Copyright
by
Sebastian Cardona
2015

**The Thesis Committee for Sebastian Cardona
Certifies that this is the approved version of the following thesis:**

**Fabric Development and Pore-Throat Reduction in a Mass-Transport
Deposit in the Jubilee Gas Field, Eastern Gulf of Mexico:
Consequences for the Sealing Capacity of MTDs**

**APPROVED BY
SUPERVISING COMMITTEE:**

Supervisors:

Sean Gulick

Lesli Wood

Lorena Moscardelli

William Fisher

**Fabric Development and Pore-Throat Reduction in a Mass-Transport
Deposit in the Jubilee Gas Field, Eastern Gulf of Mexico:
Consequences for the Sealing Capacity of MTDs**

by

Sebastian Cardona, B.S. Geo.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Masters of Science in Geological Sciences

The University of Texas at Austin

August 2015

Dedication

Dedicated to my parents; my father who taught me that creativity goes further than knowledge, and my mother who showed me the value of diligent hard work.

Acknowledgements

Many people have supported me through my process of earning this degree. I would like to sincerely thank Dr. Lesli Wood for being my supervisor during her time at The University of Texas at Austin (UT), and for giving me the privilege of working with her while also pushing me out of my comfort zone. Her mentorship and financial support through the Quantitative Clastic Laboratory (QCL) at the Bureau of Economic Geology (BEG) afforded me all the tangible and intangible tools to successfully complete my degree. Also, I am very grateful to Dr. Sean Gulick, who without hesitation took on the role of being my supervisor after Dr. Wood accepted a renowned appointment in Colorado School of Mines. Dr. Gulick's guidance and always-fast responses during my last semester at UT were vital. Likewise, I want to express my gratitude to the other members of my committee; I want to thank Dr. Lorena Moscardelli —from whom I inherited the passion for mass-transport deposits— for her always-precise advices. Furthermore, I really thank Dr. Fisher for being in my committee and I am honored to have had him as a professor. Last but not least, I want to acknowledge the *honoris causa* member of my committee, my QCL colleague Maria Prieto, who provided priceless and experienced guidance during my time at UT. I also thank all the members at the QCL; special thanks to Dallas Dunlap for teaching me fundamental tricks in seismic interpretation. Dr. Kitty Milliken, Dr. Ruairi Day-Stirrat, and Dr. Shirley Dutton are sincerely acknowledged for their guidance for me to explore the microscopic world of clays. Dr. Day-Stirrat is specially thanked for his contribution of microscopic data. I would also like to acknowledge the amazing support from the Jackson School of Geosciences, and in particular I would like to thank Philip Guerrero for all his work helping the graduate students at the Jackson School.

This research would not have been possible without the generous financial support and data donations to the QCL from the following companies: Anadarko, BHP-Billiton, ConocoPhillips, ExxonMobil, Marathon, Cairn, Statoil, Repsol, Pemex, Woodside, Ophir, Noble Energy, Maersk, INPEX, Ecopetrol, Saudi Aramco, Tullow, and Western Geco. Special thanks to Anadarko geoscientists who described the well core; in particular Todd Green. Also, Kadira Singh, former QCL-member, now with Anadarko is thanked. The support from Landmark Graphics-Halliburton to use Landmark interpretation software through the Landmark University Grant Program is similarly recognized.

Finally, I want to thank Mimi Do for her encouragement and patience during these last two years. Also, I want to thank my geology colleagues and roommates for the several interesting random conversations about climate and geology of Mars the past two years. I want to acknowledge all my dear friends in Austin who always were there for me. I truthfully thank Raymond Welder for believing in me and empowering me to keep going forward. Last but not least, I sincerely thank my family that regardless the distance keeps being my engine and source of inspiration every day. If you are reading up to this point, I should also express my candid gratitude. Thanks

Abstract

Fabric Development and Pore-Throat Reduction in a Mass-Transport Deposit in the Jubilee Gas Field, Eastern Gulf of Mexico: Consequences for the Sealing Capacity of MTDs

Sebastian Cardona, M.S.Geo.Sci.

The University of Texas at Austin, 2015

Supervisor: Sean Gulick

Mass-transport complexes (MTCs) and Mass-transport deposits (MTDs) are important stratigraphic elements in many deepwater basins. MTCs have traditionally been identified as seals but can also act as migration pathways. Studying the character of deposits within a mass-transport complex (MTC) from proximal to distal, in a framework of seismically identifiable morphologies provides a template for using seismic character to predict the petrophysical properties of such deposits. During failure and subsequent transport, MTDs are exposed to shear deformation and remolding that can enhance clay alignment and destroy large pore-throats thus creating potential seal quality facies. Deformation in the various MTC *morphodomains* can be quantified by measuring the degree of clay-fabric alignment. In this study we investigate a MTD acting as the top-seal in the Jubilee gas field, Gulf of Mexico, by integrating 3D-seismic, core, and well-log data to characterize clay fabrics. X-ray–texture goniometry analysis was performed using core material from the top-seal MTD to determine the degree of clay fabric alignment.

Final results indicate that samples have an anomalously high clay-fabric not correlated with burial depth or diagenesis. We conclude that these zones with high clay-fabric alignment in the MTD are the result of shear deformation as the gravity flow moved downslope. Recognition of zones with enhanced microfabrics has important implications for shallow geohazards as well as sealing potential evaluation. This technique —although in its infancy— could be used to identify sealing MTD facies in core samples and outcrop studies.

Table of Contents

List of Tables	xi
List of Figures	xii
Chapter 1: Introduction	1
1.1 Objectives and Scope	6
1.2 Architecture of MTCs and Implications for Seal Potential	7
Headwall Morphodomain	13
Translational Morphodomain.....	13
Toe Morphodomain	15
Chapter 2: Geologic Setting	17
2.1 Structural Framework	18
2.2 Stratigraphic Framework	22
2.3 The Jubilee Gas Field.....	25
Chapter 3: Available Data and Methodologies	30
3.1 Seismic Geomorphology Methodology	39
3.2 XRPD Method	40
3.3 MICP Method	42
3.4 XRTG Method	42
Chapter 4: Seismic Expression of the MTCs in the Jubilee Field	44
4.1 The Top-Seal MTC	44
4.2 The Scouring MTC	51
4.3 Seismic-Detectable Seal Breaches in the Top-Seal MTC in the Jubilee Field	56
Chapter 5: Microscopic Analyses of the Top-Seal MTD	61
5.1 XRPD Results	61
5.2 MICP Results	67
5.3 XRTG Results	70

Chapter 6: Discussion and Conclusions.....	77
References.....	81
Vita	92

List of Tables

Table 1: Depths of samples taken from whole core at AT349-2 well for microscopic analyses. Depth in feet (ft) subsea and meters below sea floor (mbsf). Bold depths correspond to samples within the top-seal MTD.	41
Table 2: XRPD bulk mineralogy (weight %) of samples from AT349-2 well core (Day-Stirrat, written communication).....	64
Table 3: Relative percentage of clay minerals in the <2 µm clay size fraction of samples from AT349-2 well core (Day-Stirrat, written communication)..	65
Table 4: Summary table with microscopic results from analyses of core material at AT349-2 well. Depths in red correspond to the samples from the top- seal MTD.	76

List of Figures

Figure 1.1: Classification of gravity-induced deposits employed in this study after Moscardelli and Wood (2008). Compiled from Dott (1963), Nardin et al. (1979), and Moscardelli et al. (2006).....	2
Figure 1.2: (a) Schematic model of different degrees of deformation within a MTC at X and X', proximal and distal areas of MTC respectively. (b) Schematic sections at X and X' showing the effect of shear deformation on the pore-throat architecture and clay fabric after the material has been remolded and sheared; large pores are closed and clay-platelets are aligned after shearing. Red arrows in (b) represent fluids escaping through open pores at X. Some of the fluids are trapped at X' due to deformation of pore-throats after shearing as well as development of higher clay fabric.	4
Figure 1.3: Lewis (1971) first schematic model about the 'tripartite' anatomy of a MTC in cross-section and the systematic distribution of strain. Unstippled beds have slumped; sparsely stippled beds have been disturbed; densely stippled beds have not been disturbed. Cross-hatching overlies a zone of compressional folding and thrusting at toe of MTC. Vertical hatching overlies a zone of undeformed or slightly deformed beds in the middle of the MTC. Solid lines overlie an exposed glide plane in a zone of tension at the head of the MTC. Large stipples overlie disturbed beds beneath smooth seabed.	7

Figure 1.4: Idealized MTC showing the three <i>morphodomains</i> (headwall, translational, and toe) and the likely stress-regime relative to each morphodomain. Some of the distinctive features of MTCs are labeled.	9
Figure 1.5: Summary diagram showing the key morphological criteria for the recognition of all kinematic indicator types. BSS –basal shear surface. KI –kinematic information. Bold arrows indicate direction of transport. After Bull et al. (2009).....	10
Figure 1.6: Schematic figure from Moscardelli and Wood (2015) showcasing the main differences between attached and detached MTCs in terms of causal mechanisms and scales (area versus length log-log plot).	12
Figure 1.7: (a) Examples of different styles of deformation in rafted blocks from Gamboa et al. (2012). (b) Sketch illustrating fault and fracture meshes within rafted blocks in a MTC from Gamboa and Alves (2015). Fluids can propagate vertically through the block along faults and fractures, and horizontally along sheared beds.....	14
Figure 1.8: Sequence of deformational process in the emplacement of outrunner blocks and buttressing effect in the toe morphodomain. After Nissen et al. (1999).....	16
Figure 2.1: Water depth of present Gulf of Mexico, U.S.A showing the location of the Jubilee field and the main regional physiographic features (shelf edge, Mississippi Canyon, Sigsbee Escarpment). Boundaries and names correspond to protraction areas. Bathymetric data kindly provided by M. Prieto (written communication).	17

Figure 2.2: Regional 2-D seismic line showing the location of the Jubilee field. Deep deformed autochthonous salt is the main structural control in the area of the Jubilee field. Location of 2-D line is shown in figure 2.1.19

Figure 2.3: (a) Two-way time map of top of autochthonous salt (CI=50 ms) underlying the Jubilee field. (b) Two-way time map of reservoir horizon (CI=25 ms) in Jubilee field. Extension of maps shows the available seismic coverage for this study.20

Figure 2.4: Dip section through the wells in the Jubilee field showing the influence of the autochthonous salt. White arrow points at the bright-reflectors of the reservoir deposits in the Jubilee field. Red arrow points at the MTC sequence overlying the reservoir in the Jubilee field. Location of section is in Figure 2.3. Right-inset is a schematic model of the compactional drape trap style formed in the Jubilee field (Hydrocarbons in green).21

Figure 2.5: (a) Seismic reflection profile from offshore Indonesia illustrating the typical succession of a deepwater sequence according to Posamentier and Kolla (2003); lower debris-flow deposit (lower MTC), frontal-splay deposits, levee deposits, upper debris-flow deposits (upper MTC), condensed-section deposits. (b) Schematic depiction of an idealized deepwater sequence with two hypothetical log profiles after Posamentier and Kolla (2003).23

Figure 2.6: Paleogeographic map of Upper Miocene (12-6 Ma) Gulf of Mexico. The paleogeography was dominated by the sand-rich McAVLU submarine fan that covered most of the Atwater Valley protraction, where the Jubilee field is located.....24

Figure 2.7: Anadarko presence in the Atwater Valley region. Besides Anadarko's Jubilee discovery in 2003, other field discoveries are Spiderman and Atlas. Modified after Greene & O'Neill (2006).	25
Figure 2.8 (Next two pages): (a) Uninterpreted map and seismic section of Jubilee field. (b) Interpreted map and seismic section. Map of root-mean square (RMS) amplitude extraction of frontal-splay horizon with symmetrical 30 ms window. Note high amplitude anomaly centered around AT349-1 well. Map shows the main depositional elements in the field. Red-dashed line outlines the interpreted area of the top-seal MTC. Seismic section X shows the key horizons in the Jubilee field. The Jubilee field is composed of frontal-splay deposits, a mud-filled channel complex, and subsequent capped by the top-seal MTC (outline of deposit in red-dashed line on map). Yellow arrows point at a feeder-channel of frontal-splay. Origin of megascours discussed in chapter 4. Notice high amplitude in the interpreted frontal-splay deposits as a result of gas-charge effect. See 3-D perspective of RMS map in Figure 2.9.	26
Figure 2.9: North-facing 3-D view of frontal-splay horizon with draped RMS amplitude from figure 2.8. Deep-buried salt is the main structural control in the field.	29

Figure 3.1 (Next page): Description of the core acquired at the AT349-2 well in the Jubilee field. Description was generously provided by Anadarko geoscientists to the Quantitative Clastic Laboratory at the Bureau of Economic Geology. Depths at which samples were collected for the microscopic analyses (see sections 3.2,3.3. and 3.4) marked by red tick marks. The red-box encompasses the location of the top-seal MTD (the subject of chapter 5) from 17,086 to 17,132 ft subsea (2,523 to 2,537 mbsf). Figure 3.2 shows 20 ft-interval sections of the core for more detail (Deepening from top-down. Shallow part of core on the left, deeper part on right).....31

Figure 3.2 (Next five pages): Enlarged 20-ft interval sections of core description from the AT349-2 well in the Jubilee field. Total depth interval of core is from 17,040 to 17,225 ft subsea (2,509 to 2,565 mbsf). Depths at which samples were collected for the microscopic analyses are marked in red tick marks. The red-box encompasses the location of the top-seal MTD (the subject of chapter 5) from 17,086 to 17,132 ft subsea (2,523 to 2,537 mbsf). Description of the core was generously provided by Anadarko geoscientists.33

Figure 4.1: Time-thickness map of top-seal MTC. Dashed-red line is the interpreted outline of the top-seal MTC. Notice the thickening in the accumulation zone towards the toe morphodomain of the top-seal MTC.....46

Figure 4.2: (a) Uninterpreted and (b) interpreted amplitude stratal slice between top-seal MTC-base and the top-seal MTC-top horizons. Arcuate to linear patterns in map view are interpreted as pressure ridges. Dashed-red line is the interpreted outline of the top-seal MTC; note the chaotic seismic facies towards the toe of the top-seal MTC. The producing well is located in the area between the translational and toe morphodomain. Red-arrow indicates the top-seal MTC direction of transport and magenta-arrow points at a rafted block from an older MTC discussed in section 4.2 associated to one of the megascours of Figure 2.8.47

Figure 4.3: North-northwest facing 3-D view of stratal slice through the middle of the top-seal MTC in Jubilee field exhibiting typical features of the area between the translational and toe morphodomains of a MTC; hummock relief, micro-faulting, pressure ridges, and longitudinal shear. Dashed-red line is the interpreted outline of the top-seal MTC. Magenta-arrow points at a rafted block transported by an older MTC that created one of the megascours discussed in section 4.2. Section Y-Y' shown in Figure 4.4.....48

Figure 4.4: Chair slice through the top-seal MTC in the Jubilee field. Note the imbrication-pattern of the pressure ridges in cross section. These kinematic indicators suggest a transport direction from north to south-southeast. Magenta-arrow points at a rafted block transported by an older MTC that created one of the megascours discussed in chapter 4.2.49

Figure 4.5: 2D seismic line tied to 3D seismic survey in the Jubilee field. Our interpretation suggests that instabilities on a salt diapir are a possible causal mechanism of the top-seal MTC. See Figure 1.6 for schematic model. Location of 2D seismic line in Figure 2.1	50
Figure 4.6: Interpreted map of sweetness attribute from the frontal-splay horizon at the reservoir level with TWTT-contours, CI= 25 ms. High sweetness is associated to sand-rich and hydrocarbon-charged deposits (Hart, 2008). A ₁ , A ₂ , and A ₃ referred to the areas of the three high-sweetness compartments. Compartments A ₁ and A ₂ are separated by the megascour formed by the scouring MTC whereas compartments A ₂ and A ₃ are separated a normal fault (U: upthrown, D: downthrown). Notice same hydrocarbon-water contact (HWC) for all three compartments.	52
Figure 4.7: (a) Uninterpreted and (b) interpreted arbitrary section in Figure 4.6 showing the profile of the two NW-SE trending megascours seen in map. Note high-amplitude reflectors (white arrows) directly overlying the scours. Nissen et al. (1999) interpreted high amplitude reflections located immediately above scours that contrast with surrounding low-amplitude and chaotic reflections as potential rafted or outrunner blocks. Location of section in Figure 4.6.	53
Figure 4.8: (a) Uninterpreted and (b) interpreted seismic section showing a mega-block and associated lateral scarp (yellow arrow) evidence of intense scouring (linear feature in map view). See high-amplitude reflectors (magenta arrow) associated to the outrunner block. Location of section in Figure 4.6.	54

Figure 4.9: North-Northwest facing 3D view of frontal-splay horizon with semblance attribute draped. Megascour compartmentalizing the reservoir deposits associated to the scoring MTC displays chaotic facies with low semblance. The lateral scarp (yellow arrow) is evidence of the high erosive power of this scouring MTC as a result of the confinement effect by the earlier-formed channel complex updip, and possibly the fault downdip. Red arrow delineates the interpreted runout of the scouring MTC. Inset seismic section is Figure 4.8.....55

Figure 4.10: Map of horizon defining the top of the top-seal MTC with the semblance attribute draped. The superimposed transparent RMS amplitude is from the horizon at the frontal-splay level (the reservoir deposits) that delineates the Jubilee gas field. Note the fault controlling the linear arrangement of some of the pockmarks (p) in the upthrown block (U). Only one pockmark is located in the downthrown block (D) of the fault where the Jubilee field is located, and no pockmarks are located updip the limit of the gas field. Pockmarks near the toe morphodromic of the top-seal MTC exhibit an arcuate arrangement. Pockmarks are inferred to be indicators of fluid expulsion, thus their presence can be seen as a sign of seal deficiency.57

Figure 4.11: Seismic section through pockmark train at the level of the top horizon of the top-seal MTC. Note the concave up geometry of reflector in pockmarks (p) possibly due to collapsing. Normal-fault seems to control the linear arrangement of these three pockmarks. Location of section in Figure 4.10.58

Figure 4.12: Seismic section through pockmark (p) and normal fault. Pipe directly overlying the pockmark is identified because of the disruption of stratal reflections and localized sag folding above pockmark (p). Location of section in Figure 4.10.....	59
Figure 4.13: North facing 3D view of top horizon of top-seal MTC with semblance attribute draped (semblance color scale in Figure 4.10). Pockmarks (p) in the southeastern flank of the top-seal MTC exhibit an arcuate arrangement. This arrangement seems to be controlled by the formation of pressure ridges in the toe morphodomain of the top-seal MTC. Inset seismic section shows detail of a pockmark (p). Pockmarks are known to be associated to the flanks of some MTCs (Paull et al., 2008).....	60
Figure 5.1 (Next page): Segment of AT349-2 well core showing the interval of the top-seal MTD (red box). Depth at which samples were collected for microscopic analyses are indicated by red tick marks. Description of the core was generously provided by Anadarko geoscientists.	62
Figure 5.2: Bottom-hole temperatures (BHT) from wells in the Jubilee field (AT305-1, AT349-1, AT349-2) were utilized to calculate the temperature at the interval of the top-seal MTD. The depth interval of the top-seal MTD is 2,523 to 2,537 meters below sea floor (mbsf), and the calculated temperature at this interval is ~52°C. Deeper samples reach a maximum temperature of 60°C.....	66

Figure 5.3: Values of gas column height at 35% saturation and median pore throat radius of sample plotted versus depth. Note the correlation between smaller pores and greater gas columns. The silt-rich sample at 2,536 mbsf (17,129 ft subsea) has the lowest gas column and largest pore throat. Silt particles are known to shield larger pores during burial (Day-Stirrat et al. 2010). Red box corresponds to the samples directly from the top-seal MTD.....68

Figure 5.4: (a) Plot of pore throat radius versus pore density distribution of samples showing the dominantly monomodal pore-size distribution in the samples from the top-seal MTD except in the silt-rich sample at 2,536 mbsf (17,129 ft subsea). (b) Plot of median pore throat versus MICP-derived permeability. Silt-content significantly increases permeability of sample at 2,536 mbsf (17,129 ft subsea).....69

Figure 5.5: Transmitted light microscopic images of samples from AT349-2 well core employed for XRTG analysis on left column. All images have the same scale. Depth of samples in subsea feet (ft) and meters (m) below sea floor. The corresponding pore density figure is also illustrated for each sample. The multiples of random distribution (m.r.d.) value and MICP-derived porosity for each sample are also given. The values in red correspond to the samples from the top-seal MTD. Modified after Day-Stirrat (written communication).....72

Figure 5.6: Transmitted light microscopic images of samples from AT349-2 well core employed for XRTG analysis on left column. All images have the same scale. Depth of samples in subsea feet (ft) and meters (m) below sea floor. The corresponding pole density figure is also illustrated for each sample. The multiples of random distribution (m.r.d.) value and MICP-derived porosity for each sample are also given. The values in red correspond to the samples from the top-seal MTD. Modified after Day-Stirrat (written communication).....73

Figure 5.7: Plot of values of multiples of random distribution (m.r.d.) and pore throat radius versus depth for all the samples from the AT349-2 well core. Core diagram on left side displays the general lithology; shale, siltstone (Slst.), fine sandstone (F ss.). Red box corresponds to samples from the top-seal MTD. Numbers next to the symbols indicate the % of illite in mixed layer illite-smectite. Notice deeper buried samples with weak fabrics (small m.r.d. value). No m.r.d. value for sample at 2,536 mbsf (17,129 ft subsea) could be measured due to lack of fabric because of the relatively high silt-content. Green line tracks the increase of clay fabric towards the basal shear contact of top-seal MTD.74

Figure 5.8: Detail of AT349-2 well core showing the interval of the top-seal MTD. Depth scale in feet (ft) subsea and meter below sea floor (mbsf). Resistivity curve from AT349-1 well. Values m.r.d. from core material with respective pole figure. Porosity (%) and median *pore throat radius* (PTR) (in italic font) are shown for each sample within the top-seal MTD. Porosity is relatively high for these depths, however no trend with pore throat size is noted.75

Chapter 1: Introduction

Mass-transport complexes (MTCs) and Mass-transport deposits (MTDs) are gravity-induced deposits of remobilized sediments with a wide range of lithologies, sizes, and petrophysical properties (e.g. debris flows, slides, slumps) (Dott, 1963; Nardin et al., 1979; Hampton et al., 1996; Mulder and Cochonat, 1996; Moscardelli and Wood, 2008) (Figure 1.1). MTCs are volumetrically important in modern and ancient deepwater basins (Posamentier and Kolla, 2003) and have a significant interplay with turbidites (Pickering and Corregidor, 2005; Nelson et al., 2011; Ortiz-Karpf et al., 2015)—a typical reservoir-quality deposit in petroleum exploration. Although, for obvious industrial reasons, turbidites have received the most attention during the past decades, the more recent acquisition of high-resolution three-dimensional (3-D) seismic data has shown that many slope and abyssal systems comprise a very significant portion of MTCs. In some settings around the world, up to 70-90% of the entire slope and deepwater stratigraphic record is composed of MTCs and associated deposits (Canals et al., 2004; Newton et al., 2004; Moscardelli, 2007; Madof et al., 2009; Beaubouef and Abreu, 2010; Posamentier and Martinsen, 2011). Although numerous geoscientists use the terms MTDs and MTCs interchangeably, in this study we define a MTC as a depositional architectural complex comprised of several coeval or closely chronological- and genetically-related mass-transport deposits (MTDs)—i.e. architectural element approach by Sprague et al. (2005). This hierarchical classification helps distinguish the properties identified at seismic-scale from MTCs (~50-200 ms TWT time-thickness) and those identified in core- and wireline well-scale from MTDs (5-30 meters).

GRAVITY INDUCED DEPOSITS			Genetic Classification Transport Mechanism	Descriptive Classification Sedimentary Structures	Seismically Recognizable Features (Moscardelli et al., 2006; this work)
Mass Transport Complex	Slide		Shear failure along discrete shear planes with little or no internal deformation or rotation	Essentially undeformed, continuous bedding	Continuous blocks without apparent internal deformation. High-amplitude, continuous reflections.
	Slump		Shear failure accompanied by rotation along discrete shear surfaces with various degrees of internal deformation	Plastic deformation particularly at the toe or base. Plow structures, folds, tension faults, joints, slickensides, grooves, rotational blocks	Compressional ridges, imbricate slides, irregular upper bedding contacts, duplex structures, contorted layers. Low- and high-amplitude reflections geometrically arranged as though deformed through compressive stresses.
	Debris Flow		Shear distributed throughout the sediment mass. Strength is principally from cohesion due to clay content. Additional matrix support may come from buoyancy. Plastic rheology and laminar state.	Matrix supported, random fabric, clast size variable, matrix variable. Rip ups, rafts, inverse grading and flow structures possible.	Mega rafted and/or detached blocks, irregular upper bedding contacts, lateral pinch-out geometries, oriented ridges and scours. Low-amplitude, semitransparent chaotic reflections.
Turbidity Current	Turbidite		Supported by fluid turbulence (newtonian rheology)	Normal size grading, sharp basal contacts, gradational upper contacts.	Lobate features Laterally continuous

Figure 1.1: Classification of gravity-induced deposits employed in this study after Moscardelli and Wood (2008). Compiled from Dott (1963), Nardin et al. (1979), and Moscardelli et al. (2006).

In terms of their significance to oil and gas exploration, MTCs can act as reservoirs, seals, or significantly modify the nature of pre- and post-MTC deposited strata (Moscardelli et al., 2006; Armitage et al., 2009; Meckel, 2011; Alves et al., 2014). For instance, the Jubilee gas field in the offshore Gulf of Mexico, U.S.A. is an area where the hydrocarbon-trapping role of MTCs has been proven —as of 2014 the field has produced an estimated of 198 billion cubic feet of natural gas. The gas reservoir in this field is effectively sealed by a MTC that is the main subject for the microscopic analyses discussed in chapter 5 of this study. Besides the MTC acting as seal, an example of a

highly erosive MTC compartmentalizing the reservoir in the field also exists and will be discussed in chapter 4.

Nonetheless, it is often difficult to identify why MTCs and MTDs seal and still more difficult to predict when such sealing character will occur (Aplin and Macquaker, 2011). It is possible that zones with enhanced clay alignment and reduced pore-throat structure within MTDs as a result of shear deformation and remolding are important in creating the high seal quality in MTDs (Day-Stirrat et al., 2013) (Figure 1.2). Couples (2005) noted that deformation impacts key physical properties of the rocks such as those related to fluid flow. Since degree and style of deformation vary spatially within a MTC, in this study we hypothesize that the shear deformation that MTDs experience during the remobilization of the sediments can play an important role in creating sealing facies within MTCs. Understanding the degree of shear deformation as well as its spatial distribution within a MTC and its morphodomains (i.e. headwall, translational, and toe morphodomains after Bull et al., 2009) will help predict the sealing potential of different morphodomains and better plan the locations of wells. Moreover, different types of MTCs (attached vs. detached *sensu stricto* Moscardelli and Wood, 2008) may exhibit distinctive shear deformation that can be more likely to develop quality seal facies. Attempts in determining the degree of deformation/alignment of clay particles in MTDs using microscopic methods have been pioneered by Yamamoto and Sawyer (2012) and Day-Stirrat et al. (2013). This study, however, is the first to examine the fabric of a deeply buried MTD acting as the top-seal of a proven hydrocarbon field.

Figure 1.2: (a) Schematic model of different degrees of deformation within a MTC at X and X', proximal and distal areas of MTC respectively. (b) Schematic sections at X and X' showing the effect of shear deformation on the pore-throat architecture and clay fabric after the material has been remolded and sheared; large pores are closed and clay-platelets are aligned after shearing. Red arrows in (b) represent fluids escaping through open pores at X. Some of the fluids are trapped at X' due to deformation of pore-throats after shearing as well as development of higher clay fabric.

We propose that zones with enhanced-clay fabric in MTDs play a key role in creating effective hydrocarbon-sealing facies. Previous studies in the Gulf Coast mudstones (Freed and Peacor, 1989) and North Sea siltstones (Nadeau, personal communication in Ho et al., 1999) have shown the concomitant relationship between sealing effect and clay fabric development via smectite-illite (S-I) transformation. Nonetheless, we believe that enhanced clay alignment in MTDs can also be achieved by remolding during mass-movements (Figure 1.2). These mechanically-sheared clay sediments in MTDs can attain an unusual higher degree of alignment upon deep burial (Day-Stirrat et al., 2013) and thus become better hydrocarbon seals. Based upon these observations and works we hypothesize that the core samples from the top-seal MTD will show a high degree of clay alignment compared to the surrounding turbidite and hemipelagic mudstones.

This study has two main components. First, a description of the seismic characteristics of the MTC where the top-seal MTD is located discussed in chapter 4. Second, the petrophysical characteristics from the core samples of the top-seal MTD in the Jubilee field are considered in chapter 5. The Jubilee gas field is located in the Atwater Valley protraction of the Gulf of Mexico at a depth of 2,523 meters below sea floor (mbsf). A dataset of three dimensional (3D) seismic, core, and well data was utilized to establish practical observations about the attributes of an effective seal-MTD.

1.1 OBJECTIVES AND SCOPE

Predicting the petrophysical character of MTDs is at present a challenge faced by exploration companies. It is the focus of this research to investigate the role of MTDs as hydrocarbon seals. MTDs both seal and leak, yet it is not well understood what controls the quality of the seal in MTDs. The Jubilee field and associated data provide a laboratory for the study of MTDs, and afford us the opportunity to understand some of the factors controlling the sealing capacity of deepwater (>2000 mbsf) MTDs and examine the nature of a true sealing MTD. The applicable scope of this research is to help de-risk the sealing evaluation of MTDs and MTDs when assessing prospectivity in hydrocarbon exploration. This underlying goal will be achieved by accomplishing the following multi-scale tasks:

1. Determine the seismic geomorphologic expression of the MTD overlying the Jubilee reservoir and associated MTDs as well as classify the MTDs using the classification by Moscardelli and Wood (2008), and its implications for seal assessment and potential seismic-scale seal breaches.
2. Characterize the microscopic properties of the MTD acting as seal in the Jubilee field using core material to shed some light on the petrophysical properties of a true seal MTD.
3. Summarize observations about clay-fabric development and pore-throat reduction in MTDs as a result of mass-movements toward the implications for the creation of sealing facies within MTDs.

1.2 ARCHITECTURE OF MTCs AND IMPLICATIONS FOR SEAL POTENTIAL

Lewis (1971) was one of the early workers that noticed the idealized ‘tripartite’ anatomy of MTCs later observed by others (Prior et al., 1984; Martinsen, 1994; Frey Martinez et al., 2005). He recognized the systematic distribution of strain exhibited in several MTCs offshore New Zealand; with extensional structures characterizing the upslope region, relatively undeformed strata in the middle region, and compressional structures dominating the downslope region (Figure 1.3).

Figure 1.3: Lewis (1971) first schematic model about the ‘tripartite’ anatomy of a MTC in cross-section and the systematic distribution of strain. Unstippled beds have slumped; sparsely stippled beds have been disturbed; densely stippled beds have not been disturbed. Cross-hatching overlies a zone of compressional folding and thrusting at toe of MTC. Vertical hatching overlies a zone of undeformed or slightly deformed beds in the middle of the MTC. Solid lines overlie an exposed glide plane in a zone of tension at the head of the MTC. Large stipples overlie disturbed beds beneath smooth seabed.

Bull et al. (2009) proposed three ‘domains’ to define the three particular regions that comprise the architecture of an idealized MTC: the headwall domain, translational domain, and the toe domain. In this study we adopted the tripartite model of MTCs and modified the term ‘domain’ for *morphodomain* because this term encompasses recognizable seismic-scale structural as well as morphological features and their likely stress domain (Figure 1.4). This model-driven approach allows the identification of MTCs and their morphodomains based on particular characteristics in the deposits regardless their size or lithological nature. The deformation style of some of the deposits within the morphodomains can be also used as *kinematic indicator* providing information about the direction of transport (Martinsen, 1994) (Figure 1.5). This approach can potentially be used as a tool for first-order predictions/assessments of the petrophysical properties of deposits located in different MTC morphodomains that have been deformed/remolded by mass-transport processes (Couples, 2005)—e.g. lithologies with likely poor seal-potential due to pervasive micro-faulting in headwall morphodomain, or reduction of permeability in the deposits transported towards the toe-morphodomain due to shear deformation (Yamamoto and Sawyer, 2012). Equally important, this approach can be employed to detect *seal bypass systems* in MTCs —term defined by Cartwright et al. (2007) as seismically resolvable geological features embedded within sealing sequences that promote cross-strata fluid migration and allow fluids to bypass the pore network.

Figure 1.4: Idealized MTC showing the three *morphodomains* (headwall, translational, and toe) and the likely stress-regime relative to each morphodomain. Some of the distinctive features of MTCs are labeled.

Figure 1.5: Summary diagram showing the key morphological criteria for the recognition of all kinematic indicator types. BSS –basal shear surface. KI –kinematic information. Bold arrows indicate direction of transport. After Bull et al. (2009).

Morphometric dimensions of MTCs, as defined by Moscardelli (2007) and Moscardelli and Wood (2015), refers to quantitative measurements of MTCs (area, length, width, thickness, volume, etc.) that can be used in conjunction with an understating of causal mechanisms, location of sediment source area, and the relationship of the MTC to the sediment source to identify the type of MTC. Moscardelli and Wood (2008) proposed a keen classification system to catalog different types of MTCs. In their work, MTCs are classified into two categories: attached-MTCs and detached-MCTs (Figure 1.6). In general terms, attached-MTCs are those that are attached to a shelf or slope sediment source, and are commonly triggered by regional events that have the capacity to destabilize outer-shelf/upper-slope areas thus triggering massive mass-wasting processes (e.g. sea-level fluctuations, earthquakes, hydrate dissociation, etc.). On the other hand, detached-MTCs are smaller (less than tens of km^2 in area, few kilometers in length, and volumes less than 10 km^3) and commonly triggered by localized mechanisms such as instabilities on the flanks of mud or salt masses or mid-oceanic ridges. An important point about detached-MTCs is that most of their sediments are derived locally within the minibasin of deposition. All the three aforementioned morphodomains can be present in both types of MTCs —attached and detached-styles.

Figure 1.6: Schematic figure from Moscardelli and Wood (2015) showcasing the main differences between attached and detached MTCs in terms of causal mechanisms and scales (area versus length log-log plot).

Headwall Morphodomain

This area, also known as the “evacuation zone”, encompasses the upslope, proximal region of a MTC and can occasionally be steeply dipping (Dalla Valle et al., 2013). This morphodomain is dominated by extensional stresses, thus typically forming *normal-fault systems, extensional ridges, and headwall scarps* (Bull et al., 2009) (Figure 1.4 and 1.5). Because of its proximity to the source of the MTC, the presence of rafted blocks with minor-to-moderate deformation is common (Gamboa et al., 2012) (Figure 1.7a)—exceptions exist depending on original lithology. Increasing block deformation indicates larger travel distances, as magnitude of downslope transport of deposits is a key factor controlling their final degree of deformation (Yamamoto and Sawyer, 2012).

The sealing potential of the headwall morphodomain is relatively poor because of the common presence of normal faults, scarps, and blocks that can provide pathways for fluids to migrate (Ligtenberg, 2005). Presence of rafted blocks can also hamper the formation of sealing facies (Gamboa and Alves, 2015) (Figure 1.7b). Care is advised when assessing the sealing capacity of deposits located in the headwall morphodomain.

Translational Morphodomain

Translational morphodomain is the area located between the up and downslope limits of a MTC. As noted by Martinsen (1994), the movement of failed material downslope across the basal shear surface can lead to intense deformation. This morphodomain is dominated by shear stress and strike-slip deformation; as a result, *grooves, basal shear surfaces, longitudinal shear, lateral margins, strike-slip deformation* are characteristic features to mention a few (Bull et al., 2009) (Figure 1.4 and 1.5).

The sealing potential of the translational morphodomain is relatively promising compared to the other morphodomains because of the relative absence of mass-transport-

induced faulting and the positive effect of shear deformation; as it preferentially destroys large pore-throats (Yamamoto, 2006) and can also reduce the permeability of the remolded material thus creating better sealing facies (Arch and Maltman, 1990; Dewhurst et al., 1996; Bolton et al., 2000).

Figure 1.7: (a) Examples of different styles of deformation in rafted blocks from Gamboa et al. (2012). (b) Sketch illustrating fault and fracture meshes within rafted blocks in a MTC from Gamboa and Alves (2015). Fluids can propagate vertically through the block along faults and fractures, and horizontally along sheared beds.

Toe Morphodomain

The toe morphodomain is the downslope area located near the terminus of the MTC. This morphodomain is also known as the “accumulation zone” where the mass-transport deposits come to a halt and accumulate (Frey Martinez et al., 2005). As a result of this buttressing effect, this morphodomain is dominated by compressional stresses. The characteristic features are *pressure ridges, thrust and fold systems, and ramps* (Figure 1.4 and 1.5). Sometimes, *outrunner-blocks* can also be present depending on the lithologic nature of the MTC (Nissen et al., 1999) (Figure 1.8).

The sealing potential of the toe morphodomain can also be hindered by the common presence of thrust systems that can affect sections as thick as 500 m as reported by Gafeira et al. (2007). In addition, the likely formation of low-angle reverse faults in this morphodomain can create seal bypass systems.

Figure 1.8: Sequence of deformational process in the emplacement of outrunner blocks and buttressing effect in the toe morphodomain. After Nissen et al. (1999).

Chapter 2: Geologic Setting

The Jubilee field is located in the Atwater Valley protraction area, offshore eastern Gulf of Mexico approximately 190 km off the coast at a present water depth of ~2,600 m (8,830 ft) (Figure 2.1). The complex distribution of Neogene-age reservoirs and traps around the Atwater Valley area is a function of the interaction of salt mobilization and very high sedimentation rates during the Neogene (Galloway et al., 2004).

Figure 2.1: Water depth of present Gulf of Mexico, U.S.A showing the location of the Jubilee field and the main regional physiographic features (shelf edge, Mississippi Canyon, Sigsbee Escarpment). Boundaries and names correspond to protraction areas. Bathymetric data kindly provided by M. Prieto (written communication).

2.1 STRUCTURAL FRAMEWORK

The study area is part of a regionally extensive fold belt trend at the leading edge of autochthonous salt basinward of the present day (allochthonous salt) Sigsbee Escarpment (Byrne et al., 1999; Rowan et al., 2004) (Figure 2.2). Although the deposits comprising the Jubilee field overlie the top of the autochthonous salt by almost 2 seconds two-way travel time (TWTT), the mobile substratum has been the dominant factor influencing the structural evolution of this area (Figure 2.3 and 2.4). The relatively structureless Atwater Valley area has deep deformed autochthonous salt forming a salt pillow (Hudec, 2000) that creates a compactional drape trap style in the Jubilee field (Weimer and Bouroullec, 2013) (Figure 2.4). The compactional trap has been caused by movement that occurred in the basin-fill some time after its deposition (Allen and Allen, 2013).

Figure 2.2: Regional 2-D seismic line showing the location of the Jubilee field. Deep deformed autochthonous salt is the main structural control in the area of the Jubilee field. Location of 2-D line is shown in figure 2.1.

Figure 2.3: (a) Two-way time map of top of autochthonous salt (CI=50 ms) underlying the Jubilee field. (b) Two-way time map of reservoir horizon (CI=25 ms) in Jubilee field. Extension of maps shows the available seismic coverage for this study.

Figure 2.4: Dip section through the wells in the Jubilee field showing the influence of the autochthonous salt. White arrow points at the bright-reflectors of the reservoir deposits in the Jubilee field. Red arrow points at the MTC sequence overlying the reservoir in the Jubilee field. Location of section is in Figure 2.3. Right-inset is a schematic model of the compactional drape trap style formed in the Jubilee field (Hydrocarbons in green).

2.2 STRATIGRAPHIC FRAMEWORK

During the Miocene through Pliocene, depositional rates in the Gulf of Mexico exceeded salt deformation rates creating a bypass or smoothed slope profile that served as a fairway to transport abundant sediment to the abyssal plain (Prather et al., 1998; Byrne et al., 1999). Buried salt sheets and abyssal plain fan sequences provide direct evidence that the sedimentation rates overwhelmed intraslope salt deformation (DeVay et al., 2000). The deposits of the Jubilee field exhibit a typical succession laid down in a deepwater setting (Posamentier and Kolla, 2003) whereby a MTC at the base is overlain by turbidite deposits of a frontal splay, a channel complex, and subsequently capped by a younger MTC (Figure 2.5). The MTCs in this area are believed to have been sourced from the nearby salt uplifts to the north and northwest of the field (Tripsanas et al., 2004; Madof et al., 2009).

The paleogeography of the area during the Upper Miocene was dominated by the McAVLU submarine fan (named for its location beneath the Mississippi Canyon, Atwater Valley, and Lund protractions) (Galloway et al., 2000). The McAVLU fan was fed with large volumes of sediment from the paleo-Tennessee and paleo-Mississippi fluvial systems that formed a sand-rich depocenter in the Atwater Valley area (Combellas-Bigott and Galloway, 2002; Snedden et al., 2012) (Figure 2.6).

Figure 2.5: (a) Seismic reflection profile from offshore Indonesia illustrating the typical succession of a deepwater sequence according to Posamentier and Kolla (2003); lower debris-flow deposit (lower MTC), frontal-splay deposits, levee deposits, upper debris-flow deposits (upper MTC), condensed-section deposits. (b) Schematic depiction of an idealized deepwater sequence with two hypothetical log profiles after Posamentier and Kolla (2003).

Figure 2.6: Paleogeographic map of Upper Miocene (12-6 Ma) Gulf of Mexico. The paleogeography was dominated by the sand-rich McAVLU submarine fan that covered most of the Atwater Valley protraction, where the Jubilee field is located.

2.3 THE JUBILEE GAS FIELD

The Jubilee field discovery well, Atwater 349 No.1 (AT349-1), was drilled in a water depth of 2,680 meters (8,800 ft) by Anadarko Petroleum Corporation in March 2003 targeting a high amplitude anomaly (Figure 2.8). The well reached a subsurface depth of 5,580 m (18,310 ft) with respect to sea level and encountered 25 meters (83 ft) of net natural gas pay. The estimated field size is 40 to 50 million barrels of oil equivalent (BOE). In February 2004, the current producing well AT349-2 was drilled and has produced an estimated of 198 billion cubic feet of natural gas (35 million BOE) as of 2014.

Figure 2.7: Anadarko presence in the Atwater Valley region. Besides Anadarko's Jubilee discovery in 2003, other field discoveries are Spiderman and Atlas. Modified after Greene & O'Neill (2006).

The reservoir in the Jubilee field is composed by high-density turbidites and frontal-splay deposits, compensationally stacked in an abyssal plain environment that are capped by a MTC (Figure 2.8 and 2.9). MTCs in the Jubilee field play different roles, both destroying reservoir-quality deposits and acting as top seal. The MTC acting as the top seal of the main Jubilee field reservoir is the subject of this study —herein called the top-seal MTC. The frontal-splay deposits associated to the reservoir level in the Jubilee field have an approximate age of Upper Miocene bounded by *Catinaster coalitus* (Tortonian 11.2-7.2 Ma) and *Globorotalia juanai* (Messinian 5.3-7.2 Ma) faunal tops determined from well samples (Witrock et al., 2003).

Figure 2.8 (Next two pages): (a) Uninterpreted map and seismic section of Jubilee field. (b) Interpreted map and seismic section. Map of root-mean square (RMS) amplitude extraction of frontal-splay horizon with symmetrical 30 ms window. Note high amplitude anomaly centered around AT349-1 well. Map shows the main depositional elements in the field. Red-dashed line outlines the interpreted area of the top-seal MTC. Seismic section X shows the key horizons in the Jubilee field. The Jubilee field is composed of frontal-splay deposits, a mud-filled channel complex, and subsequent capped by the top-seal MTC (outline of deposit in red-dashed line on map). Yellow arrows point at a feeder-channel of frontal-splay. Origin of megascours discussed in chapter 4. Notice high amplitude in the interpreted frontal-splay deposits as a result of gas-charge effect. See 3-D perspective of RMS map in Figure 2.9.

Figure 2.9: North-facing 3-D view of frontal-splay horizon with draped RMS amplitude from figure 2.8. Deep-buried salt is the main structural control in the field.

Chapter 3: Available Data and Methodologies

The available data for this study are a 3D reflection seismic survey in two-way-travel time (TWTT) with a dominant frequency around 40-45 Hz covering 141 km² over the Jubilee field (Figure 2.3); 56 m (185 ft) of core from 2,509 to 2,565 mbsf (17,040-17,125 ft subsea) through the top-seal MTC and underlying reservoir interval of the AT 349-2 well (Figure 3.1); and several conventional wireline well logs from wells located closely adjacent to the cored well (AT305-1, AT349-1, AT349-2). In total nine samples from AT 349-2 well core, four of which are directly from the top-seal MTD (Figure 3.2), were analyzed using X-Ray Texture Goniometry (XRTG) methods to determine the degree of alignment of clay minerals. In addition to XRTG, other microscopic methodologies used to characterize the petrophysical properties of the top-seal MTD were X-Ray Powder Diffraction (XRPD) and Mercury Injection Capillary Pressure (MICP). We have also conducted a detailed seismic geomorphologic interpretation of the 3D seismic volume with emphasis on the Jubilee reservoir interval and the overlying MTC (see seismic section at Figure 2.8b for key horizons). Proper techniques for evaluating seals need to be exercised at two different scales: a “micro” scale and a “mega” scale as originally pioneered by Downey (1984) over three decades ago.

Figure 3.1 (Next page): Description of the core acquired at the AT349-2 well in the Jubilee field. Description was generously provided by Anadarko geoscientists to the Quantitative Clastic Laboratory at the Bureau of Economic Geology. Depths at which samples were collected for the microscopic analyses (see sections 3.2,3.3. and 3.4) marked by red tick marks. The red-box encompasses the location of the top-seal MTD (the subject of chapter 5) from 17,086 to 17,132 ft subsea (2,523 to 2,537 mbsf). Figure 3.2 shows 20 ft-interval sections of the core for more detail (Deepening from top-down. Shallow part of core on the left, deeper part on right).

Figure 3.2 (Next five pages): Enlarged 20-ft interval sections of core description from the AT349-2 well in the Jubilee field. Total depth interval of core is from 17,040 to 17,225 ft subsea (2,509 to 2,565 mbsf). Depths at which samples were collected for the microscopic analyses are marked in red tick marks. The red-box encompasses the location of the top-seal MTD (the subject of chapter 5) from 17,086 to 17,132 ft subsea (2,523 to 2,537 mbsf). Description of the core was generously provided by Anadarko geoscientists.

3.1 SEISMIC GEOMORPHOLOGY METHODOLOGY

With the advent of 3D visualization and seismic acquisition in the past two decades, the opportunity to image geological features in plan view became possible and the methodologies of seismic geomorphology evolved (Posamentier, 2000). Seismic geomorphology may be defined as the application of analytical techniques concerning to the study of landforms and to the analysis of ancient, buried geomorphological surfaces as imaged by 3D seismic data (Posamentier et al., 2007). Sound seismic geomorphology interpretation integrated with borehole data (e.g. core and well data) can yield predictions regarding distribution of source, seal, and reservoir facies as well as the identification of compartmentalization.

Seismic interpretation methodologies are well documented by a variety of authors, including but not limited to Enachescu (1993); Zeng et al. (1998); Zeng et al. (1998); Partyka et al. (1999); Posamentier (2004, 2005); Posamentier et al. (2007); Hart (2008); Brown (2011). Several techniques such as horizon picking, time and stratal slicing, amplitude attribute extraction (e.g. instantaneous, root-mean square (RMS), semblance, sweetness, spectral decomposition), and 3D volume rendering were employed to explore the interaction between the reservoir-quality frontal splay deposits and the overlying MTCs in the Jubilee field. The seismic nature of the MTCs overlying the Jubilee field reservoir was studied and classified according to Moscardelli and Wood (2008).

Key horizons at the frontal splay level (*frontal splay horizon*), and on the top and base of the overlying top-seal MTC (*MTC-top and MTC-base horizons*, respectively) were mapped using automatic and manual picking techniques in *DecisionSpace*® interpretation software by Halliburton (See seismic section in Figure 2.8b for key

horizons). The internal seismic character of the MTCs were then analyzed by creating amplitude extraction stratal slices and perspective volumes. Previous studies (McGilvery et al., 2004; Moscardelli et al., 2006; Bull et al., 2009; Posamentier and Martinsen, 2011; Ogiesoba and Hammes, 2012; Alves et al., 2014) about the seismic and outcrop characteristics of MTCs and MTDs and references therein served as referents to interpret the MTCs in the Jubilee field.

3.2 XRPD METHOD

X-ray powder diffraction (XRPD) analysis is a conventional microscopic method to determine the composition of a crystalline compound or rock sample. The methodology is comprehensively described by Hillier (1999, 2002). The sample analyses were carried out by *Macaulay Analytical Consulting Ltd.* in Aberdeen, Scotland in April 2011.

Nine samples from the whole core at the AT349-2 well ranging from depths of 2,509 to 2,565 mbsf (17,040-17,125 ft subsea) were analyzed using the XRPD method to determine their bulk composition and <2 μm clay-sized fraction composition. Four of the samples are directly from the top-seal MTD overlying the gas-producing reservoir and helped in determining the lithological composition of the top-seal MTD. Detailed identification of clay minerals in the clay-sized fraction was based on the procedures presented by Hillier (2003).

Subsea Depth (ft)	Depth (mbsf)
17042	-2509
17044	-2510
17093	-2525
17101	-2527
17121	-2533
17129	-2536
17209	-2560
17181	-2552
17221	-2564

Table 1: Depths of samples taken from whole core at AT349-2 well for microscopic analyses. Depth in feet (ft) subsea and meters below sea floor (mbsf). Bold depths correspond to samples within the top-seal MTD.

3.3 MICP METHOD

Mercury-injection capillary-pressure (MICP) is a common method to determine the pore-size distribution of rock samples. The method is used routinely in the energy industry to evaluate seals for traps and explain the location of stratigraphic hydrocarbon accumulations (Pittman, 1992). The physical laws of the porosimetry method were established by Washburn (1921) whereby the capillary pressure, P_c , required to force mercury into a capillary pore of radius r is; $P_c = [-2Y\cos(\theta)]/r$, where Y is the surface tension and θ the angle of contact (Daniel and Kaldi, 2012). Consequently, smaller pore throats are associated with greater entry pressures, P_c .

The nine samples (Table 1) from the whole core at the AT349-2 well were analyzed in June 2011 by *PoroTechnology* in Houston using MICP techniques. The height of the gas columns for the samples from the core were calculated using the entry pressures and then converted into equivalent gas column heights at 35% saturation following the approach by Krushin (1997). This method helped investigate the impact of deformation as a result of mass-movement on the pore-throat architecture of the top-seal MTD. The maximum size of a hydrocarbon column a lithology can seal is limited by the sample's largest interconnected pore throat.

3.4 XRTG METHOD

X-ray texture goniometry (XRTG) method is a relatively rapid microscopic technique employed to determine the average crystallographic-preferred orientation (*texture*) over a small region ($<1 \text{ mm}^2$) of a mineral in a deformed rock (Weiss and Wenk, 1985). The degree of preferred orientation or texture can be expressed as the

maximum pole densities in multiples of random distribution — m.r.d. — in which a value of 1 corresponds to a random or isotropic distribution and higher values reflect higher degrees of preferred orientation or fabric (Weiss and Wenk, 1985; Wenk, 1985; Kanitpanyacharoen et al., 2011). Typically, the pole densities are displayed in pole figure diagrams; more highly aligned textures or fabrics yield pole figures that can be contoured as concentric rings, whereas random or isotropic fabrics yield figures that have no poles. Aplin et al. (2006) recognized that the m.r.d. values for mudstones in the Gulf of Mexico are independent of burial depth over a range of 1.5 to 5.5 km. For further information regarding XRTG methodology, the reader is referred to van der Pluijm et al. (1994).

XRTG analyses were carried out on the nine samples (Table 1) from the core at AT349-2 well by research colleague, Dr. Ruarri Day-Stirrat in May 2011. This technique allowed us to quantify the degree of phyllosilicate deformation of the samples from the AT349-2 well core, including the ones directly from the top-seal MTD. The results were expressed in m.r.d. values and pole figure diagrams for all the samples were obtained except the one at 2,536 mbsf (17,129 ft subsea). Transmitted light microscopic pictures of the thin-sections of the samples employed for the XRTG analyses were also acquired to qualitatively observe for development of fabric.

Chapter 4: Seismic Expression of the MTCs in the Jubilee Field

In this chapter, we will discuss the seismic nature of two MTCs, one overlying the reservoir facies in the Jubilee field and the other scouring into and compartmentalizing the reservoir facies. We hope that the description of the seismic expression of the MTCs in the Jubilee field can serve as practical observations to help predict the seal potential of other MTCs, and similarly, to identify potential *seal bypass systems* within MTCs. The seismic expression of MTCs is well documented by a variety of authors, including but not limited to Posamentier and Kolla (2003); Weimer and Shipp (2004); McGilvery et al. (2004); Frey Martinez et al. (2005); Moscardelli et al. (2006); Moscardelli and Wood (2008); Bull et al. (2009); Gamboa et al. (2010); Jackson (2011); Posamentier and Martinsen (2011); Alves et al. (2014).

4.1 THE TOP-SEAL MTC

The MTC associated with the Jubilee trap shows many of the basic seismic characteristics of MTCs, including chaotic and discontinuous seismic facies, weak seismic amplitude, hummock relief, micro-faulting, and pressure ridge development (Figure 4.2). Unlike other MTCs —e.g. MTCs in Figure 17 and 21 of Dunlap et al. (2010) or Figure 6 of Alves (2015)—the MTC overlying the reservoir in the Jubilee field is virtually devoid of large transported mega- blocks (Figure 4.2 and 4.3). Presence of rafted blocks in MTCs can decrease their seal capacity as they can create points of fluid migration when buried in low permeability strata as also observed by Gamboa and Alves (2015) (Figure 1.7). The top-seal MTC over the Jubilee field averages a time-thickness

between 60 ms to 80 ms TWT (Figure 4.1) and has a minimum interpreted area of about 35 km² inside the seismic survey coverage. The part of the MTC acting as the effective top seal in the field is identified as occurring in the transitional area between the translational and toe morphodomains. Kinematic indicators (Martinsen, 1994; Bull et al. 2009) interpreted from the top-seal MTC such as longitudinal shears, pressure ridges and imbricated pattern suggest a transport direction from the north to the south-southeast (Figure 4.4). A single 2D seismic line was tied to the 3D seismic survey, showing that the top-seal MTC was possibly sourced from a nearby salt diapir (Figure 4.5) — a typical slope failure driver in the area (Tripsanas et al., 2004). The MTC has a run-out distance of about 12 km to the location of the AT349-2 well; fairly short for MTCs (Moscardelli and Wood, 2015). Based on these morphometric parameters and seismic characteristics, the top-seal MTC is interpreted to be of detached style according to the classification devised by Moscardelli and Wood (2008), and its low-amplitude and chaotic seismic character is suggestive of a predominantly mud-prone composition (Posamentier and Kolla, 2003). The inferred composition is supported by XRPD results from core material presented in chapter 5.

Figure 4.1: Time-thickness map of top-seal MTC. Dashed-red line is the interpreted outline of the top-seal MTC. Notice the thickening in the accumulation zone towards the toe morphodomain of the top-seal MTC.

Figure 4.2: (a) Uninterpreted and (b) interpreted amplitude stratal slice between top-seal MTC-base and the top-seal MTC-top horizons. Arcuate to linear patterns in map view are interpreted as pressure ridges. Dashed-red line is the interpreted outline of the top-seal MTC; note the chaotic seismic facies towards the toe of the top-seal MTC. The producing well is located in the area between the translational and toe morphodomain. Red-arrow indicates the top-seal MTC direction of transport and magenta-arrow points at a rafted block from an older MTC discussed in section 4.2 associated to one of the megascours of Figure 2.8.

Figure 4.3: North-northwest facing 3-D view of stratal slice through the middle of the top-seal MTC in Jubilee field exhibiting typical features of the area between the translational and toe morphodomains of a MTC; hummock relief, micro-faulting, pressure ridges, and longitudinal shear. Dashed-red line is the interpreted outline of the top-seal MTC. Magenta-arrow points at a rafted block transported by an older MTC that created one of the megascours discussed in section 4.2. Section Y-Y' shown in Figure 4.4.

Figure 4.4: Chair slice through the top-seal MTC in the Jubilee field. Note the imbrication-pattern of the pressure ridges in cross section. These kinematic indicators suggest a transport direction from north to south-southeast. Magenta-arrow points at a rafted block transported by an older MTC that created one of the megascours discussed in chapter 4.2.

Figure 4.5: 2D seismic line tied to 3D seismic survey in the Jubilee field. Our interpretation suggests that instabilities on a salt diapir are a possible causal mechanism of the top-seal MTC. See Figure 1.6 for schematic model. Location of 2D seismic line in Figure 2.1.

4.2 THE SCOURING MTC

The second MTC of note in the Jubilee field, to the south of the producing well, actually overlies the reservoir facies incising down into the underlying frontal-splay reservoir deposits and effectively compartmentalizing the reservoir (Figure 4.6). MTCs are known to be an important cause of compartmentalization in deepwater reservoirs (Chen, 2013). This MTC carved prominent *megascours*; defined by Moscardelli et al. (2006) as erosional expressions created by significant basal erosion and gouging during erosive mass-flows. Nissen et al. (1999) demonstrated how these erosional features are commonly associated to outrunner-blocks. Studies from outcrop have demonstrated that mass-transport processes can create large scours removing up to 35 m of thickness of sandy submarine fans (Pickering and Hilton, 1998; Dakin et al., 2013). The megascour records the path of the outrunner blocks and thus can be used as a kinematic indicator.

This scouring MTC displays chaotic and discontinuous facies except where an interpreted outrunner-block is located: the mega-block exhibits a localized strong and continuous amplitude indicative of a more consolidated material (Nissen et al., 1999) (Figure 4.7). The thickness of this MTC is unresolvable in seismic data; however, a mega-block associated to one of the megascours has an average time-thickness of ~60 ms and a length of almost 500 m (Figure 4.8). This scouring MTC has a width of ~600 m and becomes slightly wider downdip where it is bounded by a lateral scarp and a fault (Figure 4.9). The scour area is at least 2-3 km² and the MTC runout is more than 5 km in a southeast direction. According to these morphometrics, this MTC is also of detached-style according to Moscardelli and Wood (2008) classification and probably also associated to intrabasinal instabilities.

We attribute the high erosive power of this MTC to the confinement effect by the earlier-formed channel complex observed to the northwest of the producing well (Figure 4.6). Posamentier and Walker (2006) call this type of MTCs “opportunistic” because it opportunistically used an earlier-formed channel, which enhances its erosive power.

Figure 4.6: Interpreted map of sweetness attribute from the frontal-splay horizon at the reservoir level with TWTT-contours, CI= 25 ms. High sweetness is associated to sand-rich and hydrocarbon-charged deposits (Hart, 2008). A_1 , A_2 , and A_3 referred to the areas of the three high-sweetness compartments. Compartments A_1 and A_2 are separated by the megascour formed by the scouring MTC whereas compartments A_2 and A_3 are separated a normal fault (U: upthrown, D: downthrown). Notice same hydrocarbon-water contact (HWC) for all three compartments.

Figure 4.7: (a) Uninterpreted and (b) interpreted arbitrary section in Figure 4.6 showing the profile of the two NW-SE trending megascours seen in map. Note high-amplitude reflectors (white arrows) directly overlying the scours. Nissen et al. (1999) interpreted high amplitude reflections located immediately above scours that contrast with surrounding low-amplitude and chaotic reflections as potential rafted or outrunner blocks. Location of section in Figure 4.6.

Figure 4.8: (a) Uninterpreted and (b) interpreted seismic section showing a mega-block and associated lateral scarp (yellow arrow) evidence of intense scouring (linear feature in map view). See high-amplitude reflectors (magenta arrow) associated to the outrunner block. Location of section in Figure 4.6.

Figure 4.9: North-Northwest facing 3D view of frontal-splay horizon with semblance attribute draped. Megascour compartmentalizing the reservoir deposits associated to the scouring MTC displays chaotic facies with low semblance. The lateral scarp (yellow arrow) is evidence of the high erosive power of this scouring MTC as a result of the confinement effect by the earlier-formed channel complex updip, and possibly the fault downdip. Red arrow delineates the interpreted runout of the scouring MTC. Inset seismic section is Figure 4.8.

4.3 SEISMIC-DETECTABLE SEAL BREACHES IN THE TOP-SEAL MTC IN THE JUBILEE FIELD

When evaluating the sealing potential of MTCs, seismic interpretation can offer a powerful technique to identify features or indicators of hydrocarbon leakage e.g. gas chimneys, pockmarks, mud volcanoes, etc. Løseth et al. (2009) proposed a methodology to investigate some of these seismic-detectable leakage indicators. Downey (1984) recognized that some high-quality seals may be breached episodically or semipermanently by a different range of geological structures — seal bypass systems of Cartwright et al. (2007).

In the Jubilee field, an array of pockmarks or ‘pockmark train’ (Pilcher and Argent, 2007) is located ~1 km to the east of the producing well and at the same depth-level as the horizon defining the top of the seal-MTC (Figure 4.10). These buried pockmarks have a diameter of 200-300 meters and their spatial arrangement seems to be controlled by a fault (Figure 4.11). The pockmarks are inferred to be indicators of fluid expulsion and soft fine-grained sediments are often suggested as a necessary recording medium for their formation (Chand et al., 2009). Moreover, the presence of an interpreted gas chimney or pipe overlying one of the pockmarks is evidence of active or past fluid migration (Heggland, 2005) (Figure 4.12). Although the pockmarks at the Jubilee field are buried more than 2 km below sea floor, when near the surface they can be a geohazard indicator (Hovland et al., 2002).

Figure 4.10: Map of horizon defining the top of the top-seal MTC with the semblance attribute draped. The superimposed transparent RMS amplitude is from the horizon at the frontal-splay level (the reservoir deposits) that delineates the Jubilee gas field. Note the fault controlling the linear arrangement of some of the pockmarks (p) in the upthrown block (U). Only one pockmark is located in the downthrown block (D) of the fault where the Jubilee field is located, and no pockmarks are located updip the limit of the gas field. Pockmarks near the toe morphodromic of the top-seal MTC exhibit an arcuate arrangement. Pockmarks are inferred to be indicators of fluid expulsion, thus their presence can be seen as a sign of seal deficiency.

Figure 4.11: Seismic section through pockmark train at the level of the top horizon of the top-seal MTC. Note the concave up geometry of reflector in pockmarks (p) possibly due to collapsing. Normal-fault seems to control the linear arrangement of these three pockmarks. Location of section in Figure 4.10.

Figure 4.12: Seismic section through pockmark (p) and normal fault. Pipe directly overlying the pockmark is identified because of the disruption of stratal reflections and localized sag folding above pockmark (p). Location of section in Figure 4.10.

Figure 4.13: North facing 3D view of top horizon of top-seal MTC with semblance attribute draped (semblance color scale in Figure 4.10). Pockmarks (p) in the southeastern flank of the top-seal MTC exhibit an arcuate arrangement. This arrangement seems to be controlled by the formation of pressure ridges in the toe morphodomain of the top-seal MTC. Inset seismic section shows detail of a pockmark (p). Pockmarks are known to be associated to the flanks of some MTCs (Paull et al., 2008).

Chapter 5: Microscopic Analyses of the Top-Seal MTD

In this chapter, the results from the microscopic analyses of core material from the AT349-2 well are presented. Nine samples in total from the core were analyzed; four of the samples were directly from what we have termed the *top-seal* MTD located directly above the producing formation in the Jubilee field (Figure 5-1).

5.1 XRPD RESULTS

XRPD results from the AT349-2 core samples suggest that the composition of the top-seal MTD is the typical composition of a Gulf of Mexico mudstone (K. Milliken, personal communication). The bulk samples are dominated by quartz (26-47%) and illite+illite-smectite (30-49%) with smaller amounts of plagioclase, K-feldspar (2.5-4.8%), calcite, dolomite, siderite, halite, muscovite, kaolinite and chlorite (Table 2). The <2 μm clay fraction is dominated by mixed-layer illite-smectite (84-92%) with smaller amounts of illite (4-7%) kaolinite and chlorite (Table 3). The average temperature for the top-seal MTD interval (2,523 to 2,537 mbsf) is $\sim 52^{\circ}\text{C}$ calculated using maximum bottom hole temperatures (BHT) of nearby wells (AT305-1, AT349-1, AT349-2) (Figure 5.2). Although the smectite-illite reaction may be influenced by several factors, reaction progress appears to be strongly controlled by temperature (Pollastro, 1993). Freed and Peacor (1992) proposed that the diagenic smectite-illite transition occurs between temperatures of 83°C to 88°C . This transformation plays a critical role in fluid migration in the subsurface (Burst, 1969).

Figure 5.1 (Next page): Segment of AT349-2 well core showing the interval of the top-seal MTD (red box). Depth at which samples were collected for microscopic analyses are indicated by red tick marks. Description of the core was generously provided by Anadarko geoscientists.

Labcode	Sample	Quartz	Plagioclase	K-feldspar	Calcite	Dolomite	Siderite	Pyrite	Halite	Muscovite	Illite+ Illite-Smectite	Kaolinite	Chlorite	Total
1060658	ATWATER-349-17044FT-B	43.9	4.0	4.7	2.7	1.1	0.0	0.5	0.4	5.8	30.0	6.3	0.9	100.3
1060659	ATWATER-349-17042FT-B	46.8	3.8	4.3	2.7	1.0	0.0	0.4	0.3	4.2	30.6	5.0	0.8	99.9
1060660	ATWATER-349-17093FT-B	25.9	3.6	3.8	7.4	0.8	0.0	0.8	0.2	2.9	46.6	7.7	0.5	100.2
1060661	ATWATER-349-17101FT-B	35.5	4.1	4.8	2.6	0.9	0.0	2.1	0.4	4.6	38.0	6.6	0.4	100.0
1060662	ATWATER-349-17121FT-B	33.7	3.6	3.4	0.7	0.8	2.6	0.3	0.0	7.8	35.6	11.4	0.2	100.1
1060663	ATWATER-349-17129FT-B	32.2	3.8	2.8	0.7	1.0	0.0	1.5	0.5	2.5	48.3	5.8	1.1	100.2
1060664	ATWATER-349-17209FT-B	28.9	3.2	2.5	2.8	1.4	0.0	0.9	0.5	3.0	47.7	8.1	1.2	100.2
1060665	ATWATER-349-17221FT-B	29.9	3.8	3.9	2.0	0.6	0.0	0.7	0.1	1.2	49.3	8.6	0.1	100.2
1060666	ATWATER-349-17181FT-B	38.1	5.5	4.7	0.3	0.6	0.0	0.8	0.4	2.1	40.9	5.7	0.9	100.0

Table 2: XRPD bulk mineralogy (weight %) of samples from AT349-2 well core (Day-Stirrat, written communication).

Lab-codes	Customer sample ID.	XRD pattern name	Chlorite	Kaolinite	Illite	Illite-smectite	%Exp*
1060658	Atwater-349 17044ft	ATWATER-349-17044FT-A,-G,-H3	2	7	7	84	50-60
1060659	Atwater-349 17042ft	ATWATER-349-17042FT-A,-G,-H3	1	6	6	87	55-65
1060660	Atwater-349 17093ft	ATWATER-349-17093FT-A,-G,-H3	1	5	5	89	55-65
1060661	Atwater-349 17101ft	ATWATER-349-17101FT-A,-G,-H3	1	5	7	87	55-65
1060662	Atwater-349 17121ft	ATWATER-349-17121FT-A,-G,-H3	1	6	8	85	55-65
1060663	Atwater-349 17129ft	ATWATER-349-17129FT-A,-G,-H3	1	3	4	92	55-65
1060664	Atwater-349 17209ft	ATWATER-349-17209FT-A,-G,-H3	2	5	7	86	55-65
1060665	Atwater-349 17221ft	ATWATER-349-17221FT-A,-G,-H3	1	4	5	90	65-70
1060666	Atwater-349 17181ft	ATWATER-349-17181FT-A,-G,-H3	1	5	4	90	70-80

Table 3: Relative percentage of clay minerals in the <2 µm clay size fraction of samples from AT349-2 well core (Day-Stirrat, written communication)..

Figure 5.2: Bottom-hole temperatures (BHT) from wells in the Jubilee field (AT305-1, AT349-1, AT349-2) were utilized to calculate the temperature at the interval of the top-seal MTD. The depth interval of the top-seal MTD is 2,523 to 2,537 meters below sea floor (mbsf), and the calculated temperature at this interval is ~52°C. Deeper samples reach a maximum temperature of 60°C.

5.2 MICP RESULTS

The maximum size of hydrocarbon column a lithology can seal is limited by the largest interconnected pore-throats (Krushin, 1997). Therefore, high gas columns in the top-seal MTD are associated with samples with small pore-throat sizes (Figure 5.3). The monomodal pore size distribution from MICP data in the top-seal MTD shows the preferential loss of the large pores in the samples except in the silt-rich sample at 17,129 ft subsea (2,536 mbsf) (Figure 5.4a). As sediments are buried, silt particles can shield the larger pore throats and inhibit compaction (Day-Stirrat et al., 2010). No pore throat radius in the mud-rich section of the top-seal MTD is greater than ~100 nm and median pore throat radii are between 13.1 and 27.7 nm (Figure 5.4a). Consequently, MICP-derived permeability values are in the microdarcy range as shown in Figure 5.4b.

Another quantitative value to represent the pore geometry from the MICP results is using the pore-throat sorting (PTS) number (Jennings, 1987). The PTS number can be determined calculating the square root of the ratio between the third and first quartile pressures obtained directly from the capillary pressure curve at 75% and 25% mercury saturation, respectively (Trask, 1932; Mian, 1992):

$$PTS = [(3^{\text{rd}} \text{ Quartile Pressure}) / (1^{\text{st}} \text{ Quartile Pressure})]^{0.5}$$

The number derived from this analysis ranges from 1.0 (perfect sorting) to 8.0 (essentially no sorting). The PTS numbers of the samples in the mud-rich section of the top-seal MTD at 17,093, 17,101, and 17,121 ft subsea are 1.6, 1.7, and 1.8, respectively indicating a fairly high sorting degree. In contrast, the silt-rich sample at 17,129 ft subsea has a PTS value of 5.1 suggesting poor pore-throat sorting.

Figure 5.4: (a) Plot of pore throat radius versus pore density distribution of samples showing the dominantly monomodal pore-size distribution in the samples from the top-seal MTD except in the silt-rich sample at 2,536 mbsf (17,129 ft subsea). (b) Plot of median pore throat versus MICP-derived permeability. Silt-content significantly increases permeability of sample at 2,536 mbsf (17,129 ft subsea).

5.3 XRTG RESULTS

The XRTG results suggest a wide variation in the fabric that does not track well with depth or porosity (Figure 5.5 and 5.6). The variation can be attributed to textural heterogeneity imparted by non-platy silt grains (Day-Stirrat et al., 2010, 2011) or different histories of shear deformation (Dewhurst et al., 1996; Haines et al., 2009). The m.r.d. values and pole figure diagrams for all the samples were determined except the one at 2,536 mbsf (17,129 ft subsea) because the relative high silt-content that inhibited the formation of a dominant fabric. The XRTG results of the samples within the top-seal MTD show an anomalously high-degree of clay fabric —measured in m.r.d. values—that increases towards the basal shear contact from 2.01 m.r.d. at 17,093 ft subsea (2,525 mbsf) to 5.18 m.r.d. at 17,121 ft subsea (2,533 mbsf) (Figure 5.7). This supports the premise that the maximum shear strain in a MTD is expected to be experienced near the basal shear surface or *décollement*; as early noted by Clark (1970); Moon (1972); Maltman (1988); Bennett et al. (1991), and more recently by Dugan (2012); Day-Stirrat et al. (2013); Jaboyedoff et al. (2013).

For reference, previous work on mudstones has generated maximum pole densities between 1 and 7 m.r.d., where very weak fabrics have values of < 2.5 m.r.d. and strong fabrics of > 4 m.r.d. Typical m.r.d. values of Gulf of Mexico deepwater mudstones exposed to intense mechanical compaction and/or diagenesis range from 1.74 to 4.05 m.r.d., and are mainly < 3 m.r.d. (Aplin et al., 2006). Anomalously high degree of clay orientation has been also recognized in several MTDs studied in the Gulf of Mexico (Sawyer et al 2009; Yamamoto and Sawyer 2012; Day-Stirrat et al 2013). The top-seal MTD in the Jubilee field shows an anomalously high-degree of clay alignment that cannot be explained only by normal compaction and/or diagenesis (Figures 5.8). Samples

from the top-seal MTD have an average value of 3.6 m.r.d., yet one sample has a value as high as 5.18 m.r.d. near the MTD *décollement* indicative of high fabric. The aforementioned changes in preferred orientation or fabric are analogous to the development of slaty cleavage in response to tectonic stress, where mineral-grain orientation changes from bedding-parallel to cleavage-parallel (Ho et al., 1999).

Figure 5.5: Transmitted light microscopic images of samples from AT349-2 well core employed for XRTG analysis on left column. All images have the same scale. Depth of samples in subsea feet (ft) and meters (m) below sea floor. The corresponding pole density figure is also illustrated for each sample. The multiples of random distribution (m.r.d.) value and MICP-derived porosity for each sample are also given. The values in red correspond to the samples from the top-seal MTD. Modified after Day-Stirrat (written communication).

Figure 5.6: Transmitted light microscopic images of samples from AT349-2 well core employed for XRTG analysis on left column. All images have the same scale. Depth of samples in subsea feet (ft) and meters (m) below sea floor. The corresponding pole density figure is also illustrated for each sample. The multiples of random distribution (m.r.d.) value and MICP-derived porosity for each sample are also given. The values in red correspond to the samples from the top-seal MTD. Modified after Day-Stirrat (written communication).

Figure 5.7: Plot of values of multiples of random distribution (m.r.d.) and pore throat radius versus depth for all the samples from the AT349-2 well core. Core diagram on left side displays the general lithology; shale, siltstone (Slst.), fine sandstone (F ss.). Red box corresponds to samples from the top-seal MTD. Numbers next to the symbols indicate the % of illite in mixed layer illite-smectite. Notice deeper buried samples with weak fabrics (small m.r.d. value). No m.r.d. value for sample at 2,536 mbsf (17,129 ft subsea) could be measured due to lack of fabric because of the relatively high silt-content. Green line tracks the increase of clay fabric towards the basal shear contact of top-seal MTD.

Figure 5.8: Detail of AT349-2 well core showing the interval of the top-seal MTD. Depth scale in feet (ft) subsea and meter below sea floor (mbsf). Resistivity curve from AT349-1 well. Values m.r.d. from core material with respective pole figure. Porosity (%) and median *pore throat radius* (PTR) (in italic font) are shown for each sample within the top-seal MTD. Porosity is relatively high for these depths, however no trend with pore throat size is noted.

Depth subsea (ft)	Depth (mbsf)	% Quartz	% Illite- Smectite	% Illite in S-I mixed layers	Median Pore Throat Radius [nm]	Ht above free water (ft) Gas/Brine at 35% Saturation	MICP Permeability (md)	MICP Porosity (%)	m.r.d. values
17042	-2509	46.8	87	7	18.3	1539	0.00378	13.2	2.68
17044	-2510	43.9	84	8	18.35	1526	0.00441	13.9	2.76
17093	-2525	25.9	89	6	15.5	2013	0.00463	16.8	2.01
17101	-2527	35.5	87	8	13.1	2013	0.00244	12.5	3.61
17121	-2533	33.7	85	9	16.8	1531	0.00429	14.3	5.18
17129	-2536	32.2	93	4	27.75	380	1.684	16.1	*
17181	-2552	38.1	90	4	13.1	2012	0.00315	15.0	2.05
17209	-2560	28.9	86	8	14.25	2012	0.0027	13.0	7.3
17221	-2564	29.9	90	6	24.05	1034	0.00915	15.0	2.12

Table 4: Summary table with microscopic results from analyses of core material at AT349-2 well. Depths in red correspond to the samples from the top-seal MTD.

Chapter 6: Discussion and Conclusions

When assessing the seal potential of deposits, a robust approach should include multi-scale observations. The top-seal MTC in the Jubilee field, buried at a depth of ~17,090 ft subsea (2,525 mbsf) present day, exhibits many of the common characteristics of other studied MTCs. Although some MTCs show abundance of rafted blocks, the top-seal MTC in Jubilee field is virtually devoid of large rafted-blocks, a feature that has been known to diminish sealing effectiveness by providing points of fluid escape (Gamboa and Alves, 2015). According to Moscardelli and Wood (2008) classification, the top-seal MTC in the Jubilee field is of detached-style. Based on the results of this work, it is appealing to propose that detached-MTCs may have a relative greater seal potential compared to their counterparts, attached-MTCs, which commonly have a higher content of exotic/shelfal particles. Alves et al. (2014) noted the importance of sediment provenance as a key control on the MTCs' potential to become a seal. Location within the overall MTC is also of importance. Three primary morphodomains have been defined by Bull et al. (2009): the headwall morphodomain with dominant extensional stresses, the translational morphodomain with dominant shear stresses, and the toe morphodomain with dominant compressional stresses. In terms of the seal potential of the morphodomains in a MTC, the area between the translational and toe morphodomain is relatively the most favorable to create seal facies as suggested by the location of the Jubilee field relative to the top-seal MTC and the introductory discussion about probable seal bypass systems in the different morphodomains of a MTC.

Although only the time-thickness of the top-seal MTC could be determined, it was long ago recognized by Hubbert (1953) that trapping efficiency is not related to the thickness of the sealing material. A few centimeters of ordinary clay shale are in theory

sufficient to trap a large vertical column of hydrocarbon. The previous notion implies that the internal pore-throat structure and fabric nature of the deposits can be more significant in controlling the hydrocarbon trapping potential than thickness by itself. We acknowledge the challenge of characterizing MTCs deeply buried (> 7,000 ft or 2,133 m) as recognized by Ogiesoba and Hammes (2012), because some of the diagnostic features used to assess their sealing efficiency are obliterated due to sediment compaction.

Based on the analyses of the core material, the top-seal MTD in the Jubilee field has the composition of a typical deepwater Gulf of Mexico mudstone, pore-throat radii smaller than 100 nm with a monomodal distribution, permeability in the microdarcy range that increases with silt content, and an anomalously high degree of clay-fabric. This degree of fabric cannot be explained only by normal compaction and/or diagenesis. Within the top-seal MTD the clay-fabric varies from 2.01 to 5.18 m.r.d. in an interval of 28 ft (~8 meters). Using an average bulk density of 2.65 g/cm³ from the AT349-2 density well log, the calculated vertical stress differential from 17,093 to 17,121 ft subsea (2,525 to 2,533 mbsf) is, $\Delta\sigma_v = 0.21$ MPa. In addition to the small overburden stress differential, two other samples with similar clay composition located deeper in the core at 17,181 and 17,221 ft (2,552 and 2,564 mbsf) have m.r.d. values of 2.05 and 2.12, respectively. Therefore, compaction is ruled out as the controlling factor of the difference in the fabric of the samples. Moreover, the relatively low temperature (~52°C) at which the top-seal MTD is buried, in addition to the high content of K-feldspar and low content of illite in the core samples indicate minimal diagenesis impact (Hower et al., 1976; S. Dutton, personal communication). This suggests that the high fabric observed on the clay samples from the top-seal MTD is the result of mechanical shearing during mass wasting and not only normal compaction and/or temperature-driven diagenesis. This conclusion

emphasizes the importance of location, both spatially and vertically in a MTD for assessing sealing potential.

The shearing processes and remolding associated with slope failure for significant distances ($> \sim 10$ km) can enhance the alignment of clay particles (Bennett et al., 1991; Day-Stirrat et al., 2013), and preferentially destroy large pore throats and pore-interconnections (Hedberg, 1926) —as shown by the monomodal pore-throat distribution in the MICP results— resulting in an overall decrease in permeability and porosity (Ikari and Saffer, 2012; Ogiesoba and Hammes, 2012; Alves et al., 2014). This reduction in permeability and porosity is even more dramatic when the MTD lithology is mud-rich. These mud-rich MTDs are highly plastic, and plasticity is noted to play an important role in seal integrity (Downey, 1984). From our research, we conclude that the initially sheared material in the top-seal MTD promoted the development of a higher degree of fabric with increasing burial. Haines et al. (2009) carried out physical experiments comparing clay samples subjected solely to compression and samples exposed to shearing before compression. They noted that shear strain is important for the development of stronger fabrics. Samples only subjected to compression exhibit uniformly weak fabrics (1.6-1.8 m.r.d.) even when compressed at high normal stresses of ~ 150 MPa (around 5 km depth using a sediment bulk density of 2.65 g/cm^3). Consequently, we suggest that fabric imparted on the clay via shearing can enhance the final clay alignment upon deep burial.

Although a larger dataset is desired, we propose that clay mineral alignment can indicate degree of shearing during mass transport. As such, the extent of clay alignment can reflect the potential seal quality. Several studies on the Gulf of Mexico mudstones (Freed and Peacor, 1989; Ho et al., 1999; Aplin et al., 2003) show the concomitant relation between sealing effect and enhanced-clay fabric. Therefore, where diagenesis is

not dominant, zones of enhanced microfabrics in mud-prone MTDs can play an important role in creating an effective sealing surface for fluids in the subsurface. Understanding the spatial distribution of these enhanced microfabric zones within a MTC is important when assessing the seal capacity of MTDs. In conclusion, MTCs can act as effective hydrocarbon seals as proven by the Jubilee gas field. Understanding the part of the MTC morphodomain overlying the hydrocarbon accumulation and the zones of enhanced microfabrics via shear deformation are key factors to identify possible seal weaknesses and seal bypass systems.

References

- Allen, P., and J. Allen, 2013, Basin analysis: Principles and application to petroleum play assessment: 133 p.
- Alves, T. M., 2015, Submarine slide blocks and associated soft-sediment deformation in deep-water basins: A review: *Marine and Petroleum Geology*, v. 67, p. 262–285, doi:10.1016/j.marpetgeo.2015.05.010.
- Alves, T. M., K. Kurtev, G. F. Moore, and M. Strasser, 2014, Assessing the internal character, reservoir potential, and seal competence of mass-transport deposits using seismic texture: A geophysical and petrophysical approach: *AAPG Bulletin*, v. 98, no. 4, p. 793–824, doi:10.1306/09121313117.
- Anadarko Petroleum Corporation, 2003, <http://investors.anadarko.com/phoenix.zhtml?c=80451&p=irol-newsArticle&ID=398540>. March 15, 2014.
- Aplin, A. C., and J. H. S. Macquaker, 2011, Mudstone diversity: Origin and implications for source, seal, and reservoir properties in petroleum systems: *AAPG Bulletin*, v. 95, no. 12, p. 2031–2059, doi:10.1306/03281110162.
- Aplin, A. C., I. F. Matenaar, D. K. McCarty, and B. A. van der Pluijm, 2006, Influence of mechanical compaction and clay mineral diagenesis on the microfabric and pore-scale properties of deep-water Gulf of Mexico mudstones: *Clays and Clay Minerals*, v. 54, no. 4, p. 500–514, doi:10.1346/CCMN.2006.0540411.
- Aplin, A. C., I. F. Matenaar, and B. A. van der Pluijm, 2003, Influence of mechanical compaction and chemical diagenesis on the microfabric and fluid flow properties of Gulf of Mexico mudstones: *Journal of Geochemical Exploration*, v. 79, p. 653–657, doi:10.1016/S0375-6742).
- Arch, J., and A. Maltman, 1990, Anisotropic Permeability and Tortuosity in Deformed Wet Sediments structure in accretionary tectonic features fluids flow from accretionary within D6collement Project (DSDP)/ ODP drill holes which have penetrated major so the examination of microscopic s: *Journal of Geophysical Research*, v. 95, no. 89, p. 9035–9045.
- Armitage, D. a., B. W. Romans, J. a. Covault, and S. a. Graham, 2009, The Influence of Mass-Transport-Deposit Surface Topography on the Evolution of Turbidite Architecture: The Sierra Contreras, Tres Pasos Formation (Cretaceous), Southern Chile: *Journal of Sedimentary Research*, v. 79, no. 5, p. 287–301, doi:10.2110/jsr.2009.035.
- Beaubouef, R. T., and V. Abreu, 2010, MTCs of the Brazos-Trinity Slope System; Thoughts on the Sequence Stratigraphy of MTCs and Their Possible Roles in Shaping Hydrocarbon Traps, *in* Submarine Mass Movements and Their

- Consequences: Dordrecht, Springer Netherlands, p. 475–490, doi:10.1007/978-90-481-3071-9_39.
- Bennett, R. H., W. R. Bryant, and M. H. Hulbert, 1991, Microstructure of Fine-Grained Sediments: New York, NY, Springer New York, Frontiers in Sedimentary Geology, doi:10.1007/978-1-4612-4428-8.
- Bolton, A. J., A. J. Maltman, and Q. Fisher, 2000, Anisotropic permeability and bimodal pore-size distributions of fine-grained marine sediments: Marine and Petroleum Geology, v. 17, p. 657–672, doi:10.1016/S0264-8172(00)00019-2.
- Brown, A. R., 2011, Interpretation of Three-Dimensional Seismic Data: AAPG & SEG, 646 p.
- Bull, S., J. Cartwright, and M. Huuse, 2009, A review of kinematic indicators from mass-transport complexes using 3D seismic data: Marine and Petroleum Geology, v. 26, no. 7, p. 1132–1151, doi:10.1016/j.marpetgeo.2008.09.011.
- Burst, J. F., 1969, Diagenesis of Gulf Coast Clayey Sediments and Its Possible Relation To Petroleum Migration: American Association of Petroleum Geologists Bulletin, v. 53, no. 1, p. 73–93, doi:10.1306/5D25C595-16C1-11D7-8645000102C1865D.
- Byrne, C. J. O., J. K. Haldar, R. Klecker, A. E. Berman, J. Martinez, and L. Lane, 1999, Dynamic Response of Deepwater Depositional Systems to Growth of the Mississippi Fan Fold Belt , Gulf of Mexico: Growth (Lakeland), v. XLIX.
- Canals, M. et al., 2004, Slope failure dynamics and impacts from seafloor and shallow sub-seafloor geophysical data: case studies from the COSTA project: Marine Geology, v. 213, no. 1-4, p. 9–72, doi:10.1016/j.margeo.2004.10.001.
- Cartwright, J., M. Huuse, and A. Aplin, 2007, Seal bypass systems: AAPG Bulletin, v. 91, no. 8, p. 1141–1166, doi:10.1306/04090705181.
- Chand, S., L. Rise, D. Ottesen, M. F. J. Dolan, V. Bellec, and R. Bøe, 2009, Pockmark-like depressions near the Goliat hydrocarbon field, Barents Sea: Morphology and genesis: Marine and Petroleum Geology, v. 26, no. 7, p. 1035–1042, doi:10.1016/j.marpetgeo.2008.09.002.
- Chen, J., 2013, Deepwater Reservoir Compartmentalization: Causes, Impacts on Production, and Methods of Identification, *in* Offshore Technology Conference: doi:10.4043/23951-MS.
- Clark, B. R., 1970, The microstructure of clay sediments: American Journal of Science, v. 269, p. 250–266.
- Combellas-Bigott, R. I., and W. E. Galloway, 2002, Origin and evolution of the middle Miocene submarine-fan system, east-central Gulf of Mexico: Transactions - Gulf Coast Association of Geological Societies, v. 52, p. 151–163, doi:10.1306/10040504132.

- Couples, G. D., 2005, Seals : The Role of Geomechanics: Evaluating fault and cap rock seals, no. 2, p. 87–108, doi:10.1306/1060758H21906.
- Dakin, N., K. T. Pickering, D. Mohrig, and N. J. Bayliss, 2013, Channel-like features created by erosive submarine debris flows: Field evidence from the Middle Eocene Ainsa Basin, Spanish Pyrenees: *Marine and Petroleum Geology*, v. 41, no. 1, p. 62–71, doi:10.1016/j.marpetgeo.2012.07.007.
- Dalla Valle, G., F. Gamberi, P. Rocchini, D. Minisini, A. Errera, L. Baglioni, and F. Trincardi, 2013, 3D seismic geomorphology of mass transport complexes in a foredeep basin: Examples from the Pleistocene of the Central Adriatic Basin (Mediterranean Sea): *Sedimentary Geology*, v. 294, p. 127–141, doi:10.1016/j.sedgeo.2013.05.012.
- Daniel, R., and J. Kaldi, 2012, *Atlas of Australian and New Zealand Hydrocarbon Seals*: Tulsa, The American Association of Petroleum Geologists, 215 p.
- Day-Stirrat, R. J., S. P. Dutton, K. L. Milliken, R. G. Loucks, A. C. Aplin, S. Hillier, and B. a. van der Pluijm, 2010, Fabric anisotropy induced by primary depositional variations in the silt: clay ratio in two fine-grained slope fan complexes: Texas Gulf Coast and northern North Sea: *Sedimentary Geology*, v. 226, no. 1-4, p. 42–53, doi:10.1016/j.sedgeo.2010.02.007.
- Day-Stirrat, R. J., P. B. Flemings, Y. You, and B. a. van der Pluijm, 2013, Modification of mudstone fabric and pore structure as a result of slope failure: Ursa Basin, Gulf of Mexico: *Marine Geology*, v. 341, p. 58–67, doi:10.1016/j.margeo.2013.05.003.
- Day-Stirrat, R. J., A. M. Schleicher, J. Schneider, P. B. Flemings, J. T. Germaine, and B. a. van der Pluijm, 2011, Preferred orientation of phyllosilicates: Effects of composition and stress on resedimented mudstone microfabrics: *Journal of Structural Geology*, v. 33, no. 9, p. 1347–1358, doi:10.1016/j.jsg.2011.06.007.
- DeVay, J. C., D. Risch, E. Scott, and C. Thomas, 2000, A Mississippi-sourced Middle Miocene (M4), fine-grained abyssal plain fan complex, Northeastern Gulf of Mexico, *in* A. H. Bouma, and C. G. Stone, eds., *AAPG Memoir 72 / SEPM Special Publication No. 68: Fine-Grained Turbidite Systems*: p. 109–118.
- Dewhurst, D. N., K. M. Brown, M. B. Clennell, and G. K. Westbrook, 1996, A comparison of the fabric and permeability anisotropy of consolidated and sheared silty clay: *Engineering Geology*, v. 42, p. 253–267, doi:10.1016/0013-7952(95)00089-5.
- Dott, R. H., 1963, Dynamics of Subaqueous Gravity Depositional Processes: *AAPG Bulletin*, v. 47, no. 1, p. 104–128, doi:10.1306/BC743973-16BE-11D7-8645000102C1865D.
- Downey, M. W., 1984, Evaluating Seals for Hydrocarbon Accumulations: *AAPG Bulletin*, v. 68, no. 11, p. 1752–1763, doi:10.1306/AD461994-16F7-11D7-8645000102C1865D.

- Dugan, B., 2012, Petrophysical and consolidation behavior of mass transport deposits from the northern Gulf of Mexico, IODP Expedition 308: Marine Geology, v. 315-318, p. 98–107, doi:10.1016/j.margeo.2012.05.001.
- Dunlap, D. B., L. J. Wood, C. Weisenberger, and H. Jabour, 2010, Seismic geomorphology of offshore Morocco's east margin, Safi Haute Mer area: AAPG Bulletin, v. 94, no. 5, p. 615–642, doi:10.1306/10270909055.
- Enachescu, M. E., 1993, Amplitude interpretation of 3-D reflection data: The Leading Edge, v. 12, no. 6, p. 678, doi:10.1190/1.1436956.
- Freed, R. L., and D. R. Peacor, 1992, Diagenesis and the Formation of Authigenic Illite-Rich I/S Crystals in Gulf Coast Shales: Tem Study of Clay Separates: Journal of Sedimentary Research, v. Vol. 62, no. 2, p. 220–234, doi:10.1306/D42678CA-2B26-11D7-8648000102C1865D.
- Freed, R. L., and D. R. Peacor, 1989, Geopressured Shale and Sealing Effect of Smectite to Illite Transition: v. 10, no. 10, p. 1223–1232.
- Frey Martinez, J., J. Cartwright, and B. Hall, 2005, 3D seismic interpretation of slump complexes: examples from the continental margin of Israel: Basin Research, v. 17, no. 1, p. 83–108, doi:10.1111/j.1365-2117.2005.00255.x.
- Gafeira, J., J. Bulat, and D. Evans, 2007, The Southern Flank Of The Storegga Slide: Imaging And Geomorphological Analyses Using 3d Seismic, *in* Submarine Mass Movements and Their Consequences: Dordrecht, Springer Netherlands, p. 57–65, doi:10.1007/978-1-4020-6512-5_7.
- Galloway, W. E., P. E. Ganey-Curry, X. Li, and R. T. Buffler, 2000, Cenozoic depositional history of the Gulf of Mexico basin: AAPG Bulletin, v. 84, no. 11, p. 1743–1774, doi:10.1306/8626C37F-173B-11D7-8645000102C1865D.
- Galloway, W. E., S. Mentemeier, M. Rowan, and L. M. Gochioco, 2004, Plumbing the depths of the Gulf of Mexico: Recent understanding of Cenozoic sand dispersal systems and ultradeep reservoir potential: The Leading Edge, v. 23, no. 1, p. 44–51, doi:10.1190/1.1645454.
- Gamboa, D., and T. M. Alves, 2015, Three-dimensional fault meshes and multi-layer shear in mass-transport blocks: Implications for fluid flow on continental margins: Tectonophysics, v. 647-648, p. 21–32, doi:10.1016/j.tecto.2015.02.007.
- Gamboa, D., T. Alves, and J. Cartwright, 2012, Seismic-Scale Rafted and Remnant Blocks over Salt Ridges in the Espírito Santo Basin, Brazil, *in* Submarine Mass Movements and Their Consequences: Dordrecht, Springer Netherlands, p. 629–638, doi:10.1007/978-94-007-2162-3_56.
- Gamboa, D., T. Alves, J. Cartwright, and P. Terrinha, 2010, MTD distribution on a “passive” continental margin: The Espírito Santo Basin (SE Brazil) during the

- Palaeogene: *Marine and Petroleum Geology*, v. 27, no. 7, p. 1311–1324, doi:10.1016/j.marpetgeo.2010.05.008.
- Haines, S. H., B. A. Van Der Pluijm, M. J. Ikari, D. M. Saffer, and C. Marone, 2009, Clay fabric intensity in natural and artificial fault gouges: Implications for brittle fault zone processes and sedimentary basin clay fabric evolution: *Journal of Geophysical Research: Solid Earth*, v. 114, no. 1, doi:10.1029/2008JB005866.
- Hampton, M. A., H. J. Lee, and J. Locat, 1996, Submarine landslides: Reviews of Geophysics, v. 34, no. 1, p. 33, doi:10.1029/95RG03287.
- Hart, B. S., 2008, Channel detection in 3-D seismic data using sweetness: *AAPG Bulletin*, v. 92, no. 6, p. 733–742, doi:10.1306/02050807127.
- Hedberg, H. D., 1926, The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: *AAPG Bulletin*, v. 10, p. 1035–1072.
- Heggland, R., 2005, Using gas chimneys in seal integrity analysis: A discussion based on case histories: Evaluating fault and cap rock seals: *AAPG*, p. 237–246, doi:10.1306/1060767H23170.
- Hillier, S., 2003, Quantitative analysis of clay and other minerals in sandstones by X-ray powder diffraction (XRPD), *in* R. Worden, and S. Morad, eds., *Clay Mineral Cements in Sandstones: Special Publication 34*: John Wiley & Sons, p. 520.
- Hillier, S., 2002, Spray drying for X-ray powder diffraction specimen preparation: *IUCR Commission on Powder Diffraction Newsletter*, no. 27, p. 7–9.
- Hillier, S., 1999, Use of an air brush to spray dry samples for X-ray powder diffraction: *Clay Minerals*, v. 34, no. 1, p. 127–135.
- Ho, N. C., D. R. Peacor, and B. A. van der Pluijm, 1999, Preferred Orientation of Phyllosilicates in Gulf Coast Mudstones and Relation to the Smectite-Illite Transition: *Clays and Clay Minerals*, v. 47, no. 4, p. 495–504, doi:10.1346/CCMN.1999.0470412.
- Hovland, M., J. V. Gardner, and a. G. Judd, 2002, The significance of pockmarks to understanding fluid flow processes and geohazards: *Geofluids*, v. 2, no. 2, p. 127–136, doi:10.1046/j.1468-8123.2002.00028.x.
- Hower, J., E. V. Eslinger, M. E. Hower, and E. A. Perry, 1976, Mechanism of burial metamorphism of argillaceous sediment: 1. Mineralogical and chemical evidence: *Bulletin of the Geological Society of America*, v. 87, no. 5, p. 725–737, doi:10.1130/0016-7606(1976)87<725:MOBMOA>2.0.CO;2.
- Hubbert, M. K., 1953, Entrapment of petroleum under hydrodynamic conditions: *AAPG Bulletin*, v. 37, no. 8, p. 1954–2026.
- Hudec, 2000, Quick-Look Chart for Salt Restoration: *Bureau of Economic Geology*.

- Ikari, M. J., and D. M. Saffer, 2012, Permeability contrasts between sheared and normally consolidated sediments in the Nankai accretionary prism: *Marine Geology*, v. 295-298, p. 1–13, doi:10.1016/j.margeo.2011.11.006.
- Jaboyedoff, M., I. Penna, A. Pedrizzini, I. Baroň, and G. B. Crosta, 2013, An introductory review on gravitational-deformation induced structures, fabrics and modeling: *Tectonophysics*, v. 605, p. 1–2, doi:10.1016/j.tecto.2013.06.027.
- Jackson, C. A. L., 2011, Three-dimensional seismic analysis of megaclast deformation within a mass transport deposit; Implications for debris flow kinematics: *Geology*, v. 39, no. 3, p. 203–206, doi:10.1130/G31767.1.
- Jennings, J. B., 1987, Capillary Pressure Techniques: Application To Exploration and Development Geology.: *American Association of Petroleum Geologists Bulletin*, v. 71, no. 10, p. 1196–1209, doi:10.1306/703C8047-1707-11D7-8645000102C1865D.
- Kanitpanyacharoen, W., H.-R. Wenk, F. Kets, C. Lehr, and R. Wirth, 2011, Texture and anisotropy analysis of Qusaiba shales: *Geophysical Prospecting*, v. 59, no. 3, p. 536–556, doi:10.1111/j.1365-2478.2010.00942.x.
- Krushin, J. T., 1997, Seal Capacity of Nonsmectite Shale: Seals, Traps, and the Petroleum System, no. 67, p. 31–47.
- Lewis, K., 1971, Slumping on a continental slope inclined at 1–4°: *Sedimentology*, v. 16, p. 97–110.
- Ligtenberg, J. H., 2005, Detection of fluid migration pathways in seismic data: implications for fault seal analysis: *Basin Research*, v. 17, no. 1, p. 141–153, doi:10.1111/j.1365-2117.2005.00258.x.
- Løseth, H., M. Gading, and L. Wensaas, 2009, Hydrocarbon leakage interpreted on seismic data: *Marine and Petroleum Geology*, v. 26, no. 7, p. 1304–1319, doi:10.1016/j.marpetgeo.2008.09.008.
- Madof, A. S., N. Christie-Blick, and M. H. Anders, 2009, Stratigraphic controls on a salt-withdrawal intraslope minibasin, north-central Green Canyon, Gulf of Mexico: Implications for misinterpreting sea level change: *AAPG Bulletin*, v. 93, no. 4, p. 535–561, doi:10.1306/12220808082.
- Maltman, A. J., 1988, The importance of shear zones in naturally deformed wet sediments: *Tectonophysics*, v. 145, no. 1-2, p. 163–175, doi:10.1016/0040-1951(88)90324-1.
- Martinsen, O. J., 1994, Mass movements, *in* A. Maltman, ed., *The Geological Deformation of Sediments*: Dordrecht, Springer Netherlands, p. 127–165, doi:10.1007/978-94-011-0731-0.

- McGilvery, T., G. Haddad, and D. Cook, 2004, Seafloor and shallow subsurface examples of mass transport complexes, offshore Brunei: Offshore Technology Conference, p. 1–13, doi:10.4043/16780-MS.
- Meckel, L. D., 2011, Reservoir characteristics and classification of sand-prone submarine mass-transport deposits, *in* R. C. Ship, P. Weimer, and H. W. Posamentier, eds., Mass-Transport Deposits in Deepwater Settings: Society of Sedimentary Geology (SEPM), p. 423–452.
- Mian, M. A., 1992, Petroleum Engineering Handbook for the Practicing Engineer: Tulsa, PennWell, 613 p.
- Moon, C. F., 1972, The microstructure of clay sediments: Earth-Science Reviews, v. 8, no. 3, p. 303–321, doi:10.1016/0012-8252(72)90112-2.
- Moscardelli, L., 2007, Mass Transport Processes and Deposits in Offshore Trinidad and Venezuela, and their role in Continental Margin Development: PhD Dissertation thesis: The University of Texas at Austin, 185 p.
- Moscardelli, L., and L. Wood, 2015, Morphometry of mass-transport deposits as a predictive tool: Geological Society of America Bulletin, p. B31221.1, doi:10.1130/B31221.1.
- Moscardelli, L., and L. Wood, 2008, New classification system for mass transport complexes in offshore Trinidad: Basin Research, v. 20, no. 1, p. 73–98, doi:10.1111/j.1365-2117.2007.00340.x.
- Moscardelli, L., L. Wood, and P. Mann, 2006, Mass-transport complexes and associated processes in the offshore area of Trinidad and Venezuela: AAPG Bulletin, v. 90, no. 7, p. 1059–1088, doi:10.1306/02210605052.
- Mulder, T., and P. Cochonat, 1996, Classification of offshore mass movements: Journal of Sedimentary research.
- Nardin, T. R., F. J. Hein, D. S. Gorsline, and B. . Edwards, 1979, A Review of Mass Movement Processes Sediment and Acoustic Characteristics, and Contrasts in Slope and Base-of-Slope Systems Versus Canyon-Fan-Basin Floor Systems: SEPM Special Publications, no. 27, p. 61–73.
- Nelson, C. H., C. Escutia, J. E. Damuth, and D. C. Twichell, 2011, Interplay of Mass-Transport and Turbidite-System Deposits in Different Active Tectonic and Passive Continental Margin Settings: External and Local Controlling Factors: SEPM Special Publication, no. 96, p. 39–66.
- Newton, C. S., R. C. Shipp, D. C. Mosher, and G. D. Wach, 2004, Importance of Mass Transport Complexes in the Quaternary Development of the Nile Fan, Egypt, *in* Offshore Technology Conference: Offshore Technology Conference, doi:10.4043/16742-MS.

- Nissen, S. E., N. L. Haskell, C. T. Steiner, and K. L. Coterill, 1999, Debris flow outrunner blocks, glide tracks, and pressure ridges identified on the Nigerian continental slope using 3-D seismic coherency: *The Leading Edge*, v. 18, no. 5, p. 595, doi:10.1190/1.1438343.
- Ogiesoba, O., and U. Hammes, 2012, Seismic interpretation of mass-transport deposits within the upper Oligocene Frio Formation, south Texas Gulf Coast: *AAPG Bulletin*, v. 96, no. 5, p. 845–868, doi:10.1306/09191110205.
- Ortiz-Karpf, A., D. M. Hodgson, and W. D. McCaffrey, 2015, The role of mass-transport complexes in controlling channel avulsion and the subsequent sediment dispersal patterns on an active margin: the Magdalena Fan, offshore Colombia: *Marine and Petroleum Geology*, v. 64, p. 58–75, doi:10.1016/j.marpetgeo.2015.01.005.
- Partyka, G., J. Gridley, and J. Lopez, 1999, Interpretational applications of spectral decomposition in reservoir characterization: *The Leading Edge*, v. 18, no. 3, p. 353, doi:10.1190/1.1438295.
- Paull, C. K., W. Ussler, W. S. Holbrook, T. M. Hill, R. Keaten, J. Mienert, H. Haflidason, J. E. Johnson, W. J. Winters, and T. D. Lorenson, 2008, Origin of pockmarks and chimney structures on the flanks of the Storegga Slide, offshore Norway: *Geo-Marine Letters*, v. 28, no. 1, p. 43–51, doi:10.1007/s00367-007-0088-9.
- Pickering, K. T., and J. Corregidor, 2005, Mass-Transport Complexes (MTCs) and Tectonic Control on Basin-Floor Submarine Fans, Middle Eocene, South Spanish Pyrenees: *Journal of Sedimentary Research*, v. 75, no. 5, p. 761–783, doi:10.2110/jsr.2005.062.
- Pickering, K. T., and V. Hilton, 1998, *Turbidite Systems of Southeast France*: London, Vallis Press., 229 p.
- Pilcher, R., and J. Argent, 2007, Mega-pockmarks and linear pockmark trains on the West African continental margin: *Marine Geology*, v. 244, no. 1-4, p. 15–32, doi:10.1016/j.margeo.2007.05.002.
- Pittman, E. D., 1992, Relationship of Porosity and Permeability to Various Parameters Derived from Mercury Injection-Capillary Pressure Curves for Sandstone (1): *AAPG Bulletin*, v. 76, doi:10.1306/BDF87A4-1718-11D7-8645000102C1865D.
- Van der Pluijm, B. A., N.-C. Ho, and D. R. Peacor, 1994, High-resolution X-ray texture goniometry: *Journal of Structural Geology*, v. 16, no. 7, p. 1029–1032, doi:10.1016/0191-8141(94)90084-1.
- Pollastro, R. M., 1993, Consideration and applications of the illite/smectite geothermometer in hydrocarbonbearing rocks of Miocene to Mississippian age.: *Clays and Clay Minerals*, 41, p. 119–133., v. 41, no. 2, p. 119–133.

- Posamentier, H.W., 2000, Seismic stratigraphy into the next millennium; a focus on 3D seismic data. American Association of Petroleum Geologists Annual Conference, New Orleans, LA, April 16-19, 2000, All8.
- Posamentier, H. W., 2005, Application of 3D seismic visualization techniques for seismic stratigraphy, seismic geomorphology and depositional systems analysis: examples from fluvial to deep-marine depositional environments: *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*, p. 1565–1576, doi:10.1144/0061565.
- Posamentier, H. W., 2004, Seismic Geomorphology: Imaging Elements of Depositional Systems from Shelf to Deep Basin Using 3D Seismic Data: Implications for Exploration and Development: Geological Society, London, Memoirs, v. 29, no. 1, p. 11–24, doi:10.1144/GSL.MEM.2004.029.01.02.
- Posamentier, H. W., R. J. Davies, J. A. Cartwright, and L. Wood, 2007, Seismic geomorphology- an overview, *in* R. J. Davies, H. W. Posamentier, L. J. Wood, and J. A. Cartwright, eds., *Seismic Geomorphology: Applications to Hydrocarbon Exploration and Production: The Geological Society of London*, p. 1–14.
- Posamentier, H. W., and V. Kolla, 2003, Seismic Geomorphology and Stratigraphy of Depositional Elements in Deep-Water Settings: *Journal of Sedimentary Research*, v. 73, no. 3, p. 367–388, doi:10.1306/111302730367.
- Posamentier, H. W., and O. J. Martinsen, 2011, The character and genesis of submarine mass-transport deposits: insights from outcrop and 3D seismic data, *in* R. C. Shipp, P. Weimer, and H. W. Posamentier, eds., *Mass-transport deposits in deepwater settings: SEPM Tulsa*, p. 7–38.
- Posamentier, H. W., and R. G. Walker, 2006, Deep-Water Turbidites and Submarine Fans: 399-520 p.
- Prather, B. E., J. R. Booth, G. S. Steffens, and P. A. Craig, 1998, Succession of Seismic Facies of Intraslope Basins , *Deep-Water Gulf of Mexico 1*: no. 5, p. 701–728.
- Prior, D. B., B. D. Bornhold, and M. W. Johns, 1984, Depositional Characteristics of a Submarine Debris Flow: p. 707–727, doi:10.1086/628907.
- Rowan, M. G., F. J. Peel, and B. C. Vendeville, 2004, Gravity-driven fold belts on passive margins: *AAPG Memoir*, v. 82, p. 157–182.
- Sawyer, D. E., P. B. Flemings, J. Buttles, and D. Mohrig, 2012, Mudflow transport behavior and deposit morphology: Role of shear stress to yield strength ratio in subaqueous experiments: *Marine Geology*, v. 307-310, p. 28–39, doi:10.1016/j.margeo.2012.01.009.
- Sawyer, D. E., P. B. Flemings, B. Dugan, and J. T. Germaine, 2009, Retrogressive failures recorded in mass transport deposits in the Ursa Basin, Northern Gulf of

- Mexico: *Journal of Geophysical Research*, v. 114, no. B10, p. B10102, doi:10.1029/2008JB006159.
- Snedden, J. W., W. E. Galloway, T. L. Whiteaker, and P. E. Ganey-Curry, 2012, Eastward shift of deepwater fan axes during the Miocene in the Gulf of Mexico: Possible causes and models: *Gulf Coast Association of Geological Societies Journal*, v. 1, p. 131–144.
- Sprague, A. R. et al., 2005, Integrated slope channel depositional models: the key to successful prediction of reservoir presence and quality in offshore West Africa, *in* CIPM, cuarto E-Exitep 2005, February 20-23: p. 1–13.
- Trask, P. D., 1932, Origin and Environment of Source Sediments of Petroleum Deposits: Gulf Publishing Company, 1899-1961 p., doi:10.1306/3D93294C-16B1-11D7-8645000102C1865D.
- Tripsanas, E. K., W. R. Bryant, and B. a. Phaneuf, 2004, Slope-instability processes caused by salt movements in a complex deep-water environment, Bryant Canyon area, northwest Gulf of Mexico: *AAPG Bulletin*, v. 88, no. 6, p. 801–823, doi:10.1306/01260403106.
- Vail, P. R., Mitchum, R. M. Jr. & Thompson, S. III 1977. Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap. In: Payton, C. E. (ed.) *Seismic Stratigraphy—Applications to Hydrocarbon Exploration*. American Association of Petroleum Geologists Memoir, 26, 63–81.
- Washburn, E. W., 1921, Note on a Method of Determining the Distribution of Pore Sizes in a Porous Material.: *Proceedings of the National Academy of Sciences of the United States of America*, v. 7, no. 4, p. 115–116, doi:10.1073/pnas.7.4.115.
- Weimer, P., and R. Bouroullec, 2013, Petroleum Geology of the Mississippi Canyon, Atwater Valley, Western Desoto Canyon, and Western Lloyd Areas, Northern Deep Gulf of Mexico: Traps, Reservoirs, and Their Timing, *in* *New Understanding of the Petroleum Systems of Continental Margins of the World: 32nd Annual: SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS*, p. 110–132, doi:10.5724/gcs.12.32.0110.
- Weimer, P., and C. Shipp, 2004, OTC 16752 Mass Transport Complex : Musing on Past Uses and Suggestions for Future Directions: no. 1, p. 1–10.
- Weiss, L. E., and H.-R. Wenk, 1985, An Introduction, *in* H.-R. Wenk, ed., *Preferred Orientation in Deformed Metal and Rocks*: Elsevier, p. 1–10, doi:10.1016/B978-0-12-744020-0.50007-9.
- Wenk, H.-R., 1985, Measurement of Pole Figures, *in* H.-R. Wenk, ed., *Preferred Orientation in Deformed Metal and Rocks*: p. 11–47.
- Witrock, R. B., Friedmann, A. R., Galluzzo, J. J., Nixon, L. D., Post, P. J., & Ross, K. M., 2003, Biostratigraphic chart of the Gulf of Mexico offshore region. Jurassic

- to Quaternary, US Department of the Interior, Minerals Management Service, New Orleans.
- Yamamoto, Y., 2006, Systematic variation of shear-induced physical properties and fabrics in the Miura-Boso accretionary prism: The earliest processes during off-scraping: *Earth and Planetary Science Letters*, v. 244, p. 270–284, doi:10.1016/j.epsl.2006.01.049.
- Yamamoto, Y., and D. E. Sawyer, 2012, Systematic Spatial Variations in the Fabric and Physical Properties of Mass-Transport Deposits in the Ursa Region, Northern Gulf of Mexico: 649-658 p., doi:10.1007/978-94-007-2162-3_58.
- Zeng, H., M. M. Backus, K. T. Barrow, and N. Tyler, 1998, Stratal slicing, Part I: Realistic 3-D seismic model: *Geophysics*, v. 63, no. 2, p. 502, doi:10.1190/1.1444351.
- Zeng, H., S. C. Henry, and J. P. Riola, 1998, Stratal slicing, Part II: Real 3-D seismic data: *GEOPHYSICS*, v. 63, no. 2, p. 514–522, doi:10.1190/1.1444352.

Vita

Sebastian Cardona was born in Medellin, Colombia on June 29, 1987, to Rodrigo De Jesus Cardona and Beatriz Elena Meneses. After graduating from the Colegio Jesus de la Buena Esperanza, he attended the Universidad Nacional de Colombia at Medellin in 2005, where he pursued the degree of Geological Engineering for two years prior to arriving to San Antonio, Texas U.S.A. in 2007. He then attended the University of Texas at San Antonio where he completed a Bachelors of Science in Geology in 2012. After graduation, he worked as a geologist for Welder E&P in San Antonio until August 2013 when he entered the Jackson School of Geosciences of The University of Texas at Austin to pursue a Master of Science degree in Geological Sciences. During his time in the Jackson School, he was a graduate research assistant for the Quantitative Clastic Laboratory at the Bureau of Economic Geology, where he conducted seismic interpretation and research in deepwater deposits of the Gulf of Mexico under the supervision of Dr. Lesli Wood. Upon the completion of this degree in August 2015, Sebastian will join Colorado School of Mines to pursue a Ph.D. degree in Geological Sciences to further his studies in deepwater deposits and seismic interpretation under the guidance of Dr. Lesli Wood. He is an active member of the American Association of Petroleum Geologist. Sebastian enjoys spending time in the outdoors and training for ultramarathons and IRONMAN triathlons when he has free time from research.

Sebastian.cardona@utexas.edu

This thesis was typed by Sebastian Cardona. All seismic figures were created by the author in Landmark Graphics and Illustrator.