2014 GRADUATE THESIS PROPOSAL

EARTH SCIENCES 6300

NAME: Dickson, Carla

DEGREE PROGRAMME: M.Sc. **FIELD(S) OF SPECIALIZATION:** Petroleum Geology & Petrophysics

SUPERVISOR and COMMITTEE:
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TITLE OF PROPOSAL: Reservoir Connectivity and Overpressure in the Sable Subbasin (Nova Scotia, Eastern Canada): Penobscot, West Sable, Thebaud, and Onondaga

KEY WORDS: Scotian Basin, Sable Subbasin, Reservoir Connectivity, Overpressure, Abnormal Pressure, Compartmentalization, Seal Integrity, Pore Pressure, Undercompaction, Hydrocarbon Generation

LIST INNOVATIONS or EXPECTED SIGNIFICANT OUTCOMES:
- Construct stratigraphic and structural three-dimensional geometric models for the Sable Subbasin, focusing on reservoir and seal interval-related lithologies
- Determine the location, apparent displacement, and effect of faults on the reservoir connectivity within the Sable Subbasin
- Develop a three-dimensional model for pressure distribution and gradients within reservoirs of the Sable Subbasin, incorporating reservoir architecture, fault behavior, and pore pressure data
- Determine the mechanism(s) for overpressure formation and present distribution

SUMMARY OF PROPOSED RESEARCH:

Overpressure is abnormally high subsurface pressure exceeding hydrostatic pressure at a given depth, and occurs when fluids trapped in the pores of sedimentary rocks are unable to escape. Overpressure has been identified as a serious risk element in several offshore basins around the world including the Sable Subbasin of the Scotian Basin. The Sable Subbasin comprises Mesozoic and Cenozoic sediments overlying a Paleozoic basement, creating a structurally-complex basin that contains carbonate banks, platforms, ridges, and sub-basins. Overpressure on the Scotian Basin has been mapped at a low resolution, but the causes for overpressure have not been resolved. Previous work has demonstrated overpressure in the basin is variable and not associated with specific depths or formations.

The objective of my M.Sc. thesis research is to integrate and interpret pore pressure, wireline log, and seismic data to determine the distribution of overpressure within reservoir compartments, and resolve the causes for overpressure formation. Understanding overpressure distribution and formation is critical for increased exploration and development of petroleum resources in the Scotian Basin, especially the underexplored deepwater region.

TIMETABLE:

Activity	Start Date	End Date
Research	1-Feb-13	31-Aug-15
Society of Petrophysicists and Well Log Analysts Scholarship ($2,500)	--	1-Apr-13
Work Term I: Husky Energy, Calgary AB	1-May-13	30-Aug-13
GeoConvention 2013 Conference: Poster Presentation	6-May-13	10-May-13
Husky Energy Aboriginal Mentorship Award ($12,000)	--	31-May-13
Avataq Academic Achievement Scholarship ($33,000)	--	30-Jun-13
ERTH 6300 & ERTH 6350	1-Sep-13	31-Apr-14
Data Collection & Database Construction	1-Sep-13	31-Dec-14
Field Work: Trinidad	15-Feb-14	22-Feb-14
Logging & Formation Evaluation Course (St.John's, NL)	17-Mar-14	21-Mar-14
Work Term II: Husky Energy, Calgary AB (Aboriginal Mentorship Program)	1-May-14	29-Aug-14
GeoConvention 2014 Conference: Poster Presentation	12-May-14	16-May-14
Petrophysical Analysis and Modelling	19-May-14	30-Apr-15
Sample Collection: Offshore NS Cores (at CNSOPB)	8-Sep-14	12-Sep-14
Sample Preparation: Offshore NS Cores (at Dalhousie University)	15-Sep-14	3-Oct-14
Sample Analysis: XRD of Offshore NS Cores (at Dalhousie University)	6-Oct-14	17-Oct-14
Work Term III: Husky Energy, Calgary AB (Aboriginal Mentorship Program)	1-May-15	31-Aug-15
GeoConvention 2015 Conference: Oral Presentation	11-May-15	15-May-15
Thesis Preparation & Writing	1-Sep-15	31-Dec-15
Thesis Defense	--	15-Jan-16

Have all permissions for access to data or samples been acquired? (Briefly explain if NO)

Yes, all permissions for access to data and samples have been acquired.

Are there any risks to data acquisition? (If YES, explain risk and mitigation)

Yes, wells were drilled from 1969 to 2005 by several operators. The advancing level of data acquisition technology over this time span means data collected from the newer wells is more detailed and reliable. It is also important to note that no wells were drilled for the specific purpose of measuring pressure, they were drilled to explore and produce petroleum resources.

PROPOSAL

(1) Statement of Problem:

Overpressure (abnormal high pressure) is a documented risk element of the petroleum systems in the Sable Subbasin, although the causes for overpressure formation, magnitude, and distribution are poorly understood. Increased exploration in the basin necessitates these issues are addressed to improve safety for personnel, protect the environment, and reduce costs (mud weight, drilling, casing program, rig time, etc.) associated with resource development.

High-resolution three-dimensional geometric models incorporating reservoir architecture, fault behavior, and pore pressure data are essential to continue successful exploration and development of petroleum systems in the Sable Subbasin, Scotian Basin. The deepwater of the Scotian Basin is experiencing a significant surge in exploration but the region is underexplored, with very limited data, therefore results from the Sable Subbasin can be extrapolated to the deepwater to increase confidence in interpretations.

(2) Background:

2.1 Overpressure

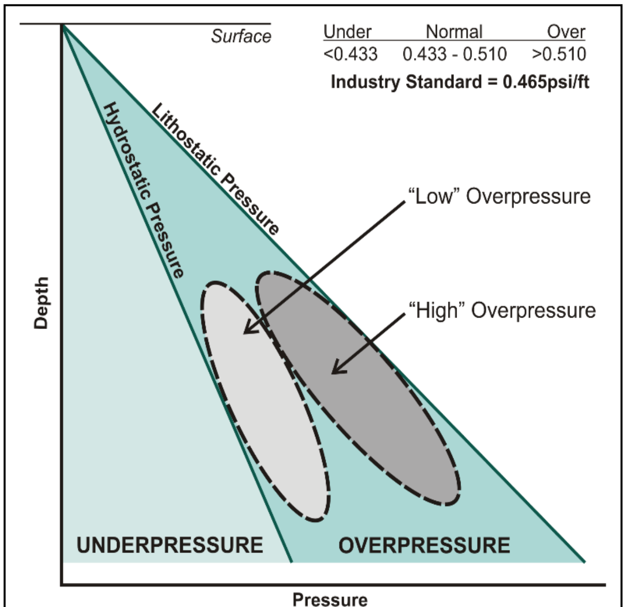

Figure 1: Generalized hydrostatic and lithostatic pressure gradient curves defining underpressure and overpressure.

Overpressure is abnormally high subsurface pressure exceeding hydrostatic pressure at a given depth, and occurs when connate fluids are unable to escape the surrounding mineral matrix (Figure 1). Hydrostatic pressure is the pressure at which the fluid contained in the pore space of a rock is maintained with depth; it is equal to the weight of the overlying fluid. Reservoir compartments are required for the formation and preservation of overpressure; the compartments are three-dimensional structures without effective migration routes for fluid or gasses. Compartmentalization occurs when hydrocarbon migration is prevented across sealed boundaries (i.e. faults) within the reservoir. The boundaries can be divided into two groups: static seals that completely seal and are able to trap hydrocarbons for a geologic time-frame, and dynamic seals that are low permeability baffles to flow that decrease rate of flow to essentially zero at the production scale but will allow for eventual equalization over a geologic scale (Vrolijk et al. 2005).

Identification of overpressure is important for safety and resource development; overpressured sediments tend to exhibit improved porosity than would be predicted based on their depth therefore they make attractive reservoir prospects. "Low" overpressure is important for determining reserves and areas with previously unrecognized potential, while "high" overpressure controls exploration risk for breached traps and helps determine connectedness of reservoir compartments (Figure 1).

Overpressure can form by several mechanisms including faulting, undercompaction, formation foreshortening, massive evaporite deposition, mineral phase change, repressuring, and hydrocarbon generation (Nguyen 2013). Faulting offsets sediment bodies and can lead to the juxtaposition of permeable and impermeable zones, creating barriers to fluid movement and the formation of reservoir compartments. Undercompaction is the rapid burial of sediments before pore fluids are able to escape (i.e. dewatering); formation pressure will increase and eventually will be overpressured. Formation foreshortening occurs during compression when there is bending of strata, intermediate beds expand to fill the void (underpressured zone), but if the movement of upper and lower strata is constrained then they will become overpressured. Salt and evaporites can be impermeable to fluids and gasses, forming seals for underlying formations by limiting/eliminating migration and allowing the underlying formations to become overpressured. Minerals can change phase under increased pressure (i.e. montmorillonite to illite), frequently resulting in a change of volume; the volume is increased and the formation becomes overpressured. Repressuring occurs due to migration of fluid from a high to low pressure zone, usually due to faulting, and can create unpredictable overpressured zones. Finally hydrocarbon generation leads to overpressure through increased fluid and gas in a confined reservoir compartment.

2.2 Regional Geology

The Scotian Basin is located offshore Nova Scotia; the total area of the basin is nearly 300,000 km^2, with half on the current continental shelf (water depth <200m) and the remaining half on the continental slope (water depth >200m) (NRC 2010). Sedimentation into the basin has been relatively continuous over the past 250 Ma, and has been predominantly sourced from the Appalachian Orogen and transported by a paleo-drainage system, which included several large delta systems (e.g. Shelburne, Sable, and Laurentian). Sediments reached a maximum thickness of 16 km (Wade et al. 1995). The geological history of the basin is recorded in the sediments and represents a diverse array of depositional environments including early-stage rifting, carbonate bank, fluvial-deltaic-lacustrine, and deep water.

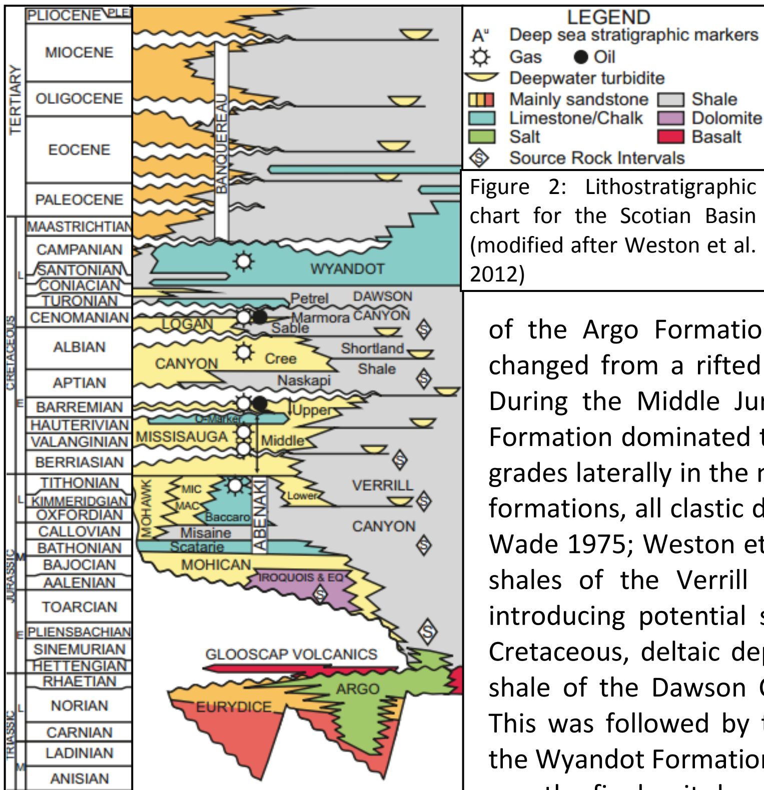

Figure 2: Lithostratigraphic chart for the Scotian Basin (modified after Weston et al. 2012)

The Scotian Basin comprises several subbasins including the Shelburne, Sable, Abenaki, Laurentian, and Orpheus Graben. Formation of the basin began with the initial rifting of the Atlantic from the Late Triassic to Early Jurassic (Wade and MacLean 1990). The basin is underlain by Paleozoic rocks, which are overlain by the Late Triassic red beds of the Eurydice Formation and evaporite deposits of the Argo Formation (Figure 2) (Weston et al. 2012). Deposition of the Argo Formation ended by the Early Jurassic as the Scotian Margin changed from a rifted margin to a passive margin depositional environment. During the Middle Jurassic to Early Cretaceous, carbonates of the Abenaki Formation dominated the central region of the margin. The Abenaki Formation grades laterally in the northeast to the Mic Mac, Missisauga, and Logan Canyon formations, all clastic deltaic deposits forming the Sable Island Delta (Jansa and Wade 1975; Weston et al. 2012; CNSOPB 2013). Distal to the delta, the marine shales of the Verrill Canyon Formation were deposited in the southeast, introducing potential source rock lithofacies into the basin. During the Late Cretaceous, deltaic deposition slowed and was topped with the transgressive shale of the Dawson Canyon Formation, and thin limestone Petrel Member. This was followed by transgressive deposition of a predominantly chalk unit, the Wyandot Formation (Wade and MacLean 1990). The Banquereau Formation was the final unit deposited in the Scotian Basin during the Late Cretaceous to Pliocene and comprises interbedded sandstones, siltstones, conglomerates and occasional chalks (Wade and MacLean 1990). Significant regression occurred during deposition of the Banquereau Formation, therefore renewed deltaic deposition shifted progradation from southwest to the northeast of the margin (Weston et al. 2012).

2.3 Petroleum Exploration

Petroleum exploration in offshore Nova Scotia began in 1959, and (to date) includes 207 wells (exploration, delineation, and production) (Figure 3A). Given the considerable area, this means that the basin is underexplored (CNSOPB 2013; OERA 2011). Studies of overpressure in the region initially focused on describing the overpressure system of the Scotian Basin including location, magnitude, and depth. However data were limited as deepwater drilling did not begin in the basin until 1983 and available seismic data were predominantly two-dimensional analog (not digital) making them more difficult to analyze and interpret (Wade 1991).

The Geological Survey of Canada (GSC) completed a study on Scotian Shelf lithostratigraphy as part of the East Coast Basin Atlas Series that included a chapter on overpressure (Wade 1991). The GSC examined the overpressure system below the eastern Scotian Shelf, focusing on the Sable area, and concluded overpressure was present in all wells drilled sufficiently deep (2700-5200 m) southeast of the Abenaki Formation platform. Overpressure is present in several lithologies including sandstone, limestone, and shales. Sonic logging recorded a decrease in shale velocities, likely due to overpressured fluid and gas present in pores.

The first comprehensive study of overpressures on the Scotian Shelf examined overpressure magnitude, maximum (top) overpressure, and relation to burial depth, maturity, and stratigraphic formations (Wielens 2003). It also investigated whether correlations existed between any of these attributes. The study concluded that overpressure is not present in all wells; it does not appear related to specific stratigraphic formations, burial depths, or temperatures; and it does not have a consistent or predictable signal on the wireline log (Wielens 2003). Wielens also concluded the role of faults in the formation and distribution of overpressure, and the source of overpressure are both unknown and must be resolved. Potential reasons for overpressure formation include fluid and gas volume increase as a result of temperature increase, and hydrocarbon generation. The study recognized reservoir compartments must be present to allow for overpressure to be formed and preserved in the Scotian Basin.

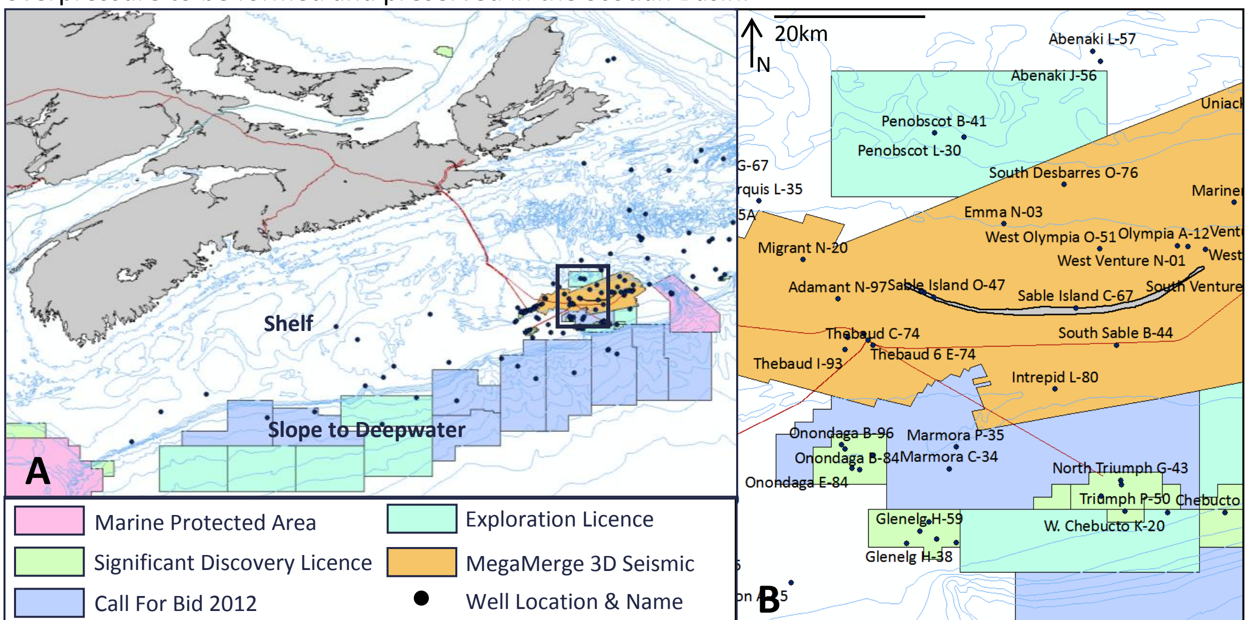

Figure 3: (A) Location of all wells and study area on Scotian Margin, black box, relative to Nova Scotia. Note location of MegaMerge 3D Seismic Dataset. (B) Study area including (north to south) Penobscot, West Sable, Thebaud, and Onondaga fields, with all associated seismic, wireline, and pressure-related data (modified after CNSOPB, 2013).

A Play Fairway Analysis (PFA) was completed on the Scotian Basin by the Offshore Energy Research Association of Nova Scotia (OERA) in 2011, with the intention of increasing offshore petroleum exploration. The PFA did not investigate the presence of abnormal pressures in the Scotian Basin in detail (OERA 2011).. The PFA concluded source rocks are present throughout the basin, and they are oil-prone in the western half and gas-prone in the eastern half. The study also developed predictive models for four potential reservoirs but only considered the reservoirs at a basin-scale and did not investigate whether there are reservoir compartments present or connectivity between them (OERA 2011).

2.4 Reservoir Connectivity Analysis

Vrolijk et al. (2005) defined Reservoir Connectivity Analysis (RCA), an organized set of processes to combine structural, stratigraphic, pressure, and composition data into three-dimensional geometric models explaining connectivity between reservoir compartments. RCA studies completed in other basins (i.e. Jeanne d'Arc, North Sea, and Taranaki basins) have demonstrated the effectiveness of the method for increased understanding of hydrocarbon distribution, pressures, and contacts in reservoirs, allowing for confident application to the Sable Subbasin (Ainsworth 2006; Richards et al. 2010; Vrolijk et al. 2005). Vrolijk et al. (2005) divided the RCA process into three main phases:

Phase 1 - geologic and fluid compartment description;

Phase 2 - geologic and fluid connection definition;

Phase 3 - construction of a reservoir connectivity analysis geometric model.

In Phase 1, the geologic compartment description focuses on identifying and analyzing geometry of all compartments within the study area using available seismic and well log data (Vrolijk et al. 2005). The fluid compartment description focuses on determining fluid type and distribution, usually based on interpretations of wireline log data. Fluid pressure data are also analyzed in order to determine fluid pressure gradients based on temperature, pressure, and composition (Vrolijk et al. 2005). Phase 2 defines geologic and fluid connections between the reservoir compartments identified by Phase 1. Geologic connections include structural and stratigraphic features allowing the reservoir compartments to interact. Structural geologic connections include reservoir connections across fault surfaces, known as 'fault juxtaposition connections' that are normally assumed to be transmissive connections unless the opposite is demonstrated (James et al. 2004; Vrolijk et al. 2005). Phase 3 of the RCA process is integrating the information generated by Phases 1 and 2 to generate a three-dimensional geometric model indicating the location and connection between reservoir compartments. The model allows for increased understanding of reservoir connectivity, and can potentially explain abnormal production results that could be related to overpressure conditions.

(3) Objectives:

I. Establish the location and effect of faults on the reservoir connectivity within the Sable Subbasin. Where are faults located in the subbasin and how much displacement has occurred? Do the faults penetrate the reservoir and/or seals, and are they transmissive or sealing?
II. Determine the location and architecture of reservoir and seal lithologies for the Sable Subbasin, and document them as stratigraphic and structural three-dimensional geometric models. Where are the reservoirs in the subbasin? How have the faults affected reservoir structure, and have reservoir compartments been formed?
III. Establish overpressure distribution and gradients within the reservoir compartments. Where is overpressure located, and what is the magnitude of overpressure? Does overpressure correlate with burial depth, lithology, or stratigraphic formation?
IV. Determine overpressure mechanism(s) and present distribution in the Sable Subbasin. What initiated overpressure formation, and why has it been preserved? Why is overpressure found in the present distribution?

(4) Methods:

4.1 Field Work

Trinidad is an analogue for offshore Nova Scotia, providing the opportunity for outcrop-scale examination of lithologies present and compare these to observations in core, wireline, and seismic data for the Sable Subbasin. Trinidad and Nova Scotia have experienced compressional and extensional tectonic regimes during their formation, which affected the development of their respective petroleum systems significantly. The major basins for both regions include linked fluvial-estuarine, shelf-margin delta, and deepwater depositional systems, leading to a wide variety of petroleum plays. Overpressure occurs in potential and producing reservoirs of Trinidad and offshore Nova Scotia. The basins of Trinidad predominantly comprise deltaic, pro-deltaic, and deepwater sediments, which are the same sediment types observed in the Scotian Basin. Structural complexities affecting reservoir connectivity, such as faults, are present throughout the Scotian Basin however it is difficult to establish fault behaviour because they are inaccessible in the offshore subsurface. Faults present in deltaic deposit outcrops of Trinidad provide an opportunity to examine similar fault structures, and better predict the Scotian Basin faults as a result of this comparison.

4.2 Database Construction

Substantial amounts of data have been collected within the boundaries of the study area and is hosted by three facilities including the Canada Nova Scotia Offshore Petroleum Board (CNSOPB), Natural Resources Canada (NRC), and the Basin and Reservoir Lab at Dalhousie University (BRL). Data available from these sources can be downloaded to an internal network in the BRL and include offshore seismic data in 2D and 3D, digital wireline log data, pressure-related data, and geochemical data. For this study, the database will include two 3D seismic blocks, two 2D seismic surveys totaling 13 seismic lines, wireline log, geochemical, and pressure data from 26 wells. The wireline log data will be filtered to include only those wells that are in a digital format and with pressure data available. The data from the two 3D seismic survey blocks are already in a digital vector format; the largest block is the MegaMerge 3D seismic dataset, donated to Dalhousie University by ExxonMobil SOEP (Figure 3B). The data from the two 2D seismic surveys is available as raster images, therefore they will be sent to a company (Ovation Data) that specializes in digitizing and vectoring, to convert the scans to a digital vector format. The database will be compiled at the Basin and Reservoir Lab using three petroleum industry-standard software programs: Microsoft Excel™, Petrel™, and Techlog™.

4.3 Structural and Stratigraphic Geometric Models

Schlumberger's Petrel™ software will be used to combine wireline log and seismic data into a single dataset. A synthetic seismogram for each well will be created for each well, and is then used to convert the remaining wireline log data for the corresponding well from depth- to time-based, allowing the well to be "tied" to the seismic. The synthetic seismogram is generated by convolving reflectivity data from the acoustic and density logs with the wavelet developed from the seismic data.

Modelling will begin with mapping of reflections (horizons), formed as a result of acoustic impedance (contrasting velocity and density between adjacent lithologies), providing information on lateral extent of lithologies (Yilmaz 1987). Seismic horizons will be tied back to wells, where wireline log data will provide detailed information not resolved in seismic data. Surfaces will also be mapped for faults present so their relationship to the reservoirs can be observed, especially apparent fault displacement, which will affect juxtaposition of the reservoirs across the fault planes.

Schlumberger's Techlog™ will extract the required wireline data from the project database to complete a detailed petrophysical analysis of the wells, resulting in the construction of a petrophysical model. Petrophysical models are important in reservoir characterization and integrate shale volume, total porosity, effective porosity, water saturation, permeability. This information will then be fed back into Petrel™ for use in the three-dimensional structural and stratigraphic models.

4.4 Fault-Seal Analysis

To understand connectivity between reservoir compartments, it is important to know how the faults between compartments have been affecting flow of hydrocarbons – are they baffles (significantly impeding) or barriers (preventing)? Faults typically contain gouge and breccia formed by tectonic movement along a localized zone of brittle deformation. Grinding and milling occurs when the opposing sides of the fault zone move along each other, and the gouge/breccia is the various lithologies that the fault cuts. If there is a sufficient amount of smectite-type clays present in the gouge/breccia, the ultrafine-grained clay particles can seal the fault, effectively alter the flow of hydrocarbons across the fault.

Cores for wells drilled in the Sable Subbasin are catalogued and stored at the CNSOPB, and are available for observation and (limited) sampling. The 29 cores available within the study area will be logged and selectively sampled for representative lithologies; wells which intersect faults will be focused on for sampling of fault gouge. Fault gouge will analyzed to determine the types and relative amounts of clay present. Sample preparation for XRPD will be done at the Basin and Reservoir Lab (BRL) at Dalhousie University. The identification of clay species can be difficult, especially if multiple mixed-layer clay species are present.

The X-Ray Powder Diffraction (XRPD) method is an effective means of identifying and semi-quantifying (relative proportions) clay species in a sample (Chipera and Bish 2001). For the purposes of this study, it is not necessary to know the exact amount of each clay present; it is sufficient to know the relative proportions. The clay fraction (<2µm) will be isolated from the bulk sample, then treated with acetic acid to remove carbonates, and hydrogen peroxide to remove remaining organics. Samples will be mounted on glass slides and flooded with acetone, allowing crystals to randomly orient before the acetone evaporates. Each sample will have 3 slides prepared before XRPD analysis: (1) only treated as described above, (2) treated with ethylene glycol vapour, and (3) heat treated to 550°C. Ethylene glycol is used to expand smectite clay minerals, allowing them to be identified from other clay minerals. The heat treatment allows for identification of clay minerals based on changes in crystal structure spacing or complete dehydration (Poppe et al. 2001). All XRPD analysis will be completed at the Department of Earth Sciences (Dalhousie University) on a Siemens D500 Powder X-Ray Diffractometer using Cu-Kα radiation and a solid-state Si(Li) detector, based on Bragg-Brentano focus geometry. XRPD analysis for each sample will produce a diffraction pattern, uploaded to Jade™, a software application for analysis of XRPD diffraction patterns. The d-spacing between peaks in the diffraction pattern will be compared to a standard database from the International Centre of Diffraction Data© for identification of clay minerals.

Petrographic analysis on core samples will focus on overpressured reservoirs and associated seal(s), to determine if evidence of overpressure is reflected in mineralogy or texture (e.g. alteration of clays, mineral cement) (Huggett 1992; Jansa and Urrea 1990; Jeans 1994). Sealed reservoir compartments that are continuously buried and undergoing mineral diagenesis have the potential to develop significant overpressures, and as a result can preserve porosity that would normally be lost under such overburden. Saturation of pore-fluids in the reservoirs can lead to the development of insoluble mineral cements between the grains, reducing permeability and eliminating a migration pathway for the hydrocarbons (Jeans 1994).

4.5 Pressure Distribution and Gradient Models

Using Microsoft Excel™, pressure measurements for each well can be converted into a synthetic wireline log (depth versus pressure) that can be added to both the Petrel™ and Techlog™ databases. The pressure data can then be plotted within each of the reservoir compartments in the structural and stratigraphic models. This will illustrate the lateral and vertical pressure distribution within the project area. If there is connectivity between the reservoir compartments then they should have similar pressures; however if there is little to no connectivity then there should be notable differences in pressures.

4.6 Pressure Source and Migration

There should be three pressure domains present: (1) hydrostatic, (2) overpressured but below lithostatic, and (3) at or very-near lithostatic. To determine which mechanisms are the cause for observed pressures, I will examine geochemical, lithological, and petrographic data for each well. These data include all the previous data collected and analyzed throughout the study in addition to vitrinite reflectance and Total Organic Carbon (TOC). Overpressure results in the preservation of volatiles, which prevent the molecular restructuring required to produce higher reflectance values than expected for a given hydrocarbon maturity (Carr 1999).

Pressure can migrate by several pathways: pre-existing faults, fault gouge, capillary leak, fractured seals, and dynamic pressure release. By completing the fault-seal analysis (XRD and petrography) I can determine whether the faults within the Sable Subbasin are transmissive, or baffles or barriers to hydrocarbon flow. Using the petrophysical data I can assess whether the seals for the reservoirs are able to allow preserve overpressure based on their properties, or at what point they should fracture allowing vertical pressure migration (Yassir 1994, 2002; Osborne and Swarbrick 1997). This would also be effective in determining if dynamic pressure release (leaking) is occurring.

(5) Significance:

This study aims to define reservoir connectivity and overpressure within the Sable Subbasin by integrating and interpreting pore pressure, wireline log, and seismic data to develop three-dimensional geometric models. This will be completed by determining the location and architecture of reservoir and seal lithologies, and establishing the location and effect of faults on the reservoir connectivity within the Sable Subbasin. Overpressure distribution and gradients will be mapped within reservoir compartments. Finally the reasons for overpressure formation and present distribution will be resolved.

Overpressure is economically significant to help identify potential reservoirs and produce resources. However it is important to understand overpressure to increase safety for personnel during drilling and to protect the environment from complications (i.e. well blowout due to uncontrolled surge in pressure). Offshore drilling is considerably more expensive due to the locations involved and specialized equipment required, and that cost can be further increased if the well encounters overpressure. Understanding the mechanisms, magnitudes, and locations of overpressure in the Sable Subbasin allows safer, cost effective drilling and well casing programs to be designed. This is especially important as exploration for petroleum resources increases throughout the Scotian Basin.

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