[AV]Integrated Reservoir Evaluation as a Means for Unlocking Maximum Resource Value in an Unconventional Reservoir: Niobrara Formation, DJ Basin, Colorado*

Marshall Deacon[1] and Robert Lieber[1]

Search and Discovery Article #110168 (2013)**
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Please refer to companion article presented by the authors and their co-workers and entitled "Stratigraphic Controls on Reservoir Properties, Cretaceous Niobrara Formation, DJ Basin, Colorado," Search and Discovery Article #80314 (2013).

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Summary

- The Niobrara is areally extensive in northeastern Colorado and adjacent states.
    - Thermal history parallels GOR trends.
- Traditional petrophysical workflows, with added rigor where needed, will allow full scale reservoir evaluation.
    - There is a correlation between geologic rock types and log response.
- Conventional stratigraphic nomenclature does not always relate to subsurface rock properties.
- 3D seismic decreases operations and targeting risk.
    - Opportunities for dynamic geosteering.
    - Static and dynamic reservoir modeling.
- Integrated data gathering resulted in increased OOIP estimates and actual recovery.

Reference Cited

Koskella, D., and R. Parney, 2012, Niobrara horizontal drilling: Planning and geosteering technologies for maximizing production: Horizontal Drilling and Completion Fall Symposium, PTTC, Rocky Mountain Region. Unpublished.

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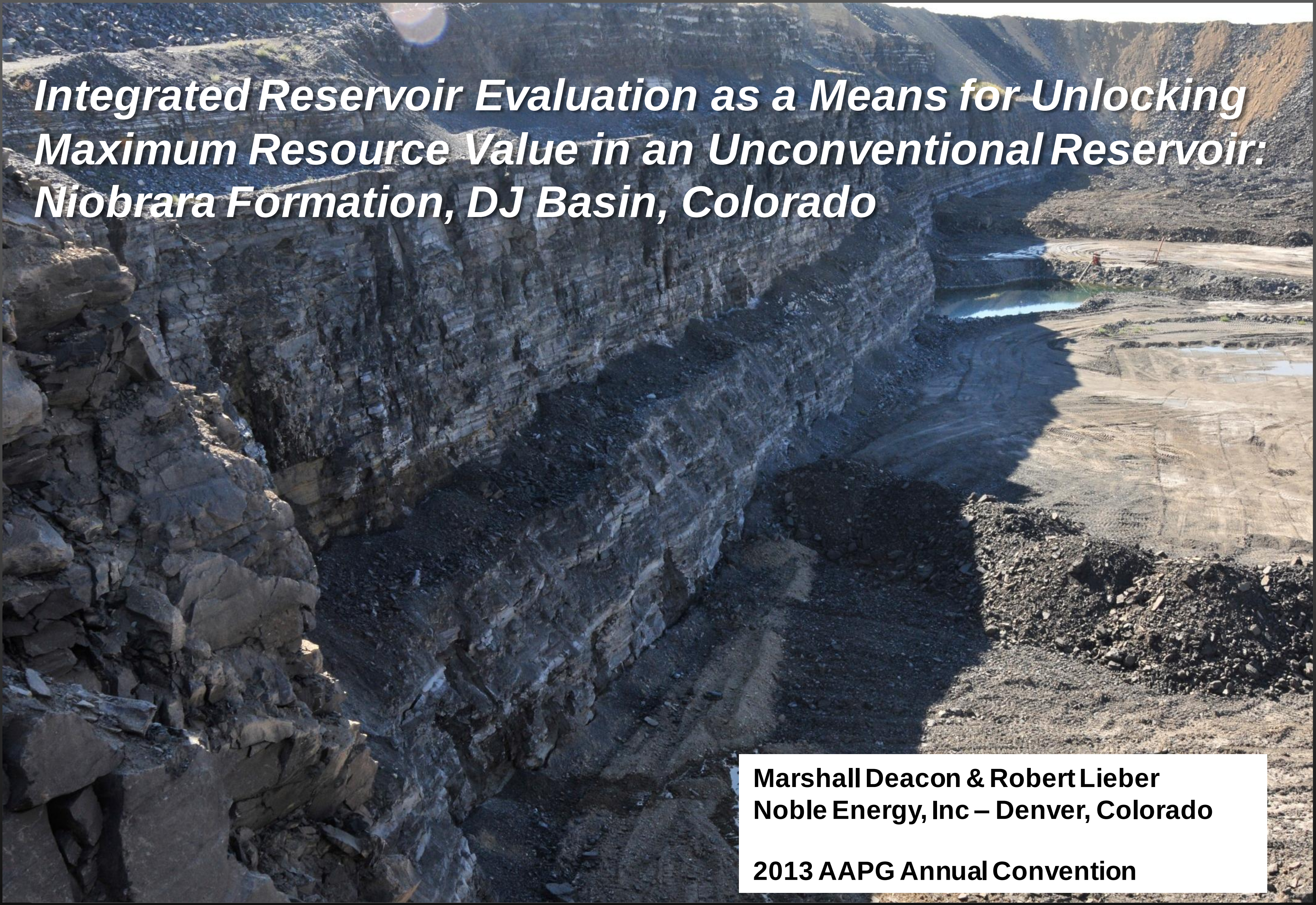
Blakey, R., 2006, North American Paleogeographic Maps, Late Cretaceous (85 Ma): North Arizona University [now Colorado Plateau Systems, Inc.]. Website accessed July 27, 2013. http://www2.nau.edu/rcb7/namK85.jpg

Integrated Reservoir Evaluation as a Means for Unlocking Maximum Resource Value in an Unconventional Reservoir: Niobrara Formation, DJ Basin, Colorado



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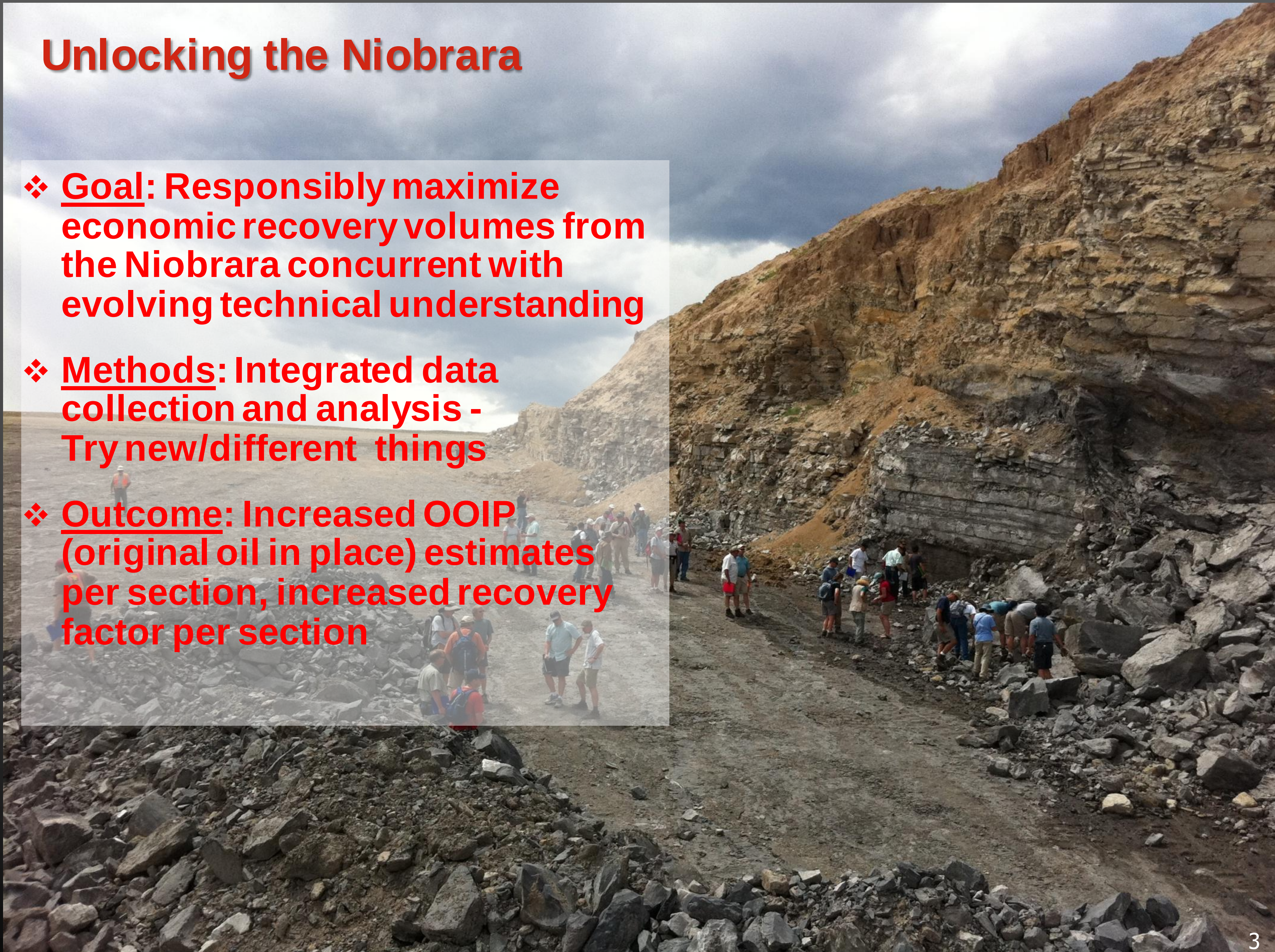
Noble Energy, Inc – Denver, Colorado

2013 AAPG Annual Convention

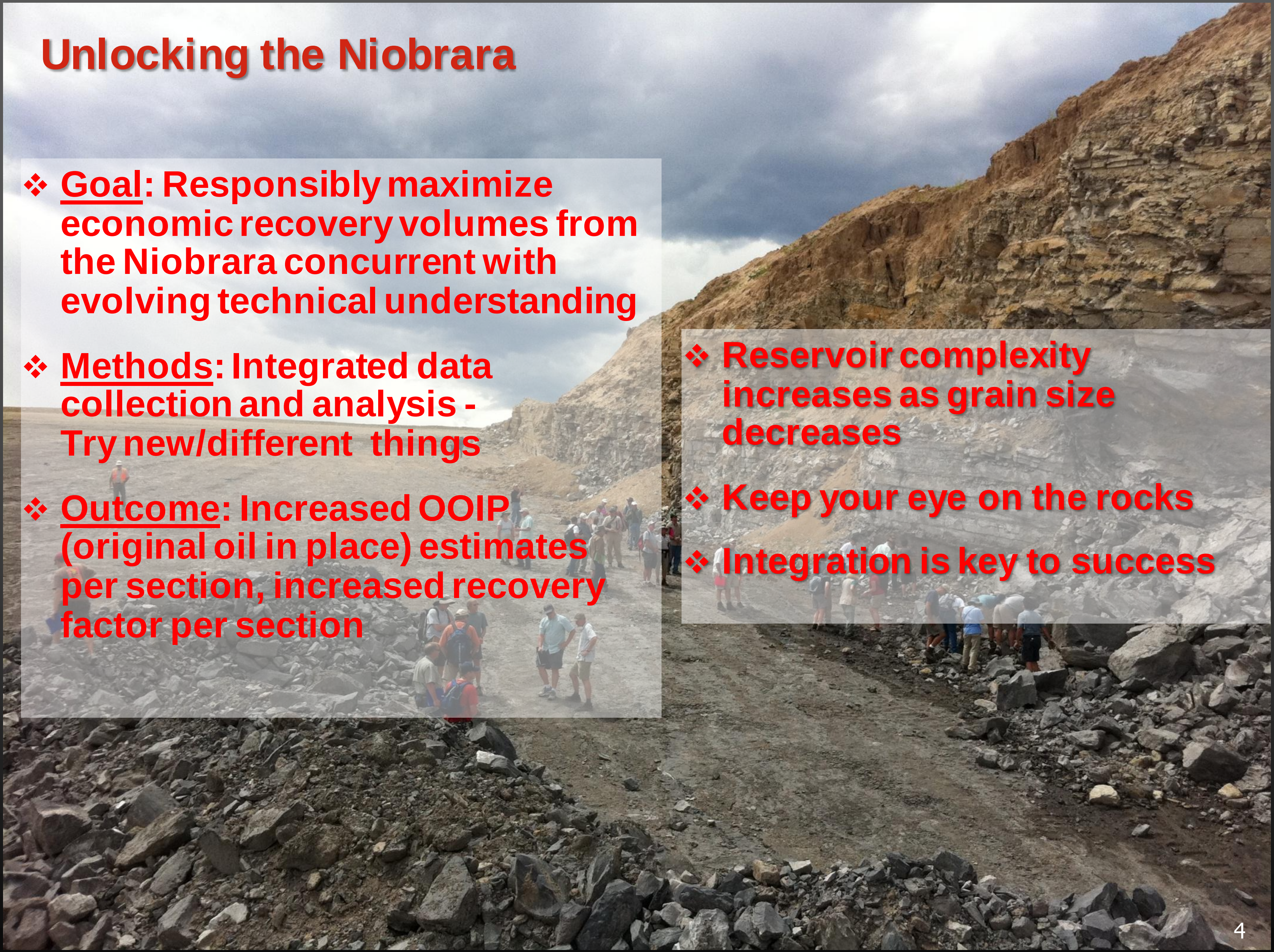
Unlocking the Niobrara

Unlocking the Niobrara



- **<u>Goal</u>: Responsibly maximize economic recovery volumes from the Niobrara concurrent with evolving technical understanding**
- **<u>Methods</u>: Integrated data collection and analysis - Try new/different things**
- **<u>Outcome</u>: Increased OOIP (original oil in place) estimates per section, increased recovery factor per section**

Unlocking the Niobrara



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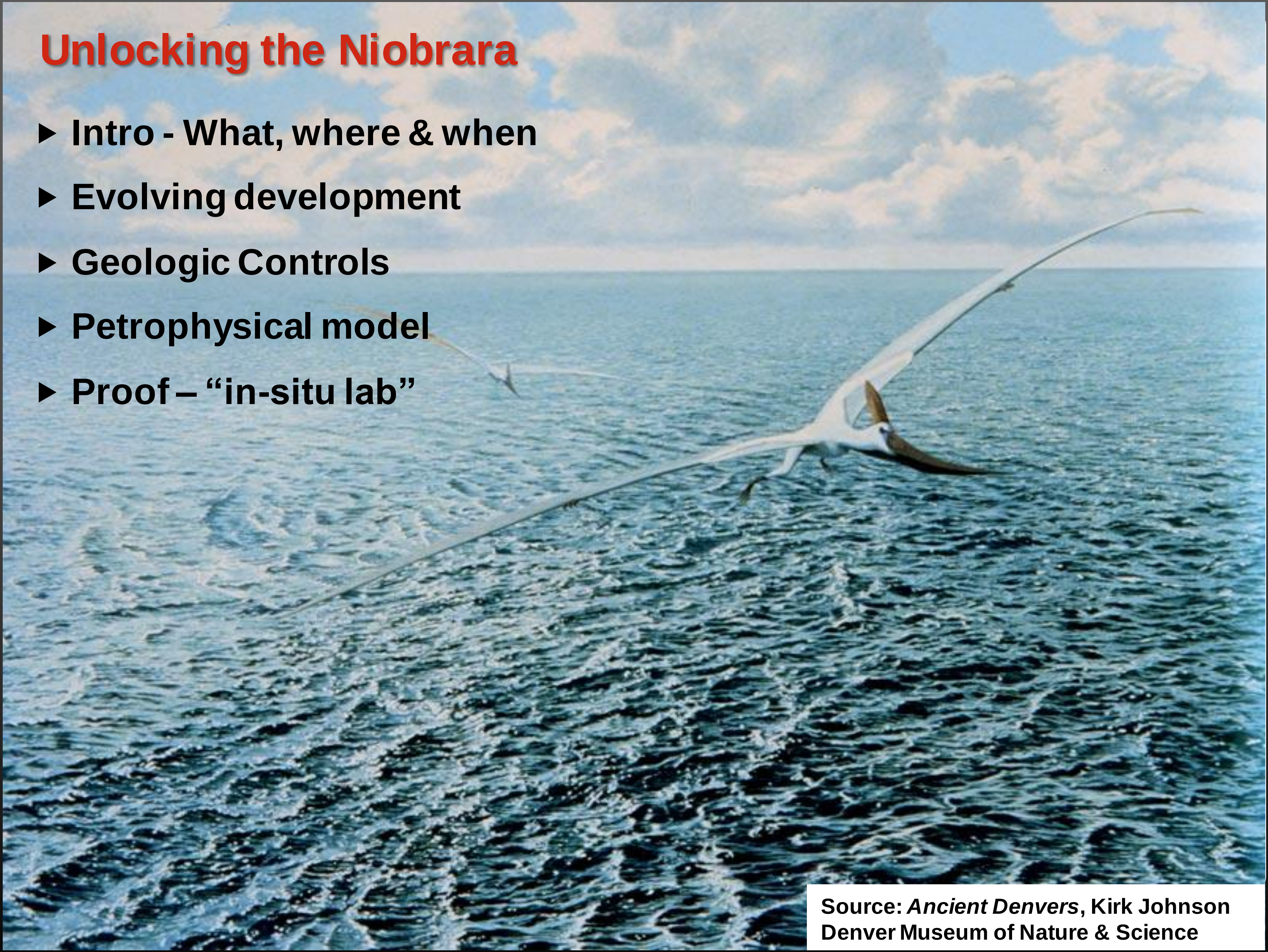
- Reservoir complexity increases as grain size decreases
- Keep your eye on the rocks
- Integration is key to success

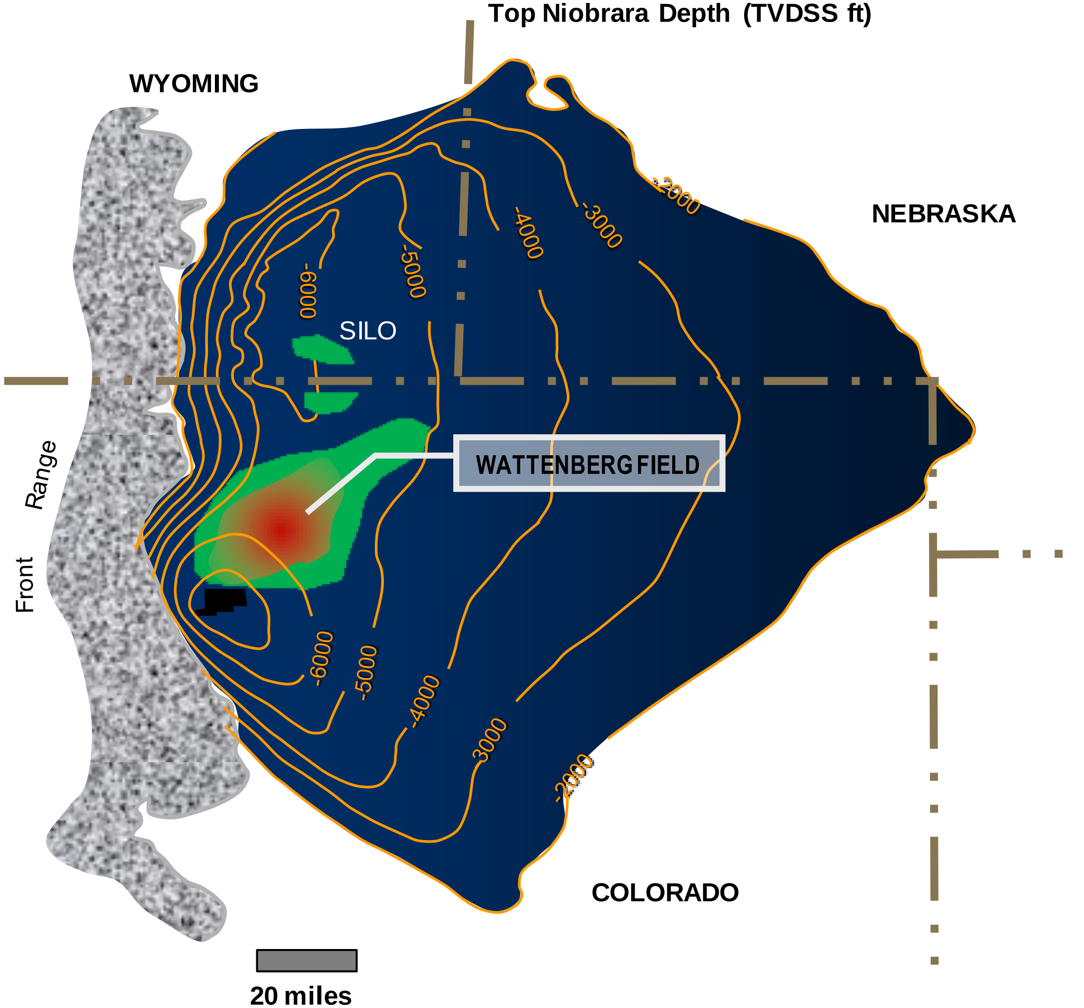
Unlocking the Niobrara

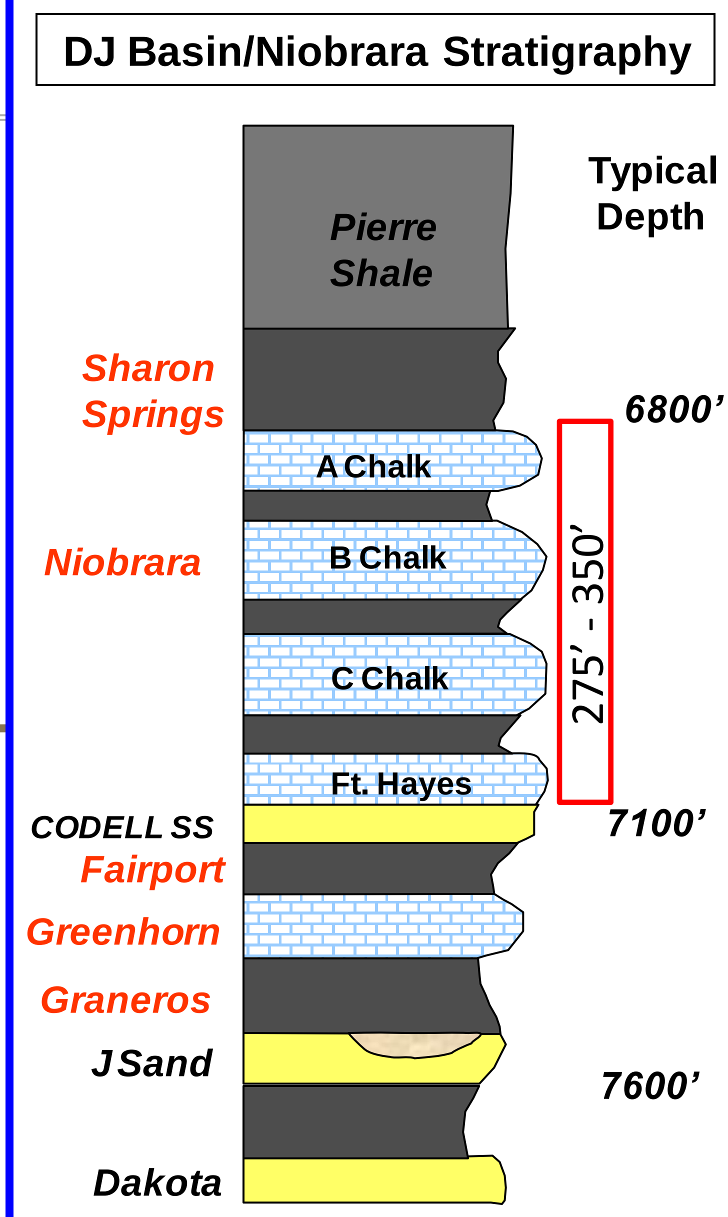
- Intro - What, where & when
- Evolving development
- Geologic Controls
- Petrophysical model
- Proof – “in-situ lab”



Source: *Ancient Denvers*, Kirk Johnson
Denver Museum of Nature & Science

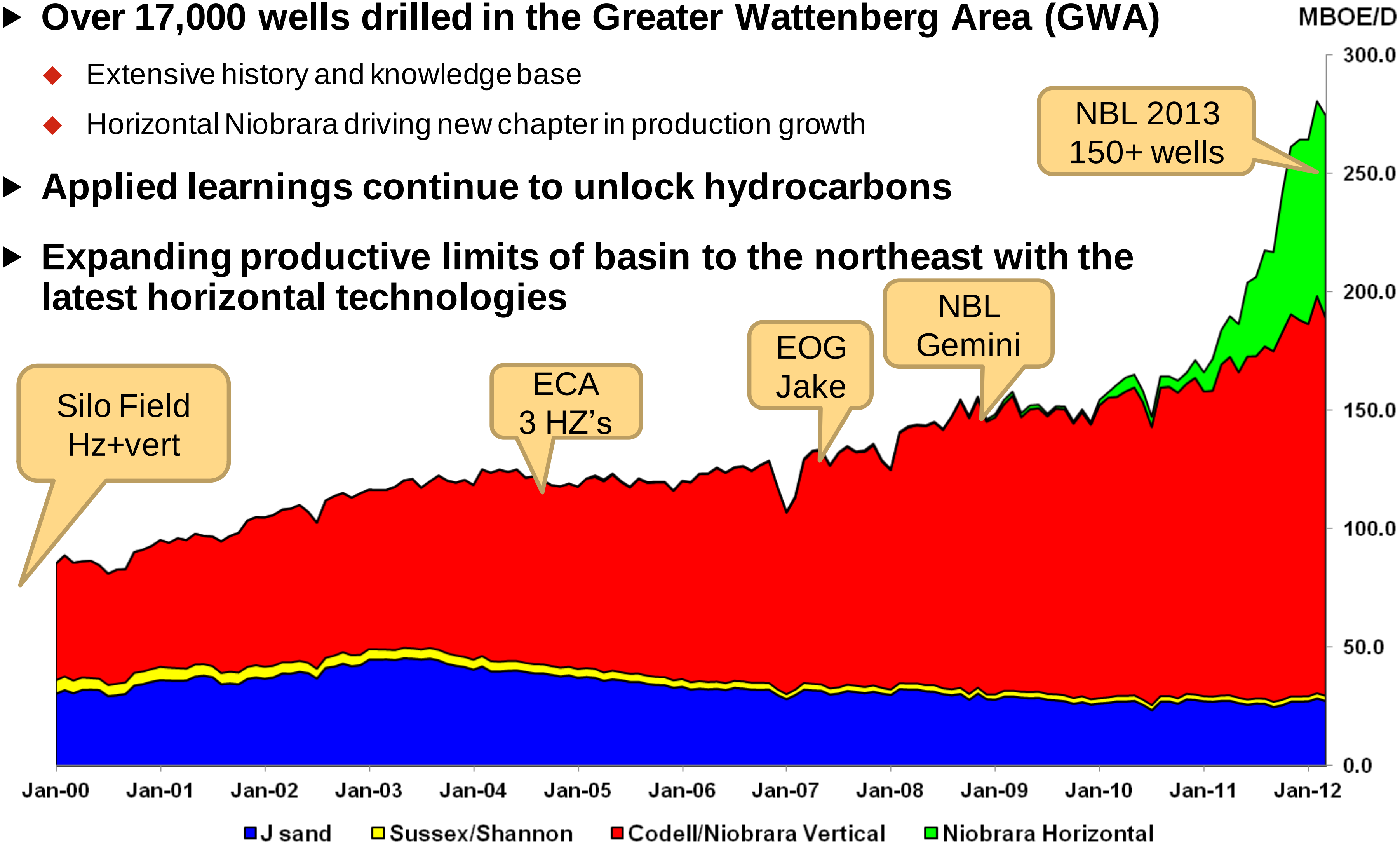
Denver Basin Setting & Niobrara Stratigraphy





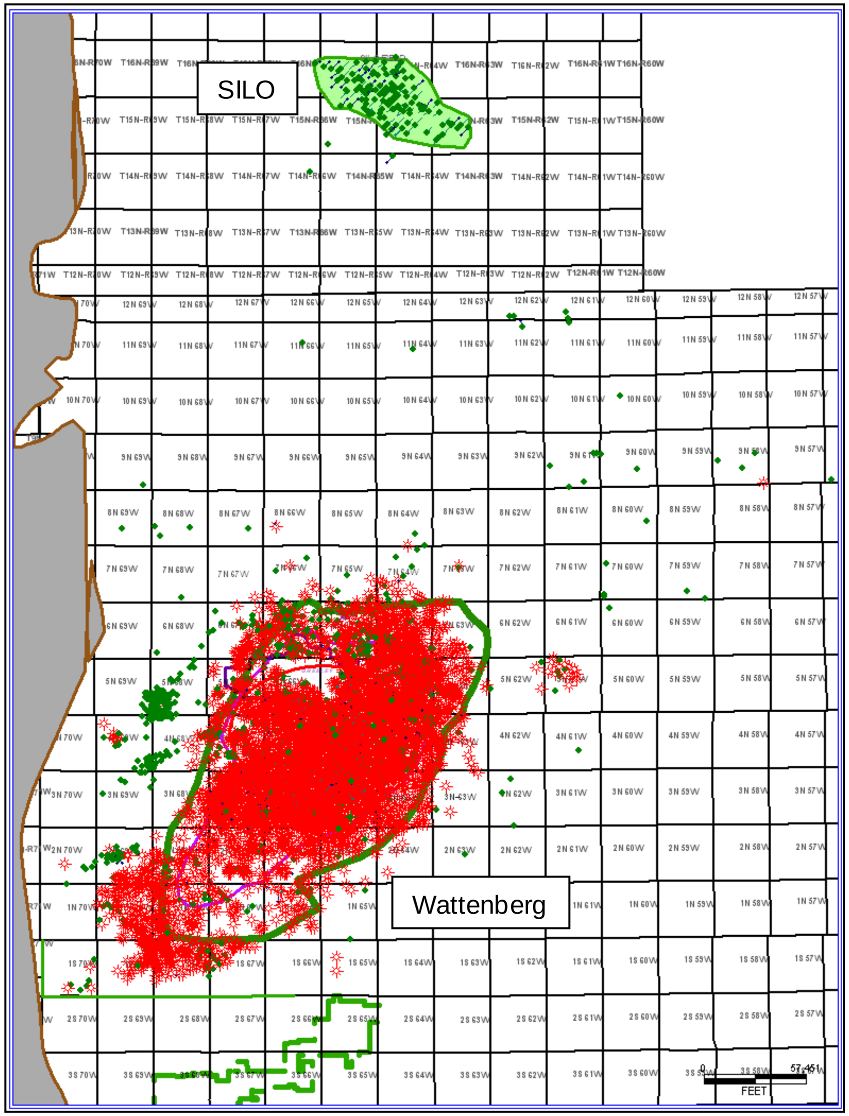
Wattenberg/Niobrara Production History

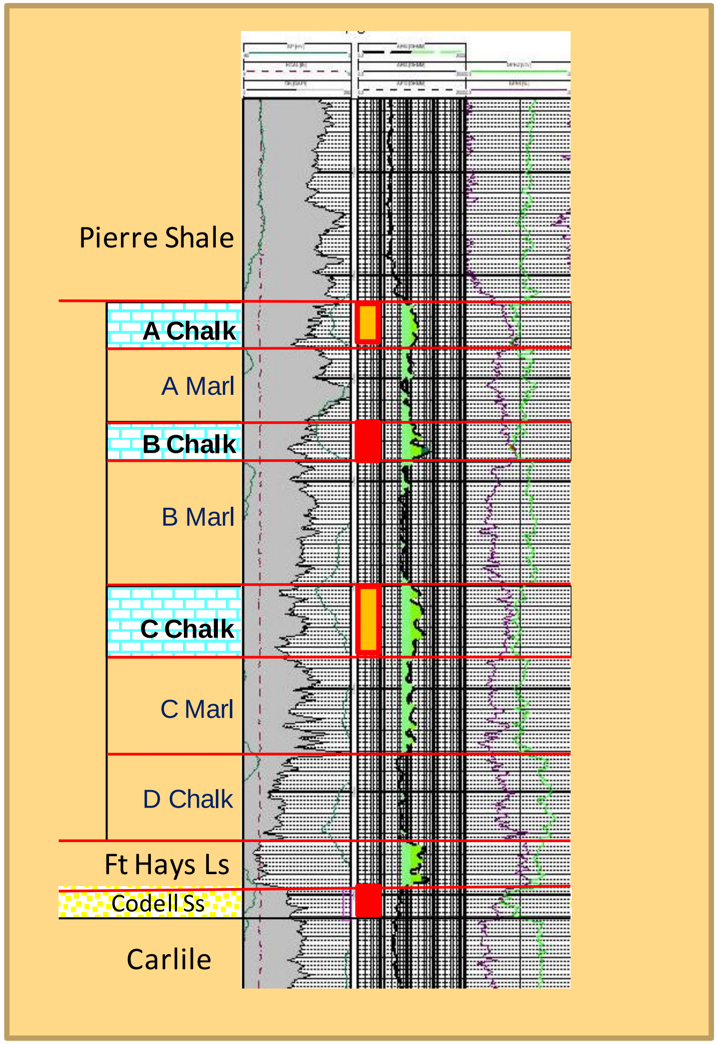
- **Over 17,000 wells drilled in the Greater Wattenberg Area (GWA)**
  - Extensive history and knowledge base
  - Horizontal Niobrara driving new chapter in production growth
- **Applied learnings continue to unlock hydrocarbons**
- **Expanding productive limits of basin to the northeast with the latest horizontal technologies**



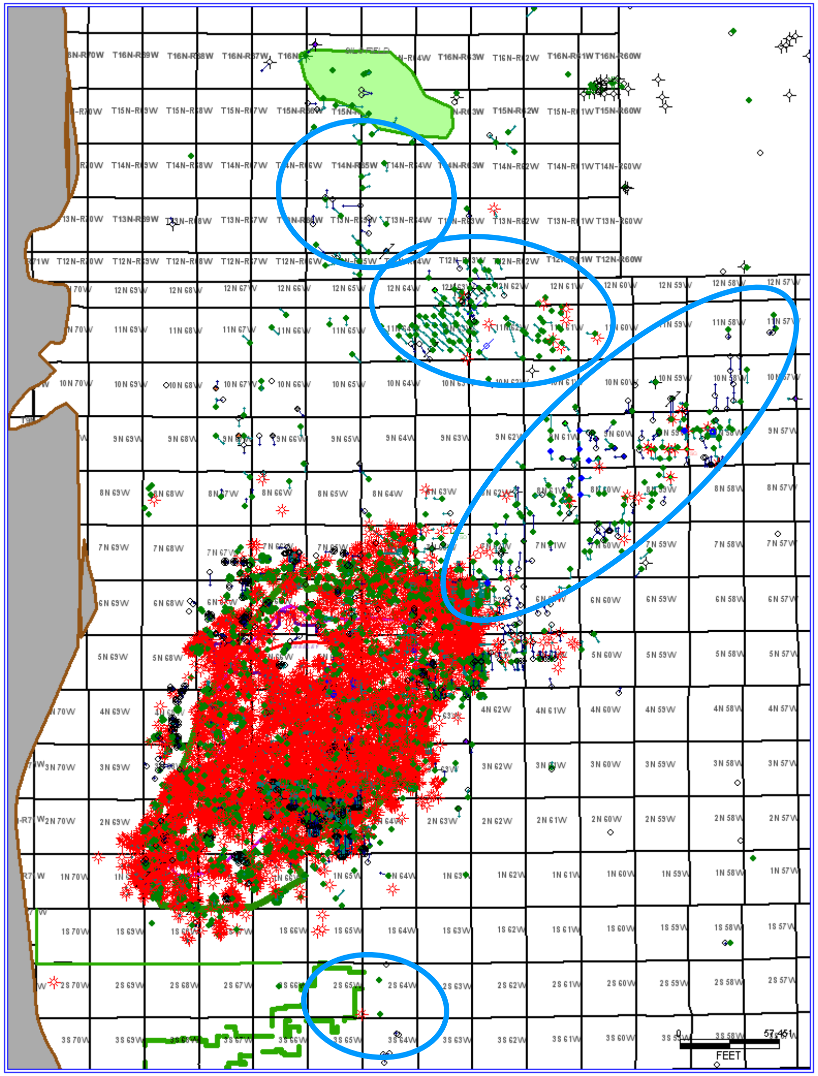
Source: IHS

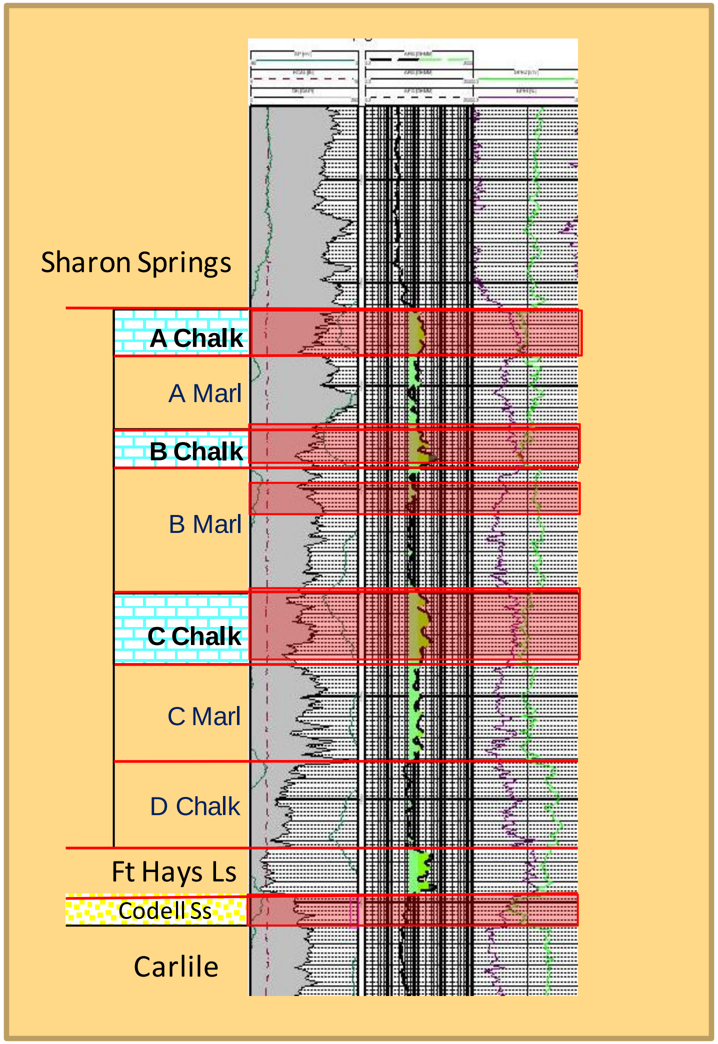
Niobrara Development: 1950-2006 Vertical Times



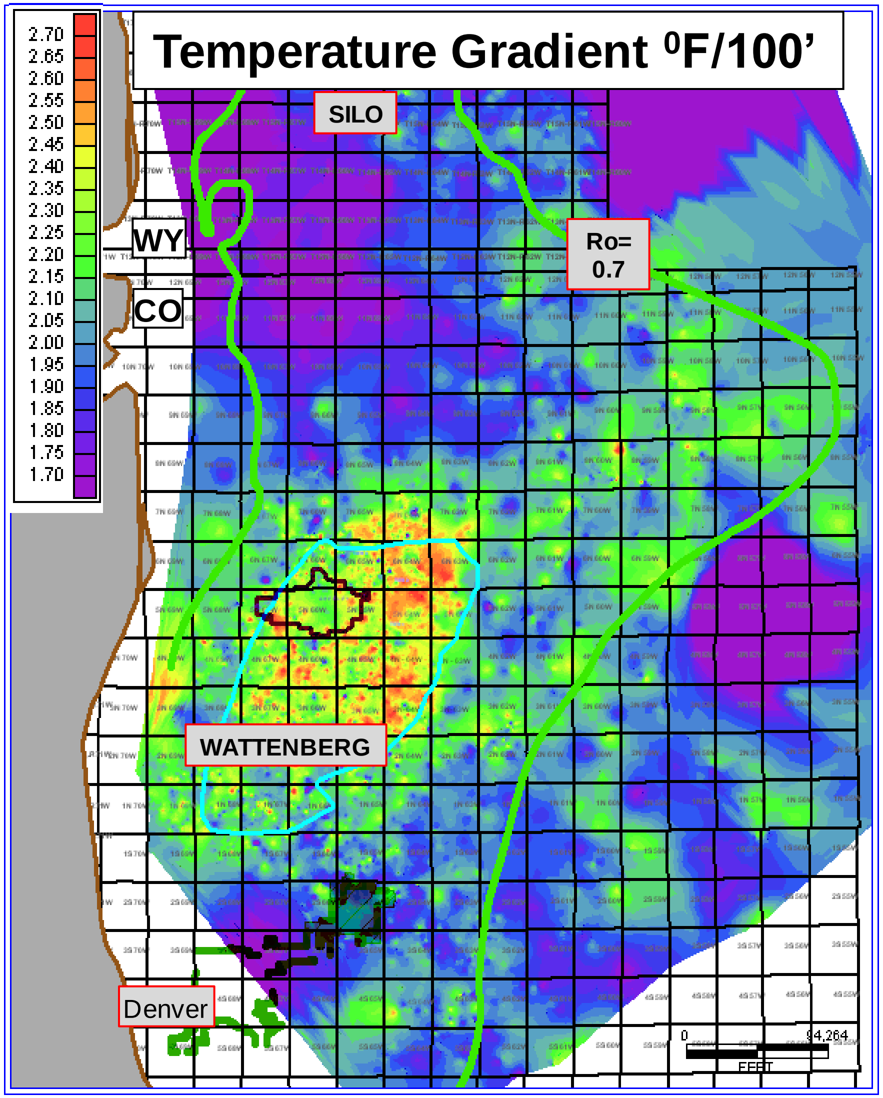


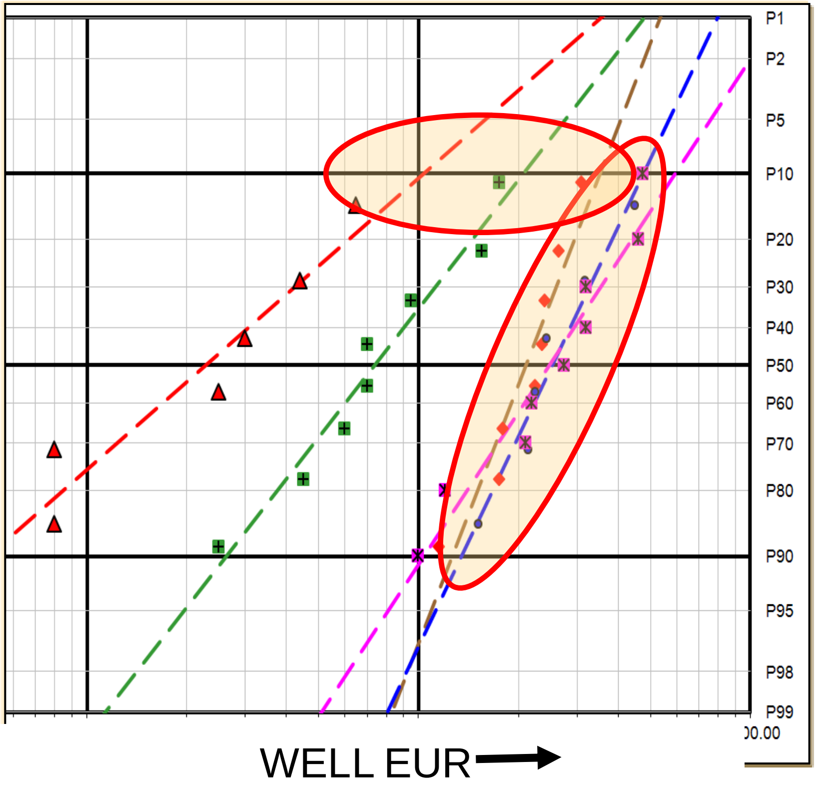
Niobrara Development: 2007-2013 Horizontal Breakthrough





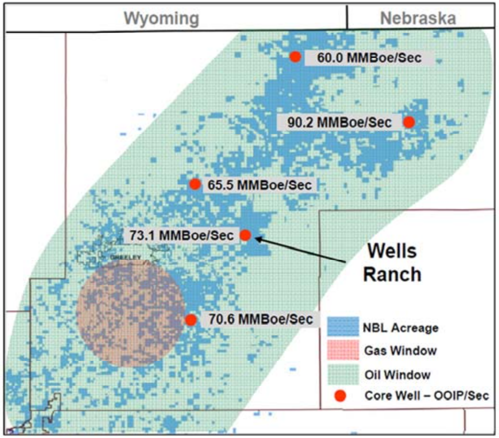
Determining Sweet Spots & Resource Distributions





Data Collection for Integrated Exploration Efforts

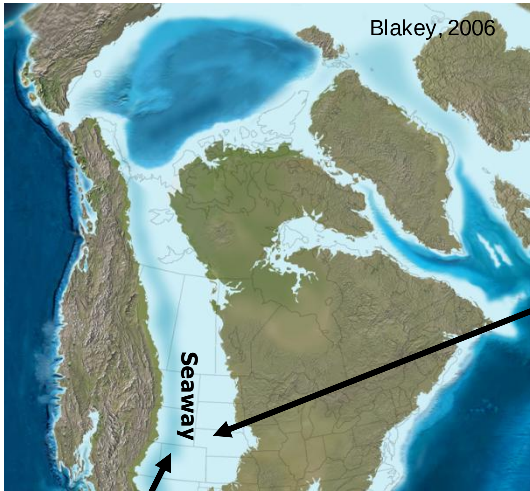
- **8 Strategically Placed Core Wells**
  - Over 2400 ft of core
- **1650 mi^2 3D seismic**
- **Petrophysical Logs**
  - Formation image logs on laterals
- **Microseismic on 55 wells**
- **Production data**
- **"In-situ lab" section**
  - DTS, tracers

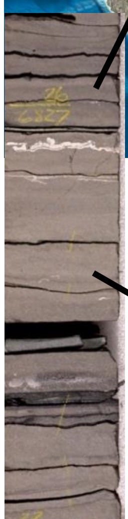


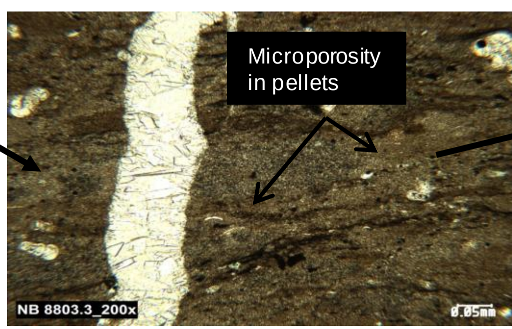
Presenters' notes: This is resource in place. 8100+ wells, including 275+ Hz wells. 2013 plans are to drill 300 hz Niobrara wells.

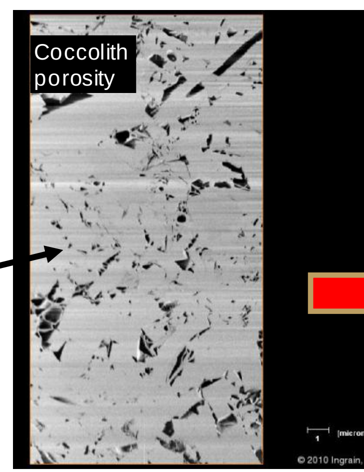
Unlocking the Niobrara: understanding the rocks

Basin to nanometer scale – it all plays a role



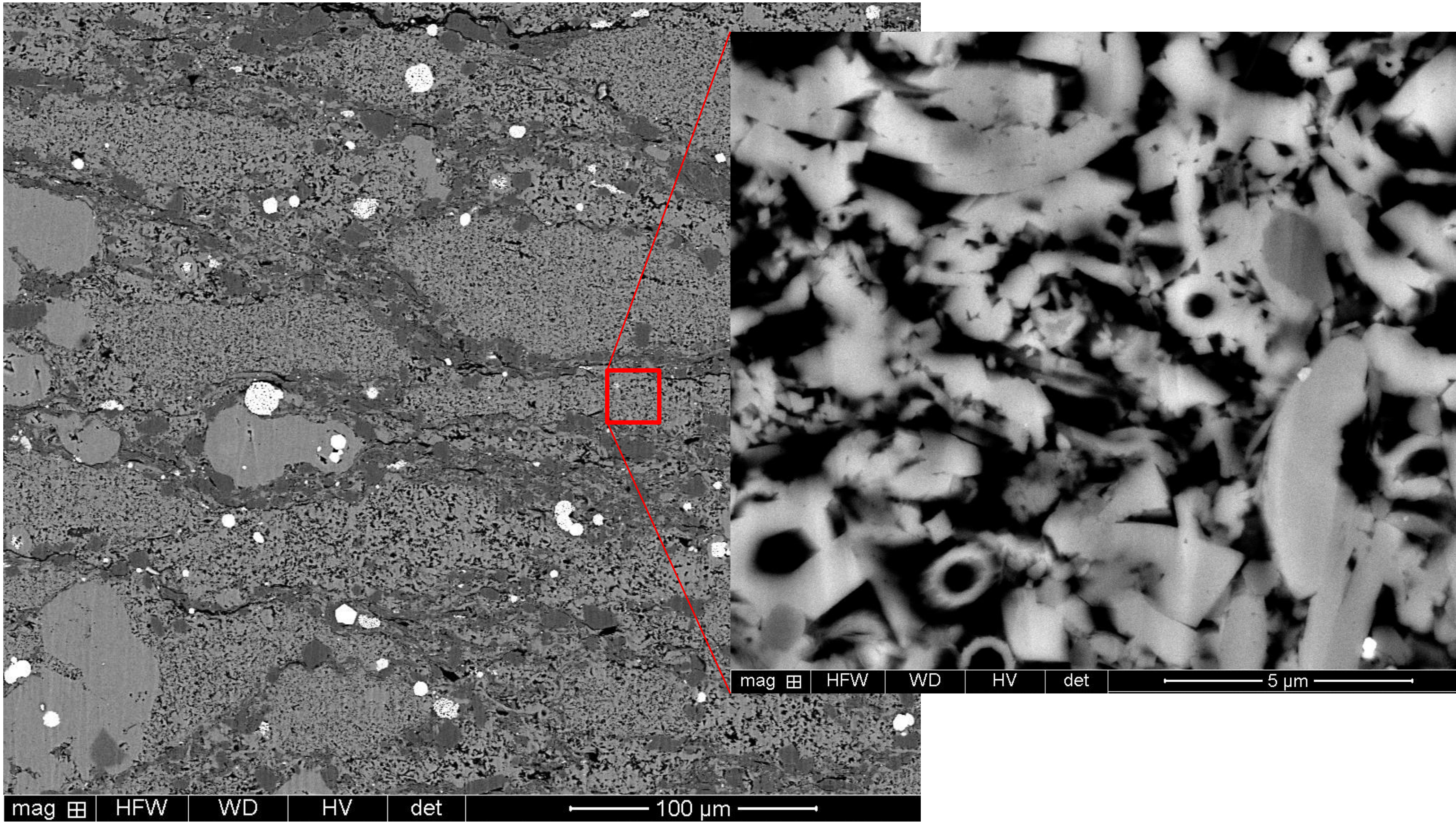






- Depositional Facies
- Rock Properties; Ym, Pr
- TOC, Vclay, Phi
- Thermal Maturity, GOR
- Faulting/fractures, Stress
- Wetness, Sw

Niobrara Rock Properties -
Starts With Understanding The Pellets



Niobrara Carbonate Facies:

Burrowed Chalks/Marls	Bioturbated Chalk	2-6 in
	Bioturbated Marly Chalk	2-6 in
	Bioturbated Chalky Marl	2-6 in
	Burrowed Slightly Chalky Marl	2-6 in
Laminated Chalks/Marls	Laminated, Burrowed Chalk-Marly Chalk	laminae- to 0.5 inch
	Laminated, Burrowed Chalky Marl	laminae- to 0.5 inch
	Laminated Chalky Marl (and rare thin marly chalk)	laminae-scale
Alternating Beds: Burrowed/Laminated	Interbedded Bioturbated/Laminated Marly Chalk	> 4" (break out individ chalk bed if > 5-6")
	Bioclastic Alternating Bioturbated/Laminated Marly Chalk	1-3"
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"Crinkly"-Laminated Chalks/Marls	**Crinkly-Lam** Bedded Chalk and Marly Chalk	> 4" (break out individ chalk bed if > 5-6")
	Alternating **Crinkly**-laminated/bioturbated Marly Chalk and Chalky Marl	0.5-4.0"
	(Lump with above} **Alternating -- Crinkly**-Laminated Burrowed Marly Chalk	1-2"

Bioturbated chalks + marly chalks

Laminated chalks + marly chalks

Alternating bioturbated/ laminated beds

Crinkly-laminated Chalk + Marl interbeds

3 inches

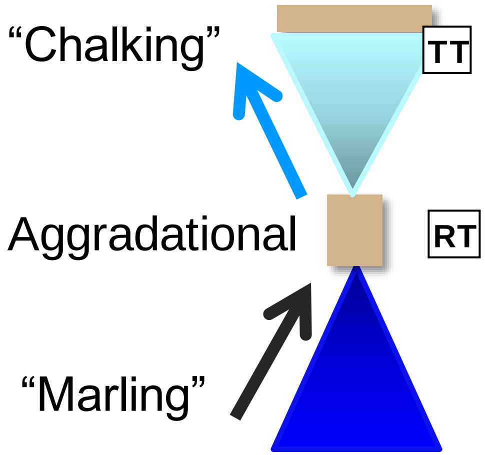
Burrowed chalk *(Chondrites)*

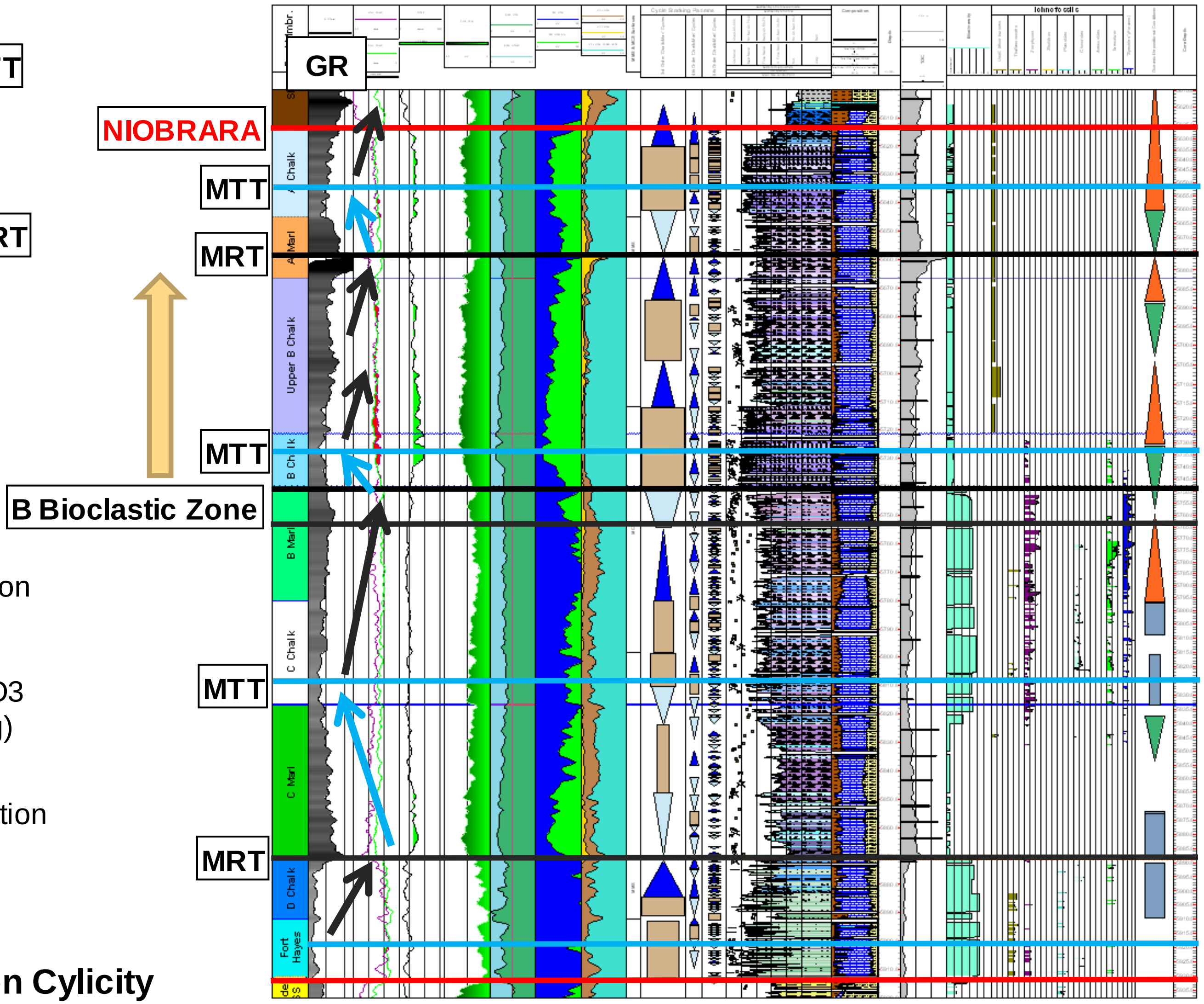
Laminated Chalk & marl. Inverse and regular graded laminae of squashed pellets

Cyclic alternation between laminated marls and thin, burrowed chalk beds

Pure CO3 chalk/ Organic-rich, high TOC beds - Microbial mats?

Niobrara Depositional Sequence Summary





TT: Transgressive, open circulation

- Chalk-rich, dry cycle
- Low TOC
- Biotic processes dominate (CO3 productivity, microbial, burrowing)

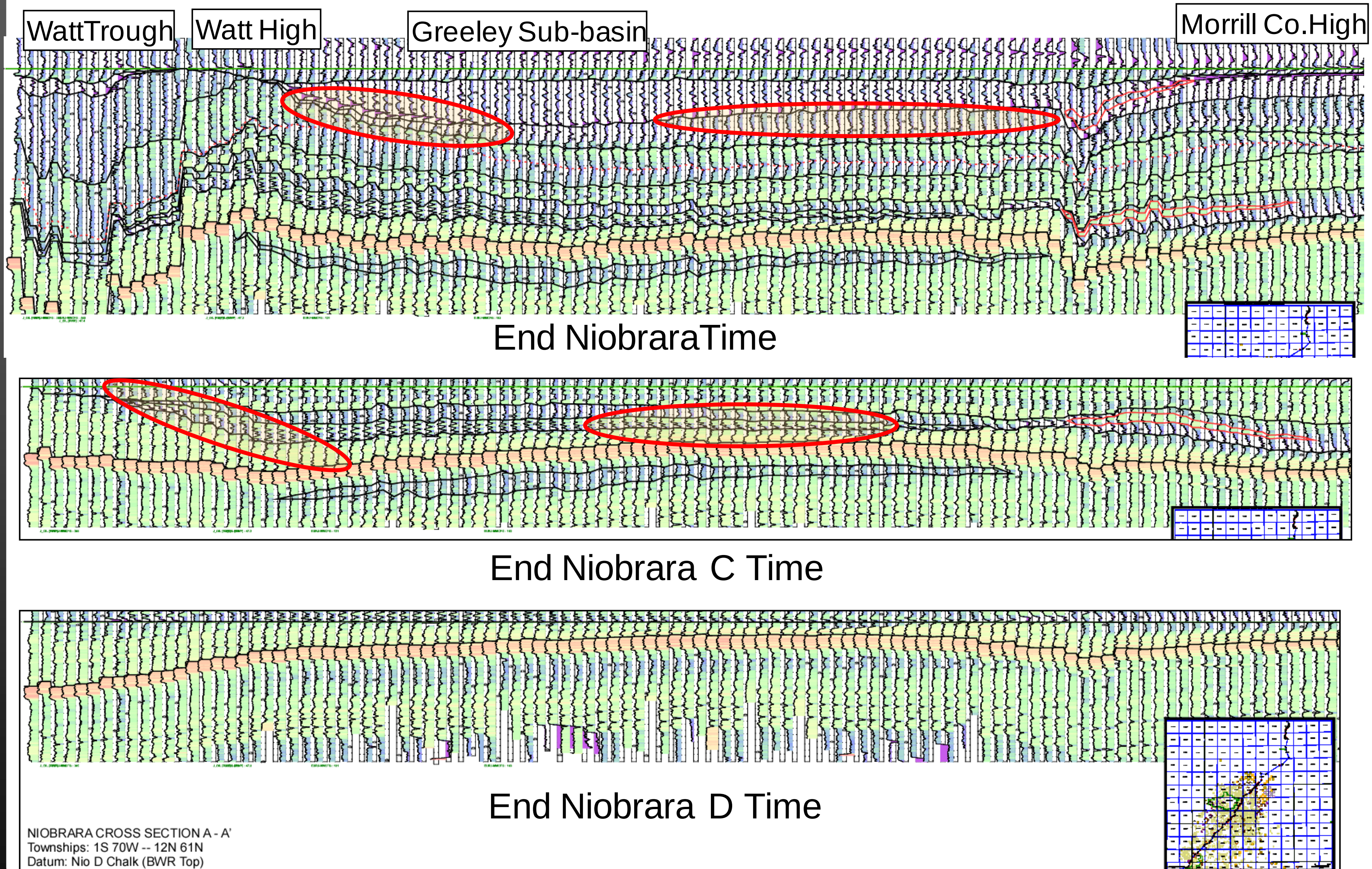
RT: Regressive, restricted circulation

- Clay-rich
- Terrigenous Influx, wet cycle
- High TOC

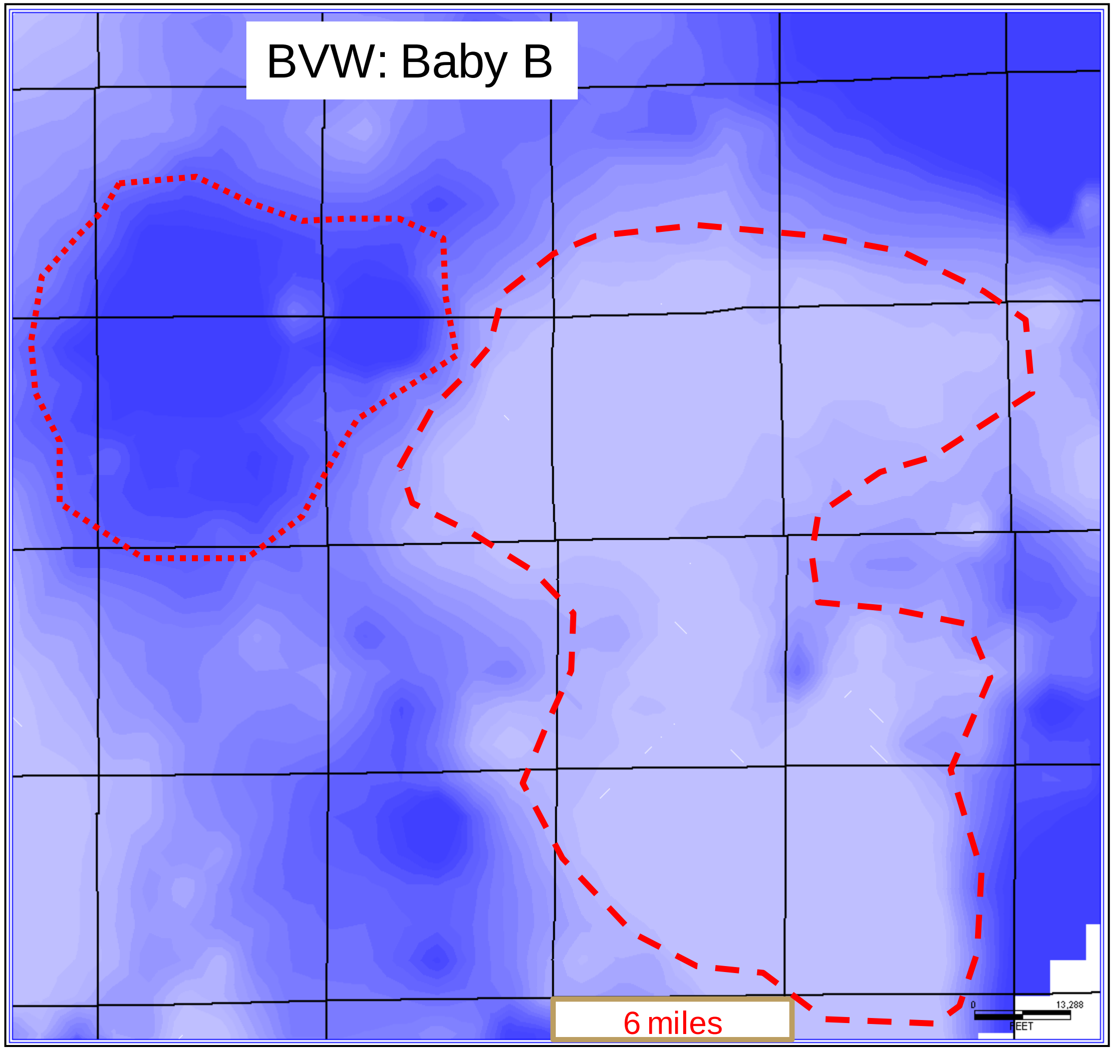
Climate Driven Cylicity

Sequence Architecture –

Intra-basinal tectonics results in varying sedimentation rates & lateral facies changes



Reservoir Property Mapping Within Sequences

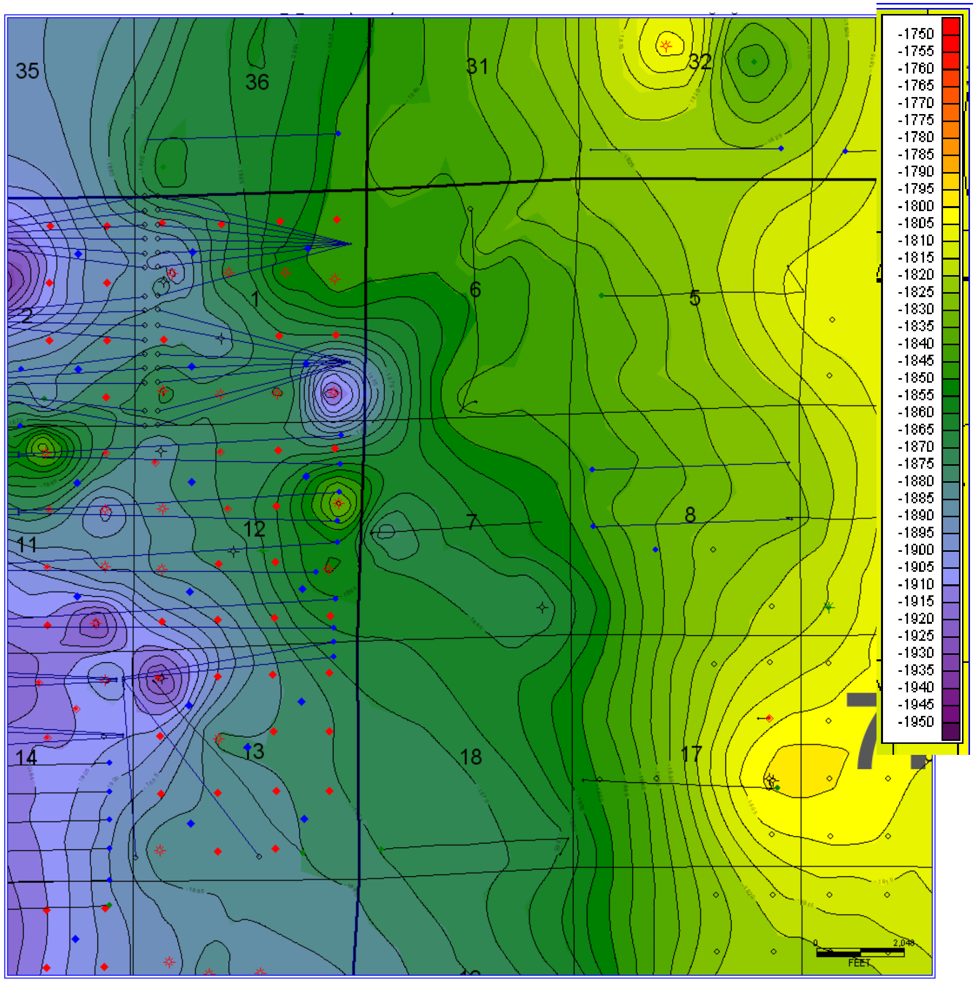


Multi - Township Scale Pods

Understanding lateral extent of properties facilitates appraisal & development

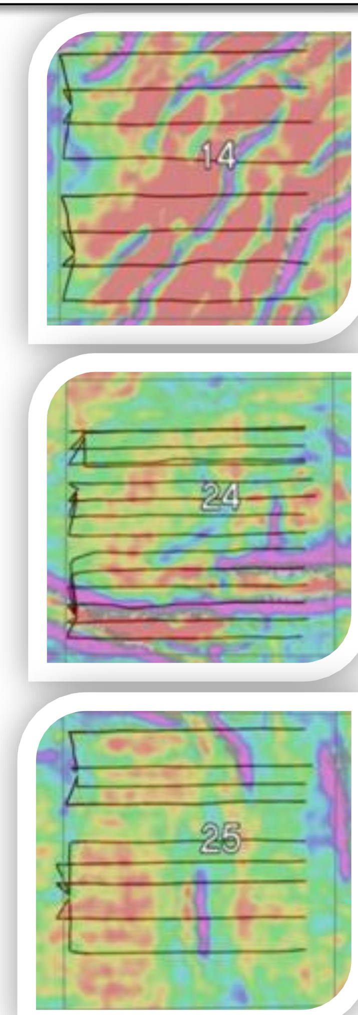
More accurate OOIP determinations

3D Seismic: Don't drill a well without it



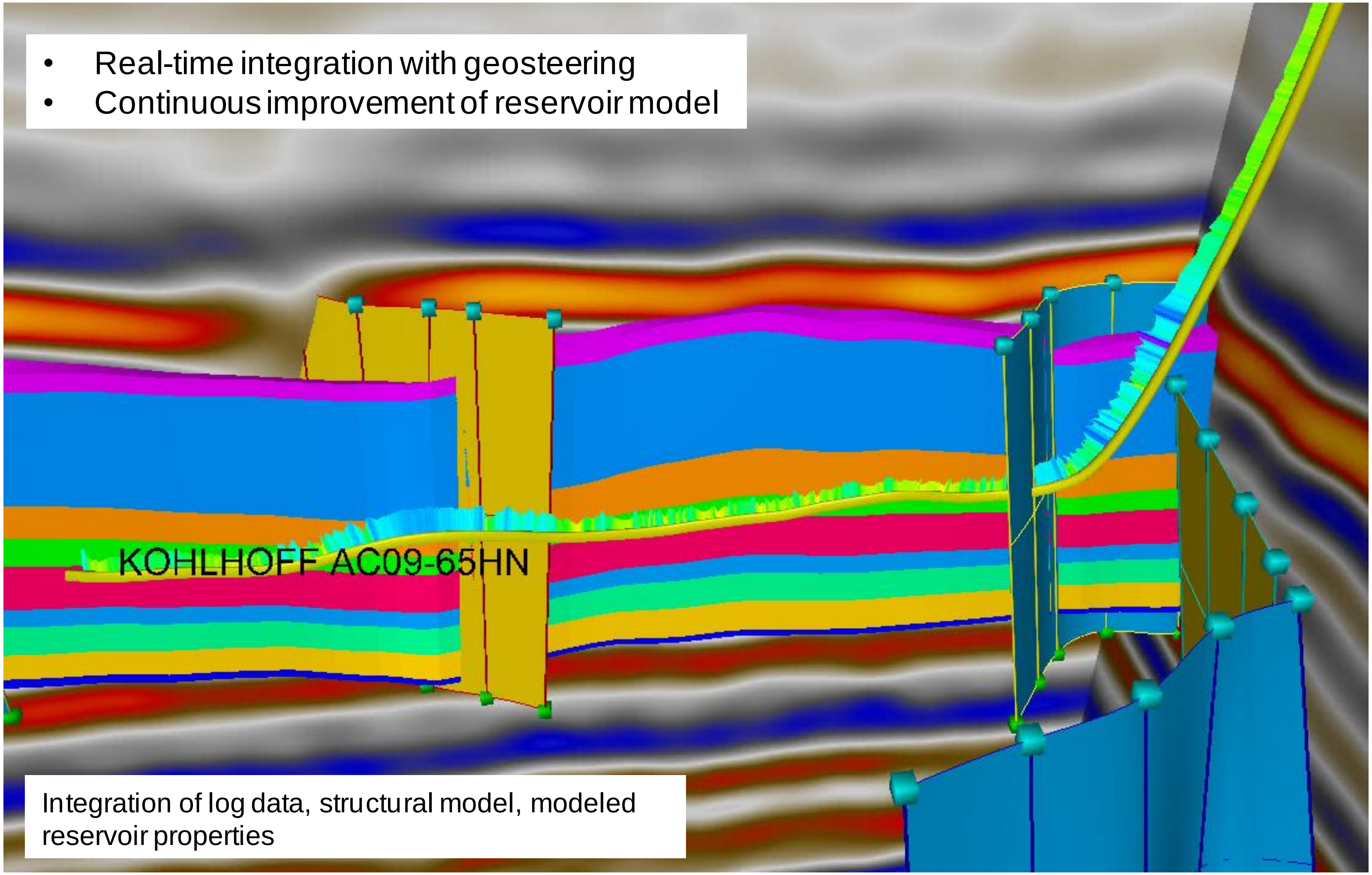
Top Nio A least square gridded surface; C.I. 5 ft

Seismic Amplitude & Structure



Iterative Loop Between Models and Borehole Data

- Real-time integration with geosteering
- Continuous improvement of reservoir model



Integration of log data, structural model, modeled reservoir properties

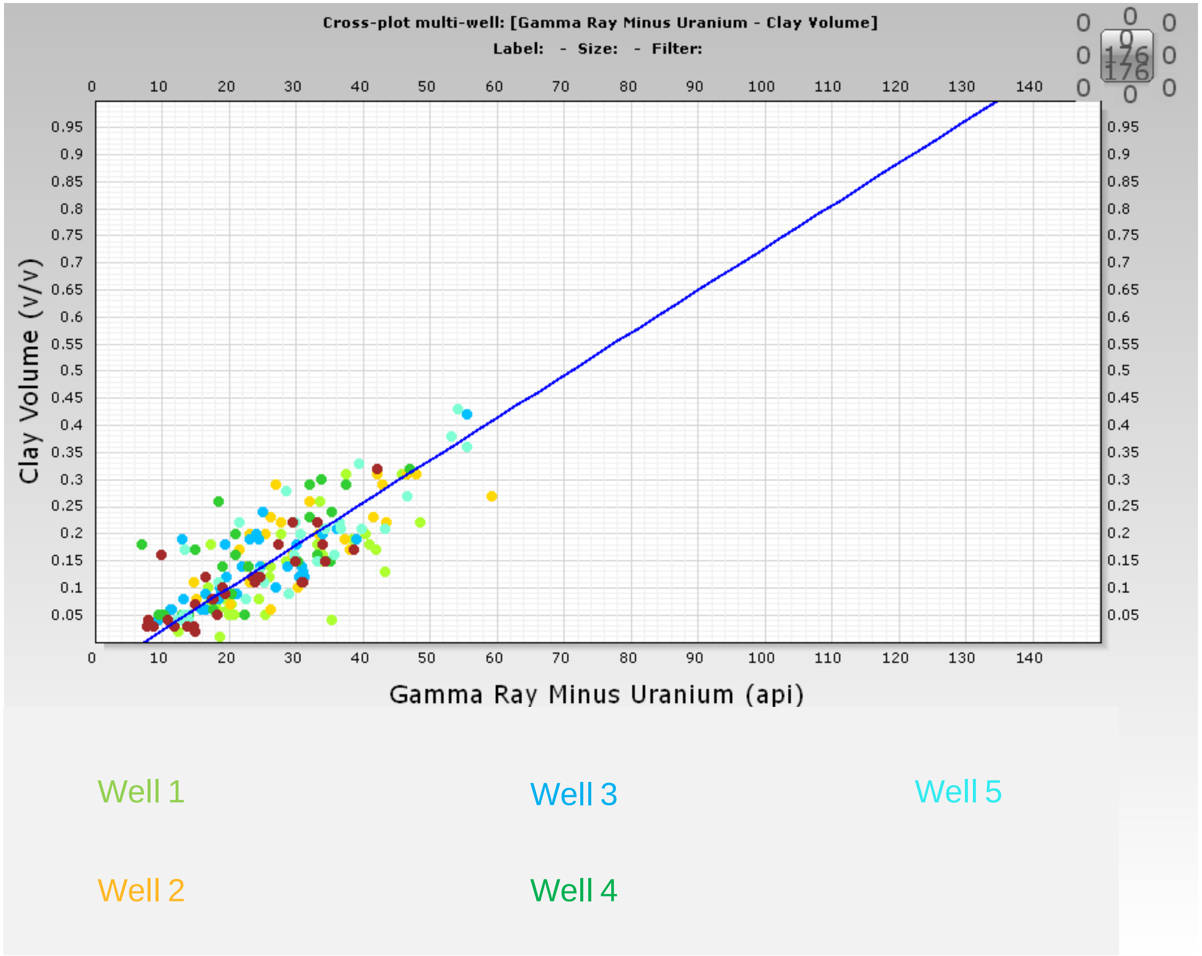
Petrophysics Discussion

What Goes into the Petrophysical Analysis of a Shale Reservoir?

- **Not surprisingly the same things that go into the analysis of conventional reservoirs with a few caveats.**
  1) Fluid saturation is not controlled by capillarity
  2) Pore systems are complex and pore/pore throats are very, very small
  3) Wettability is complex and most mudstones are possibly mixed wettability to strongly hydrocarbon wet.
     - This is an essential part of the story; otherwise it is impossible for hydrocarbons to flow through the matrix
     - Correcting for clay porosity is even more essential than in a conventional reservoir
- **All of these issues impact the Niobrara**

Petrophysics of Unconventional Reservoirs
Example of Clay Volume Determination From the Niobrara

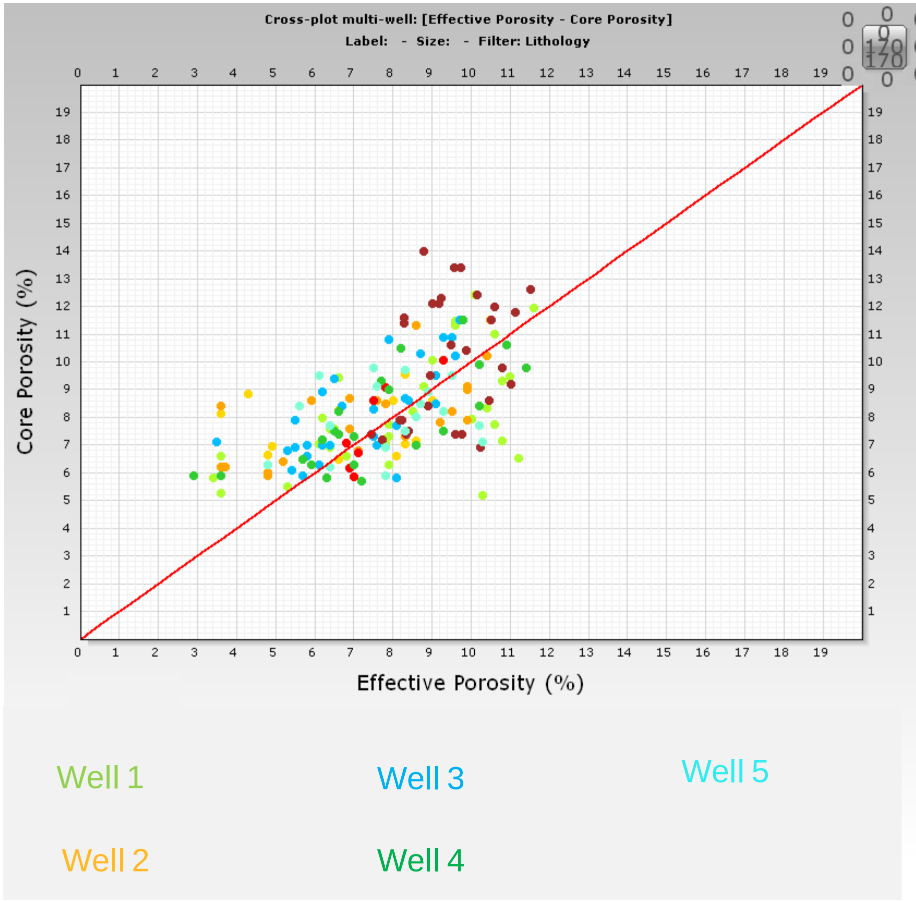
- Clay volume is coming from our spectral gamma ray data
- Does a much better job than total GR



Petrophysics of Unconventional Reservoirs
Example of Clay Corrected Porosity From the Niobrara

- **The density porosity is using a variable matrix and a variable fluid.**
  - The RHOM is a function of the VCL
  - The RHOF is a function of the quick look saturation, the hydrocarbon density and an invasion exponent

- **PHI_DN is used when there is X-Over**



Petrophysics of Unconventional Reservoirs
Example of Clay Corrected Fluid Saturation From the Niobrara

- **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 reservoir fluids (changes in GOR) were also accounted for in the model.**

Major Geologic Rock Types

Burrowed Chalks/Marls	Bioturbated Chalk	2-6 in
	Bioturbated Marly Chalk	2-6 in
	Bioturbated Chalky Marl	2-6 in
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Bioturbated chalks + marly chalks

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Alternating bioturbated/laminated beds, with variable bed thicknesses (1-6")

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	(Lump with above} **Alternating -- Crinkly**-Laminated Burrowed Marly Chalk	1-2"

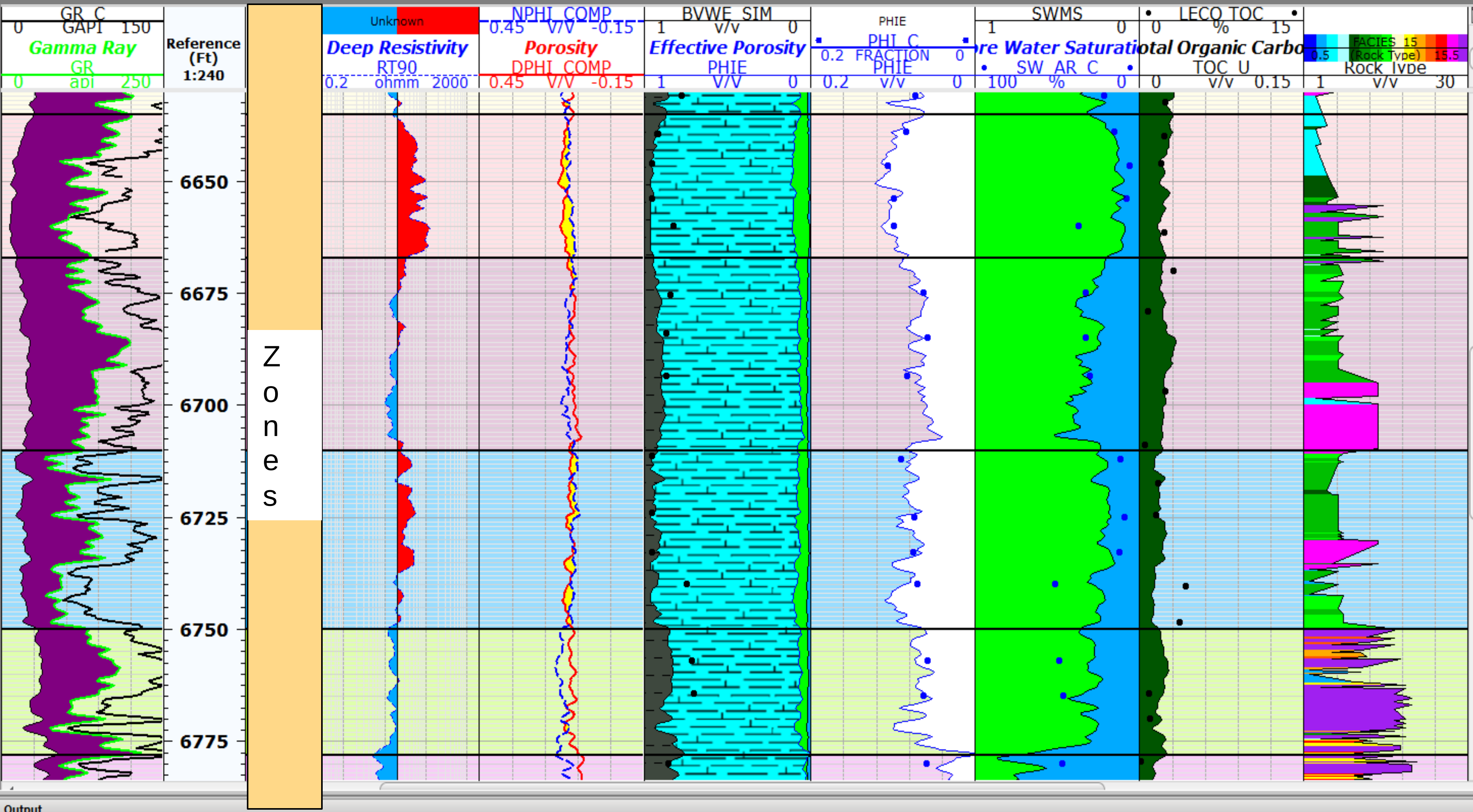
Alternating bioturbated / "crinkly-laminated" beds with variable bed thicknesses (1-6")
Reservoir Facies

(Dunham Classif) Burrowed Grainstones to Marlstones (~ Ft. Hays)	Bioturbated bioclastic foram Packstone (grain-dominated) (assumed > 50% coccoliths)	2-6 in
	Bioturbated bioclastic foram Packstone/Wackestone	2-6 in
	Bioturbated Wackestone/Mudstone ("Marlstone")	2-6 in
	Burrowed Marl/Chalky Marl	2-6 in

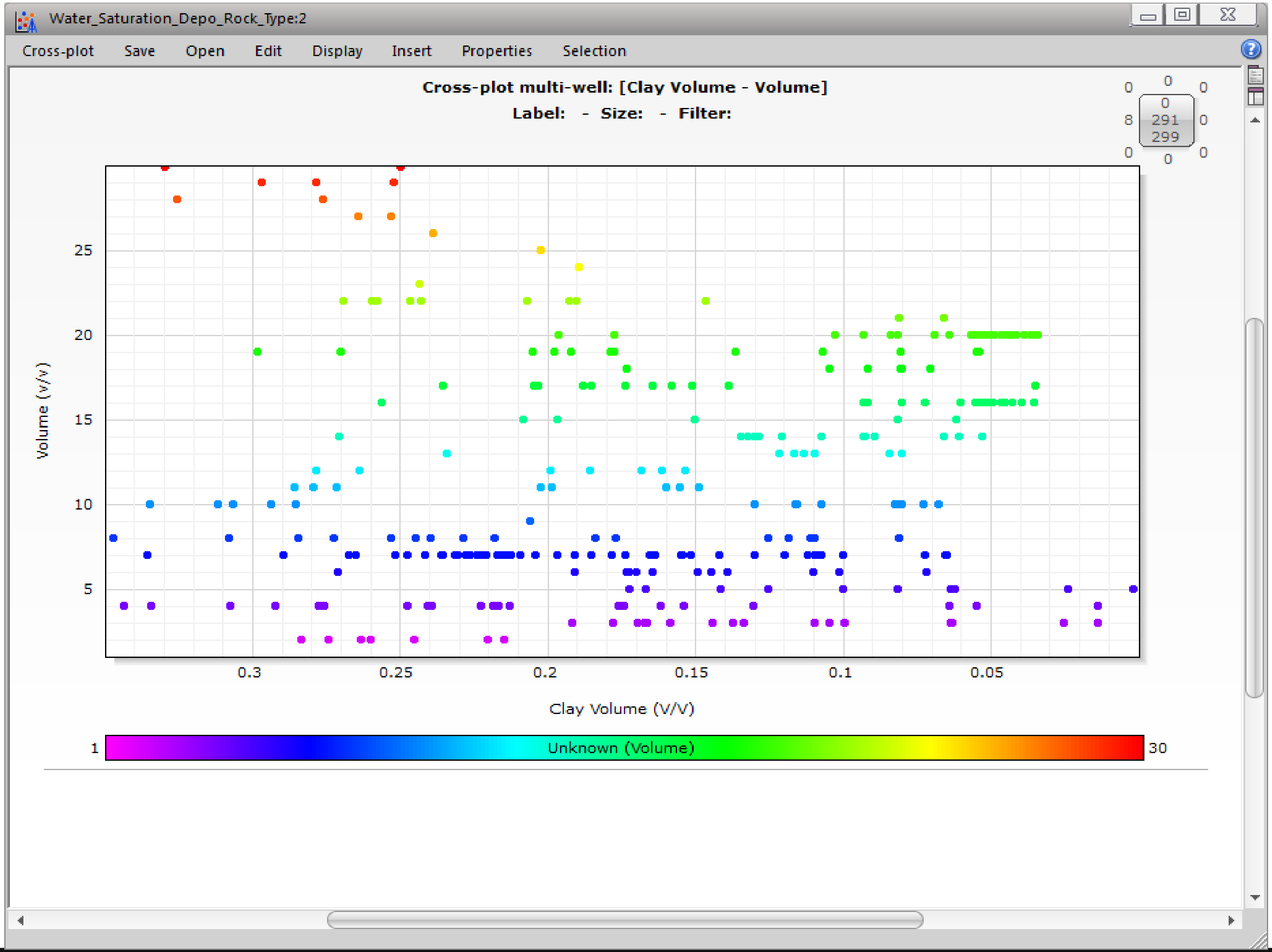
Bioturbated foram/bioclastic packstones (Ft. Hays)

noble energy

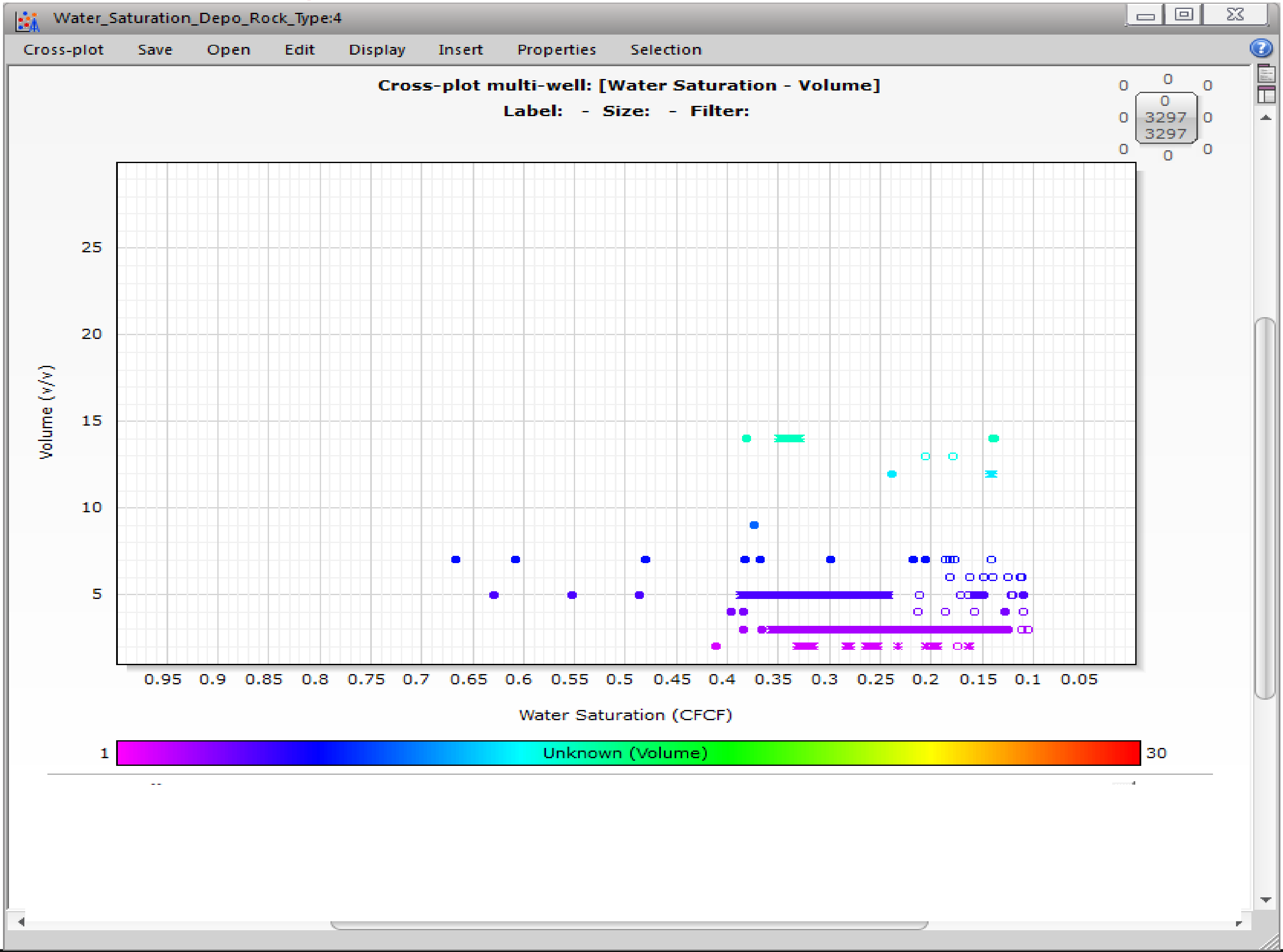
Key Well 1 Computer Processed Log with Geologic Rock Types



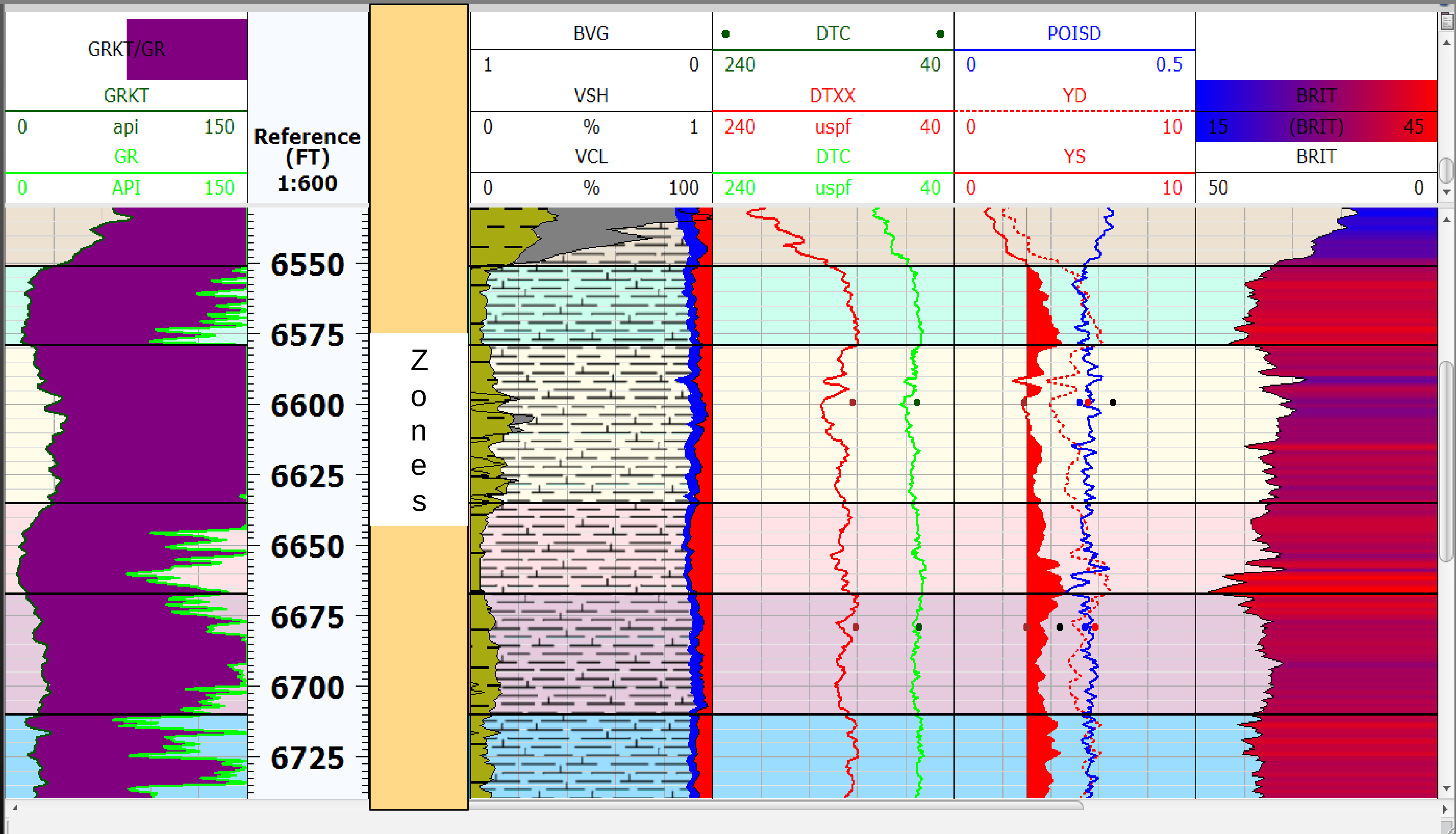
Total Niobrara from Key Well 1 in Wattenberg Crossplot Geologic Rock Type vs VCL



Four Colorado Cored wells Zone 3 Niobrara Crossplot Geologic Rock Type vs SW



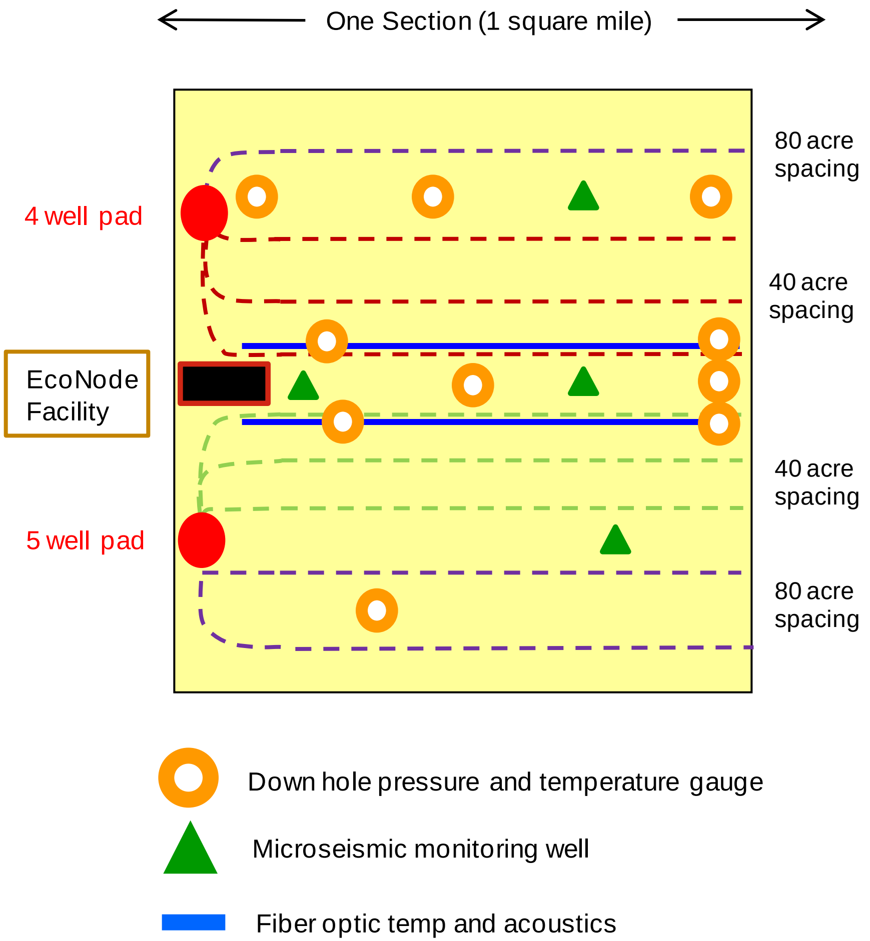
Key Well 1
Mechanical Rock Properties Plot



In-Situ Underground Laboratory

- **Subsurface Data Acquisition**
  - 10 down hole pressure and temperature gauges
  - 43,800 ft of down hole fiber optic cable for temperature and acoustic measurement
  - Direct in-situ pressure, stress, fracture mechanics measurement
  - 3D seismic, down hole microseismic, and vertical seismic profile
  - Well logs: spectral gamma ray, resistivity logs, porosity logs
  - Liquid tracers
  - 374 ft whole core analysis
  - Core extract and produced oil geochemistry

Research Section



Summary

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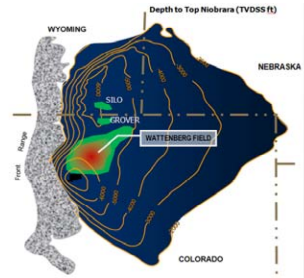
  - Thermal history parallels GOR trends
- **Traditional petrophysical workflows, with added rigor where needed, will allow full scale reservoir evaluation**
  - There is a correlation between geologic rock types and log response
- **Conventional stratigraphic nomenclature does not always relate to subsurface rock properties**
- **3D seismic decreases operations and targeting risk**
  - Opportunities for dynamic geosteering
  - Static and dynamic reservoir modeling
- **Integrated data gathering resulted in increased OOIP estimates and actual recovery**



Koskella & Parney, 2012

Presenters' notes: 10,000 locations planned to drill, executing a 300-500 well program per year. $1.7 B capital program. Rate of returns per well is excellent. Leverage expertise to unlock additional resources.

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