RESERVOIR COMPARTMENTALIZATION AND OVERPRESSURE IN THE SABLE SUBBASIN (NOVA SCOTIA) & PORCUPINE BASIN (IRELAND)

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PIP Petroleum Infrastructure Programme

INTRODUCTION

OBJECTIVES

The objective of this study is to interpret the reservoir compartments and pressure cells of the Sable Subbasin and pressure data of the Porcupine Basin in order to better understand the cause(s) for the present (preserved) observed pressure distribution and gradients.

In the Sable Subbasin:
- Determine location, apparent displacement, and effect of faults on reservoir connectivity
- Construct stratigraphic and structural 3D models, focusing on seal and reservoir lithologies, to identify compartmentalization
- Create 3D models for pressure distribution and gradient, integrating reservoir architecture, fault behavior, and pore pressure data
- Determine mechanisms potentially responsible for overpressure formation and present distribution

In the Porcupine Basin:
- Complete a petrophysical analysis on 5 wells
- Integrate pressure data, and attempt to determine if there is pressure communication between vertically stacked reservoir units
- Create a multi-well correlation to investigate potential lateral communication across the basin

PROJECT RATIONALE

Overpressure is abnormally high subsurface pressure exceeding hydrostatic pressure at a given depth, and occurs when fluids become trapped in the pores of sedimentary rocks. Overpressure has been identified as a risk element in the Sable Sub-basin of Nova Scotia, and has been identified as a poorly understood risk element in the Porcupine Basin of Ireland. Previous work has established overpressure in the Sable Subbasin is variable in magnitude and unpredictable, not associated with specific depths or formations. Faults were assumed to be either dynamic (allow communication) or static (does not allow communication), which is inaccurate. This study has access to more recently acquired digital seismic and well log data, and the use of new software than previous studies, which allows for a novel approach for studying pressure in the region.

Abnormal pressure and pressure distribution has received limited study in the Porcupine Basin. Pressure measurements have been collected (repeat formation tests, formation leak off tests, and drill stem tests) in several wells, providing a preliminary dataset to begin investigating pressure behavior in the basin.

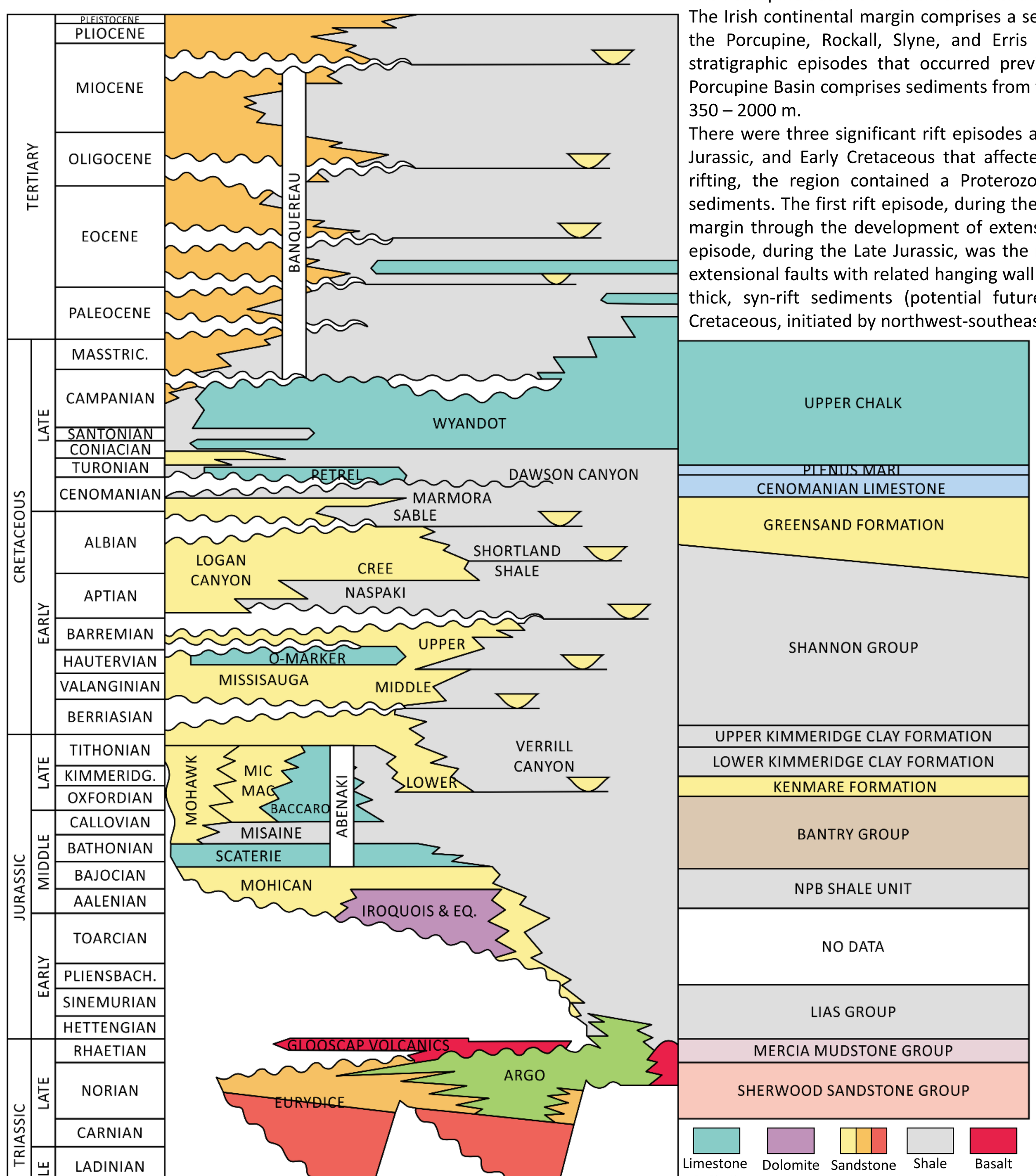
Increased understanding of the context and contributing factors to overpressure in pressure cells or compartments can reduce drilling and environmental risk during exploration and development of offshore resources.

GEOLOGICAL SETTING

SABLE SUBBASIN

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 and the remaining half on the continental slope. Sedimentation into the basin has been near continuous over the past 250 Ma, and has been 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 18 km. The geological history of the basin represents diverse tectonic styles and an array of depositional environments including early-stage rifting, passive margin, carbonate bank, fluvial-deltaic-lacustrine, and deep water. Petroleum exploration in offshore Nova Scotia began in 1959, and (to date) includes 207 wells. Given the considerable area, this means that the basin is underexplored. The Scotian Basin comprises several sub-basins including Sable, Shelburne, Abenaki, Orpheus and Laurentian. Thick salt deposits formed from evaporation of restricted shallow marine waters, leading to the deposition of the Argo Formation. Significant sediment loading after deposition causes displacement of salt vertically and horizontally to create structures such as diapirs, pillows, and turtles. Salt structures are common along the offshore Scotian Margin, including within the Sable Sub-basin, and have become a topic of increased interest due to their unique physical properties allowing for hydrocarbon reservoir preservation. Salt deformation is predominantly controlled by the rheology of the overlying sediments.

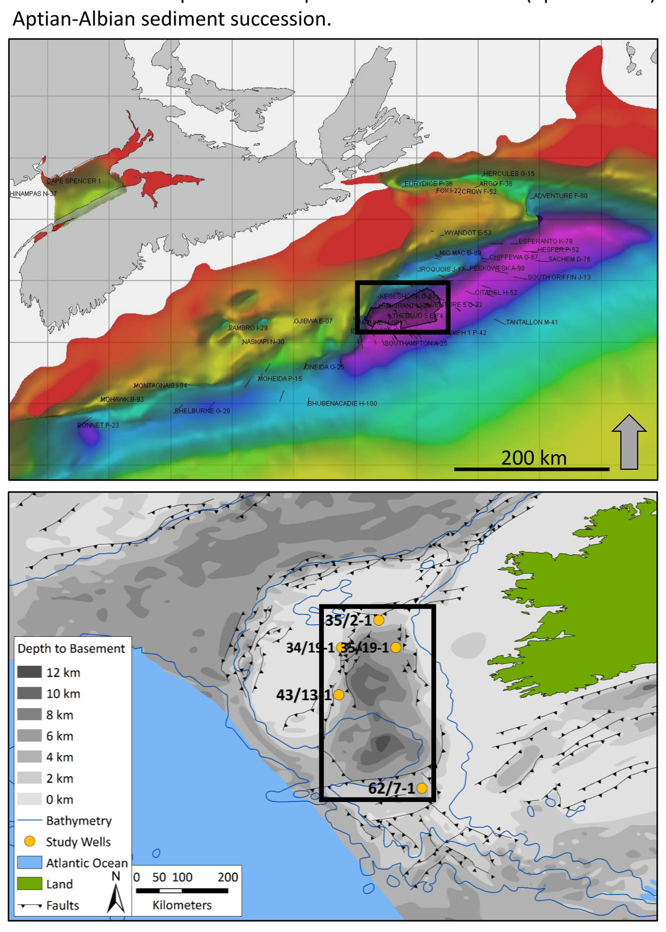
There are several energy projects active or recently active on the Scotian Margin, including Cohasset Panuke (1992-1999), Sable Offshore Energy Project (1999-present), and Deep Panuke (2013-present). Cohasset Panuke was Canada's first offshore oil project, and produced 44.5 MMbbls of oil. Peak production was in October 1993 with 37,500 bpd. The Sable Offshore Energy Project (SOEP) comprises 6 natural gas fields: Venture, South Venture, Thebaud, North Triumph, Glenelg, and Alma. There are an estimated 3 tcf of recoverable gas and 74.8 MMbbl condensate. Deep Panuke began production in the Panuke field in 2014, and has an appraised production life of 13 years but has recently been plagued with water production issues.



Scotian Basin and Porcupine Basin lithostratigraphy.

The Porcupine Basin is a north-south trending Mesozoic-Cenozoic age basin, located on the Irish continental margin. The Irish continental margin comprises a series of north-south and northeast-southwest trending basins, including the Porcupine, Rockall, Slyne, and Erris basins. These basins contain a preserved record of structural and stratigraphic episodes that occurred previous-to and during the formation of the North Atlantic Ocean. The Porcupine Basin comprises sediments from the Carboniferous to Holocene (359.2 mya – present) in waters depth of 350 – 2000 m.

There were three significant rift episodes as a result of crustal extension, which occurred during the Triassic, Late Jurassic, and Early Cretaceous that affected the basin formation and deposition of sediment. Prior to onset of rifting, the region contained a Proterozoic-age crystalline basement overlain by Carboniferous fluvial-deltaic sediments. The first rift episode, during the Triassic, resulted in the formation of the basins of the Irish continental margin through the development of extensional faults and the associated half-graben structures. The second rift episode, during the Late Jurassic, was the most important episode of the three as it resulted in the formation of extensional faults with related hanging wall basins and footwall high. These structures provided accommodation for thick, syn-rift sediments (potential future hydrocarbon reservoirs). The third rift episode, during the Early Cretaceous, initiated by northwest-southeast and west-east crustal extension. This episode reactivated faults from the second and first rift episodes, and led to the deposition and preservation of a thick (up to 10 km) Aptian-Albian sediment succession.

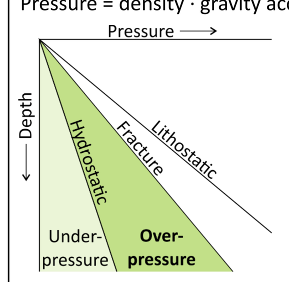


Depth to basement in present arrangement the (top) Sable Subbasin and (bottom) Porcupine Basin.

SUBSURFACE PRESSURE

DEFINITION & FORMATION

Pressure = density · gravity acceleration · depth

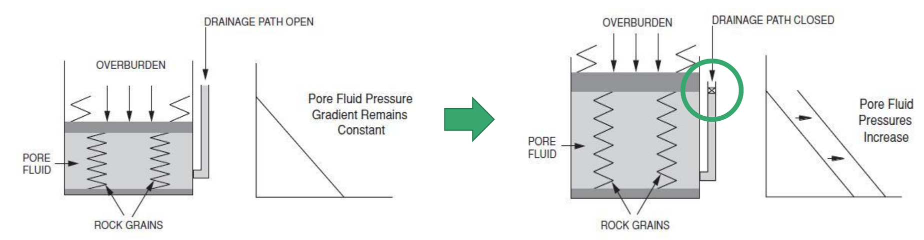


Pressure is the force exerted on area, and depends on density, acceleration of gravity, and depth. **Pore Pressure** is the pressure of fluids within the pores of a reservoir. If impermeable lithologies (i.e. shales) form as sediments are compacted and the pore fluids are unable to escape, the fluids will then support the overburden. Reservoir pressure changes as fluids are produced, meaning any measurements should include a reference to a identifiable time (i.e. initial shut-in pressure versus final shut-in pressure). **Lithostatic Pressure**: pressure exerted per unit area by the overburden (also called geostatic pressure). **Hydrostatic Pressure**: pressure exerted per unit area by a column of water from sea level to a given depth. **Overpressure**: abnormally high pressure exceeding hydrostatic pressure at a given depth. It is not when a specific pressure is reached, instead it is an abnormally high amount of pressure for a particular depth. Overpressure occurs when excess pressure above hydrostatic values associated with fluids trapped in the pores of sedimentary rocks are unable to escape.

LIQUID V_1: CH_3-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_3 decane → LIQUID V_2: CH_3-CH_2-CH_2-CH_2-CH_2-CH_2-CH_3 heptane + GAS V_2: CH_3-CH=CH_2 propene

$V_1 < V_2$

Hydrocarbon Generation: increased pressure as a result of the addition of hydrocarbon fluids and gasses to a confined compartment. Shales deposited with significant organic material will produce hydrocarbons as the shale is exposed to temperature and pressure. Types of hydrocarbon generated (oil vs gas) contribute to overpressure, but generally gas generation leads to higher pressure. Organic by-products can also form salts, which will precipitate in the pore space – these reduce porosity and can form seals (baffles and barriers to flow).

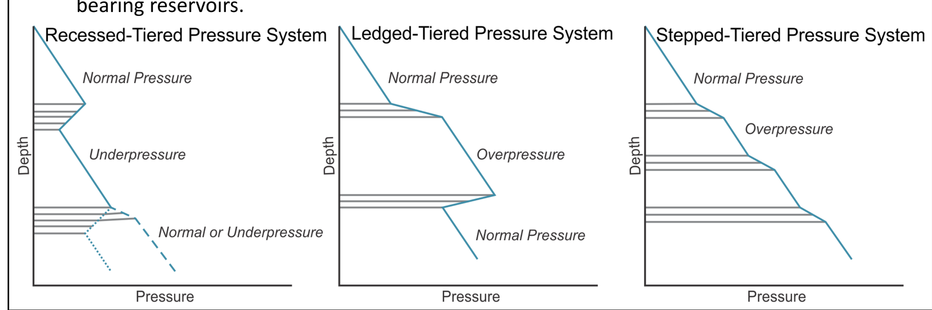


Undercompaction: pressure formed due to rapid burial (typical of deltaic system) coupled with low-k sediments, where dewatering does not occur at the rate required for normal compaction, trapping fluids in pores. The weight of overlying sediments is supported partly by rock matrix and partly by pore fluid, resulting in an overpressured formation. Manifestations on well logs may appear as 'reversals' of resistivity and sonic data when overpressure is penetrated. Transgressive and regressive cycles associated with deltaic depositional environments can produce reservoir-seal pairs, which act as baffles and barriers to flow, and that contribute to overpressure preservation.

PRESSURE DISTRIBUTION PATTERNS

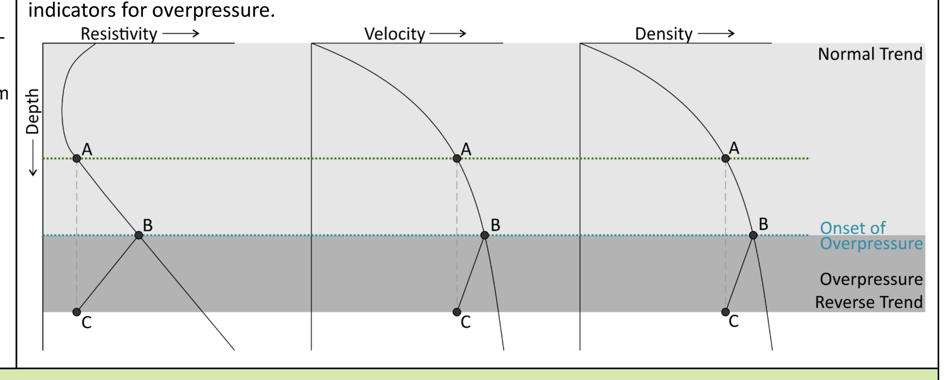
Tiered pressure systems are observed in dynamic basins, and basins with similar depositional histories are more likely to have comparable distribution patterns. Abnormal pressure in subsurface can lead to multiple potential pressure distribution patterns:

(I) Recessed-Tiered: underpressure zone bounded by normal pressure.
(II) Ledged-Tiered: overpressure zone bordered by normal pressure.
(III) Stepped-Tiered: basin containing several low-permeability units isolating hydrocarbon-bearing reservoirs.



SHALE WIRELINE INDICATORS

High overpressure can produce indicators in wireline logs, specifically sonic velocity, resistivity, and density measurements. The data will "reverse" and decrease below normal trend values. Resistivity can reverse for reasons other then pore pressure including changes in temperature and salinity. It is important to complete temperature corrections to logs before using reversals as potential indicators for overpressure.



PORE PRESSURE ALGORITHMS

There are many methods for calculating pore pressure, to the right are three of the most well known/used - Eaton's Method, Bower's Method, and Miller's Method. All methods will require calibration, which is normally done empirically. Calibration points are provided from drilling data, and are based on either well kicks or on observed instabilities in shales. In the case of well kicks, the pore pressure in the sand producing the kick must be higher than the equivalent mud weight and lower than the kill mud weight, and it is assumed that the pore pressures in shales and adjacent sands are the same. With shale instabilities the assumption is that the instabilities occur when the mud weight has fallen below the pore pressure. Wellbore instabilities can be due to compressive breakouts at pressures that are higher or lower than the pore pressure, which means the initial assumption that collapse occurs at mud weight equal to the pore pressure will result in an underestimate or overestimate of the pore pressure. Further complication is caused by the fact that all these methods assume that the rock is obeying a single compaction trend that is consistent throughout, which is unrealistic. Other effects operating can greatly affect measurements including cementation, elevated temperatures, and diagenesis.

Eaton's Method (1972, 1975)

Resistivity Log: $P_{pg} = OBG - (OBG - P_{ng})\left(\frac{R}{R_n}\right)^n$

Sonic Log: $P_{pg} = OBG - (OBG - P_{ng})\left(\frac{\Delta t_n}{\Delta t}\right)^3$

Bower's Method (1995)

$$p = \sigma_v - \left(\frac{V_p - V_{ml}}{A}\right)^{\frac{1}{B}}$$

Miller's Method (2008)

No Unloading: $p = \sigma_v - \frac{1}{\lambda}\ln\left(\frac{V_p - V_{ml}}{V_m - V_p}\right)$

Unloading: $p_{ulo} = \sigma_v - \frac{1}{\lambda}\ln\left(a_m\left(1 - \frac{V_p - V_{ulo}}{V_m - V_{ml}}\right)\right)$

OBG - overburden stress gradient
σ_v - overburden stress
P_{ng} - hydrostatic pore pressure gradient
R - shale resistivity from well logging
a_m - ratio of slopes of loading:unloading
R_n - shale resistivity at hydrostatic pressure
n 1.2 - drilling exponent
Δt_n - sonic transit time in shale at normal P
Δt - sonic transit time in shale from well logging
V_p - compressional velocity at given depth
V_{ml} - compressional velocity at mudline
A - based on offset velocity vs effective stress
B - based on offset velocity vs effective stress
λ - rate of increase in velocity with effective stress

METHODS & TECHNIQUES

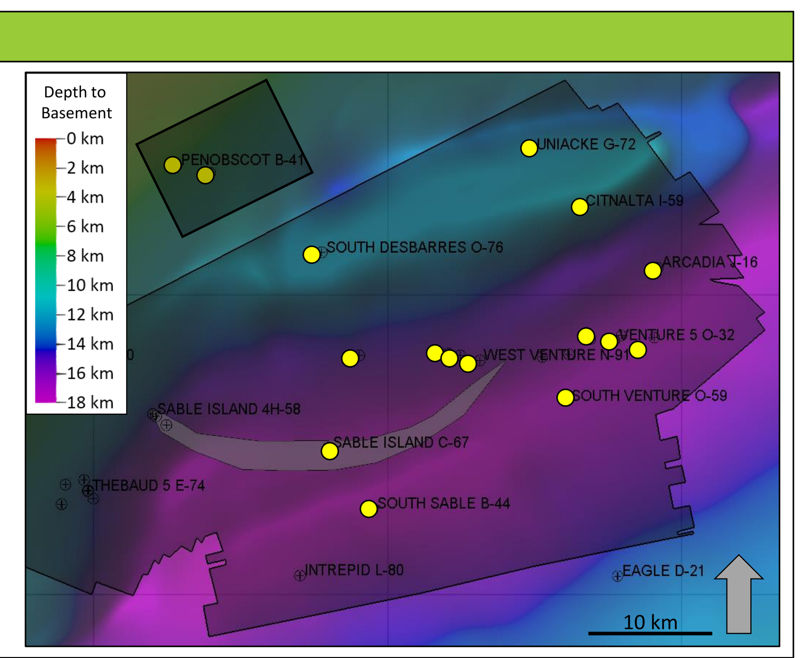
PHASE 1: Petrophysical Analysis & Data Compilation
- Compile data and digitize any required files
- Petrophysical analysis of wells (ϕ, V_{sh}, S_w, S_g, S_o, R_w, etc.)
- Quality check and review pressure data
- Pressure-depth plots
- Synthetic seismograms & seismic-well ties

PHASE 2: Geocellular Modelling
- Locate and model faults
- Identify and model reservoir & seal intervals (horizons)
- Pillar grid and develop geometric model
- Develop velocity model using horizons

PHASE 3: Pressure Modelling
- Determine HWC
- Complete property model utilizing pressure data
- Establish pressure cell distribution
- Compare adjacent pressure cells for communication
- Compile results into a fault & pressure map

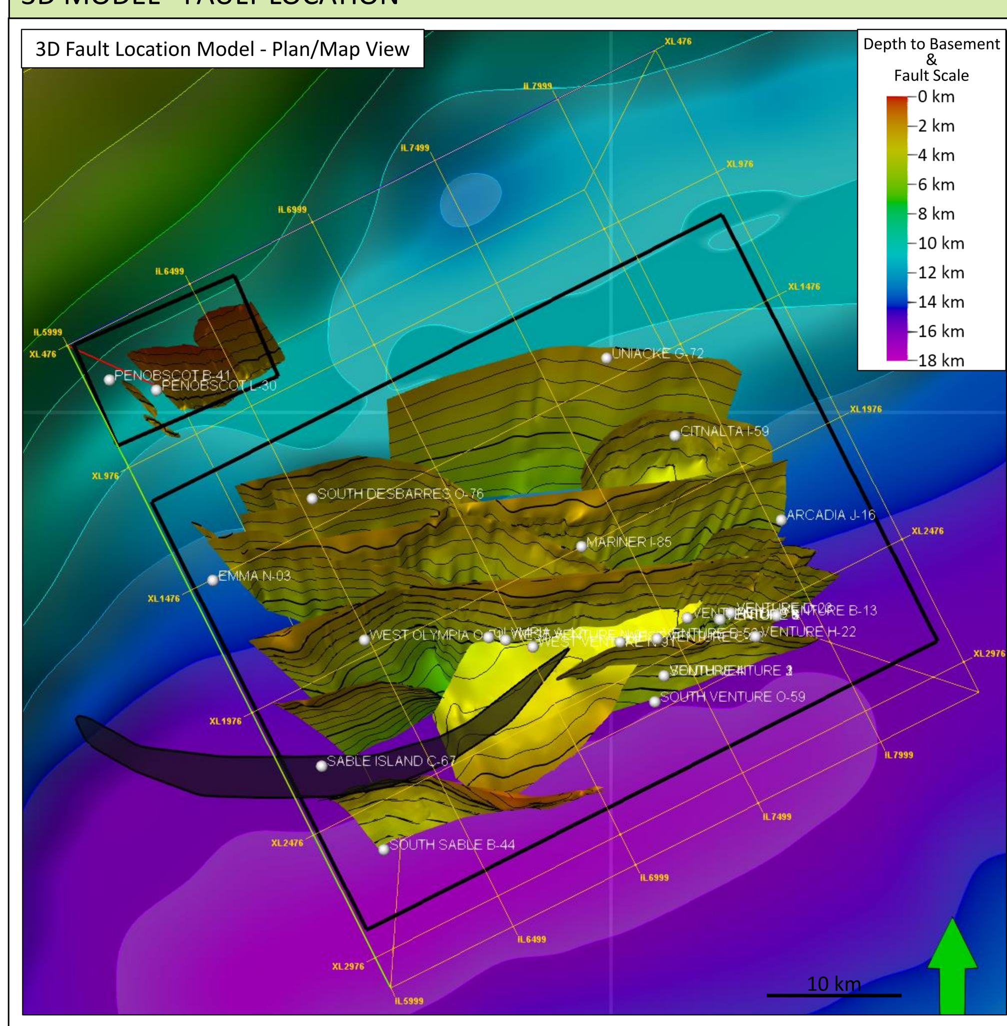
Reservoir Architecture → Establish Competence of Seal → Describe Compartments Within Reservoir → Determine Connections between Compartments

Sable Subbasin Wells	Porcupine Basin Wells
Arcadia J-16	62/7-1
Citnalta I-59	35/19-1
Emma N-03	43/13-1
Olympia A-12	34/19-1
Penobscot B-41	35/2-1
Penobscot L-30	
Sable Island C-67	
South Desbarres O-76	
South Sable B-44	
South Venture 1 P-60	
South Venture 2 P-60	
South Venture 3 P-60	
South Venture O-59	
Uniacke G-72	
Venture 1 O-32	
Venture 3 O-32	
Venture 4 O-32	
Venture 5 O-32	
Venture B-13	
Venture B-43	
Venture B-52	
Venture D-23	
Venture H-22	
West Olympia O-51	
West Venture C-62	
West Venture N-01	
West Venture N-91	



PRELIMINARY RESULTS

3D MODEL - FAULT LOCATION

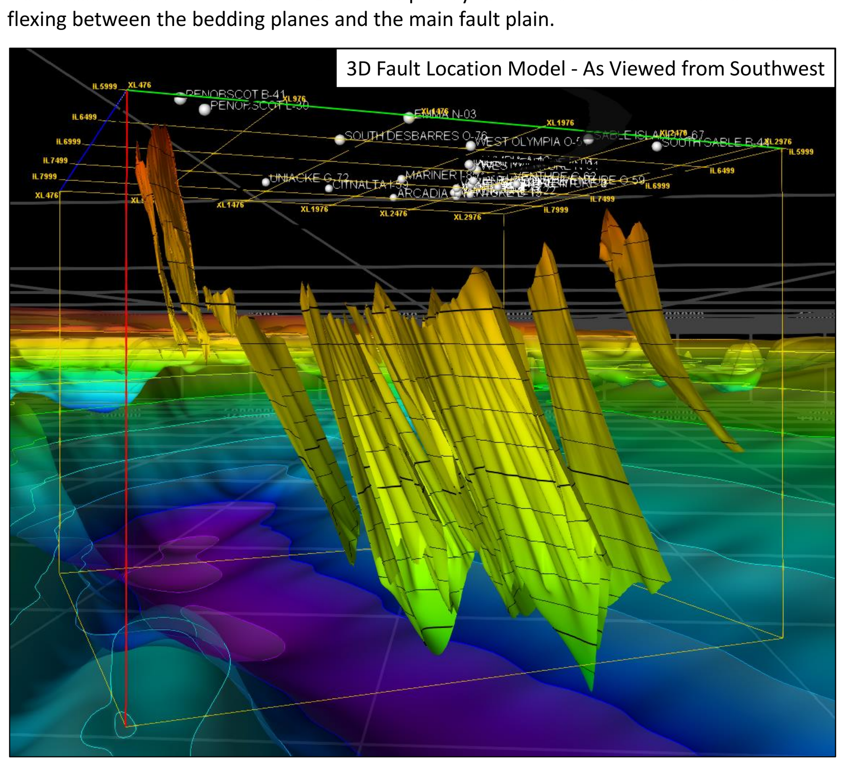


(Left) 3D model of faults within the project area, overlain on basement structure. Identical visual colour scale used for faults and basement to allow for better understanding of relative depth of faults to depth of basement. Faults are listric, generally trend east to west, and are shallower in the northwest and become deeper to the southeast.

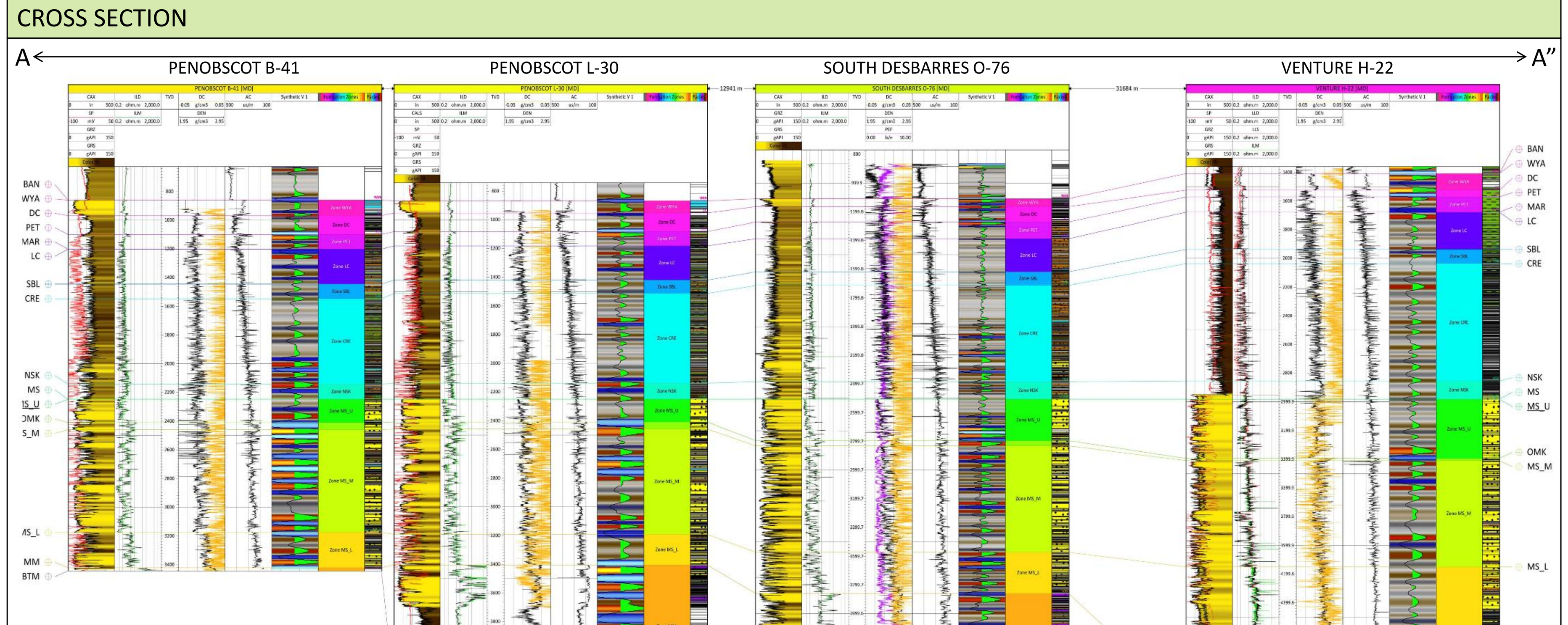
Number of faults: 40

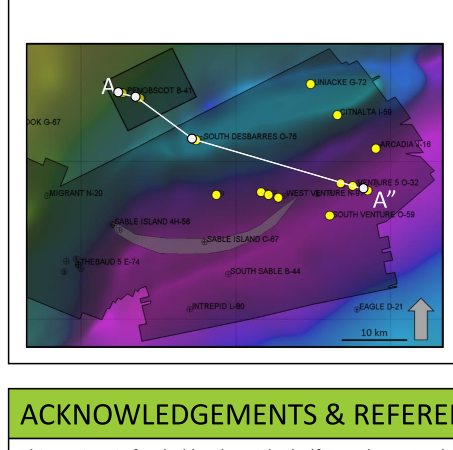
Maximum fault depth: 8443 mTVD

(Bottom) View of faults at 4000 mTVD from southwest (to northeast) showing overall trends described above. Faults formed syn-rift, and demonstrate the overall expansion trend associated with the Scotian Basin. Frequently roll-over anticlines formed as a result of flexing between the bedding planes and the main fault plain.

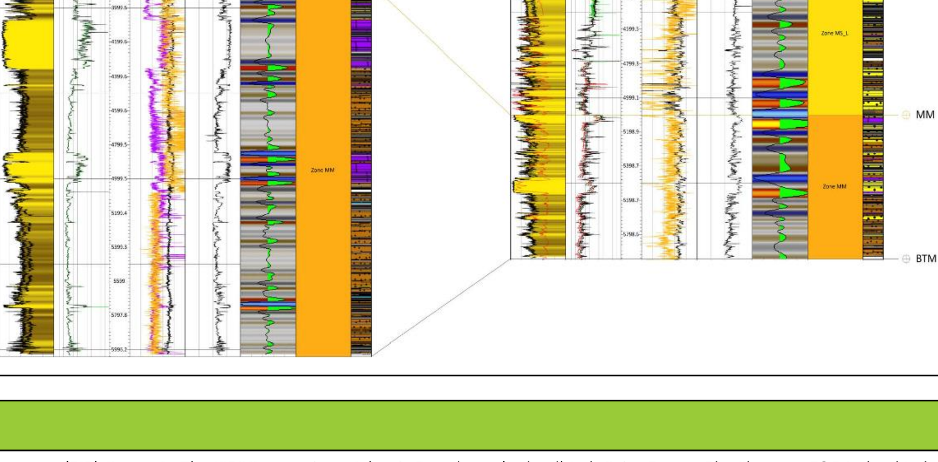


CROSS SECTION

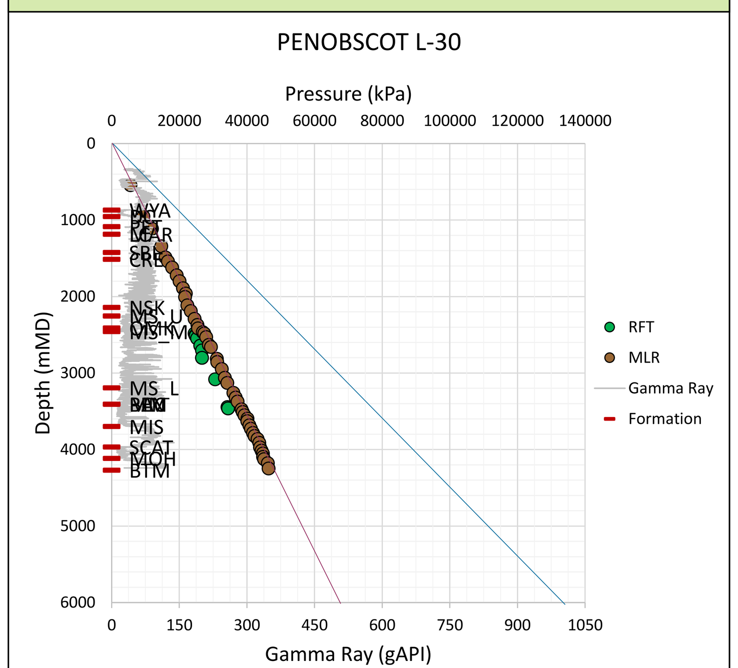


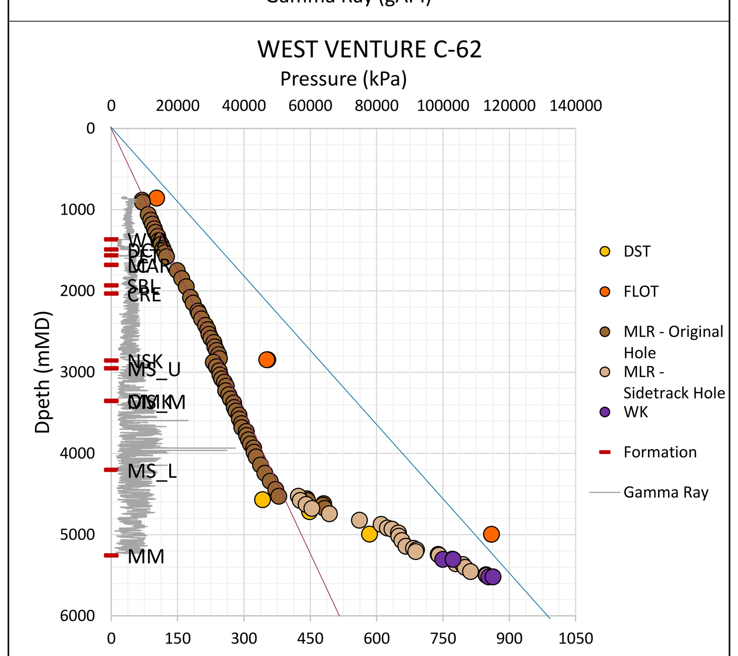


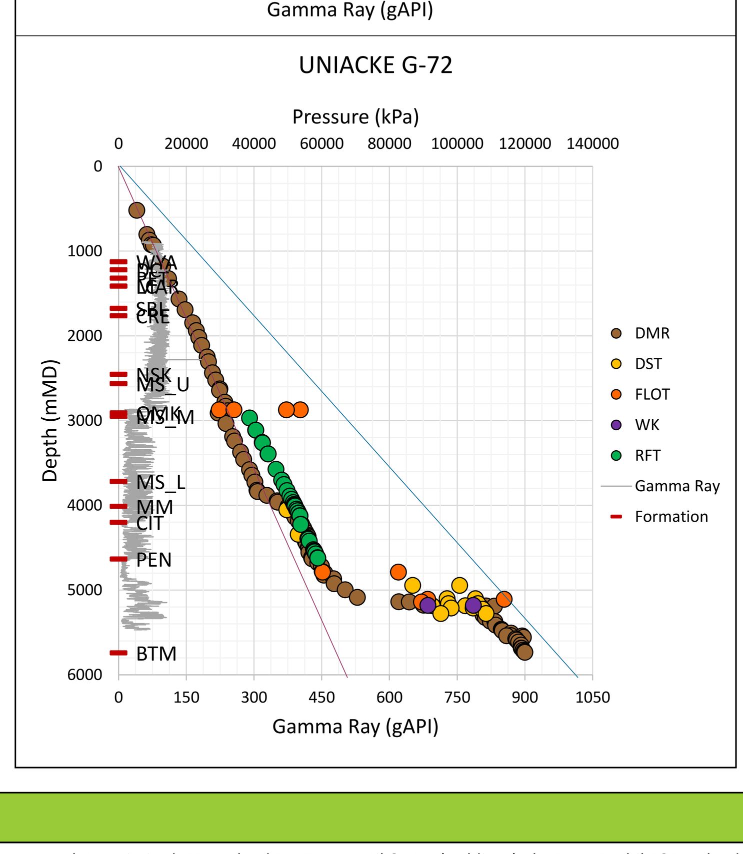
Increasing accommodation space in Scotian Basin (to east & southeast) as rifting continued and North Atlantic Ocean formed, allowed for greater deposition from the Jurassic (Mic Mac Formation) to Early Cretaceous (Cree Member). This can be seen in the cross section. After the Early Cretaceous, sediment deposition stabilized more equally between the continental shelf, slope and the basin.



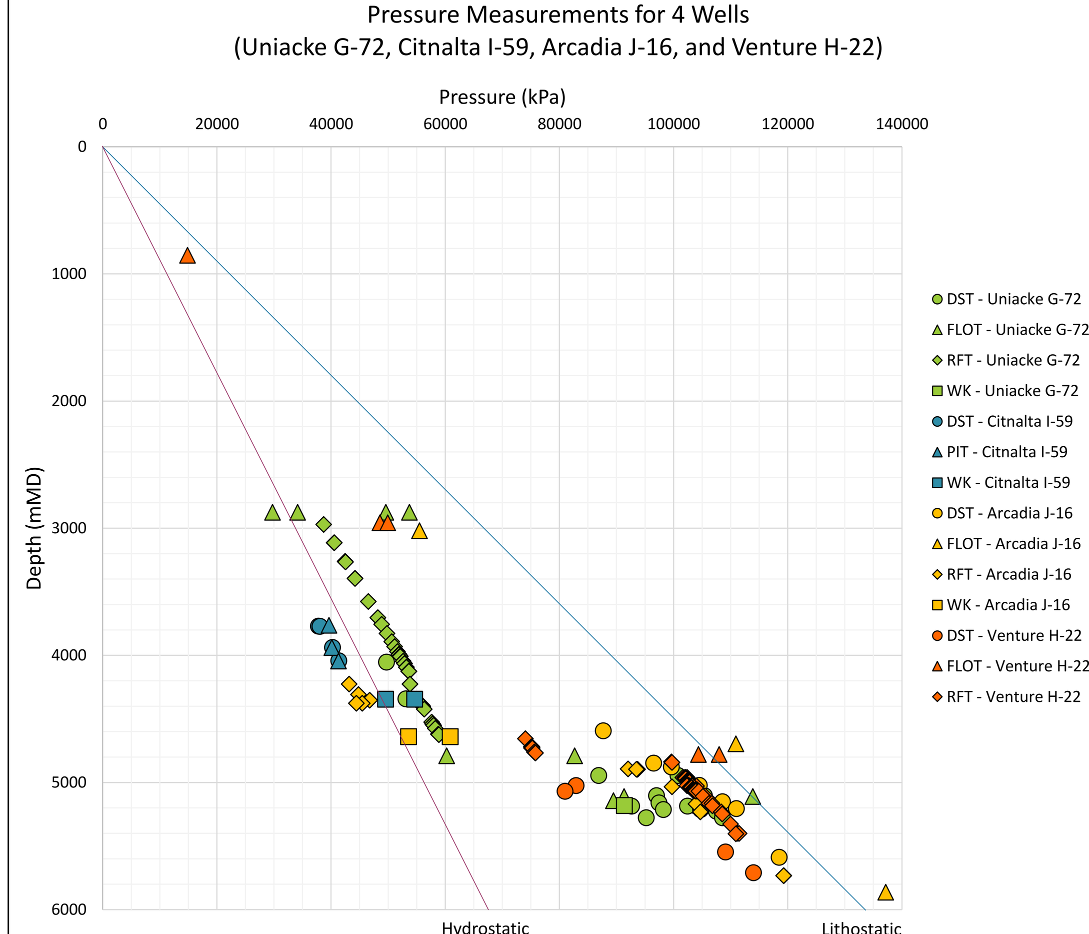
PRESSURE – DEPTH PLOTS OF SELECTED INDIVIDUAL WELLS IN SABLE SUBBASIN







PRESSURE – DEPTH GRAPHS OF 4 FIELDS IN SABLE SUBBASIN

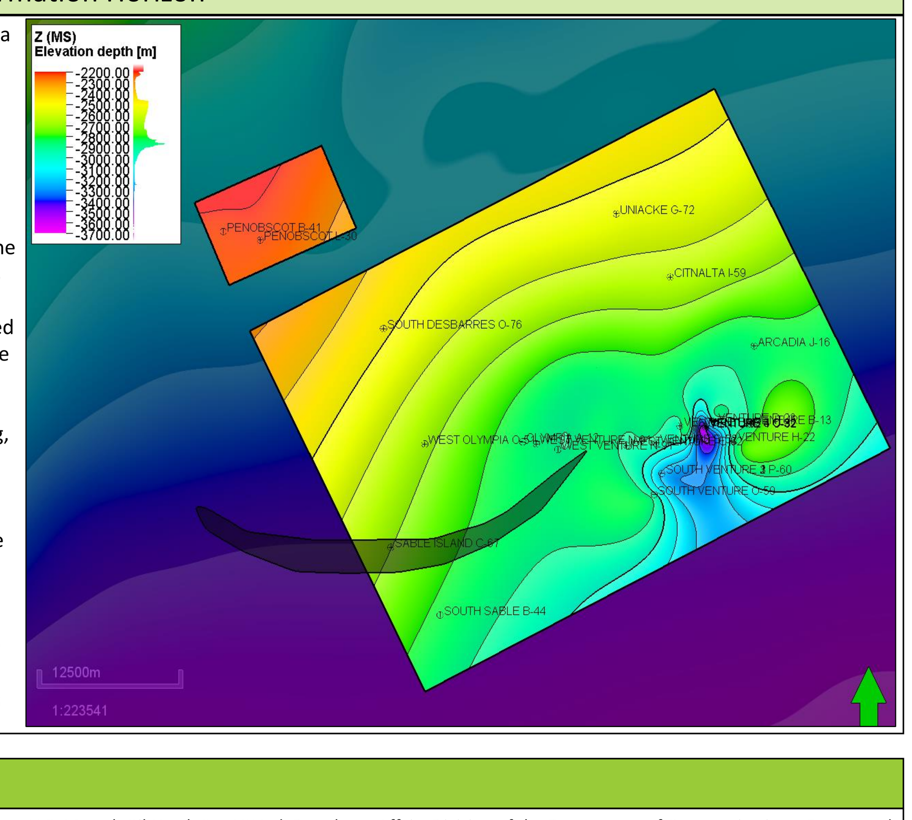


A wide variety of overpressure distribution patterns are observed when pressure data for wells within the study area are plotted against depth. All wells analyzed demonstrate a 'stepped-tiered' pressure system, and no zones of underpressure are found within the study area. Several wells have clusters of overpressure data points, suggesting multiple pressure compartments. These pressure cells are potentially a result of delta lobe avulsion during deposition, where sand bodies are isolated by mudstone layers. The mudstone tends to be thinner and discontinuous, providing a limited seal and allowing for partial communication between the sand bodies – similar to a pressure-relief valve allowing for a slow release. There is also considerable variability in whether the top overpressure is "hard" or "soft", where hard is the rapid onset of overpressure and soft is a more steady increase into overpressure.

Although the drilling mud record (DMR) or mud loggers record (MLR) are not direct indicators of pressure, they are valuable in providing insight as to what pressure were expected to be encountered. The data are also helpful in wells where no pressure measurements were recorded as they still allow some understanding on what the pore pressure would have potentially been as the mud weight cannot be too far below or over this point. The mud weights act as proxies for pressure data.

Missisauga Formation Horizon

This is the Missisauga Formation horizon, generated from the well picks (provide vertical control), underlain by the basement structure. There is poorer well control away from the Venture region, thus the horizon is less developed or detailed away from there. The 3D seismic data is being used to refine the horizon mapping, providing the lateral detail and fill in for the lack of well data in these regions. The process will be completed for all formations in the stratigraphic column with a special focus on production sands



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