PS Correlation of the Pore Pressure Gradient and Maturity of the Niobrara Formation Across the Powder River Basin, Wyoming*

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Search and Discovery Article #30634 (2021)**
Posted February 8, 2021

*Adapted from poster presentation given at 2019 AAPG Hedberg Conference, The Evolution of Petroleum Systems Analysis: Changing of the Guard from Late Mature Experts to Peak Generating Staff, Houston, Texas, March 4-6, 2019
 DOI:10.1306/30634Perez2019

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Abstract

This study presents the results obtained from the Petroleum System Modelling (1D) performed at different well locations across the Powder River Basin (PRB), Wyoming. The forward simulation technique was applied to correlate the variability of the pore pressure gradient in relation to thermal maturity and hydrocarbon generation in the Niobrara Formation. Calibration and generation of the petroleum systems models involved consideration of the following: 1) Thermal aspect, 2) Lithologic composition 3) Porosity and Permeability, 4) Pore pressure gradient (this calibration was carried out by using the pore pressure gradient obtained from pore pressure prediction (Yale et al., 2018)); and 5) Source rock properties.

The results showed that the variations in the thermal evolution of the organic matter within the Niobrara Formation across the PRB have important implications for pore pressure variability, being suggested as one of the main mechanisms of pore pressure generation. In areas where the organic matter was affected by high thermal stress (such as northeastern part of PRB), increased pore pressure, hydrocarbon generation pressure, and overpressure are observed. Inversely, areas where the organic matter was subjected to low thermal stress, the pore pressure, hydrocarbon generation pressure, and overpressure are lower. The driving mechanism is likely the generation of liquid and gaseous hydrocarbons from primary and possibly secondary cracking of organic matter. In areas where the Niobrara Formation has a high level of maturity, secondary cracking would have been contributing to hydrocarbon generation post Late Paleocene. The evolution of the fluid-flow system is caused by the addition of hydrocarbons to the fluid phase as part of the catagenetic process due to continuous burial and increasing thermal exposure converting the fluid-flow system to a multiphase regime. Based on the 1D petroleum systems modeling results, it is suggested that, in more mature areas, high levels of overpressure was developed after 62 Ma, coinciding with the onset of hydrocarbon generation, corresponding to a vitrinite reflectance of ~0.55%Ro.

A change in the lithostatic pressure caused by uplifting is also affecting pore pressure. In general, a decrease in the pore pressure is observed with uplift. However, depending on the magnitude of the uplift and sealing capacity of the facies above, below, and within the Niobrara

Formation, the overpressure can be preserved or increased. In this particular case, it is important to consider that the sealing capacity (which is a function of the permeability and pore throat size) of intervals within and above and below the Niobrara Formation plays a significant role in overpressure preservation. A high sealing capacity reduces the ability of fluids to be expulsed from the rock, and sealing capacity is mainly controlled by permeability changes in the Niobrara Formation (and in the formations above and below) from one location to another. The permeability derived from 1D petroleum systems modeling (required for pore pressure gradient calibration) suggests that there is a reduction in permeability of approximately 30% from the wells in the central and deeper part compared to the wells in the south and east areas of the PRB. Furthermore, permeability variations were observed within the formations above and below of the Niobrara Formation from one location to another. These variations can cause significant changes in pore pressure.

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Hesler, H.P., R.C. Surdam, and J.H. George, 1994, Pressure Compartmentalization in the Powder River Basin, Wyoming and Montana, As Defined by DST Data, *in* P.J. Ortoleva (ed.), Basin Compartmentalization and Seals: American Association of Petroleum Geologists Memoir 61, p. 235-262.

Surdam, R.C., Z.S. Jian, and R.S. Montgomery, 1994, The Regional Pressure Regime in Cretaceous Sandstones and Shales in the Powder River Basin, *in* P.J. Ortoleva (ed.), Basin Compartmentalization and Seals: American Association of Petroleum Geologists Memoir 61, p. 213-233.

Tischer, M., G. Zimbrick, and M. Dolan, 2014, Importance of Structural and Tectonic Inheritance for Unconventional Basin Play Prospectivity: An Example from the Powder River Basin: Unconventional Resources Technology Conference (URTeC), URTeC 1922121. doi:10.15530/urtec-2014-1922121

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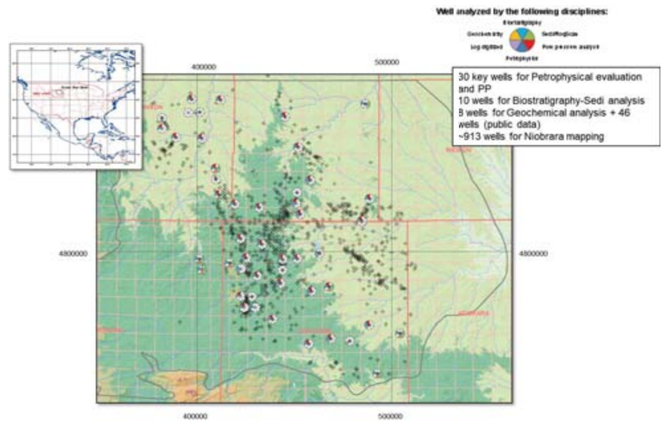
Introduction

- Pore pressure is a key factor in determining hydrocarbon productivity of unconventional plays.
- Pressure higher than hydrostatic pressure at reservoir depth is defined as overpressure. If the pressure gradient is more than 0.53 psi/ft (or the ratio between the fluid pressure and hydrostatic pressure is more than 1.2), it is referred to as overpressure. Contrary, if the pressure gradient is less than 0.43 psi/ft (or the ratio between the fluid pressure and hydrostatic pressure is less than 1.0), it is referred to as under pressured (Xia *et al.*, 2013).
- Overpressuring is known to occur by several different mechanisms related commonly to burial, tectonism, hydrocarbon generation, mineral transformation and fluid expansion.
- Overpressure in the PRB has been investigated by Parks and Gale (1996), Heasler *et al.*, (1994), and Surdam *et al.*, (1994). Recently, pore pressure variability of the Niobrara Formation and other formations were analyzed recently by Yale *et al.*, 2018 in the PRB. This later study performed the pore pressure prediction across the PRB which identified important variations of pore pressure within the Niobrara Formation across the basin.
- The Niobrara Formation can be described as an unconventional play because it hosts both source and reservoir rock, and because source rock intervals are juxtaposed to organic-lean facies (e.g. clean "chalk" facies).

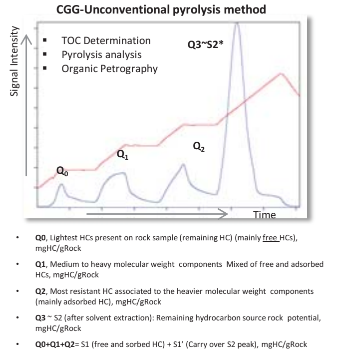


Study Area

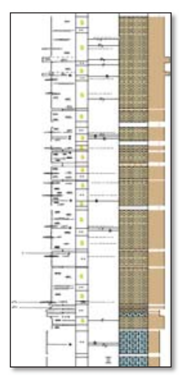
Methodology

Geochemistry

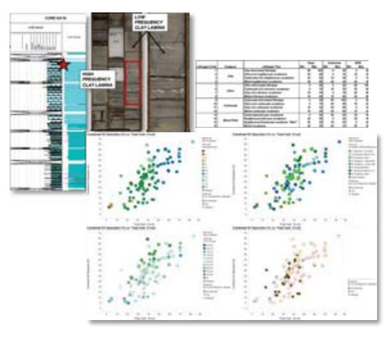
CGG-Unconventional pyrolysis method



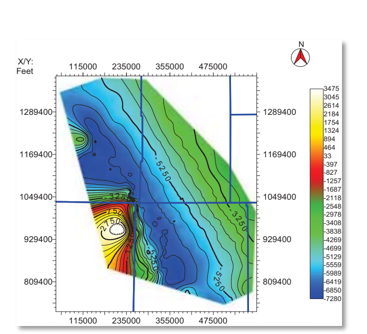
Biostratigraphy



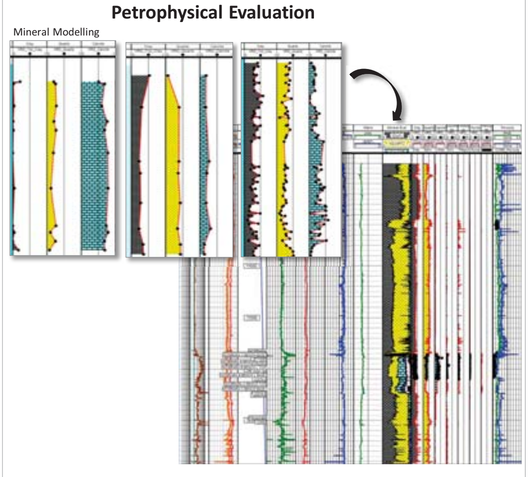
Sedimentology



Regional Mapping of the Niobrara Formation



Petrophysical Evaluation



Geomechanics

Pore Pressure Prediction (gradient)

Modified Eaton-Yale lithology-porosity correct PPP (Yale *et al.*, 2018)

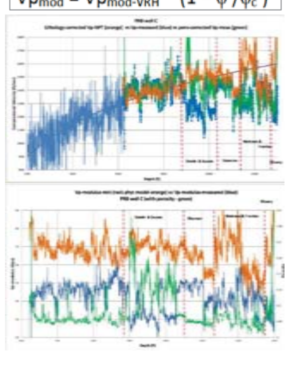
$$Pp = (OBP - (OBP - \alpha P_{hyd}) * C * (V_{p\text{-meas-porocorr}} / V_{p\text{-NPT-lithcorr}})^{EE}) / \alpha$$

Porosity variation is accounted for through the critical porosity method (Mavko *et al.*, 1991)

$$Vp_{mod} = Vp_{mod\text{-}VRH} * (1 - \phi / \phi_c)$$

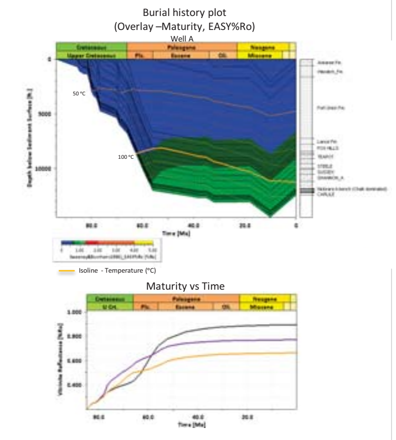
OBP: overburden pressure
Phyd: hydrostatic pore pressure
Vp-meas-porocorr: measured compressional velocity with porosity corrected.
Vp-NPT-lithcorr: extrapolated normal pressure trend of Vp with lithology corrected.
EE: Eaton exponent which is generally between 2 and 3 for young, offshore basins.
α: Biot's alpha
C: calibration factor

ϕ: Porosity
ϕc: Critical porosity
$Vp_{mod\text{-}VRH}$: Voight-Rhuess hydrid (VRH) Vp modulus



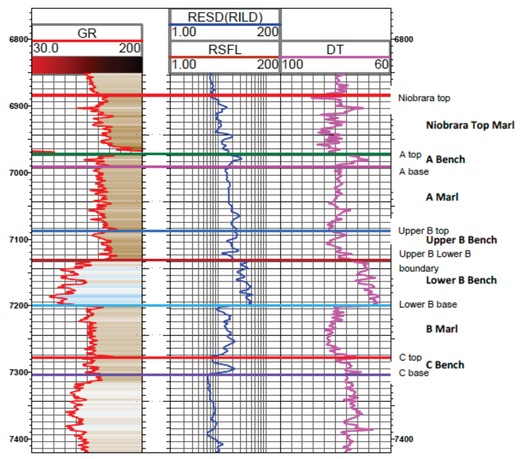
✓Correct for lithology via $V_{p\text{-NPT-lithcorr}}$ from rock physics model of mineral components
✓Correct for effective stress via Biot α from rock physics model of mineral components
✓Correct for porosity via critical porosity model
✓Calibration of the predicted pressure profile with measured pore pressures from DFIT, DST, or shut in pressures

Petroleum System Modelling (1D)



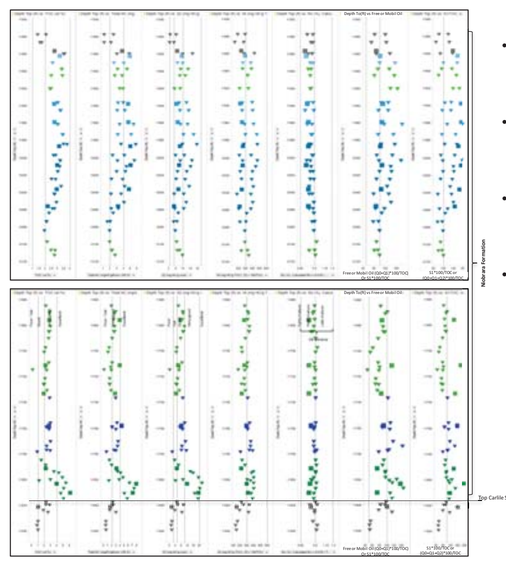
Results

Niobrara Formation type well



The Niobrara Formation shows higher resistivity than the underlying Carlile Formation and overlying Pierre Shale.

Composite Geochemical profile of the Niobrara Formation

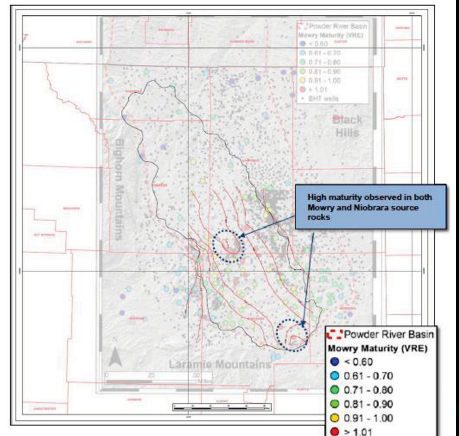


- TOC measurements range between 0.11 and 6.10 wt%, averaging 2.31 wt% throughout the Niobrara Formation.
- Upper B Bench and C Marl have the best source rock properties. However, the C Marl is not present across the whole of the study area.
- Organic matter within the Niobrara Formation is dominated by Amorphous Organic Matter (AOM) with 5% humic debris.
- The kerogen is classified as Organofacies Class B, which corresponds to a marine siliciclastic source rock dominated by aquatic, algal- and bacteria-derived precursor lipids. The main expelled product expected at peak maturity is oil.

Niobrara Stratigraphy: Niobrara (undifferentiated); Niobrara – Top Marl; Niobrara – A Bench; Niobrara – A Marl; Niobrara – Upper B Bench; Niobrara – Lower B Bench; Niobrara – B Marl; Niobrara – C Bench; Niobrara – C Marl

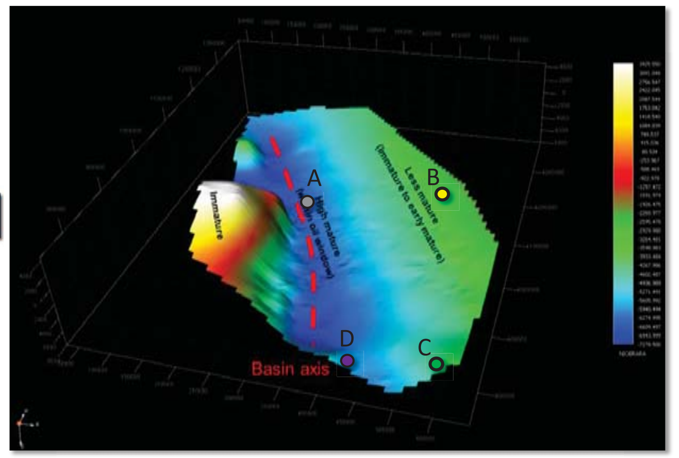
▼ Analyzed by other lab
■ Analyzed by CGG
◆ Public Source (Taylor *et al.*, 2012)

Maturity map of the Mowry Shale (from Rock-Eval pyrolysis data of Tischer *et al.*, 2014) overlaid with the maturity contour map (%Roeq) of the Niobrara Formation



- The heat flow distribution across the PRB is influenced by the presence of thermal anomalies and changes in basement composition.
- Localized thermal anomalies represent major tectonic boundaries between different types of basement. However, as these anomalies do not extend along the contacts between the Archean granite and gneiss bodies across the basin, it is suggested that they could be influenced by other geologic features e.g. basement-controlled fault which become pathways for fluids and/or heat.

Structural contour map of the Niobrara Formation, Powder River Basin, Wyoming



A high level of thermal stress was observed along the axis of the basin, compared to the rest of the study area where the Niobrara Formation shallows.

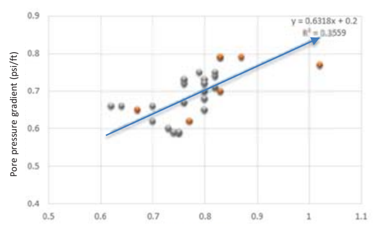
Well A
- Niobrara Depth 11805.95 ft (Top)
- TOC 2.79 wt.% (average)
- Maturity >~0.83%Ro (average)
- Pressure gradient > 0.70 psi/ft

Well B
- Niobrara Depth 8284.34 ft (Top)
- TOC 2.24 wt.% (average)
- Maturity ~0.65%Roeq (average)
- Pressure gradient ~0.59 psi/ft

Well C
- Niobrara Depth 10304 ft (Top)
- TOC 2.90 wt.% (average)
- Maturity ~0.92 %Ro (average)
- Pore pressure gradient ≤0.6 psi/ft

Well D
- Niobrara Depth 11833.89 ft (Top)
- TOC 1.79 wt.% (average)
- Maturity ~0.77 %Ro, (average)
- Pore pressure gradient 0.65 psi/ft

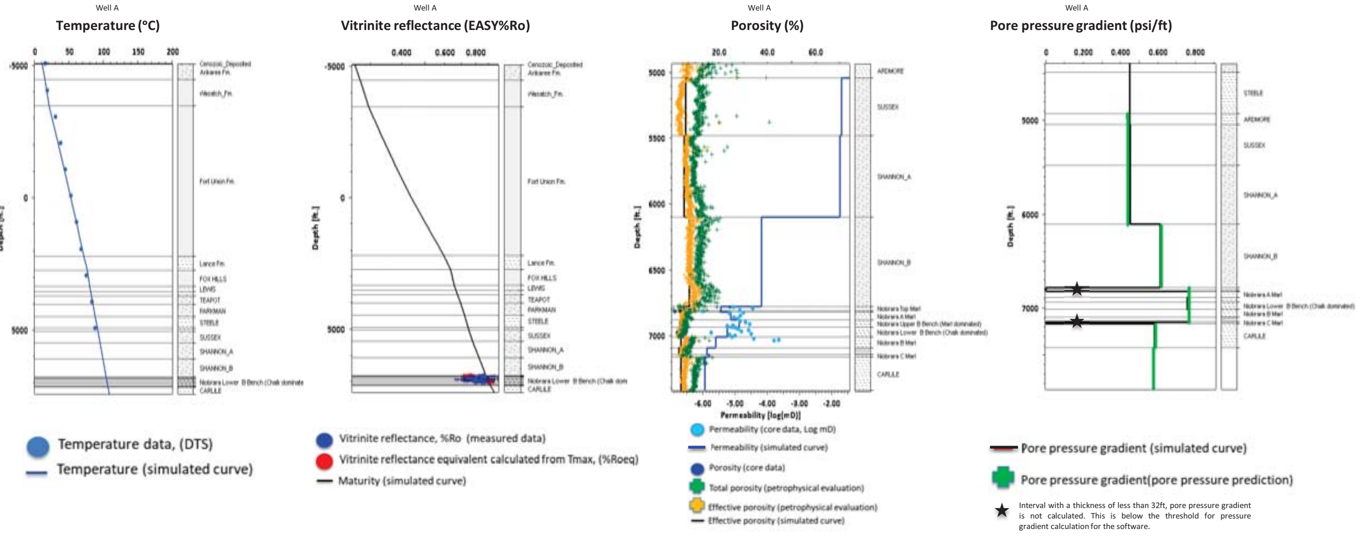
Thermal maturity vs. pore pressure gradient in the Powder River Basin of Niobrara Formation

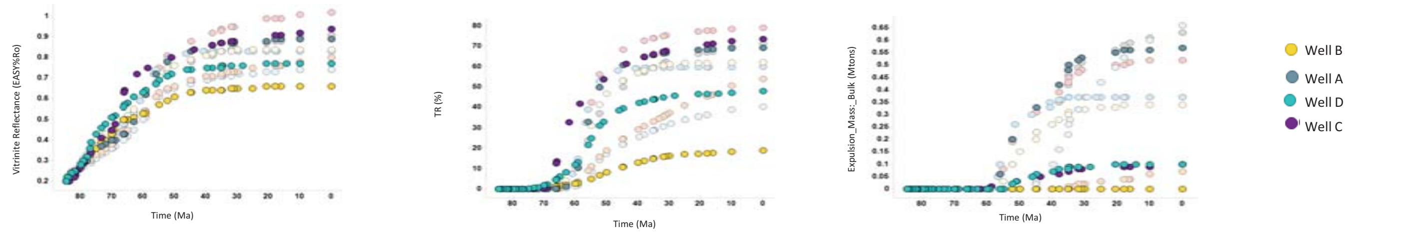


The Niobrara Formation shows a positive correlation between increasing maturity with increasing depth. When the pore pressure gradient (psi/ft) data are incorporated, a good correlation is generally observed with some variation.

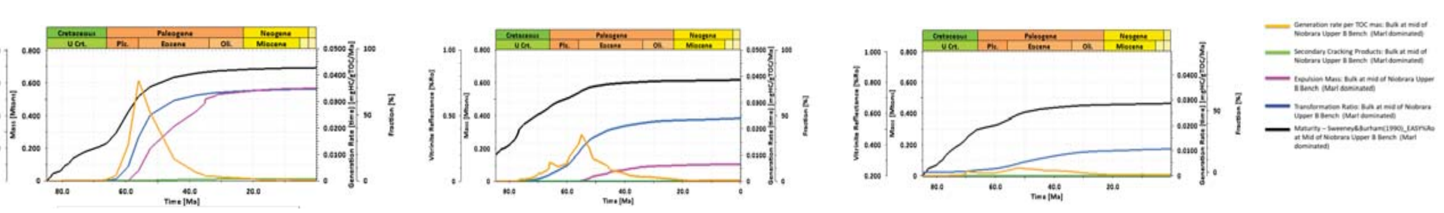
1D Calibrations

Well A: Temperature (°C); Vitrinite reflectance (EASY%Ro); Porosity (%); Pore pressure gradient (psi/ft)

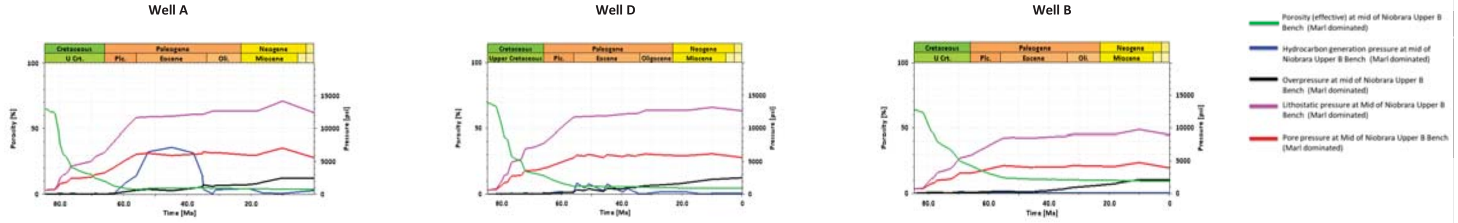




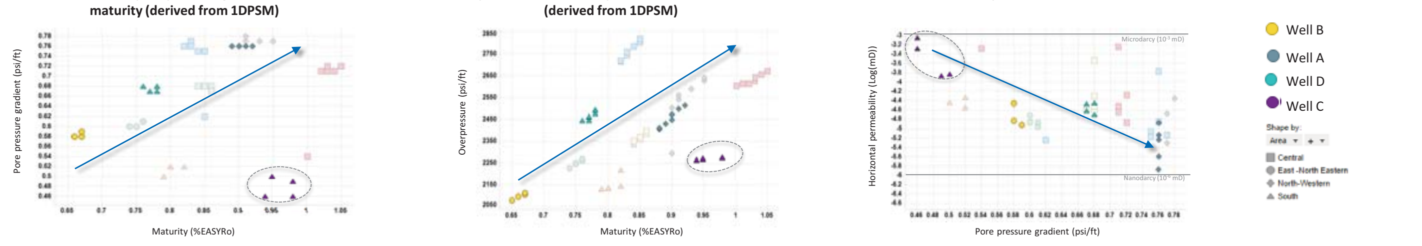
Well A; Well D; Well B



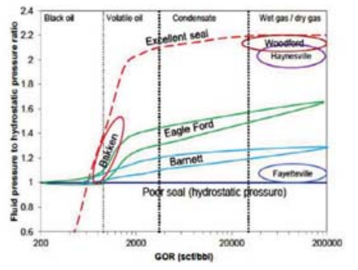
Well A; Well D; Well B



Calibrated pore pressure gradient and maturity (derived from 1DPSM); Overpressure and maturity of the Niobrara Formation (derived from 1DPSM); Permeability (derived from 1DPSM)

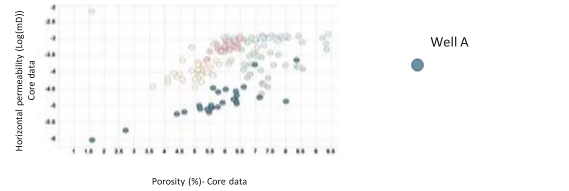


Impact of thermal maturity and seal quality on overpressure in a range of unconventional plays (from Xia *et al.*, 2013)



- Although the C well displayed a high maturity level, the overpressure and pore pressure gradient is low. This can be associated to the Niobrara Formation in this location hosting better permeability compared to the wells located in the deeper part of the basin.
- Changes in permeability were observed between well A and well C. These variations (sealing capacity) may control the preservation of pore pressure within the Niobrara Formation.

Core data



Conclusions

- Variations in the thermal evolution of the organic matter within the Niobrara Formation have important implications for pore pressure variability across the PRB.
- In areas where the organic matter was affected by high thermal stress, increased pore pressure, hydrocarbon generation pressure, and overpressure are observed. Most of the wells in these areas showed a maturity equivalent to a vitrinite reflectance >0.7%Roeq and a TR >70%.
- A positive correlation was obtained in areas where the organic matter was affected by high thermal stress, with increases in pore pressure, overpressure and pore pressure gradient. High hydrocarbon generation pressures and overpressures are observed in the intervals with the highest maturities and best source rock properties.
- In general, the overpressure was largely developed after 62 Ma, at the start of hydrocarbon generation and aligning approximately with a maturity equivalent to a vitrinite reflectance of 0.55%Ro. The highest pore pressure gradient was obtained in wells showing a vitrinite reflectance >0.7%Roeq, transformation ratio >70% and permeability of -4.5 (log mD).
- The driving mechanism is likely the generation of liquid and gaseous hydrocarbons from the primary of organic matter and secondary cracking (a minor contribution). The secondary cracking will have occurred in the more mature areas across the PRB. The evolution of the fluid-flow system is caused by the addition of hydrocarbons to the fluid phase as part of the catagenesis process due to continuous burial and increasing thermal exposure converting the fluid-flow system to a multiphase regime.
- Tectonic evolution plays an important role in the generation and preservation of hydrocarbons and pore pressure in the PRB.
- Permeability changes were observed above, below and within the Niobrara Formation across the PRB. These variations can cause significant changes in pore pressure and its preservation through geologic time.

Acknowledgment

CGG -MCNV and Geoscience – Reservoir Americas for the permission to publish this work.

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