The Curious Case of Hydrocarbon-Expulsion Fractures: Genesis and Impact on the Bakken Shales*

Mohammed Duhailan[1] and Steve Sonnenberg[1]

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Abstract

The genesis and impact of hydrocarbon-expulsion fractures on the Bakken shales were investigated by integrating epifluorescence petrographic and pressure transient analyses. In early exploration vertical wells, drilling breaks from ten minutes to one minute per foot with gas increases from ten units to several hundred units were considered poor shows in the source rocks of the Bakken shales. drill stem tests (DST) over the Bakken shales were reported with average production rates that reach several tens of barrels per day. These shales were overpressured with no matrix porosity in evidence and permeability in the micro-Darcy scale. Production was assumed to come from fractures. Speculative conclusions were drawn about these fractures being related to source-rock maturity, hydrocarbon expulsion, and overpressuring. These conclusions were a significant promoter for exploration in the Bakken Formation. The curious case of hydrocarbon-expulsion fractures has encouraged a review of 64 DSTs over different intervals that include the Bakken Formation and/or the underlying Three Forks Formation. Resistivity logs, cores, and thin-sections were studied in order to conduct an integrated geological interpretation for pressure-transient behaviors of the Bakken shales. The study shows that the Bakken shales are naturally fractured and can be interpreted on resistivity-curve separation. The Three Forks and Middle Bakken pressure-transient behaviors show spherical flow, which indicate that there is always contribution from the Bakken Shales. The Bakken pressure-transient behavior shows dual permeability (naturally fractured), with low storage capacity within the fracture system, implying that fluid is stored mostly in the matrix. The study also revealed that the matrix releases its fluid rapidly to the fracture system, indicating rather high temporal permeability and implying that hydrocarbon-expulsion fractures contribution is present. The significance of hydrocarbon-expulsion fractures resides in their ability to provide higher permeability pathways through the Bakken shales and explains their high deliverability. The volume expansion due to hydrocarbon generation is invoked as a mechanism to increase pressures to levels of inducing expulsion fractures responsible for primary migration of hydrocarbons.

References Cited

Meissner, F.F., 1978, Petroleum geology of the Bakken Formation Williston Basin, North Dakota and Montana: Montana Geological Society: Twenty-fourth Annual Conference: 1978 Williston Basin Symposium: The Economic Geology of Williston Basin, p. 207-227.

Sonnenberg, S.A., and A. Pramudito, 2009, Petroleum geology of the giant Elm Coulee field, Williston Basin: AAPG Bulletin, v. 93/9, p. 1127-1153.

Webster, R.L., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota, *in* J. Woodward, F.F. Meissner, and J.C. Clayton, eds., Hydrocarbon Source Rocks of the Greater Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, p. 57-81.

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AAPG 2014 Annual Convention and Exhibition

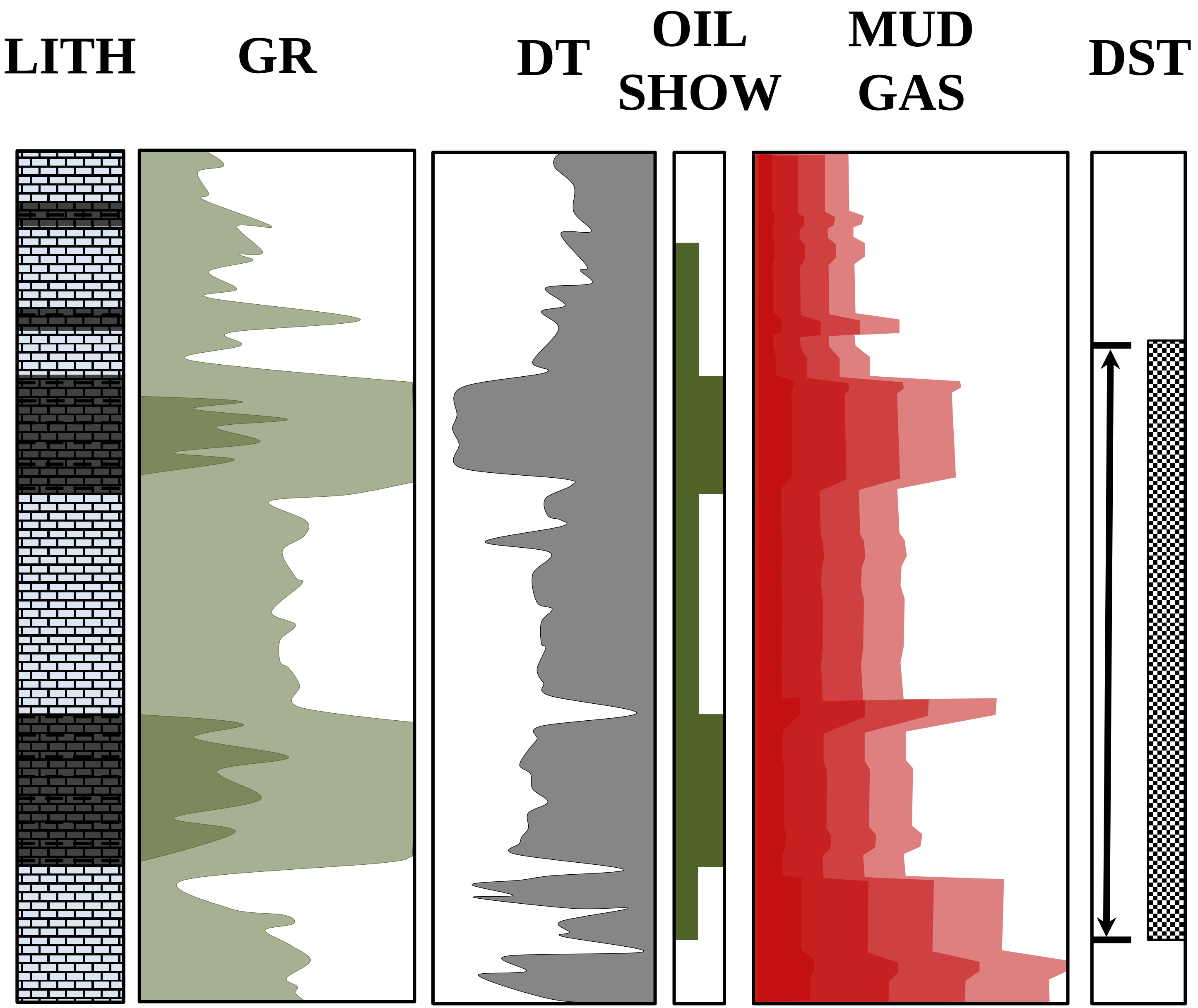
The Curious Case of Hydrocarbon-Expulsion Fractures:

Genesis and Impact on the Bakken Shales

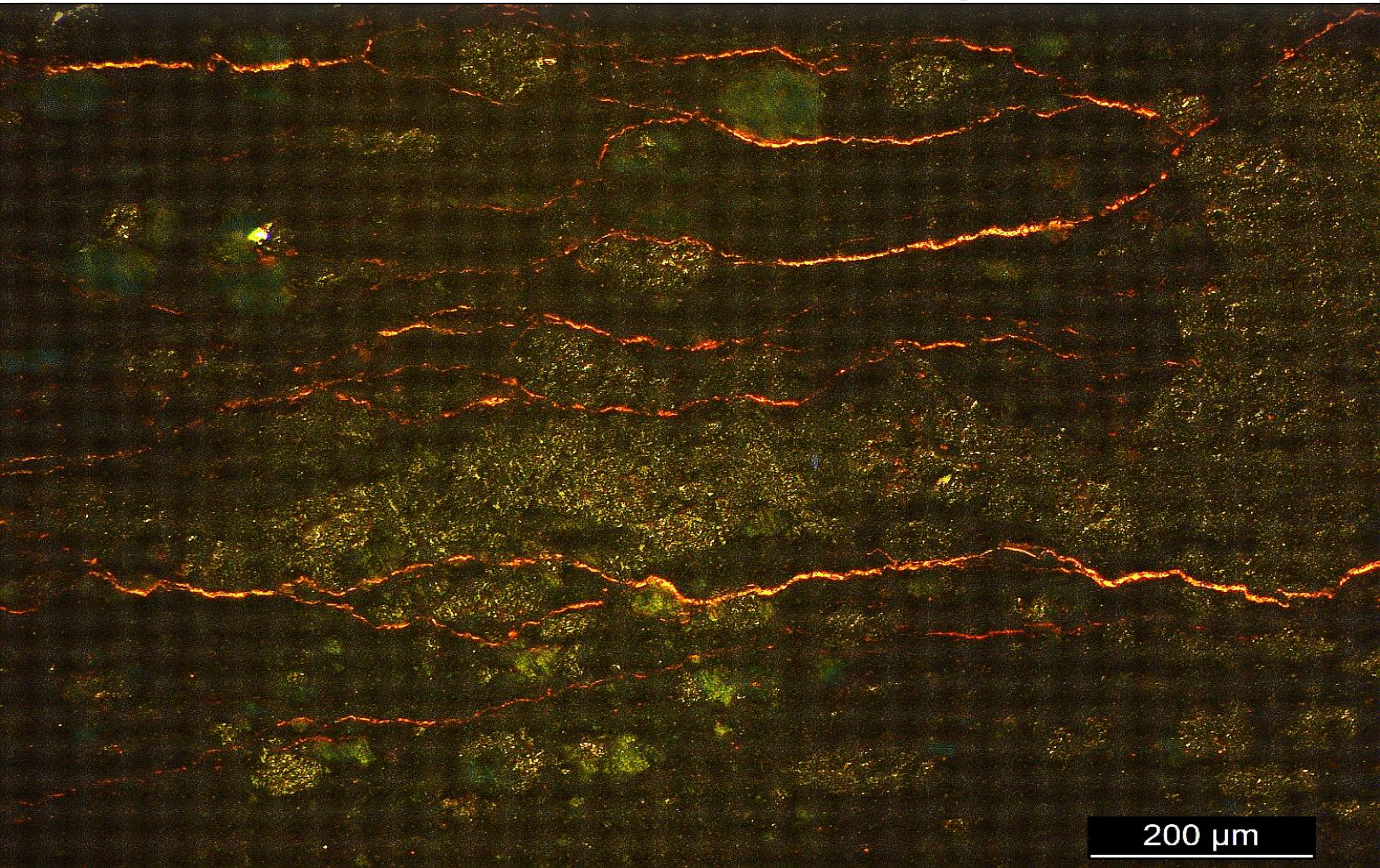
"Speculative conclusions regarding the relationship between **source-rock maturity, hydrocarbon generation, geopressuring and fracturing** suggest an opportunity in exploration for unrecognized and unlooked-for **"unconventional"** accumulations of potentially very large regional extent."

(Meissner, 1978)

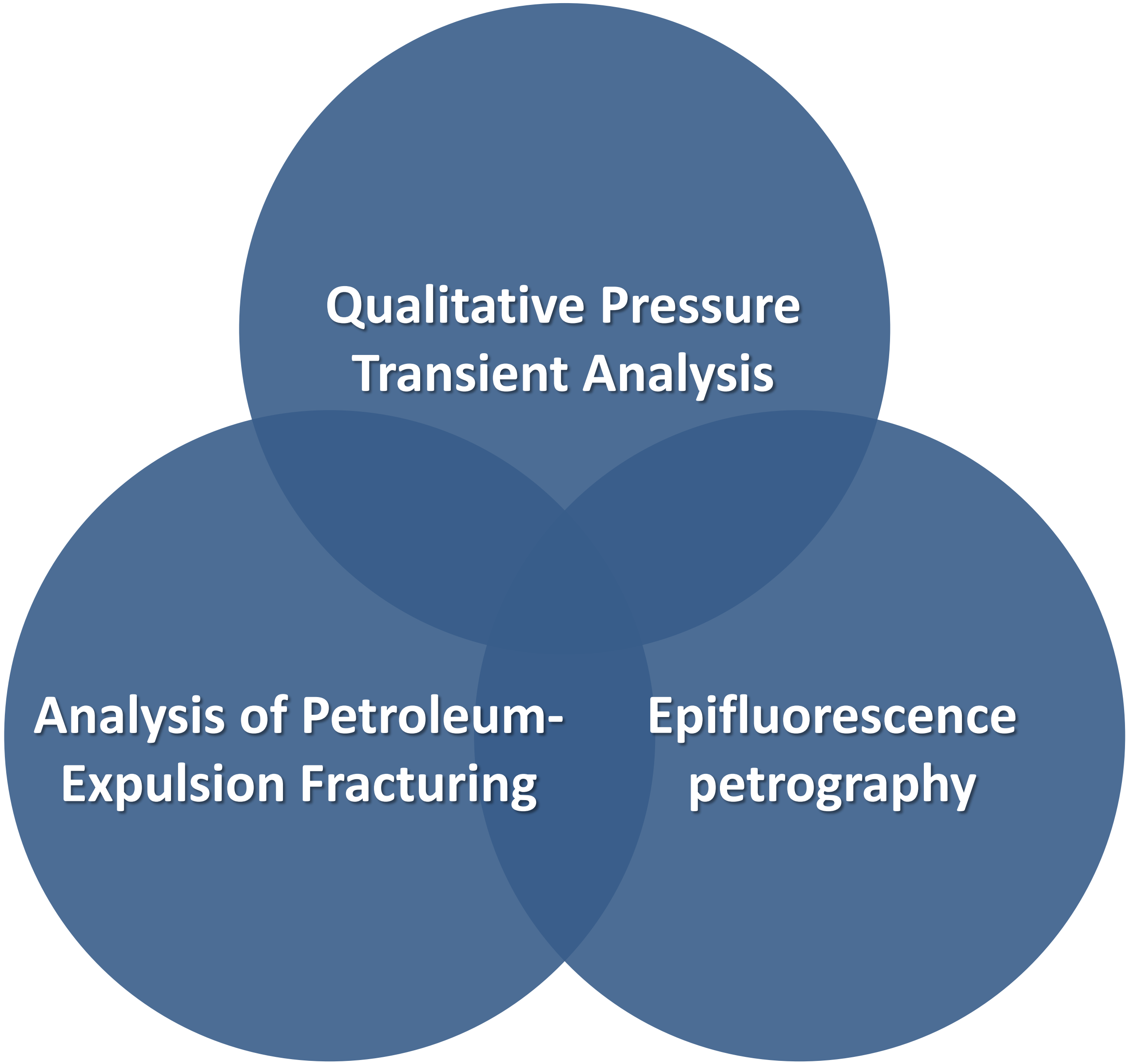
Motivation



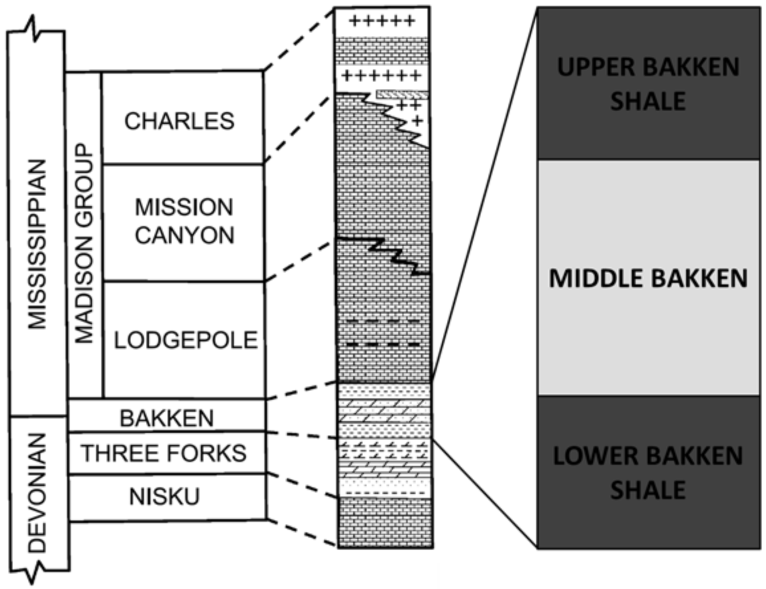
The shale did contain some oil show in the black carbonaceous pieces, which were primarily non-calcareous, with fine disseminated pyrite, and displayed a slow to moderate streaming cuts. No matrix porosity was in evidence in the black shale, and the cuts were assumed to have come out of micro-fractures or off of fracture planes.

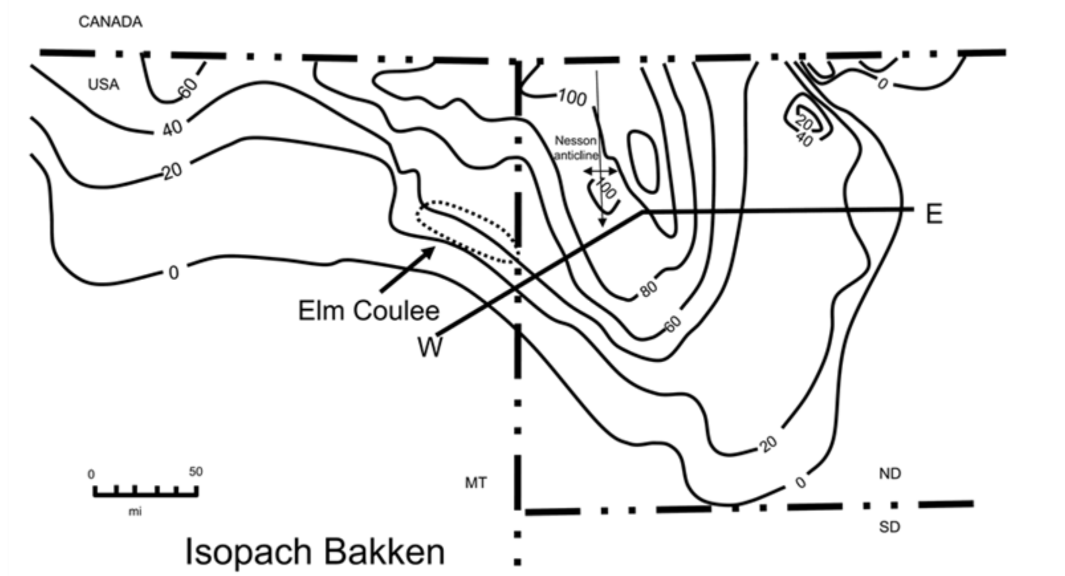


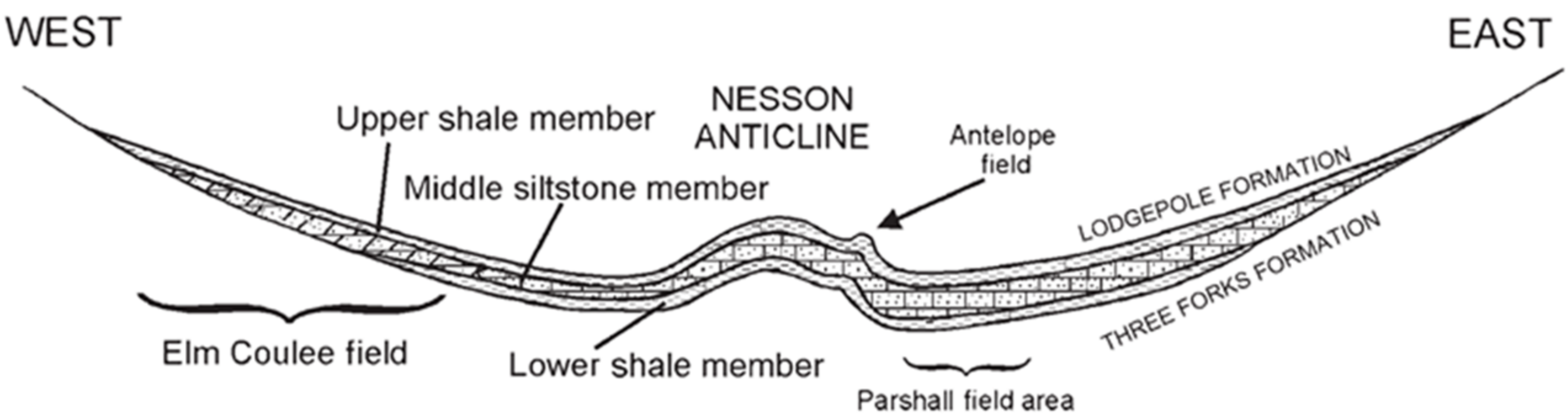
Objectives


Qualitative Pressure Transient Analysis
Analysis of Petroleum-Expulsion Fracturing
Epifluorescence petrography

Geological Background



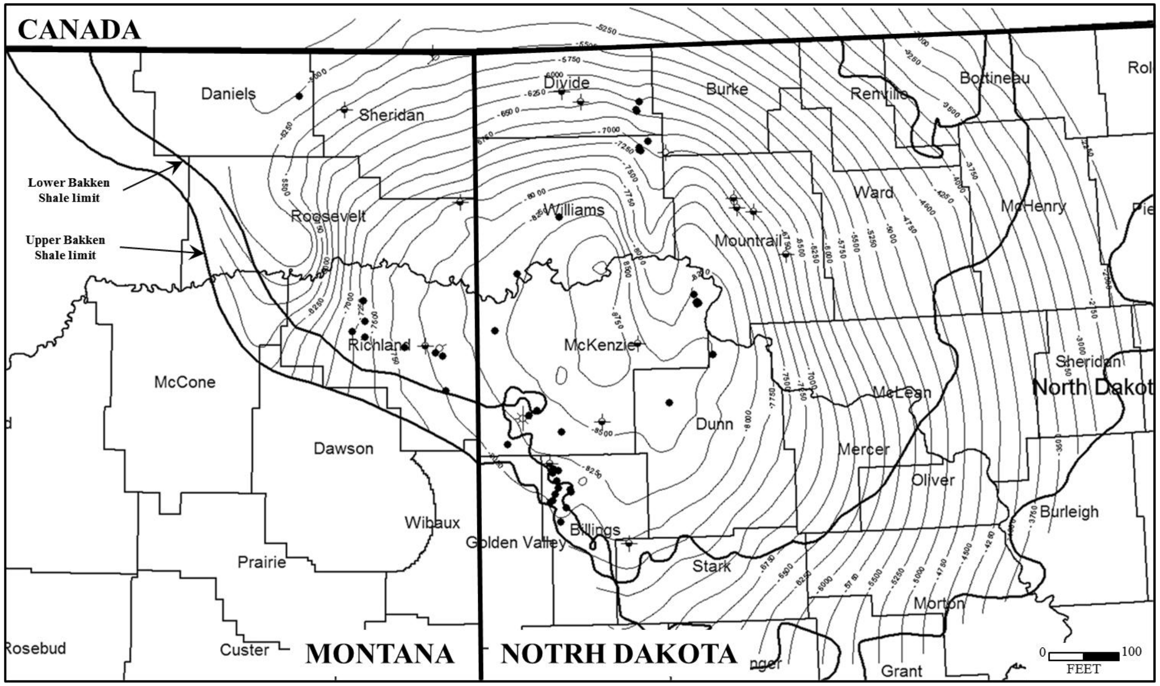




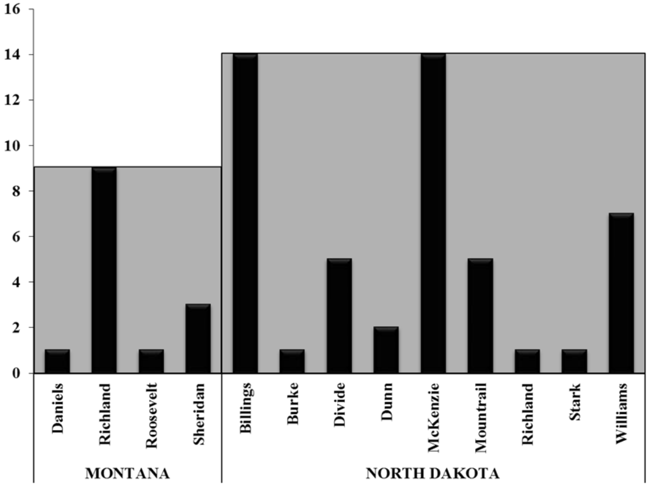
(modified fromSonnenberg, 2009 which is modified from Webster, 1984 and Meissner, 1978)

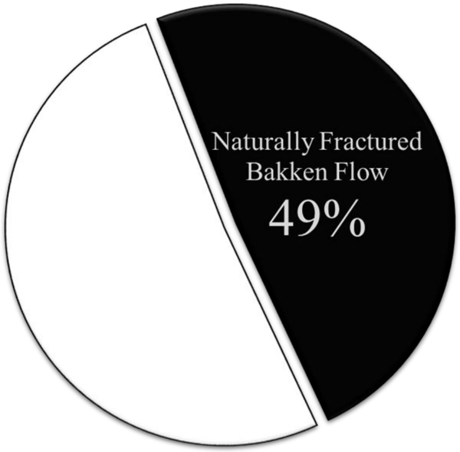
Qualitative Pressure Transient Analysis

- Due to no flow or not enough pressure build-up, 30% of the DSTs can't be analyzed

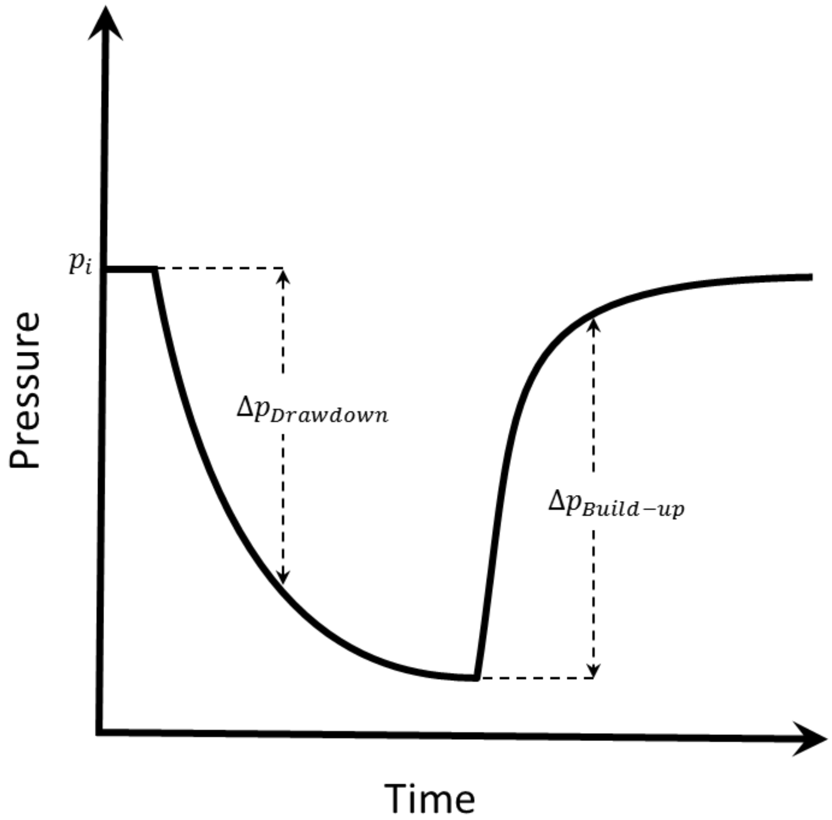


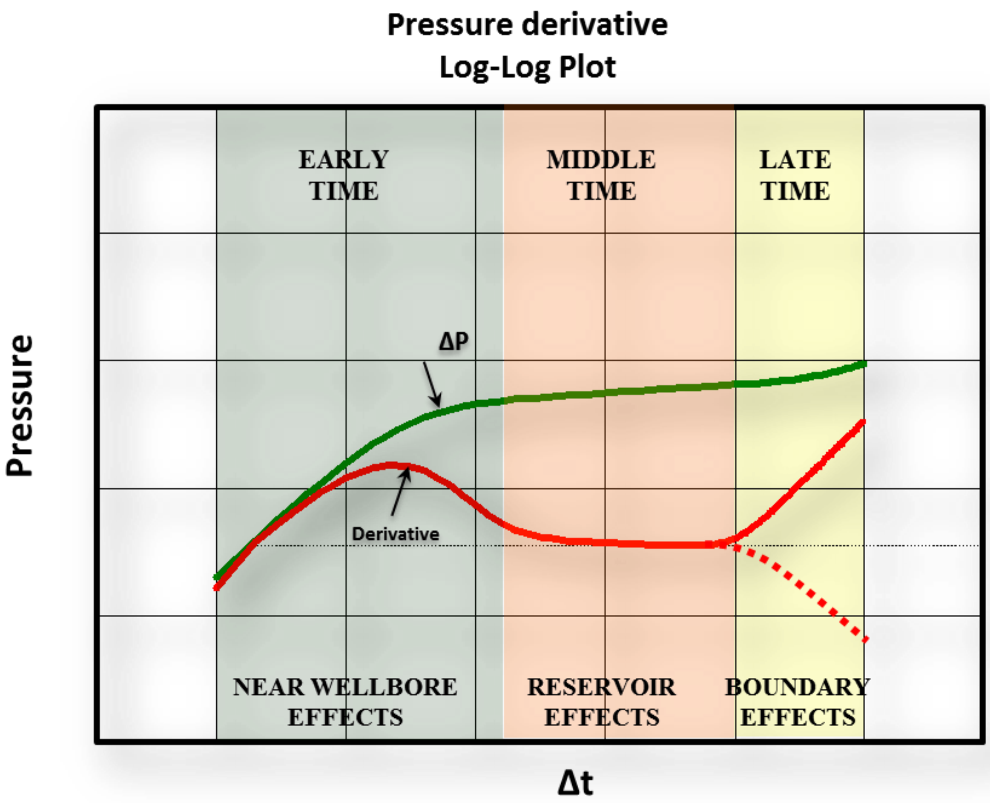
- 49% of the DSTs that can or could be analyzed imply naturally fractured Bakken



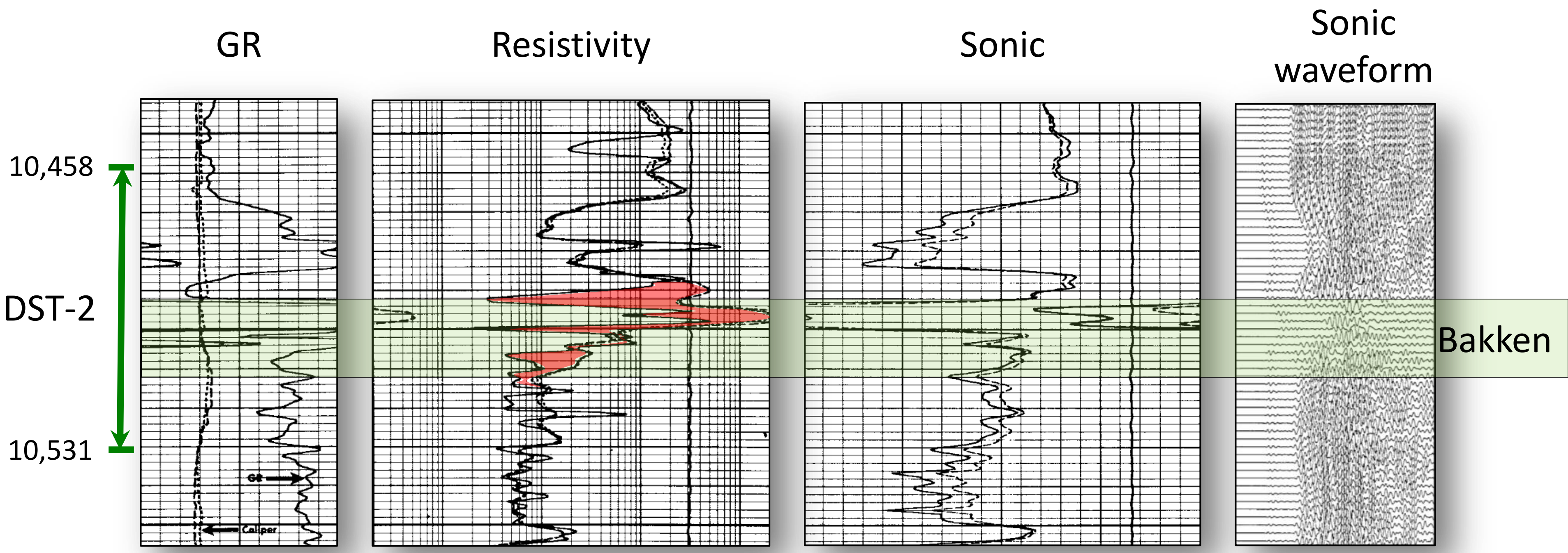


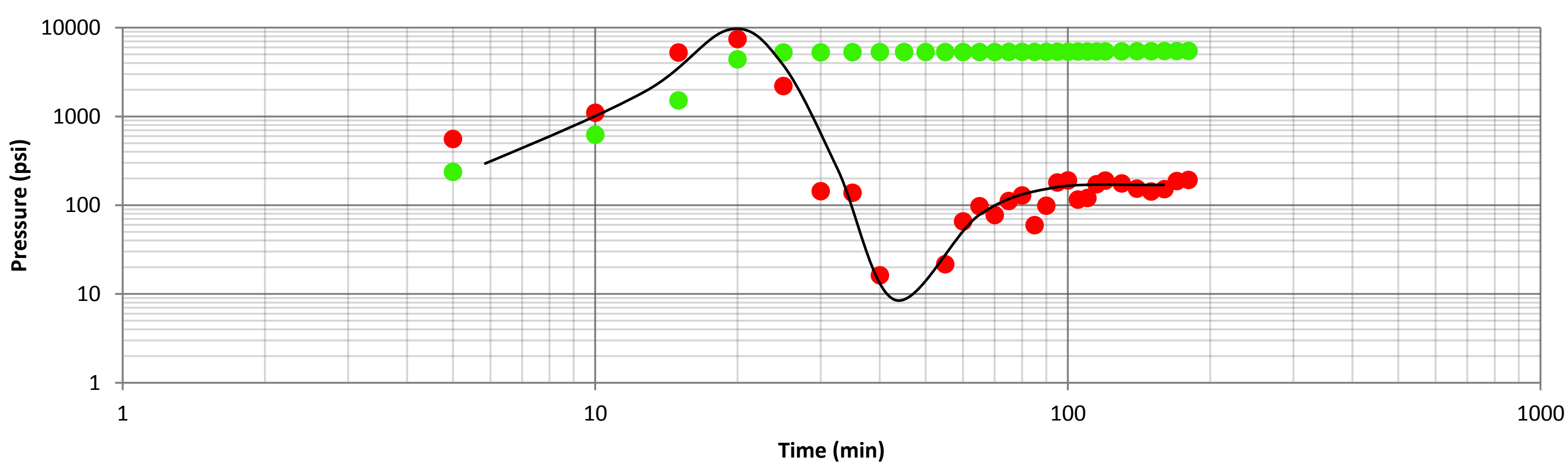
Qualitative Pressure Transient Analysis





Meridian MOI 21-11

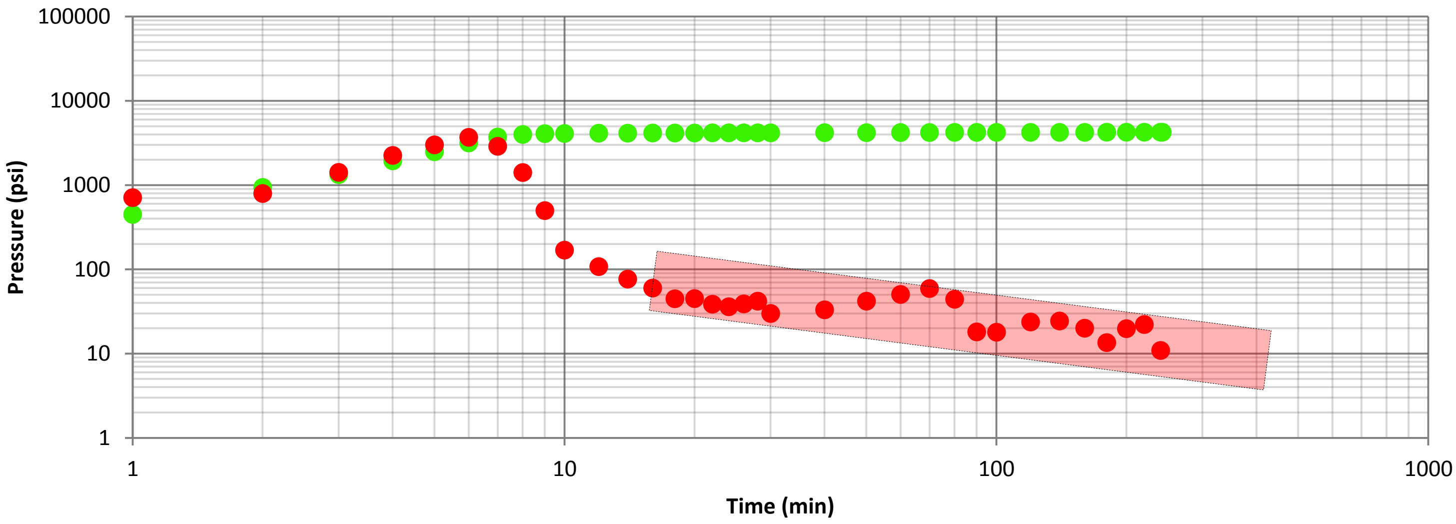




Three Forks Spherical Flow

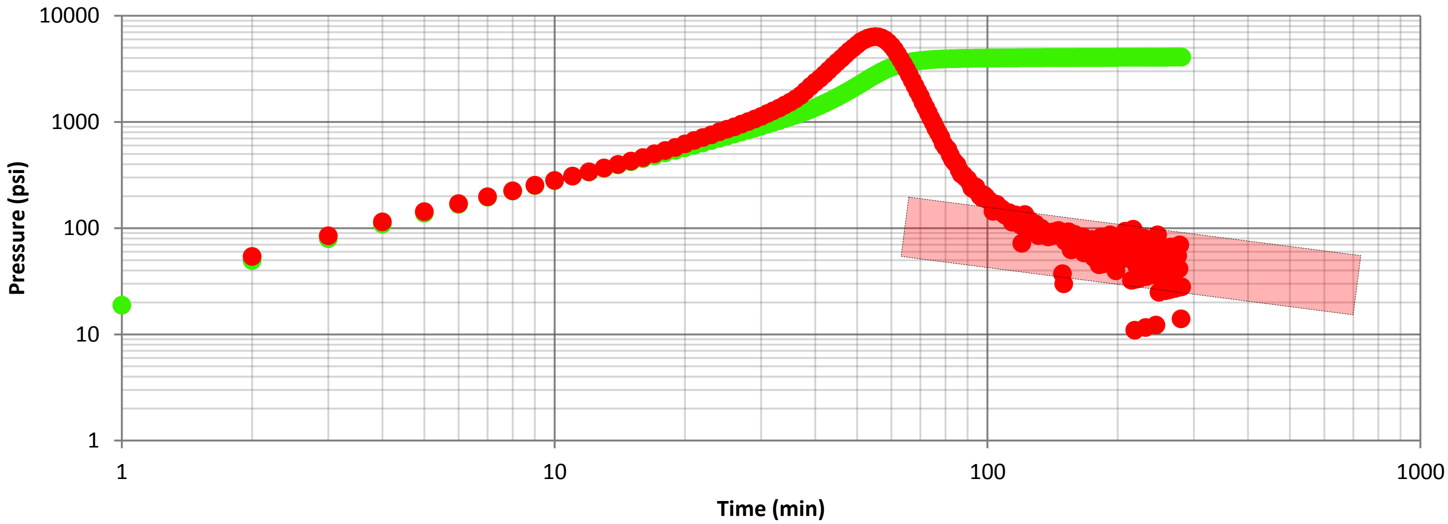
Big Sky #1

DST-1
10,048-10,142
Rec Depth
(10140)
Three Forks



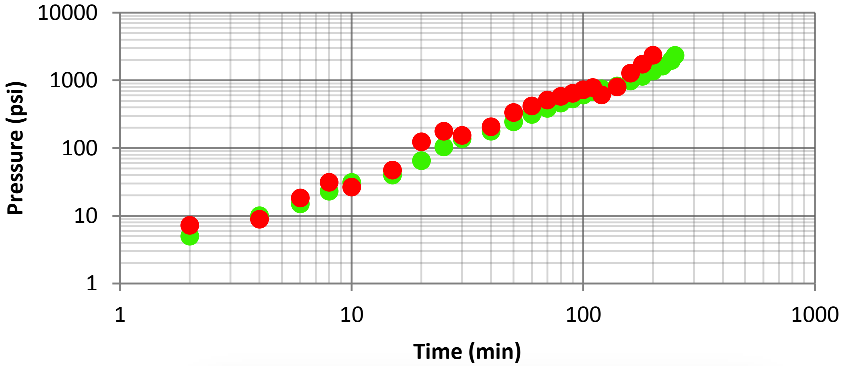
Davis #1-16

DST-2
8624-8647
Mid Bakken

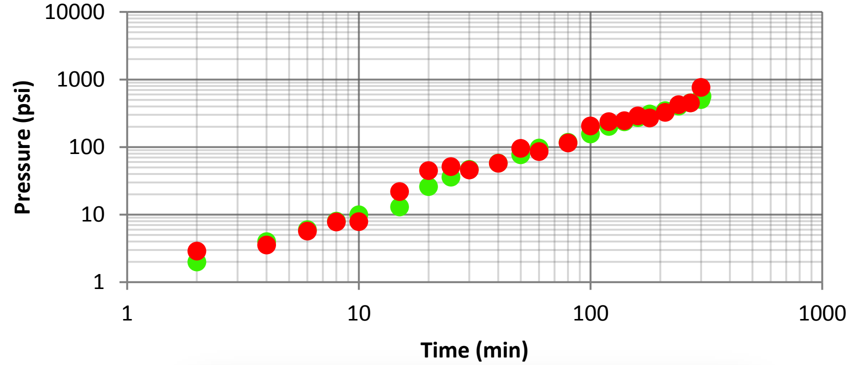


Tight Formation?

Bakken #1



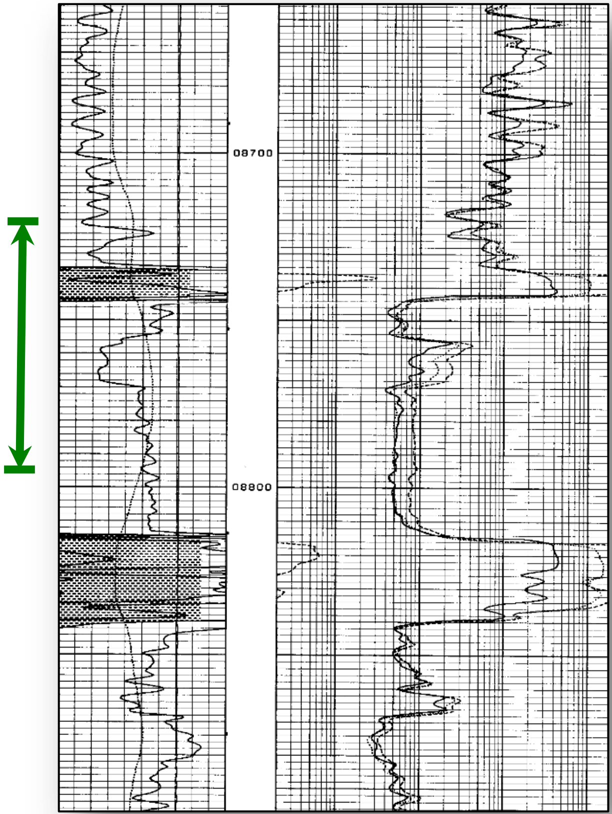
Wolf Federal #1



8720

DST-3

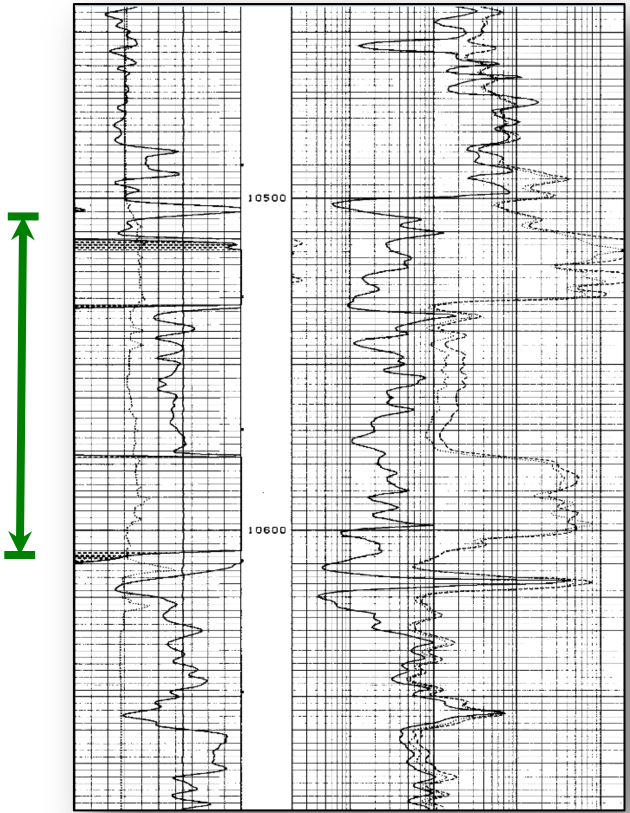
8796



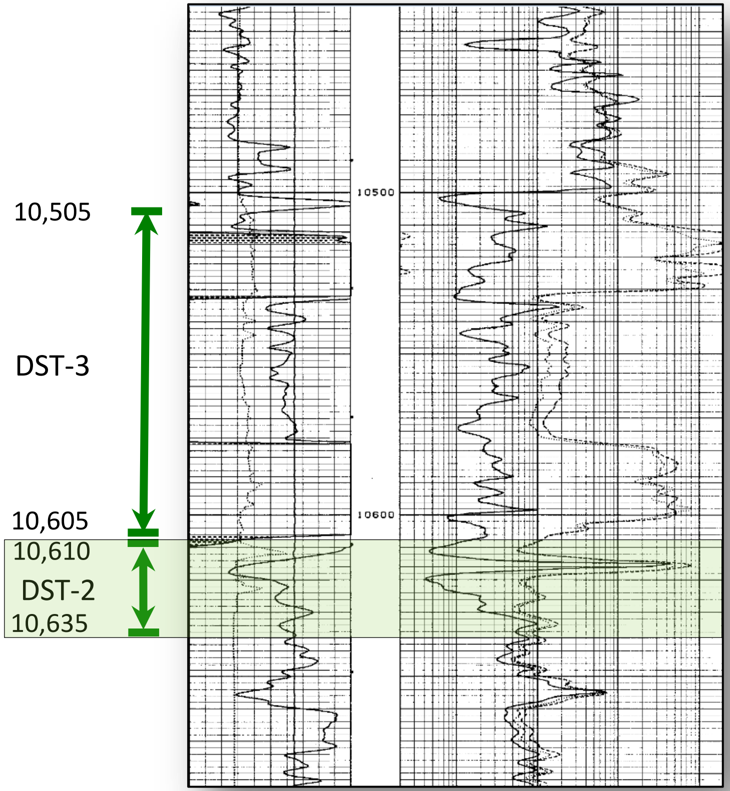
10,505

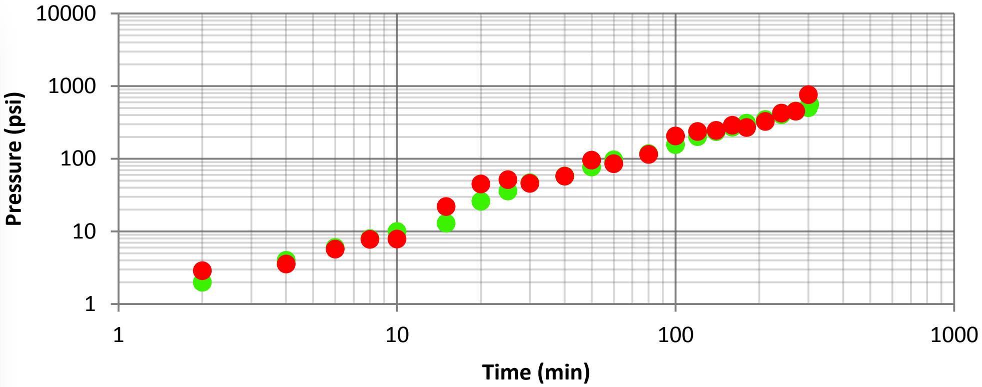
DST-1

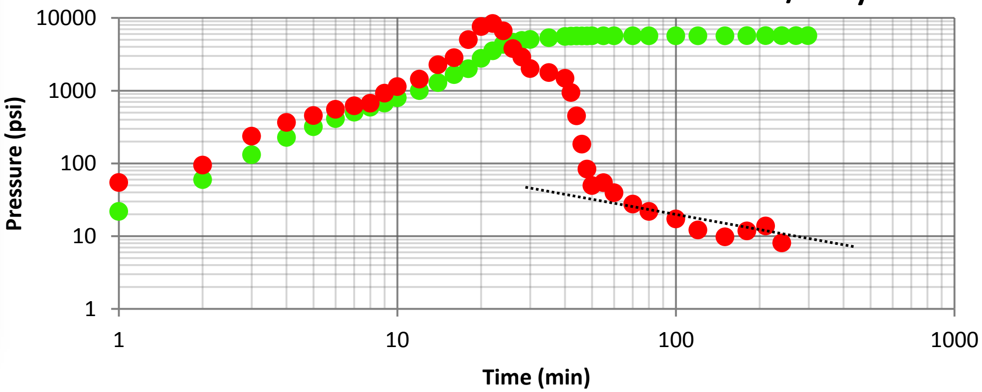
10,605



Fractured Bakken should have flowed!!







The calculated Damage Ratio of 11.49, indicates that significant well-bore damage was present at the time of this drillstem formation test. The Damage Ratio implies that the production rate should have been 11.49 times greater than that which occurred if well-bore damage had not been present.

Qualitative Pressure Transient Analysis

- **Upper and Lower Bakken Shales** are interpreted to be **naturally fractured based on resistivity curves separation**

- **Three Forks and Mid Bakken** pressure-transient behaviors show **spherical flow** which indicates vertical contribution from either within, or from the Bakken Shales

- Bakken pressure-transient behavior shows dual permeability (naturally fractured) with **low fracture system's storage capability (ω) implying that fluid is mostly stored in the matrix**

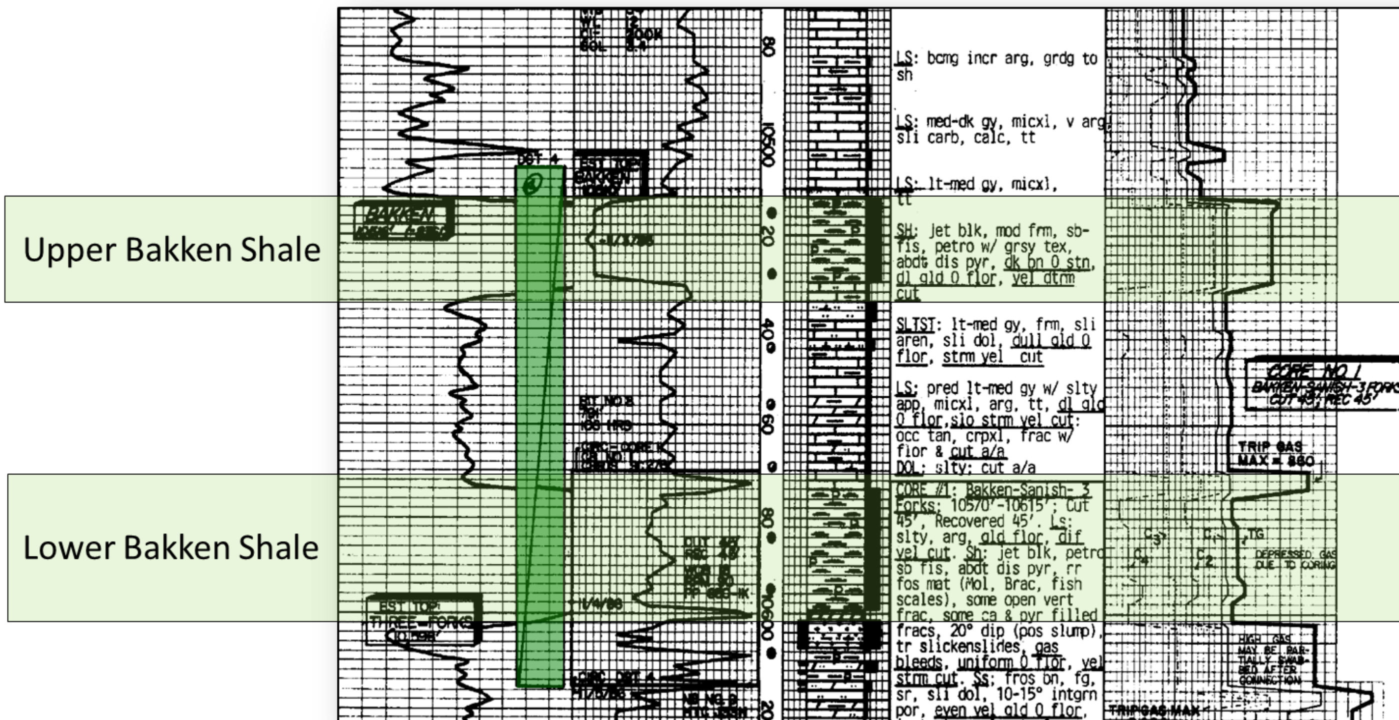
- **Matrix gives up its fluid rapidly to fracture system indicating high temporal permeability (λ)** implying that microfractures contribution is present

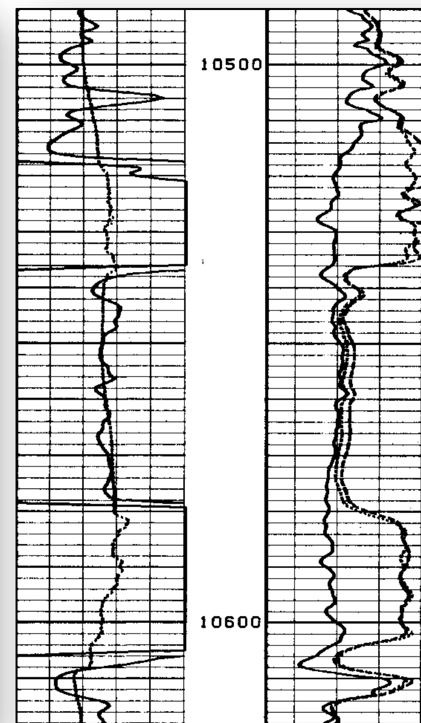
Epifluorescence petrography

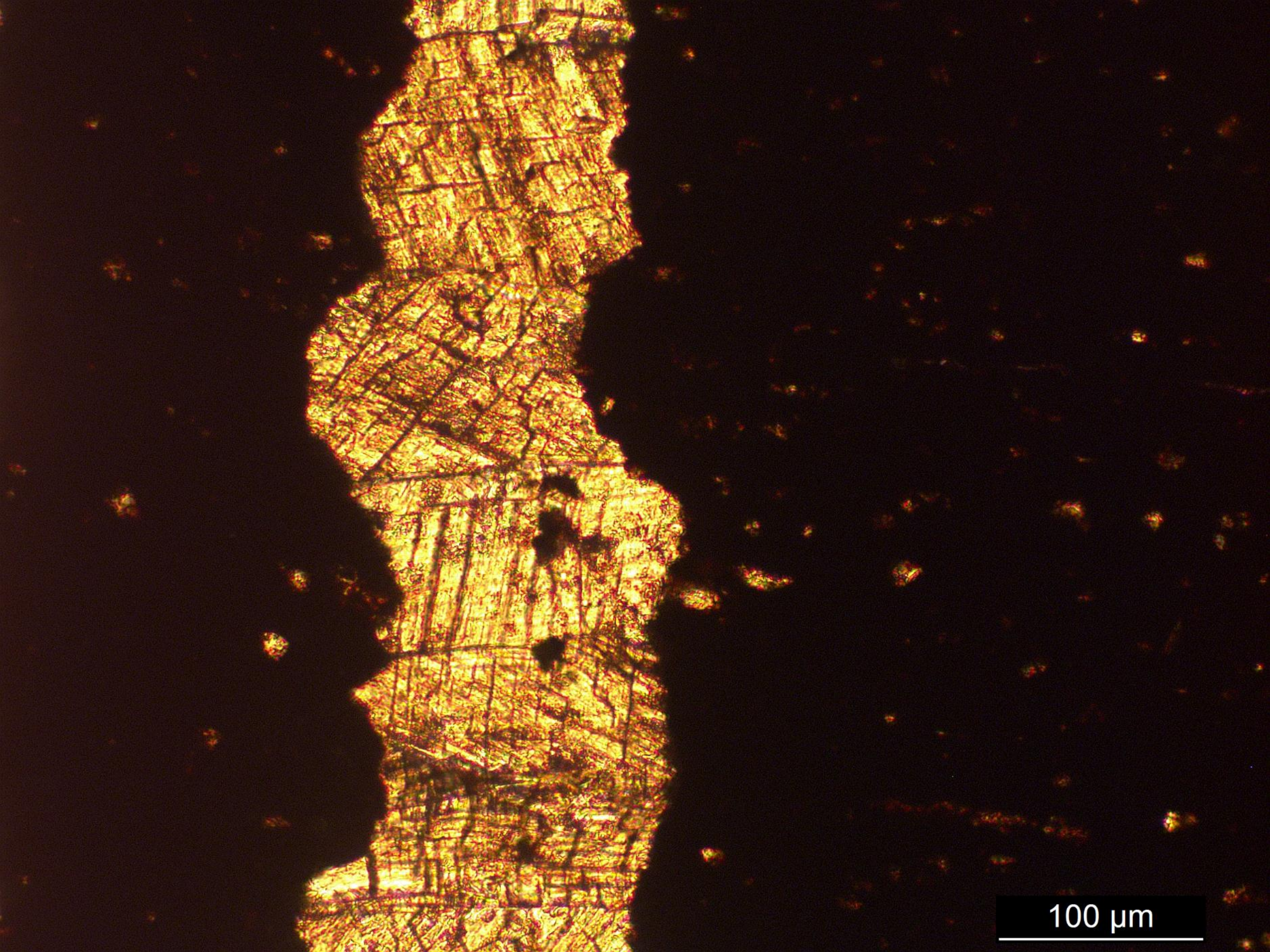
Rose #1, 1986

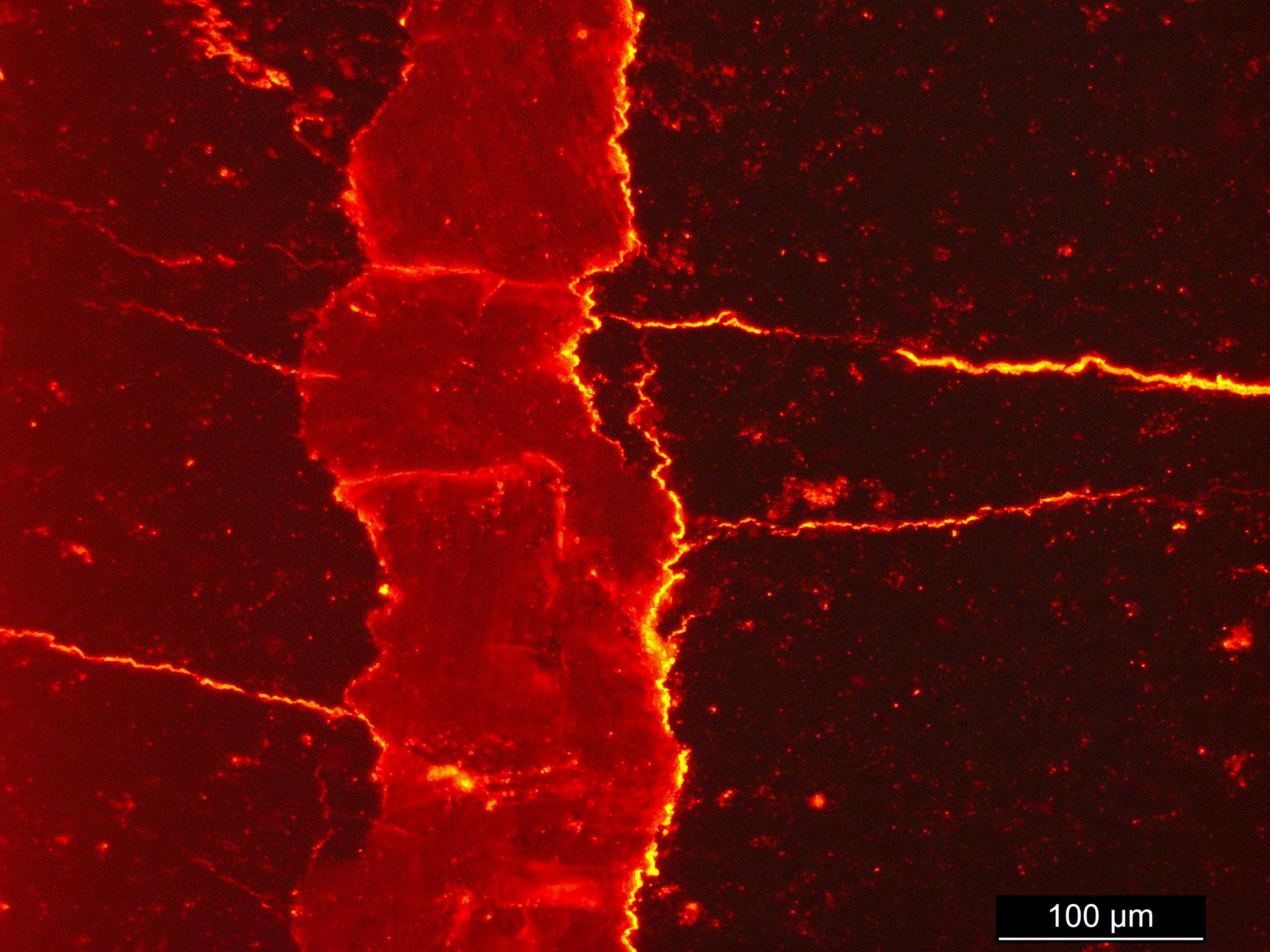
- Drilling break
- Oil Shows
- Natural fractures

- DST-4: Flowed 42.30 bbls/day
- Abnormally high pressure
- Core k ≈ 0.01 md   Core Ø ≈ 4 %



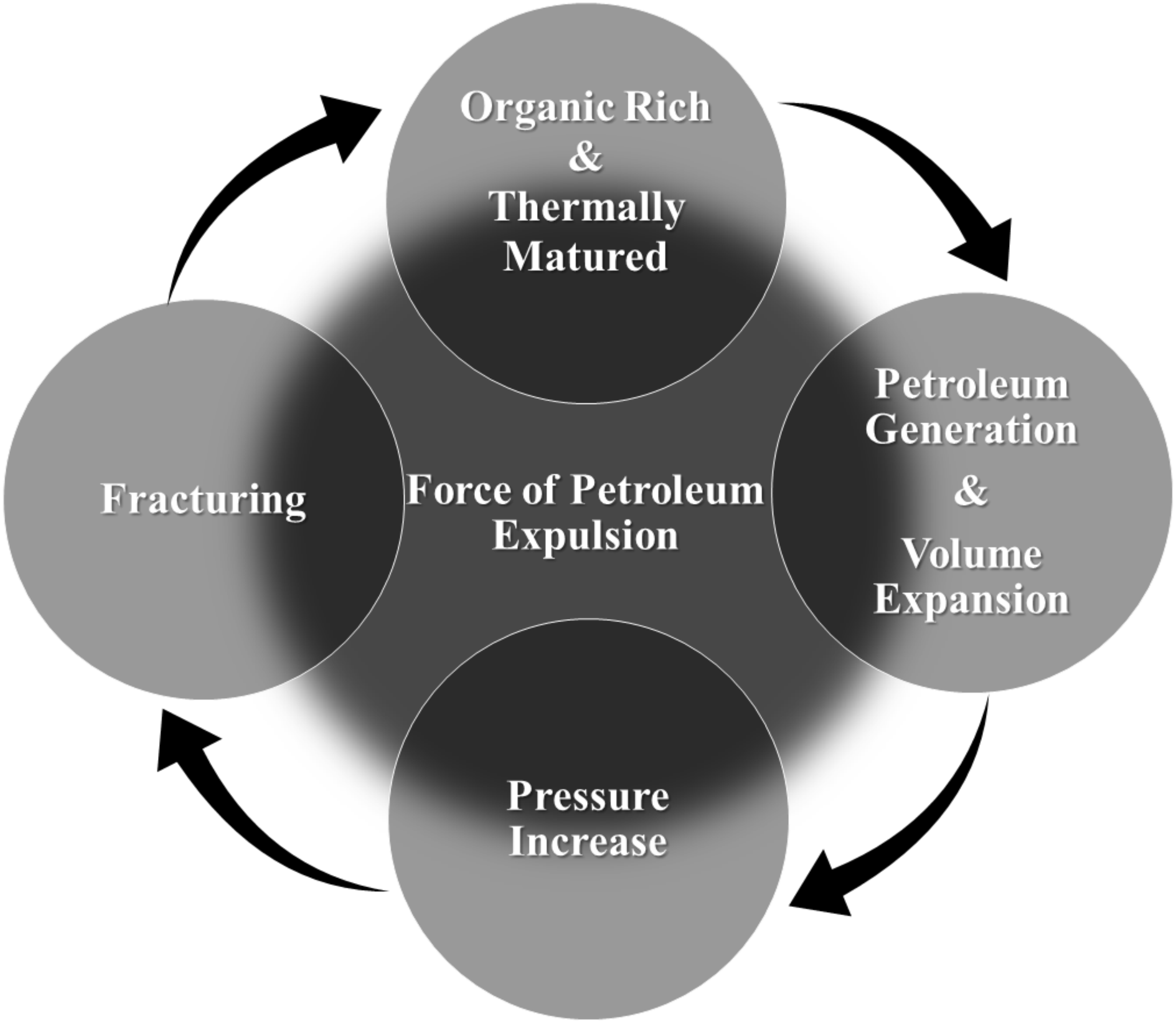



100 µm


100 µm

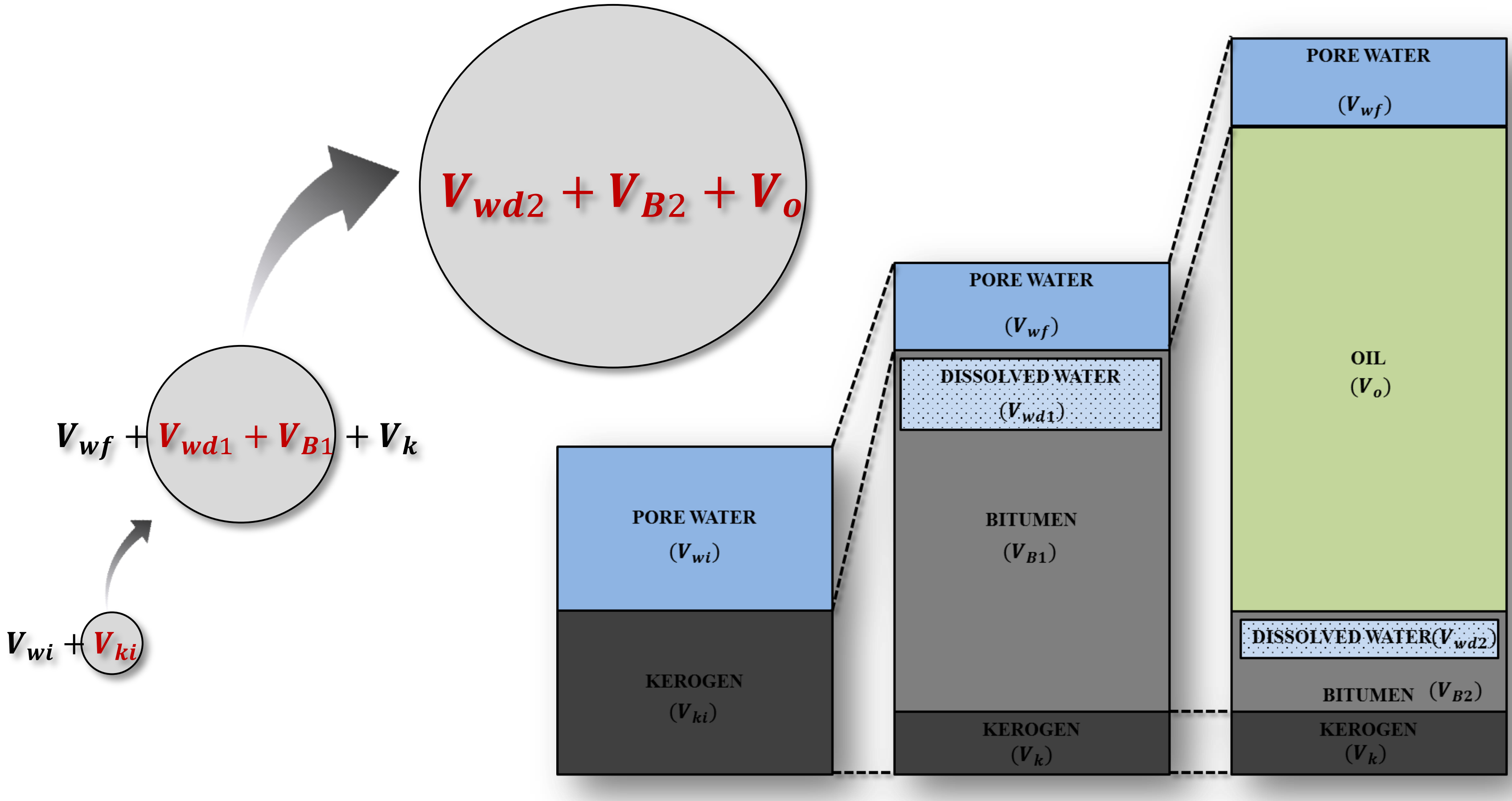
Analysis of Petroleum-Expulsion Fracturing

Force of Petroleum Expulsion



Analysis of Petroleum-Expulsion Fracturing

Volume Expansion

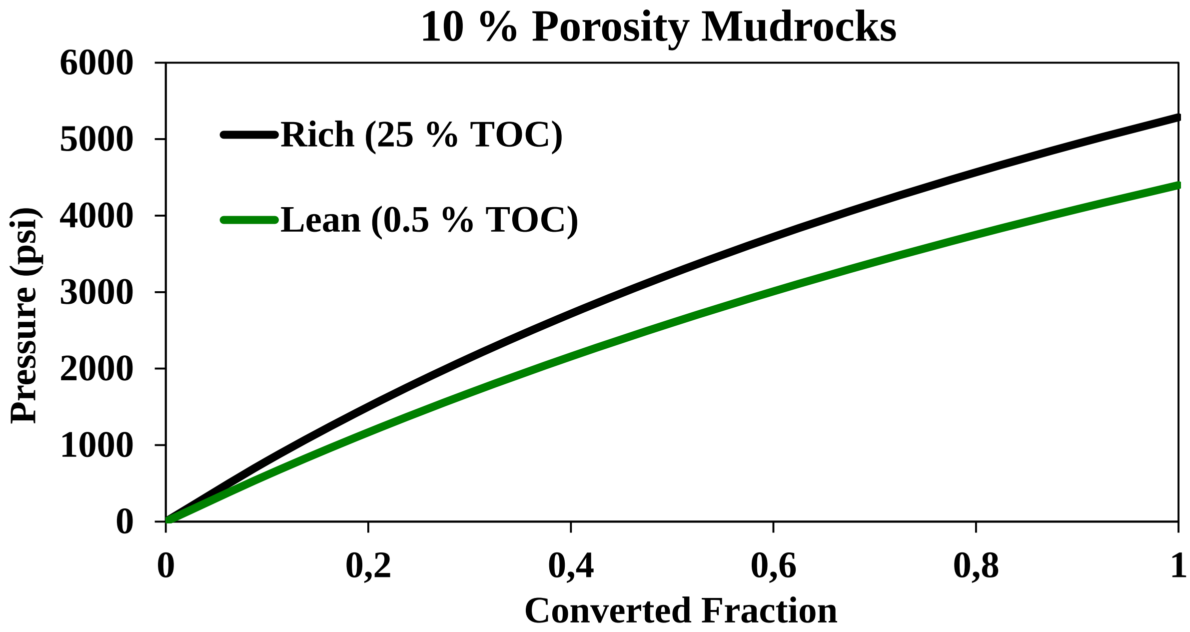


Analysis of Petroleum-Expulsion Fracturing

Pressure Increase

Kerogen-to-Bitumen
(Role of organic richness)

$$\Delta P_{kB} = \frac{F(D_{kB} - 1)}{V_R\left(\frac{3(1-2v)}{E} + C_w\right) + F(D_{kB}C_O - C_k) + \left(\frac{3(1-2v)}{E} + C_k\right)}$$

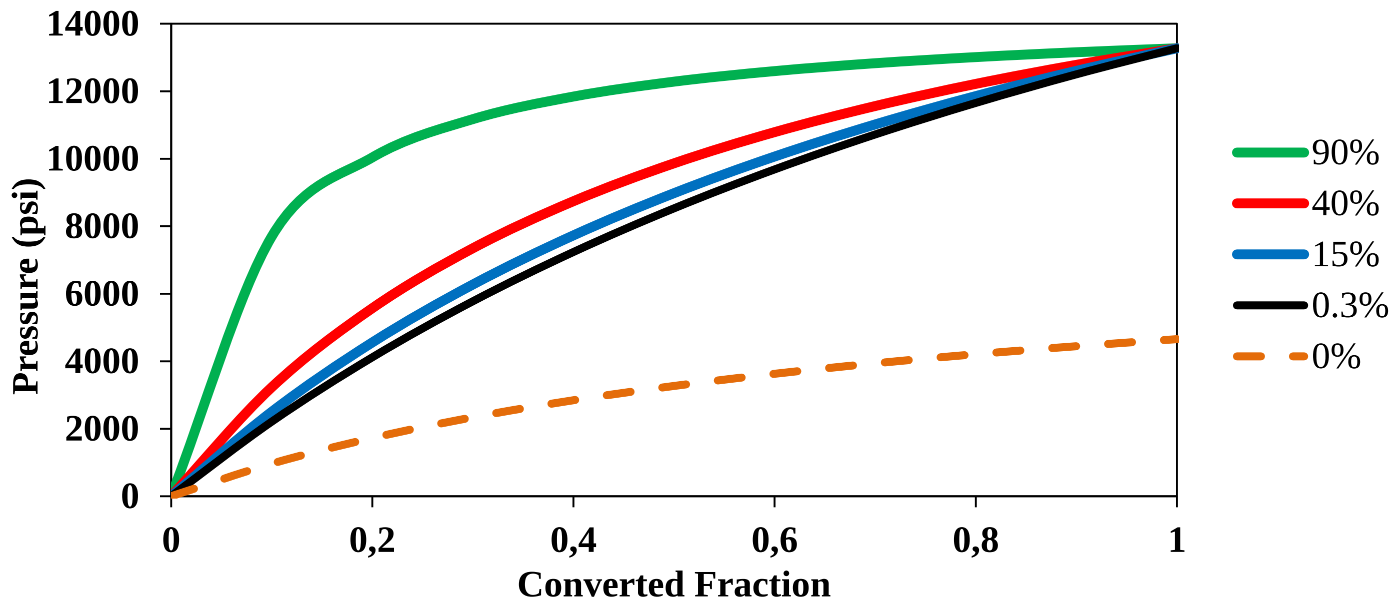


Analysis of Petroleum-Expulsion Fracturing

Pressure Increase

Bitumen-to-Oil
(Role of water)

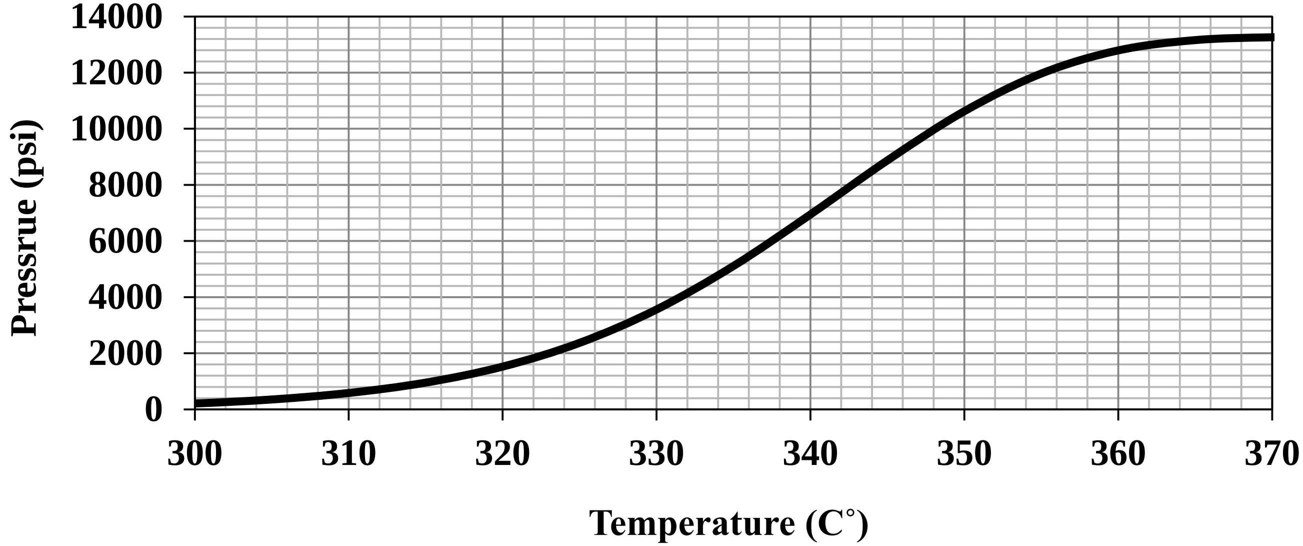
$$\Delta P_{BO} = \frac{F\left[D_{Bo}\left(\frac{x_w}{1-x_w}+1\right)-\left(\frac{x_w}{1-x_w}-1\right)\right]}{\left(\frac{x_w}{1-x_w}\right)\left(\frac{3(1-2v)}{E}+C_w-FC_w+FD_{Bo}C_o\right)+F(D_{Bo}C_o-C_B)+\left(\frac{3(1-2v)}{E}+C_B\right)}$$



Pressure Increase

Bitumen-to-Oil
(Role of Time & Temperature)

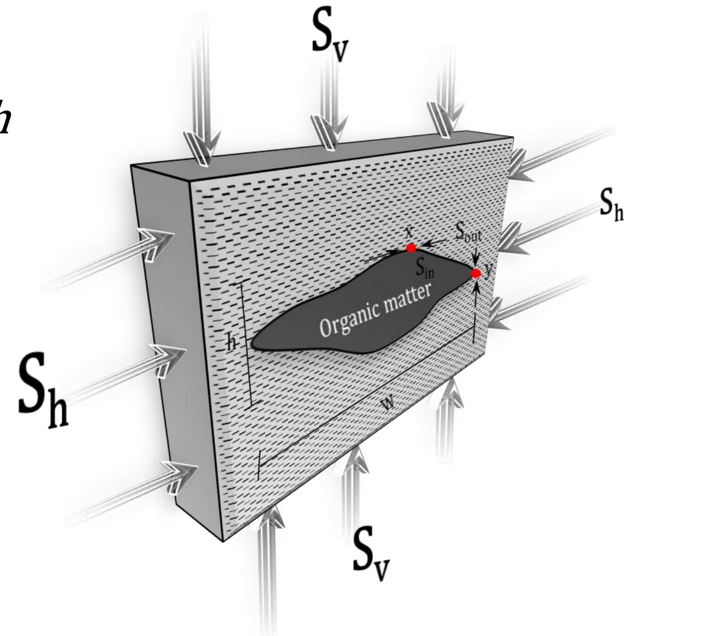
$$\Delta P_{BO} = \frac{\left(1 - e^{\left(-tA_o e^{\left(\frac{-E_a}{RT}\right)}\right)}\right)\left[D_{Bo}\left(\frac{A_x e^{B_x T}}{1 - A_x e^{B_x T}} + 1\right) - \left(\frac{A_x e^{B_x T}}{1 - A_x e^{B_x T}} - 1\right)\right]}{\left(\frac{A_x e^{B_x T}}{1 - A_x e^{B_x T}}\right)\left(\frac{3(1-2v)}{E} + C_w - \left(1 - e^{\left(-tA_o e^{\left(\frac{-E_a}{RT}\right)}\right)}\right)C_w + \left(1 - e^{\left(-tA_o e^{\left(\frac{-E_a}{RT}\right)}\right)}\right)D_{Bo}C_o\right) + \left(1 - e^{\left(-tA_o e^{\left(\frac{-E_a}{RT}\right)}\right)}\right)(D_{Bo}C_O - C_B) + \left(\frac{3(1-2v)}{E} + C_B\right)}$$



Expulsion Fracturing
Organic matter aspect ratio/tensile strength anisotropy and poroelastic behavior

Initiation of microfracture:
(negative) Total tangential stress > Tensile strength

$$-S_t > T$$



Tangential stress at x, y due to S_v and S_h:

At x: $S_{out} = S_h(1 + {}^2/_\psi) - S_v$
At y: $S_{out} = S_v(1 + 2\psi) - S_h$

Tangential stress at x, y due to internal stress S_{in} that is due to Pressure P:

At x: $S_{in} = P(1 - {}^2/_\psi)$
At y: $S_{in} = P(1 - 2\psi)$

Total tangential stress at x and y:

$S_t = S_{out} + S_{in}$

$S_{t_x} = S_h\left(1 + {}^2/_\psi\right) - S_v + P\left(1 - {}^2/_\psi\right)$
$S_{t_y} = S_v(1 + 2\psi) - S_h + P(1 - 2\psi)$

Analysis of Petroleum-Expulsion Fracturing

Expulsion Fracturing

Bitumen aspect ratio/tensile strength anisotropy and poroelastic behavior

For horizontal microfracturing considering strength anisotropy and anisotropic poroelastic behavior:

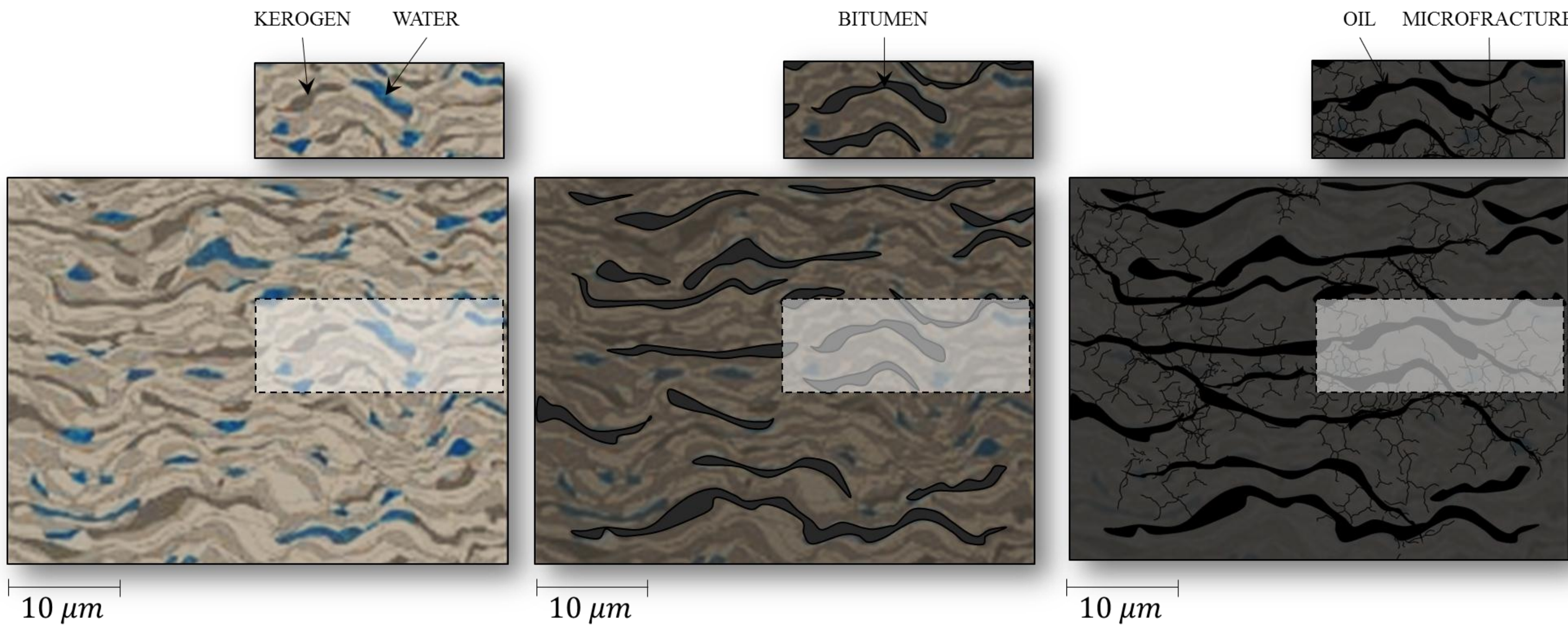
$$\Delta P > \frac{S_v(1+2\psi) - \frac{E_h}{E_v}\frac{v_v}{1-v_h}(S_v - \alpha P_{water}) + \alpha P_{water} + \frac{T_h}{T_{ratio}}}{2\psi - 1}$$

For vertical microfracturing considering strength anisotropy and anisotropic poroelastic behavior:

$$\Delta P > \frac{\left[\frac{E_h}{E_v}\frac{v_v}{1-v_h}(S_v - \alpha P_{water}) + \alpha P_{water}\right](1+2/\psi) - S_v + T_v T_{ratio}}{2/\psi - 1}$$

Analysis of Petroleum-Expulsion Fracturing

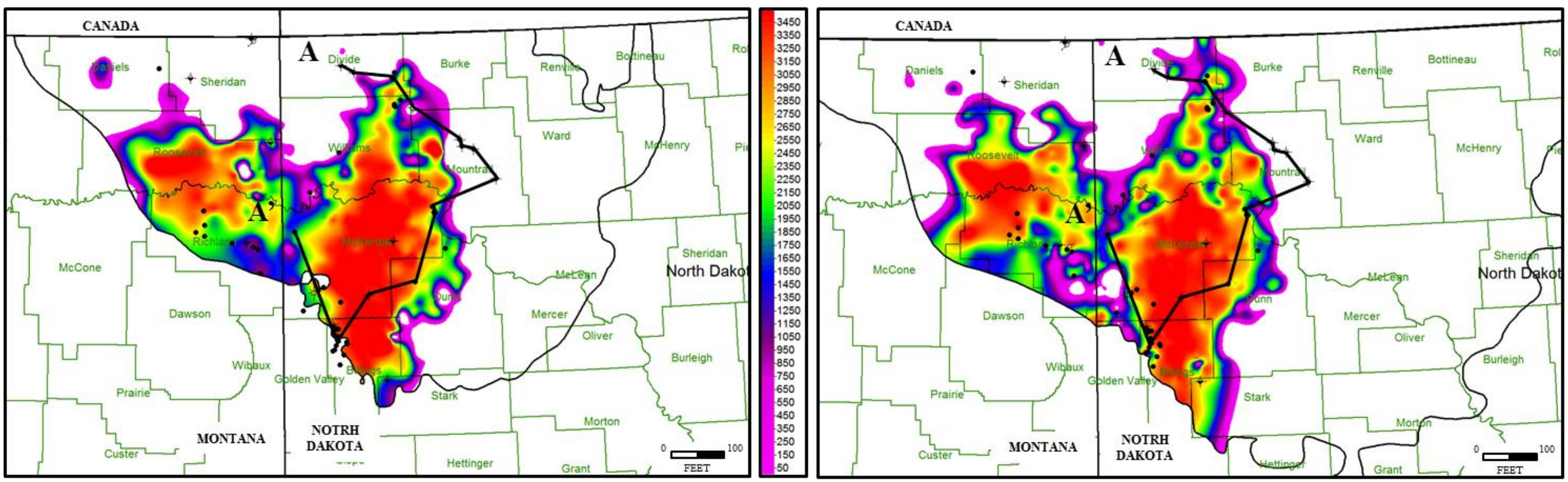
Sequence of petroleum-expulsion fracturing



Pre-oil Generation	Initial oil Generation	Primary oil Generation	Post-oil Generation
	Initial Expulsion	Primary Expulsion	Post-Expulsion
	Initial Migration	Internal Migration	External Migration

Petroleum-Expulsion Fracture Map

Expulsion Fracture Map = (Expulsion Pressure) – (Expulsion-Fracturing Pressure)



Lower Bakken Shale

Upper Bakken Shale

Summary

“The relationship between **source-rock maturity, hydrocarbon generation, geopressuring and fracturing** suggest an opportunity in exploration for unrecognized and unlooked-for **“unconventional”** accumulations of potentially very large regional extent.”

(Meissner, 1978)

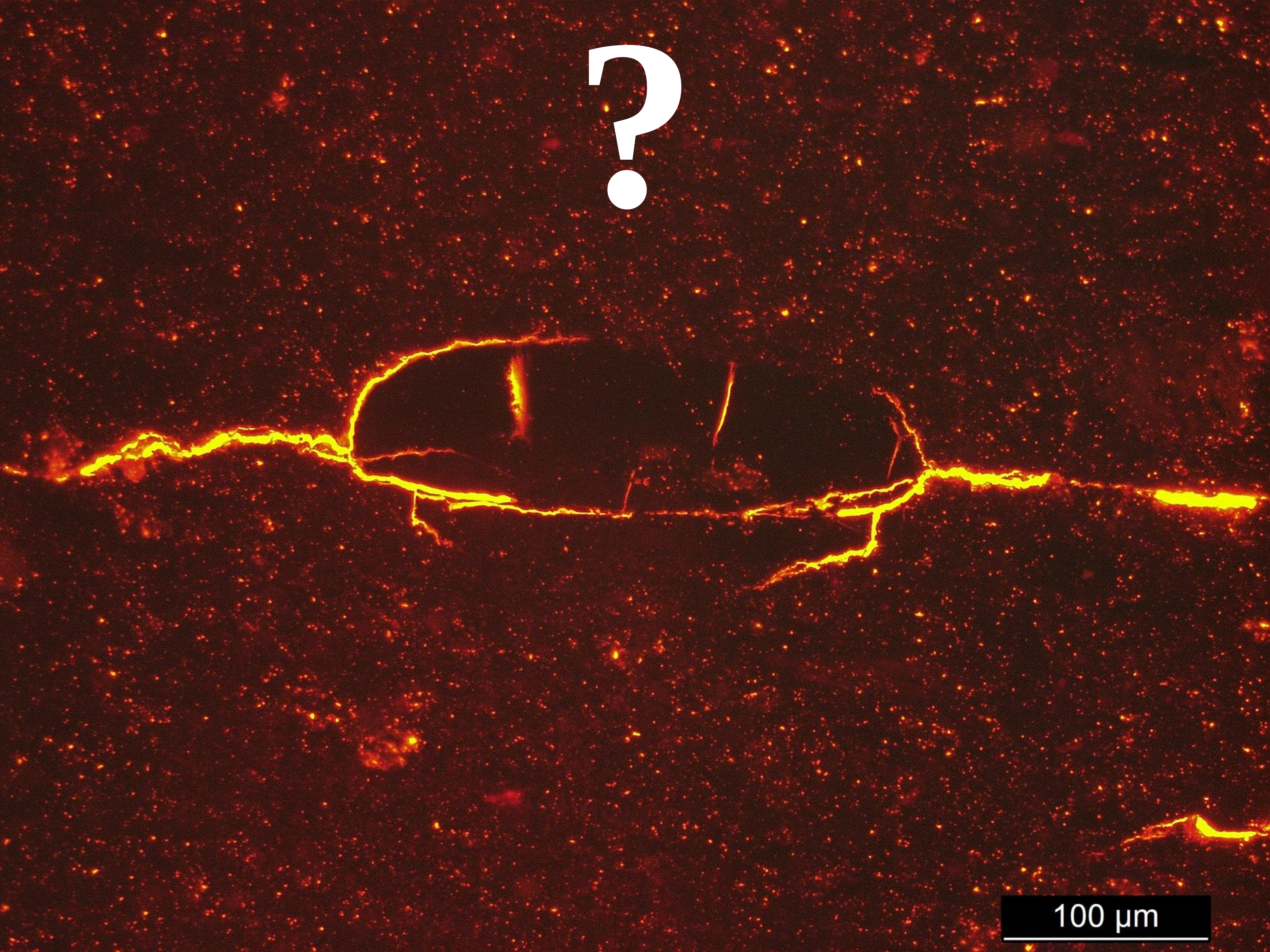
Acknowledgments

Colorado School of Mines Bakken Consortium

North Dakota Geological Survey

Wagner Petrographic

Saudi Aramco


?
100 µm