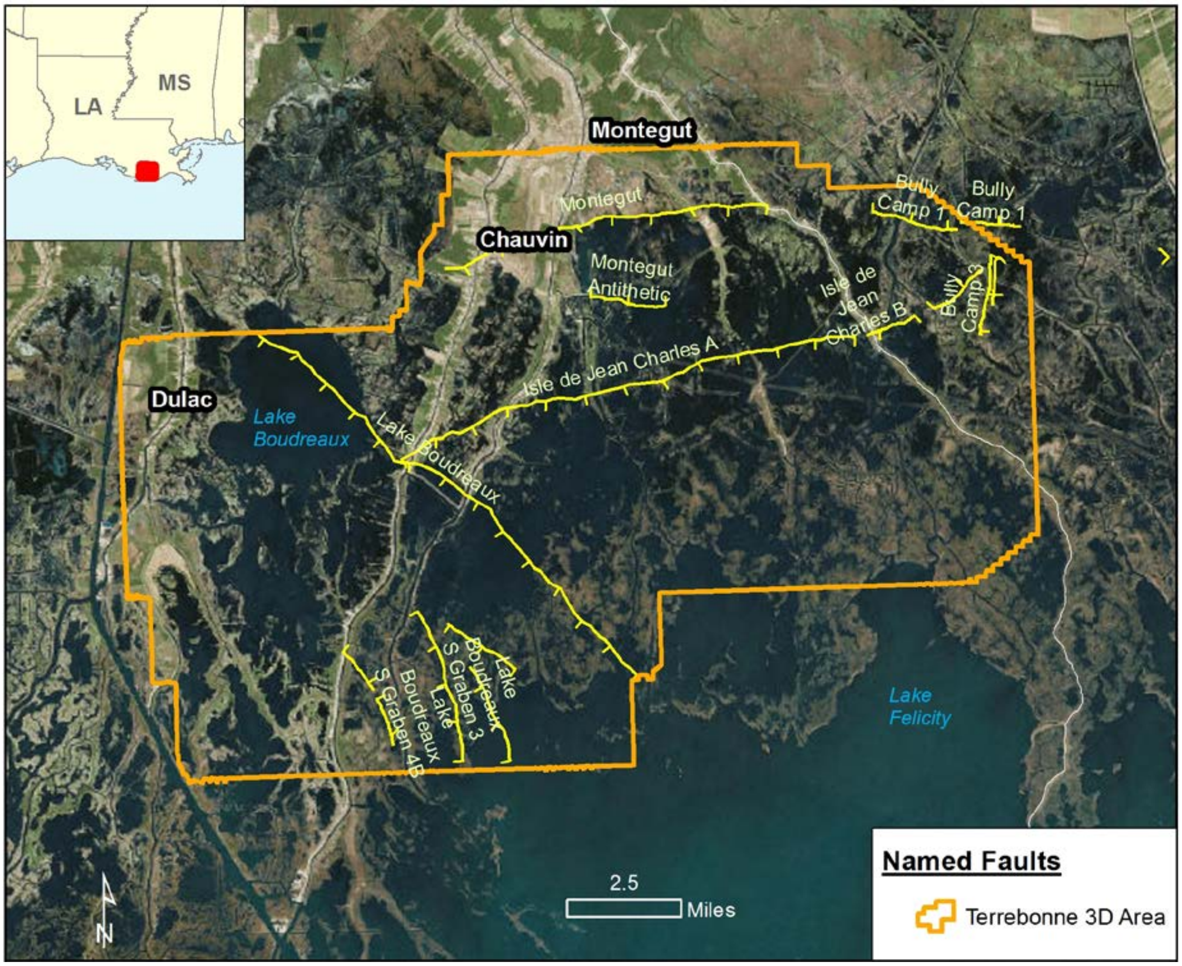


Figure 11. Terrebonne study area: faults are yellow and dip direction is indicated with short hachure marks.

5.2.2. Golden Meadow Area

3D data in the important LA 1 transportation area from Golden Meadow to Leeville (Figure 12) was mapped by Johnston et al. *(2016)*. A graben system is observed in southern Golden Meadow where DTS and DTN faults form a low relief trough. Generally, highways do not appear to intersect these faults, although flood control structures may be affected. However, the southern-most fault in the Golden Meadow area is a DTN fault that crosses the proposed elevated extension of LA 1. Similarly, the LA 1 extension crosses a down to east (DTE) fault associated with the Leeville Salt Dome in the southern part of the study area. CPT data is available across this interface and our recommendation would be to use the Arc-GIS tool to compare CPT results with position of the faults.

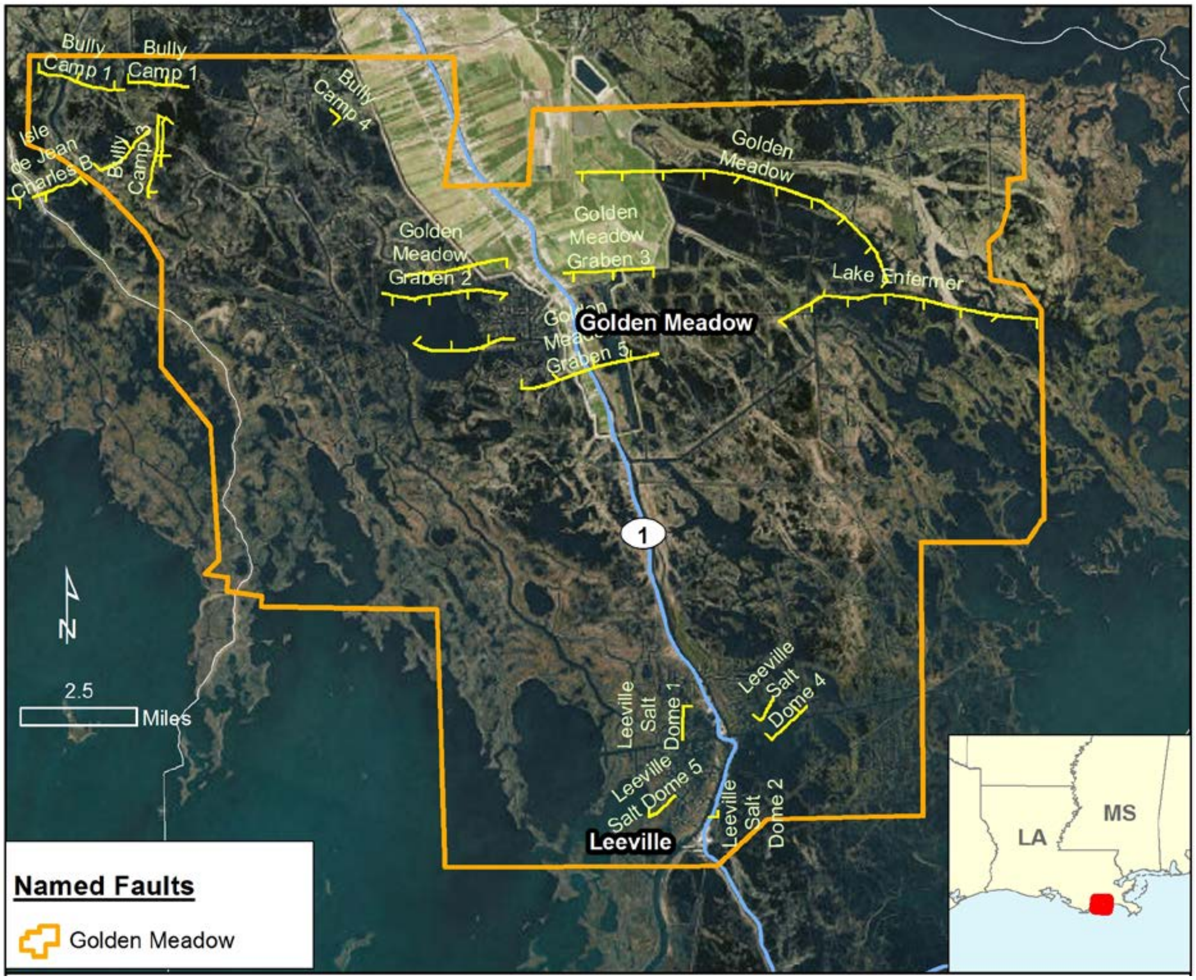


Figure 12. Golden Meadow study area.

5.2.3. Lake Pontchartrain and Lake Borgne

Figure 13 shows Lake Pontchartrain faults mapped on 2D seismic data (outlined in green) with a rough line spacing of 3 mi, whereas Lake Borgne faults were mapped using 3D seismic data (orange outline) and confirmed with high-resolution chirp seismic data.

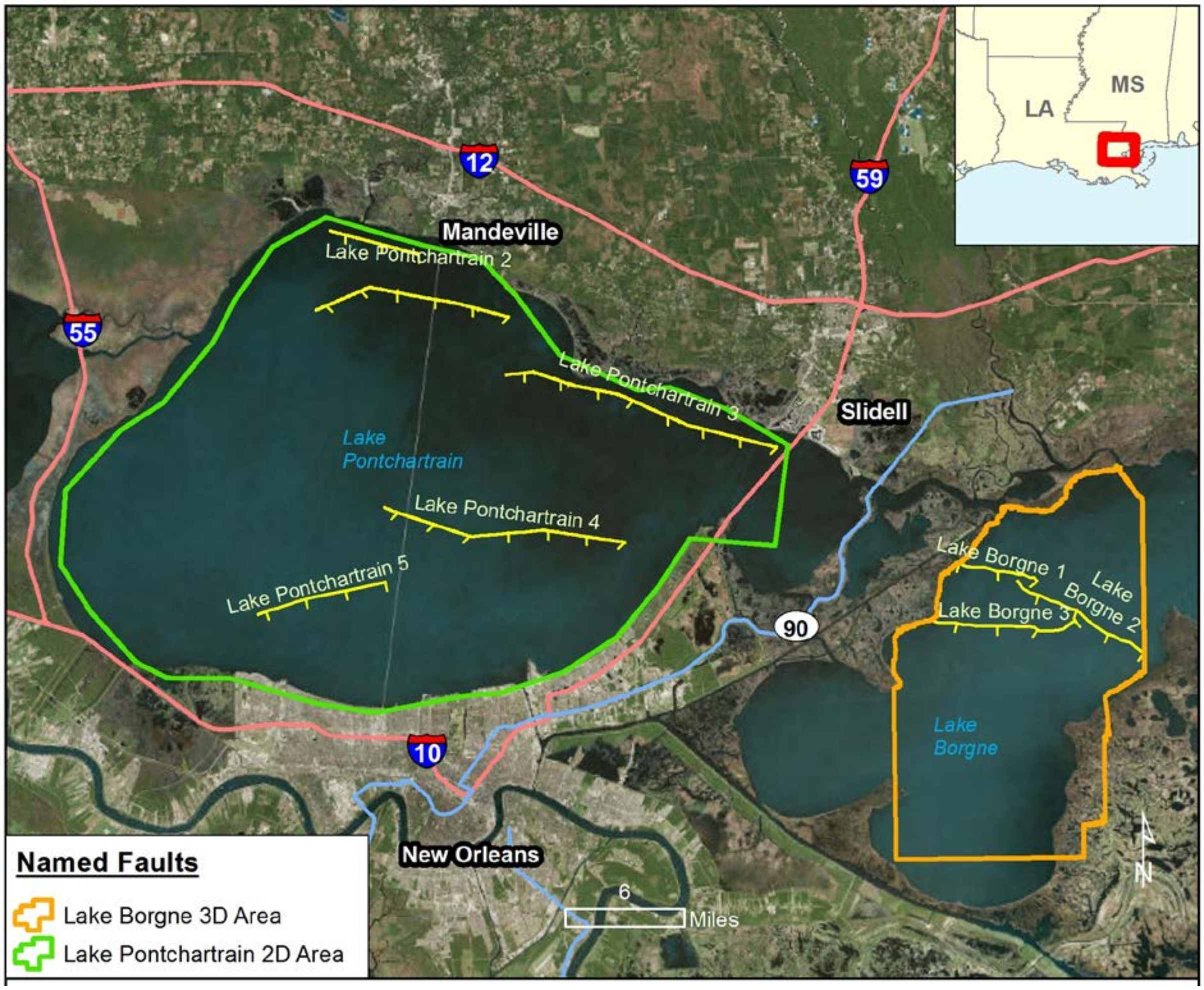


Figure 13. Surface fault traces in Lake Pontchartrain and Lake Borgne.

5.3. Field Confirmation

5.3.1. Energy Sector Seismic Data

An examination of the industry seismic data in Lakes Pontchartrain and Borgne resulted in the identification of numerous faults within the deep subsurface of the Pontchartrain Basin and was originally completed by Frank *(18)*. Figure 14 presents an interpreted example of the quality of the industry seismic data as well as an indication of the usefulness and limitations of the datasets. In Figure 14 a series of generally DTS faults are shown. The majority of the faults along this cross section do not extend upward to the near surface, however at least two of the faults (indicated in red and blue) appear to reach relatively shallow stratigraphic intervals and may intersect the Lake bottom, but because of the limited processing of the data at shallow stratigraphic intervals whether they intersect the Lake bottom cannot be fully determined.

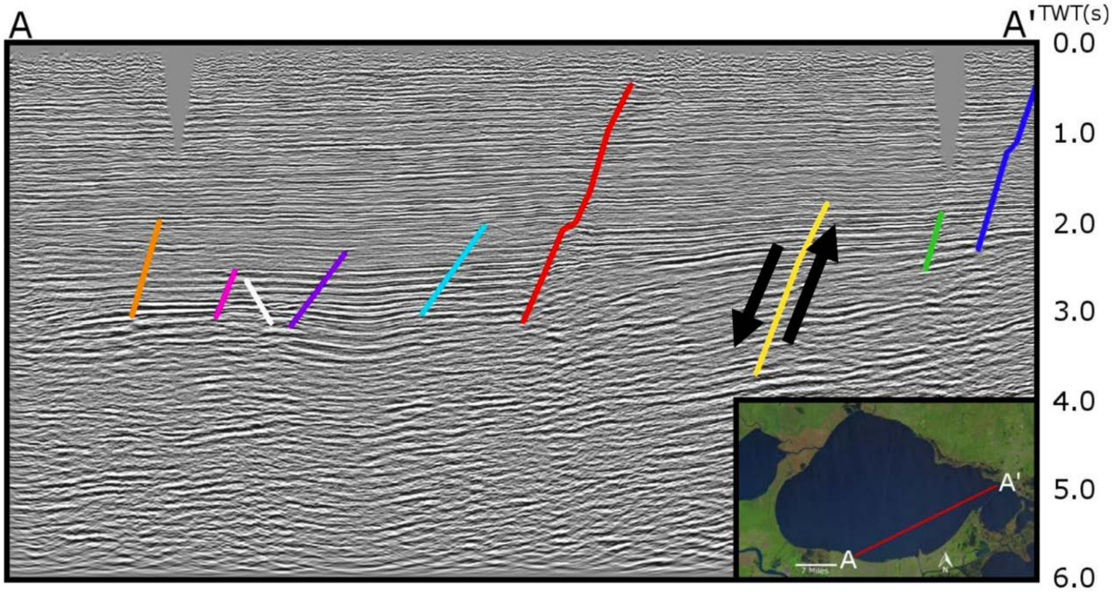


Figure 14. Surface fault traces in Lake Pontchartrain and Lake Borgne *(17, 18)*.

Nonetheless a full examination of the Lakes Pontchartrain and Borgne seismic data does provide an overview of the distribution of faults within the two areas that may or do extend to shallow depths (Figure 15). Efforts are currently ongoing to accurately project deep-seated faults from depth to shallow stratigraphic intervals and establish the distribution of faults within the Lakes that may have affected Holocene strata and consequently bridge and road infrastructure extending across Lake Pontchartrain and the East New Orleans Land Bridge. Industry seismic data of this nature clearly provides an important dataset for assessing whether fault induced subsidence is a possibility and whether it has the potential for causing structural disturbance to existing or planned infrastructure.

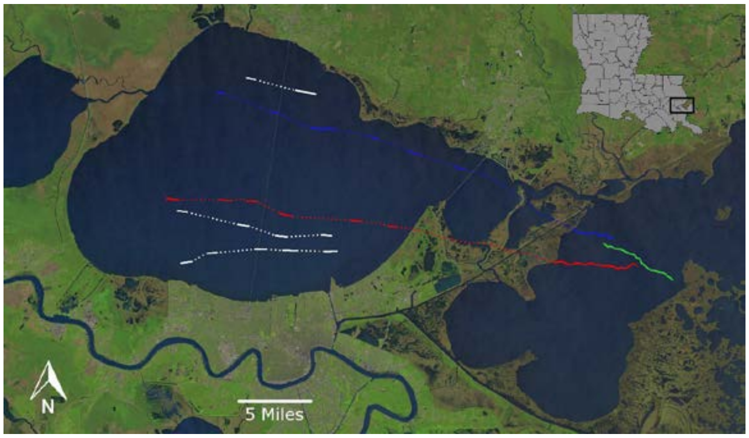


Figure 15. Traces of faults mapped in both the 2D and 3D surveys of Lakes Pontchartrain and Borgne.

As shown in Figure 15, solid traces indicate confirmed fault traces within 3D seismic, whereas dotted lines indicate inferred fault traces between 2D seismic transects. The red and blue faults are correlated across the East New Orleans Landbridge, an important connection between New Orleans and communities to the north. Across the Land Bridge note the alignment of fault traces to linear and rectilinear open-water and marsh edge relationships as well as the decrease in width of eastern Lake Pontchartrain and Lake St. Catherine. Note that colors depicted on this base map do not directly correspond to fault colors shown in Figure 14.

5.3.2. Vibracore Data

To determine the magnitude of fault motion in the vicinity of the Highway 11 Bridge that crosses Lake Pontchartrain, five vibracores were taken in 2018 along an approximately south-trending transect located just east of the Highway 11 Bridge (Figure 16) where previous studies *(5)* and more recent work *(17, 18)* have identified deep faults that extend to shallow stratigraphic intervals. The goal of the vibracoring effort was to determine whether indications of stratigraphic offset are identifiable in shallow stratigraphic relationships proximal to the fault. Additionally, the goal was to determine whether vibracoring may provide a method of establishing the magnitude of recent fault offset, and hence impact to infrastructure, but also provide an approach to determining the rates of fault motion during the late Holocene through age dating of sediments. The following provides a short description of each of the cores acquired in this effort (Figure 17). Their vibracore description sheets are presented in Appendix A.

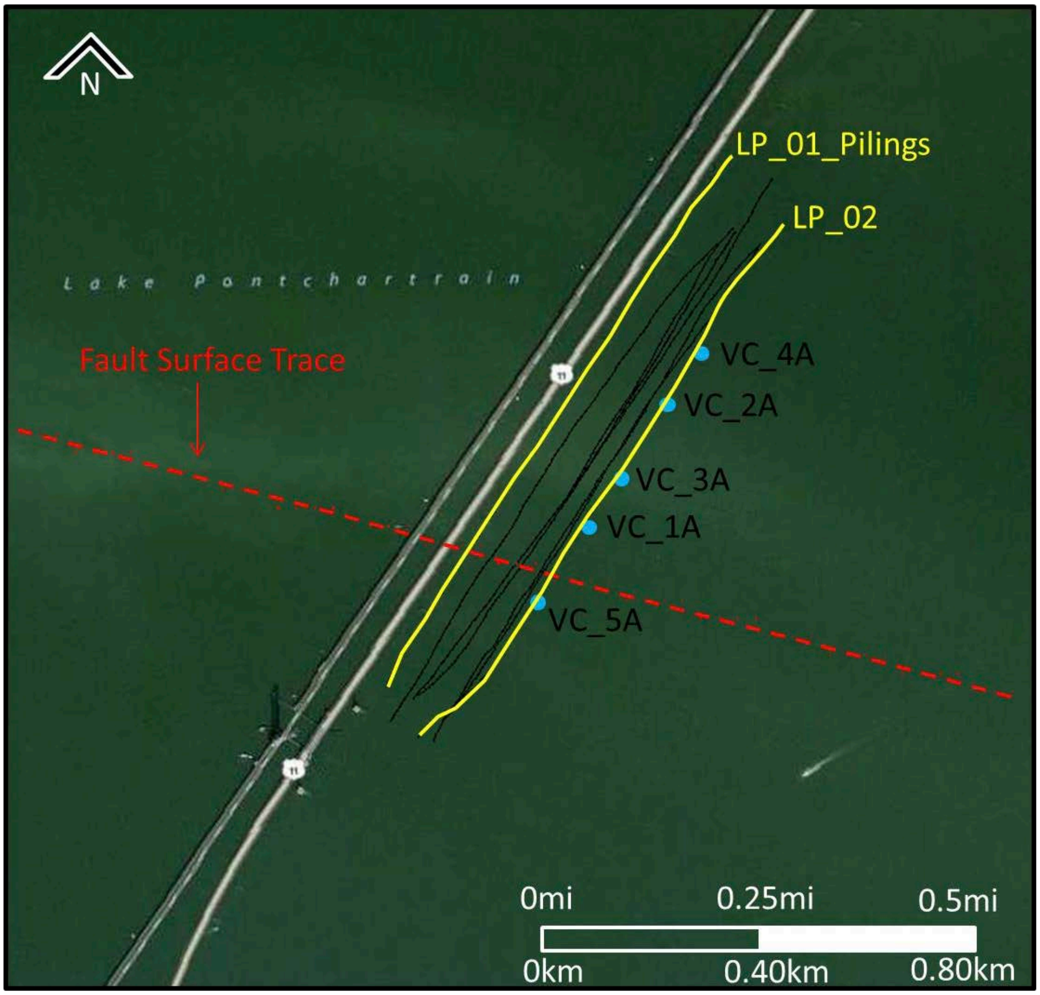


Figure 16. Base map showing the location of five vibracores taken near Highway 11 Bridge that crosses Lake Pontchartrain.

The dashed red line in Figure 16 indicates the projected surface trace of the down-to-the-south blue fault shown in Figure 15.

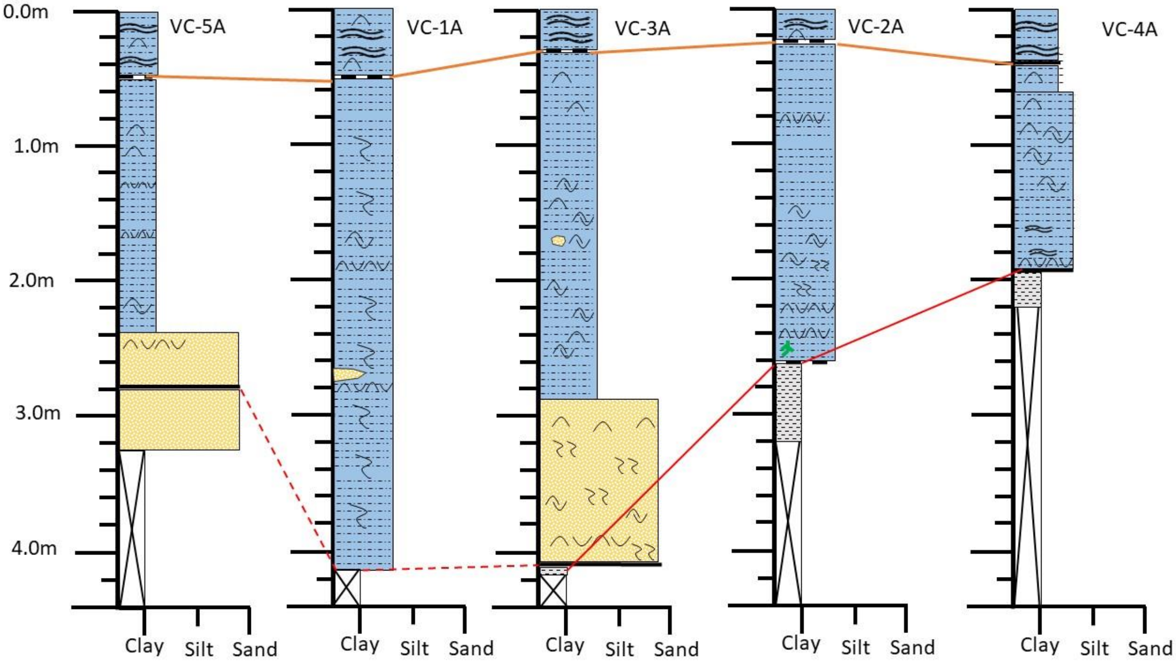


Figure 17. Stratigraphic cross section constructed from vibracores collected near the Highway 11 Bridge.

As shown in Figure 16, the upper orange correlation line is drawn on the base of unconsolidated, silty, olive-gray clay that is present within the upper approximately 0.4 m of all of the cores and reflects recently deposited, fine-grained sediments in the Lake. The lower red correlation line marks the interpreted boundary between Holocene and Pleistocene strata, which is more evident in vibracores VC-2A and 4A and becomes less easily identifiable toward the south where sand content increases in the bottom of the core.

VC-1A: VC-1A had a total length of 4.2 m and penetrated two distinct lithofacies. The uppermost 0.5 m of the core consisted of unconsolidated olive-grey, silty-clay with massive bedding and some fragmented shells. From 0.5 to 4.2 m a second distinct lithofacies of massively bedded, olive-grey silty-clay sediment was present. The lowermost facies contained numerous sand-filled burrows and shell clasts. Lithologically distinct *Rangia cuneate* shell lags were observed at 1.9 and 2.7 m.

VC-2A: A total of 3.2 m of core was obtained at location VC-2A, and this core penetrated three distinct lithofacies. The uppermost 0.3 m of the core consisted of massively bedded unconsolidated olive-grey silty-grey sediment, with shell fragments present throughout the interval. From 0.3 to 2.6 m the sediment consisted of medium dark grey, silty-clay with massive bedding and shell lags at 0.8 to 0.9 m, 2.2 m, and 2.4 to 2.5 m. At 2.6 to 2.9 m there was a gradational change into the lowermost facies consisting of very light-grey to medium, light-grey clay, which extended to the bottom of the core.

VC-3A: A total of 4.2 m of core was obtained at station VC-3A and consisted of three distinct lithofacies. The uppermost 0.3 m of the core was dominated by massive bedding of unconsolidated olive-grey, silty-clay. Between 0.3 and 2.8 m the strata consisted of a silty-clay with some shell fragments and shell halves. From 2.8 to 4.1 m the strata consisted of sandy-clay with minor bioturbation, shell halves, shell fragments, as well as a shell lag between 3.8 to 3.6 m. Light-grey clay with dusky yellow and pale-olive hues was present from 4.1 to 4.2 m.

VC-4A: Similar to the other cores, three distinct lithofacies were penetrated at location VC-4A for a total core length of 2.2 m. The uppermost 0.4 m of the core consisted of unconsolidated olive- grey silty-clay sediment with no distinct bedding. Massively bedded medium dark-grey, silty clay was present between 0.4 and 1.9 m, between 0.6 and 1.9 m there was a slight increase in the silt content along with fragmented shells. A shell lag was present between 1.7 and 1.9 m. The lowermost lithofacies between 1.9 and 2.2 m consisted of a massive, light grey clay with patches of dusky yellow sediment.

VC-5A: VC-5A penetrated a total of 3.2 m of sediment. In the upper 0.5 m of the core the was massively bedded unconsolidated olive-grey silty-clay sediment. Trace amounts of shell fragments (< 0.5 cm in size) were also present. The interval from 0.5 to 2.8 m contained medium grey, silty-clay with shell halves and trace amounts of shell fragments, mostly concentrated around the shell lags. Shell lags within this interval were present at 1.2 to 1.4 m, 1.5 to 1.7 m, 2.3 to 2.4 m, and 2.5 to 2.8 m. Between 2.8 and 3.2 m the sediment consisted of medium light-grey to very dark-grey, sandy clay with some yellowish orange hue present.

Vibracore Interpretations: A total of three primary lithofacies were present within all of the cores and can be used to clearly identify the depth of the Pleistocene and Holocene stratigraphic contact as well as the magnitude of stratigraphic offset associated with the Baton Rouge Fault Trend.

The uppermost facies are characteristic of the uppermost Holocene sediments and consists of unconsolidated olive-grey silty-clay, and often contains minor amount of shell halves or shell fragments. Facies 2 represents the lower Holocene. It is characterized by silty-clay sediment that locally becomes coarser with depth. Shell fragments and shell halves are present throughout this stratigraphic interval as well as some bioturbation. The stratigraphic base of facies 2 locally represents the transition from Holocene strata into the uppermost Pleistocene. Facies 3 represents Pleistocene strata, characterized by a typically sharp stratigraphic contact between lesser consolidated clays and more highly consolidated medium light-grey to dark-grey clay.

Vibracore Cross Section: A stratigraphic cross section and correlation of the sedimentary units penetrated by the vibracores suggests that there has locally been a reduction in the elevation of the Holocene and Pleistocene contact proximal to the suggested fault trace indicated by examination of the deep industry seismic data. From north to south across the cross section (Figure 17) the interpreted contact of the Holocene and Pleistocene boundary increases in depth from approximately 2.0 m in VC-4A to possibly as deep as 4.0 m in VC-3A. Vibracore VC-1A did not penetrated a clearly identifiable stratigraphic boundary between the Holocene and Pleistocene, which may be a reflection of a deeper stratigraphic position for the contact then what the vibracore could penetrate or a change in sedimentary character of the boundary that does not make the contact easily recognizable. Finally, vibracore VC-5A also did not contain a clearly identifiable Holocene and Pleistocene contact, which again may be that the vibracore did not penetrate to the appropriate stratigraphic level, especially inasmuch that the core encountered a thick sand- rich deposit at the base that would have limited the penetration, or the contact simply was of a different character than the common clay-rich, stiff uppermost horizon of the Pleistocene units along this section of the Louisiana coastal plain. Nonetheless the offset of similar stratigraphic horizons across such short distances suggest that proximal to the fault trace, determined from deep seismic imaging, stratigraphic offset has taken place within relatively recently (~ last 5,000 yrs) deposited sedimentary units and that the zone of deformation associated with the fault extends across approximately 200 m on each side of the projected surface trace of the fault.

During examination of the cores several intervals of material that could be radiocarbon dated were identified, which would help establish chronostratigraphic horizons and determine the timing and rates of fault offset for future work. A full chronostratigraphic analysis required to complete this was well beyond the intent of this project and thus not completed. It could however, be an important topic of future investigations designed on establishing the timing and rates of fault induced subsidence.

5.3.3. Chirp High Resolution Seismic

A total of eight high-resolution seismic survey transects were collected parallel to the vibracore transects collected for this project and to the trend of the Highway 11 Bridge (Figure 16). These Chirp seismic lines represent the first high-resolution Chirp lines collected in the Lake for the purpose of assessing the subsurface stratigraphic relationships and whether faults have impacted the Lake stratigraphy and infrastructure. The goal of the seismic collection was to assess what geophysical parameters provide the overall best depth of penetration and resolution within the Lake stratigraphy and whether faults can be identified within this geophysical data. The *Edgetech* SB-216 tow fish used in this study has a total frequency range of 2-16 kHz but the system can be adjusted to collect data at a range of frequency intervals. During seismic data collection a series of seismic lines were acquired using a frequency range of 2-15 kHz and 2-10 kHz, and acoustic pulse power was adjusted between 80 and 100% of full power. At higher frequency ranges resolution of imaged horizons is increased but at the sacrifice of depth of penetration. Determining the most appropriate frequency range requires manual adjustment of settings that are most well suited for the project goals and the underlying subsurface sedimentary compositions.

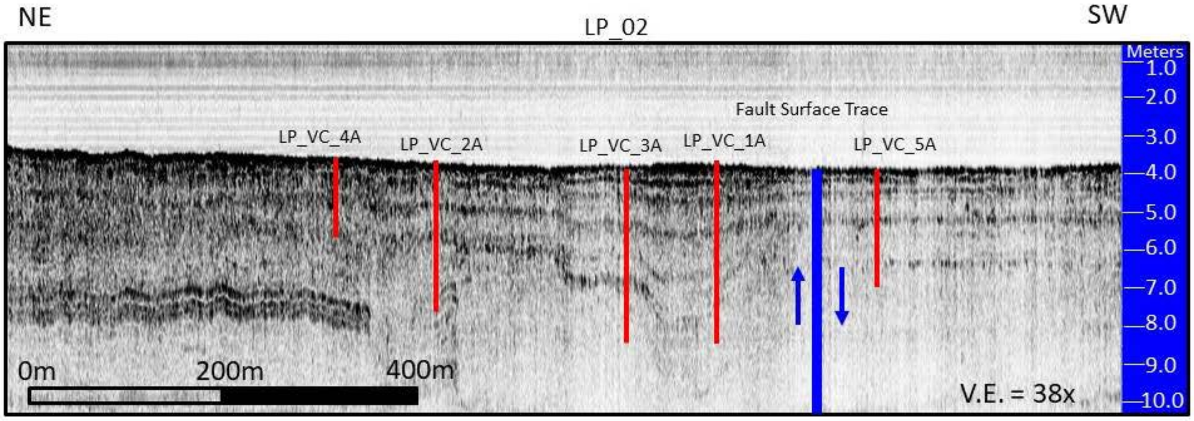


Figure 18. Chirp seismic line LP_02 collected along the trend of the stratigraphic cross section shown in Figure 16 and perpendicular to the suggested trend of the Highway 11 fault.

Chirp Line LP_02: Seismic line LP_02 (Figure 18) was acquired nearly directly above the location of the vibracore cross section presented in Figure 17 with system settings of 2-15 kHz at 80% pulse power. These settings provided acoustic penetration of approximately 5 m below the Lake bottom and a resolution of several centimeters. Numerous clearly defined seismic reflectors are present, especially in the upper several meters, but locally become less obvious where the cores indicate sand-rich strata such as at the bases of core LP_VC_5A and 3A. An approximately 100- m wide channel-like set of reflectors in the vicinity of core LP_VC_1A is also visible in Figure 18. An apparent plane of fault slip is not readily obvious in seismic line LP-02, there appears to be horizontal continuity of the shallow stratigraphic reflectors across the projected location of the fault plane.

It is important to recognize that these fault traces are projected from depth and slight deviations in the angle of their upward projection would alter the location of the surface fault trace. Thus slight alterations in the fault plane angle projected upward could result in a shift of the fault plane by a few hundred meters. For example, if the fault trace of LP-02 was shifted 200 m to the northeast of its current location then the channel like feature previously discussed would be located along the downthrown side of the fault, a relationship that Frank and Kulp *(17)* and Frank *(18)* documented in Lake Borgne. Finally, it is important to recognize that at shallow depths (~<50 m) deep faults would primarily encounter soft, unconsolidated sediments that would deform in a ductile fashion rather than a brittle fashion, likely resulting in a broad zone of stratigraphic deformation rather than a discrete surface of fault discontinuity as was documented by Yeager et al. in their Pearl River work *(9)*.

Chirp Line LP_01_Pilings: Seismic Line LP_01_Pilings (Figure 19) was acquired from as close to the eastside of the pilings of the Highway 11 Bridge as was determined to be safe. During this acquisition the Chirp system was run at 2-10 kHz with a pulse power of 80% of full power, which provided good imaging of subsurface stratigraphic relationships and a clear indication of stratigraphic offsets at depths of 2 to 4 m below the Lake bottom. Clearly identifiable on Figure 18 are offsets of seismic reflectors proximal to the projected fault plane from depth in the industry seismic data. Interestingly the apparent offset of the shallow reflectors is opposite to the sense of motion indicated by the deeper seismic data. However, shifting the upward projected fault plane only 200 m toward the northeast would place observable offset seismic reflectors in the seismic image on the downthrown side of the fault plane.

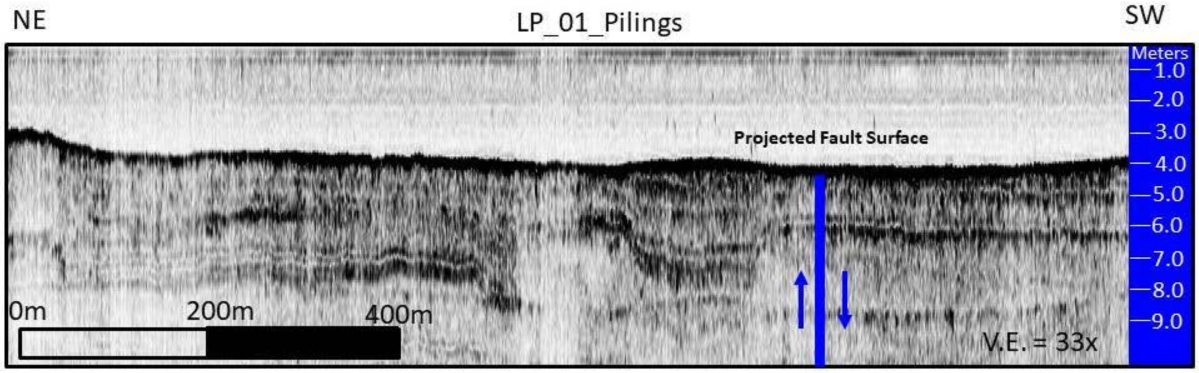


Figure 19. Chirp seismic line LP_01_Pilings that was collected within approximately 50 m of the east side of the Highway 11 Bridge.

The dashed blue line represents a shift in the projected fault plane from depth (solid blue line) that would result in the alignment of the footwall block (downthrown side) of the fault to the location of downward offset seismic reflectors at approximately 7 m depth below the water surface.

5.4. Fault Mitigation and Rehabilitation

An overarching objective of this study is to break down barriers between the energy sector and designers of infrastructure, flood control, and coastal restoration projects in a subsiding deltaic basin complex.

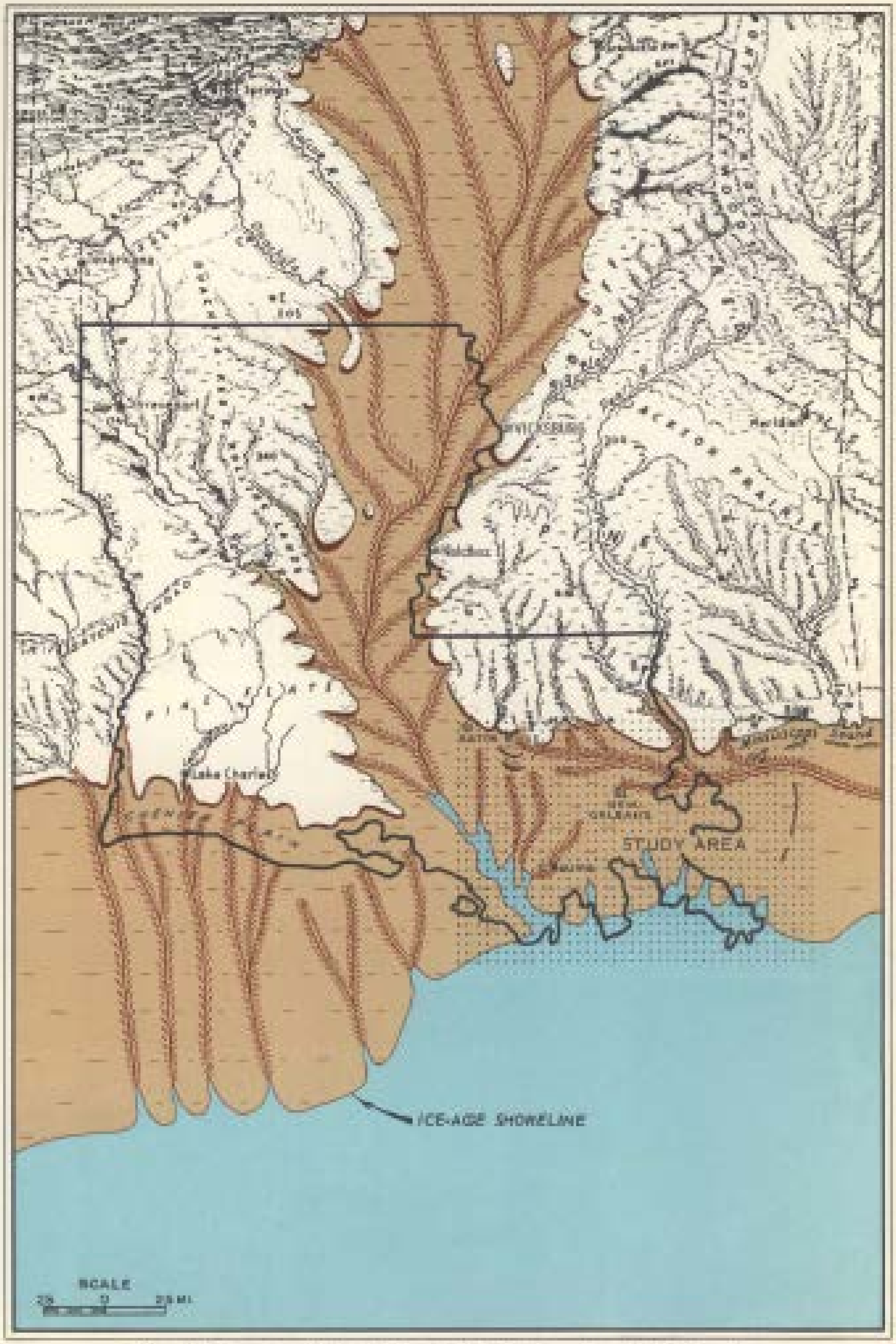
These efforts include:

- Integration of geology, geophysics, and engineering into what can be described as geotechnical geology.
- Inclusion of shallow, high-resolution and deep, 3-D geophysics, combined with remote sensing applications, in the planning and design of infrastructure, flood control, and coastal restoration projects.
- Integration of artificial intelligence and machine learning in to seismic techniques for surface, near-surface, and tectonic fault and sediment deformation characterization.
- The integration of geologic, geomechanical, geophysical and geotechnical geology in to GPS and computational models.

The degree of fault mitigation should correspond with the level of importance of a structure and the potential of loss of life and/or economic loss. Thus site characterization for a structure with a higher consequence for failure, along with a more robust subsurface investigation, are warranted. These would include borings, in-situ testing, instrumentation, geophysical surface, etc., coupled with a knowledge of geology, as well as consultation with geologists familiar with the site. It is common to find much undulation between Marsh, Intradelta, and Interdistributary deposit, given that the Mississippi River has so many past courses and Deltas in the Louisiana Coastal Region. The Marsh and Swamp deposits can have thick layers of peat and organic soils, which need to be accurately delineated.

It is difficult to ascertain which faults encountered will potentially generate a surface rupture. With the extensive geological record available from energy-sector 3D seismic data, surface ruptures in coastal environments in southeast Louisiana could be considered a fault that impacts sediments of Holocene age. Ruptures and fractures tend to follow planes of weakness within the fault zone and can affect geotechnical and superstructures differently depending on fault displacement magnitude and surface fault rupture location in relation to the structure.

For purposes of this section, faults affecting or located within unconsolidated Holocene sediments are considered for potential mitigation and rehabilitation. Subsidence of post-glacial, recent sediments in the Mississippi Valley have been the subject of research since the 1950s *(19)*. Figure 20 contains a depiction of the Mississippi Valley during the Pleistocene (ice age) epoch. Fault motion, either by slow creep or more sudden slip, can cause deformation of engineered structures. Land subsidence of Holocene sediments associated with faults contributes to land subsidence that can result in increased infrastructure maintenance and repair costs. Design of effective mitigation techniques to counteract fault-related displacement hazard benefits from collaboration between disciplines. To investigate surface fault rupture, to perform engineering designs against such hazards, to develop techniques to construct resilient infrastructure, and to carefully document distress and failures when fault surface rupture occurs are the keys to understanding this hazard.



Frontispiece. Mississippi Valley during the Ice Age

Figure 20. Depiction of the Mississippi Valley with the Louisiana shoreline during the Pleistocene (ice age) epoch.

In addition to seismic wave propagation, surface or near-surface fault rupture has recently become a subject of research on both sediments and infrastructure *(20)*. With the benefit of extensive coverage of both 2D and 3D seismic data in southeast Louisiana by the energy sector, the understanding of pre-Pleistocene geology of the Mississippi River Delta has often been scientifically verified by geoscientists within the energy sector. Because of the proprietary nature that hydrocarbon energy plays, however, many salient features of faults assessments that could potentially affect surface infrastructure are not being published or made readily available to engineers designing transportation infrastructure projects. An example of the robust nature of energy-sector seismic data used for geologic structural modeling is provided in Figure 21.

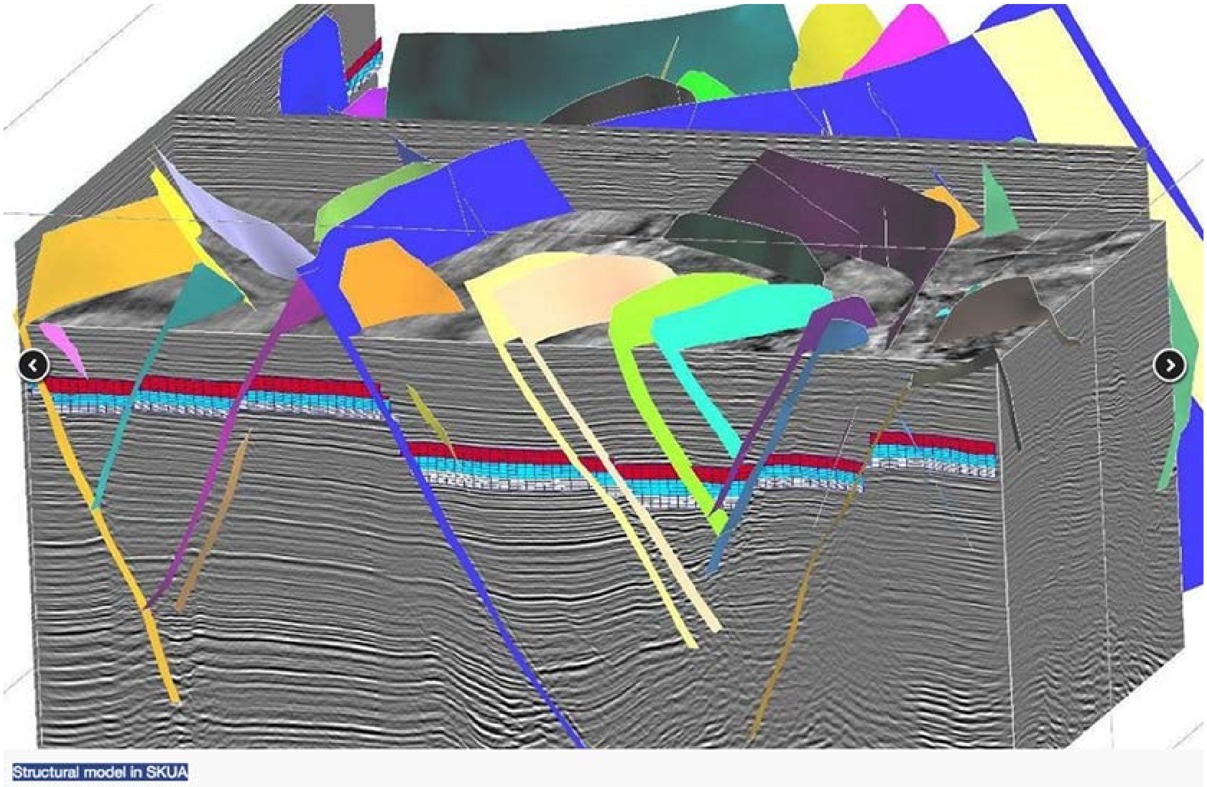


Figure 21. Image of a structural model in SKUA™ (courtesy of Emerson Exploration & Production Software).

5.4.1. Surface Deformation from Slip on a Buried Fault

This section relies upon the findings as reported of the potential surface-faulting hazard presented by tectonic surface deformation in the absence of discrete faulting. It is difficult to assess, because past rupture on the causative fault did not extend to the ground surface. It is unknown whether future rupture on the fault will continue to deform the ground surface, and whether structures built in surface deformation zones consisted of engineering-design techniques (such as reinforced slab-on- grade foundations and flexible utility lines and hookups).

Quantifying the future effects of surface faulting at a site within a surface deformation zone may not be possible even after a careful investigation, because tectonic surface deformation may expand over time, or future rupture on the causative fault may eventually extend to the ground surface. Therefore, the USGS does not make a standard recommendation for mitigating tectonic surface deformation in the absence of discrete faulting, but rather recommends that the engineering geologist responsible for the surface-faulting investigation make and justify an appropriate mitigation recommendation. Whether that recommendation is to set back from a narrow deformation zone or to implement engineering-design mitigation methods will depend on individual site conditions and project considerations. Barrell *(21)* provides an example from New Zealand of the classification and proposed mitigation of tectonic surface deformation in the absence of surface faulting. The authors refer readers to *California Geological Survey Special Report 42* for relevant guidelines, recommendations, and detailed information *(22)*.

5.5. Fault Mitigation

Effective site characterizations are an essential element of undocumented fault infrastructure mitigation. A recent peer-reviewed publication by Avar and Hudyma *(20)* provides a useful overview of current research on fault mitigation.

In common practice, it is usual to check for seismic activity when designing a structure. When the published seismicity maps and tables prescribed by code are checked in southeast Louisiana, the ground motion is not high enough to warrant special seismic design for structures. Seismic design for accelerated ground as typified during earthquakes, however, is likely not a reliable indicator of future land deformation in Louisiana.

Avoidance of faults is the obvious solution, if possible. However, in situations where that is not possible, remedial actions can include soil inclusions such as steel dowels or nails, which cross moving planes adding a structural member that takes the lateral load caused by slow ground motion. Close spacing of structural elements can inhibit soil flow between the elements in such a way that a bridging effect is realized. Soil doweling, or nails may not be able to completely arrest creep but could reduce the creep rate by one or more orders of magnitude. Ground improvement that introduces binders into the soil, so as to strengthen it, can also slow movement while remaining ductile; while strengthening soil by an order of magnitude and still allowing movement and deformation without sudden movements caused by more brittle solutions.

Introduction of wick drains in combination with preloads can remove future settlements prior to construction. Geosynthetics such as geotextiles, geofabrics, and geogrids can help distribute loads so as to limit soil squeeze beneath them and improve bearing capacity. Soils can be pile founded and designed for additional loads to account for faulting.

Objectional soils can be removed via de-mucking and replaced with lightweight fill (such as expanded clay) so as not to induce settlement. Structural Styrofoam is another option for areas where solvents are or not expected to be present.

5.6. Fault Rehabilitation

For existing structures found to be in areas with faults, thorough periodic monitoring should be conducted at reasonable intervals to look for fault-induced damages. Rehabilitation for structures could include underpinning with deeper stouter piles, which can receive previously undersigned loads from ground movement. A series of pin piles surrounding the structure could inhibit damage from ground motion by confining lateral movement. The same approach could be realized via ground improvement, such as deep mixing or jet grouting. Other possible techniques include grouting and mudjacking.

6. CONCLUSIONS

6.1. Overview

The state of Louisiana has a significant amount of subsurface data that has been under-utilized for near-surface engineering applications outside of the energy sector, including transportation-related infrastructure projects. This study has organized and synthesized such fault mapping data, utilizing existing 3D seismic surveys, 2D seismic data, and industry datasets available to the research team. The research team has compiled these resources in an Arc-GIS-based system, for LTRC and LADOTD personnel, for simple retrieval to aid and support future infrastructure projects; the database will act as a resource to identify the importance of faulting in any particular project area during the planning stages of such project.

6.2. Analysis of Collected Field Data

The Baton Rouge Fault System is a documented fault system within southern Louisiana that has been active through the Cenozoic, as indicated by offsets in stratigraphic units that are as much as 10 million years old. Cracked foundations of structures, surface scarps, and deformed roads that sit on or cross the fault system in the area around Baton Rouge and Mandeville are anecdotal proof that fault motion has been recent. The Highway 11 Bridge that crosses Lake Pontchartrain similarly shows deformation proximal to segments of the larger Baton Rouge Fault System. The long-lived, episodic motion along the fault system and evidence of movement within recent historic times suggests that fault slip will continue into the future, suggesting that transportation infrastructure within the study area will continue to be subjected to deformation.

Deep, energy-sector, seismic data for Lakes Pontchartrain and Borgne indicate that there is, at depth, an eastward extension of the Baton Rouge Fault System. Less certain is whether these faults continue upward to intersect the modern Lake bottoms and if and how exactly they connect below the Lake Pontchartrain I-10 Bridge or the East New Orleans Land Bridge and affect Highway 90. The along strike alignment of major faults in Lakes Pontchartrain and Borgne suggest that the clearly identified fault systems of both Lakes do have some amount of connection and land loss fragmentation patterns and scarps along the East New Orleans Land Bridge, which be indicative of fault control through the generation of subsidence created by slip along the faults.

7. RECOMMENDATIONS

In order to fully and accurately determine whether deep-seated faults could impact modern bridge and roadway infrastructure, a detailed assessment of near surface stratigraphy using methods such as high-resolution seismic surveying is recommended. It is also recommended that rates and timing of motion be constrained by age-dating of key stratigraphic marker horizons. The effort demonstrated in this report indicates that a comprehensive approach using a variety of available geophysical and direct sampling datasets could provide detailed insight into the location, magnitude, timing, and rates of fault slip in areas of important transportation infrastructure. Such data could also be used in conjunction with available deep seismic imaging techniques utilized by the energy-sector.

The research team recommends that a model be developed, through use of a demonstrative project, that includes licensing and utilizing of energy industry 2D and 3D seismic data during planning for the LA 1 Bridge expansion between Golden Meadow and Leeville, LA. Shallow, high-resolution, land and marine seismic reflection is recommended. This study will generate seismic images of the subsurface with the specific objective of better determining character of the Golden Meadow and Leeville fault complexes, and what effect, if any, these faults have on subsidence within Holocene units. Rates of vertical subsidence will be estimated using subsurface geologic mapping methods and age-dating. Subsurface mapping skills used routinely by experts in the oil and gas geoscience community will be applied, and it is anticipated that the methods used in this study can form the framework of a new work flow to include geologic fault mapping in early development stages of LADOTD projects.

If present but unaccounted for near LADOTD structures, active faulting could contribute to unexpected outcomes or even project failure due to vertical or lateral movement resulting from movement that seismic mapping could have assisted in predicting. A better understanding of fault-related subsidence could also ensure the optimal use of limited sediment resources. Accurate surface fault mapping in southern Louisiana could be a decision-driver for long-term planning and action.

Experience gained during this project can be used to assemble a technically proficient project team consisting of geoscience and engineering practitioners. The objective of the demonstrative project would be further development of a guidance document to assess potential effects of geologic faults on future state-wide transportation, flood control, and coastal restoration projects. It is suggested that this project solicit guidance from geoscience and engineering researchers and stakeholders.

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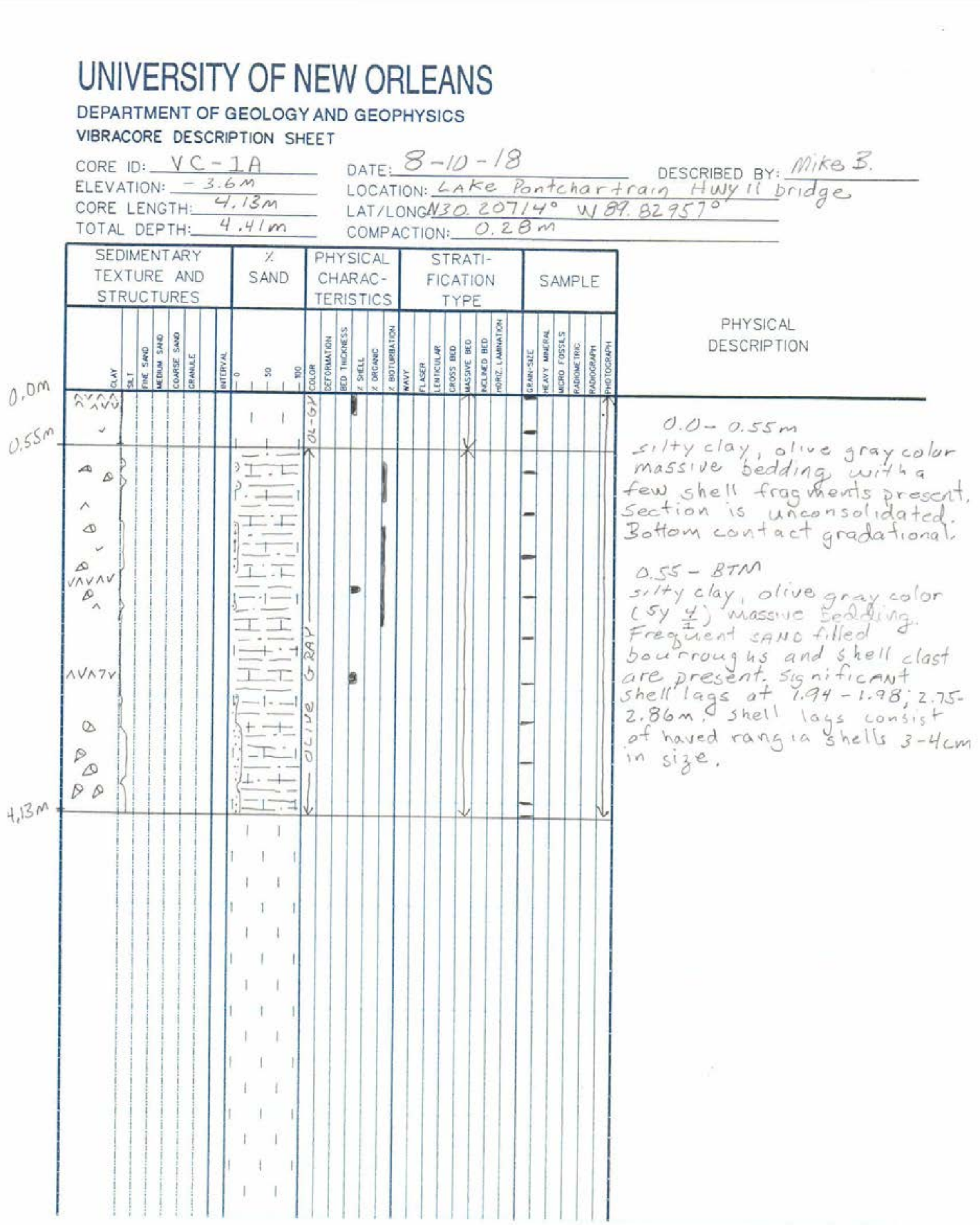
APPENDIX A: VIBRACORE DESCRIPTION SHEETS



UNIVERSITY OF NEW ORLEANS
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
VIBRACORE DESCRIPTION SHEET

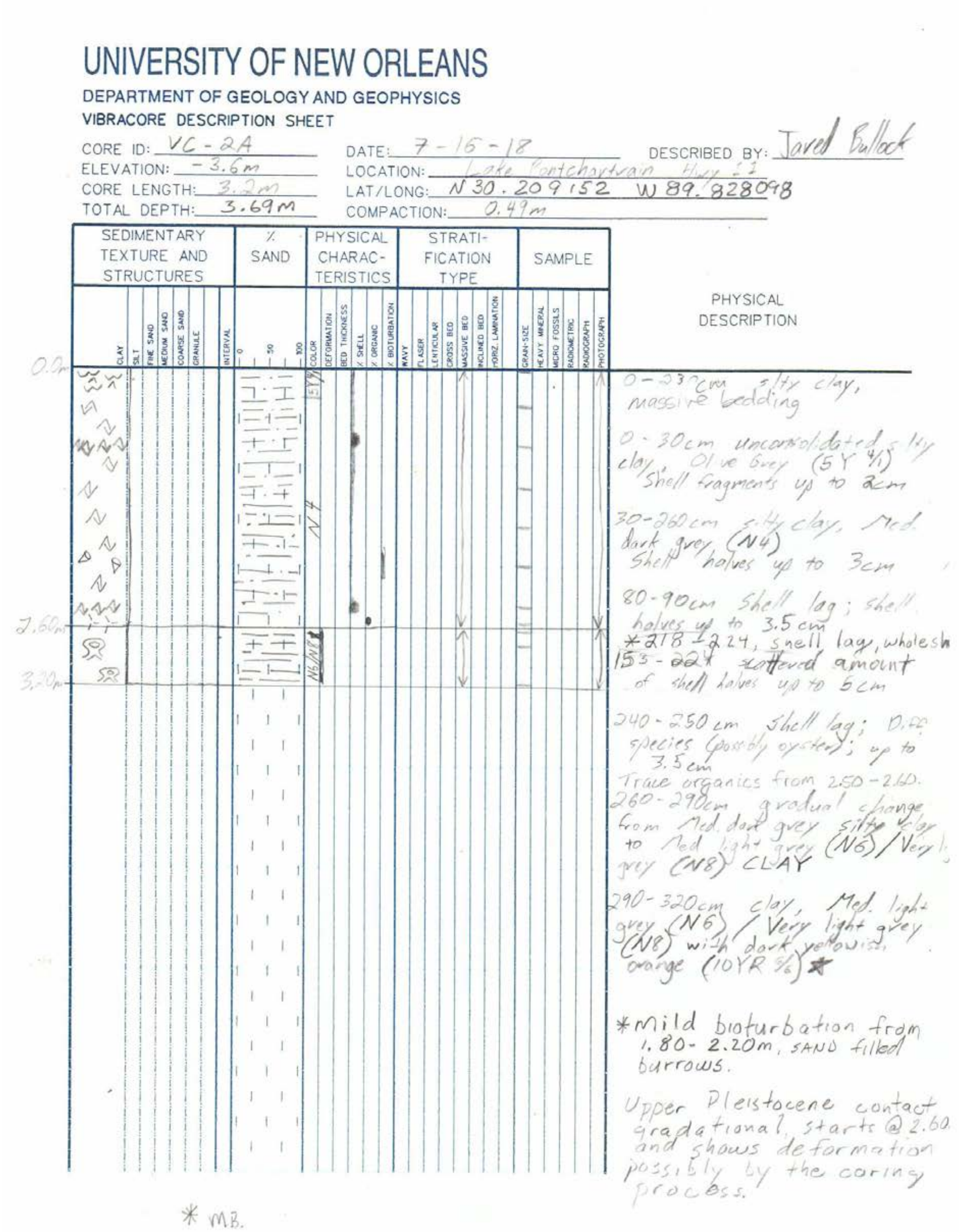
CORE ID: VC-1A
ELEVATION: -3.6m
CORE LENGTH: 4.13m
TOTAL DEPTH: 4.41m
DATE: 8-10-18
LOCATION: Lake Pontchartrain Hwy 11 bridge
LAT/LONG N30.20714° W 89.82957°
COMPACTION: 0.28m
DESCRIBED BY: Mike B.

PHYSICAL DESCRIPTION

0.0 - 0.55m
silty clay, olive gray color massive bedding with a few shell fragments present. Section is unconsolidated. Bottom contact gradational.

0.55 - BTM
silty clay, olive gray color (5y 4/1) massive bedding. Frequent SAND filled bourroughs and shell clast are present. Significant shell lags at 1.94 - 1.98; 2.75-2.86m. shell lags consist of haved rangia shells 3-4cm in size.

Figure A-1. Vibracore description sheet for VC-1A.



UNIVERSITY OF NEW ORLEANS

DEPARTMENT OF GEOLOGY AND GEOPHYSICS

VIBRACORE DESCRIPTION SHEET

CORE ID: VC-2A
ELEVATION: -3.6m
CORE LENGTH: 3.2m
TOTAL DEPTH: 3.69m

DATE: 7-16-18
LOCATION: Lake Pontchartrain Hwy 11
LAT/LONG: N 30.209152 W 89.828098
COMPACTION: 0.49m

DESCRIBED BY: Jared Bullock

PHYSICAL DESCRIPTION

0-23cm silty clay, massive bedding

0-30cm unconsolidated silty clay, Olive Grey (5Y 4/1) Shell fragments up to 2cm

30-260cm silty clay, Med. dark grey (N4) Shell halves up to 3cm

80-90cm Shell lag; shell halves up to 3.5cm
*218-224, shell lag, whole sh
153-224 scattered amount of shell halves up to 5cm

240-250cm Shell lag; Diff species (possibly oyster); up to 3.5cm
Trace organics from 250-260.
260-290cm gradual change from Med. dark grey silty clay to Med light grey (N6)/Very light grey (N8) CLAY

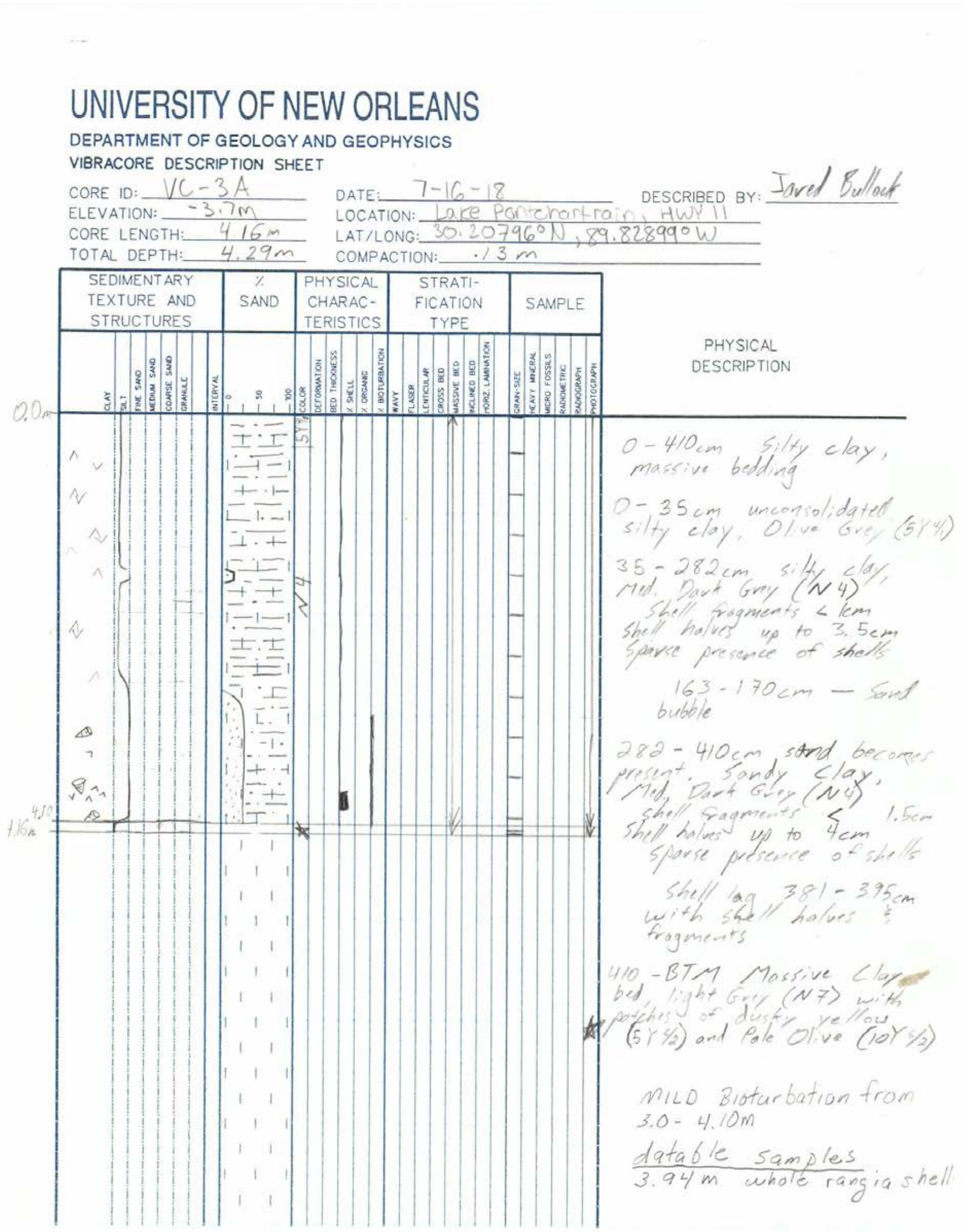
290-320cm clay, Med. light grey (N6) / Very light grey (N8) with dark yellowish orange (10YR 5/6) ★

*mild bioturbation from 1.80-2.20m, SAND filled burrows.

Upper Pleistocene contact gradational, starts @ 2.60 and shows deformation possibly by the coring process.

* MB.

Figure A-2. Vibracore description sheet for VC-2A.



UNIVERSITY OF NEW ORLEANS

DEPARTMENT OF GEOLOGY AND GEOPHYSICS

VIBRACORE DESCRIPTION SHEET

CORE ID: VC-3A
ELEVATION: -3.7m
CORE LENGTH: 4.16m
TOTAL DEPTH: 4.29m
DATE: 7-16-18
LOCATION: Lake Pontchartrain, HWY 11
LAT/LONG: 30.20796° N, 89.828990° W
COMPACTION: .13 m
DESCRIBED BY: Jared Bullock

PHYSICAL DESCRIPTION

0 - 410cm Silty clay, massive bedding

0 - 35cm unconsolidated silty clay. Olive Grey (5Y4/1)

35 - 282cm silty clay, Med. Dark Grey (N4)
Shell fragments < 1cm
Shell halves up to 3.5cm
Sparse presence of shells

163 - 170cm — Sand bubble

282 - 410cm ~~stand~~ sand becomes present. Sandy Clay, Med. Dark Grey (N4)
Shell fragments ≤ 1.5cm
Shell halves up to 4cm
Sparse presence of shells

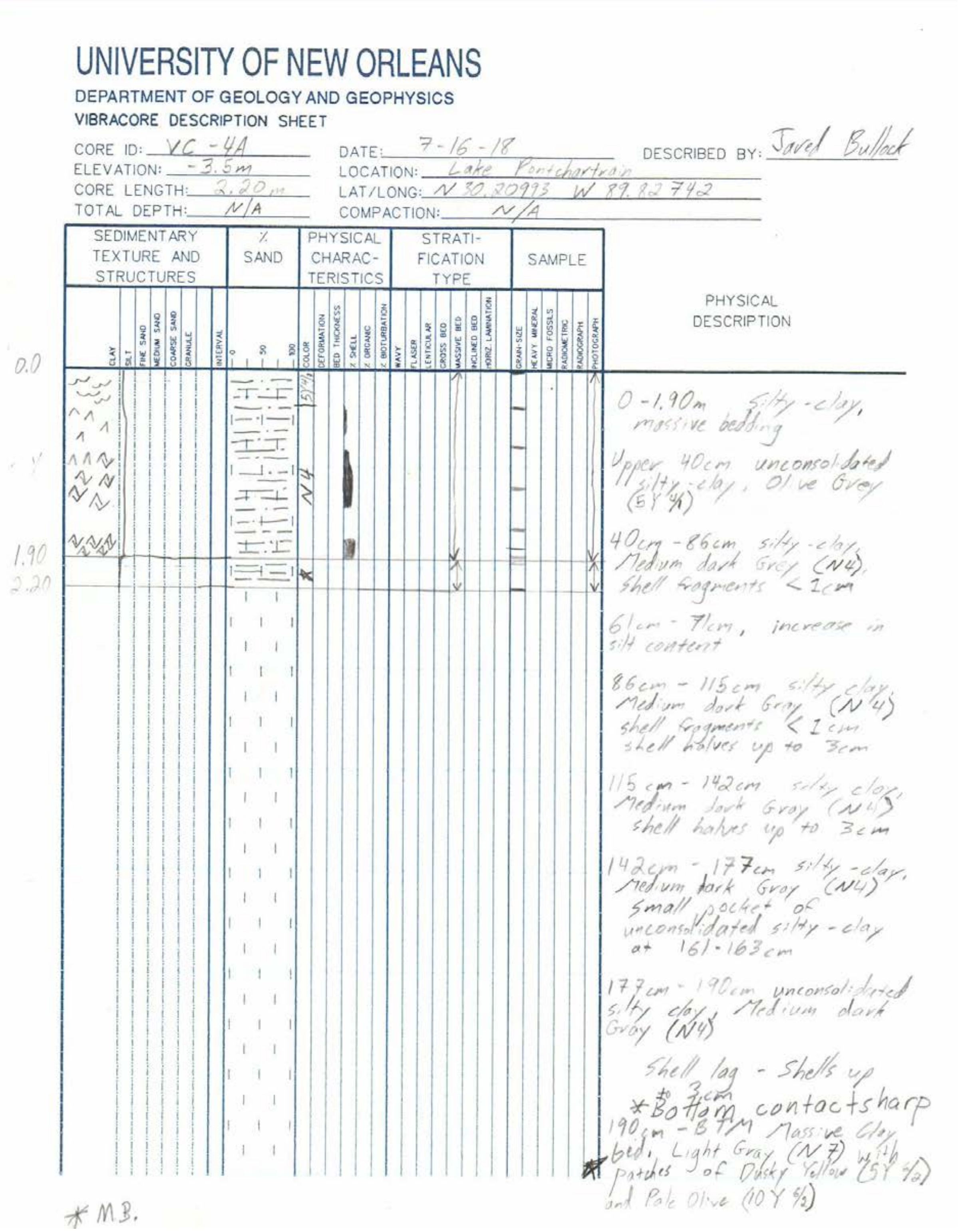
Shell lag 381 - 395cm with shell halves & fragments

410 - BTM Massive Clay bed, light Grey (N7) with patches of dusky yellow (5Y 6/2) and Pale Olive (10Y 6/2)

MILD Bioturbation from 3.0 - 4.10m

datable samples
3.94m whole rangia shell

Figure A-3. Vibracore description sheet for VC-3A.



UNIVERSITY OF NEW ORLEANS

DEPARTMENT OF GEOLOGY AND GEOPHYSICS

VIBRACORE DESCRIPTION SHEET

CORE ID: VC - 4A
ELEVATION: - 3.5m
CORE LENGTH: 2.20m
TOTAL DEPTH: N/A
DATE: 7 - 16 - 18
LOCATION: Lake Pontchartrain
LAT/LONG: N 30.20993 W 89.82742
COMPACTION: N/A
DESCRIBED BY: Jared Bullock

PHYSICAL DESCRIPTION

0 - 1.90m silty - clay, massive bedding

Upper 40cm unconsolidated silty - clay, Olive Grey (5Y 4/1)

40cm - 86cm silty - clay, Medium dark Grey (N4), shell fragments < 1cm

61cm - 71cm, increase in silt content

86cm - 115cm silty clay, Medium dark Gray (N 4) shell fragments < 1cm shell halves up to 3cm

115 cm - 142cm silty clay, Medium dark Gray (N4) shell halves up to 3cm

142cm - 177cm silty - clay, Medium dark Gray (N4) small pocket of unconsolidated silty - clay at 161 - 163cm

177cm - 190cm unconsolidated silty clay, Medium dark Gray (N4)

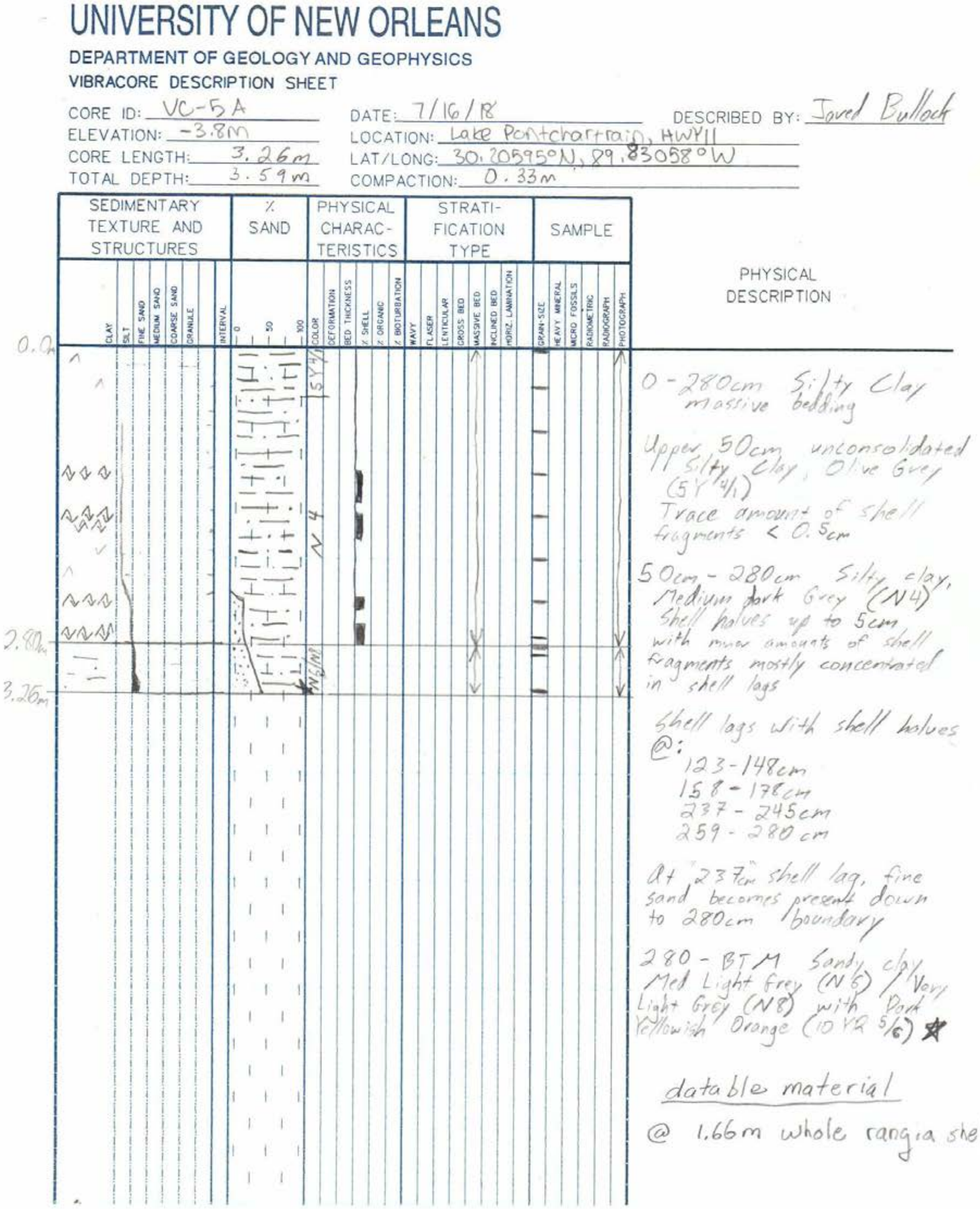
Shell lag - Shells up to 3cm

*Bottom contact sharp

190cm - BTM Massive Clay bed, Light Gray (N 7) with patches of Dusky Yellow (5Y 6/2) and Pale Olive (10Y 6/2)

* M.B.

Figure A-4. Vibracore description sheet for VC-4A.



UNIVERSITY OF NEW ORLEANS
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VIBRACORE DESCRIPTION SHEET

CORE ID: VC-5A
ELEVATION: -3.8m
CORE LENGTH: 3.26m
TOTAL DEPTH: 3.59m
DATE: 7/16/18
LOCATION: Lake Pontchartrain, HWY11
LAT/LONG: 30.20595°N, 89.83058°W
COMPACTION: 0.33m
DESCRIBED BY: Javed Bullock

PHYSICAL DESCRIPTION

0-280cm Silty Clay
massive bedding

Upper 50cm unconsolidated
" Silty Clay, Olive Grey
(5Y 4/1)
Trace amount of shell
fragments < 0.5cm

50cm - 280cm Silty clay,
Medium Dark Grey (N4)
Shell halves up to 5cm
with minor amounts of shell
fragments mostly concentrated
in shell lags

Shell lags with shell halves
@:
123-148cm
158-178cm
237-245cm
259-280cm

At "237cm" shell lag, fine
sand becomes present down
to 280cm boundary

280-BTM Sandy clay
Med Light Grey (N6) / Very
Light Grey (N8) with Dark
Yellowish Orange (10YR 5/6) ★

datable material

@ 1.66m whole rangia shell

Figure A-5. Vibracore description sheet for VC-5A.