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Using Fault Kinematics to Evaluate the Relationship Between Cenozoic Fault Activity, Sedimentation Rates and Salt Movement in the Gulf of Mexico - A Comparison Between Southwest Louisiana and Southeast Louisiana

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USING FAULT KINEMATICS TO EVALUATE THE RELATIONSHIP BETWEEN CENOZOIC FAULT ACTIVITY, SEDIMENTATION RATES AND SALT MOVEMENT IN THE GULF OF MEXICO- A COMPARISON BETWEEN SOUTHWEST LOUISIANA AND SOUTHEAST LOUISIANA

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfilment of the requirements for the degree of Master of Science

in

The Department of Geology and Geophysics

by

Abah Philip Omale
B.Tech., Federal University of Technology, 2009
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Lastly, I thank all my friends for their support, scientific and otherwise.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ ii

ABSTRACT ......................................................................................................................... iv

CHAPTER 1. INTRODUCTION.............................................................................................. 1
  1.1 Problem of this study ................................................................................................. 1
  1.2 Fault activity in the Gulf of Mexico ......................................................................... 2
  1.3 Models for fault reactivation in the Gulf of Mexico ................................................ 3
  1.4 History of Cenozoic sediment deposition in the Gulf of Mexico ........................... 6

CHAPTER 2. DATA AND METHODS ................................................................................ 12
  2.1 Kinematic analysis of faults in south Louisiana ...................................................... 12

CHAPTER 3. RESULTS ........................................................................................................ 18
  3.1 Fault kinematics in the Cenozoic of southwest Louisiana ........................................ 18
  3.2 Fault kinematics in the Cenozoic of southeast Louisiana ......................................... 39

CHAPTER 4. DISCUSSION .................................................................................................. 57

CHAPTER 5. CONCLUSIONS .............................................................................................. 62

REFERENCES ..................................................................................................................... 64

APPENDICES .................................................................................................................... 67
  A Cumulative throw and depth for cross sections A-A’ – F-F’ (southwest Louisiana) ... 67
  B Slip rates for cross sections A-A’ – F-F’ (southwest Louisiana) ................................ 74
  C Cumulative throw and depth for cross sections M-M’ – Q-Q’ (southeast Louisiana)... 78
  D Slip rates for cross sections M-M’ – Q-Q’ (southeast Louisiana) ............................. 83
  E Well logs used in this study ...................................................................................... 86

VITA ....................................................................................................................................... 91
ABSTRACT

Fault initiation and reactivation across south Louisiana during the Cenozoic was driven by either clastic sediment progradation mobilizing underlying salt or by sediment progradation inducing tensional bending stresses during lithospheric flexure. Climate and tectonics within the North American continent during the Cenozoic created differences in the source location, amount of sediments transported, as well as the spatial and temporal distribution of sediments transported into the Gulf of Mexico. This study analyzes 140 fault intercepts along 11 regional cross sections containing well log data in south Louisiana. Cumulative throw, incremental throw, and fault slip rates indicate fault activity punctuated by periods of fault inactivity in southwest and southeast Louisiana. Results show a correlation between the timing of fault reactivation and the location of sediment depositional centers in the Cenozoic. In southwest Louisiana and southeast Louisiana faulting increases significantly in the Oligocene-Early Miocene and Early Miocene respectively during the emergence of new depositional centers in these areas. The pattern of fault activity correlates with the pattern of sediment deposition by showing a similar shift in major activity from southwest to southeast Louisiana through time. The Eocene period marks a time when most faults in southwest and southeast Louisiana were inactive, possibly because the sediment depositional center existed in central Louisiana. These data show that the timing of fault activity correlates with the timing of sediment loading and salt movement as opposed to lithospheric flexure in the Cenozoic.
CHAPTER 1. INTRODUCTION

1.1 Problem of this study

Fault initiation and reactivation have been documented in the south Louisiana portion of the Gulf of Mexico in the Cenozoic (Thorsen, 1963; Hanor, 1982; Lopez, 1990; Heinrich, 2000; Al Dhamen, 2014). The cause of fault activity has been attributed to either salt movement or lithospheric flexure caused by the weight of prograding Cenozoic clastic sediments because the timing of fault reactivation correlates with the timing of sediment deposition, salt movement and predicted lithospheric flexure (Nunn, 1985; Diegel et al, 1995; Peel et al., 1995; McBride, 1998).

The Cenozoic depositional history of the Gulf of Mexico implies a difference in the sediment volumes, fluvial deltaic axes, location and timing of sediment deposition between southwest and southeast Louisiana as the result of the different tectonic activities and climates affecting the sediment source areas and drainages within the North American continent in the Cenozoic. Tectonics and climates influenced the source to sink relationship of the Gulf Coast by influencing the locations of the sediment source, the locations of drainages and also the amount of runoff available for transportation of sediments (Galloway, 2000; Combellas-Biggot and Galloway, 2006; Galloway, 2011). The resulting difference in the timing and amount of sediment deposition between southwest and southeast Louisiana also implies a difference in the timing and amount of fault reactivation via salt displacement or lithospheric flexure due to sediment loading.

The aim of this study is to understand the major driving mechanism for fault reactivation in south Louisiana. In addition, this work will determine the amount and timing of fault reactivation and also provide a better understanding of the spatial distribution of fault reactivation in southwest Louisiana and southeast Louisiana. Furthermore, this study also compares the faulting history between southwest and southeast Louisiana to provide a better
understanding of the interaction among Cenozoic fault activity, sediment loading, possibly salt movement or lithospheric flexure.

1.2 Fault activity in the Gulf of Mexico

By the Cenozoic Era, the geologic evolution of the Gulf Coast in terms of structure and stratigraphy had been defined by interactions among salt tectonics, sediment loading and growth faulting (Fisk, 1944; Ocamb, 1961; Murray, 1961; Hardin and Hardin, 1961, Thorsen, 1963; Worrall and Snelson, 1989; Diegel et al., 1995; Peel et al., 1995; Schuster, 1995; Vendeville, 2005). Growth faulting is interpreted to be the result of syn-depositional extension associated with sediment loading driving vertical and lateral salt movement. With progressive sediment deposition and consequent salt withdrawal, accommodation is created allowing for extension in the form of growth faulting (Diegel et al., 1995; Peel et al., 1995; McBride, 1998).

Growth faults along the coastal plain of the Gulf of Mexico have been determined to be part of a regional system of listric normal faults (Fisk, 1944; Murray, 1961; Nunn, 1985) (Figure 1). The origin of these growth faults is related to down to basin fault movement contemporaneous with deposition, and in south Louisiana faulting is younger basinward in conformity with the regional sedimentation pattern (Hardin and Hardin, 1961; Murray, 1961; Nunn, 1985). The fault systems in the Gulf of Mexico have been classified on the basis of their time of activity as Jurassic-Cretaceous and Tertiary to Holocene (Nunn, 1985).

Two distinct periods of fault reactivation have been defined for faults from southwest Louisiana- a period of initial movement contemporaneous with deposition in the upper Eocene followed by a period of inactivity in the Oligocene-Late Pliocene and a second period of movement in the Late Pliocene or Early Pleistocene (Heinrich, 2000). A study of the Tepetate
fault zone (Hanor, 1982) also reveals two distinct periods of fault activity, the first period in the Eocene-Oligocene time followed by a period of inactivity through to a Pleistocene reactivation.

1.3 Models for fault reactivation in the Gulf of Mexico

Two major models exist to explain the cause of faulting in the Gulf of Mexico. The first model is related to salt tectonics (Worrall and Snelson, 1989; Diegel et al., 1995; Peel et al.,
In this model salt flows through differential loading and gravity spreading. Differential loading by sediments causes salt to flow in response to the difference in load caused by a seaward thinning wedge of sediment. As a result the salt moves laterally and vertically inducing normal faulting in overlying sediments (Figure 2). During gravity spreading, the unstable slope of a sediment wedge causes the sediment to spread over the underlying weak salt layer (Vendeville, 2005). Spreading results in a proximal extensional region where the sediment overburden deforms through normal faulting, a middle translation region where the sediment overburden is translated seaward, and a distal region where the sediment overburden deforms by contraction in the form of folding or thrusting (Vendeville, 2005) (Figure 2C). Within these models, the regions of extension and contraction are translated seaward during clastic sediment progradation such that a zone of contraction previously overlain by the distal and less dense part of the sedimentary wedge can become an extensional zone if loaded by thicker and denser part of the sedimentary wedge (Vendeville, 2005) (Figure 3).

The Mesozoic and Cenozoic of the Gulf Coast are characterized by sediment gravity-driven tectonics associated with salt displacement where differential loading of sediments results in salt withdrawal and diapirism and also by seaward gravity gliding or spreading which results in updip extension defined by growth faulting and downdip contraction defined by shortening of salt canopies or development of fold and thrust belts salt (Peel et al, 1995).

Diegel et al. (1995) described a salt dome minibasin province and a salt based detachment province of Cenozoic age where large regional and counter-regional faults exist due to extension resulting from salt withdrawal induced by clastic sediment progradation over underlying salt in the Cenozoic. This salt based detachment province comprising growth faults is
also interpreted to be present in southeast Louisiana and is associated with the formation of the Terrebonne trough by evacuation of allochtonous salt in response to sediment loading in the Oligocene/Miocene depocenter (McBride, 1998).

Figure 2: Model showing salt response to differential loading of sediment (B) and the resulting proximal extension of the overburden and distal contraction (C) (Vendeville, 2005). Salt is the black layer and sediments are the grey layers above the salt.

The second model describes fault initiation and reactivation as the result of tensional bending stresses acting on the lithosphere due to the loading by sediments (Nunn, 1985). The model suggests that the south Louisiana portion of the Gulf of Mexico is currently in a tensional state of stress at the periphery of the Pleistocene depositional center. Rapid sedimentation rates (1.2-1.8mm/yr) allow for these stresses to accumulate and reactivate pre-existing growth faults (Nunn, 1985).
The two models ‘salt tectonics’ and ‘flexure’ both present sediment loading as the driving force for fault movement and predict that the timing and location of sedimentation should correlate with the timing and location of fault activity.

1.4 History of Cenozoic sediment deposition in the Gulf of Mexico

Different sources of sediment, fluvial/deltaic axes and depositional centers affected the sedimentation in the Gulf Coast at different times in the Cenozoic (Galloway et al., 2011). The
Cenozoic depositional pattern of the Gulf Coast shows progradation of the shelf margin basinward with time (Winker, 1982). Eight fluvial/deltaic axes supplied sediments to the Northern Gulf of Mexico throughout the Cenozoic (Galloway et al., 2011) (Figure 4). Three of these principal fluvial/deltaic axes affected south Louisiana, namely; the Red River, the ancestral Mississippi River and the ancestral Tennessee River (Galloway, 2000; Combellas-Biggot and Galloway, 2006; Galloway et al., 2011).

The time when each of these fluvial/deltaic depositional centers was most active in the Cenozoic reflects a shift in the axes of deposition from west to east and back to the west (Woodbury et al., 1973; Galloway, 2000) (Figure 5). The shifting depositional center timing and location are the result of tectonic and climatic (tectono-climatic) changes occurring in the North American continent. These climatic and tectonic forces are associated with the Late Laramide orogeny, Basin and Range extension, and regional crustal heating, volcanism, uplift, erosional unroofing of the Appalachians mountains and epeirogenic uplift of the Rocky mountains at different times in the Cenozoic. These tectono-climatic changes converted topographic lows to highs and previous uplands to low lands in addition to influencing the amount of runoff available to transport sediment. Consequently, these forces control the amount and location of sediments brought into southwest and southeast Louisiana by controlling the location of sources, amount of runoff available to transport sediment, location of drainages, and amount of sediment transported, making the amount of Cenozoic sediment deposition differ in time and space (Galloway, 2000; Combellas-Biggot and Galloway, 2006; Galloway et al., 2011).

In the Paleocene, the rate of sediment influx into the Gulf was initially low but increased abruptly in the Late Paleocene marked by deposition of the Lower Wilcox formation. The initial low sedimentation in the Paleocene was due to the Laramide orogeny that uplifted several
uplands and allowed for the infilling of other basins within the continent e.g. Denver, Raton and San Juan basins (Galloway et al., 2011). The later increase in sedimentation, which records one of the highest sedimentation rates in the Gulf coast in the Cenozoic, was due to the migration of a drainage divide between the Gulf basins and interior basins, limited fluvial accumulation and bypass of interior basins, and the integration of the western interior forming two large rivers-Colorado and Mississippi rivers that drained into the Gulf coast (Galloway et al., 2011) (Figure 4).

Figure 4; Eight principal fluvial/deltaic axes of sediment deposition in the Cenozoic. Positions of this depositional axes shifted spatially and some were inactive at some time in the Cenozoic. RB=Rio Bravo, RG=Rio Grande, G=Guadalupe, C=Colorado, HB= Houston Bravos, R=Red, M=Mississippi, T= Tennessee (Galloway et al., 2011).
Figure 5: Cenozoic onshore locations of sediment depositional centers in south Louisiana. Three main rivers/fluvial axes were active. The width of the ellipses represents approximate longitudinal extent while the height of the ellipses represents the approximate latitudinal extent of the major depositional area. Note however, that the latitudinal extent of the major depositional area is approximately the same for the Middle Miocene and Late Miocene. Modified from AlDhamen 2014; Galloway et al., 2011; Combellas-Biggot & Galloway, 2006; Galloway, 2000; Woodbury et al., 1973.

In the Eocene at the terminal phase of the Laramide orogeny, deposition of the Upper Wilcox occurred in the Early Eocene. During this time, the fluvial axes and center of deposition shifted basinward in response to high sedimentation rates. A new fluvial/deltaic axis called the Rio Grande fluvial axis evolved, the previously existing Colorado axes shifted southward and the Mississippi axes was split into the Houston Brazos axis and Mississippi axis (Galloway et al., 2011) (Figure 4). The Middle Eocene was a time of relatively lower sedimentation rates. The Mississippi axis was initially a broad marine bay with no fluvial deposition at this time but was reactivated. Sediment supply to the Gulf was derived mainly from the local uplands in New
Mexico and the Laramide uplands of Northern Mexico (Galloway et al., 2011). The climate in the Gulf Coast was subtropical at this time. The Late Eocene tectonics was marked by thermally driven uplift and volcanism which initially contributed significant sediment input to the Gulf Coast but later lowered the sediment input as a result of volcanic fields affecting drainages to the Gulf Coast. Overall, the Eocene was a time of relatively lower sedimentation rates and coastal retreat (Hardin and Hardin, 1961; Galloway, 2000; Galloway et al., 2011).

Regional thermally-driven volcanic associated uplift within the North American continent in the Oligocene allowed for the persistence of four fluvial depositional axes; Rio Grande, Rio Bravos, Houston Brazos and Mississippi drainages in the Gulf for a 10my period by supplying sediment to the Gulf coast (Galloway et al., 2011) (Figure 4). However, in the later stages of the Oligocene, the rate of sediment supply was affected by the development of sub-arid climate across the western interior which limited the availability of significant runoff resulting in moderate sedimentation rates (Galloway et al., 2011). In addition, in the very late stages of the Oligocene, the Red river emerged as a fluvial and depositional axes, forming a depositional center in southwest Louisiana (Figures 4 and 5).

The Miocene began with a time of initially low sedimentation rates. However, sedimentation rates increased especially in the later part of the lower Early Miocene. Very significant increase in the sedimentation occurred during the Middle Miocene due to the possibly climate-influenced rejuvenation of the Appalachian Mountains in the eastern part of America. This rejuvenation caused the evolution of a new drainage system- the ancestral Tennessee River drainage system and the emergence of a new depositional center (Galloway, 2000; Combellas-Biggot and Galloway, 2006, Galloway, 2011) (Figures 4 and 5).
The Middle Miocene represents a time of eastward shift in the Gulf coast deposition as a result of arid climate and changing tectonic activities in the Western interior. In the Late Miocene, the climate and tectonics of the continent remained the same as during the Middle Miocene, however sedimentation rates decreased as a result of waning of the unroofing and uplift of the Appalachian mountains, and because the Rocky Mountains and Rio Grande rift obstructed Gulf coast sediments from the Western uplands (Galloway et al., 2011).

In the Pliocene, the uplands, drainage basins and depositional style evolved to the modern day system (Galloway et al., 2011). Climate change facilitated increased runoff, and seasonal flooding allowed for stream incision across the Colorado Plateau and the erosion of alluvial aprons from the Rocky Mountains. Erosion and transportation of sediment may have also been aided by epeirogenic uplift of the Rocky Mountains (Galloway et al., 2011).
CHAPTER 2. DATA AND METHODS

2.1 Kinematic analysis of faults in south Louisiana.

Kinematic analysis of faults involves measuring the apparent cumulative stratigraphic throw across faults and making graphical plots of apparent cumulative stratigraphic throw-versus-depth in the hanging wall (T-Z) and calculated incremental throw-versus-time (\(\Delta T-t\)) (Mansfield and Cartwright, 1996; Cartwright et al., 1998; Castelltort et al., 2004) in order to study the fault motion history throughout the Cenozoic in southwest and southeast Louisiana. The apparent cumulative stratigraphic throw measured in this study is equivalent to the fault component vertical separation (Tearpock and Bischke, 2003).

Faults originally identified by Bebout and Gutierrez, 1982; 1983 and verified by this study are analyzed in well log data along 11 regional cross sections in order to define the structure and stratigraphy in the study area (Bebout and Gutierrez, 1982; 1983) (Figure 6, Appendix E). Six (6) of these regional cross sections are across the entire southwest Louisiana and the other 5 are across southeast Louisiana along strike and dip. These cross sections are structural cross sections and comprise 150 correlated and interpreted spontaneous potential and resistivity logs containing dated stratigraphic horizons with ages constrained by biostratigraphy from within the Cenozoic depositional centers in south Louisiana. Additional well logs were correlated in this study in order to verify the structure and stratigraphy defined in the regional cross sections (Appendix E). Well logs (Drilling Info Inc.) were displayed using Geographix software (LMKR, 2014). The stratigraphic intervals on the well logs defined by lithostratigraphy and biostratigraphy are the major formations in Louisiana (Bebout and Gutierrez, 1982; 1983) (Figure 7).
Figure 6: Regional cross sections used in this study. Cross sections are labelled A-A’-F-F’ for southwest Louisiana and M-M’-Q-Q’ for southeast Louisiana. Small triangles represent some of the wells used in the cross sections. Horizontal lines of all lengths represent faults identified (Bebout & Gutierrez, 1982; 1983; this study) in the cross sections between the wells, and black circles represent salt domes (modified from Bebout and Gutierrez, 1982; 1983).
The well logs used in this study do not sample depths shallower than 3000 ft. For this study, the 12 Cenozoic stratigraphic horizons are listed from the youngest to the oldest and the numerical age of each formation top is assumed to correlate with published chronostratigraphic ages for that formation (Hackley, 2012) (Figure 7).

Furthermore, this study also involves the analysis of 140 fault intercepts from within these regional cross sections (Figure 6). Eighty-six (86) of these faults are from southwest Louisiana and the other 54 from southeast Louisiana. To define periods of fault activity using the ΔT-t and T-Z plot methods, we apply the ‘fill to the top assumption’ where we assume that the sedimentation keeps up with subsidence and accommodation creation, leaving no persistent fault scarp after the deposition of sediments at any given time (Mansfield and Cartwright, 1996; Cartwright, 1996; Castelltort et al., 2004). In addition, there is also the assumption that no significant erosion occurs on the hanging wall or the footwall to affect the measured throw values.

With the ‘fill to the top assumption’, any throw experienced by a stratigraphic interval is defined as post-depositional and the difference in throw between two time periods can be calculated by subtracting the throw of all the younger intervals from the older interval. With this assumption also, any increase in throw (ΔT) with depth (Z) at any time (t) can be defined as a period of fault activity (Figure 8). Slopes in the T-Z plot are defined as periods of fault activity whereas periods of no slope represent periods of fault inactivity. If the ‘fill to the top assumption’ does not hold and there is the preservation of fault scarp, then a period of actual fault activity may be defined as a period of apparent fault inactivity as in the case of pelagic sedimentation depositing equal thickness on both the hanging wall and footwall during fault growth (Cartwright et al., 1996).
Also if the fault scarp is preserved, and there is the deposition of different sediment thicknesses on both hanging wall and footwall, a period of actual inactivity may be defined as a period of apparent fault activity whereas it only represents a filling of the previously generated fault topography. Differential erosion may also occur when a fault scarp is preserved and sediments from the footwall are eroded and transported onto the hanging wall. Reduction of the thickness in the footwall will lead to a reduction in the measured fault displacement values.

<table>
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Figure 7: Ages of formation and other sediment unit tops used in this study to correlate well logs in the regional cross sections A-A’-F-F’ and M-M’-Q-Q’ (Bebout and Gutierrez, 1982; 1983), (Hackley, 2012) (Figure 6).
Figure 8: Cumulative throw across a fault. Numbers 1 and 2 represent time during the deposition of units B-B’ and C-C’ respectively. At time (1) the cumulative throw across unit B-B’ = TB and at time (2) the cumulative throw across unit across unit C-C’ is TC. At this time (2) the cumulative throw across unit B-B’ is increased to TB (1) + TC where TB (1) is throw at time 1. Note that there is not preservation of fault scarp following the deposition of any unit.

Slip rates of horizon tops through time are calculated and compared with calculations of decompacted one-dimensional sedimentation rates calculated from measured sediment thicknesses in order to determine the relationship between changes in depositional location, sedimentation rates and changes in fault motion. The data are also presented as plots comparing slip rates and sedimentation rates between southwest and southeast Louisiana. The slip rates are calculated by dividing the throw at each time period by the numerical age for the same period.

The sediment decompaction is done in order to give estimates of the original thickness of sediment deposited by accounting for porosity loss during sediment burial. Sediment is decompacted using a decompaction software program, Flex-De-Comp™ (Kusznir et al., 1995) (Appendix F). In decompaction, grain size is important because shales compact more than
sandstones during burial (Allen and Allen, 2006). In this study, the decompaction is done by assuming a silt grain size for the whole section. Electric log patterns for the 11 cross sections show alternations of sand and clays within a particular formation with the wells showing nearly equal thickness of sand and clay. Consequently, although the use of silt sized particles for the decompaction may cause some errors, the errors are minimized by using an intermediate grain size and by also using the same grain size for all the sections. Sedimentation rates are obtained following decompaction by dividing the original thickness of sediments by the numerical duration of its corresponding formation. Finally, interpretations of a major driving mechanism are made from the results by checking for correlations with model predictions of salt movement or lithospheric flexure.
CHAPTER 3. RESULTS

3.1 Fault kinematics in the Cenozoic of southwest Louisiana

The kinematics of 86 faults from southwest Louisiana are presented herein. These faults are numbered in increasing order from north to south (Figure 6) (Tables 1-8, Figures 9-26, Appendices A and B). These faults record the fault slip history throughout the Cenozoic Era. The measured apparent cumulative stratigraphic throw for 72 faults show continuous fault activity from the Paleocene to the Pliocene as defined by increase in throw with depth (Appendix A, Figures 9-22). The measurements of cumulative throw-versus-depth also define periods of fault inactivity in 14 faults by showing no change in cumulative throw with depth (Appendix A, Figure 23-26). The measurements of the incremental throw-versus-time for the same faults also confirm the increment in throw of a single horizon through time (Tables 1-6, Figures 9-22). The results of incremental throw at each time for these 14 faults constrain the periods of inactivity to within the Eocene (Tables 1-6, Figure 23-26, Appendix A). The maximum throw in the faults is in the Early Miocene, however, the maximum incremental throw across a particular formation top tends to increase along most of the different faults in a basinward direction (Figure 5, Tables 1-6, Appendix A).

Calculated incremental throw and average slip rates show five-fold increase in the Late Oligocene- Early Miocene (Tables 1-8, Figures 27-32, Appendix B) and calculated average sedimentation rates show maximum in the Oligocene (Table 9). These maximum slip rates and sedimentation rates represent relatively high values for the Gulf Coast.
Table 1: Incremental throw for 15 faults along regional cross section A-A’. 1-15 represent faults from north to south (Figure 6)

**Incremental throw (ΔT) for cross section A-A' (m)**

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Table 2: Incremental throw for 11 faults along regional cross section B-B’. Numbers 1-11 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section B-B' (m)**

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Table 3: Incremental throw for 13 faults along regional cross section C-C’. Numbers 1-13 represent faults along the cross section from north to south.

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<tr>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
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<td>Middle Miocene</td>
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<td>Anahuac</td>
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<tr>
<td>Frio</td>
</tr>
<tr>
<td>Vicksburg/Jackson</td>
</tr>
<tr>
<td>Cockfield (Yegua)</td>
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<tr>
<td>Sparta</td>
</tr>
<tr>
<td>Wilcox</td>
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Table 4: Incremental throw for 14 faults along regional cross section D-D’. Numbers 1-14 represent faults along the cross section from north to south. (Figure 6)

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<td>Middle Miocene</td>
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<tr>
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<tr>
<td>Anahuac</td>
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<tr>
<td>Frio</td>
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<tr>
<td>Vicksburg/Jackson</td>
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<td>Cockfield(Yegua)</td>
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</tr>
<tr>
<td>Wilcox</td>
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Table 5: Incremental throw for 13 faults along regional cross section E-E’. Numbers 1-13 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section E-E' (m)**

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Table 6: Incremental throw for 20 faults along regional cross section F-F’. Numbers 1-20 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section F-F' (m)**

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<td>112.5</td>
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21
(Table 6 continued)

**Incremental throw ($\Delta T$) for cross section F-F' (m) continued**

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Figure 9: T-Z plot for fault 8 along regional cross section A-A’ (Table 1) showing cumulative throw of 188 m. Positive slopes indicate continuous fault reactivation.

Figure 10: $\Delta T$-t plot for the same fault in Figure 9 above showing increase in throw in the Eocene and Oligocene (48.6-25 Ma). Maximum increment of ~98 m in the Eocene.
Figure 11: T-Z plot for fault 7 along regional cross section B-B’ (Table 2) showing cumulative throw of 150 m. Positive slopes indicate continuous fault reactivation.

Figure 12: ∆T-t plot for the same fault in Figure 11 above showing increase in throw in the Eocene and Oligocene (48.6-25 Ma). Maximum increment of ~90 m in the Eocene.
Figure 13: T-Z plot for fault 12 along regional cross section C-C’ (Table 3) showing cumulative throw of 90 m. Positive slopes indicate continuous fault reactivation.

Figure 14: $\Delta T$-$t$ plot for the same fault in Figure 13 above showing increase in throw in the Oligocene and Miocene (25Ma-11.63 Ma). Maximum incremental throw of ~53 m in the Lower Miocene.
Figure 15: T-Z plot for fault 7 along regional cross section D-D’ (Table 4) showing cumulative throw of 150 m. Positive slopes indicate continuous fault reactivation.

Figure 16: ΔT-t plot for the same fault in Figure 15 above showing increase in throw in the Oligocene and Miocene (28.1-15.97 Ma). Maximum increment of ~75 m in the Oligocene (Frio).
Figure 17: T-Z plot for fault 10 along regional cross section E-E’ (Table 5) showing cumulative throw of 135 m. Positive slopes indicate continuous fault reactivation.

Figure 18: ΔT-t plot for the same fault in Figure 17 above showing increase in throw in the Oligocene and Miocene (25-11.63 Ma). Maximum increment of ~98 m in the Lower Miocene period.
Figure 19: T-Z plot for fault 5 along regional cross section F-F’ (Table 6) showing cumulative throw of 888 m. Positive slopes indicate continuous fault reactivation.

Figure 20: ΔT-t plot for the same fault in Figure 19 above showing increase in throw in the Eocene through Miocene (48.6-15.97 Ma). Maximum increment of ~390 m in the Eocene/Oligocene (Vicksburg/Jackson).
Figure 21: T-Z plot for fault 20 along regional cross section F-F’ (Table 6) showing cumulative throw of 105 m. Positive slopes indicate continuous fault reactivation.

Figure 22: ΔT-t plot for the same fault in Figure 21 above showing increase in throw in the Miocene (16 Ma) and Pliocene (2.6 Ma). Maximum increment of ~30 m in both Lower and Middle Miocene.
Figure 23: T-Z plot for fault 2 along regional cross section C-C’ (Appendix A) showing cumulative throw of ~82.5 m. Zero slope between central three interpolated points represents periods of fault inactivity.

Figure 24: ΔT-t plot for the same fault in Figure 23 above showing no increase in throw during the Eocene- Oligocene (42 Ma-28 Ma). Maximum incremental throw of ~68 m also occurs during the Eocene.
Figure 25: T-Z plot for fault 6 along regional cross section C-C’ showing cumulative throw of ~30 m. Zero slope between interpolated points represents periods of fault inactivity.

Figure 26: ΔT-t plot for the same fault in Figure 25 above showing no increase in throw from the Eocene (37 Ma-28 Ma). Maximum incremental throw of ~15 m occurs during the Oligocene.
Figure 27: Juxtaposed profiles of incremental throw vs time for 14 faults along cross section A-A’. Faults are arranged from North to South as they appear in cross section (Figure 6).

Figure 28: Juxtaposed profiles of incremental throw vs time for 11 faults along cross section B-B’. Faults are arranged from North to South as they appear in cross section (Figure 6).
Figure 29: Juxtaposed profiles of incremental throw vs time for 13 faults along cross section C-C’. Faults are arranged from North to South as they appear in cross section (Figure 6).

Figure 30: Juxtaposed profiles of incremental throw vs time for 14 faults along cross section D-D’. Faults are arranged from North to South as they appear in cross section (Figure 6).
Figure 31: Juxtaposed profiles of incremental throw vs time for 13 faults along cross section A-A’. Faults are arranged from North to South as they appear in cross section (Figure 6).
Figure 32: Juxtaposed profiles of incremental throw vs time for 20 faults along cross section F-F’. Faults are arranged from North to South as they appear on cross section (Figure 6).
Table 7: Average slip rates for 11 regional cross sections (mm/yr) (Figure 6)

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<th>Southeast Louisiana (M-M' - Q-Q')</th>
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<tbody>
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<td>A-A'</td>
<td>B-B'</td>
</tr>
<tr>
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<tr>
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Table 8: Average slip rates and Incremental throw for southwest and southeast Louisiana (mm/yr) (Figure 6)

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<td>Incremental Throw (m)</td>
<td>Slip rates (mm/yr)</td>
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<td>0.013</td>
<td>133.75</td>
<td>0.008</td>
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Table 9: Average sedimentation rates for 11 cross sections (Figure 6)

Average Sedimentation rates for all 11 regional cross sections (mm/yr)

<table>
<thead>
<tr>
<th></th>
<th>Southwestern Louisiana (A-A’- F-F’)</th>
<th>Southeastern Louisiana (M-M’- Q-Q’)</th>
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<td></td>
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<td>0.223</td>
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<td>0.165</td>
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<td>0.323</td>
<td>0.250</td>
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<td>Frio</td>
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<td>0.313</td>
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<tr>
<td>Vicksburg/Jackson</td>
<td>0.064</td>
<td>0.074</td>
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<tr>
<td>Cockfield (Yegua)</td>
<td>0.172</td>
<td>0.137</td>
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<tr>
<td>Sparta</td>
<td>0.079</td>
<td>0.104</td>
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<tr>
<td>Wilcox</td>
<td>0.138</td>
<td>0.157</td>
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3.2 Fault kinematics in the Cenozoic of southeast Louisiana

The 54 faults studied in southeast Louisiana record the fault slip history in the Cenozoic. These faults are numbered in increasing order from north to south (Figure 6) (Tables 10-14, Figures 33-49, Appendices C and D). The measurements of the apparent cumulative stratigraphic throw-versus-depth for 47 faults show continuous fault reactivation from the Paleocene to the Pliocene (Tables 10-14, Appendix C, Figures 33-40). The other 7 faults studied indicate periods of fault reactivation punctuated by periods of inactivity (Tables 10-14, Figures 41-44, Appendix C). Incremental throw-versus-time calculations imply that the timing of fault reactivation occurs between the Paleocene through the Pliocene in 48 faults (Tables 10-14, Appendix C, Figures 3-40). The calculations also show that the periods of inactivity are in the Eocene, Oligocene, Early Miocene and Late Miocene (Tables 10-14, Figures 41-44, Appendix C). However most of the fault inactivity is in the Eocene (Tables 10-14, Figures 41-44, Appendix C). The maximum incremental throw occurs during the Late Miocene. The maximum cumulative throw across a particular formation top tends to increase along the different faults in a basinward direction (Appendix A and C, Figure 5).

Calculated incremental throw and average fault slip rates show the maximum slip rate in the Late Miocene (Tables 8, 10-14, Figures 45-49, Appendix D), however the stratigraphy displayed in the well logs does not show the Pliocene and younger sediments making it difficult to constrain the value to this time because without younger sediments we cannot determine if the throw is cumulative or a single increment. Calculated average sedimentation rates show maximum in the Middle Miocene (Table 9). These maximum slip rates and sedimentation rates represent relatively high values for the Gulf Coast.
Table 10: Incremental throw for 14 faults along regional cross section M-M’. Numbers 1-14 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section M-M’ (m)**

<table>
<thead>
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<td>67.5</td>
</tr>
<tr>
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<td>262.5</td>
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<tr>
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<td>30</td>
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<td>90</td>
<td>135</td>
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<tr>
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<td>120</td>
<td>105</td>
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<tr>
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<td>7.5</td>
<td>45</td>
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<tr>
<td>Sparta</td>
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Table 11: Incremental throw for 17 faults along regional cross section N-N’. Numbers 1-17 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section N-N’ (m)**

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<tr>
<td>Anahuac</td>
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<tr>
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</tr>
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(Table 11 continued)

**Incremental throw (ΔT) for cross section N-N' (m) continued**

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Table 12: Incremental throw for 7 faults along regional cross section O-O’. Numbers 1-7 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section O-O' (m)**

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<td>405</td>
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Table 13: Incremental throw for 8 faults along regional cross section P-P’. Numbers 1-8 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section P-P’ (m)**

<table>
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<td>367.5</td>
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<td>Middle Miocene</td>
<td>360</td>
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<td>195</td>
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<tr>
<td>Lower Miocene</td>
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</tr>
<tr>
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Table 14: Incremental throw for 20 faults along regional cross section Q-Q’. Numbers 1-17 represent faults along the cross section from north to south. (Figure 6)

**Incremental throw (ΔT) for cross section Q-Q’ (m)**

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<td>450</td>
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<td>120</td>
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<td>Frio</td>
<td>15</td>
<td>15</td>
<td>15</td>
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<tr>
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</tr>
<tr>
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<td></td>
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Figure 33: T-Z plot for fault 6 along regional cross section M-M’ showing cumulative throw of \( \sim 480 \) m. Positive slopes indicate continuous fault reactivation.

Figure 34: \( \Delta T-t \) plot for the same fault in Figure 33 above showing increase in throw during the Oligocene-Miocene (25-11 Ma). Maximum incremental throw of \( \sim 195 \) m in the Lower Miocene.
Figure 35: T-Z plot for fault 2 along regional cross section N-N’ showing cumulative throw of ~330 m. Positive slopes indicate continuous fault reactivation.

Figure 36: ΔT-t plot for the same fault in Figure 35 above showing increase in throw during the Eocene- Middle Miocene (48-11 Ma). Maximum incremental throw of ~90m in the Lower Miocene.
Figure 37: T-Z plot for fault 7 along regional cross section O-O’ showing cumulative throw of ~1080 m. Positive slopes indicate continuous fault reactivation.

Figure 38: ΔT-t plot for the same fault in Figure 37 above showing increase in throw during the Upper Miocene (~12-5 Ma). Maximum incremental throw of ~1005m in the Upper Miocene.
Figure 39: T-Z plot for fault 1 along regional cross section Q-Q’ showing cumulative throw of ~180 m. Slopes indicate continuous fault reactivation.

Figure 40: ΔT-t plot for the same fault in Figure 39 above showing increase in throw during the Paleocene- Middle Miocene (59-11 Ma). Maximum incremental throw of ~38 m in the Lower Miocene.
Figure 41: T-Z plot for fault 1 along regional cross section O-O’ showing cumulative throw of ~420 m. Zero slope between interpolated points represents periods of fault inactivity.

Figure 42: ΔT-t plot for the same fault in Figure 41 above showing no increase in throw from the Eocene (42-37 Ma) and Oligocene (25-23 Ma). Maximum incremental throw of ~180 m also occurs during the Middle Miocene.
Figure 43: T-Z plot for fault 2 along regional cross section Q-Q’ showing cumulative throw of ~165 m. Zero slope between interpolated points represents periods of fault inactivity.

Figure 44: ΔT-t plot for the same fault in Figure 43 above showing no increase in throw from the Eocene-Oligocene (48 -28 Ma). Maximum incremental throw of ~60 m occurs during the Early Miocene.
Figure 45: Juxtaposed profiles of incremental throw vs time for 14 faults along cross section M-M’. Faults are arranged from north to south as they appear on cross section (Figure 6).

Figure 46: Juxtaposed profiles of incremental throw vs time for 17 faults along cross section N-N’. Faults are arranged from north to south as they appear on cross section (Figure 6).
Figure 47: Juxtaposed profiles of incremental throw vs time for 7 faults along cross section O-O’. Faults are arranged from North to South as they appear on cross section (Figure 6).

Figure 48: Juxtaposed profiles of incremental throw vs time for 8 faults along cross section P-P’. Faults are arranged from North to South as they appear on cross section (Figure 6).
Figure 49: Juxtaposed profiles of incremental throw vs time for 7 faults along cross section Q-Q’. Faults are arranged from North to South as they appear on cross section (Figure 6).

Figure 50: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections.
Figure 51: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.

Figure 52: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.
Figure 53: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.

Figure 54: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.
Figure 55: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.

Figure 56: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.
Figure 57: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.

Figure 58: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.
Figure 59: Average slip rates across the 11 regional cross sections, A-A’ – F-F’ in southwest Louisiana and M-M’-Q-Q’ in southeast Louisiana (Figure 6). Horizontal scale represents the average longitudinal distance between the cross sections. Bars represent errors.
CHAPTER 4. DISCUSSION

The salt tectonics model (Vendeville, 2005) predicts that the timing and location of sedimentation should correlate with the timing and location of fault activity and salt movement. In addition, salt structures within the sedimentary sequence may provide further evidence for syn-depositional salt movement.

The incremental throw increases five-fold in the Late Oligocene to Early Miocene during the emergence of a fluvial dominated deltaic depositional center (Red River axis) in southwest Louisiana in addition to a shift in the Mississippi River fluvial dominated deltaic system from southcentral Louisiana toward the southwest (Galloway, 2000; Galloway, 2011) (Figure 5, Figures 27-32). The shift in the depositional center location records the westernmost shift in deposition from the center of the south Louisiana portion of the northern Gulf Coast margin in the Cenozoic.

In southeast Louisiana, during the Early Miocene, incremental throw increases six-fold over the previous values. The Early Miocene increase correlates with the time when the fluvial depositional axis and center began to shift eastward and a new depositional axis, the Tennessee river depositional axis, emerged (Galloway, 2000; Galloway, 2011) (Figure 5, 45-49). The incremental throw and slip rates increase in southeast Louisiana from this time until the Late Miocene and then decrease in the Pliocene. However, the Pliocene slip rates (0.032 mm/yr) are significantly higher than the relatively lower Eocene-Oligocene rates (0.007-0.016 mm/yr) (Table 7-8).

To study further the correlation between the timing of fault activity and the timing of sediment deposition and salt movement, the fault activity between southwest and southeast Louisiana are compared (Figures 50-59). A comparison between the slip rates and incremental
throw in southwest and southeast Louisiana (Figures 27-32, Figures 45-49, Figures 50-59) conforms to the pattern of a shift in the depositional center from the west to the east in the Cenozoic. From the Paleocene to the Early Miocene, the slip rates and incremental throw in southwest Louisiana are 1.5-3.5 times greater than those of the southeast. In the Early Miocene, the slip rates and incremental throw are approximately the same between southwest and southeast Louisiana and are 1.5-10 times higher in the southeast between the Early Miocene and Pliocene.

The resulting local sedimentation rates (Table 9) calculated from decompacted sediment thicknesses could not be used effectively in this study because they do not show a correlation with the slip rates at all times in the Cenozoic possibly due to inadequate data. Proper correlation with older, more deeply buried sediments was not possible because along some parts of the cross sections these sediments were not penetrated by the well logs. As a result, incremental throw values could not be calculated along these parts of the cross sections leaving insufficient values available to calculate the average values for the time periods represented by the sediments. Southward of the cross section, faulting is expected to increase in the direction of the depositional center (Murray, 1961; Winker, 1982; This study). Older, deeper, unpenetrated sediments with higher sedimentation rates may show larger slip rates and incremental throw which will then reflect in the average rates calculated for that time period. However along individual faults incremental throw magnitudes correlate with sedimentation rates (Tables 1-6, 10-14).

Periods of fault inactivity mainly occur during the Eocene, a time when the depositional center was located in central Louisiana. The Eocene is a time of relatively low sedimentation rate and coastal retreat (Galloway et al., 2011).
Within the regional cross sections, there are 10 notable salt structures (Figure 6, Appendix E) some of which pierce the youngest sediments. The salt diapirs which pierce the sediments suggest vertical salt displacement from differential loading or gravity spreading. Relatively high changes in sediment thickness (Appendix E) and incremental throw magnitude also occur on the flanks of these salt structures suggesting syn-depositional salt movement. Salt piercement structures are more consistent with differential loading and gravity spreading models (Vendeville, 2005).

Observations in this study show that in southwest Louisiana, faulting is most active during the Paleocene Wilcox deposition and the Oligocene-Early Miocene time, and in contrast, in southeast Louisiana faulting is relatively higher during the Early Miocene to Late Miocene. During these most active periods, salt movement is associated with faulting and sediment loading using model predictions of an updip extension zone, a middle translation zone and a downdip (basinward) contraction zone observed from salt and sediment stratigraphy and structure in seismic sections from southwest and southeast Louisiana (Diegel, 1995; McBride, 1998). Offshore southwest and southeast Louisiana are fold belts associated with the downdip contraction formed by the evacuation of salt from onshore updip areas of extension in southwest Louisiana (Diegel, 1995) and southeast Louisiana (McBride, 1998).

The model for salt movement via differential loading or gravity spreading is considered more likely over the lithospheric flexure model in explaining the cause of faulting in the Cenozoic. The lithospheric flexure model predicts that the tensional stresses that induce faulting occur on the periphery of the loading zone. Although the depositional center in the Pliocene is offshore (Figure 5) and faulting should be expected onshore in southeast Louisiana, significant
slip rates and incremental throw are not observed across faults onshore in the Pliocene except in the 3 cross sections where prominent salt piercement structures exist.

The calculated slip rates and incremental throw in this study represent values of minimum fault-related subsidence rates for south Louisiana in the Paleocene-Pliocene. Together with sedimentation rates, these subsidence rates can be compared with Pleistocene-present day sedimentation rates and slip rates to further understand sedimentation-related fault activity associated with ancient and modern river systems in south Louisiana. This can provide important considerations for future sustainability by allowing for predictions of rates of coastal land loss and planning for preventive measures. The results of this study also imply that future subsidence may be expected in areas of sediment deposition where there is salt at depth. There is also the implication of residual motion in older branches of the depositional center which explains why there is fault activity in areas outside the main depositional center although this movement is relatively lower than the fault movement within the depositional center (Figure 5, Tables 7-8).

This study is subject to some limitations and errors. The well logs in the study do not sample depths above 3000 ft. so that the Pliocene is not sampled in three of the regional cross sections (A-A’, B-B’, C-C’) from southwest Louisiana. As well, the top of the Pliocene/bottom of the Pleistocene is only sampled in 1 cross section.

However, in 8 cross sections which nevertheless sample the Pliocene sediments allow for a correlation and comparison between the fault activity and salt movement in both southwest and southeast Louisiana in the Cenozoic because the fault throw is measured from the bottom of the stratigraphic interval in the foot wall and hanging wall. The calculated errors in the measurement of the cumulative throw from which incremental throw and slip rate values are calculated is approximately five percent (Figure 50-59). Additional error may result in the slip rates because
the numerical ages used in calculating the slip rates represent published ages recorded for particular formations in south Louisiana, however the deposition of the formation in the cross section may not have spanned the entire period and as such would result in higher slip rates/subsidence rates. Overpressuring can cause weakness in sediments and increase susceptibility to faulting (Dugan and Sheahan, 2012). The Gulf Coast Tertiary sediments are known to be overpressured in some areas, this may influence fault activity outside model predictions of salt displacement and lithospheric flexure.
CHAPTER 5. CONCLUSIONS

Faults have been reactivated in south Louisiana throughout the Cenozoic. Periods of fault reactivation are punctuated by periods of fault inactivity. Faulting along the coastal plain of south Louisiana is sensitive to changes in depositional center location. The slip rates and incremental throw magnitude increases five to six times over previous amounts in space and time concomitant with the emergence of deltaic depositional centers in southwest and southeast Louisiana. In addition, the periods of inactivity and low fault slip rates are mostly constrained to the period when the depositional center moved away and the area experienced minimal sediment input. Furthermore, the amount and timing of faulting differs between southwest and southeast Louisiana in a pattern reflective of the spatial and temporal changes in sediment deposition between these areas. This correlative pattern between sediment deposition and fault reactivation is marked by a shift in the major activity from the west to the east in south Louisiana in the Cenozoic.

The timing of fault activity correlates with the timing of salt movement suggesting salt movement via differential loading or gravity spreading. The interaction among fault activity, sediment deposition and salt movement are consistent with model predictions of fault initiation and reactivation due to sediment induced salt displacement in contrast to model predictions of fault activity due to lithospheric flexure.

Future analysis of faults in south central Louisiana may provide more verification of the interaction among major fault activity, sediment deposition and salt displacement described in this study. Structural and stratigraphic studies of Pleistocene and Holocene sediments is recommended, as this will provide data to aid in defining the relationship between ancient and
modern systems. The role of over-pressuring in fault activity should be considered in greater detail than in this study because Tertiary Gulf Coast sediments are known to be overpressured. Finally, these faults hold a record of the interaction among climate, tectonics, sediment deposition and salt movement and should be further studied in this regard.
REFERENCES


Molnar, P., 1990, Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg?: Nature, no. 346.


Ocamb, R., 1961, Growth faults of south Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 11, p. 139-175.


Appendix A: Cumulative throw and depth for cross sections A-A’ – F-F’ (southwest Louisiana).

Bold numbers at the head of each column on all tables represent faults as they appear from North to south in cross section (Figure 6)

Cumulative throw (T) for cross section A-A' (m)

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Appendix B: Slip rates for cross sections A-A’ – F-F’ (southwest Louisiana).

Bold numbers at the head of each column on all tables represent faults as they appear from North to south in cross section (Figure 6)

**Slip rates for cross section A-A' (mm/yr)**

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Appendix C: Cumulative throw and depth for cross sections M-M’ – Q-Q’ (southeast Louisiana).

Bold numbers at the head of each column on all tables represent faults as they appear from North to south in cross section (Figure 6).

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Appendix D: Slip rates for cross sections M-M’ – Q-Q’ (southeast Louisiana)

Bold numbers at the head of each column on all tables represent faults as they appear from North to south in cross section (Figure 6)

### Slip rates for cross section M-M' (mm/yr)

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Appendix E: Well logs used in this study

Portion of cross section B-B’ (Bebout and Gutierrez, 1982)
Portion of cross section B-B’ continued (Bebout and Gutierrez, 1982).
Portion of cross section N-N’ (Bebout and Gutierrez, 1983)
Portion of cross section N-N’ continued (Bebout and Gutierrez, 1983).
Portion of cross section M-M’. Additional wells were used to verify the structure observed in the original cross sections. Details of well logs listed below (Drilling Info Inc.)

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<td>1</td>
<td>St. James</td>
<td>Rutherford Oil Corporation</td>
<td>Vua; F. Graugnard #001</td>
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<td>Bowie Lumber Company #001</td>
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<td>3</td>
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<td>Triton Oil &amp; Gas corp.</td>
<td>J B Levert SWD #001</td>
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<td>MIRE RD SU A; LR&amp;P #011</td>
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<td>Freeport Sulphur Co.</td>
<td>Dibert Stark &amp; Brown #010</td>
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<td>6</td>
<td>Terrebonne</td>
<td>Lamar Hunt</td>
<td>E W Brown Jr et al B #001</td>
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</table>
VITA

Abah Philip Omale received his Bachelor of Technology in Applied Geology from Federal University of Technology, Akure, Nigeria in 2009. He joined the Department of Geology and Geophysics at LSU in January 2013 to pursue a Master’s degree in Geology.