Contribution Of Shallow Geology To Hydrocarbon Seep Formation In Green Canyon Block 600

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CONTRIBUTION OF SHALLOW GEOLOGY TO HYDROCARBON SEEP FORMATION IN GREEN CANYON BLOCK 600

A Thesis
presented in partial fulfillment of requirements
for the degree of Master of Science in Engineering Science
in the Department of Geological Engineering
The University of Mississippi

By
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ABSTRACT

The Green Canyon federal protraction area in the Gulf of Mexico is rich in hydrocarbons. The movement of the Sigsbee Salt Escarpment in Green Canyon has resulted in a complex bathymetric profile and extensive shallow faulting that has allowed migration of hydrocarbons to the surface creating cold seep sites. Green Canyon Block 600 (GC600) contains multiple naturally occurring, active hydrocarbon seeps. Multi-beam bathymetry, backscatter, and polarity-preserving chirp data were collected for GC600 to study the development of these naturally occurring seeps. Using these data, the structure and sedimentation of the first fifty meters can be studied in relation to the formation of hydrocarbon seeps. Studying the subsurface will contribute to a better understanding of the migration of hydrocarbons and the formation of future seep sites. The subsurface chirp data provide a visual representation of the movement of hydrocarbons near the seafloor and recent depositional history. This movement in combination with the bathymetric profile will help with understanding the current conditions and the evolution of similar depocenters in the Green Canyon federal protraction area in the Gulf of Mexico and the resulting flow of hydrocarbons. By analyzing the bathymetric profile and subsurface data, a geologic base map can be constructed to provide a foundation for future research.
DEDICATION

I dedicate my dissertation work to my family and friends. This dissertation could not have happened without their support. A special thanks to my parents, Dennis and Michelle Lucker whose encouragement and support made this all possible. Thank you to my brother, Zachary Lucker, as well for the help along the way. Your own work helped to inspire me to do more in my science.

I also would like to recognize all my friends who have supported me throughout this endeavor. Evan Menkes, Alex Abrams, and Ethan Arndt, who graduated with me at Missouri University of Science and Technology, for the long conversations and questions that made me work harder on my dissertation. Catherine Henry, Chris Kunhardt, Alex Weatherwax, Devin Thomas, Lee New, Elsie Okoye, and Dakota Kolb for the technical support and pushing me to learn more. Alessandra Conti for helping to develop the technical skills I needed for this dissertation.

Finally, I would like to make a special dedication to Lauren Kelly, a lifelong friend. I am a better person for knowing her. Lauren passed away one year into my graduate studies at the age of twenty three from cystic fibrosis. She taught me to spend the short time I have doing what I love. Thank you for the life lessons.
LIST OF ABBREVIATIONS AND SYMBOLS

GOM  Gulf of Mexico

GC600  Green Canyon Block 600

NFED (#) Normal Fault East Dipping (specific fault number)

NFWD (#) Normal Fault West Dipping (specific fault number)

MBES  MultiBeam Echo Sounder

AUV  Autonomous Underwater Vehicle

SBP  Subbottom Profiler
ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

The federal protraction area of Green Canyon is a region of the Gulf of Mexico which is rich in hydrocarbons (Figure 1.1). The movement of the Sigsbee Salt Escarpment in Green Canyon has resulted in a complex bathymetric profile and extensive faulting that has allowed for the migration of some of the hydrocarbons to the surface resulting in cold seep sites. Block 600 of Green Canyon (GC600) is one of these naturally occurring active hydrocarbon seep sites (Figure 1.2). By studying GC600 we are able to distinguish features that can help identify other bathymetric anomalies. GC600 can be used as an analogue for other natural seep locations, particularly in the Gulf of Mexico. GC600 also is interesting because the lack of benthic organisms located around the seep sites. While many of the other seep locations studied in the Gulf of Mexico provide an environment for organisms such as bivalves and tubeworms to thrive, GC600, however, does not exhibit the same benthos development.

On May 6-15, 2013 a multi-beam and sub-bottom profile survey was performed at GC600 in order to study the processes and features resulting in the formation of two hydrocarbon seep sites. By analyzing the bathymetric profile and subsurface data, a geologic base map can be constructed to provide a foundation for future research. The subsurface profile data provide a visual representation of the movement of hydrocarbons near the seafloor and recent depositional history. This movement in combination with the bathymetric profile will help with understanding current conditions and evolution of minibasins in Green Canyon and resulting flow of hydrocarbons.
Figure 1.1: Location of Green Canyon federal protraction area within the Gulf of Mexico.
Figure 1.2: Location of Green Canyon Block 600 within Green Canyon. GC600 is approximately 130 miles off the coast of Cocodrie, Louisiana and contains the western edge of a minibasin.
CHAPTER 2: GEOLOGIC SETTING

2.1 General

During the late Triassic and middle Jurassic Periods two separate rifting episodes caused the Yucatan microplate to split from the North American plate resulting in the opening of the early Gulf of Mexico. This coincided with the breakup of Pangea. The second rifting episode was directly associated with the deposition of Callovian (Louann) salt throughout the Gulf of Mexico. The salt then mobilized and during the Late Jurassic sea floor spreading began, lasting approximately 10 m.y. (Weimer et al., 1998b).

In the Green Canyon federal protraction area, deep-water shales and marls were deposited during the middle Jurassic to lower Cretaceous periods, creating an environment conducive to the formation of hydrocarbons. The early Cenozoic Era brought sediment from erosion of the Laramide orogeny into the shallow waters of the Gulf of Mexico forming localized sedimentary depocenters (Weimer et al., 1998b). During the Miocene, these depocenters moved to the east and all central North America sediment was funneled into the Louisiana area (Figure 2.1). Bathyal sediments created turbidite systems in the minibasins that formed on top of and between the allochthonous salt bodies. These salt bodies developed as a result of extensive loading of Cenozoic sediment on top of autochthonous salt. The turbidite systems deposited inside these minibasins make up the majority of reservoirs currently being drilled in Northern Green Canyon (Weimer et al., 1998b).
2.2 Salt Tectonics

Thermal subsidence, caused by the rapid cooling of oceanic crust following rifting, controlled the late Jurassic through Cretaceous evolution in the Gulf of Mexico. Most subsidence occurred to the south resulting in a regional dip of approximately 0.5° that the Jurassic-aged Louann Salt followed laterally (McBride, 1998). In the Green Canyon federal protraction area, the Louann Salt remained at a fairly constant depth into the Oligocene except for the development of some allochthonous salt bodies sourced from the autochthonous Louann Salt. Extensive loading from the rapid deposition of thick sediments occurred throughout the Cenozoic, resulting in the characteristic irregular appearance of the Green Canyon bathymetry (McBride, 1998). Salt
structural highs and intra-slope basins formed allowing for the deposition of Neogene turbidite systems (Weimer et al., 1998b).

Present day salt geometry in the Gulf of Mexico is divided into six main provinces (Figure 2.2). Green Canyon lies in the tabular salt-minibasin province, which consists of large, shallow, allochthonous salt sheets and suprasalt minibasins (McBride, 1998). Worrall and Snelson (1989) used the term ‘minibasin’ while describing the short growth faults associated with shallow salt features that formed small basin features in the northern Gulf of Mexico. These minibasins formed as a result of Cenozoic loading on underlying allochthonous salt bodies. These allochthonous salt sheets can reach thicknesses of 3 km and are sourced from the autochthonous Louann Salt. Above these salt bodies lies the suprasalt sediment which was deposited during the Pliocene and Pleistocene Epochs. Subsalt strata that truncate against the allochthonous salt bodies are Miocene to Pleistocene in age (McBride, 1998).

Figure 2.2: Map view of the six main salt provinces within the Gulf of Mexico (Diegel et al., 1995)
2.3 Petroleum Systems

The Green Canyon federal protraction area contains multiple large petroleum systems (Weimer et al., 1998a). These systems are not named in the traditional sense due to the mixing of petroleum from multiple sources in individual reservoirs and the abundance of reservoirs during the Neogene Period. The systems in Green Canyon are named first by the stage in which their source came from and then by the period of the reservoir deposition. Green Canyon contains the Oxfordian-Neogene, Tithonian-Neogene, Albian-Neogene, Turonian-Neogene, and Priabonian-Neogene petroleum systems (McBride et al., 1998).

Most reservoirs currently producing in the deep water Gulf of Mexico are comprised of Neogene siliciclastic turbidite systems. The majority of these turbidites formed between the Pliocene to the Lower Pleistocene and are fine grained in composition (Weimer et al., 1998b). The deeper the turbidites were stratigraphically in the mini-basins, the more bathyal to distal sediments were deposited. These turbidite systems can be divided into four common elements that are present in ancient and modern turbidite systems; erosional features, lobes, channels, and overbank shales (Weimer et al., 1998b).

The primary source rocks for these petroleum systems were formed during the Mesozoic to the Cenozoic Eras, during the Oxfordian, Tithonian, Albian, Turonian ages, and the Eocene Epoch. Deposition of source material was thought to be widespread throughout the northern Gulf of Mexico (McBride et al., 1998). Current biomarker compounds and geochemical analyses indicate that the main source rocks are Mesozoic carbonates and siliciclastic rocks as well as Eocene siliciclastic rocks (McBride et al., 1998). These rocks were deposited in marine environments during global oceanic anoxic events and are connected with worldwide organic rich
source rocks and petroleum accumulation. They primarily contain kerogen type II or type II-S (sulfur rich). Most Cenozoic source rocks contain kerogen type III which produces natural gas (McBride et al., 1998).

Migration and accumulation of petroleum began during the Late Cretaceous and continues to this day (McBride et al., 1998). The majority of petroleum migration in Green Canyon occurs through vertical pathways that were driven by buoyancy that was then enhanced by compaction, dewatering, overpressures, micro-fractures, and faulting (Weimer et al., 1998b). Overpressure occurred during the Cenozoic with the extensive loading of sediments and affected primarily vertical pathways (McBride et al., 1998). Fault zones have been known to act as migration pathways in the GOM, allowing concentrations of petroleum to accumulate in Neogene turbidite systems. In Green Canyon, however, faulting is not a key pathway for migration. Faults in this region are primarily steeply dipping and connect to small drainage areas (Weimer et al., 1998a). Some migration along faults does occur to form hydrocarbon seeps on the sea floor following fault traces. The GC600 survey area is an example of one of these hydrocarbon seep systems. Seep sites like those at GC600, however, only make up a small portion of the total petroleum systems in Green Canyon (McBride et al., 1998).

Salt has had a major effect on the migration of hydrocarbons throughout the basins within the Green Canyon federal protraction area. When hydrocarbons encounter a salt structure, the salt forms a barrier to vertical migration, which forces hydrocarbons to migrate laterally beneath the salt. Subsalt zones have been drilled in Green Canyon and petroleum migration patterns have been tracked throughout the region. Most traps that form in this region are both structural and stratigraphic (McBride et al., 1998).
In the Green Canyon protraction area over 100 wells have been drilled (BOEM, 2014). During 2005-2006 Green Canyon contained two of the top 20 producing fields in the Gulf of Mexico; both blocks were operated by BP. Project Holstein is located in Green Canyon Block 644 at a water depth of 4,340 ft. and produced 23.5 million BOE (barrels of oil equivalent) between January 2006 and December 2007 (U.S. Department of the Interior, 2009). In September 2012 the Holstein field was bought by Plains Exploration & Production. Plains Exploration & Production was then acquired by Freeport-McMoRan in May 2013 and the Holstein platform ceased production. In 2014 Freeport-McMoRan reactivated the Holstein platform rig and hope to re-establish production by mid-year 2016. Project Mad Dog located in Green Canyon block 782 at 4,420 ft and had a net daily production of 4,000 BOE and 1 million cubic feet of natural gas in 2014 (Chevron, 2014).

2.4 Current Depositional Environment of Green Canyon

2.4.1 Fuji Basin and Survey Extent

The Fuji basin in Green Canyon (Figure 2.3) was used as an analogue for the depositional environment of GC600 due to its similarities in location, orientation, depth, and sedimentation mechanisms. In addition, the stratigraphic architecture and controls on salt-withdrawals in the Fuji basin have been widely studied. The Fuji basin is a minibasin oriented north-south roughly 20 miles north-west of GC600 and is approximately 30 km long and 15 km wide (Madof et al. 2009). The maximum water depth for the Fuji basin is 4200 ft. and the maximum water depth for GC600 is 4390 ft. The comparison of the Fuji basin and GC600 is based on data collected on the Fuji basin to investigate the stratigraphic controls on a salt-withdrawal intraslope minibasin and the implications for misinterpreting sea level change (Madof et al. 2009).
Data for this investigation of GC600 was collected by the Mississippi Mineral Resources Institute (MMRI), the National Institute for Undersea Science and Technology (NIUST), and the Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) during an AUV (autonomous underwater vehicle) cruise. Data collected included multi-beam and backscatter data at a vertical offset of 50 meters covering a region of approximately 5km by 3km (Figure 2.4 & 2.5). This region has a vertical relief of approximately 288 meters from the west (where structural highs are present) to the east.
Figure 2.4: GC600 bathymetry data collected by the AUV Eagle Ray covering a survey area of 18.5 km$^2$. Vertical resolution for the bathymetry data is ~0.5-1m and horizontal resolution is ~1.5-2m.
Figure 2.5: Backscatter intensity values for GC600. Hard ground is indicated by red while softer sediments range from blue to light yellow.
2.4.2 Facies Assemblages and Interpretation of Sedimentation

According to Galloway (1998), there are seven basic facies associated with slope systems. They are (1) turbidite channel fills, (2) turbidite lobes, (3) sheet turbidites, (4) slide, slump, and debris-flow sheets, lobes and tongues, (5) fine-grained turbidite fills and sheets, (6) contourite drifts, and (7) hemipelagic drapes and fills (Galloway, 1998). In the Fuji basin, west of GC600, late Pleistocene to Holocene sediments appear to be primarily hemipelagites and muddy turbidites (Madof et. al, 2009). The remaining deposition is composed of mass transport complexes and channelized sandy turbidites.

The hemipelagites and muddy turbidites in the Fuji basin are relatively homogeneous with relatively consistent thickness; however, some successions can range from 65 m up to 665 m in thickness (Madof et. al, 2009). These assemblages typically drape over the basins and thin towards the margins causing planar and parallel features on seismic profiles (Prather et al., 1998). The deposition of these hemipelagic sediments appears to be relatively uniform throughout the region of Green Canyon and the deposition occurred during periods of relative sea level stability.

Mass transport complexes can be divided into slides, slumps, debris slides, and debris flows (Figure 2.6). On seismic profiles these mass transport complexes appear as hummocky, mounded, chaotic features with a variety of basal erosional features (Madof, 2009 and Prather et al., 1998). Many of these mass transport complexes also contain reverse faulting or folding.
The main sand delivery path into the Green Canyon federal protraction area is through channelized sandy turbidites. On seismic profiles these channels appear as concave, lenticular, or tabular features with erosional or low angle lower bounding surfaces (Prather et al., 1998). These channel complexes are composed of vertically amalgamated channels (Madof et al., 2009).

Backscatter data from GC600 indicate that the western rim of the GC600 minibasin is composed entirely of soft sediments (likely hemipelagic sediment). Backscatter values also highlight two main hydrocarbon seep sites in the middle of the survey as indicated by high intensity
backscatter values (Figure 2.5). A statistical analysis of backscatter values will be required to more accurately identify specific sediment type over the complete survey area.

2.4.3 Primary Sedimentation Controls

Two main controls of sedimentation commonly exist on continental slopes: eustasy change and steady state bathymetry. In Green Canyon however, sedimentation is also controlled by passive salt movement on the Sigsbee salt escarpment. Originally, deposition was thought to be primarily controlled by changes in eustasy, but research on the Fuji basin has pointed to passive salt motion as the primary control (Madof et. al, 2009).

Passive salt motion, also known as halokinetic autocyclicity, is the variation of slope stability and sediment accumulation controlled by the movement of salt. As hemipelagites and muddy turbidites are deposited in a mini-basin, the loading causes salt to migrate away from the center of the basin and towards salt-controlled structural highs (Fort and Brun, 2012). This in turn produces high-angled slopes resulting in an environment conducive to the formation of intrabasinal mass transport complexes. The weight of the mass transport complexes causes more salt to migrate and the process repeats itself (Madof et. al, 2009 and Mallarino et al., 2006). Inside the intrabasinal mass transport complexes reverse faulting or folding can occur as the sediment shifts and settles. All the salt from under the depocenter will eventually be displaced and the effects from passive salt motion will cease. Deposition will then return to control by eustasy changes or steady state bathymetry (Madof et. al, 2009 and Mallarino et al., 2006).
CHAPTER 3: MATERIALS AND METHODS

3.1 Eagle Ray AUV data

On May 7th, 2013 at 10:00pm the National Institute for Undersea Science and Technology (NIUST)-operated AUV Eagle Ray was deployed at GC600 and preformed a MultiBeam Echo Sounder (MBES) survey over an 18.5km² area. The vehicle reached its surveying altitude 50 m above the seafloor at 10:41pm and at 5:00pm on May 8th, 2013 the survey was completed. Using a Kongsberg EM2000 (200 kHz) and a Konsberg GeoAcoustics subbottom profiler (SBP) Eagle Ray mapped 175 m wide swaths of the seafloor. This survey generated high-resolution bathymetry, acoustic backscatter data, and high resolution sub-bottom profiles along the nadir of the vehicle’s track.

3.2 Eagle Ray AUV navigation system

The Eagle Ray utilized a Kearfott 5053 SeaDeVil device to acquire accurate geospatial data during surveys. The Kearfott 5053 SeaDeVil includes an Internal Navigation System (INS) and a RD Instruments Doppler Velocity Log. Communications to and from the AUV are obtained through an Ultra-Short Baseline LinkQuest (USBL) 5000HA transponder/modem system mounted on Eagle Ray the AUV. The USBL modem reported the INS derived position through acoustic telemetry while the surface vessel tracked the AUV using the USBL transponder. This allowed for the comparison between positions and estimates the offset of the vehicle from its actual position. This USBL has an inherent system error on the order of 10 m, after calibration.
3.3 MBES data processing

The MBES raw data contain the coordinates (X, Y, and Z) for the survey and backscatter intensity data. These data were used to create various cartographic data (bathymetry, slope terrain, and backscatter imagery) which were further analyzed using a Geographic Information System. These bathymetry data have a lateral resolution of 1.5-2 m and a vertical resolution of 0.5-1.0 m. The MBES data used in this study were processed using Caris Hips and Sips and non-standard procedures implemented in-house by Alessandra Conti. The processing steps she used are as follows.

3.4 MBES bathymetry data

After the collection of MBES bathymetry data from Eagle Ray, corrections were applied for errors in the AUV positioning system as calculated in Section 3.2. Other alterations made include attitude parameters, SVP (speed of sound in the water), and tidal corrections. The MBES bathymetry data then underwent sound editing and spike removal in Caris Hips and Sips to ensure that good quality data were used to produce the bathymetry grid. This grid was created from X, Y, and Z data at a one meter resolution with a vertical exaggeration of ~4-6X. The vertical exaggeration helped identify seafloor anomalies and distinctive features. Without a large vertical exaggeration some these feature would not be readily visible.

3.5 MBES backscatter data

The backscatter data set is the reflection of the time series of a beam inside the side scan footprint from the Eagle Ray and allowed us to infer the composition of the sea floor. High backscatter values generally represent hard ground or gravel, intermediate represents sand-like sediment, and low backscatter values indicate mud or soft sediment. Seep sites often have high backscatter values due to carbonate deposits on the seafloor.
3.6 Chirp Sub-bottom Data Processing

Chirp sub-bottom profiler data were collected using the Kongsberg GeoAcoustic custom-built sub-bottom profiler system mounted on the Eagle Ray AUV. This profiler generated high resolution sub-bottom imagery down to 40-50 m below the seafloor. The source transducer from the profiler system produced “chirp” pulses, or frequency modulated pulses, with a bandwidth between 1.5-11.5 kHz. Activation of the seismic source generally occurs at 1 Hz with a record length of approximately 200 milliseconds. These seismic traces are sampled at 20 microseconds and the raw data was stored in GeoAcoustic format. Once the collection of the data was complete, in-house software was used to convert the GeoAcoustic format to standard SEG-Y in order to be input into Kingdom Suite.

3.7 Kingdom Suite Interpretation and Analysis

3.7.1 Fault and Horizon Interpretation

After processing, the SEG-Y files were input into Kingdom Suite and a basemap of the backscatter grid and hillshade of GC600 was uploaded. The process of picking faults began with a general description of the region and identification of dominant trends. Identified in the multi-beam survey were a scarp, two hard ground locations (carbonate platforms), and gullies that had formed leading into the center of the depocenter (Figure 3.1). In the subsurface multiple normal faults were identified, most dipping southeast towards the center of the basin. Undulations were identified in the southeastern portion of the study area. Seismic reflectors found above the scarp and below the scarp appeared to correlate indicating that the scarp was a large normal fault dipping to the southeast.

Once the general description the survey area was finished, faults were picked first based on their surficial expression on the basemap. The faults were picked survey line by survey line
from west to east. After all the faults were picked five horizons were picked based on lateral continuity throughout the subsurface. There horizons were strong, continuous seismic reflectors found throughout the GC600 survey area. All horizons were picked manually as 2-D hunt and other automated picking methods produced inadequate results.
Figure 3.1: Location of the northern and southern hard ground platforms, large scarp, and gullies at GC600
3.7.2 Horizon Surface Interpolation and Issues

The horizons were then used to create grids which interpreted the horizon surfaces between surveys. Unfortunately, all grids created formed unnatural sinks and rises in locations where there were not solid horizon lines. The formation of these sinks and rises, despite using various interpolation methods, made it impossible to construct a three-dimensional model within Kingdom Suite. To compensate for this, all horizon lines were exported from Kingdom Suite and imported into ArcGIS to undergo further interpolation methods.

3.7.3 Fault Displacement and Dip Calculations

The strike of the majority of the faults in the survey area trend north-south requiring the surveys to be corrected to accurate dip calculations and fault displacements. In addition to correcting for dip, a correction for vertical exaggeration was applied as well. In order to correct for vertical exaggeration the length of the survey line in meters were measured and compared to the inches on the profile. Next, time on the vertical axis was converted into meters and also compared to an inch on the profile. Vertical exaggeration was then calculated by dividing the horizontal meters per inch by the vertical meters per inch. This process was repeated for each profile. The vertical exaggeration was then used to calculate the true vertical offset of each fault. Figure 3.2 shows a visual representation angles and displacements used in the following calculations to correct for apparent dip.
3.7.4 Apparent Dip Correction Proof:

\[ \tan(COD) = \frac{CD}{OC} = \frac{AB}{OC} \]

Replace OC: \( \cos(COA) = \frac{OA}{OC} \); \( OC = \frac{OA}{\cos(COA)} \)

\[ \tan(COD) = \frac{AB}{OA \sec(COA)} \]

Replace AB: \( AB = OA \tan(AOB) \)

\[ \tan(COD) = \frac{\tan(AOB)}{\sec(COA)} \]

\[ \tan(COD) = \tan(AOB) \cos(COA) \]

Replace angles:

\[ COD = \alpha \]
\[ AOB = \delta \]
\[ COA = 90^\circ - \beta \]

\[ \tan \alpha = \tan \delta \sin \beta \]

\[ \tan \delta = \frac{\tan \alpha}{\sin \beta} \]

\[ \delta = \tan^{-1} \left( \frac{\tan \alpha}{\sin \beta} \right) \]

Figure 3.2: Location and names of angles and displacement vectors used in the apparent dip correction proof to calculate true dip for faults within GC600.
Using the profiles in Kingdom Suite, the vertical and horizontal displacements were measured for each continuous fault. The vertical displacement is equivalent to the distance the horizon was displaced down the fault and the horizontal displacement is equivalent to the heave of the horizon. These displacements were then used to calculate the angle $\alpha$. $\beta$ was measured as the angle between the strike of each fault and the survey lines. These angles were then used to calculate the true dip of each fault. Dips were calculated on the faults in the survey area that were continuous through at least two survey lines (Tables 4.1 & 4.2). The separation between each survey line is approximately 175 meters making it difficult to correlate faults between surveys. This meant that the majority of faults throughout the survey area were only present in one survey line. Nine faults in total were used to calculate dip correction.

3.8 Geospatial Database

The geospatial database for Green Canyon Block 600 is divided into four main themes; backscatter, bathymetry, structure, and horizons. Backscatter and bathymetry contain the original acoustic backscatter and bathymetry grids. Using the bathymetry and slope grid, and aspect analysis was performed on GC600.

The structure database contains features identified through the sub-bottom profiles and bathymetry (Figure 3.3). This includes all known seep sites, a large scarp formation, and major normal faults. There are two fault feature classes, one for southeast-dipping faults and another for northwest-dipping faults. An attribute table was created for each fault detailing their apparent dip, true dip, throw displacement and heave displacement (Tables 4.1 & 4.2).

Part of the geospatial database included interpolating surfaces from the horizons picked in the sub-bottom profiles. Multiple methods were used to interpolate these surfaces including inverse distance weighting, kriging, and natural neighbor. The bathymetry grid was used as a control to
compare interpolated depth values. The seafloor picked in the sub-bottom profile was compared using these various interpolation methods. Natural neighbor proved to be the best fit for the data provided. Both inverse distance weighting and kriging had problems interpolating the seafloor surface due to the distance between survey lines.
Figure 3.3: Left: High resolution bathymetry depth data taken from the multi-beam survey at GC600. Right: Natural neighbor interpolation of the seafloor using the seafloor horizon picked in Kingdom Suite. The Natural Neighbor interpolation method best represents the original bathymetry data.
CHAPTER 4: RESULTS

4.1 Faults

In the survey area, all faults are normal faults. The majority of these faults dip to the southeast towards the center of the minibasin. Due to the distance between survey lines, major faults were classified as faults that appeared in two or more surveys while minor faults were any fault that appeared in only one survey line. In total, 209 minor faults and nine major faults were identified. All faults in the area appear to strike northeast to southwest and six of the major faults dip southeast and the other three dip northwest.

In the western portion of the study area a large scarp cuts across the survey from north to south (Figure 4.1). Based on the information from the one survey crossline, this scarp is a normal fault that marks the western rim of the minibasin. In the sub-bottom profiles we can see the displacement of multiple horizons through this scarp, however, due to the size of the scarp it is difficult to get an exact heave and throw displacement on these horizons (Figure A.2, Appendix). In addition, the survey was conducted in such a way that the scarp runs parallel with the majority of the survey lines. The only sub-bottom profile that shows a clear image of this scarp is the cross-section for the survey (Figure A.2, Appendix). Unfortunately, due to time constrains during the mapping of GC600, only one cross-section was taken for this study. More sub-bottom profiles would be needed running perpendicular to this scarp to better define the scarp and the role it plays in the development of this minibasin.

Major and minor faults in the survey part of GC600 are concentrated between the scarp to the west and NFWD 3 (Normal fault west dipping #3) to the east (Figure 4.1 & A.3, Appendix).
Although some faults do occur to the west of the scarp, approximately 160 of the 209 minor faults and five of the nine major faults lie within the region to the east of the scarp. To the southeast of NFWD 3 there are fewer faults and the subsurface shows little sign of disturbance (Figures 4.1 & A.7, Appendix). The sediment deposited in this area appears undisturbed and evenly distributed.

In the center of the survey area between the scarp and NFWD 3, there is extensive faulting. The major faults in this area reach the surface and display distinctive surficial expressions on the bathymetry data. Many of the minor faults do not show any surface expression although the faults do appear to reach the seafloor in the sub-bottom profiles. In the northeastern corner of the survey area there are a series of surficial features that appear to be indicators of subsurface faulting, however, the majority of these features showed no subsurface offset (Figure 4.1).

Tables 4.1 and 4.2 lists all the major faults in the study area and their displacement values. The range between dip angles for major faults shows large variations. Faults dipping to the northwest have a shallower dip angle than those dipping to the southeast. As for displacement, two faults stand out as having unusually high heave displacements (Figure 4.2). NFED 5 (Normal fault east dipping #5) and NFWD 3 both show heave displacement values that are well above the average for this survey area (Table 4.1 & 4.2).

NFED 5 is the only major fault that runs directly through a hard ground platform. This hard ground is a carbonate platform that formed as a byproduct of hydrocarbon seep sites. Hard ground locations obscure the subsurface profiles as acoustic waves bounce off the seafloor rather than penetrate it. NFED 5 runs directly through the northern-most hard ground platform (Figure 4.1). Figure A.1 (Appendix) shows Survey Line A before NFED 5 intersects with the hard ground platform and Figure 4.4 is a close up of the northern platform. This fault also displays the largest vertical offset of all the major faults in the area.
NFWD 3 is another fault that may cut through the southern hard ground platform and a nearby gas chimney (Figures A.3 & A.5, Appendix). The seep sites in the southern hard ground are not associated with any known faults in GC600 but the trend of NFWD 3 does coincide with location of the seeps. The bathymetry data also indicate that the fault might continue further south. There is also no evidence that NFWD 3 ends to the south, however, due to gas chimneys and the location of the southern hard ground the fault cannot be traced to the known seep sites (Figure 4.1 & A.5, Appendix). NFWD 3 does not have a high vertical offset like NFED 5. These results correlate with findings detailed by McBride et al. (1998) which state that relatively steep faults do not provide good conduits for hydrocarbon migration. Shallower faults provide more area for hydrocarbons to intersect the fault plane, increasing the chance of migration. NFWD 3 and NFED 5 appear to be responsible for the migration of hydrocarbons to the surface suggesting that the heave of the fault is more important than vertical throw to the migration of hydrocarbons.
Figure 4.1: Hillshade of GC600 overlaid with backscatter data. All gas chimneys in the sub-bottom profiles are marked as well as all known seep sites. Note the concentration of gas chimneys and faults in the north of the survey.
Figure 4.2: Location of nine major faults with varying heave displacement values
Table 4.1: Displacement and angle data for the three major faults in GC600 that dip to the northwest. Note NFWD 3 has a high heave displacement value.

<table>
<thead>
<tr>
<th>Faults</th>
<th>Throw</th>
<th>Heave</th>
<th>β</th>
<th>α</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.494</td>
<td>0.963</td>
<td>43.0°</td>
<td>27.2°</td>
<td>37.0°</td>
</tr>
<tr>
<td>2</td>
<td>0.329</td>
<td>1.925</td>
<td>43.0°</td>
<td>9.7°</td>
<td>14.1°</td>
</tr>
<tr>
<td>3</td>
<td>0.823</td>
<td>7.7</td>
<td>22.0°</td>
<td>6.1°</td>
<td>8.9°</td>
</tr>
</tbody>
</table>

Table 4.2: Displacement and angle data for the six major faults in GC600 that dip to the southeast (towards the middle of the minibasin). Note NFED 5 has a high heave and throw displacement value.

<table>
<thead>
<tr>
<th>Faults</th>
<th>Throw</th>
<th>Heave</th>
<th>β</th>
<th>α</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.151</td>
<td>4.813</td>
<td>48.0°</td>
<td>13.4°</td>
<td>17.8°</td>
</tr>
<tr>
<td>2</td>
<td>0.329</td>
<td>0.963</td>
<td>45.0°</td>
<td>18.9°</td>
<td>25.8°</td>
</tr>
<tr>
<td>3</td>
<td>1.645</td>
<td>1.925</td>
<td>27.0°</td>
<td>40.5°</td>
<td>62.0°</td>
</tr>
<tr>
<td>4</td>
<td>1.398</td>
<td>3.850</td>
<td>33.0°</td>
<td>20.0°</td>
<td>33.8°</td>
</tr>
<tr>
<td>5</td>
<td>2.385</td>
<td>5.775</td>
<td>17.0°</td>
<td>22.4°</td>
<td>54.7°</td>
</tr>
<tr>
<td>6</td>
<td>1.151</td>
<td>1.925</td>
<td>28.0°</td>
<td>30.9°</td>
<td>51.9°</td>
</tr>
</tbody>
</table>

4.2 Horizons

For the surveyed portion of GC600, five horizons were picked through analysis of the sub-bottom profile data. The first horizon picked was the seafloor to act as a comparison between the bathymetry data and the sub-bottom profiler data (Figure 4.3). Figure 3.3 illustrates that although the chirp data is lower resolution than the bathymetry, it still provides a good representation of the seafloor that matches well with the higher resolution multi-beam data. Deeper horizons were picked based on reflectance and continuity throughout the survey area. Horizon 4 is the only horizon that is not completely continuous through the survey area, disappearing in the southeast corner as the survey progresses toward the center of the minibasin.

Overall the distance between horizons present in GC600 are uniform in thickness and each horizon dips to the southeast towards the center of the minibasin (Figures 4.3 - 4.7). These horizons
also show that the scarp on the western portion of the survey is a normal fault as all horizons can be traced through the scarp. However, without a well-defined fault plane the throw and heave displacement of this fault cannot be accurately calculated. More cross-sections would be needed to accurately define this fault plane. The seafloor and horizons 01, 02, and 03 also show uplifting in the areas of the known hard ground platforms. In addition, all horizons display uplift surrounding NFWD 3 (Figure A.3, Appendix). Although each horizon was picked based partially on continuity throughout the survey area, none of the horizons could be identified inside scarp or below the hardground platforms. Many of the horizons are not continuous where gas chimneys are present as well.
Figure 4.3: Left: Seafloor interpolated using the natural neighbor method. Right: Location of the individual points picked on the inlines and crossline used to interpolate the seafloor. This interpolation matches well with the high resolution bathymetry data.
Figure 4.4: Left: Horizon 01 interpolation using the natural neighbor method. Right: Location of the individual points picked on the inlines and crossline used to interpolate Horizon 01. Below the seafloor the large scarp and hard ground
Figure 4.5: Left: Horizon 02 interpolation using the natural neighbor method. Right: Location of the individual points picked on the inlines and crossline used to interpolate Horizon 02. More points are missing as more gas chimneys block the seismic data collection.
Figure 4.6: Left: Horizon 03 interpolation using the natural neighbor method. Right: Location of the individual points picked on the inlines and crossline used to interpolate Horizon 03. Almost all gas chimneys present in this survey area cut through this horizon.
Figure 4.7: Left: Horizon 04 interpolation using the natural neighbor method. Right: Location of the individual points picked on the inlines and crossline used to interpolate the surface on the left. Large sections of the inlines to the east are missing as the horizon drops below the penetration limits of the sub-bottom profiler.
4.3 Gas Chimneys

Within the survey area in GC600 there are 25 gas chimneys present (Figure 4.8). Gas chimneys are areas in the subsurface where gas rises in concentrated plumes but has not yet reached the seafloor. Hydrocarbon seep sites are locations where gas plumes have reached the seafloor and are actively releasing hydrocarbons. These 25 gas chimneys occur between the scarp on the western edge of the study area and NFWD 3 to the east. Outside of the area bounded by these features neither gas chimneys nor hard ground were seen in the survey data. In addition to being bounded to the west and east, 21 of the 25 chimneys are in the northern half of the survey. Although there are only eight known active seep sites within this survey area, the abundance of gas chimneys shown in the sub-bottom data would suggest that more seep sites may develop in the future as the gas chimneys reach the seafloor.

The gas chimneys are in various stages of development and have reached different depths in the subsurface (Figure A.6, Appendix). Some coincide with increased backscatter values while others show no increase in backscatter values. A few of these chimneys occur on known fault locations (primarily major faults), but a large portion of these chimneys do not directly correlate with a known fault. However, with the abundance of minor faults in GC600 many of these chimneys may coincide with these smaller faults or with faults that are indistinguishable on the available data.

Based on the location of some of the gas chimneys and their proximity to increased backscatter response, it would appear that some of these chimneys are connected to one another (Figures 4.1 & A.6, Appendix). Unfortunately, with a distance of 175 meters between sub-bottom profiles this cannot be definitively defined. Of these 25 gas chimneys, 12 follow the trend of the large scarp (Figure 4.1).
4.4 Undulations

In the southeastern portion of the survey area there is an undulation of the sediments shown in the sub-bottom profiler data and in the bathymetry data (Figures A.7, Appendix). In the bathymetry data, these undulations appear as gullies with the distance between each gully approximately 60 meters. These features do not propagate below horizon 01, but does exist in all sediment layers above this horizon. The undulations do not appear to be connected to any faulting within this area as this region is consists of little to no faulting. The reason for these undulations is still unclear. The layers in the subsurface are continuous and maintain a consistent thickness throughout this phenomenon. Horizon 01 also maintains a consistent thickness throughout this region and shows no undulation. These features will require additional investigation.
CHAPTER 5: DISCUSSION

5.1 Hydrocarbon Seep Sites

The GC600 survey area is an active hydrocarbon seep site with eight known seep locations. These seep locations are all centered on or around the two hard ground platforms. Each of these platforms are located in an area of GC600 that is extensively faulted with 209 known minor faults and nine known major faults. The northern-most platform is connected to NFED 5, a major fault with the largest throw in this study area and second largest heave (Figure 4.1 & Table 4.2). The southern platform is located in line with NFWD 3, another major fault with a large heave offset, but average throw displacement (Table 4.1 & Figure A.3, Appendix). Although NFWD 3 cannot be traced through the southern platform in the sub-bottom profiles the surficial expression present on bathymetry data suggest that this fault does continue further south (Figure 4.1).

The connections of these seep sites to faulting in the area and the concentration of gas chimneys in the north where faulting is most prevalent suggest a connection between the migration of shallow hydrocarbons and faulting. However, the abundance of gas chimneys in locations where there are no major faults implies that minor faults may be as significant in the migration of hydrocarbons as major faults. This could also imply that the minor faults would be defined as major faults if more data was acquired. Twelve of these gas chimneys also follow the trend of the large scarp. These chimneys, although separated from the scarp, might indicate evidence for hydrocarbon migration along the scarp. Only five gas chimneys in this survey do not occur near or on a fault. Many of these chimneys also occur along the strike of known faults that could not be traced through the subsurface due to the wipeout of the sub-bottom profile data by the movement
of gas. Based on this the relationship between the faults and gas chimneys, the migration of hydrocarbons in the surveyed portion of GC600 is primarily controlled by normal faulting. The dip direction appears to have little to no significance on where hydrocarbons chose to migrate, however, the heave displacement does appear to have some relevance. This can be seen in the migration of hydrocarbons along NFED 5 and NFWD 3. Eight known seep sites occur along faults with high heave displacements, however, further study will be required to support this theory. In the future, GC600 could see the formation of multiple new seep sites as the gas chimneys continue to develop. These sites would likely be concentrated in the northern part of the survey area and be bounded by the scarp to the west and NFWD 3 to the east, as this area is the most extensively faulted.

5.2 Undulations

The reason for the formation of undulations (Figure 4.9) in the southeastern corner of the study area is still unknown. The only current theory surrounds horizon 01. If horizon 01 was eroded at one point in time, but not sufficiently to be visible in our high resolution sub-bottom profiles, it could influence the deposition of all sedimentary layers above it. The consistency in the thickness of the layers above horizon 01 suggests that erosion is not currently happening along these gullies. In the future, if the minibasin subsides more, these gullies could reactivate and erosion could begin again. In order to see if this theory could be correct, deeper profiles would be required to see if this type of feature has existed before. Unfortunately, in order to get a deeper profile, the resolution would have to be reduced. At a lower resolution these structures would likely not be present. Other minibasins in the Gulf of Mexico should be analyzed for similar gullies and undulations to further study the cause of these formations.
5.3 Future Research

The GC600 block is a complicated active hydrocarbon seep site. With survey line 175 meters apart and only one cross line, it is difficult to trace faults through the subsurface and connect them with gas chimneys or current seep sites. Another survey was taken at GC600 with tighter survey lines shortly after this survey was taken. That survey should be closely analyzed to see if hydrocarbon migration is truly controlled by normal faulting, if heave displacement has any influence on where hydrocarbons will migrate, and if some of these minor faults can be better quantified. The smaller survey should clarify many of the issues present in this survey.

In addition, deep seismic profiles could be used to see if any of the faults in this or the smaller survey reach the salt bodies below. If these faults connect to deep structures then the migration of hydrocarbons could be driven by the size of the fault rather than the displacement.
REFERENCES


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VITA
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