Pitfalls of Model Driven Unconventional Development – The Stratigraphic Trends that Drive Oil & Gas Productivity in Divide County, North Dakota

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Abstract

Early in unconventional oil and gas plays, it is often deemed economically necessary to begin large scale development before a full understanding of the play's geology is established. Unfortunately, permeability variability related to stratigraphic complexities almost invariably creates large pressure differences in the targeted reservoirs. These higher perm rocks drain preferentially, producing the bulk of the fluids recovered from early wells. The higher perm, lower pore-pressure zones attract much of the of the frac energy of later infill wells, making subsequent development difficult or completely uneconomic. Early quantification of which stratigraphic intervals significantly contribute to production during the life of a well is essential in helping operators better develop the full resource. Models of the producing zones are frequently created to identify the reservoir rocks that are contributing to each well's production. Unfortunately, these models almost always prove to be overly simplistic and much too small when compared to later measured pore-pressure data.

Beginning in 2011 horizonal drilling began to target the stratigraphic pinch-out of the best dolostones in the first bench of the Three Forks Formation in Divide County in the extreme NW corner of North Dakota. Strangely, it was eventually shown that the best production was from the thinnest Three Forks reservoirs and that the large volumes of oil produced from these wells could not be reconciled to the limited reservoirs mapped in the pinch-out. This presentation uses core-facies mapping from the large dataset of cores available at the ND Core Repository for Divide County to build a comprehensive stratigraphic model to explain Bakken/Three Forks production trends found across the margins of the Williston Basin. This presentation will show data consisting of reservoir pressure, facies mapping, geochemistry and production data pointing to the existence of a large stratigraphic trap within the Middle Bakken that defines productivity trends in horizontals in both the Three Forks and Middle Bakken. The trap tips out just across the border in Saskatchewan where the lowest water cuts and best production per lateral foot is found and extends down to the Divide-Williams county line, with gradual increasing water cut and decreased well performance. This

presentation will show the extents of the trap, its internal character, evidence for its contribution to both Three Forks and Middle Bakken wells, evidence for its uneven depletion, how it fits with the low maturity data and what operators can do improve future infill wells.

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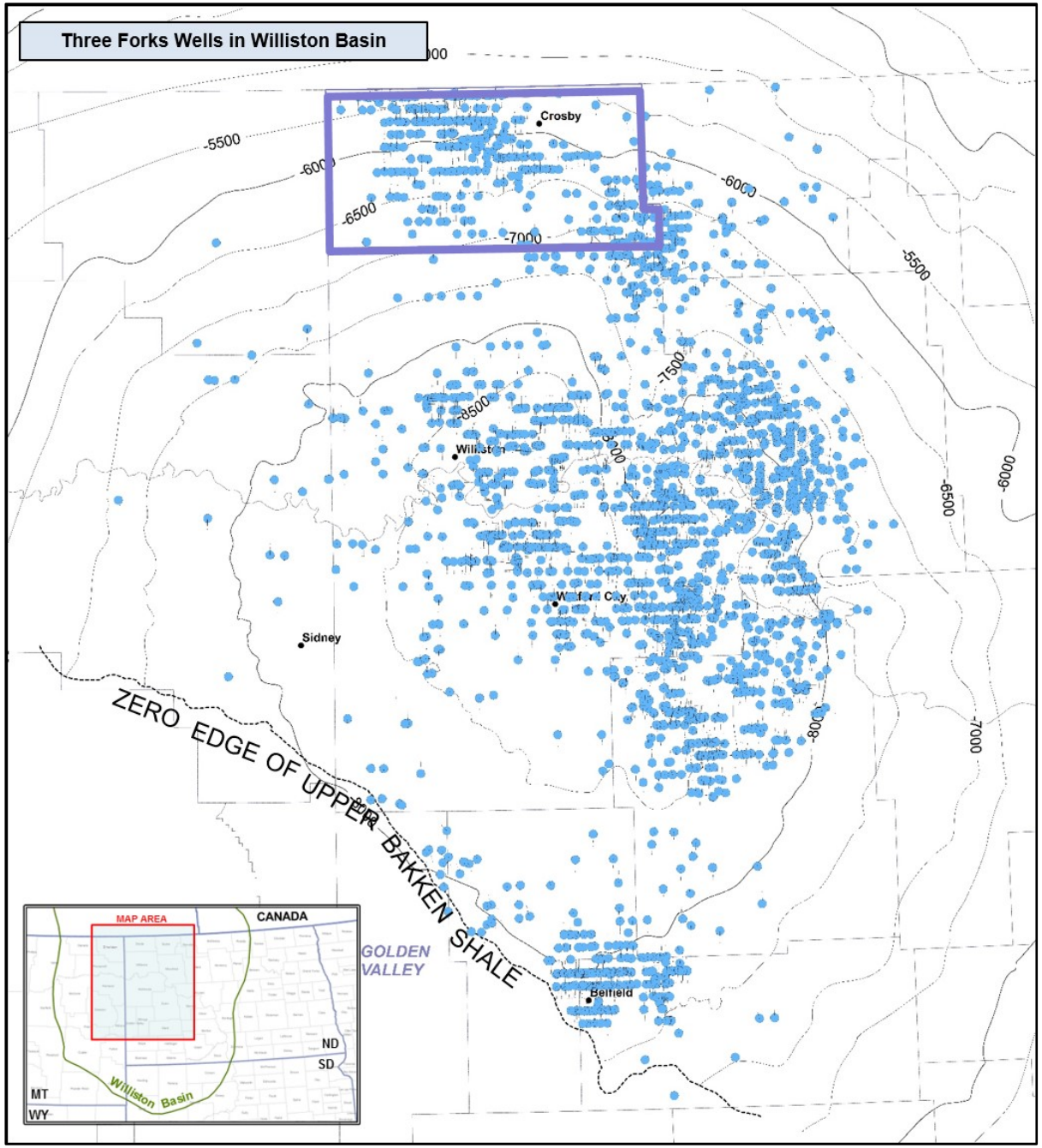
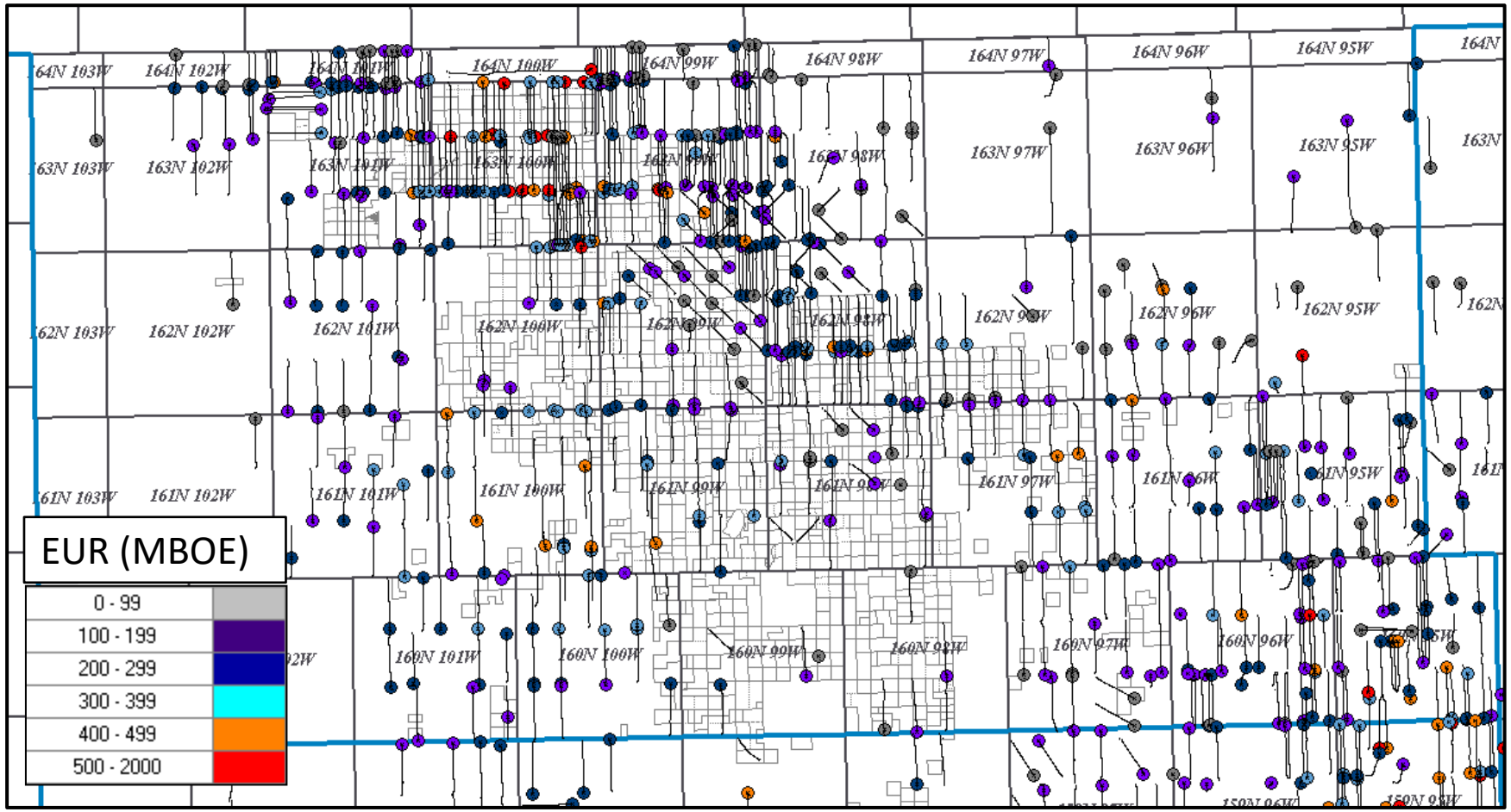
- Riley Brinkerhoff – Wasatch Energy Management
- Tim Nesheim – North Dakota Core Center
- Mark Millard –Rockies Resources

Living on the (Basin) Margin

- Better understanding the mix of migrated and in-situ generated reservoirs is essential to developing reserves economically
- Quantifying which intervals contribute to production during the life of a well would help operators better develop the full resource
- The Three Forks has been targeted in Divide County since 2005
  - Current landing targets, frac jobs, and well spacing are designed to maximize oil recovery from the Three Forks first bench
- Divide County has been more extensively developed than other portions of the Williston Basin margin outside of the overpressure cell



What Controls Divide County's Variable Well Results?

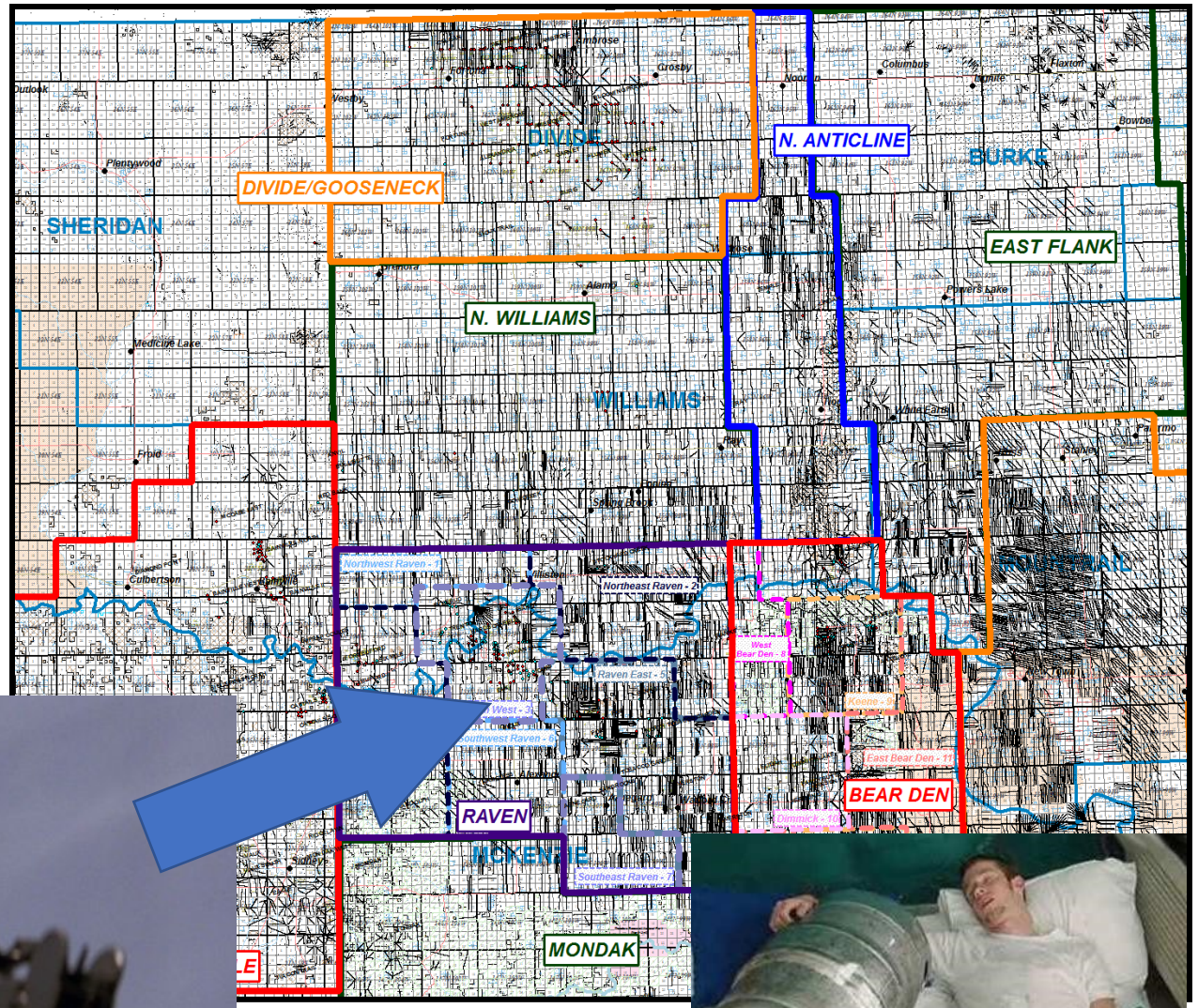


- A simple review of production bubbles shows massive lateral variability
- Certain definable areas show much better production
- Conversely, some show much poorer production
- What factors controls production?

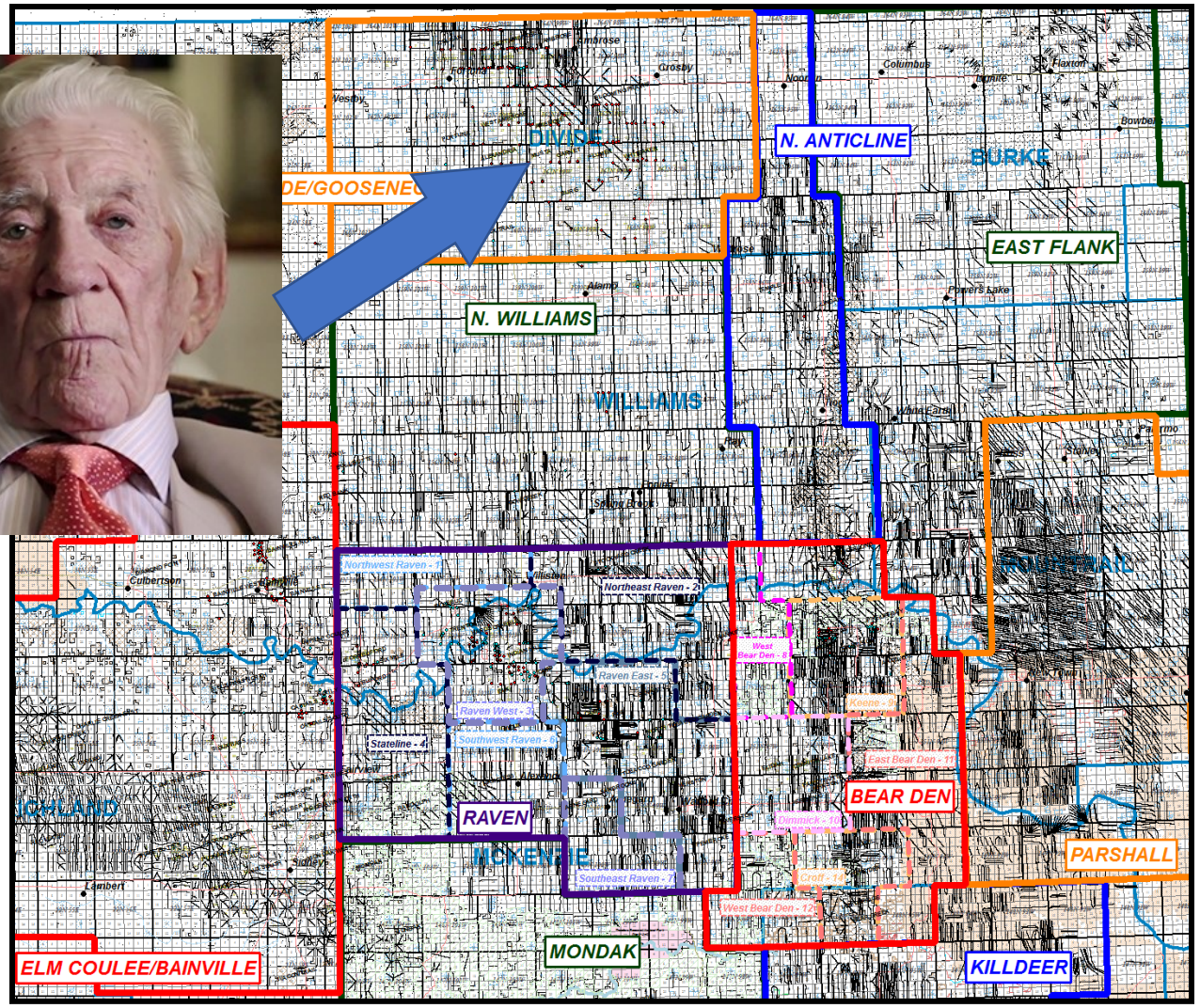
Oil Fields in the Williston Basin are Like Petroleum Engineers

The Bakken/Three Forks petroleum system in basin center is like a new engineer:

- It's under enormous pressure
- It's not particularly efficient compared to older fields/engineers
    - But can be prodded to greater production with the prodigious expenditure of frac energy
- It holds its fluids tightly



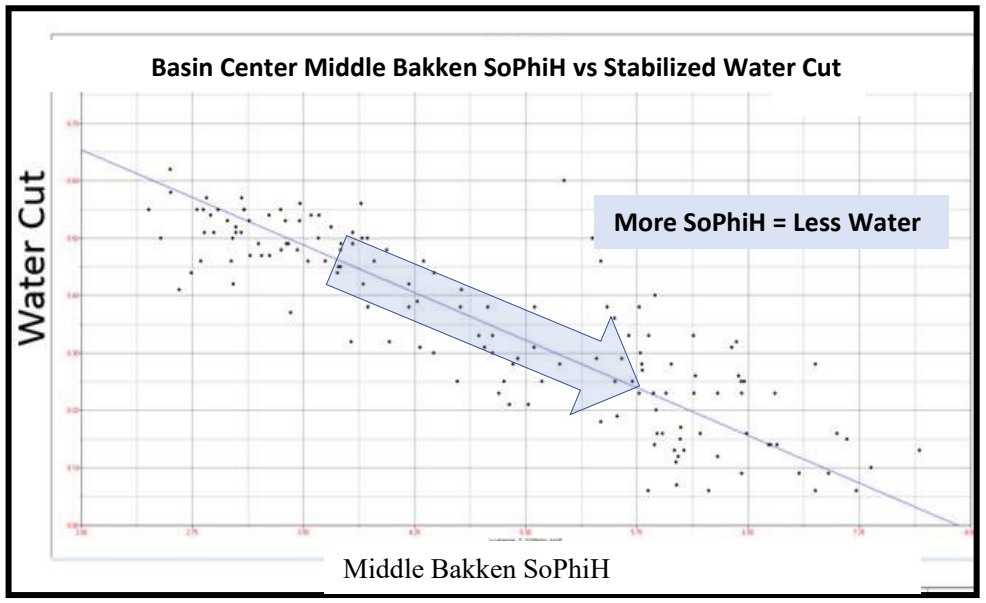
Oil Fields in the Williston Basin are Like Petroleum Engineers

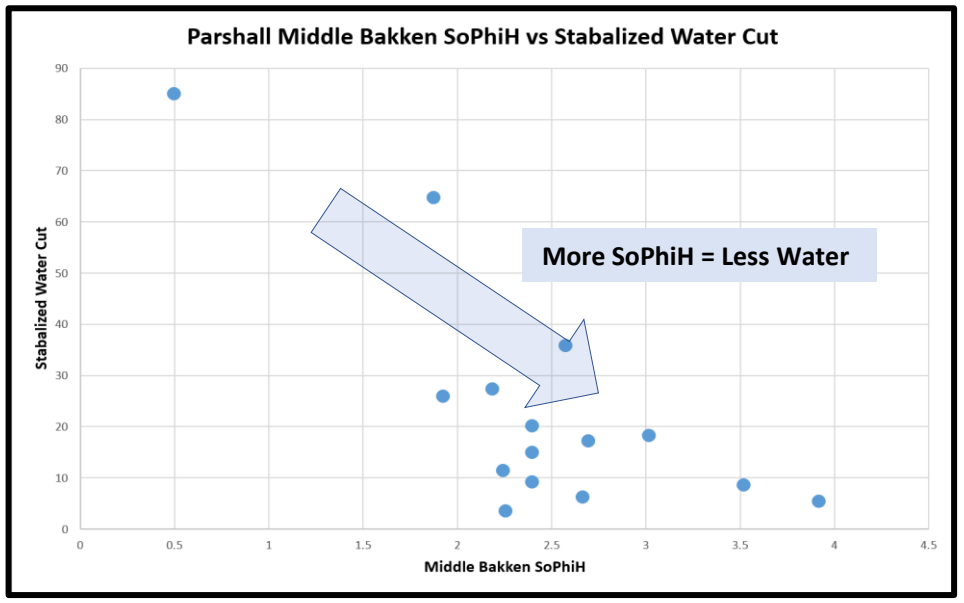


The Bakken/Three Forks in Divide County is much more like an old engineer:

- It hasn't felt pressure in years
- It's pretty efficient when it does work
- Fluids pass through it easily

SoPhiH Calculations vs. Water Cuts





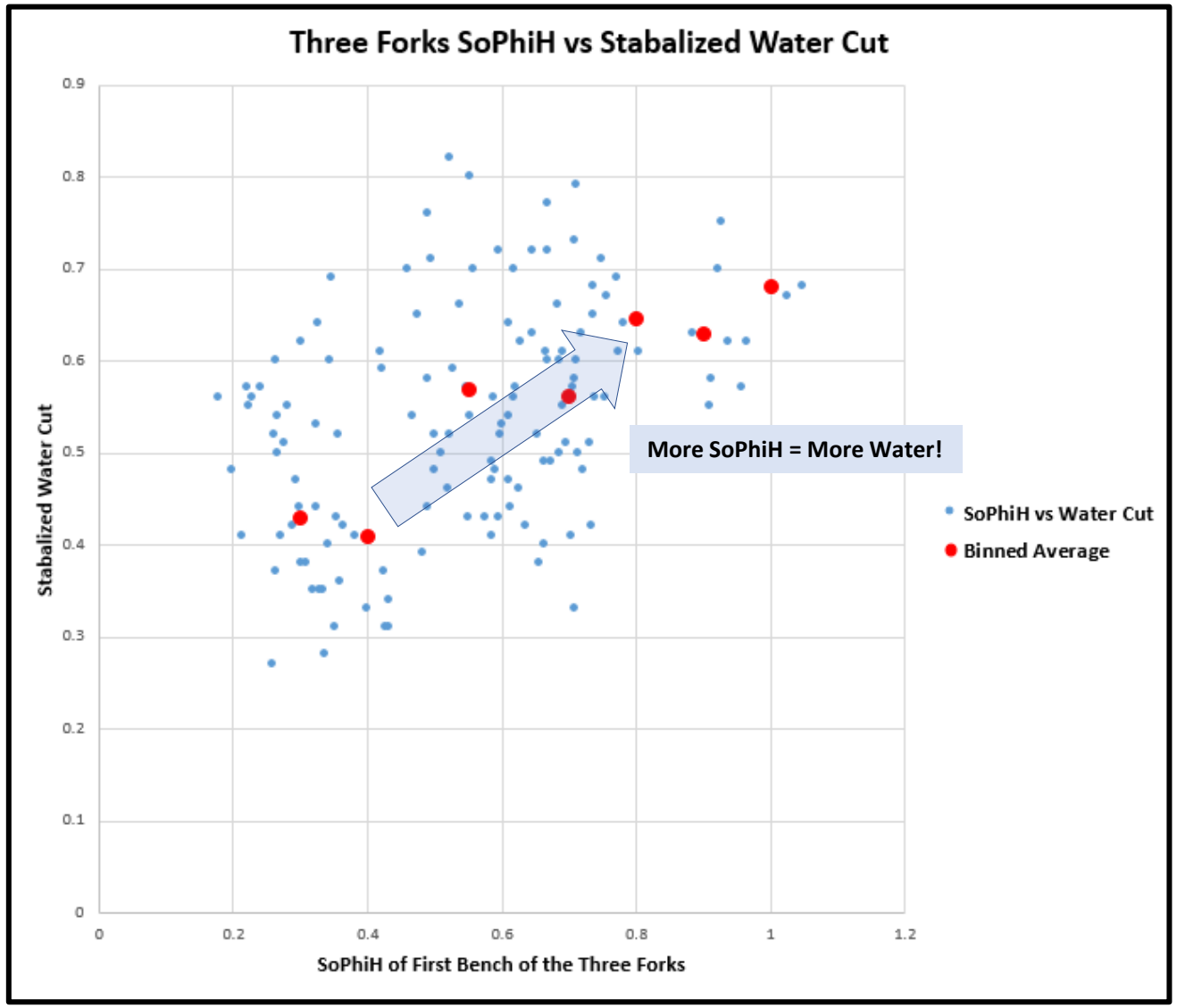
These cored wells with excellent geologic control in the Parshall Field have thicker, oil saturated Middle Bakken intervals that produced less water.

In the highly over-pressured basin center, SoPhiH, which here is largely influenced by variations in Middle Bakken thickness, also correlates strongly with reduced water cut.

- In the Bakken/Three Forks play in the Basin Center, lower water cuts correlate to better oil production
- In this part of the Williston Basin, SoPhiH mapping ties with lower water cuts
- **Many operators expected similar trends outside of the Basin center**

Using Core Data to Reduce Risk

- In Divide County, the water cut of the Three Forks play have a positive correlation to SoPhiH
  - This is bad for a geologist's career



Do Your Mapped Values Correlate With Production?

- In Divide County, production from horizontals in the Three Forks appears to be inversely correlated with SoPhiH
- Thicker reservoirs with more oil in place consistently have poorer production results
- This would suggest that the effective reservoir model used in mapping is flawed

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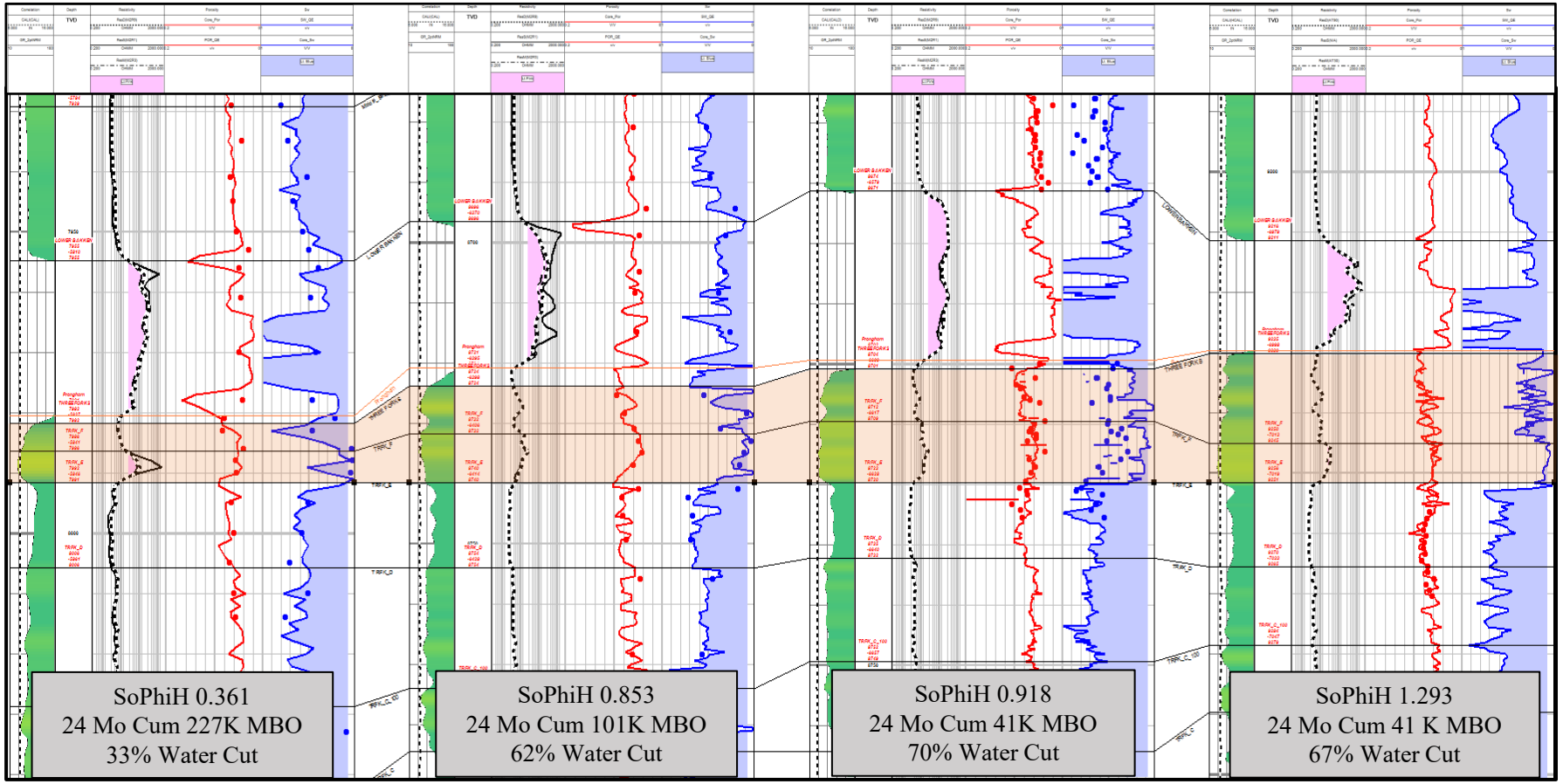
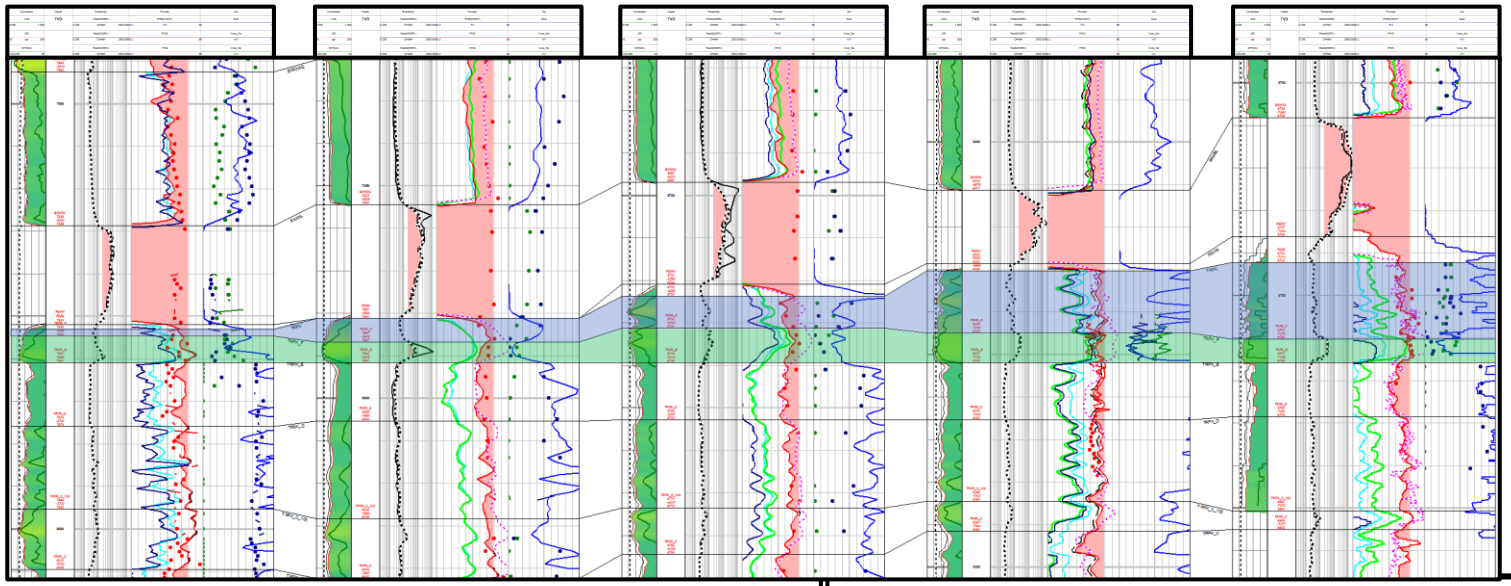


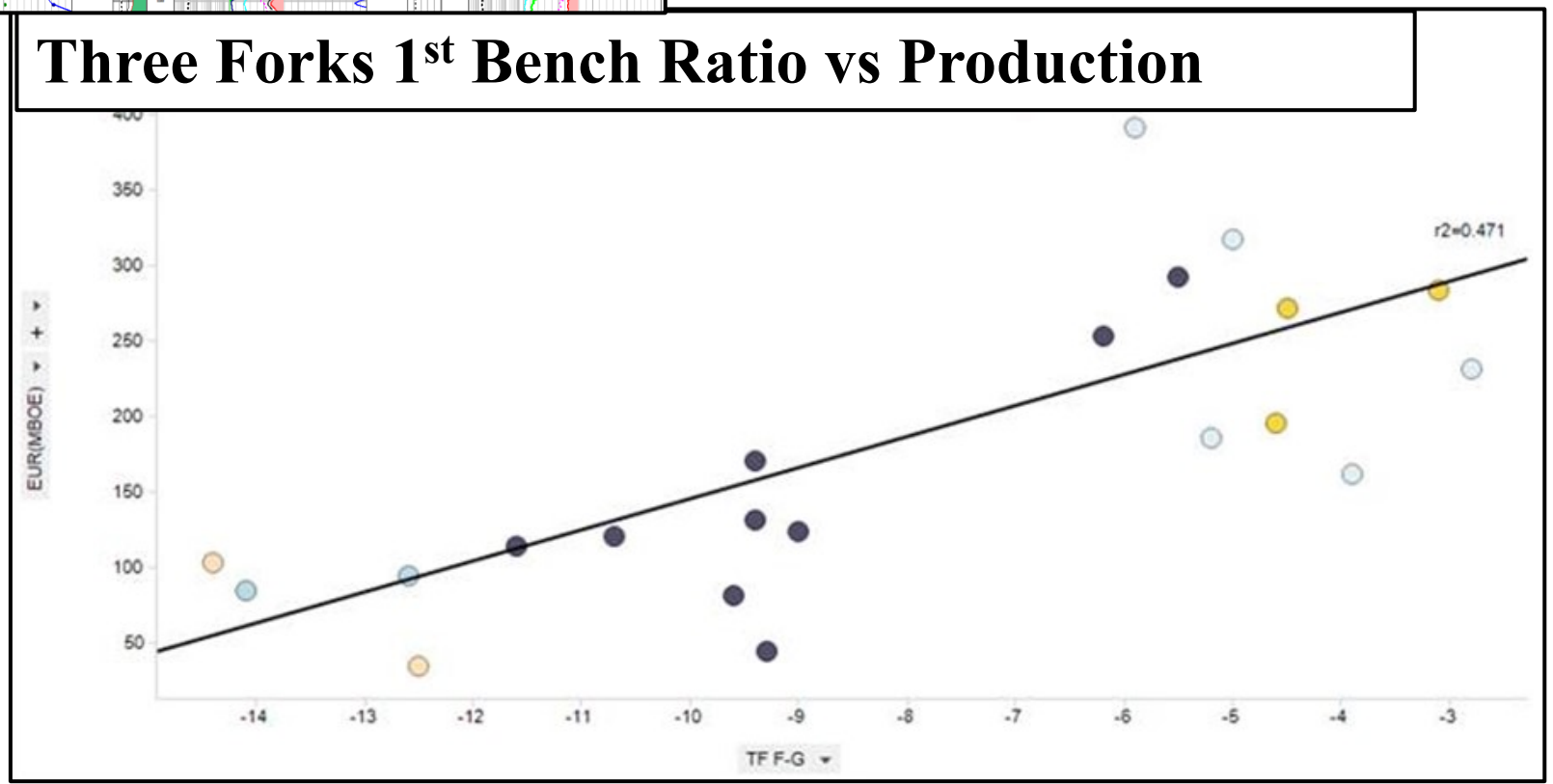
Cross-section of the upper Three Forks in Divide County from north to south

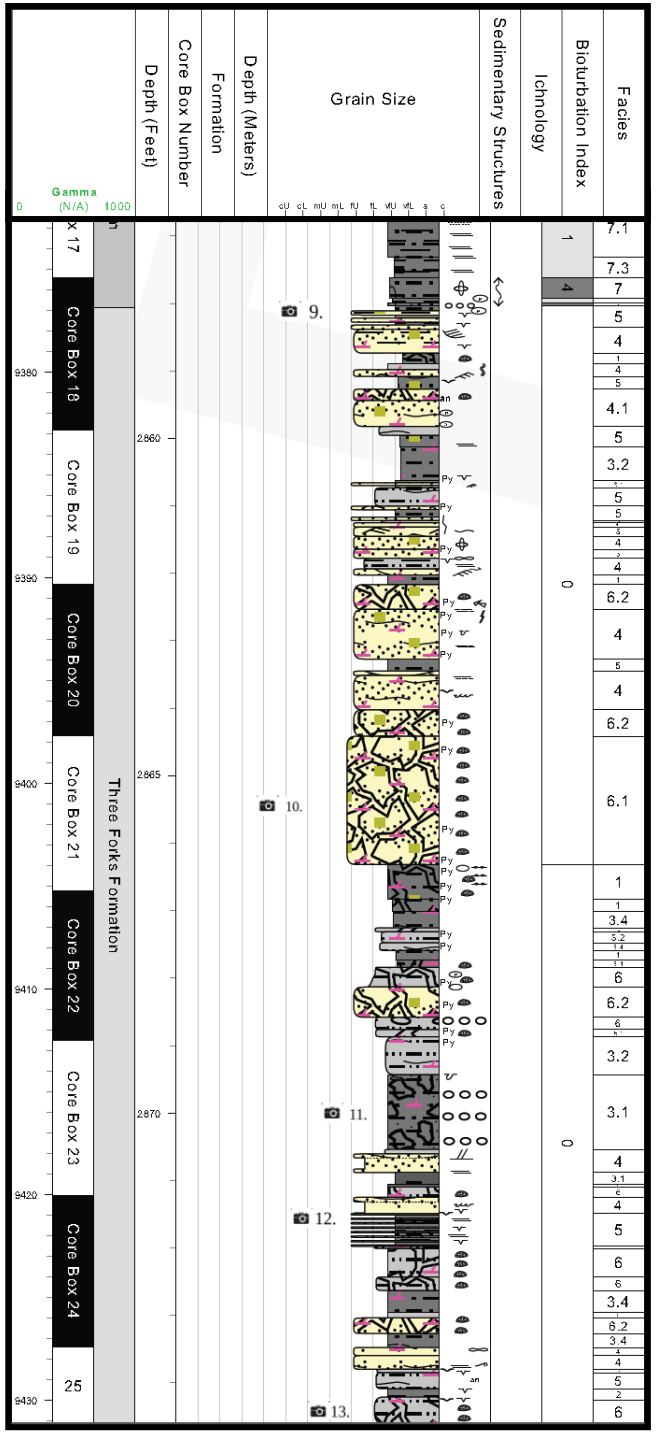


Mapping Methods

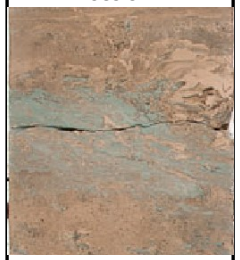
If simple SoPhiH methods don't predict production, perhaps ratios of the involved stratigraphy will?

- The productivity of the Three Forks correlates with the ratio of the brown dolostone to the overlying mixed lithologies
- Regions with the highest brown-dolostone to mixed lithologies ratio produce the best





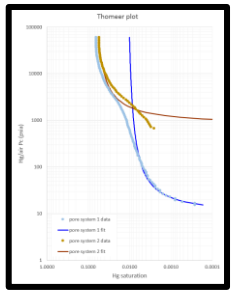
7985.5’



10.0% Phi 40% Sw

Mixed Lithologies

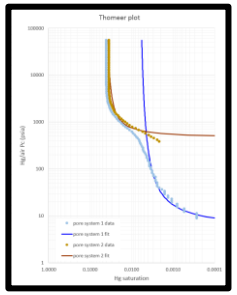
Mixed green and brown breccia
- Average composition
  - 44% dolomite
  - 39% quartz-feldspar
  - 17% clay minerals



7988.75’

6.4% Phi 38.3% Sw

Mixed green and brown laminated
- Average composition
  - 35% dolomite
  - 39% quartz-feldspar
  - 22% clay minerals

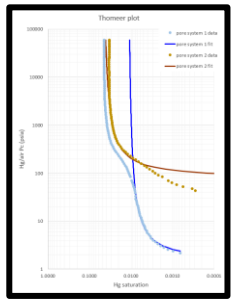


End Member Lithologies

7991.7’

6.5% Phi 17% Sw

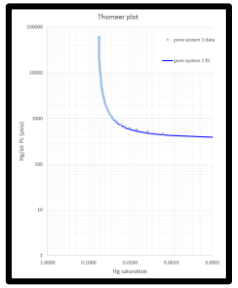
Brown to tan, silty to sandy dolostone
- Average composition
  - 63% dolomite
  - 30% quartz-feldspar
  - 3% clay minerals



8003.85’

8.5% Phi 88.5% Sw

Green silty mudstone
- Average composition
  - 36% dolomite
  - 30% quartz-feldspar
  - 30% clay minerals
  - 2% pyrite



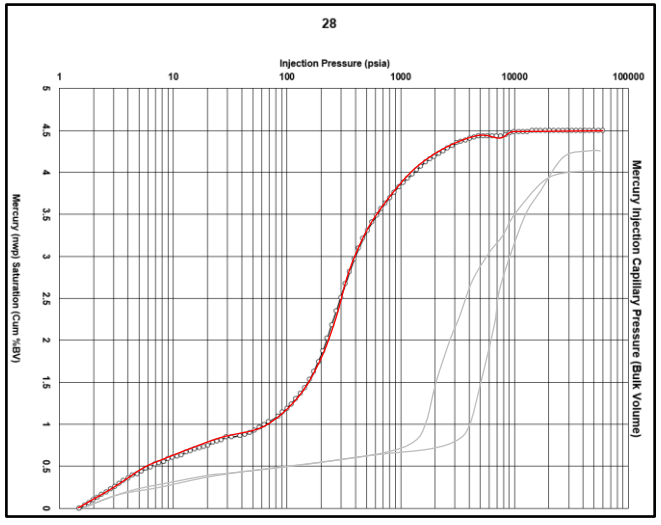
Lithotypes

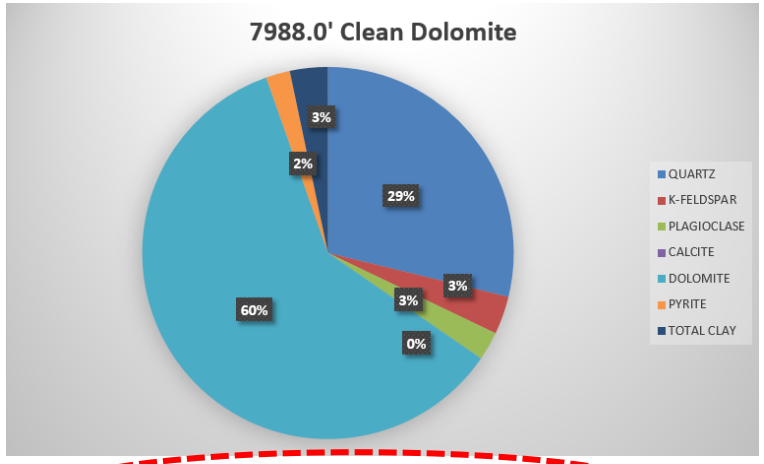
- A common mistake in mapping the Three Forks is averaging the different rock properties of the first bench
- In many simplified cross-sections, the entire first bench appears to have water saturations and porosities that have been averaged to a single value
- Interpreters tend to miss important differences in the reservoir quality of the various lithologies due to
  - Log resolution limits
  - Biased core sampling

Brown Dolostone Core Fluorescence & Reservoir Quality

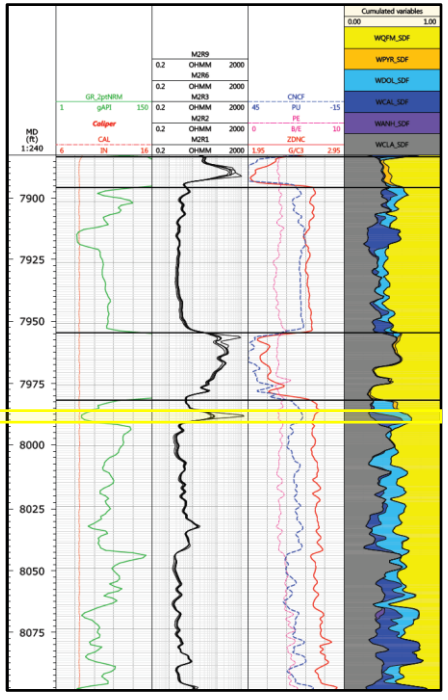
Torgeson Core – In the Best Part of Divide County

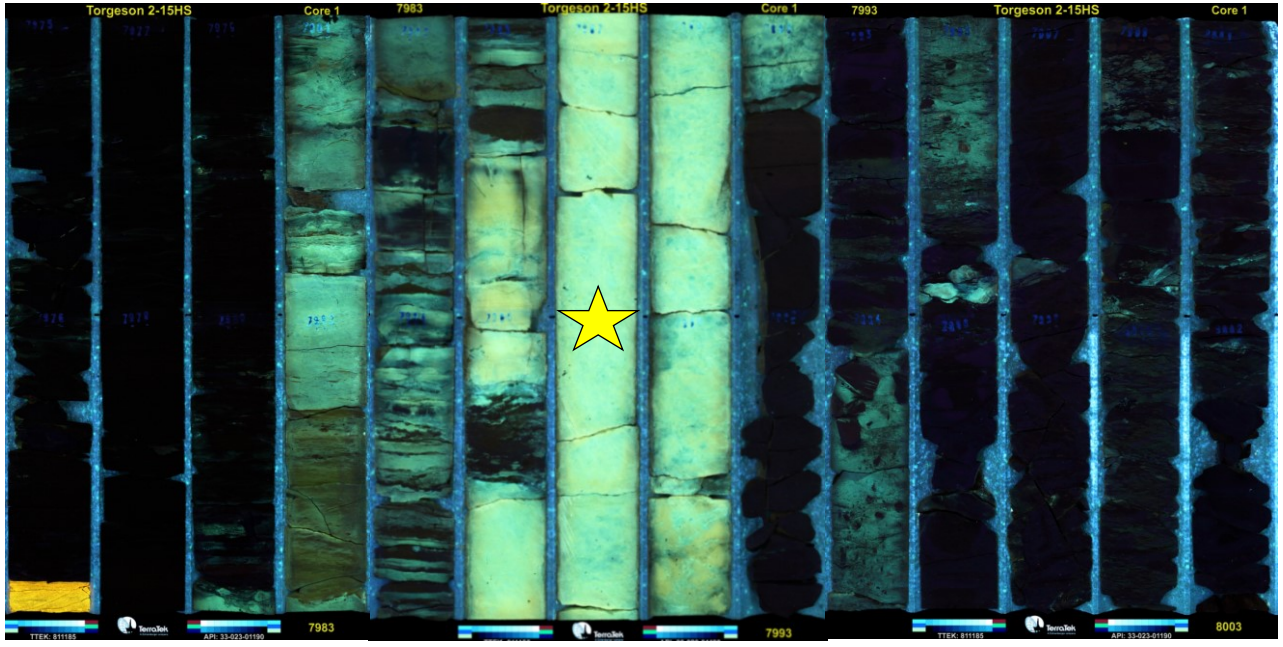
- The Brown dolostone is by far (two orders of magnitude) the most effective reservoir
- Fluorescence shows that it is full of oil
- It's very thin!



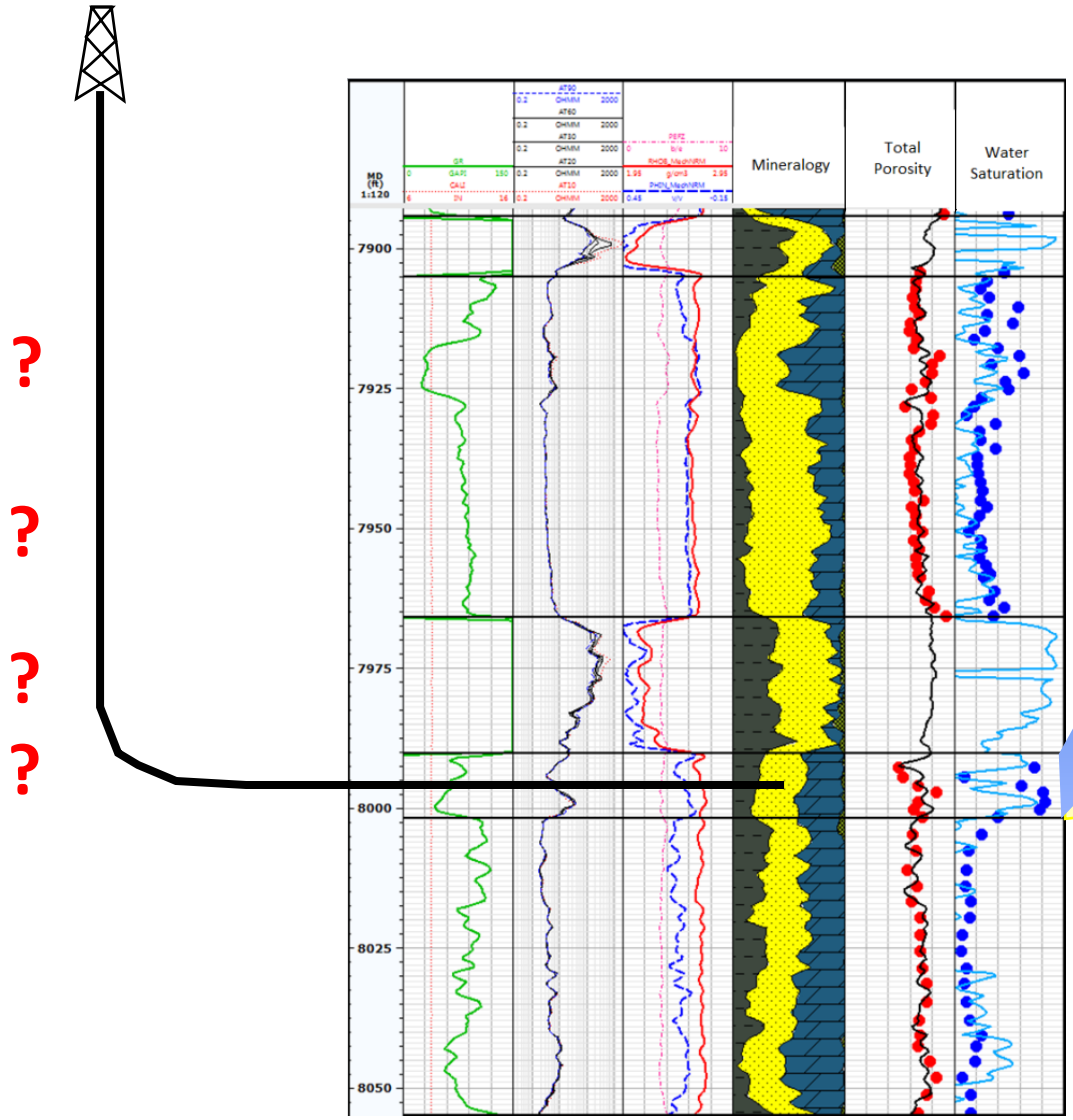


MICP Perm 0.0519 mD

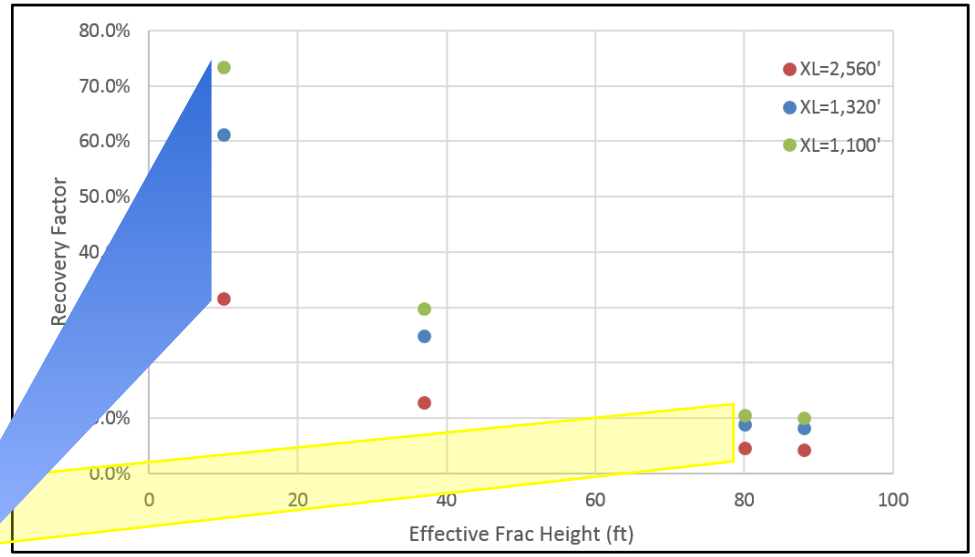




What is the Effective Frac Height?



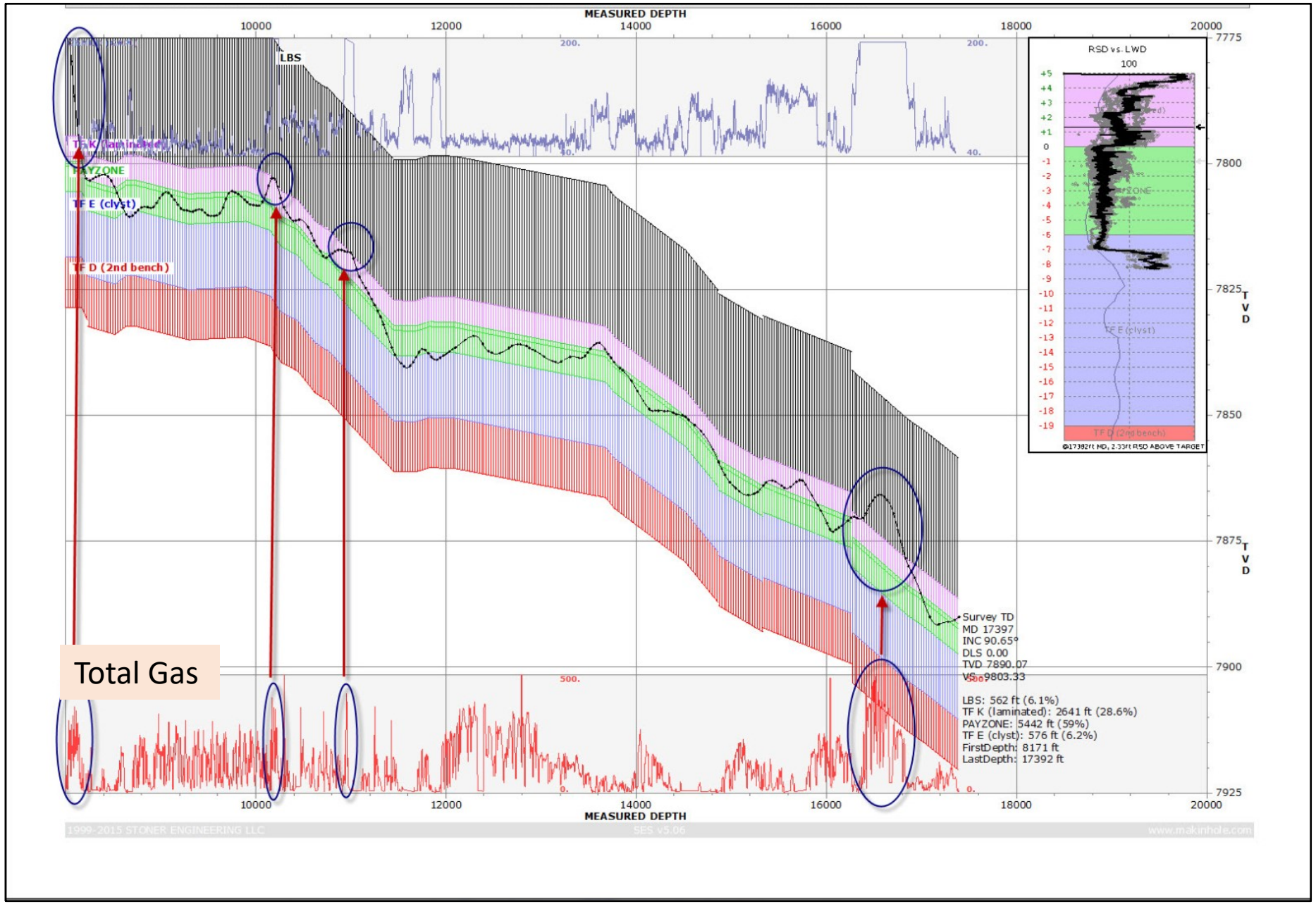
Plot below shows calculated recoveries from an average Three Forks well, depending on effective frac length and height



If the Three Forks produces by itself, then it must have a very high recovery factor

Gas Shows in the Lower Bakken Shale

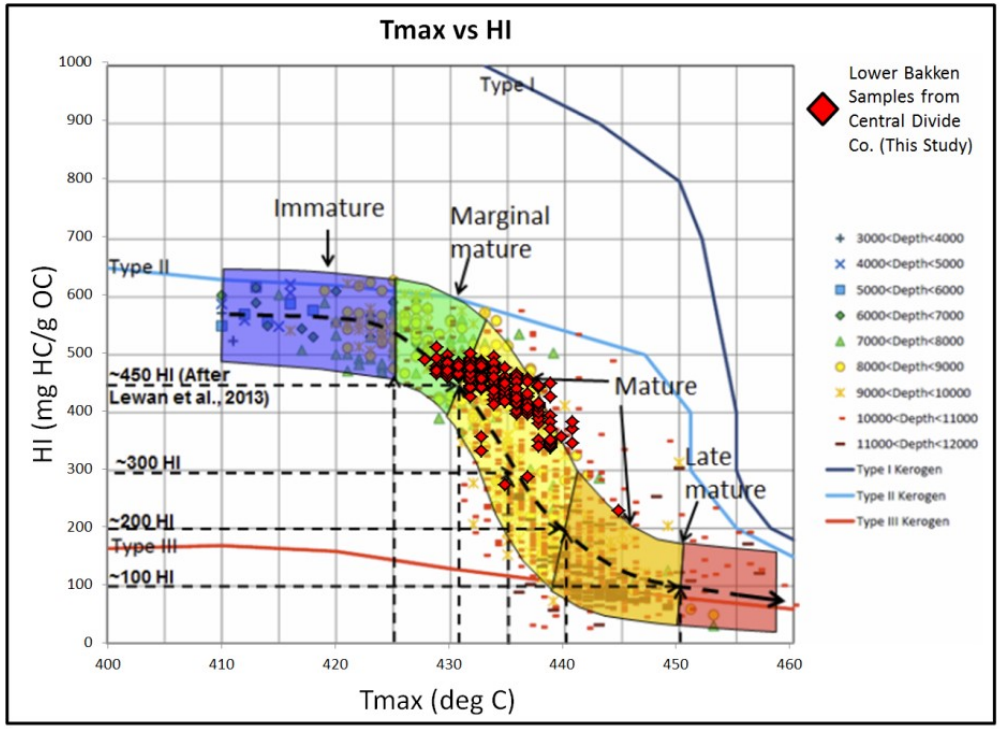
Additional evidence of oil and gas generation is the superb gas shows operators encounter when drilling through the shale.



Lower Bakken Shale Kerogen Conversion

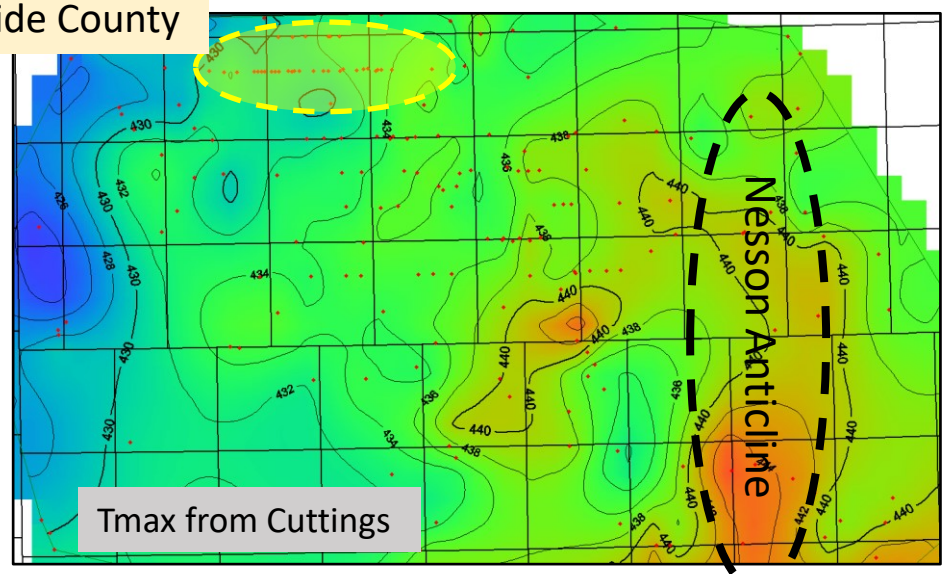
Pyrolysis derived hydrogen index (HI) and Tmax cross-plot

- HI falls as Tmax rises
- Demonstrates that kerogen is converted to hydrocarbons with maturity
- Red dots are Divide County samples showing significant hydrocarbon generation



Modified from Jin (2013)

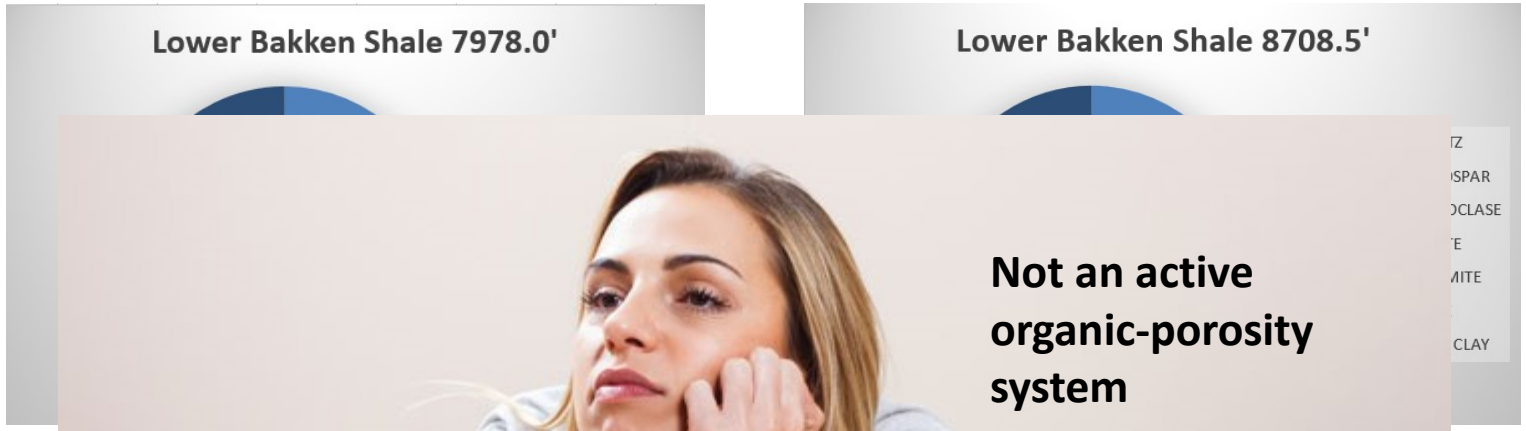
Best Producers in Divide County

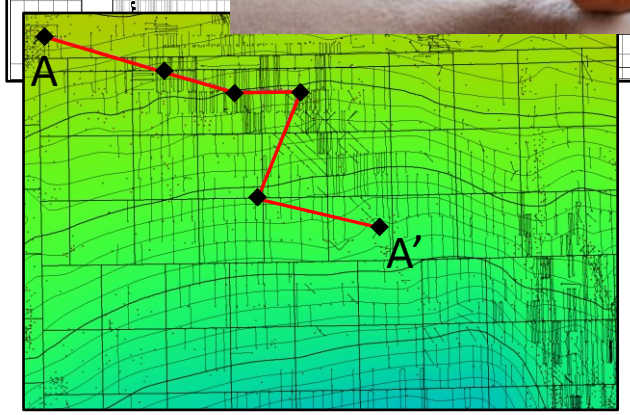


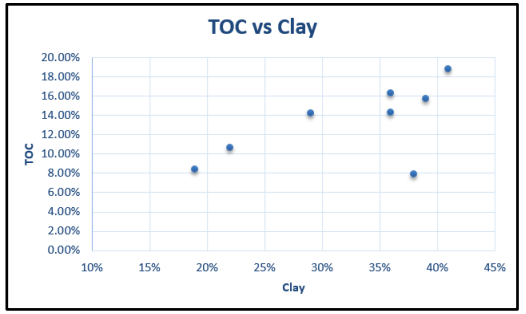
Tmax's in Divide County range from 440 in the SE corner to 420 in the NW corner

- Most of the Lower Bakken Shale in the county generated hydrocarbons
  - Barely (low end of generation)

Lower Bakken Shale Stratigraphy

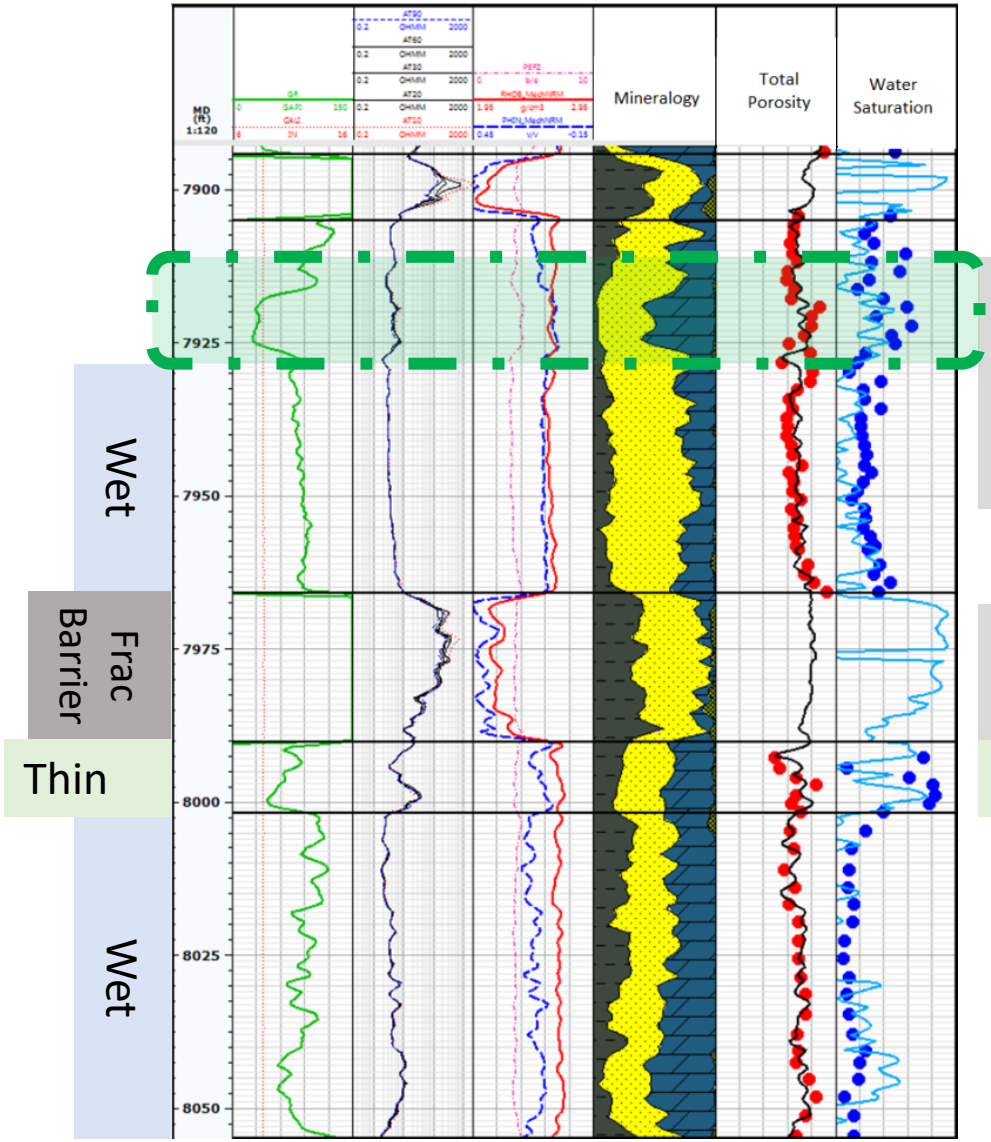






- Lower Bakken Shale TOC correlated positively with modal clay volumes, but not with effective Phi's
- **This strongly suggests Divide County does not have an active organic porosity system**

Where is the Production Coming From?



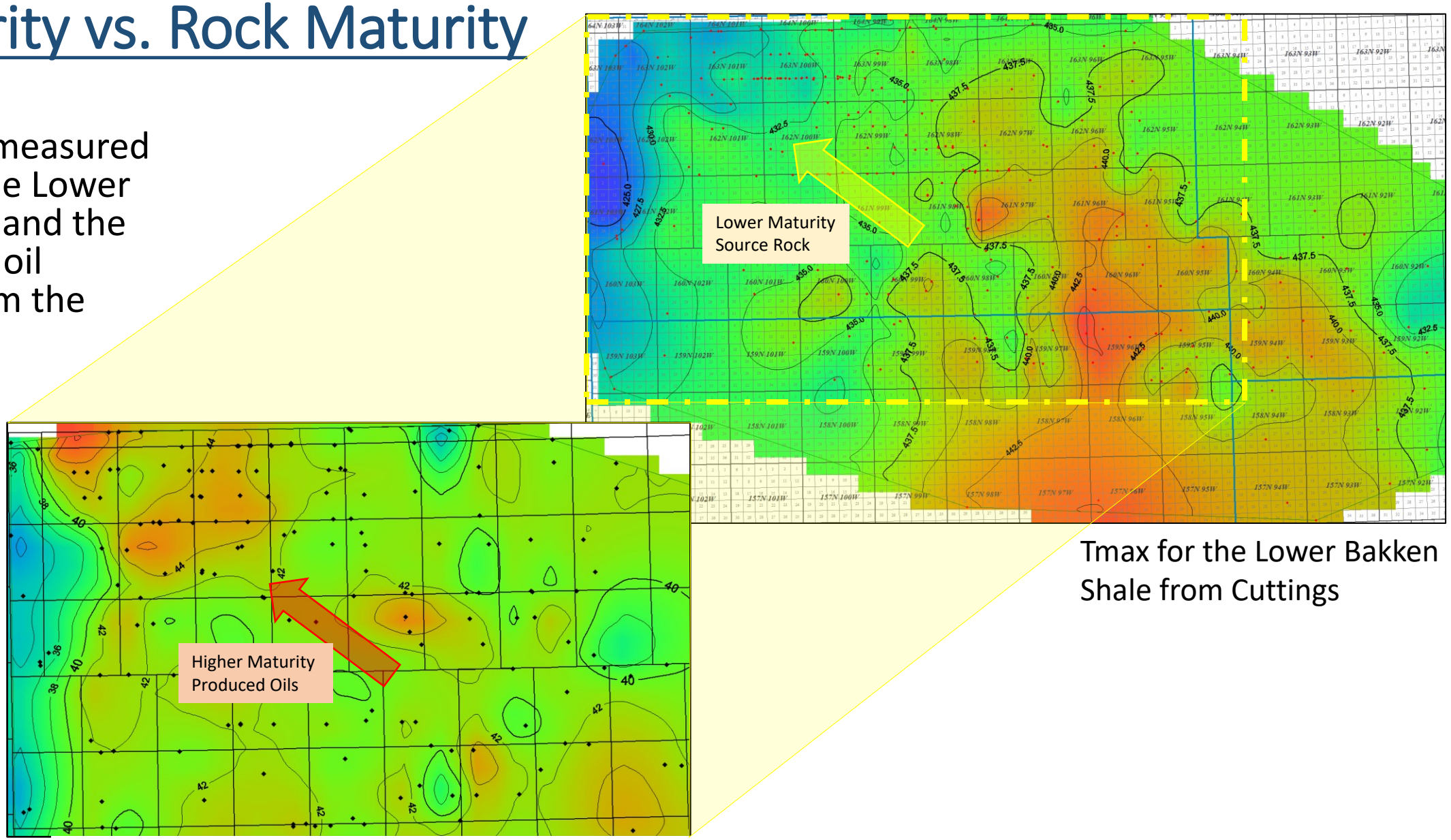
- Possible Effective Reservoir, but
  - Above the frac barrier
  - Higher Sw
  - Still limited Reservoir Volume

Maybe, but probably not

- Not Enough Effective Porosity
  - Classic Frac Barrier
- Not Enough Reservoir Volume

Oil Maturity vs. Rock Maturity

Mismatch in measured maturity in the Lower Bakken Shale and the API gravity of oil produced from the Three Forks



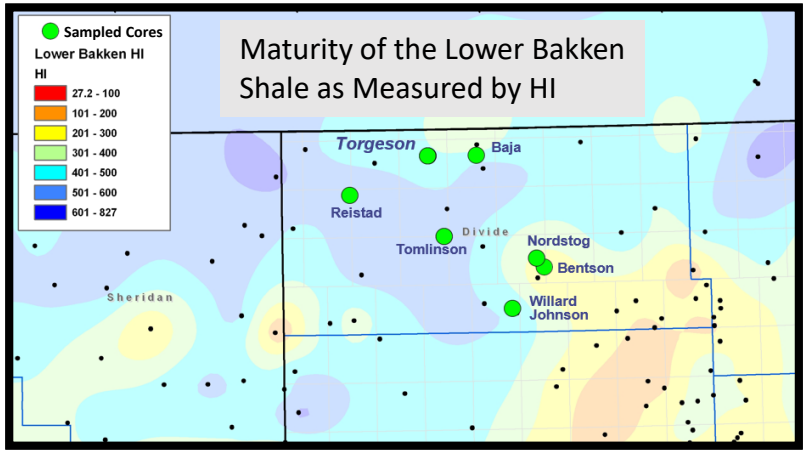
Tmax for the Lower Bakken Shale from Cuttings

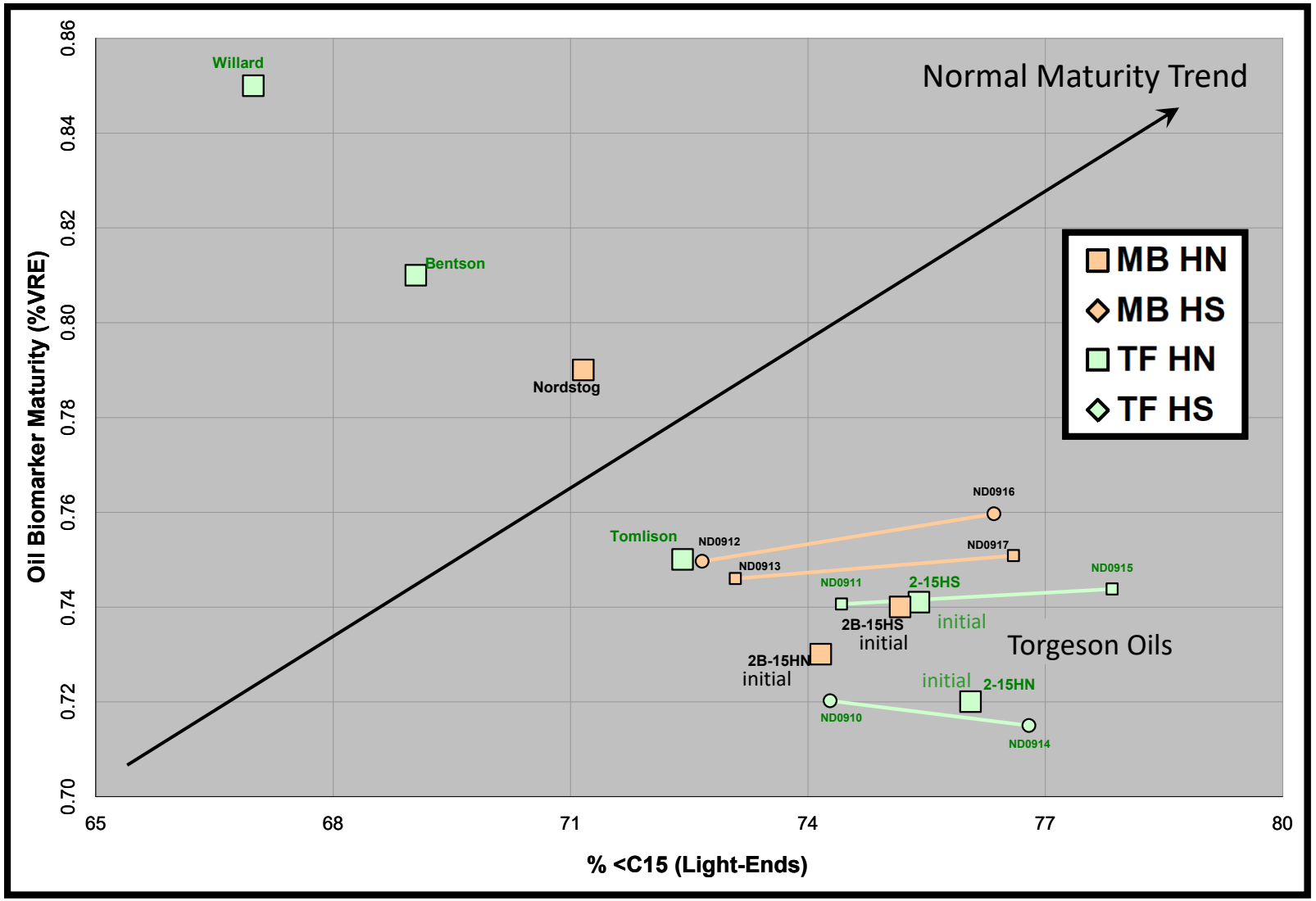
Oil Gravity (API) from Completion Reports

Heavy-End Oil Maturity vs % Light-Ends

Suggests mixing of local and migrated oils

- The oil biomarker maturity represents the maturity of the heavy-end (C15+) components of crude oil
- As the maturity of the source increases, the amount of light-end oil (and API gravity) should increase
    - The exact opposite trend appears to occur with the Divide Co. oils
- The Torgeson reservoirs received additional light oil (biomarker-poor) from much more mature down-dip Bakken sources, mixing with the more locally generated, biomarker-rich oils

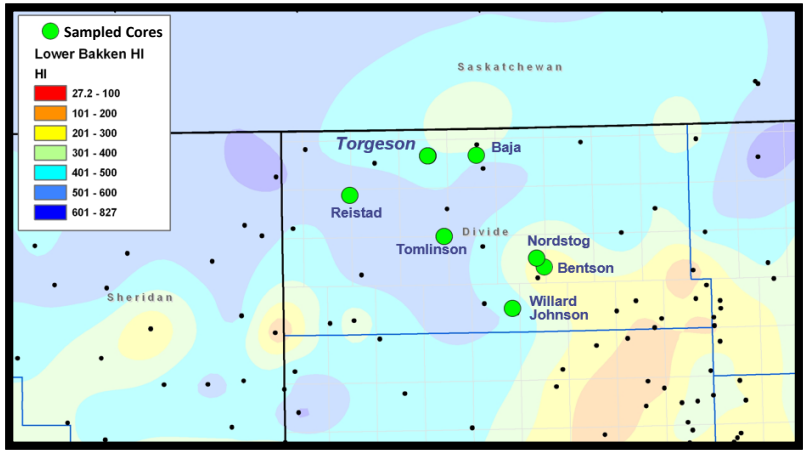


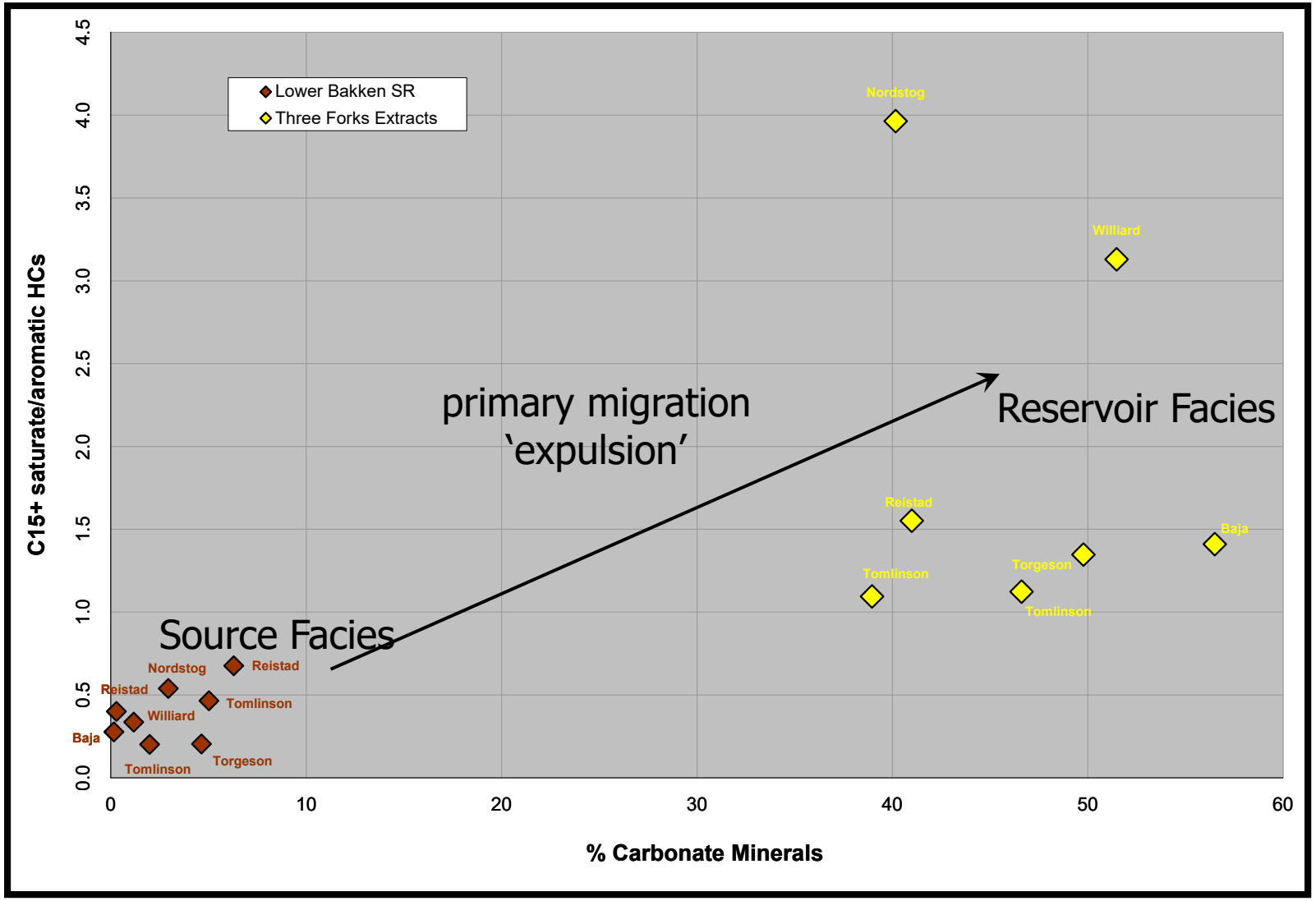


Effects of Expulsion (Migration Happens)

The most polar hydrocarbons stay behind in the Bakken Shales

- As oil is expelled from high TOC/clay-rich source facies to reservoir facies (e.g., the carbonate-rich/no TOC Three Forks), the more polar oil/bitumen components are preferentially left behind since they have a high affinity for the source rock kerogen
- This is especially true for the asphaltenes, but even the aromatic hydrocarbons are reduced relative to the non-polar saturate hydrocarbons

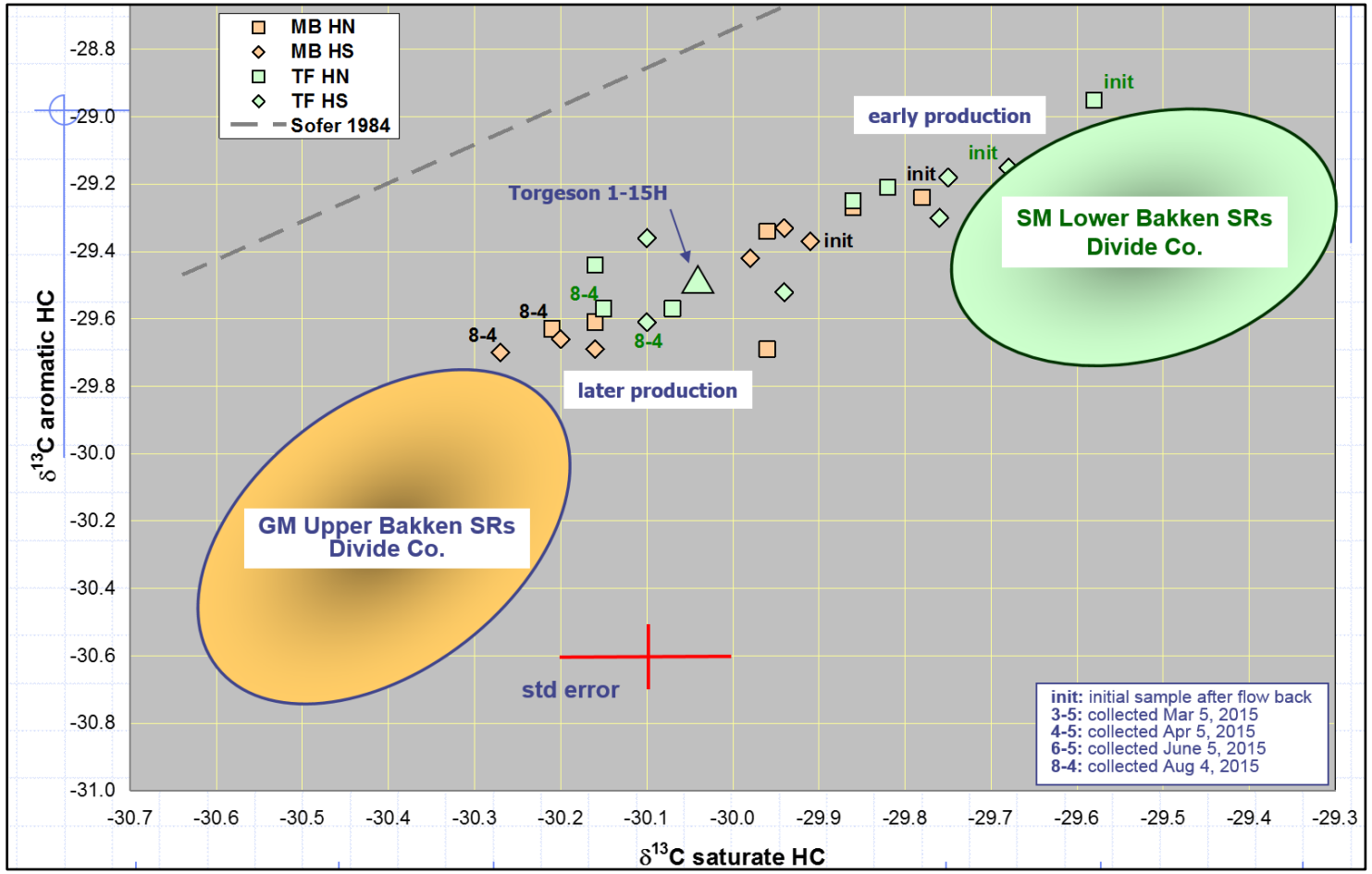




Evidence of Middle Bakken Oils in Three Forks Production

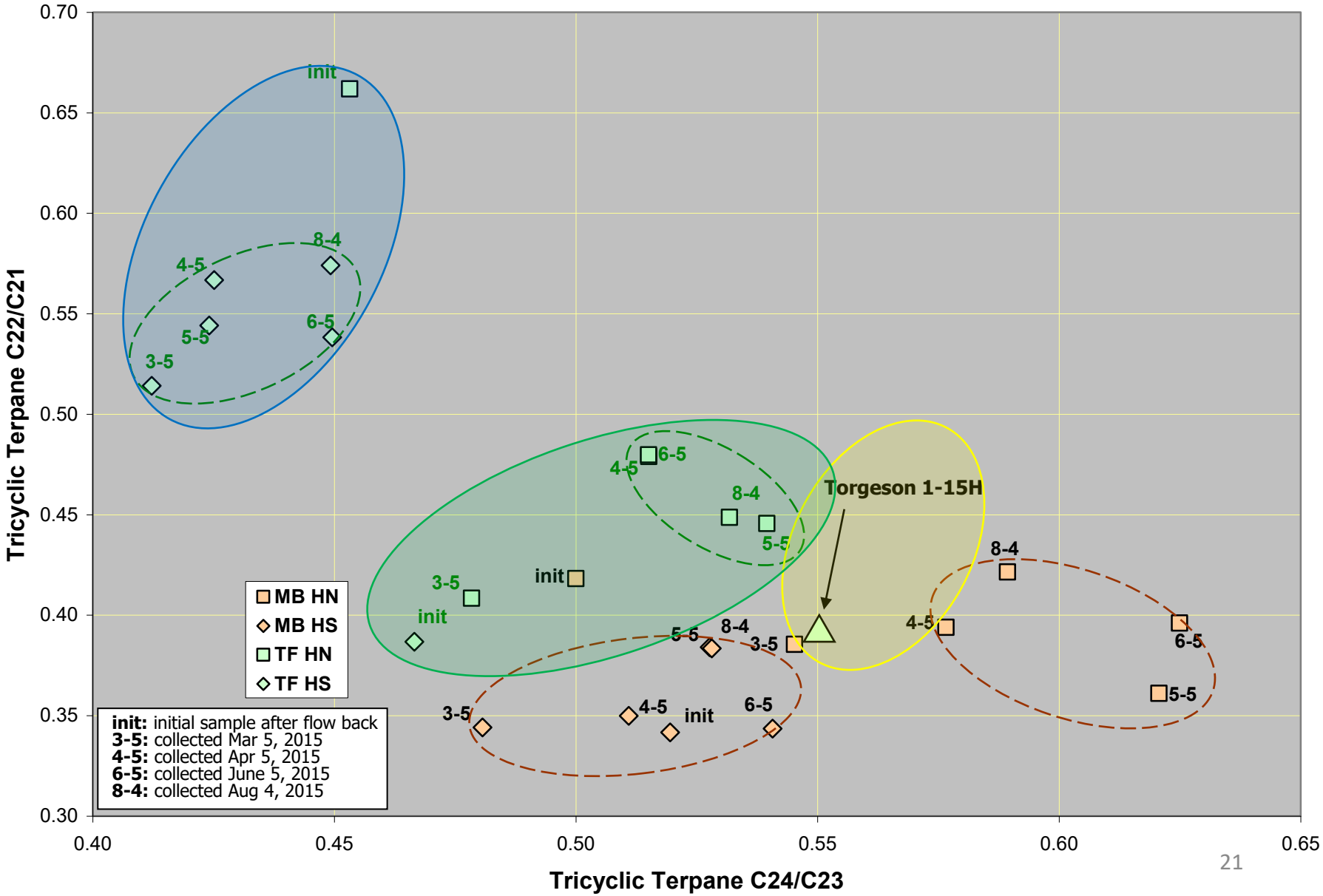
The most polar hydrocarbons stay behind in the Bakken Shales

- Geochemical analysis done through GeoMark to trace produced oils to source rocks and reservoirs supports the connection between Three Forks production and Middle Bakken stratigraphy
- Geochemical markers from Three Forks production become progressively more like Middle Bakken production and extracts over time
  - The parent well, Torgeson 1-15H (a Three Forks big producer) has oil markers roughly equivalent to Middle Bakken production



Three Forks vs. Bakken Geochemical Markers

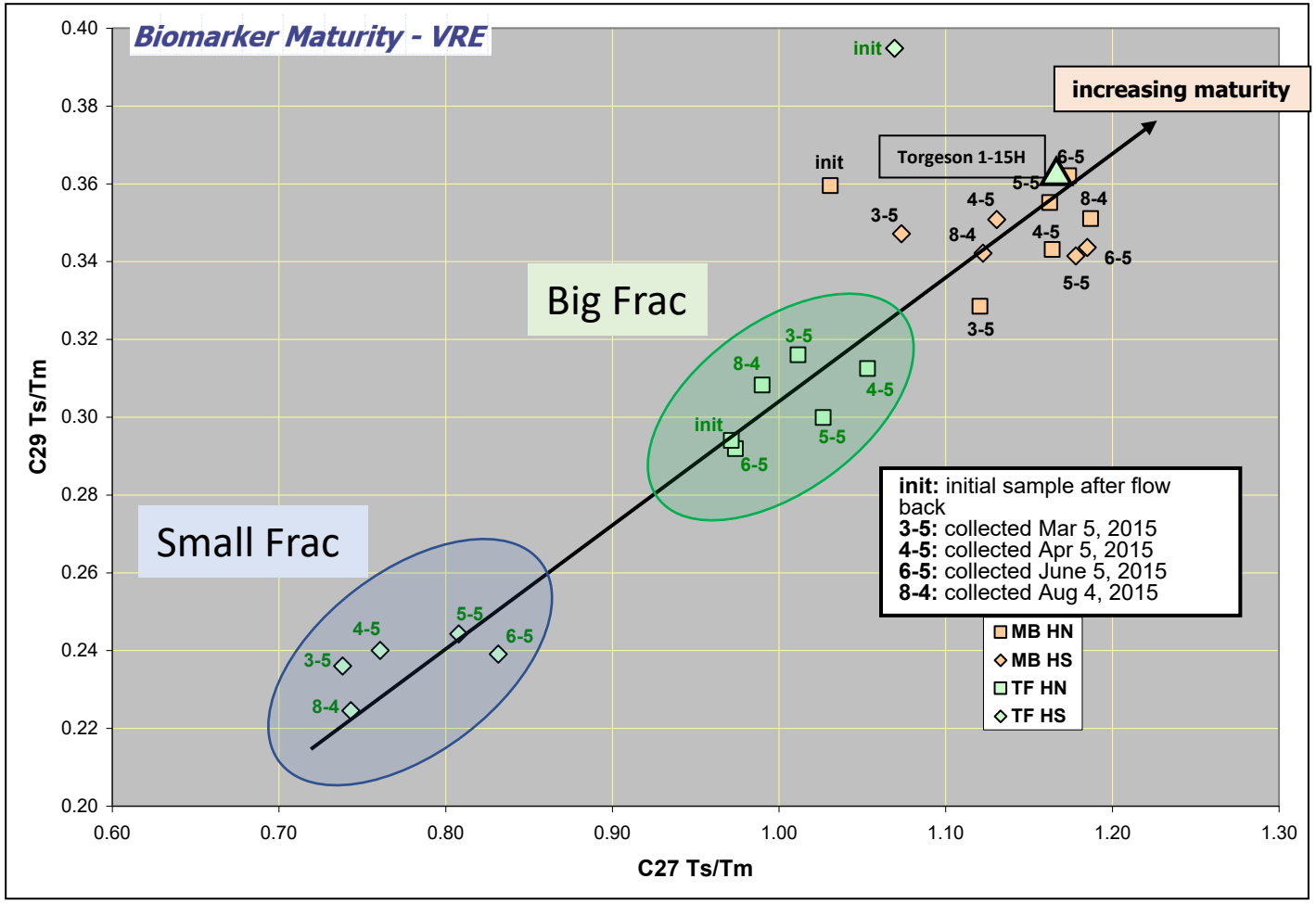
- The Torgeson 1-15H (original horizontal) and 2-15HN (new horizontal with a large frac) plot close to Middle Bakken producer, but the 2-15HS (small frac) plots near Three Forks extracts
- Independent modeling work done by Sanjel showed the 2-15HS did not likely break up into the Middle Bakken due to the type of frac job pumped
  - Low rate, small job, sliding sleeves
- The 2-15HS is also a much poorer producer with a higher water cut



Size of Frac Job Shows Up in Geochemistry

Suggests out-of-zone frac growth and resulting connected reservoirs

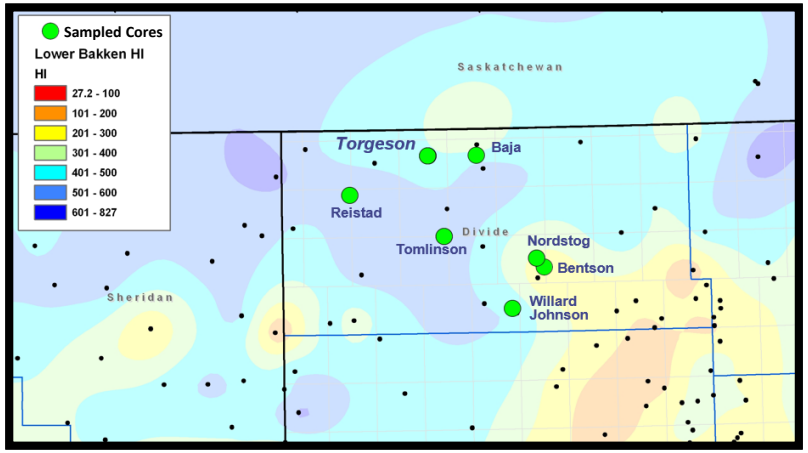
- The big producer, Torgeson 1-15H, has oil markers roughly equivalent to Middle Bakken production
- The 2-15HS (small, low rate frac) produces a less mature oil that is more like the extracts from the Lower Bakken Shale
- The 2-15HN (big, high rate frac) initially produced an oil that had mixed characteristics, and has become more like the Middle Bakken oils over time

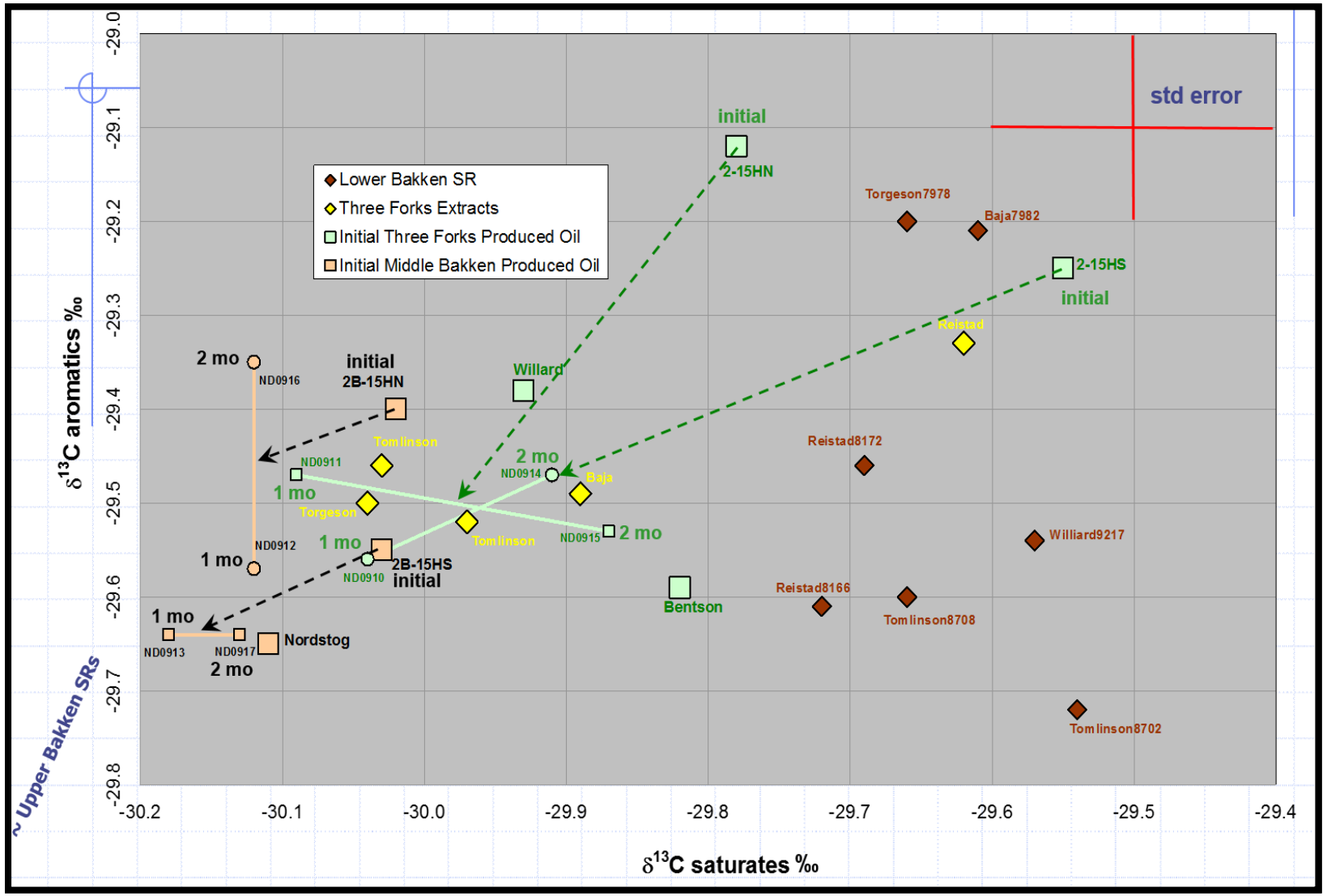


Stable Carbon Isotopes – Production vs. Core Extraction

Production from wells drilled in the Three Forks changes over time

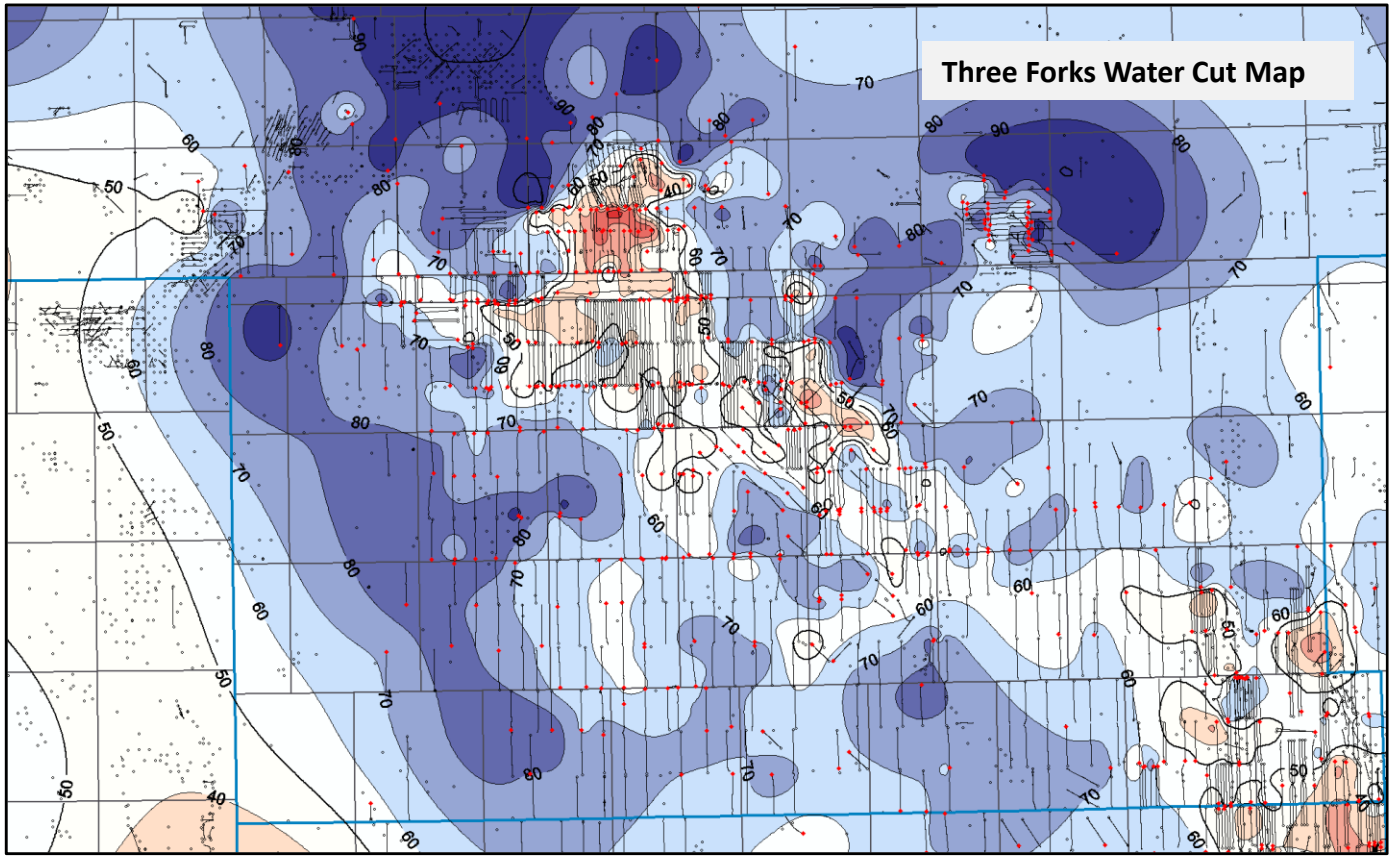
- Isotopic 'time evolution' of Torgeson oils can be observed in the isotopic shifts in the samples collected ~1 mo. and 2 mo. after the initial production
- Three Forks oils from both the Torgeson HN & HS wells appear to have picked-up oil from the Middle Bakken, especially after 1 mo production
- Initial Torgeson oils may also have had considerable contribution from oil in Lower Bakken natural fractures that is diluted upon further production
- Middle Bakken Torgeson oils also acquired a bit more Lower Bakken component at initial production, but this component dropped out quickly





Water Cut Trends in Divide County by Targeted Formation

- Water cut maps for Three Forks and Middle Bakken wells overlie each other perfectly, with both having the lowest water cuts on the structurally highest point of the trend
    - The lowest water cuts are north of the border in Saskatchewan

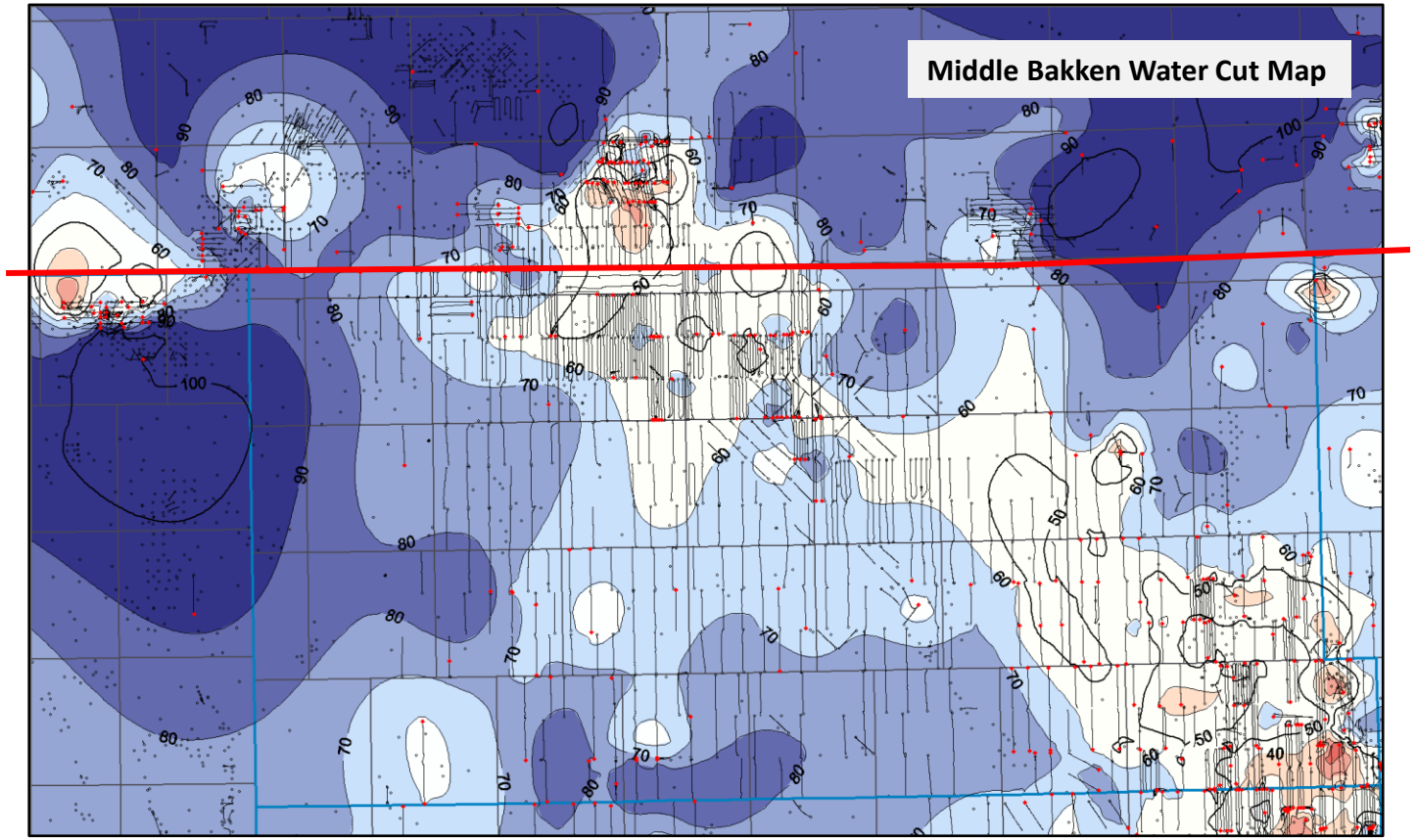


Percentage of Water in the Total Produced Fluids for Each Well

90%+ 80% 70% 60% 50% 40% 30% 20% -10%

Water Cut Trends in Divide County by Targeted Formation

- Water cut maps for Three Forks and Middle Bakken wells overlie each other perfectly, with both having the lowest water cuts on the structurally highest point of the trend
  - The lowest water cuts are north of the border in Saskatchewan
  - The artificial data cut-offs at the US-Canada border kept me from recognizing this obvious trend for years

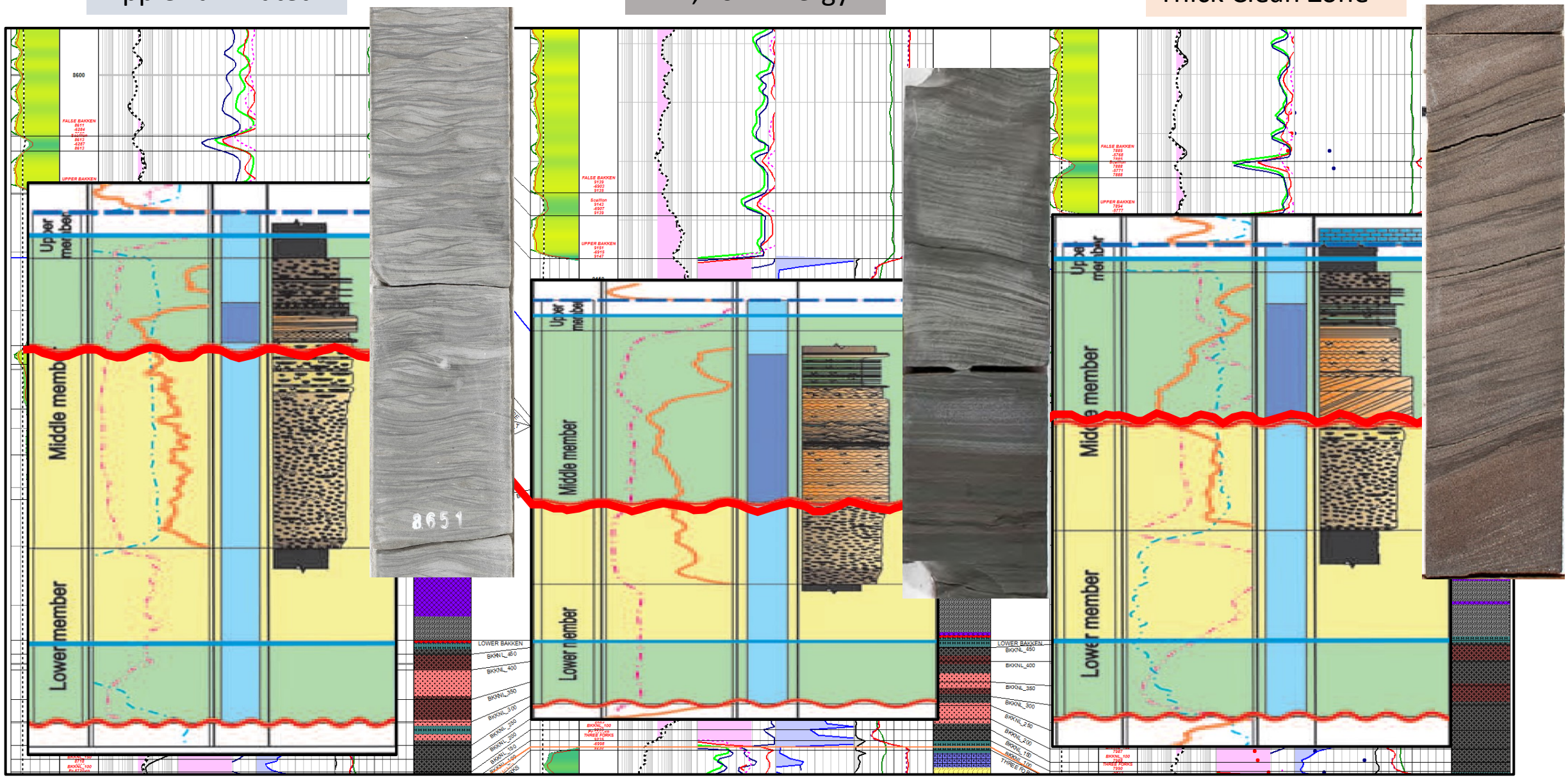


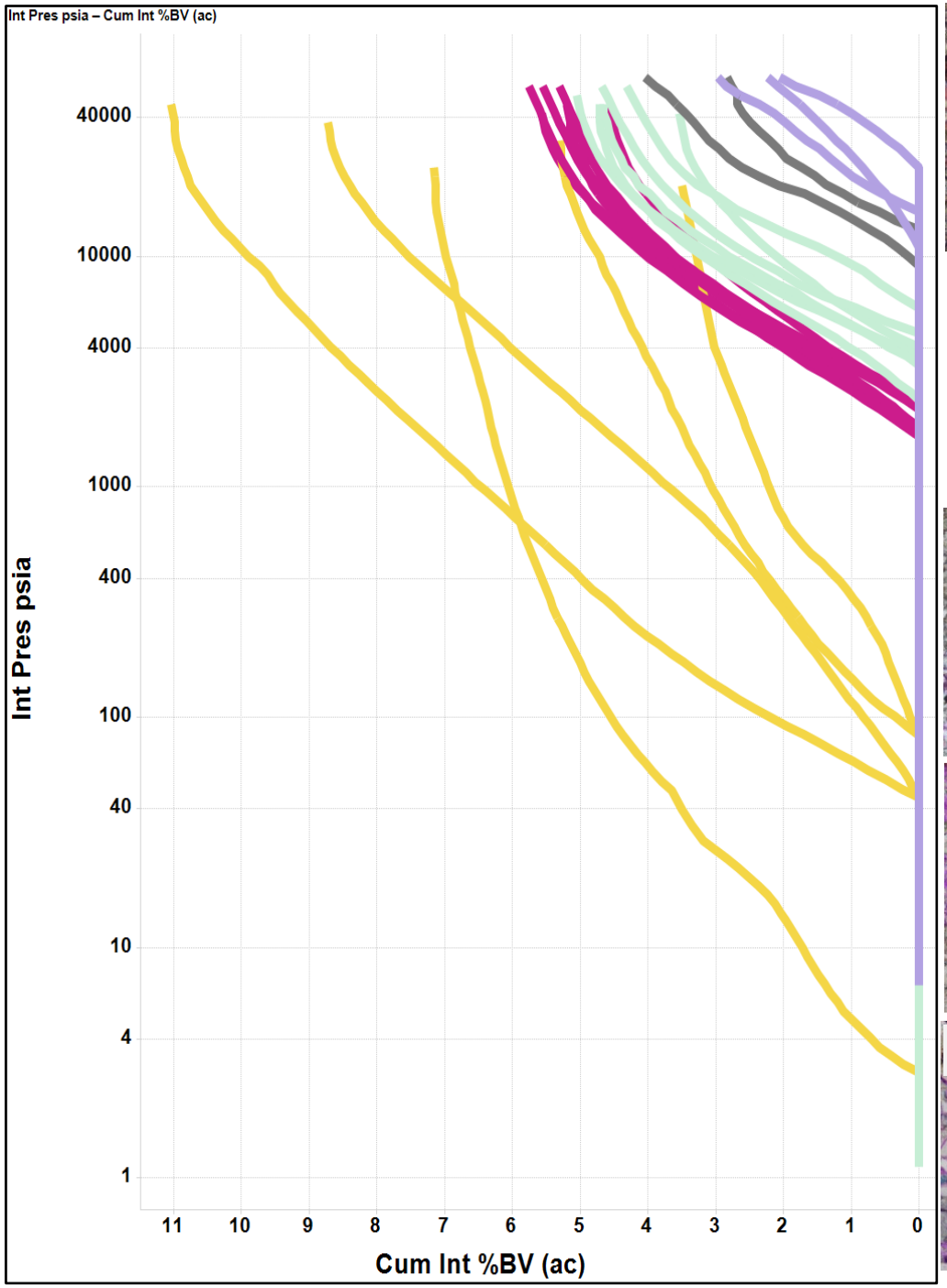
Divide County Stratigraphy

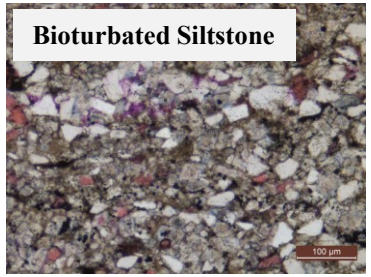
Ripple Laminated

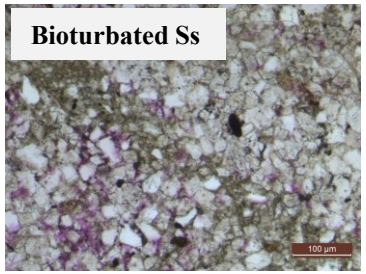
Thin, Low Energy

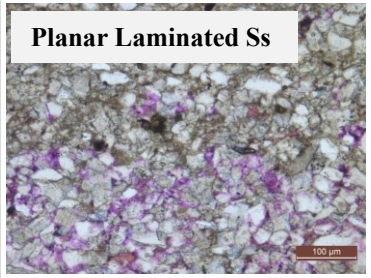
Thick Clean Zone

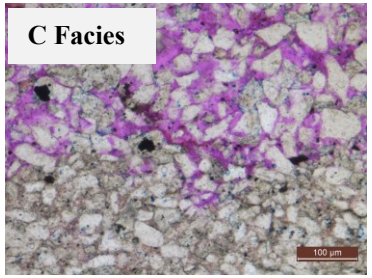


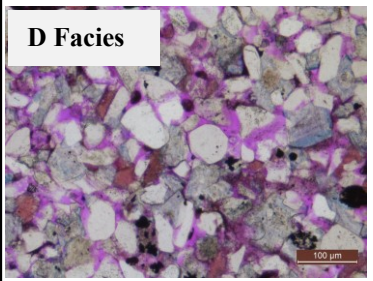












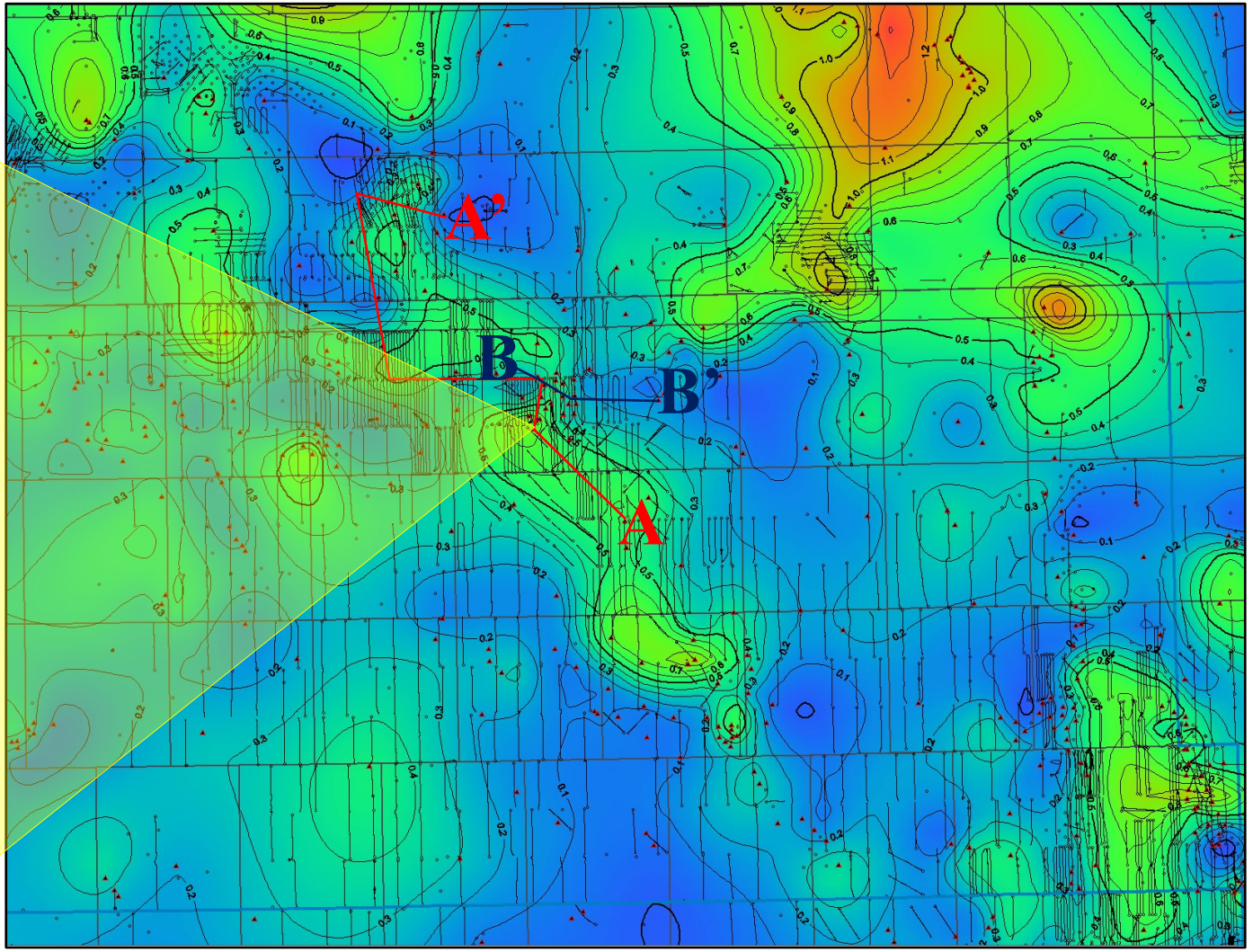
Reservoir Quality

- Capillary pressure (MICP) data is a relatively cheap method to identify the most effective Bakken reservoirs and run comparisons
- It is also a great reality check on which rocks are likely to be producing reservoirs
- If a sampled rock does not have significant Hg intrusion until 10,000 psi, and likely reservoir pressures are less than 3,000 psi, it is very unlikely that it will contribute much production

Middle Bakken D Facies PhiH Map

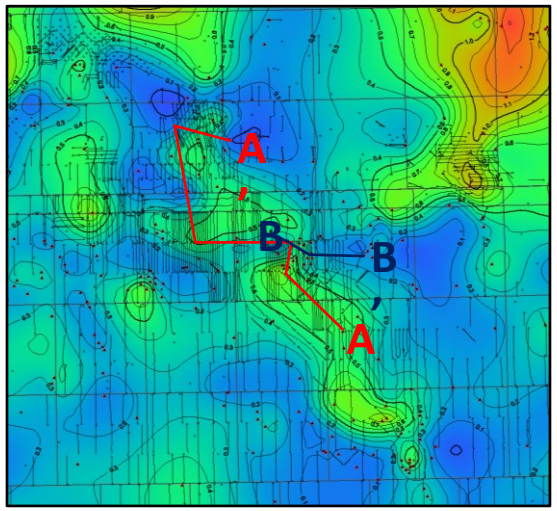
- A porosity*height (PhiH) map of the Middle Bakken D facies
- The map demonstrates an area of high porosity rock
- It corresponds to
  - Higher oil production in ***both*** Three Forks and Middle Bakken horizontal wells
  - Lower water cuts in both formations
  - Lower bubble points

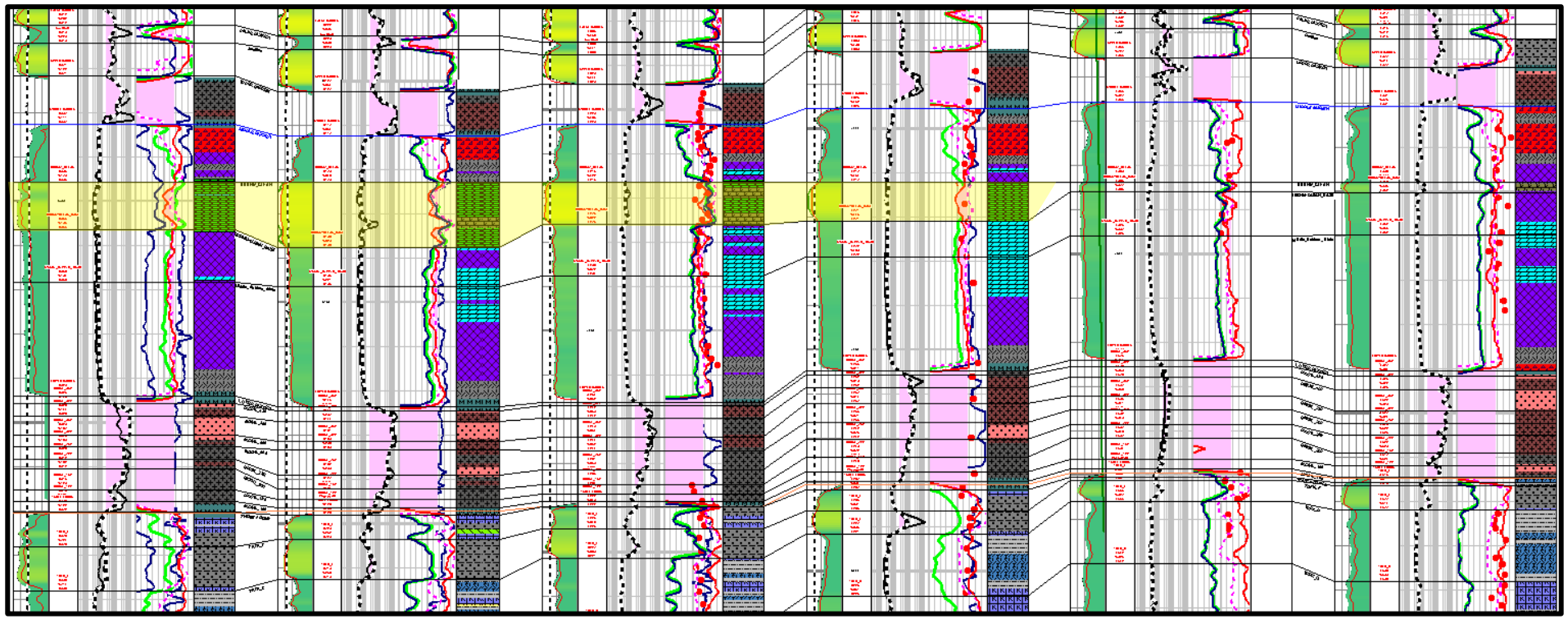
D Facies from Tomlinson core



Cross-Section of the D Facies

A north-south cross-section clearly shows the Middle Bakken D facies through the center of Divide County and the strat-trap pinch-out in Saskatchewan

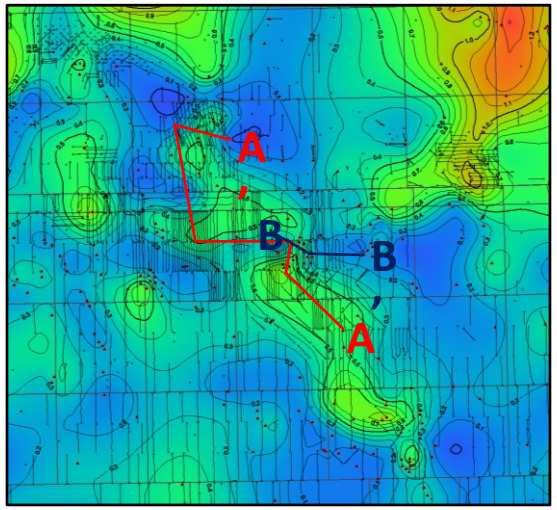


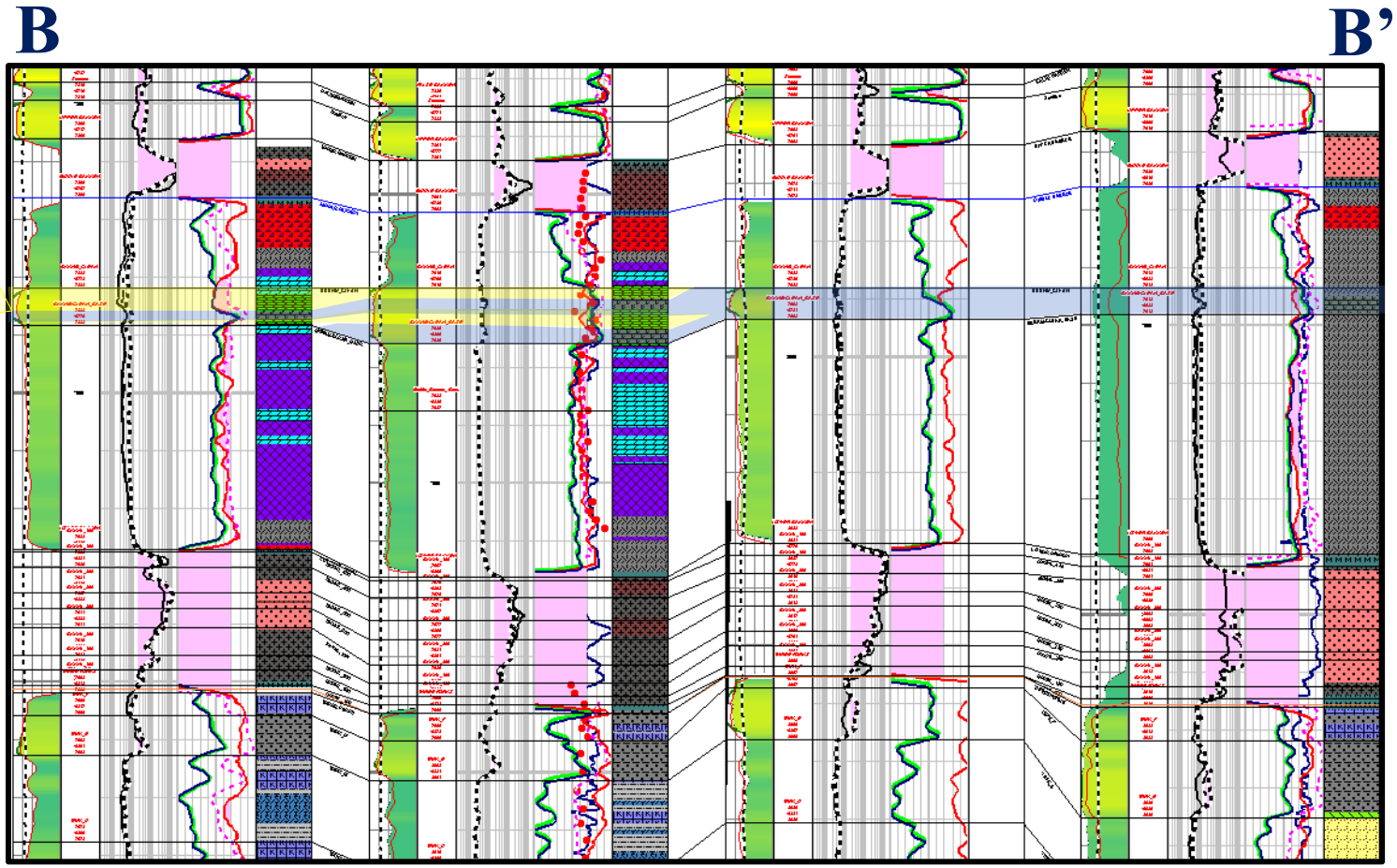


Cross-Section of the D Facies

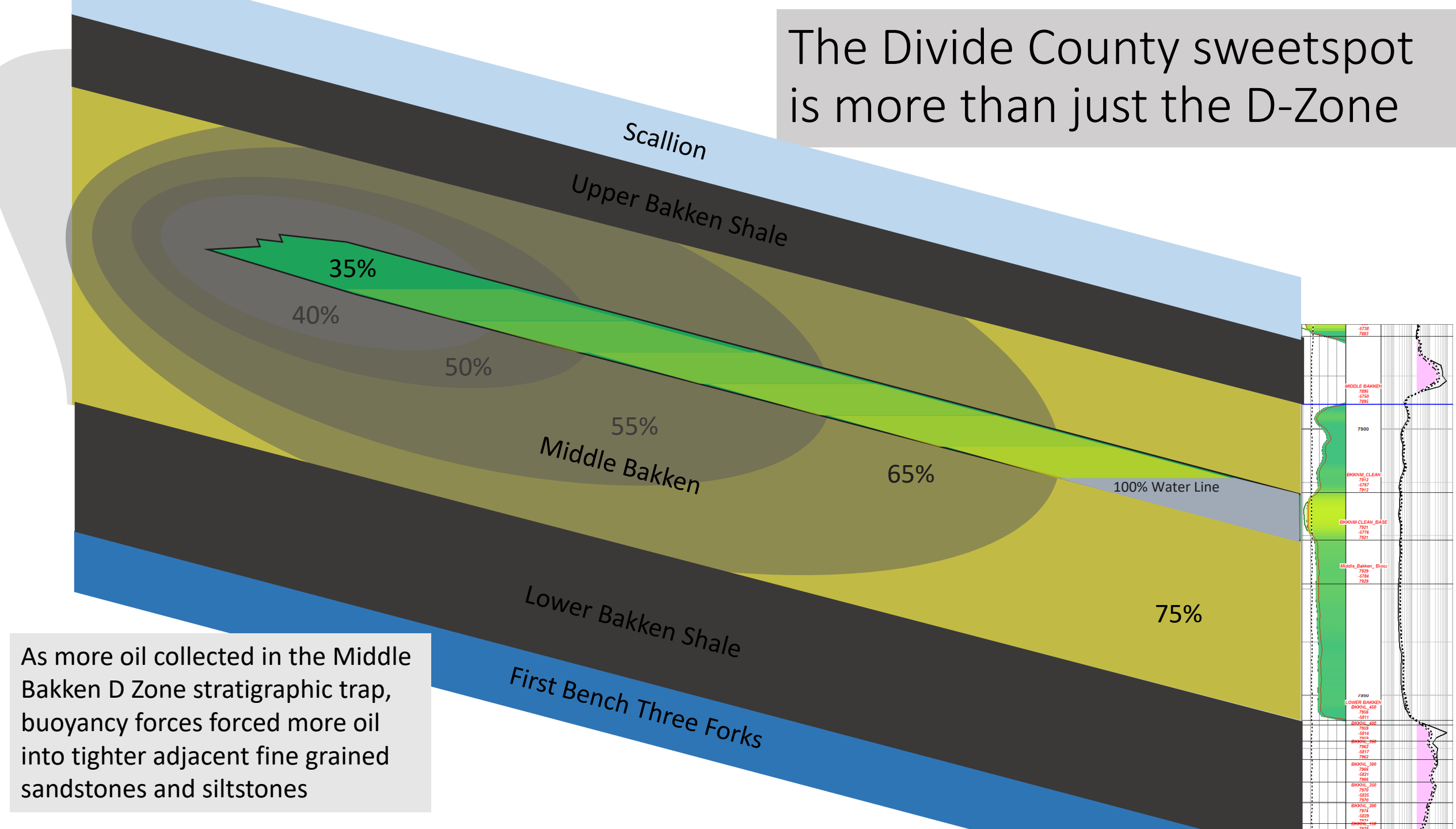
D Facies from Baja core

These cross-sections demonstrate the lateral continuity of the porous D zone and the sealing facies





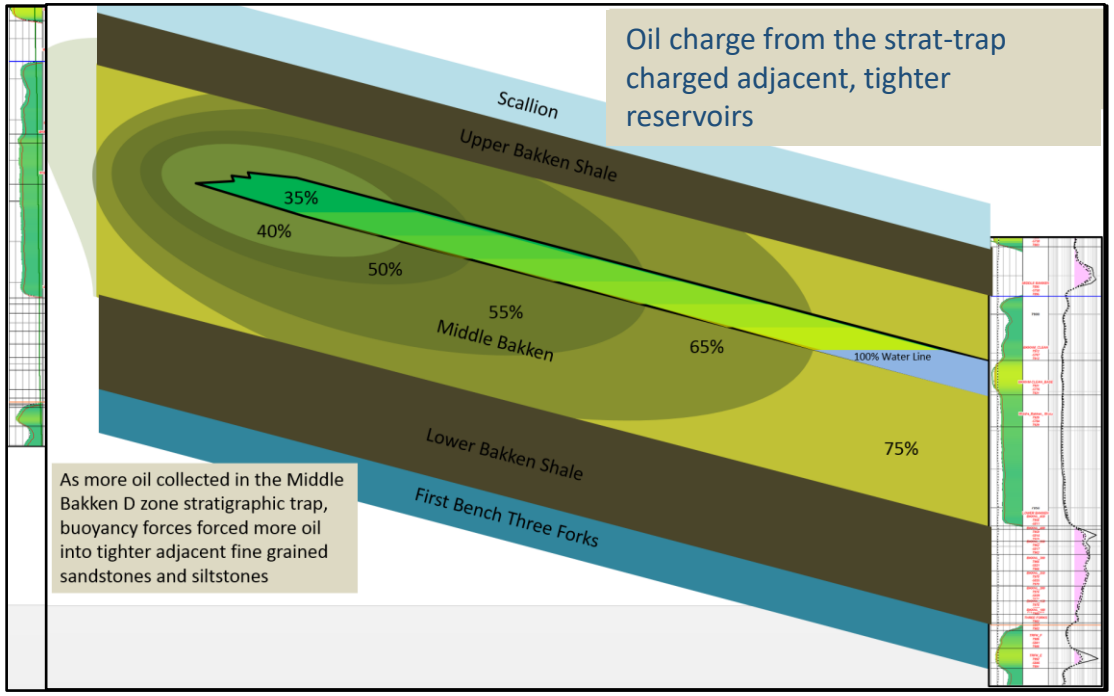
The Divide County sweetspot is more than just the D-Zone

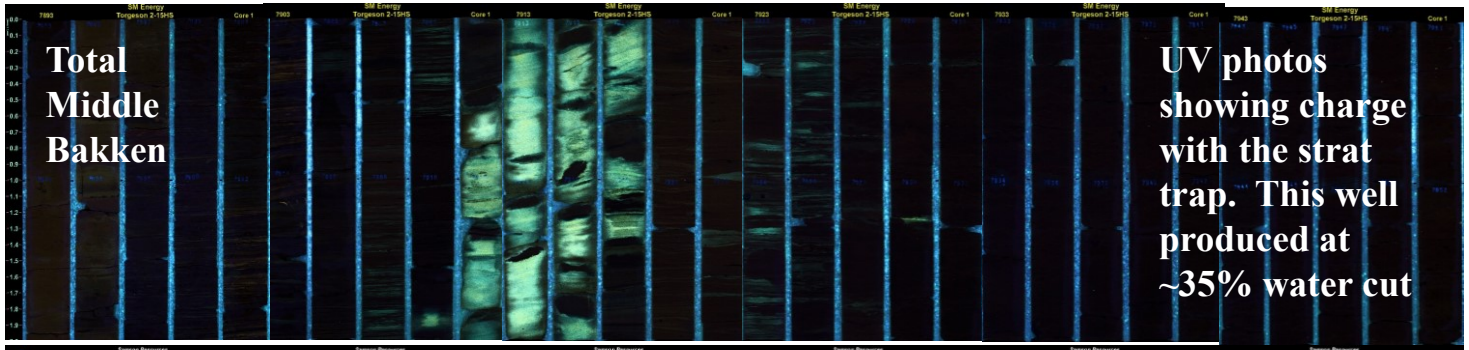


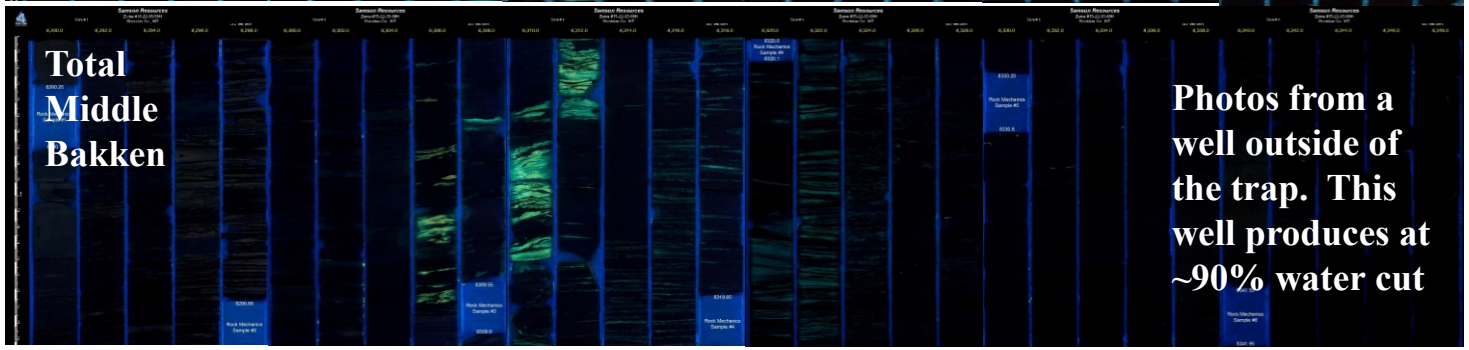
As more oil collected in the Middle Bakken D Zone stratigraphic trap, buoyancy forces forced more oil into tighter adjacent fine grained sandstones and siltstones

Model for the Divide County Stratigraphic Traps

- Several different facies in the Bakken/Three Fork petroleum system form strat traps that have caught oil migrating up-dip out of the basin center
- As oil pooled in the traps, buoyancy forces raised oil saturations in tighter adjacent rocks

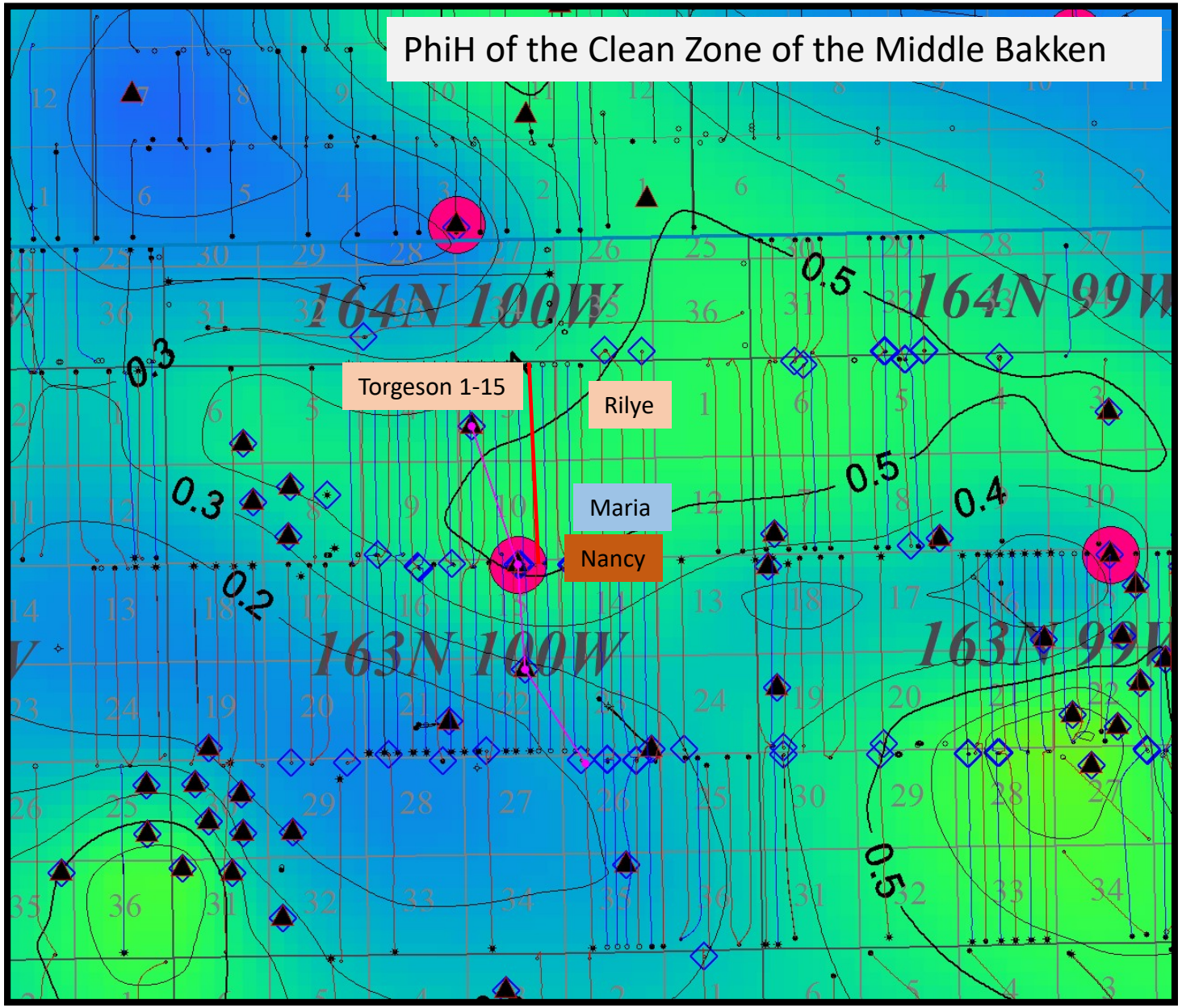






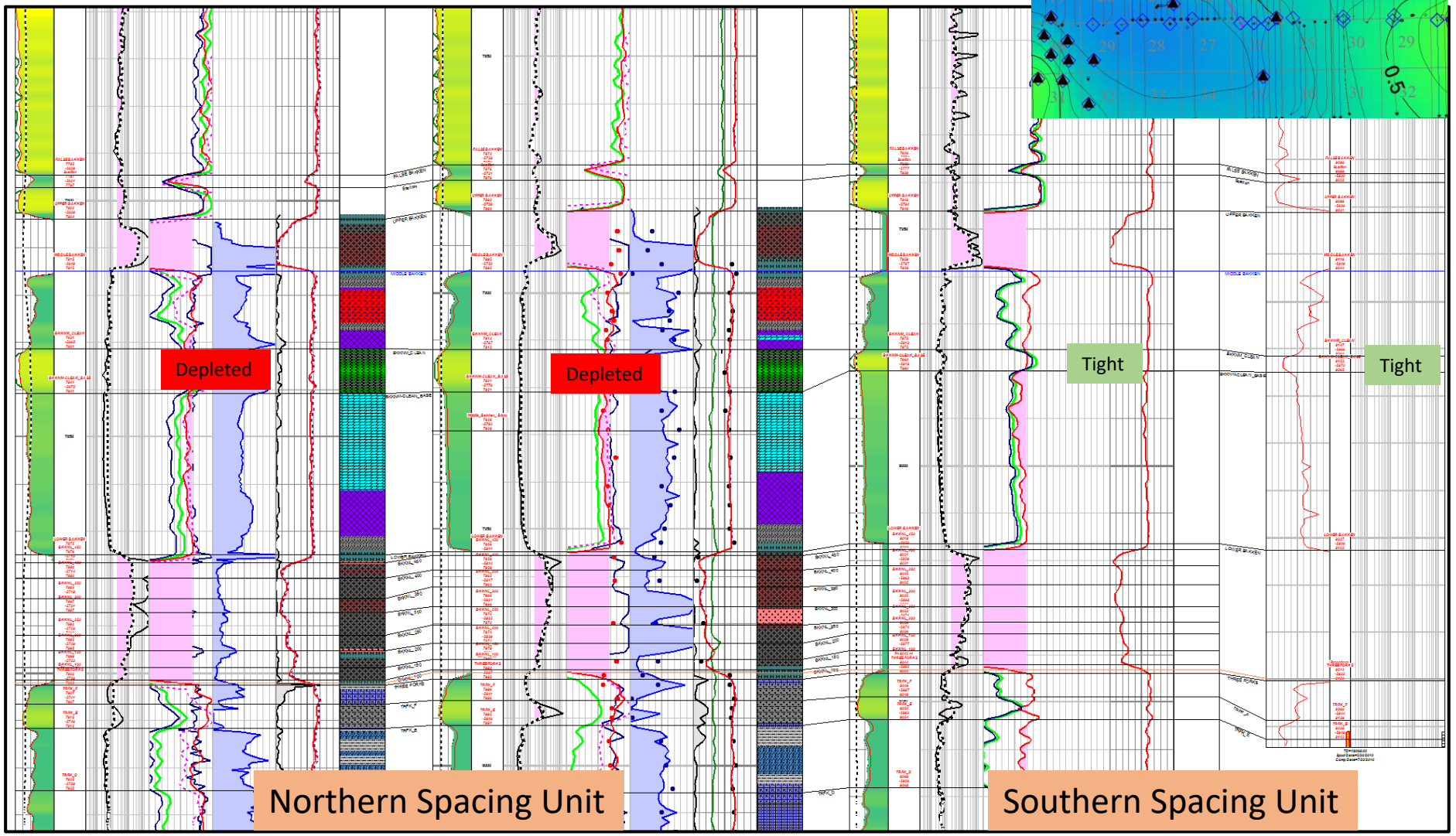
Common Reservoir

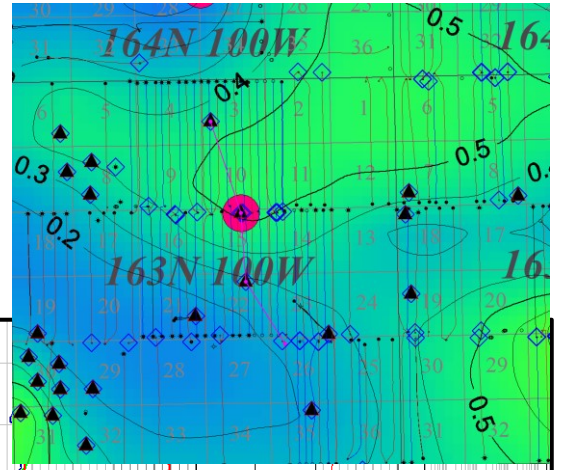
- Further evidence of Middle Bakken reserves being produced by Three Forks wells can be found in pore-pressure data
- Large Three Forks wells are depleting the D facies of the Middle Bakken
  - Not the Three Forks first bench
- Pressure tests in the Maria and Rilye horizontals show the clean zone of the Middle Bakken to have significant depletion (1953 psi)
- Three Forks is much less depleted, even between big wells
  - The Nancy had ~3879 psi (close to virgin pressure)



Where is the depletion?

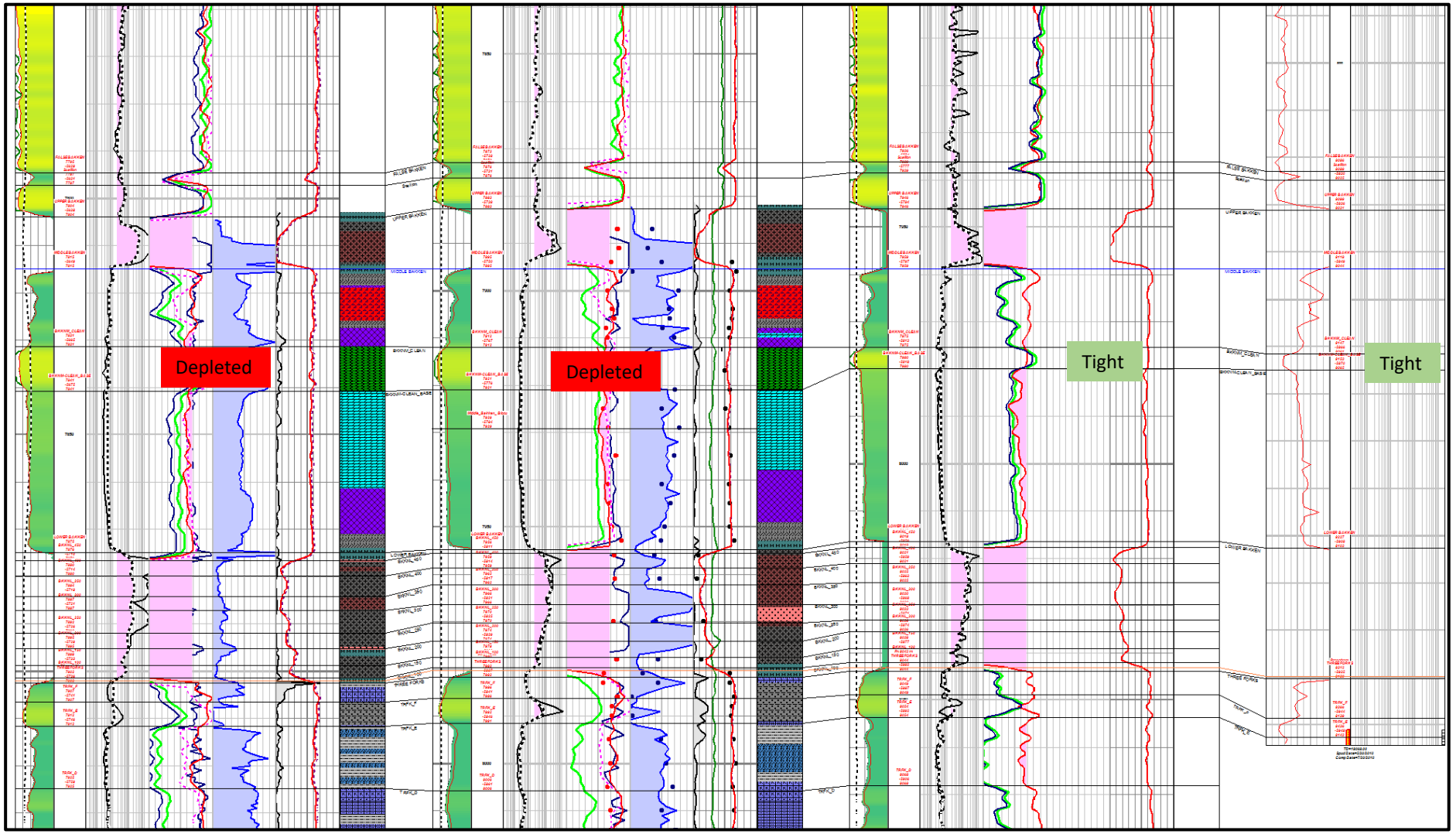
- The D facies has the best flow characteristics and depletes first
  - Northern spacing unit
- Middle Bakken intervals with no porous C or D facies deplete from the tighter siltstones and Three Forks dolostones
  - Southern spacing unit





Important Spacing implications

- The clean zone has the best flow characteristics and depletes first
- Middle Bakken intervals with no porous clean zones deplete from the tighter siltstones and Three Forks dolostones



- Details matter in the Bakken/Three Forks system
  - Spend the time and money to look at the rocks!
  - Averaging reservoir properties hides important risks and opportunities
- Geology doesn't respect political boundaries, and neither should you
- Calcite cementation in the Middle Bakken is a major risk factor
  - Where clean sandstones and siltstones are adjacent to carbonate grains, intergranular porosity is occluded, and the reservoir is ineffective
  - Authigenic clay is present where porosity is preserved
- MICP data, tied with conventional core analysis, is a powerful tool in identifying effective Bakken reservoirs
  - Cross-plots of MICP PhiH data and production is the gold standard
- Reservoir pressure measurements can save you a lot of money

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