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

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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


Website Cited

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Marshall Deacon & Robert Lieber
Noble Energy, Inc – Denver, Colorado

2013 AAPG Annual Convention
Goal: Responsibly maximize economic recovery volumes from the Niobrara concurrent with evolving technical understanding

Methods: Integrated data collection and analysis - Try new/different things

Outcome: 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

DJ Basin/Niobrara Stratigraphy

Top Niobrara Depth (TVDSS ft)

Typical Depth

- Pierre Shale: 6800'
- Sharon Springs: 275' - 350'
- Niobrara: 7100'
- CODELL SS Fairport Greenhorn Graneros J Sand Dakota: 7600'

- A Chalk
- B Chalk
- C Chalk
- Ft. Hayes
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

- NBL 2013 150+ wells
- J sand
- Sussex/Shannon
- Codell/Niobrara Vertical
- Niobrara Horizontal
Niobrara Development: 1950-2006 Vertical Times

Pierre Shale

A Chalk
A Marl
B Chalk
B Marl
C Chalk
C Marl
D Chalk
Ft Hays Ls
Codell Ss
Carlile
Niobrara Development: 2007-2013 Horizontal Breakthrough

Sharon Springs

- A Chalk
- A Marl
- B Chalk
- B Marl
- C Chalk
- C Marl
- D Chalk
- Ft Hays Ls
- Codell Ss
- Carlile
Determining Sweet Spots & Resource Distributions

Temperature Gradient °F/100’

SILO

Ro = 0.7

WATTENBERG

Denver

WELL EUR
8 Strategically Placed Core Wells
- Over 2400 ft of core
1650 mi² 3D seismic
Petrophysical Logs
- Formation image logs on laterals
Microseismic on 55 wells
Production data
“In-situ lab” section
- DTQ, 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

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

Basin to nanometer scale – it all plays a role

Microporosity in pellets

Coccolith porosity

Blakey, 2006

Seaway
Niobrara Rock Properties - Starts With Understanding The Pellets
### Niobrara Carbonate Facies:

#### Burrowed Chalks/Marks
- 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/Marks
- 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 Bioturbated/Laminated Beds
- Interbedded Bioturbated/Laminated Marly Chalk: > 4” (break out individual chalk bed if > 5-6”)
- Bioturbated Alternating Bioturbated/Laminated Marly Chalk: 1-3”
- Alternating Bioturbated/Laminated Marly Chalk: 1-3”
- Alternating Bioturbated/Laminated Chalky Marl: 1-3”

#### Crinkly-Laminated Beds
- Crinkly-Lam Bedded Chalk and Marly Chalk: > 4” (break out individual chalk bed if > 5-6”)
- Alternating Crinkly-laminated/bioturbated Marly Chalk and Chalky Marl: 0.5-4.0”

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- Bioturbated chalks + marly chalks
- Laminated chalks + marly chalks
- Alternating bioturbated/laminated beds
- Crinkly-laminated Chalk + Marl interbeds

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- 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

“Chalking”

Aggradational

“Marling”

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

WattTrough  Watt High  Greeley Sub-basin  Morrill Co.High

End Niobrara Time

End Niobrara C Time

End Niobrara D Time

NIOBRARA CROSS SECTION A - A'
Townships: 1S 70W -- 12N 61N
Datum: No D Chalk (EWR Top)

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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.l. 5 ft
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
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

Bioturbated chalks + marly chalks

Laminated chalks + marly chalks

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

Alternating bioturbated / ”crinkly-laminated” beds with variable bed thicknesses (1-6”)

Reservoir Facies

Bioturbated foram/bioclastic packstones (Ft. Hays)
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

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Legend:

- BVG
- DTC
- POISD

- VSH
- USPF
- DTC
- YD
- YS

- BRIT
- (BRIT)

Zones:

- 6575 - 6600
- 6625 - 6650
- 6700 - 6725
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
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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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