PS Stratigraphic Controls on Reservoir Properties, Cretaceous Niobrara Formation, DJ Basin, Colorado*

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Please refer to companion audio-video article presented by the Marshall Deacon, prepared with Robert Lieber, and entitled "Integrated Reservoir Evaluation as a Means for Unlocking Maximum Resource Value in an Unconventional Reservoir: Niobrara Formation, DJ Basin, Colorado," Search and Discovery Article #110168 (2013).

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Abstract

The Cretaceous Niobrara Formation produces oil and gas from the well studied chalk/marl cycles deposited in the Western Interior Cretaceous (WIS) Seaway. Despite relatively easy subsurface correlation, the problem of understanding reservoir property distribution persists. We evaluate the correspondence between depositional facies, cycle stacking pattern and reservoir characteristics, such as porosity, permeability, wetting phase, and brittleness.

This work follows detailed facies delineation resulting from our analysis of twelve slabbed cores through the Niobrara interval in the DJ Basin. Facies characteristics were defined conventionally (lithology, sedimentary structures, ichnofabrics), enhanced with petrographic analysis and SEM imaging. Facies and sedimentologic data were captured quantitatively using WellCAD core description software. We then integrated facies and cycle data at two scales: 1) basin scale, by detailed correlation and mapping the extent of facies tracts within chronostratigraphic units, and 2) reservoir scale, by processing well logs with a fully integrated petrophysical model, calibrated with the depositional facies. Both raw and processed log data crossplots yielded reasonable relationships with depositional facies, although some features remain underdetermined using conventional log-data suites.

Regionally, several sequences and their associated systems tracts were defined. Within sequences, lateral shifts in facies tracts occur at cycle boundaries, corresponding to sea-level- and climate-driven changes in ocean circulation pattern. Increasingly open marine conditions ("transgression") resulted in widespread 'chalking' cycles, whereas increasingly restricted marine conditions ("regression") indicated by

increasing clay-rich fluvial detritus resulted in regional and local ‘marling' cycles. Aggradational cycle turnarounds are associated with two important facies - the most favorable reservoir facies and highest source-rock facies. At chalking-to-marling turnarounds, reservoir facies occur interbedded with thin organic-rich zones having a crinkled, microbial mat-like aspect.

Integration of this facies- and sequence-based model resulted in an improved understanding of the controls and predictability of Niobrara reservoir performance.

Reference Cited

Blakey, R., 2006, North American Paleogeographic Maps, Late Cretaceous (85 Ma): North Arizona University [now Colorado Plateau Systems, Inc.]. Website accessed July 27, 2013. http://www2.nau.edu/rcb7/namK85.jpg

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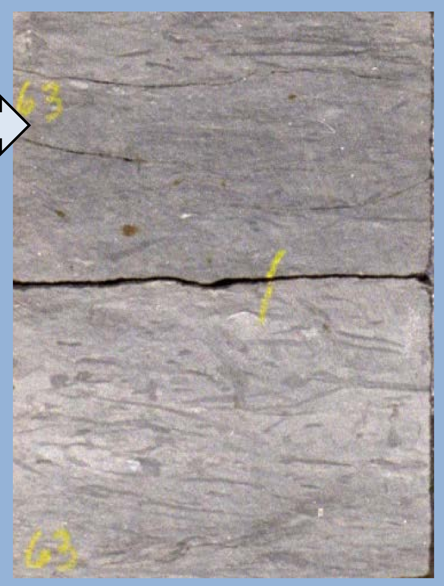
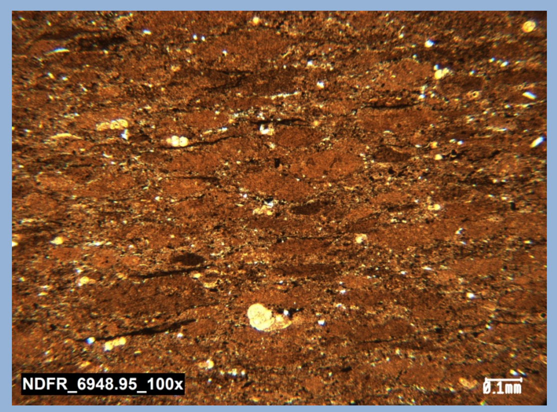
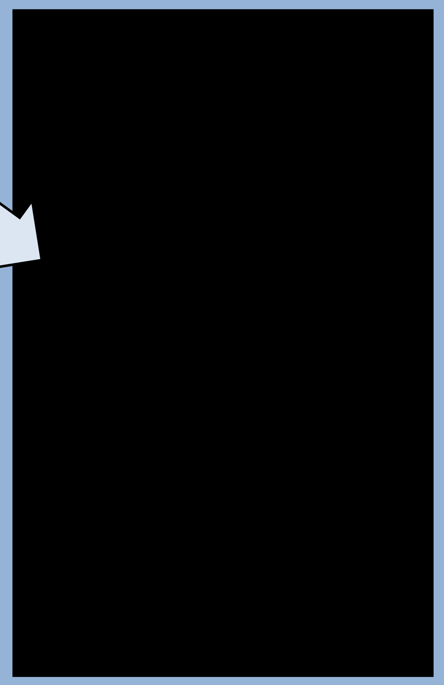
DJ Basin study area in the Western Interior Cretaceous Seaway.

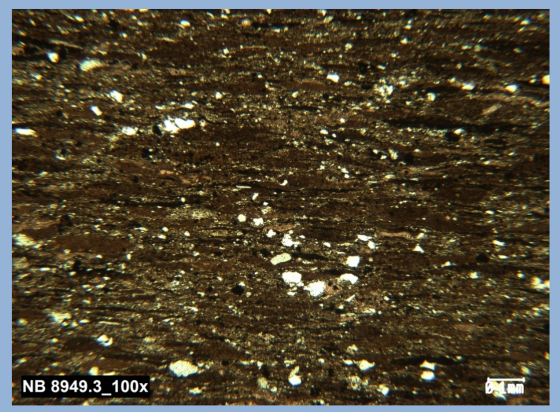
Facies Identified in Core Study

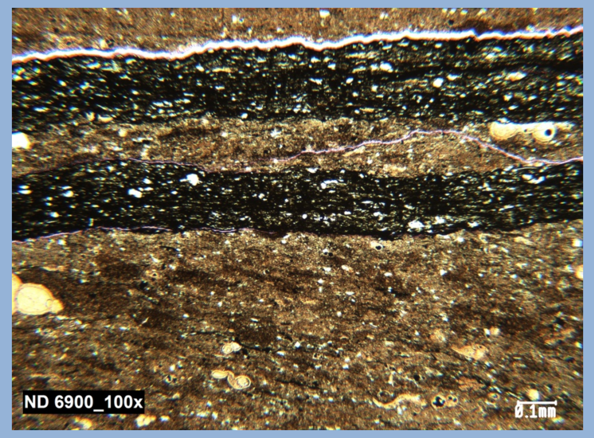
Burrowed Chalks/Marls	Bioturbated Chalk (coccolith biomicrite and coccolith-rich fecal pellets)
	Bioturbated Marly Chalk
	Bioturbated Chalky Marl
	Burrowed Slightly Chalky Marl
Laminated Chalks/Marls	Laminated, Burrowed Chalk-Marly Chalk
	Laminated, Burrowed Chalky Marl
	Laminated Chalky Marl (and rare thin marly chalk)
Alternating Beds: Burrowed/Laminated	Interbedded Bioturbated/Laminated Marly Chalk
	Bioclastic Alternating Bioturbated/Laminated Marly Chalk
	Alternating Bioturbated/Laminated Marly Chalk
	Alternating Bioturbated/Laminated Chalky Marl
"Crinkly"-Laminated Chalks/Marls	**Crinkly-Lam** Bedded Chalk and Marly Chalk
	Alternating **Crinkly**-laminated/bioturbated Marly Chalk and Chalky Marl
	(Lump with above) **Alternating -- Crinkly**-Laminated Burrowed Marly Chalk



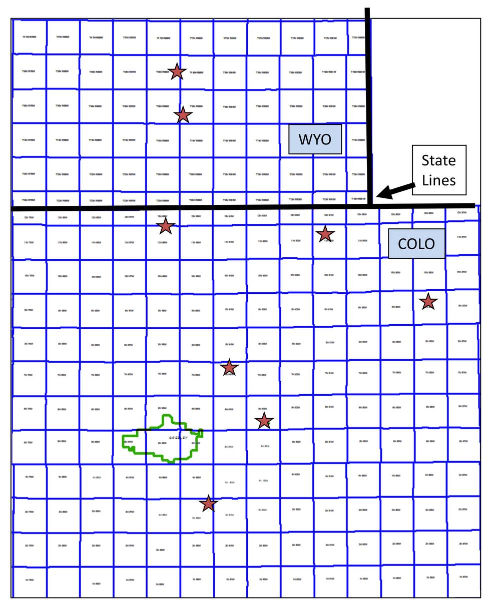








Rock Typing in Unconventional Reservoirs

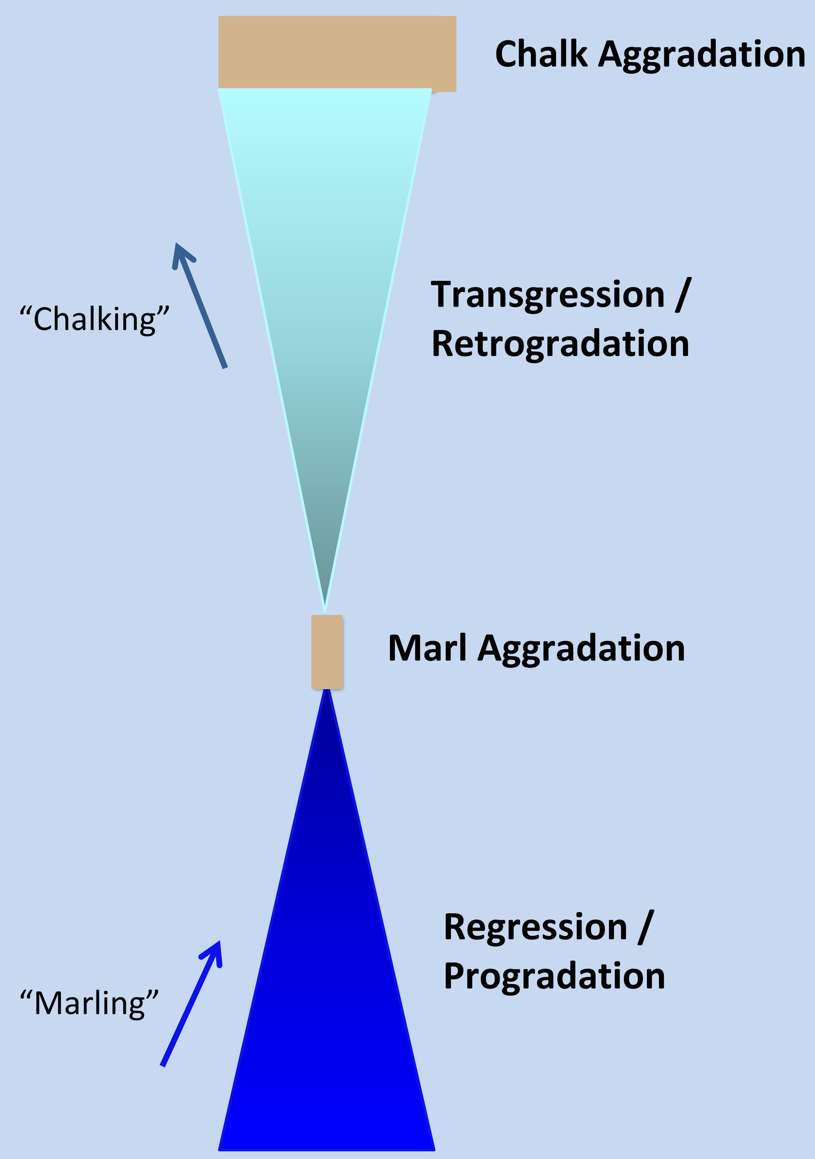


- Complete Niobrara cores in 8 new wells
- 18 Facies or Rock Types delineated from core
- Rigorous core analysis (TRA)
- Develop Petrophysical Model
- Tie to deliverability

Rock Types Used in Petrophysical Analysis

Facies Name	Numeric Facies Code
Crinkly-lam bedded Chalk-Marly Chalk	1
Bioturbated Chalk	2
Interbedded bio/Lam Marly Chalk	3
Alternating Bio/Lam Marly Chalk	4
Bioclastic Alternating Bio/Lam	5
Bioturbated Foram Packstone	6
Alternating Crinkly/Bio Lam CM-MC	7
Bioturbated Marly Chalk	8
Bioturbated Foram Packstone-Wackestone	9
Laminated Burrowed Chalk-Marly Chalk	10
Laminated Burrowed Chalky Marl	11
Alternating Bio/Lam Chalky Marl	12
Laminated Chalky Marl/Marly Chalk	13
Bioturbated Chalky Marl	14
Bioturbated Foram Wackestone-Mudstone	15
Burrowed Slightly Chalky Marl	16
Burrowed Marl	17
Marl	18

Niobrara Cycles and Dominant Processes



Transgressive:
- Chalk-rich
- Biotic processes dominate (CO3 productivity, microbial, burrowing)

Regressive:
- Clay-rich
- Physical sedimentologic processes dominate (wave, storm and hyperpycnal currents)

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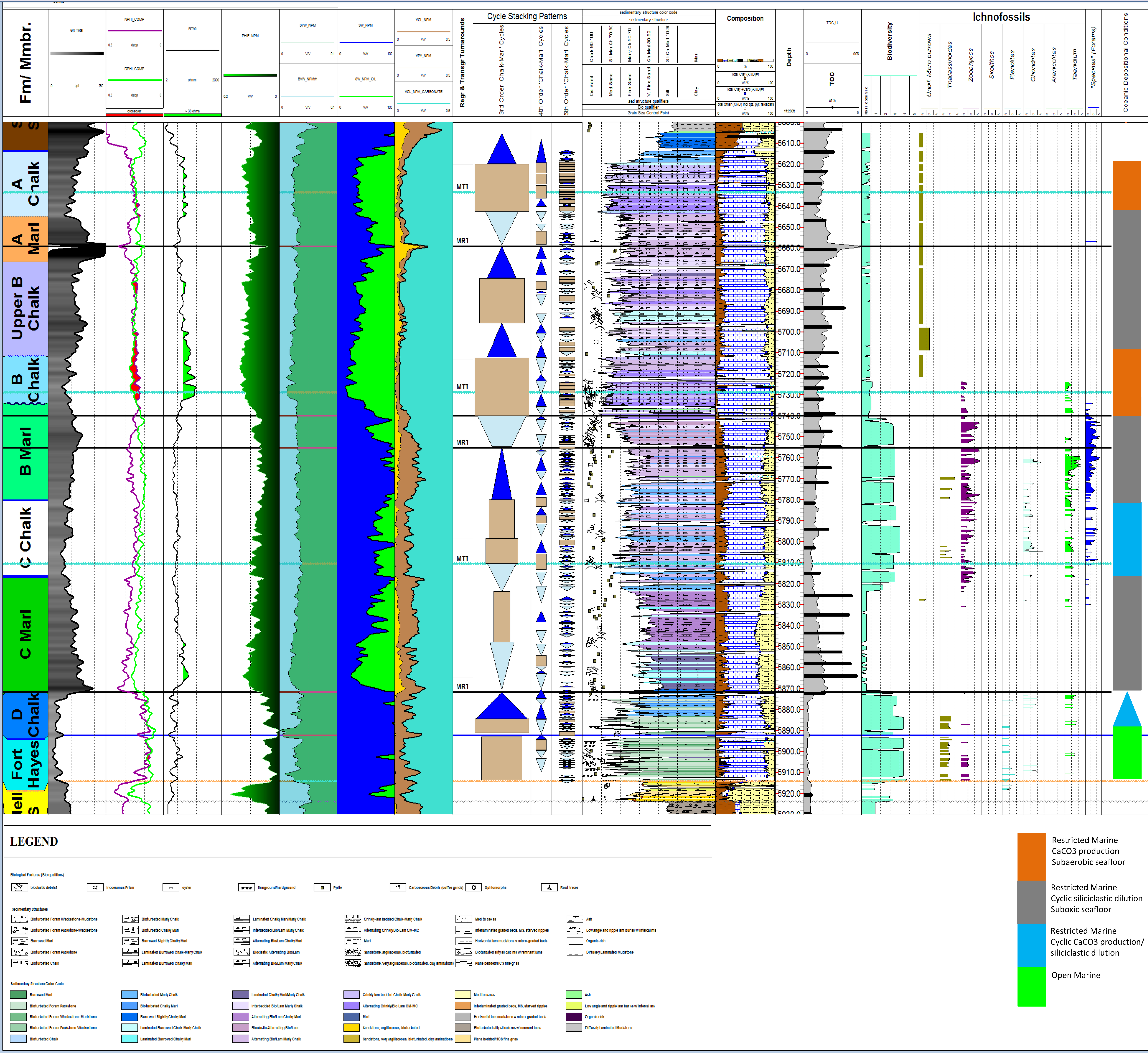
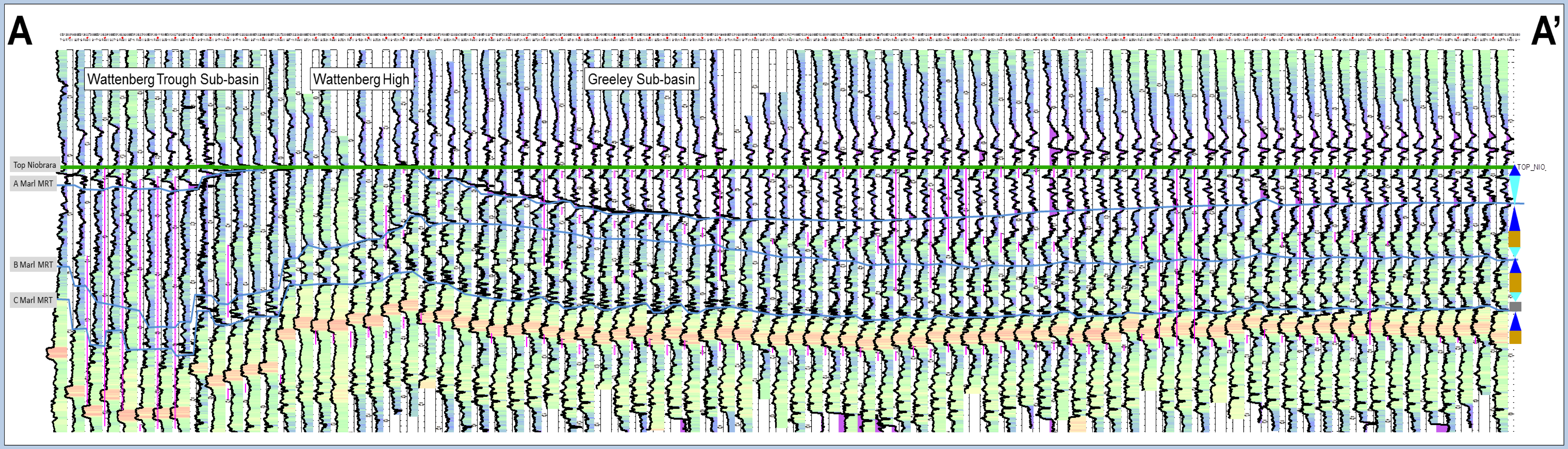
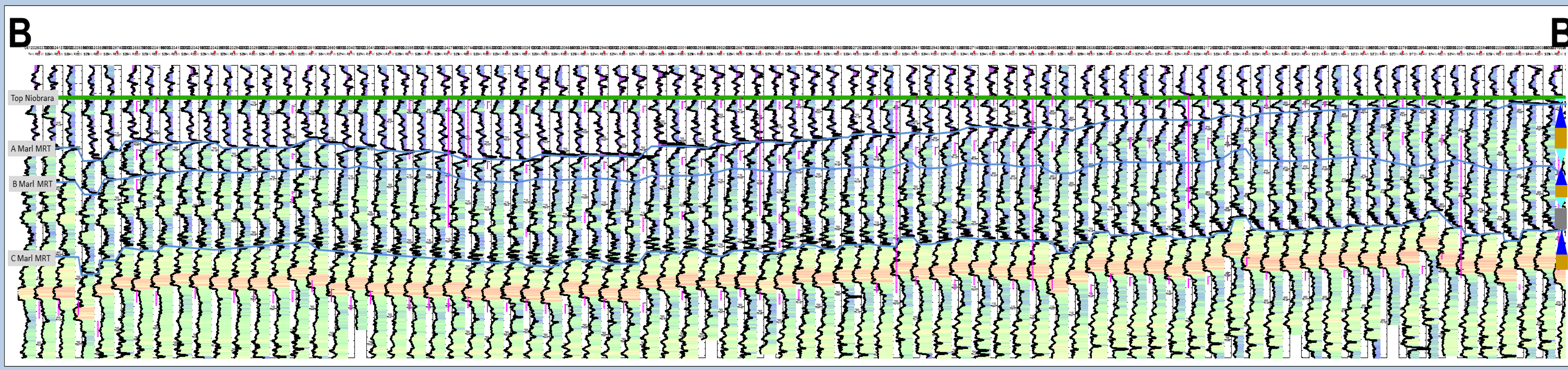


Niobrara Regional GR Cross Sections & Stratigraphy

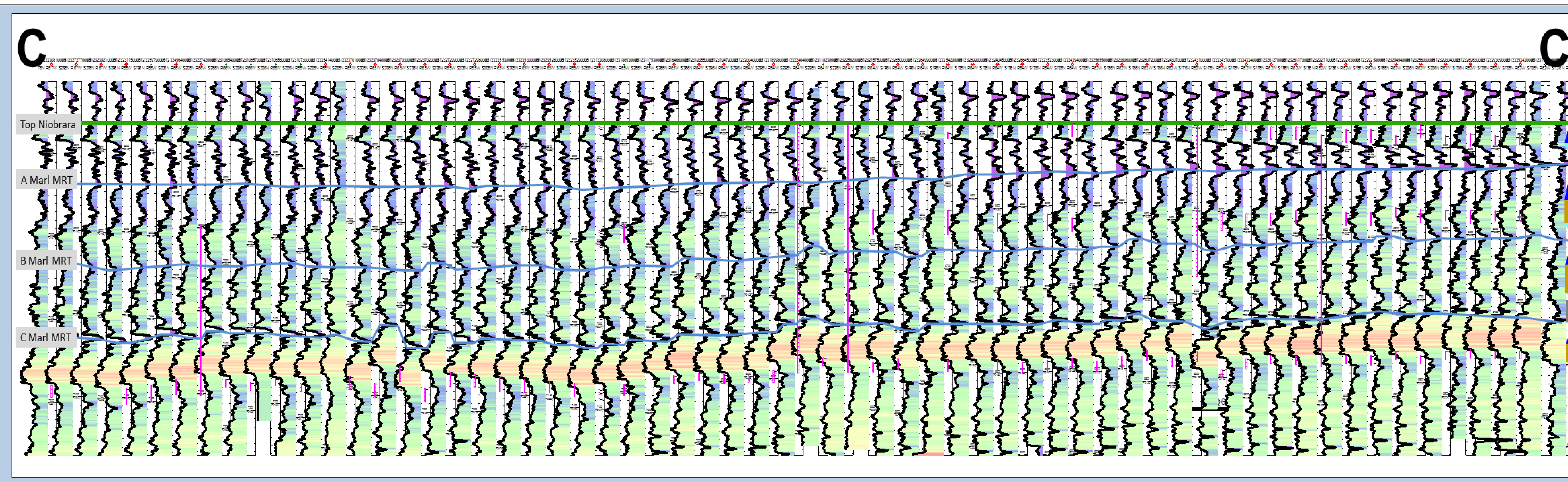


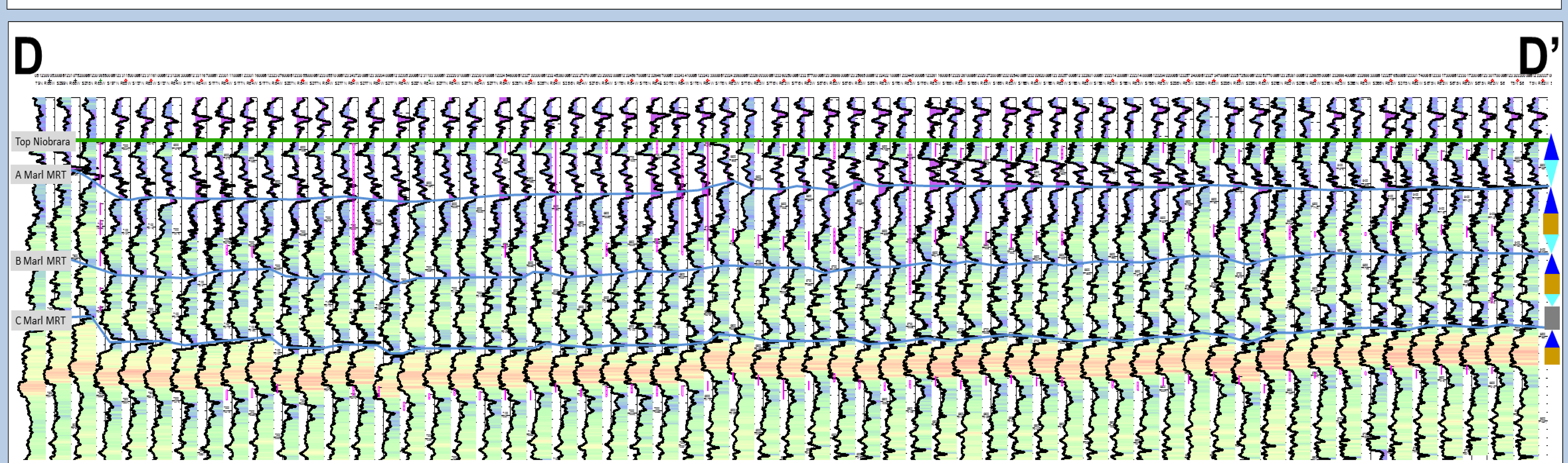


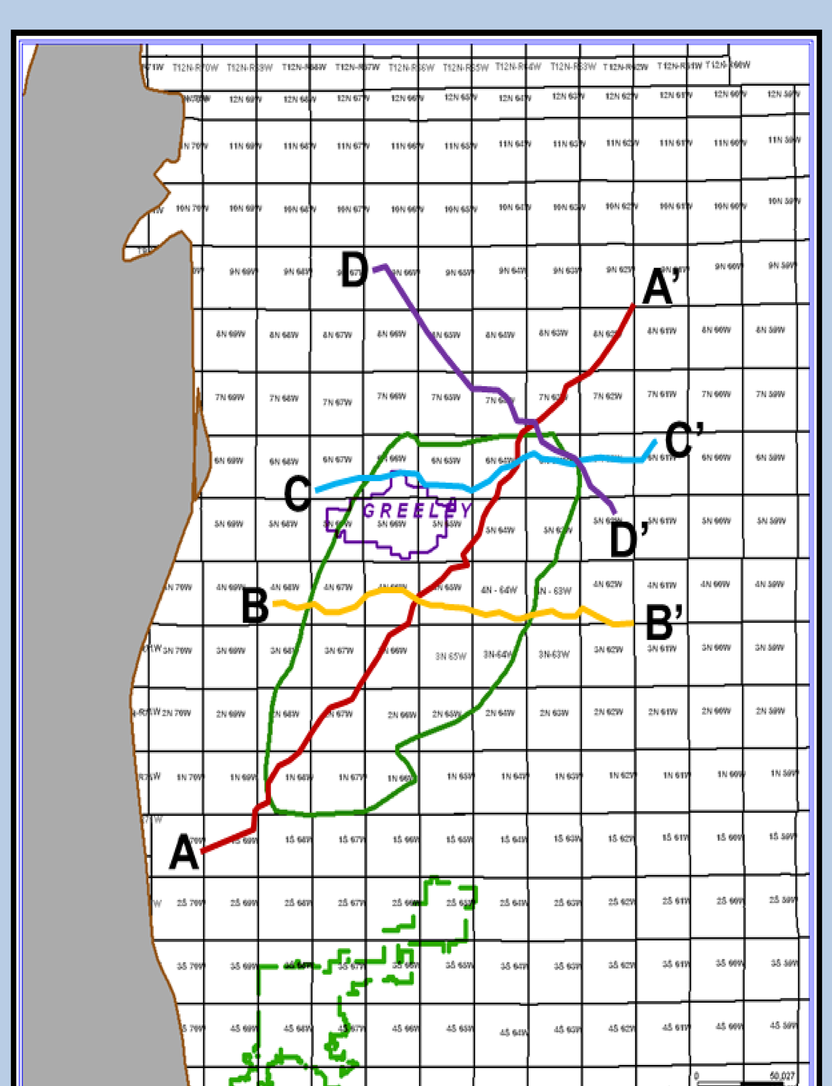
Niobrara stratigraphy influenced by differential subsidence rates across structurally controlled sub-basins.

On-lapping relationships are evident at Maximum Regressive Turnarounds (MRT)

Note lateral development of chalk and marl pods







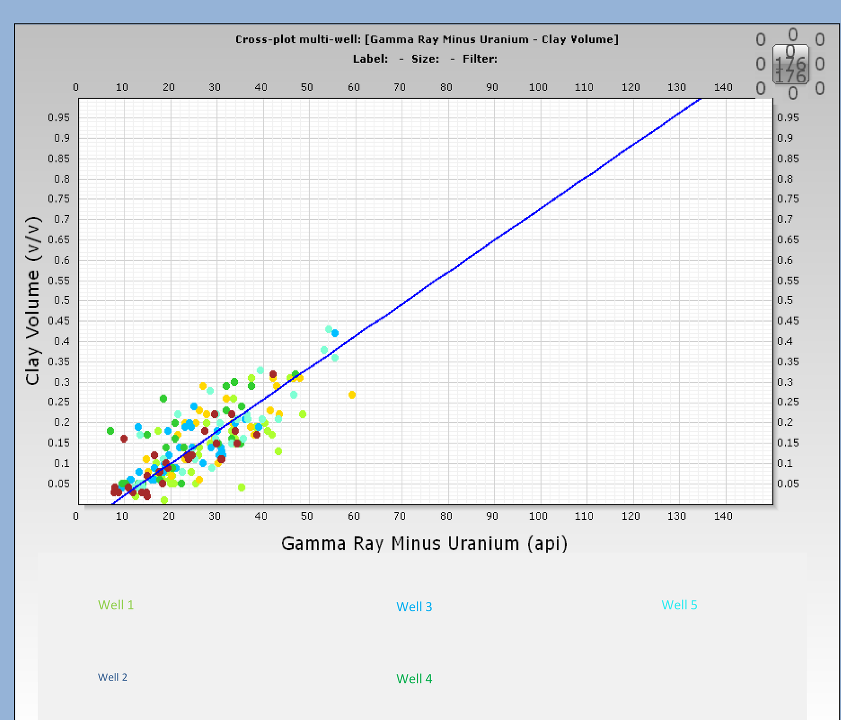
Petrophysical Rock Typing The Niobrara:
Flow-Based Rock Types and Connections to Geologic Rock Types

Rock Typing in Unconventional Reservoirs

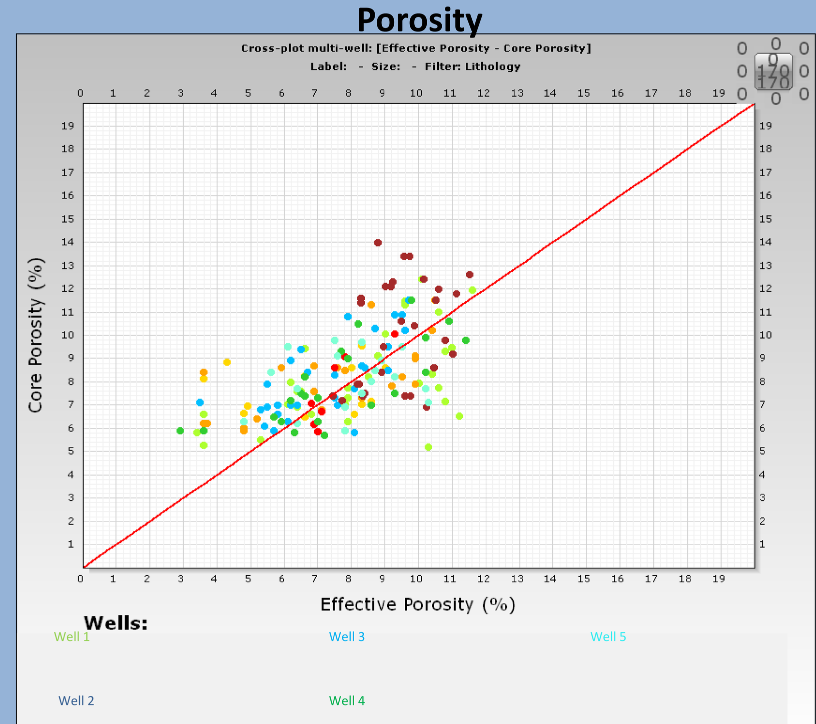
- In conventional reservoirs rock typing is based on flow capacity (i.e., permeability) which is greatly influenced by depositional rock texture
- In unconventional reservoirs (like the Niobrara) flow capacity is even more strongly influenced by depositional fabric, represented as rock type.
- Each of the key elements (HPV, Brittleness, and Deliverability) must be accounted for in developing a rock-typing scheme
- Methods to integrate these three elements will depend on your reservoir, operating practices and available data
- Key steps are HPV, Brittleness, and Deliverability

Basic Petrophysical Model for HPV Is Key Initial Step

Volume of Clay



Porosity



Fluid Saturation

- Resistivity-based model calibrated to both RCA and GRI core-based analysis
- Density-based model inherently flawed due to issues around density measurement
  - Large volume of core-based analysis is essential for calibration of final model
- At the end of the day that is all that the Archie Equation does
- Model must take into account clay-based fluids and calculate a clay-corrected water and hydrocarbon saturation
- Regionally varying in situ reservoirs fluids (changes in GOR) were also accounted for in the model.

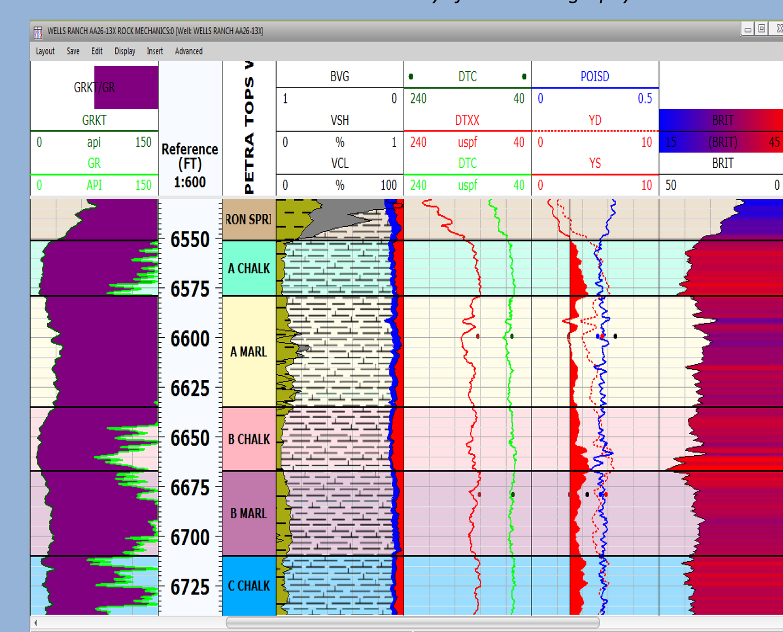
Brittleness as a Estimate of Mechanical Rock Properties

- What is needed is "relative" brittleness, or the most brittle rock in a given interval
- Absolute brittleness values have no meaning
  - Industry has not reached consensus on brittleness definitions

Computer Processed Log with Calculated Brittleness

Key is understanding relative Brittleness of Niobrara

Brittleness does not always follow stratigraphy



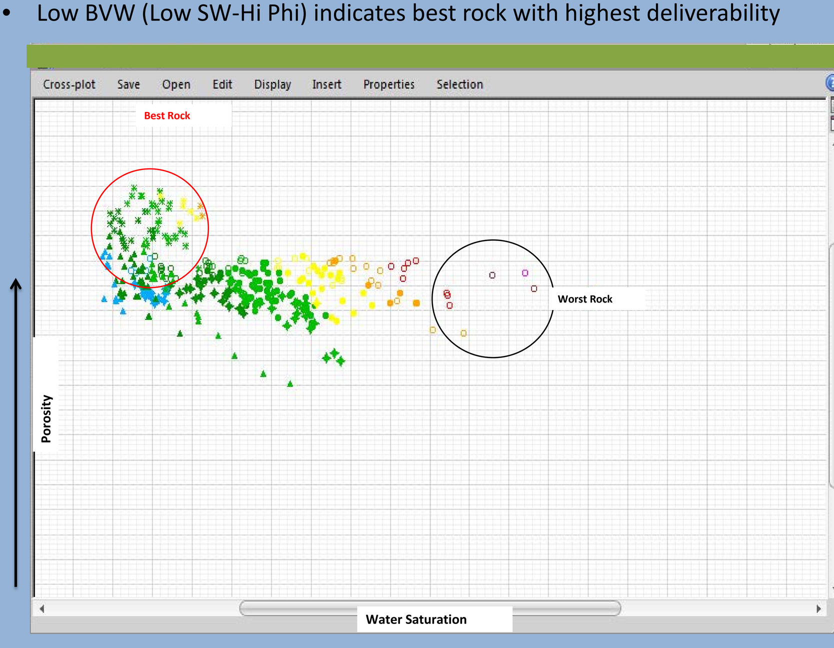
Deliverability

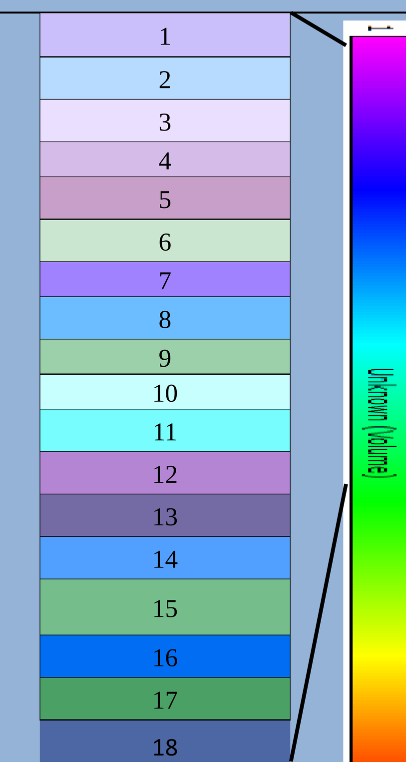
- The holy grail in unconventional reservoirs
- The rock property which ties most closely to production is deliverability (production is the only real parameter we measure).
- We think in terms of absolute permeability, but what we really want to know is: which rock will deliver the most oil and gas to the well-bore post-fracture stimulation
- The term "permeability" is misleading, as it is determined in the realm of Darcy flow. Fluid flow is likely non-Darcy in the matrix of mudstone reservoirs

Buckles Plot

Layer 2 Niobrara Five Noble Cored Wells in Colorado

- Buckles Plot crossplots SW and PHI
- Color is Bulk Volume Water (SW*PHI)
- Low BVW (Low SW-Hi Phi) indicates best rock with highest deliverability

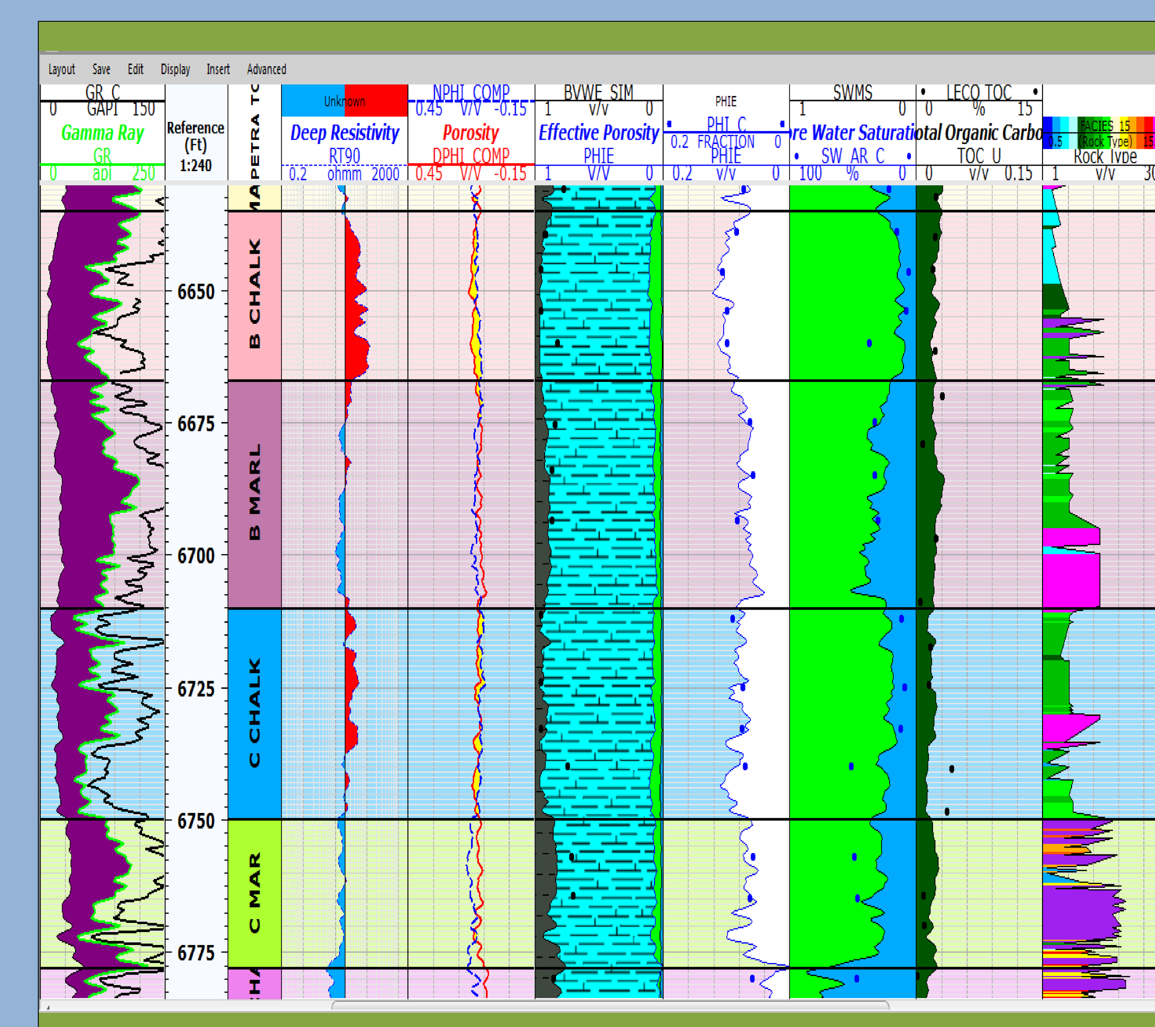




Major Geologic Rock Types

- Assigned digital value
- Loaded into petrophysics project
- Relationship between geologic rock types and petrophysical curves explored and documented

Computer Processed Log with Geologic Rock Types



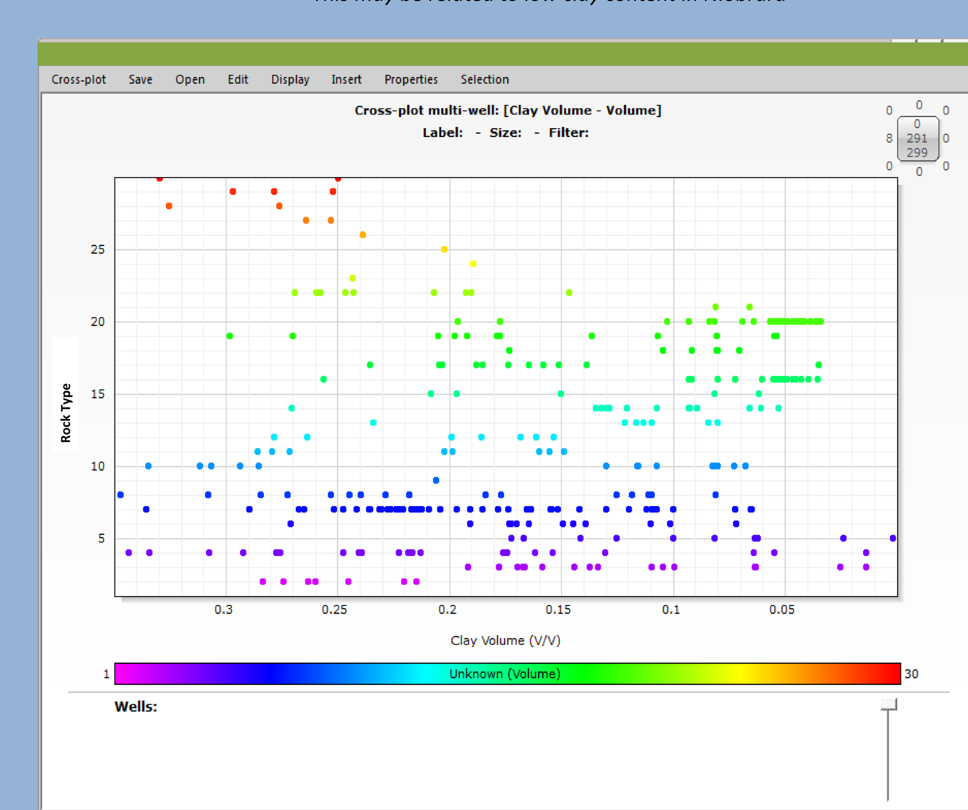
Observations

▪There is a relationship between geologic rock types, log properties, and stratigraphy

Cross Plot of VCLAY with Geologic Rock Types

Clay content fairly static across geologic rock types

This may be related to low clay content in Niobrara



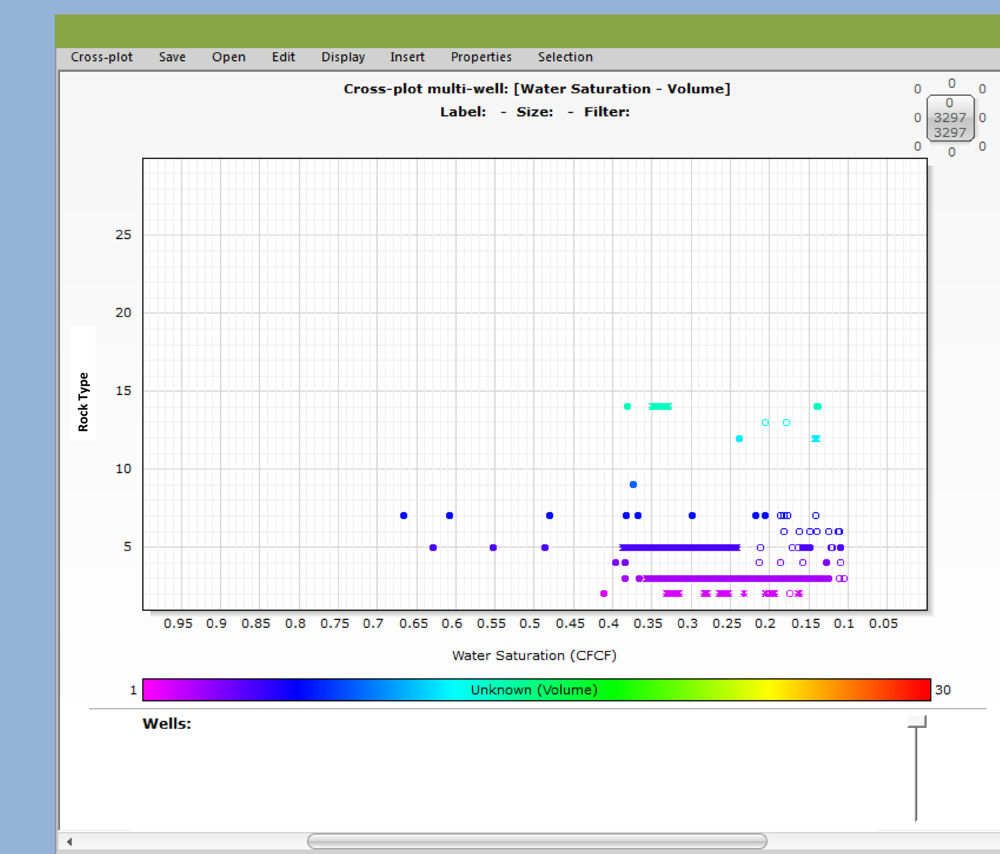
Cross Plot of Water Saturation with Geologic Rock Types

Hydrocarbons are concentrated in certain geologic rock types

Crinkly bedded facies (various types) contain vast majority of HPV

Low SW = Maximum deliverability

Depositional texture has significant impact on productivity



Niobrara Petrophysics Conclusions

- **Traditional petrophysical workflows, with added rigor where needed, will allow full scale reservoir evaluation**
  - **Core-calibrated model is critical**
- **Conventional lithostratigraphic nomenclature does not always relate to subsurface rock properties**
- **There is a correlation between geologic rock types and calculated log response**
- **A significant portion of the HPV resides in a core-based, identifiable geologic rock type**
- **Flow-based rock typing is possible in unconventional reservoirs where data types and integrated analysis are undertaken**

Acknowledgements

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