Detecting overpressure using the Eaton and Equivalent Depth methods in Offshore Nova Scotia, Canada

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Abstract. Overpressure is an abnormal high subsurface pressure of any fluids which exceeds the hydrostatic pressure of column of water or formation brine. In Offshore Nova Scotia Canada, the values and depth of overpressure zone are determined using the eaton and equivalent depth method, based on well data and the normal compaction trend analysis. Since equivalent depth method is using effective vertical stress principle and Eaton method considers physical property ratio (velocity). In this research, pressure evaluation only applicable on Penobscot L-30 well. An abnormal pressure is detected at depth 11804 feet as possibly overpressure zone, based on pressure gradient curve and calculation between the Eaton method (7241.3 psi) and Equivalent Depth method (6619.4 psi). Shales within Abenaki formation especially Baccaro Member is estimated as possible overpressure zone due to hydrocarbon generation mechanism.

1. Introduction
There are several aspects to do the geomechanics research such as overpressure, pore pressure and stress state relationship. Overpressure can be formed by several mechanisms including faulting, undercompaction, formation foreshortening, massive evaporite deposition, mineral phase change, repressuring, and hydrocarbon generation (Nguyen, 2013).

Pore pressure calculations is a function of distance. Equivalent depth, Eaton, and effective stress are several methods to determine pore pressure. In this research, we use equivalent depth and Eaton methods called as “vertical” and “horizontal” methods to identify the potential of abnormal pressure exist, according to many studies of overpressure in this location. The evaluation is limited by well data without seismic data as the method requires.

The location of research is in Penobscot area, Offshore Nova Scotia, Canada. The previous research indicates there are overpressured zone in this region. There are two wells that was drilled in Penobscot area, the first well is Penobscot L-30 with hydrocarbons were recovered by Repeat Formation Tester (RFT) and the second well is Penobscot B-41 (Clack, 1992). Different conditions with the Penobscot L-30 well, hydrocarbon in Penobscot B-41 were not encountered significantly. Both of well were drilled to 13950 feet for Penobscot L-30 and Penobscot B-41 to 11320 feet.

2. Geology Regional
The Scotian Basin is located on the northeastern flank of the Appalachian Orogen and covers an area of approximately 280,000 km² with a maximum sediment thickness of about 24 kilometers (Figure 1). The continental-size drainage system of the paleo-St. Lawrence River provided a continuous supply of
sediments that accumulated in a number of complex, interconnected subbasins. Early synrift, carbonate margin, fluvial-deltaic-lacustrine and deep water depositional systems are all represented in the basin's stratigraphic succession (CNSOPB, 2013).

Figure 1. Research area located in Offshore Nova Scotia for Basin and Components (Penobscot L-30 and Penobscot B-41)

During the Middle Jurassic to Early Cretaceous, carbonate deposition dominated sedimentation around the entire North Atlantic margin, reflecting a period of continuous global sea level rise and gentle downwarping and thermal subsidence of rift-bounding continental crust (Kidston et al, 2005). Reef, platform and related facies were established along the margins of the Atlantic and Tethys Oceans under ideal conditions of broad, stable low relief and shallow shelves, warm oxygenated waters with limited oceanic circulation, limited background clastic sedimentation and low fluctuations of oxygen and nutrient levels.

2.1. Stratigraphy
Abenaki formation divided into 4 members (Figure 2): Scaterie, Misain, Baccaro, and Artimon member (Wade et al, 1995). Scaterie Member is the most areally extensive sequence of the Abenaki Formation. It is a seaward-thickening wedge of predominantly platformal oolitic lime grainstones and packstones, with at least four deepening-upward transgressive sequences recognized. Misaine Member is the only clastic component of the Abenaki Formation and this neritic facies is representative of the Callovian global transgressive event in the Sable Basin. The Misaine is composed predominantly of dark grey, slightly calcareous shales with minor beds of pelleted and laminated lime mudstones. Baccaro Member is the thickest and best developed carbonate unit of the Abenaki Formation. The dominant lithology is limestone with minor shale and sand intervals representing the reworked remnants of lowstand events. Artimon Member is the youngest sequence of the Abenaki Formation which thinnest about 30-115 metres with a very modest and patchy areal distribution limited to the eastern part of Abenaki platform margin edge. Lithologically, the Artimon is composed of argillaceous, cherty limestones representing
thrombolitic sponge and stromatoporoid mound deposition, with occasional interbedded calcareous shales (Wade et al, 1995).

![Figure 2. Scotian Basin Generalized Stratigraphic Chart](image)

3. Methodology

There are some pore pressure calculation methods are available, which differ in the way the effective stress is derived from data sets as logs and seismic. In this case, researcher estimating pore pressure in shales using the Eaton and Equivalent Depth methods based on well logs.

3.1. Equivalent Depth

Equivalent depth method is based on the reasonable assumption that formations having same interval velocities would have the same effective vertical stress irrespective of the depth (Ham, 1966). The initial method is defined by relationship between pore pressure, effective stress, and the overburden stress explained by the Terzaghi relationship.

When the data set deviates from the normal compaction trends, the approximation of the pore pressure at any depth can be calculated if the measured value isn’t on normal compaction trend because measured values itself related to effective stress (Figure 3) and also represent depositional sequence. Pore pressure is calculated using the following equation 1:

\[ P_{za} = P_{zn} + (S_{za} - S_{zn}) \]  

Where,

- \( P_{za} \), \( P_{zn} \) = Pore pressure at \( za \) point (observed) and pore pressure at \( zn \) point (compacted normally)
- \( S_{za} \), \( S_{zn} \) = Stress at \( za \) point (observed) and pore pressure at \( zn \) point (compacted normally)
The only unique assumption required by equivalent depth methods is that effective stress is a linear function of depth.

3.2. Eaton

The Eaton method has been described as a “horizontal” pressure method because it compares an in-situ physical property to a “normally-compacted” equivalent physical property at the same depth (Figure 4). Eaton’s method approximates the effective vertical stress with ratio of sonic log velocities or resistivity values. This method is based on the principle that the relationship between this ratio and pore pressure depends on changes in the vertical stress gradient (Eaton, 1972; Mouchet and Mitchell, 1989) in Ruth, 2002. The estimation value is calculated by following equation:

\[
P_p = \sigma_{ob} - (\sigma_{ob} - P_{p normal})\left(\frac{V_{observed}}{V_{normal}}\right)^x
\]

Where,
\[P_p\] = Pore pressure (psi)
\[\sigma_{ob}\] = Overburden pressure (psi)
\[P_{p normal}\] = Normal Pressure (psi)
\[V_{observed}, V_{normal}\] = velocity value at the depth of observed zone and at normal pressure (feet/s)

The accuracy of equivalent depth method and the Eaton method is dependent on the extent to which the acoustic travel time anomalies are related to overpressure via changes in porosity.

4. Discussions

Eaton’s and Equivalent depth methods require the use of a NCT (normal compaction trend), which means the trend of any physical property (example: travel time, resistivity, density, etc) is plotted as a function of depth through the normally pressured strata. According Figure 5 and 6, velocity data is plotted from both logs (Penobsct L-30 and Penobsct B-41) that has been filtered before, on gamma ray value using cut off 70 API. This analysis only evaluating pore pressure in shales due to high possibility become overpressured.

The NCT’s analyze is used to identify abnormal pressure possibility by the existence of deflection data trend. Deflection exist at well Penobsct L-30, it’s more represent possibility of overpressure and neither at well Penobsct B-41. Due to only Penobsct L-30 that has deflection data trend, so for next calculation only use Well Penobsct L-30. The NCT value in well Penobsct L-30 is \(y = 1.1707x - 5783.3\). Overpressure possibility point is picked from software (Figure 7) to get accurate value yield top at depth 11804 feet as interest zone.
In normal pressurised formation, porosity will decrease with depth as the fluid expelled out of the pore due to increasing overburden weight, it maintains the effective communication of pore fluids with surface. So at any depth pore pressure is simply the same as the hydrostatic pressure (1.03 g/cm$^3$ or 0.433 psi/ft) of the water column (Saran, 2011).
4.1. Method Calculation

The main evaluation is method calculation, for Eaton method we have to calibrate the x value (exponent coefficient) using equation from graphic relation between travel time and effective stress shown Figure 9, it represents the value of Eaton exponent coefficient seems like $\Delta t = C \sigma^{-x}$, $y = 3082.8x^{-0.43}$ equation provide eaton exponent coefficient ($x = 2.32$). Although there are formation test data that measure pressure at some interval depth, but there is no fix relation between pressure test and calculation result. Eaton formula (Equation 2) assume that ratio (velocity or resistivity) influence the effective stress value, but in this case we only use velocity ratio, then the result of pore pressure is 7241.3 psi.

Equivalent depth is kind of pressure estimation method that simple enough for calculating using effective vertical stress principle, yield pore pressure value of zone interest 6619.4 psi. Generally both methods has each specific quality that related to another seems like Eaton method has been described as a “horizontal” method and the equivalent depth method has been described as “vertical” pressure method. The Eaton and Equivalent depth methods calculation must yield similar pore pressure estimation, but in this case result different value. It might be caused by the different approximation of both method.

The abnormal evaluation at 11804 ft describe pressure value 6619.4 psi (equivalent depth method) and 7241.3 psi (Eaton method) compare with normal pressure at the same depth is 5111.3 psi (Figure 10). It means there is possibility overpressure zone in Abenaki formation especially Baccaro Member. As we know Baccaro Member is part of carbonat platform from Abenaki and proven to produce hydrocarbon in this field.

Potential causes of overpressure in Nova Scotia are hydrocarbon generation and undercompaction (Dickson, 2012). In this case, its tend to be caused by hydrocarbon generation occurs when pressure increase as a result of the addition of hydrocarbon fluids and gasses to a confined compartment and also types of hydrocarbon itself contribute to overpressure level. Due to lack of data sets and analysis makes
detecting overpressure is too difficult to get the valid result, moreover this evaluation only use single well from two wells provided. And there is ambiguity about detect abnormal pressure zone in Penobscot L-30 due to th deflection data trend caused by truly overpressure zone or it just caused by gas content within porous carbonate reservoir.

Overpressure analysis is important and needed for helping identify potential and produce resources. Moreover to increase safety for personnel during drilling and protect the environment from complication (i.e. well blowout due to uncontrolled pressure). It will more challenging in Offshore drilling include condition and cost.

5. Conclusions
Based on analysis before (Eaton and Equivalent Depth method), pressure evaluation only applicable on Penobscot L-30 well. Principally pressure estimation using the Eaton method is better than equivalent depth method caused considers physical property ratio (velocity) and has flexible exponent coefficient for specific formation character. An abnormal pressure is detected at depth 11804 feet as possibly overpressure zone, based on pressure gradient curve and calculation between the Eaton method (7241.3 psi) and Equivalent Depth method (6619.4 psi). Shales within Abenaki formation especially Baccaro Member is estimated as possibile overpressure zone due to hydrocarbon generation mechanism.

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