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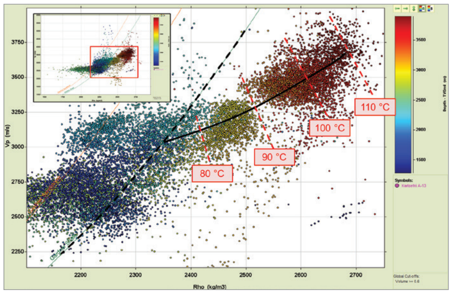
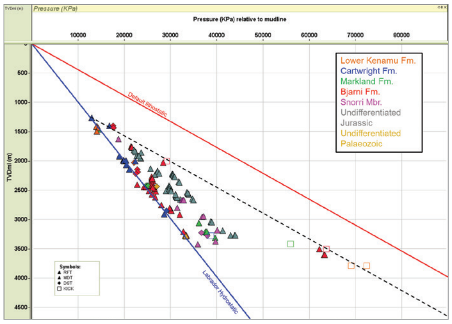
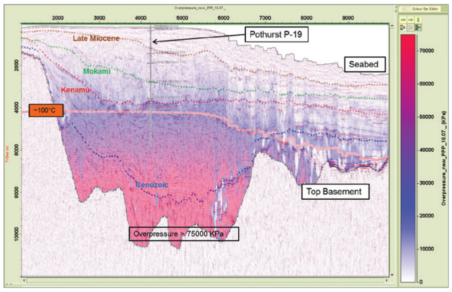
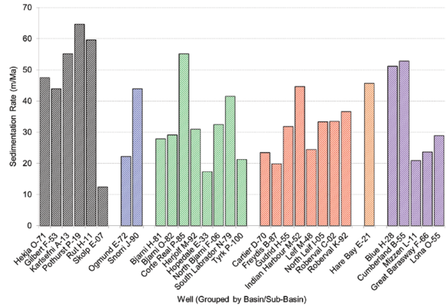
Regional Pore Pressure Analysis of Offshore Newfoundland and Labrador:

Unlocking the Shelf-to-Deep-Transition









Roknowledge

GeoPressure

nalcor energy

Executive Summary

Study Overview

- This study by Ikon GeoPressure was commissioned by Nalcor Energy in order to examine and interpret pressure and related data from all data-rich wells drilled on the Labrador Shelf.
- The area studied included the Saglek, Hopedale (including Nain, Hamilton and Harrison sub-basins) and Orphan Basins, and additionally the newly identified deep-water Henley, Chidley and Holton Basins in which there are no wells drilled to date.
- The objective is to provide (a) a framework for future drilling by helping to define the elements of the drilling window (pore and fracture pressure) and (b) to examine how pressure data may improve the quantification and exploration risk of future prospects by, for example, analysis of the risk for mechanical seal failure.
- Ikon GeoPressure have extensive worldwide experience of regional pressure analysis and a further objective of this study has been the use of analogues from other either present or ancient deep-water settings globally to help understand how relationships in the shallow water manifest in the deep-water

Database Summary

- Data from a total of 30 wells were used in the study: petrophysical logs, wireline test data (e.g. RFT, MDT), DST and Leak-Off Test data plus mudweight and other data from end-of-well reports were compiled for each well.
- Petrophysical conditioning of the wireline logs led to improvements in the well log analysis and the ability to properly define a V-shale (with appropriate cut-off) to delineate shales which would be used for pore pressure prediction.
- Analysis of available direct pressure data reveals many normally-pressure reservoirs to depths of 3500m, some reservoirs which are variably overpressured from depths of 1400m and deeper, and the highest overpressure recorded in Pothurst P-19 of 34246 kPa. Many mudweights are low, however, in those wells with thick shale packages Kicks are taken. Mudweights show rapid increase in the wells with Kicks and a degree of under-balance is implied.
- Only in the Orphan Basin is there sufficient data to explore the potential for stratigraphic/structural isolation of pressures into “cells” with the suggestion of stratigraphic

zonation of pressures. In all other basins the results were inconclusive. Compartmentalization is considered more likely, certainly by faults, in syn-rift deposits such as the Bjarni Formation. This faulting can result in preferential down-thrown structural closure. As sediments are progressively younger in the deep-water, the development of syn-rift deposits will reduce.

Pressure Mechanisms

- Overpressure mechanism analysis using velocity-density cross-plot techniques show only disequilibrium compaction as the primary mechanism to create overpressure. However, the plots do show chemical compaction trends in three wells in the Saglek Basin. No velocity reduction is observed suggesting little contribution to overall overpressure. However, it should be noted that only 13 wells have temperatures in excess of 80^{o}C (a potential lower threshold for thermally-driven processes).
- There remains the potential for long-distance lateral transfer along connected reservoir systems could contribute overpressure generated from deep processes not encountered in the wells drilled to date, although reservoir data so far have not revealed this process.

Well Planning

- For the overburden, and following basin-by-basin analysis of the available density data, a three-layer model (Sea-floor to Top Bjarni; Top Bjarni to Top Basement; Basement) was created for the Saglek and Hopedale Basins, but with northern and southern variations. A separate overburden was generated for the Orphan Basin.
- In the deeper-water more volcanics are expected and less glacial tills; both may affect the overburden. From global analogues, deep-water overburdens are less than those in the shallow water thus the provided overburden may, if anything, over-estimate shale pressure to a small degree.
- Normal compaction trends (NCTs) were developed for the study area, and applied to velocity and resistivity data to estimate the magnitude of overpressure in shales in each basin. There is a common NCT which can be applied to most basins and sub-basins. In West Greenland, compaction models based on shallow water well-data were applied successfully in the deep-water.
- The resulting overpressure trends in the shales reveal the following characteristics:

- Thick shales exhibit overburden-gradient parallel profiles of increasing overpressure with depth, consistent with disequilibrium compaction as the primary source of overpressure in those shales;
    - Many shale-reservoir contacts have trends of decreasing overpressure in the shales, consistent with lateral drainage (loss of overpressure due to leakage) in the reservoirs.
    - The Fluid Retention Depth or "FRD" method of estimating overpressure in shales using average sedimentation rates provides a good test of the overpressure estimated from the shales as well as matching the "Kick" data in several wells providing a means of estimating theoretical shale pressure in the deep-water.
    - Lateral drainage affects most of the reservoirs (all stratigraphic ages) and is most prevalent in the Hamilton Sub-basin (Hopedale Basin). Hydrodynamic trapping is to be anticipated where laterally draining reservoirs exist.
    - Lateral drainage characteristics (i.e. shale pressures in excess of reservoir pressures, coupled with overpressure trends which show decreasing lateral drainage effects with distance from the contact with the reservoirs) are present in 19 of the 30 wells analysed.

- A variety of traditional methods (e.g. Matthews and Kelly (1967), Eaton (1969)) were used to estimate fracture gradient in each of the basins, calibrated where applicable with available LOT data, which are generally sparse.
- An alternative approach, termed the Swarbrick and Lahann (2008) method, was also applied, which related fracture pressure (FP) to overburden (Sv) but also includes a pore pressure-stress coupling (PP-FG) term. The relationship of FP to Sv is 0.87 when normally pressured, with a PP-FG coupling term of 0.38.
- A set of five theoretical vertical pore pressure profiles were modeled, four in the deep-water. The pore pressure profiles were based on (a) theoretical pressure build-up based on offset well analysis, and (b) seismic interval velocity. In both cases, pore pressures were predicted to be high and parallel to the overburden. Below the 120-130^{o}C isotherm, pore pressures were modelled to converge on the overburden to reflect additional pressure generating mechanisms acting. The seismic velocity data tending to drift to lower pressure with increasing depth below the Top Lower Kenamu. Seismic velocity data appears to be a useful tool for first-approximation pore pressure estimation in Labrador, certainly in the Tertiary.

High Pressure Trap Risking

- The dataset was insufficient to demonstrate a relationship between pore pressure and fracture strength which suggests potential seal failure. Lateral drainage, identified in the majority of wells/reservoirs, has the effect of strengthening the effectiveness of the top seal.
- There is no evidence of seal failure or other fluid flow escape phenomena identified above any of the drilled structures for those wells where seismic data were examined, although gas chimneys have been report close to wells such as Blue H-28 in the Orphan Basin.
- Blue H-28 had the lowest seal capacity calculated at 3900kPa In several other Sub-Basins e.g. Hopedale, Saglek, comparing the seal capacity of a dry hole and a discovery in close geographical proximity may provide a useful set of threshold values for breach.
- The risk of breach was considered high in the modelled TPP's in the Markland and Cartwright Formations only below the 120-130^{o}C isotherm.
- Dry holes in the well database are therefore unlikely to be without hydrocarbons on account of top seal failure due to hydraulic leakage. Other possible explanations include lack of charge, and lack of overall structure/stratigraphic geometry to ensure adequate trapping at the well location.

Deep-Water Analogues

- The report includes an overview of the geological evolution of the Labrador Shelf region offshore Eastern Canada, based on a literature review.
- Analogues for the Labrador Shelf have been examined the following comparisons with many different types of analogues ranging from current deep-water exploration areas both close to (Scotian Slope) and far from (Mid-Norway) the Labrador complex to shallow water wells than penetrate deep-water facies that provide useful analogue information. Additionally, some areas are analogous to the challenges of deep-water exploration, such as the deep-water Gulf of Mexico
- Mid-Norway proves the presence of both laterally drained deep-water reservoirs via basin floor fan complexes that link to the shelf and isolated highly overpressured reservoirs. The same observations can be made in East Canada, Nova Scotia, Niger Delta and the Central North Sea.
- A lack of structural faulting is expected in the deep-water therefore a lack of structurally controlled pressure compartments is expected. Polygonal faulting, which tends to form in layer-bound, shale-dominated environments and may be expected in the deep-water of Labrador.

- In the Ormen Lange Field in Mid-Norway, polygonal faulting is present, which has implications on the likely behaviour of the field fluid dynamics. Interestingly, this style of complex faulting does not preclude hydrodynamics (laterally drained reservoirs).

- Stratigraphic isolation is more likely to be common in the deep-water, however, communication in-board is possible as demonstrated in the deep-water West Greenland where the Cretaceous Fylla Formation is normally-pressured; the implication is that the deep-water, sands such as the Freydis in the Markland Formation can drain laterally and lose pressure despite the distal nature of the sands.
- Narrow Margin Drilling (NMD) is a common feature of deep-water environments world-wide. As the facies is likely shale-dominated in the deep-water Labrador the onset of overpressure will be shallower than on the Shelf for comparative stratigraphy. Pore pressure profiles will, therefore, build relatively shallow overpressure parallel to the overburden and continue for the remainder of a well.
- Rates of sediment loading will strongly influence the depth at which no more fluid can escape from the shale ("FRD"), and overpressure builds by disequilibrium compaction. FRD modelling has been used successfully in deep-water settings world-wide such as Niger Delta and Nile Delta to produce overburden-parallel shale pore pressure profiles. Applying this approach to wells with deep high pressure on the Labrador Shelf, produces a pressure profile that matches closely the Kicks taken in these wells.

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Authorship

This report (and the technical analysis within) was undertaken and written by Dr. Sam Green, William Goodman, Dr. Niklas Heinemann and Dr. Alex Edwards from Ikon Science and underwent technical management, review and guidance by Stephen O'Connor, Prof. Richard Swarbrick, Edward Hoskin and Dr. Richard Lahann from Ikon Science. All the above are members of the geopressure division of Ikon Science, termed Ikon GeoPressure, with exception of Richard Lahann who is an consultant to the Ikon GeoPressure group.

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