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4D Seismic Monitoring for Assessing Reservoir Heterogeneity and its Impact on Hydraulic Fracture Stimulation

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Geophysical Engineer,
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Poll Question

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What is your professional background?

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Acknowledgements

- Reservoir Characterization Project (Colorado School of Mines)
- Dr. Ali Tura, Dr. Tom Davis, Dr. Bob Benson, Dr. Jennifer Miskimins (from the Colorado School of Mines)
- Dr. Bob Barree (GOHFER)
- RCP sponsors, students and supporting staff

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4D Seismic Monitoring for Assessing Reservoir Heterogeneity and its Impact on Hydraulic Fracture Stimulation

- Motivation for Seismic Monitoring
- Seismic Monitoring Techniques in Unconventional Reservoirs
- Case Study: The Niobrara Shale
  - Study area
  - Reservoir characterization for stress heterogeneity
  - Simulation modeling of hydraulic fracture stimulation treatment
  - Microseismic & 4D seismic integration with hydraulic fracture simulation
- Summary

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Motivation for Seismic Monitoring

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- EUR in many Unconventional Oil reservoirs could be as low as 2% → **Increase EUR**
- Limited drainage areas around horizontal wells → **Increase effective drainage area**
- **Identify bypassed production** intervals within the reservoir
- **Validate** reservoir simulation models

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Microseismic Monitoring in UR

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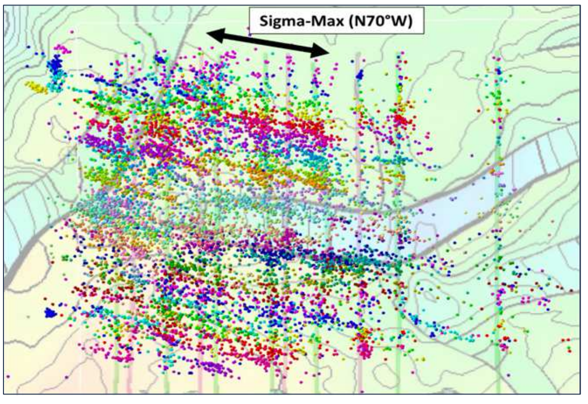
- Events represent small earth-quakes within the reservoir that depict the affect of shear caused by the induced hydraulic fracturing
- The event density typically captures the intensity of shear within the reservoir
- Useful for predicting possible well interference and guiding plans for well spacing within development
- Useful for inferring azimuth of Sigma-H Max



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4D Seismic Monitoring in UR

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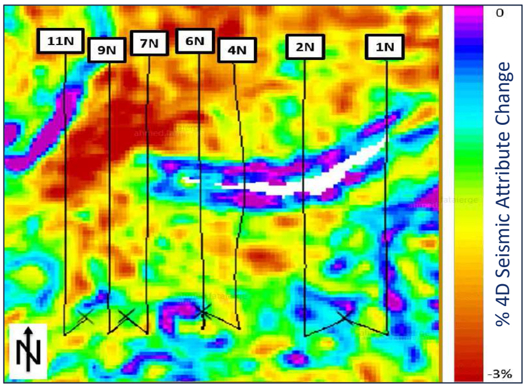
– 4D Time-lapse Multicomponent 3D Seismic Surveys
– Seismic surveys are acquired at different life cycles within field development and compared through attribute differencing of simultaneously processed surveys
– P wave seismic interpretations are used to monitor the affect of fluid and pressure changes within the reservoir
– Shear "S-wave" seismic interpretation (not affected by fluid in reservoir) used to map and monitor fractures within the reservoir



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Optimization is Key to Increasing Hydrocarbon Recovery

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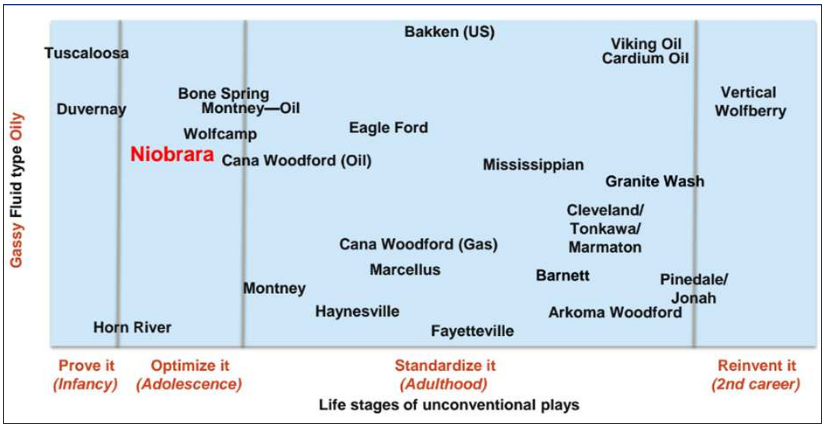
- Niobrara shale play is calculated to have a total of technically recoverable reserve around **3.7 billion barrels** of oil and **46.5 Tcf** of gas
- Still Room for **optimization** in hydraulic fracturing operations (IHS, 2015)



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(IHS, 2015)

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Case Study: The Niobrara Reservoir

- Early development through hydraulic fracturing of vertical wells (1979)
- Multistage Hydraulic Fracturing in Horizontal wells (2009)
  - Plug and Perf Completions
  - Sliding Sleeve Completions
  - Up to 18 horizontal wells per section
  - Up to 30 frac stages per well
- Optimizing field development through
  - Well spacing
  - Stimulation treatment design (fluid selection, number of stages, proppant)
  - **Reservoir monitoring**

IHS 2015

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IHS 2015

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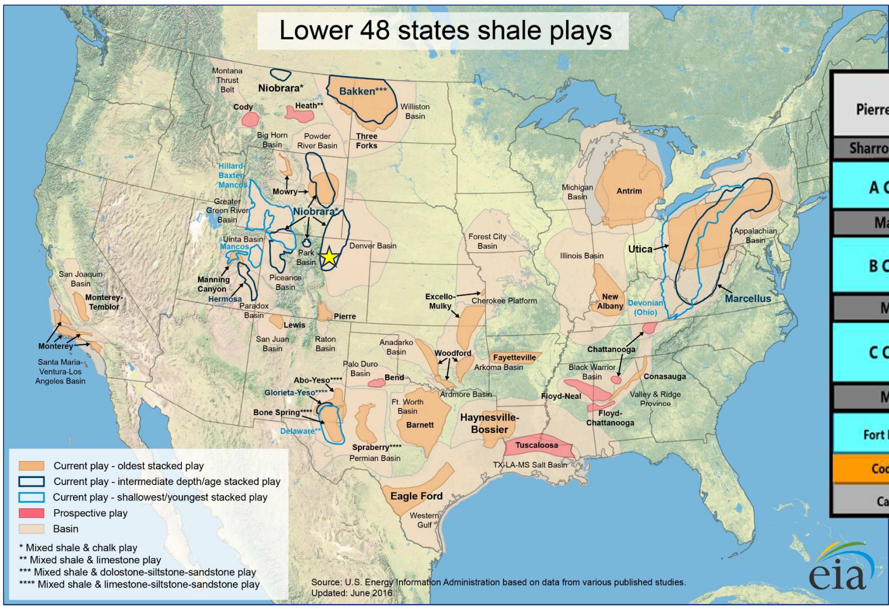
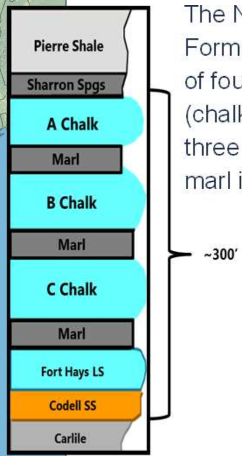
Niobrara Shale Play Extent





The Niobrara Formation consists of four limestone (chalk) units and three intervening marl intervals

Sonnenberg 2011

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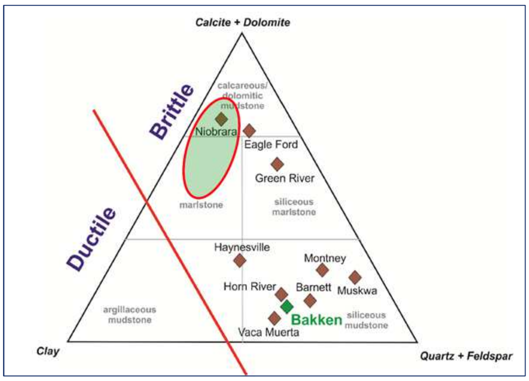
The Niobrara Shale

- Similar to the Eagle Ford
- Predominantly Calcite Rich
- Clay Content 5-10% in Chalk



(Sonnenberg, 2012)

	Barnett	Bakken	Marcellus	Niobrara
Depth	6500-8500ft	1000-9000ft	4000-8000ft	**6800-7100ft**
Net thickness	100-600ft	20ft	50-250ft	**120ft**
TOC	4.5%	5-20%	1-5%	**1-6%**
Clay content	<35%	<20%	20-35%	**10%**
Porosity	Average ~4.5%	5.5-9%	1.6-7%	**2-8%**
Lithology	Siliceous shale, Calcareous layer	Shale, Dolomite, Siltstone	Shale, Limestone	**Chalk, Marl**

(U.S. Energy Information administration, 2011)

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Study Area: The Niobrara within Wattenberg Field

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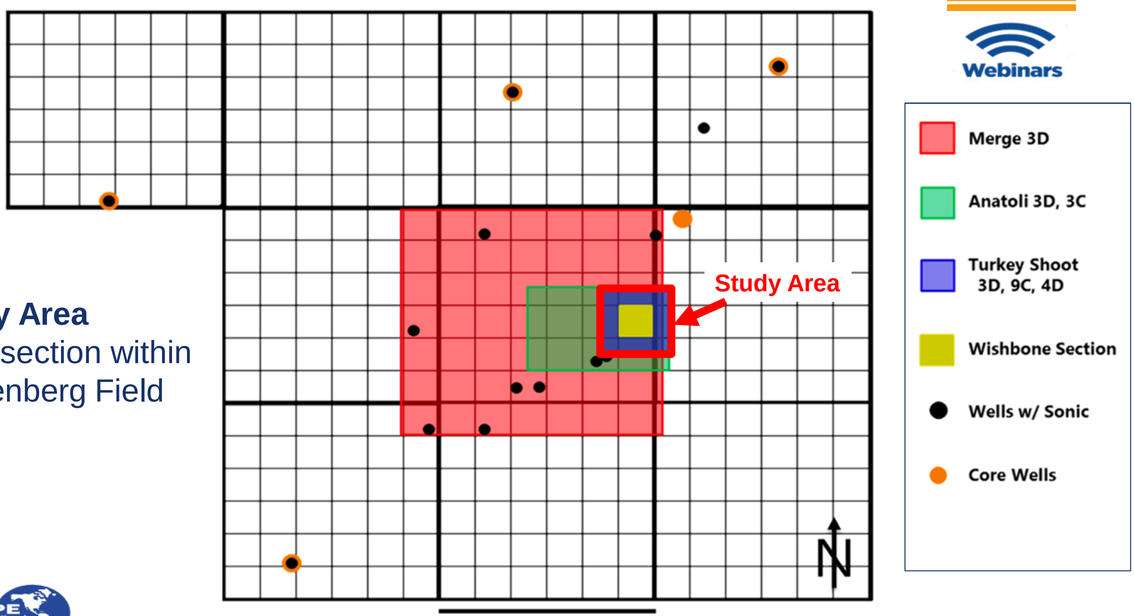

Study Area
1 mi^2 section within Wattenberg Field

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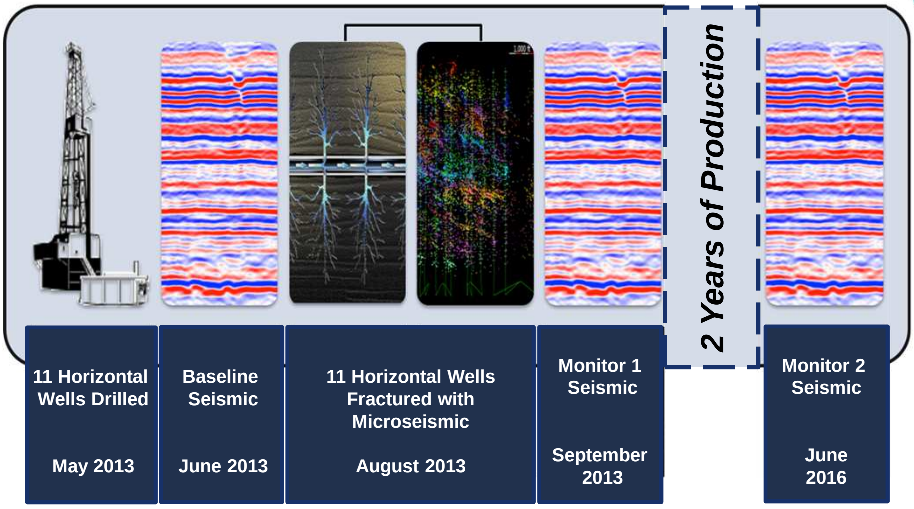
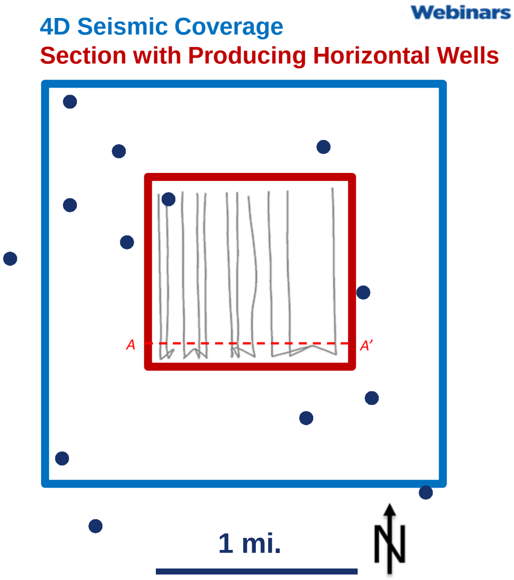
4D Time-lapse Seismic Acquisition Time-line

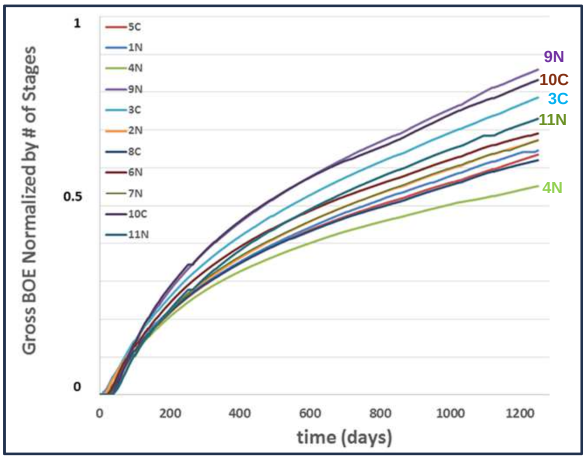


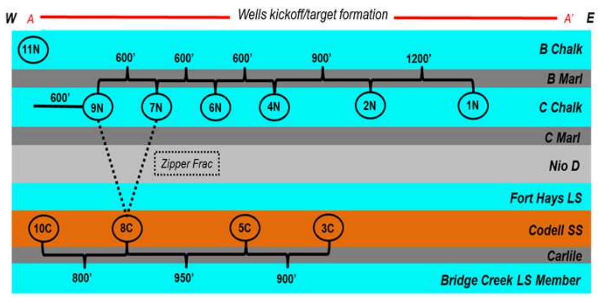
Integrated Data-set for Assessment

- 11 hydraulically fractured horizontal wells
- 4D time-lapse seismic
  - Pre-Hydraulic Fracturing
  - Post-Hydraulic Fracturing
  - Post-Production
- Surface microseismic
- Vertical wells with petrophysical logs
- 2 year production data from 11 Hz Wells



Normalized Oil Production from Wells





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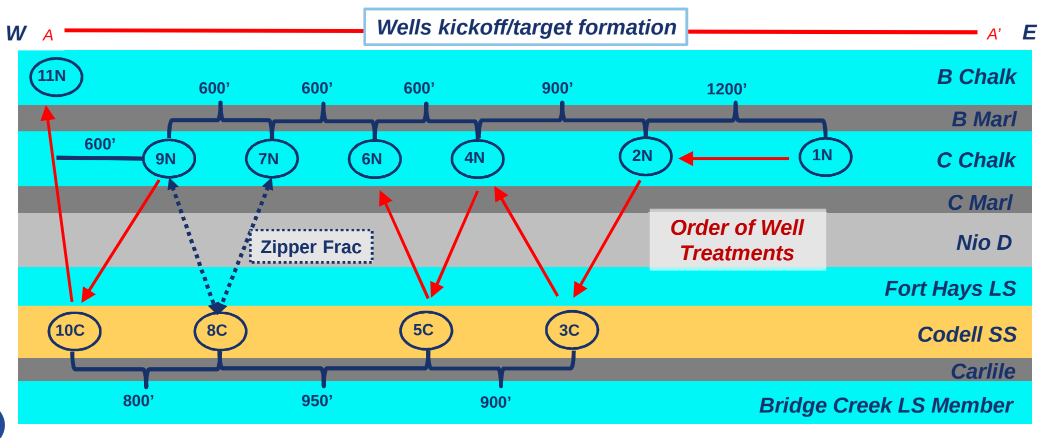
Drilling and Completion

- Wells are completed from east to west
- Closer well spacing towards the west (600ft – 1200ft)
- ~32 stages per well (predominantly sliding sleeve completions)



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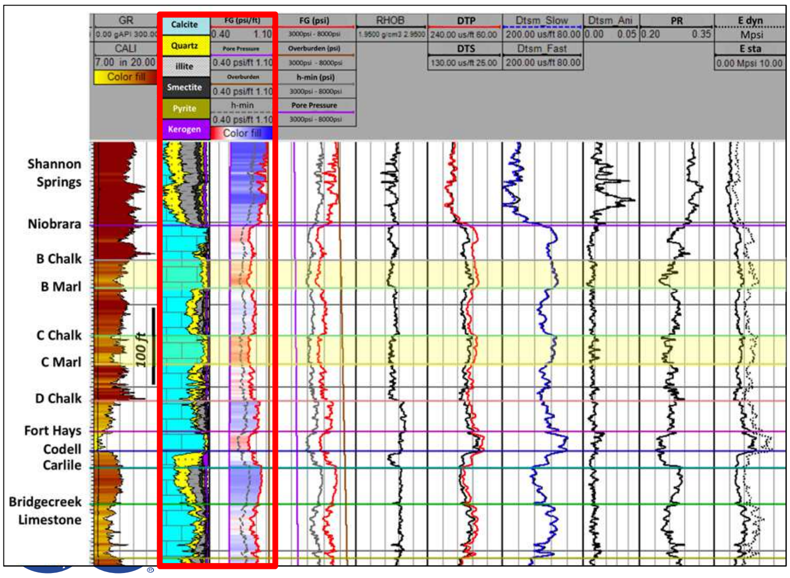
1D Vertical Stress Profile (Homogeneous Stress Model)



Chalk intervals targeted for more favorable hydraulic fracturing

- **Lower stress intervals**
- **High Young's, Low Poisson's**

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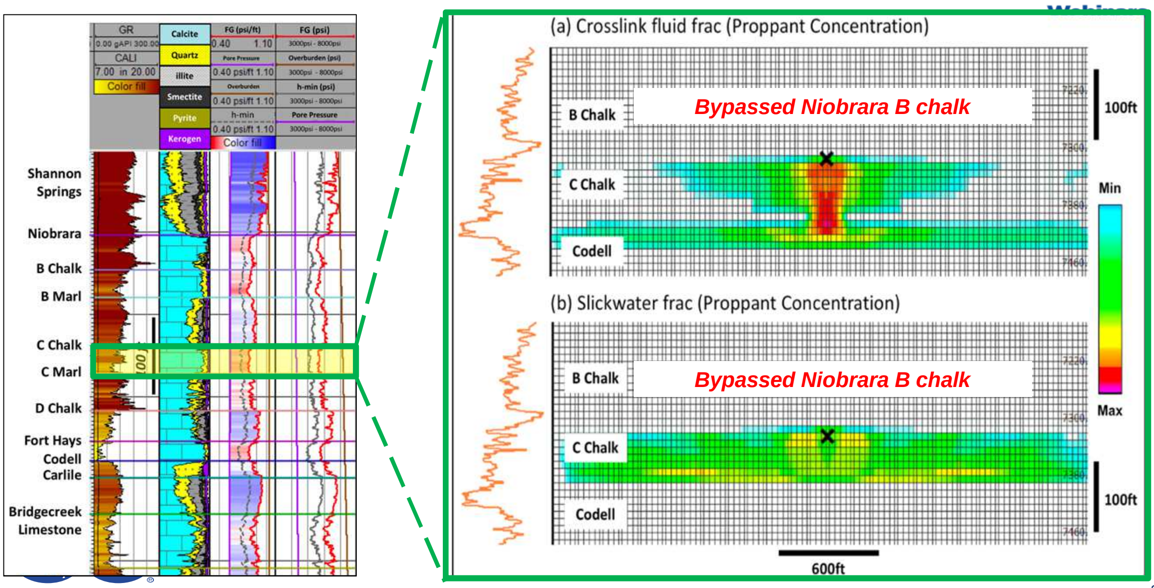
Niobrara C chalk stimulation treatment (Homogeneous Model)



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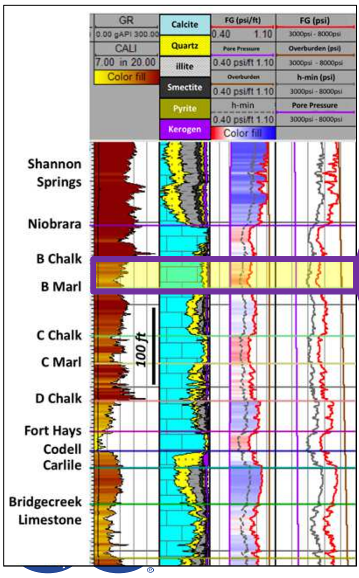
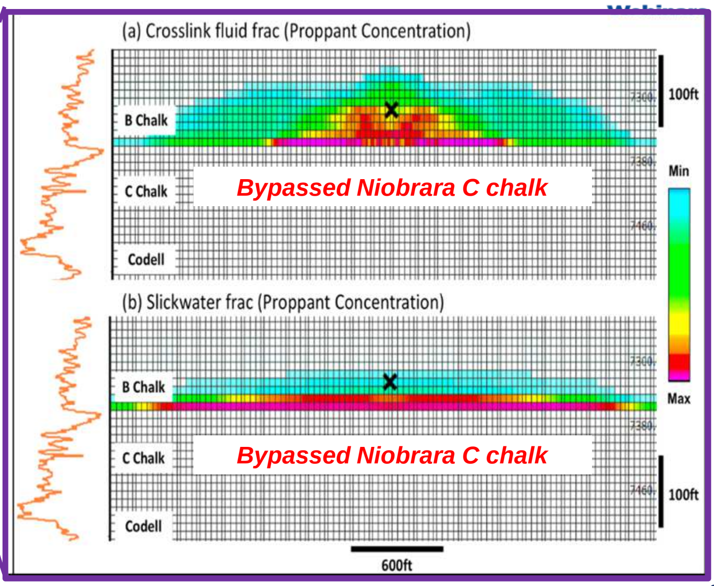
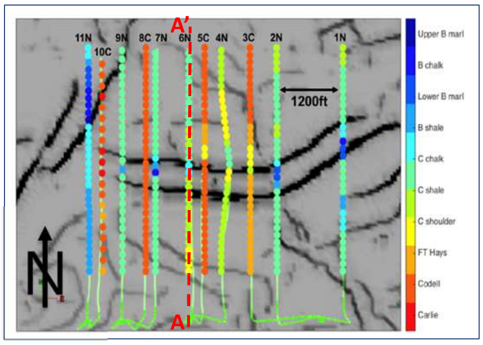
Niobrara B chalk stimulation treatment (Homogeneous Model)



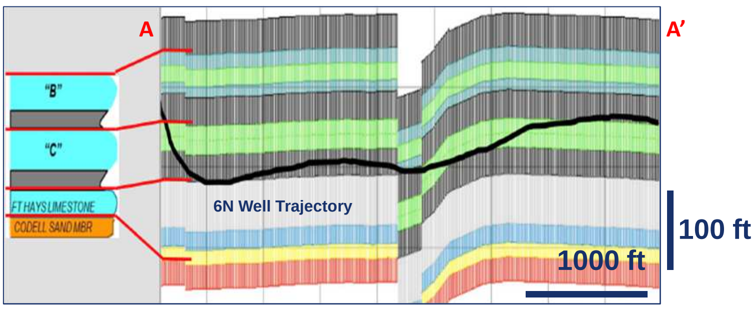


Reservoir Heterogeneity

Homogeneous 1D stress model is not suitable for analyzing the affects of reservoir heterogeneity on hydraulic fracturing and production



Seismic Fault Map within the Niobrara



Seismic cross section along a horizontal well traverse

3D Geomechanical Model Used to Characterize the Reservoir Heterogeneity

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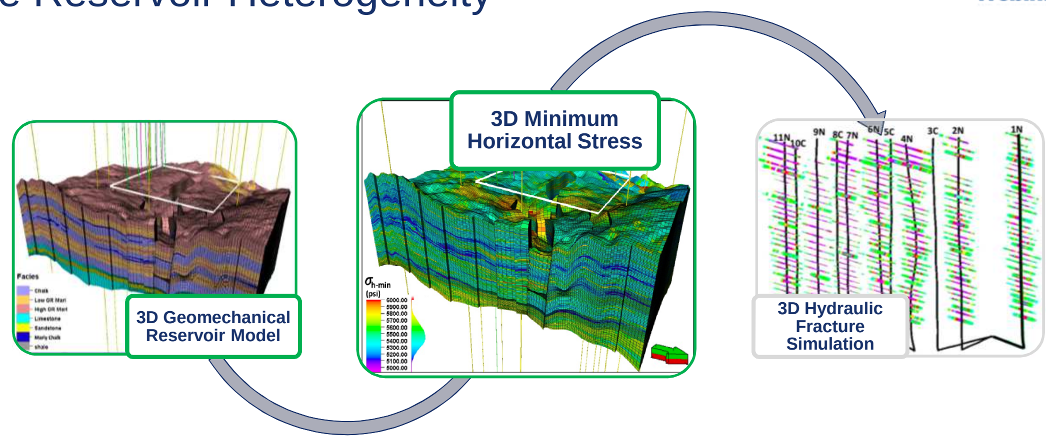

A 3D geomechanical model was used to map the distribution of stress within the reservoir while taking into account the lithological variability and fault planes within the reservoir

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Heterogeneity Better Represented in 3D Stress Model

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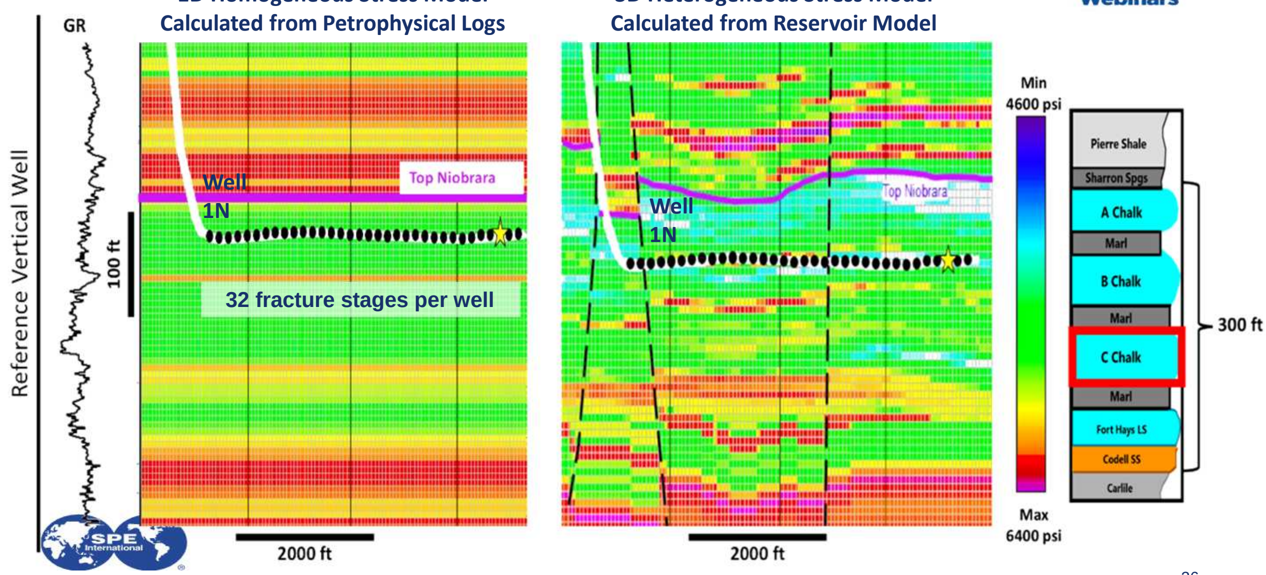
1D Homogeneous Stress Model Calculated from Petrophysical Logs

3D Heterogeneous Stress Model Calculated from Reservoir Model



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Post Treatment Analysis of HF Stimulation

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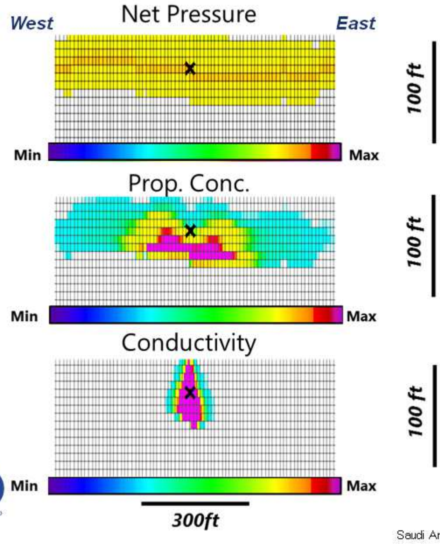
HF Simulation using 1D Stress Model

HF Simulation using 3D Stress Model



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Post Treatment Analysis of HF Stimulation

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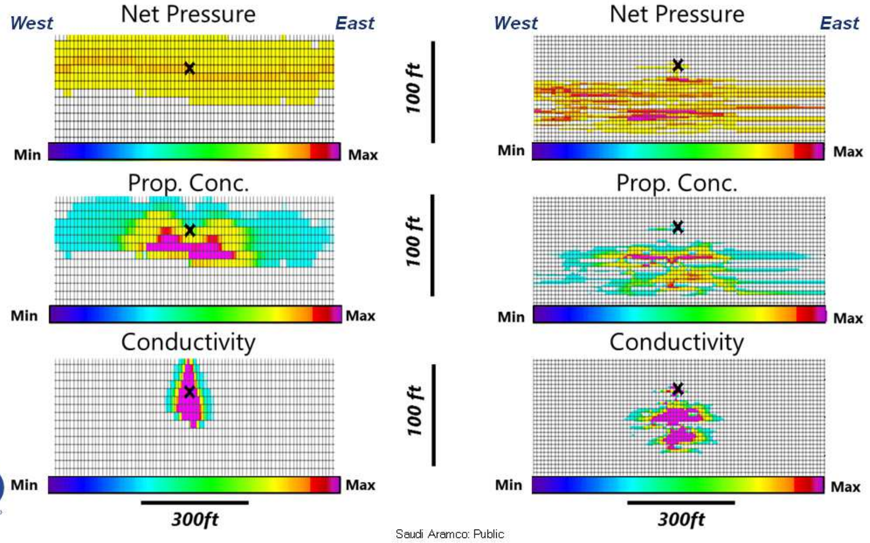
HF Simulation using 1D Stress Model

HF Simulation using 3D Stress Model



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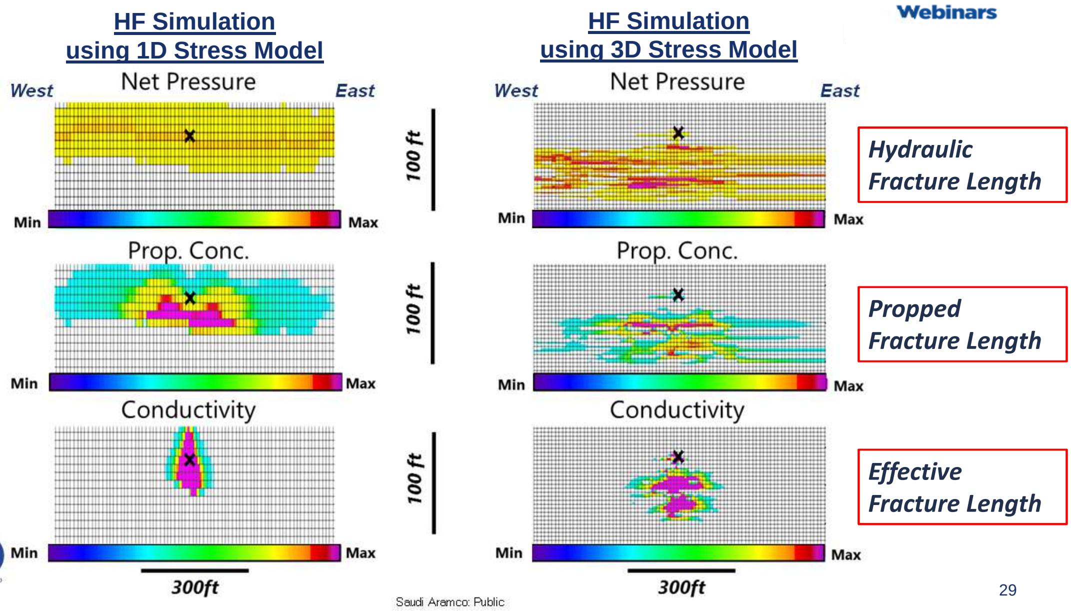
Post Treatment Analysis of HF Stimulation



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What is Effective Fracture Length?

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- **Hydraulic fracture length** is the pressure communication length caused by the hydraulic fracturing while the hydraulic pumps on surface are actively pumping
- **Propped fracture length** is the length of the fracture containing proppant
- **Effective fracture length** is the propped fracture length that provides communication with the wellbore during the production cycle

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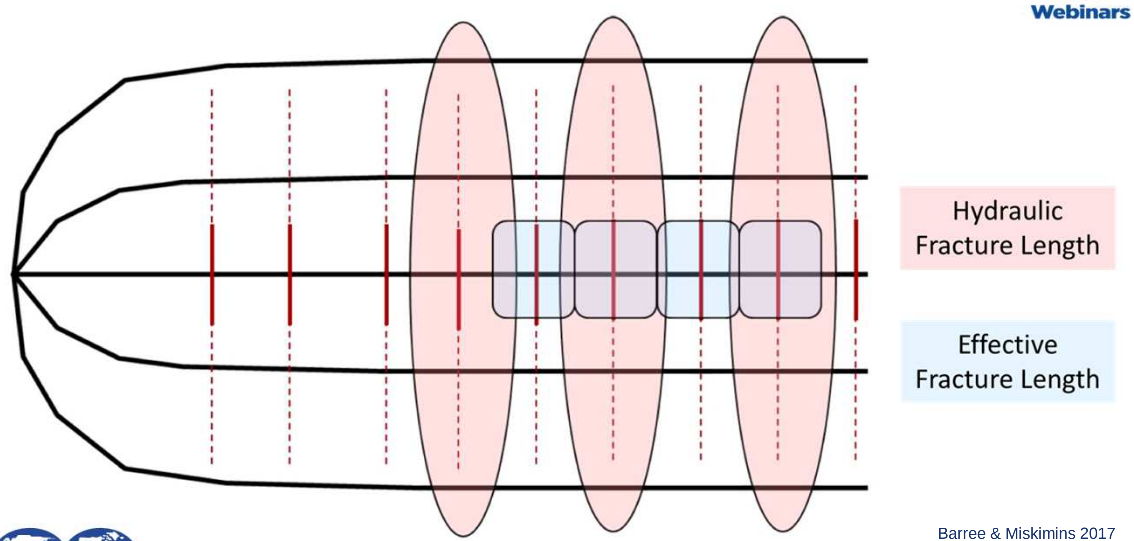
Hydraulic Fracture Length ≠ Effective Fracture Length



Barree & Miskimins 2017

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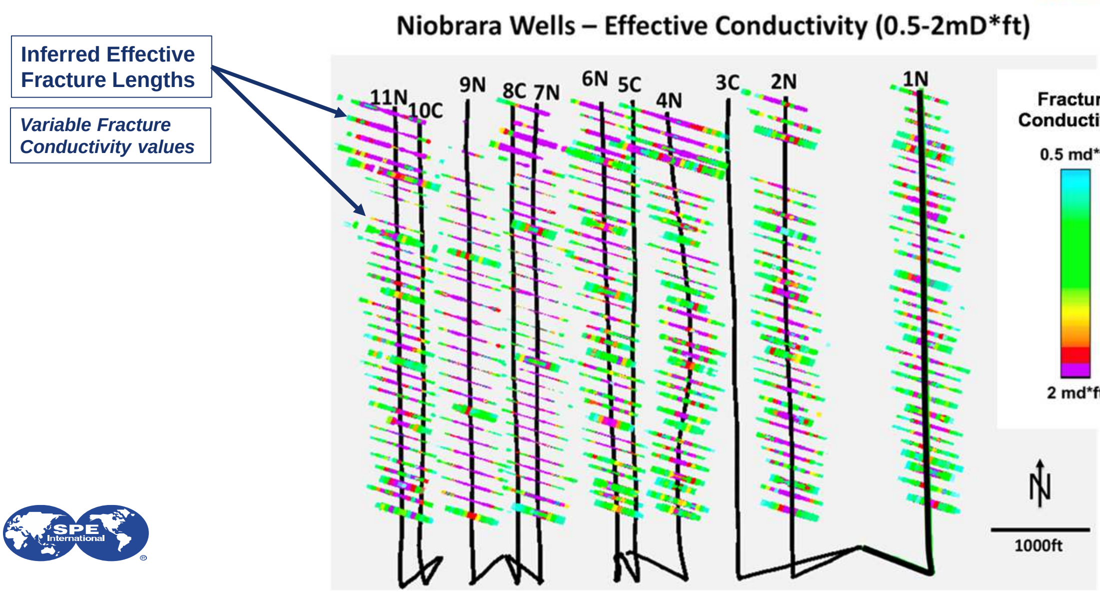
Effective Fracture Lengths Inferred from 3D HF Simulation

(Niobrara – Codell Wells)



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Effective Fracture Lengths Inferred from 3D HF Simulation

(Niobrara – Codell Wells)

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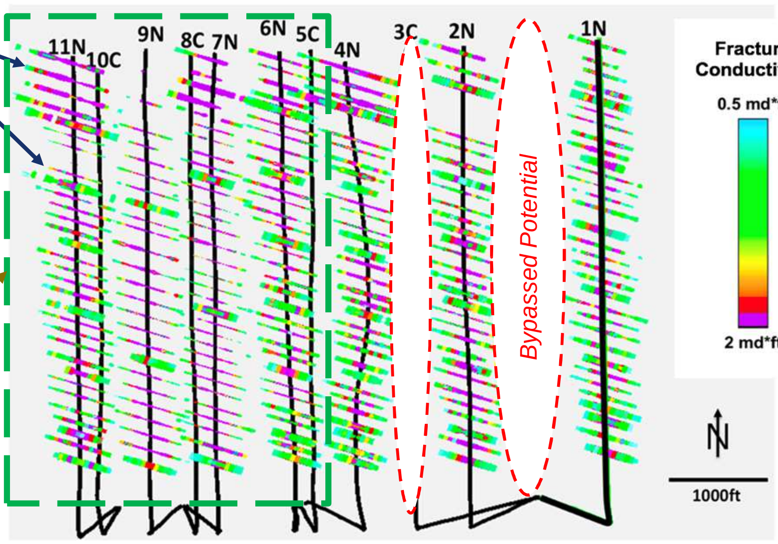
Inferred Effective Fracture Lengths

Variable Fracture Conductivity values

Closer well spacing appear to allow for interference between wells



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Hydraulic Fracturing Geometry (In-Zone Stages)

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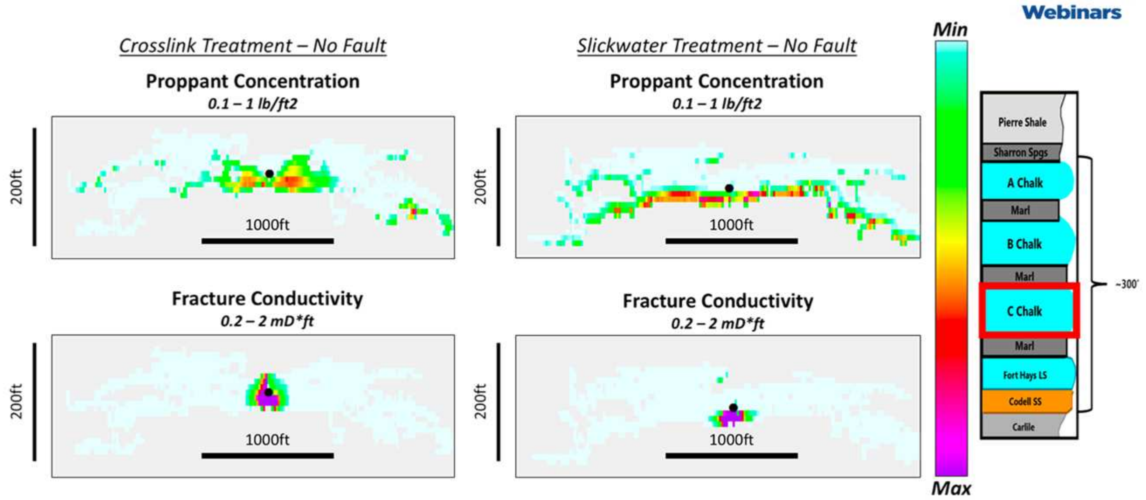

Well 6N – Stage 5 – No Faults

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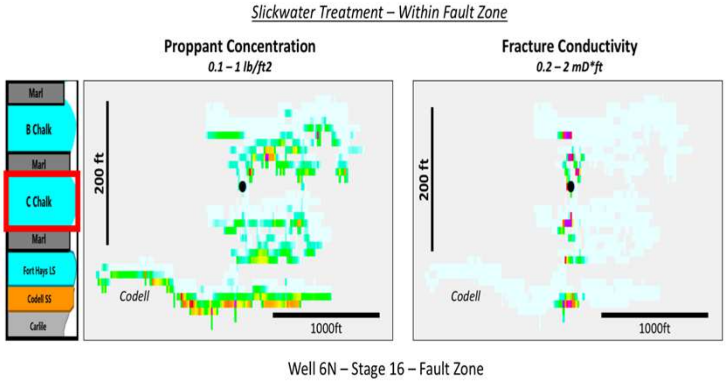
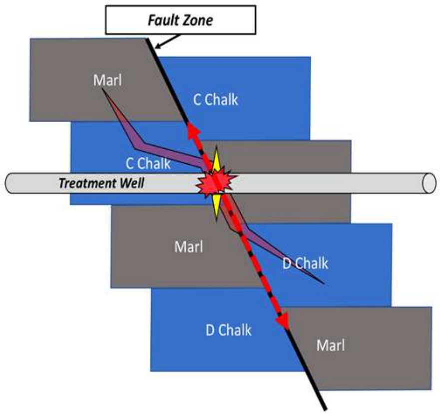
Faults Affect Hydraulic Fracture Growth





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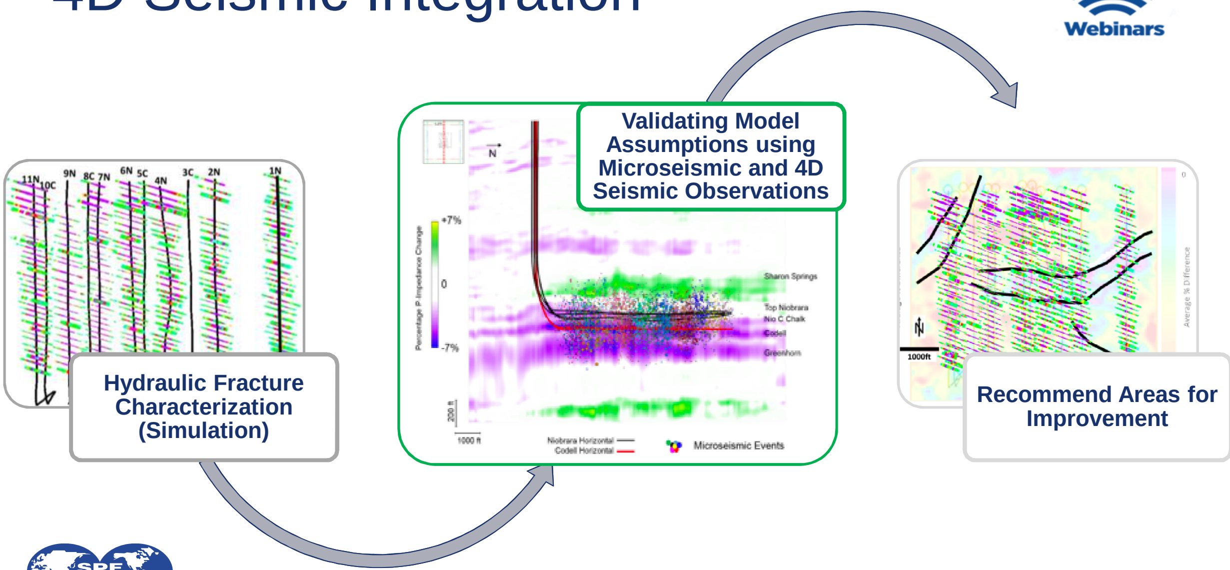
4D Seismic Integration



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Identifying Principal Stress Direction

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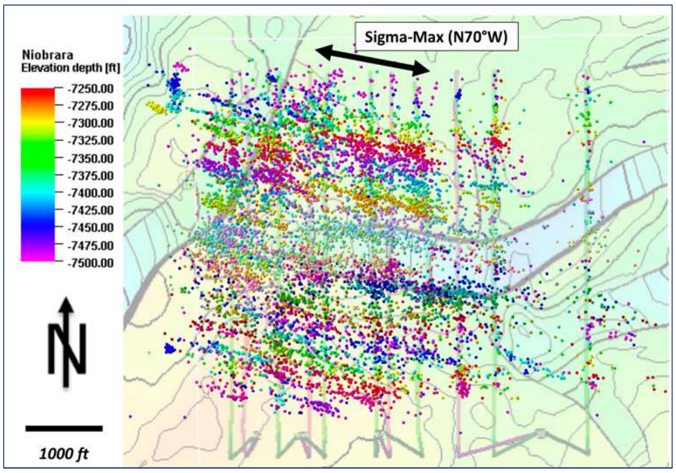
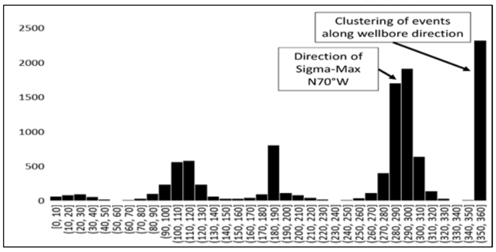
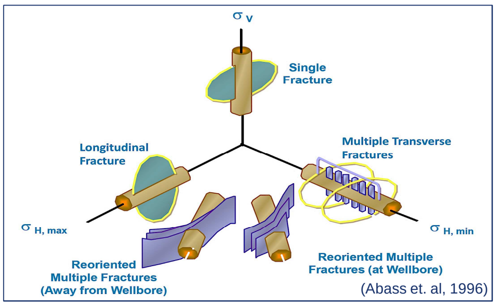
- Maximum Horizontal Stress Direction observed N70ºW
- Minimum Horizontal Stress Direction observed N30ºE







(Abass et. al, 1996)

Inferring Hydraulic Fracture Communication

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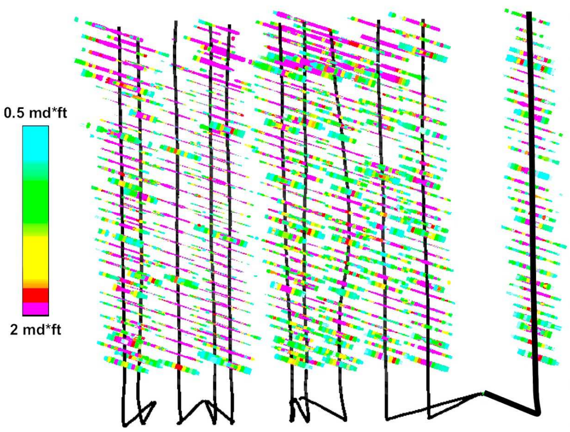
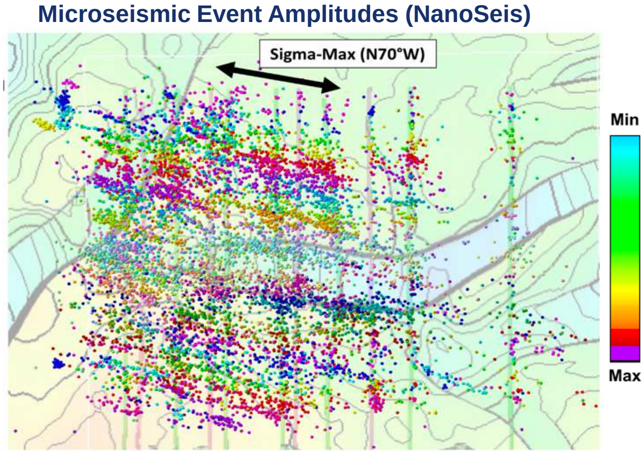
Effective Fracture Conductivity



Microseismic Event Amplitudes (NanoSeis)



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Inferring Well/Stage Interference

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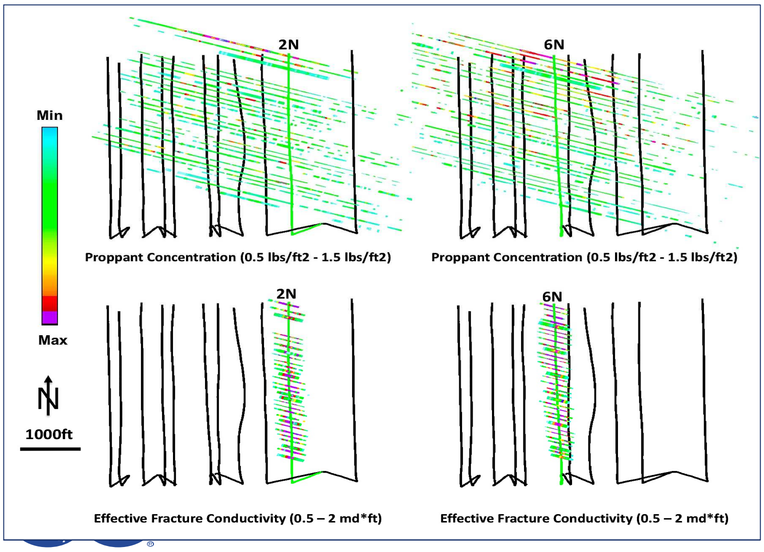
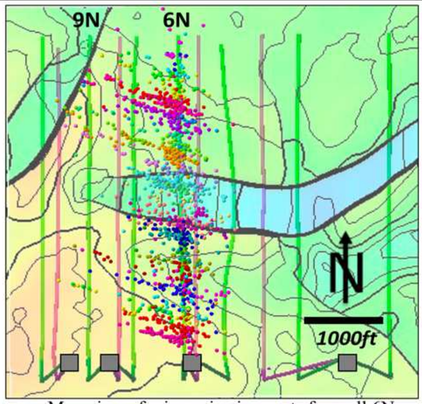


Microseismic events only observe hydraulic fracture lengths



Map view of microseismic events for well 6N

Inferring Well/Stage Interference

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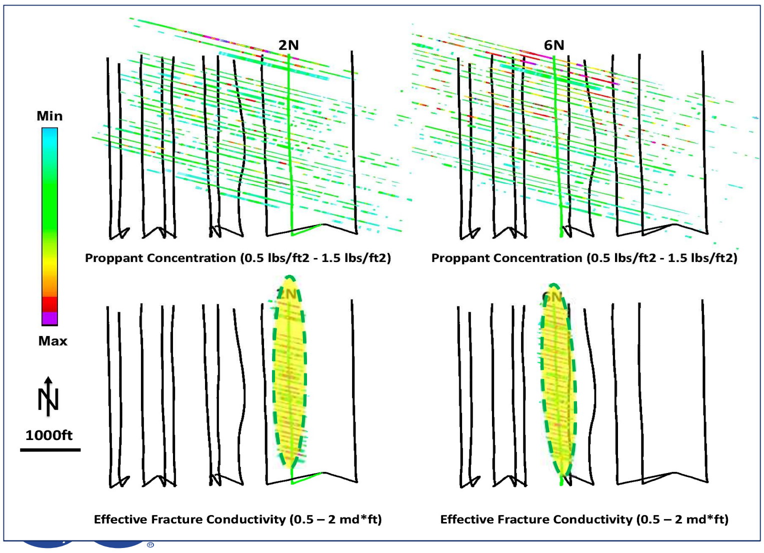
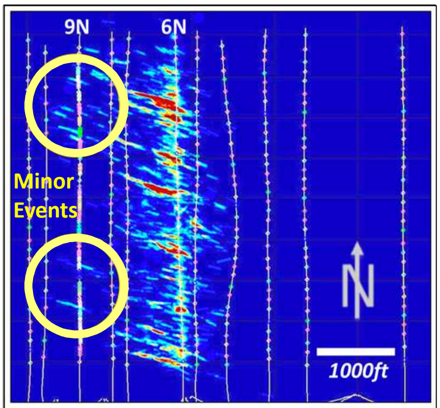


Microseismic events only observe hydraulic fracture lengths



Map view of summed amplitudes for microseismic events

Planning for Optimum Well Spacing

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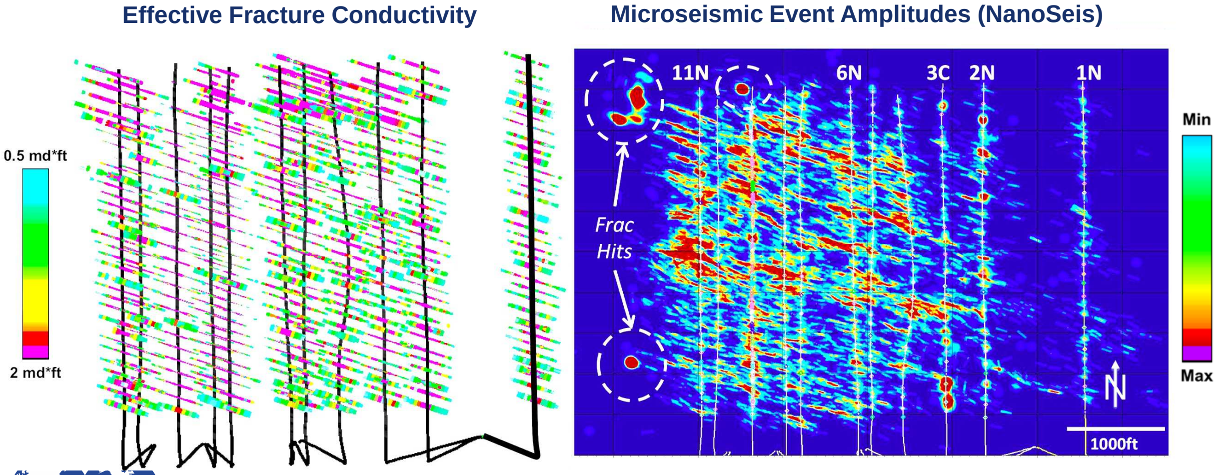

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Identifying Potential Bypassed Pay

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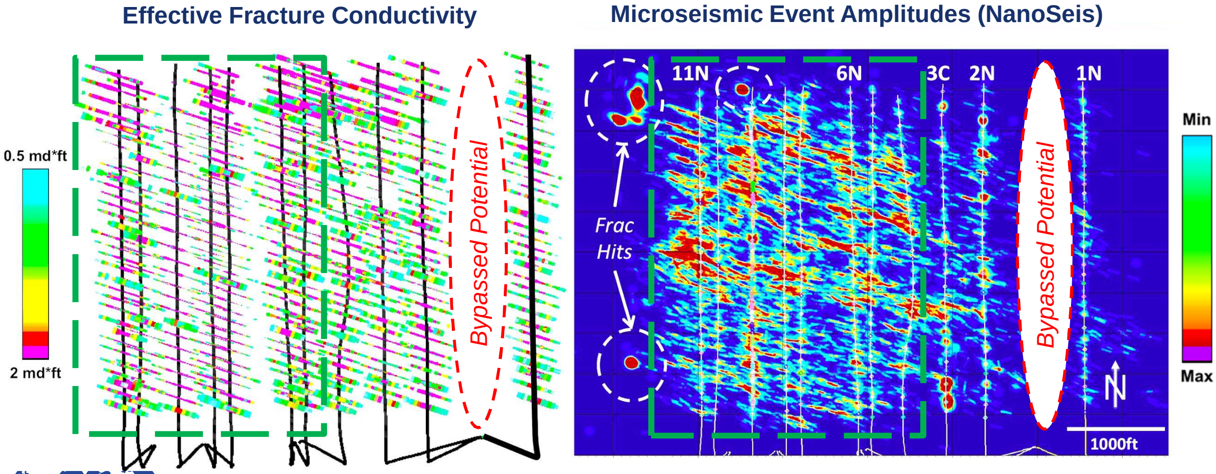

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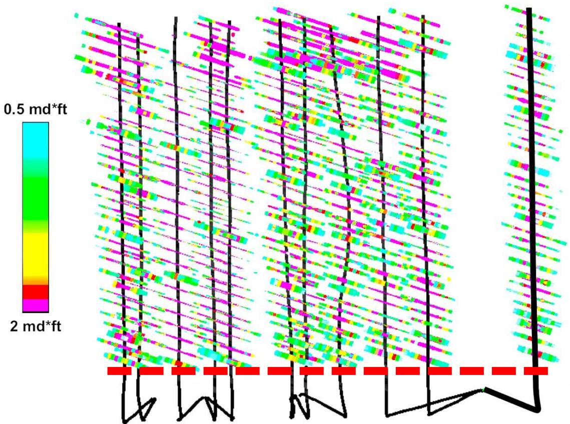
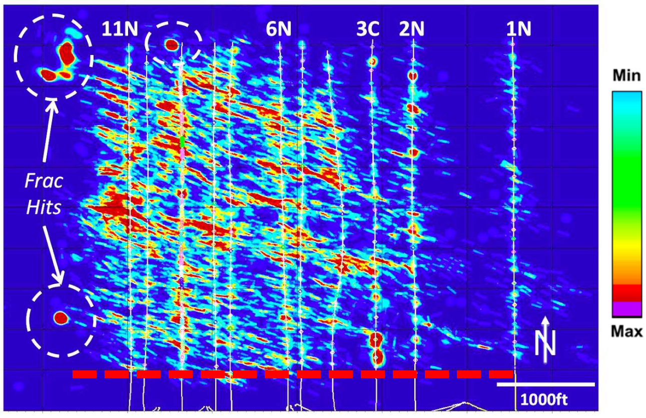
Cross Section Through the Heel of the Horizontal Wells

Effective Fracture Conductivity



Microseismic Event Amplitudes (NanoSeis)



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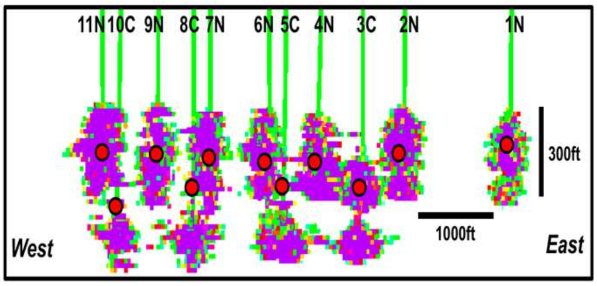
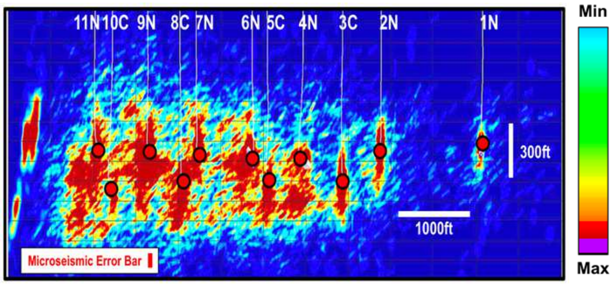
Validating Simulation with Microseismic

HF Simulation Modeling Results
Effective Fracture Conductivity



Microseismic Event Amplitudes (NanoSeis)



- Fracture interference observed west of section
- Predominant downward fracture growth observed on microseismic

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4D Seismic Post-Hydraulic Fracturing

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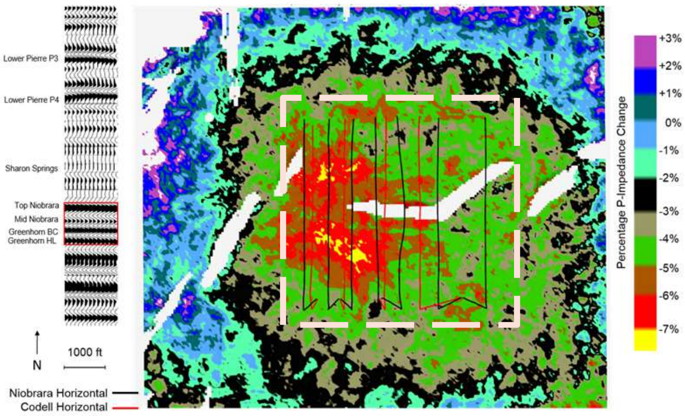
P-impedance: Hydraulic Fracture Response



White 2015

- 4D P-wave Seismic response to hydraulic fracturing
- Pressure compartmentalization observed around faults
- Increased pressure pulse towards the west indicative of well interference

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4D Seismic Post-Hydraulic Fracturing

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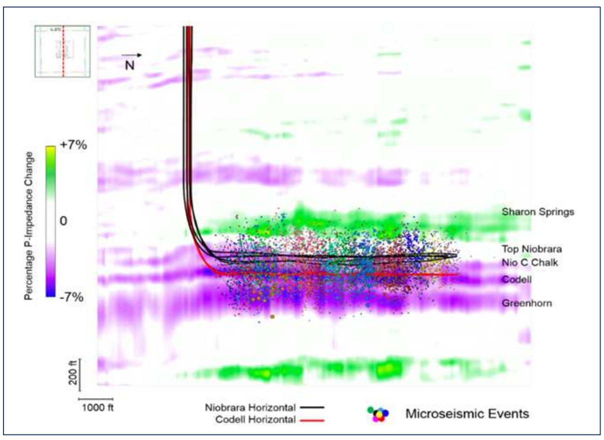
P-impedance: Hydraulic Fracture Response



White 2015

- 4D P-wave Seismic response to hydraulic fracturing
- Effective top stress barrier observed from impedance cross section
- Observed downwards growth of hydraulic fractures

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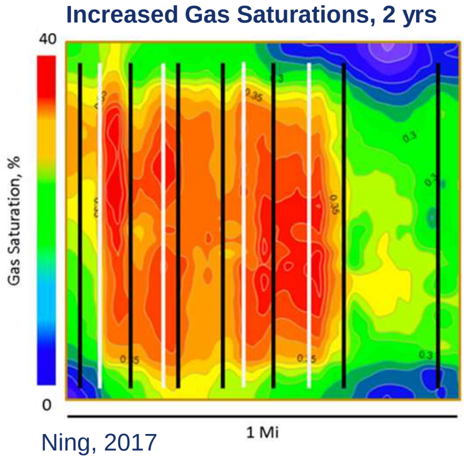
Production History Matching

(CMG Simulation Model)



Ning, 2017

- Strong pressure depletion after 2 years of production
- Reservoir pressures dropped below "bubble point" causing gas to release from solution
- Increased Gas saturations observed around all producing horizontal wells

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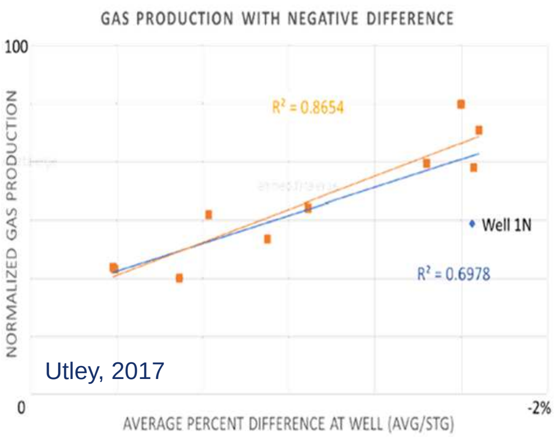
Gas Saturation Increase = Seismic Bright Spots



Utley, 2017

- Possitive correlation between the production of gas from the horizontal wells compared to the P-wave production seismic attribute response within the reservoir
- P-wave production seismic attribute shows the distribution of gas release from oil within the reservoir caused by the pressure drop
- Useful attribute to inferring areas in reservoir undergoing depletion

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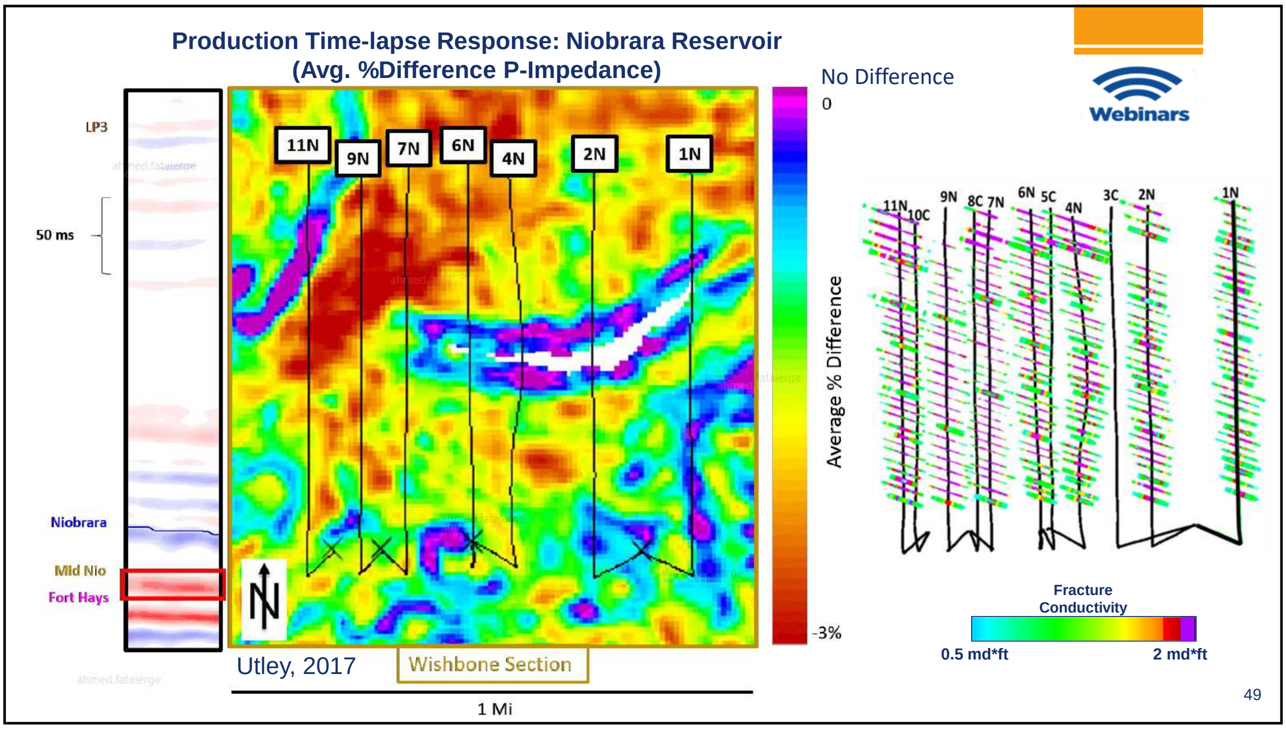
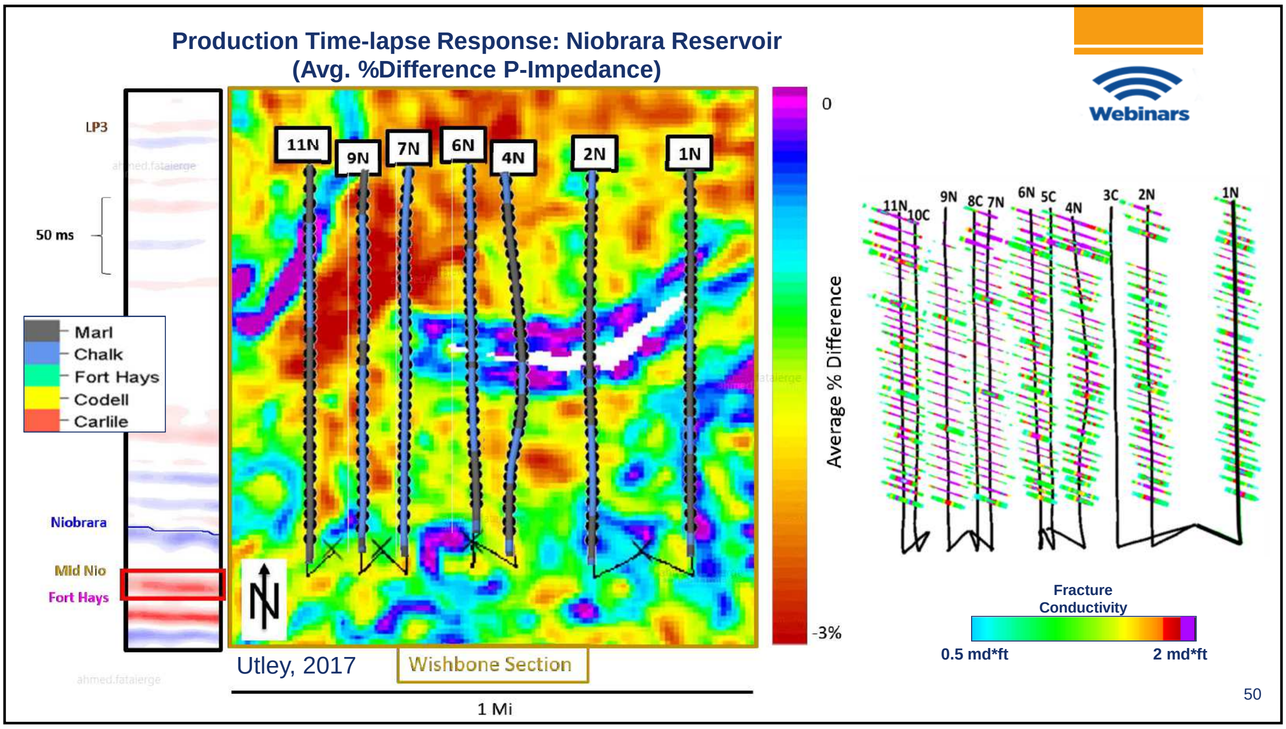

Production Time-lapse Response: Niobrara Reservoir
(Avg. %Difference P-Impedance)
LP3
50 ms
Niobrara
Mid Nio
Fort Hays
11N
9N
7N
6N
4N
2N
1N
No Difference
0
Average % Difference
-3%
Webinars
11N
10C
9N
8C
7N
6N
5C
4N
3C
2N
1N
Fracture
Conductivity
0.5 md*ft
2 md*ft
Utley, 2017
Wishbone Section
1 Mi
49


Production Time-lapse Response: Niobrara Reservoir
(Avg. %Difference P-Impedance)
LP3
50 ms
Marl
Chalk
Fort Hays
Codell
Carlile
Niobrara
Mid Nio
Fort Hays
11N
9N
7N
6N
4N
2N
1N
0
Average % Difference
-3%
Webinars
11N
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5C
4N
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2N
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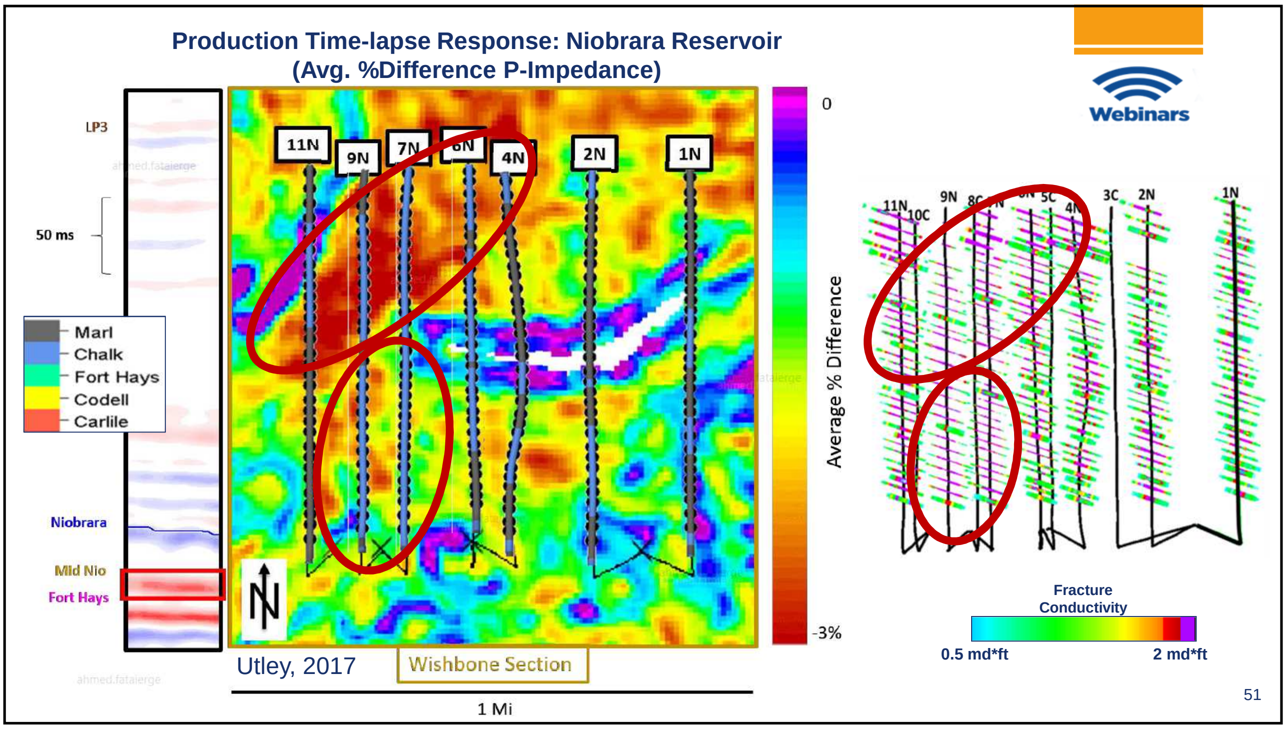
Fracture
Conductivity
0.5 md*ft
2 md*ft
Utley, 2017
Wishbone Section
1 Mi
50


Production Time-lapse Response: Niobrara Reservoir
(Avg. %Difference P-Impedance)
Webinars
LP3
50 ms
Marl
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Fort Hays
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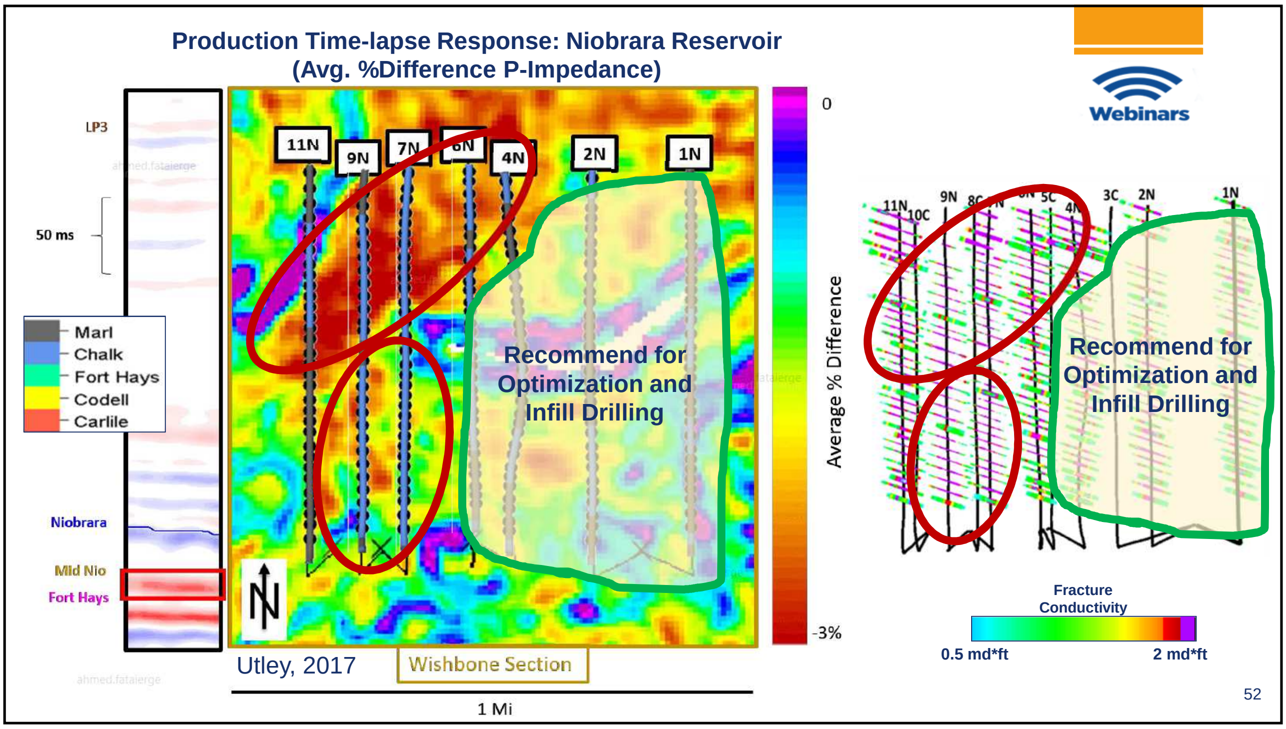
11N
9N
7N
6N
4N
2N
1N
0
-3%
Average % Difference
Utley, 2017
Wishbone Section
1 Mi
11N
10C
9N
3C
2N
1N
5C
4N
Fracture
Conductivity
0.5 md*ft
2 md*ft
51


Production Time-lapse Response: Niobrara Reservoir
(Avg. %Difference P-Impedance)
Webinars
LP3
50 ms
Marl
Chalk
Fort Hays
Codell
Carlile
Niobrara
Mid Nio
Fort Hays
11N
9N
7N
6N
4N
2N
1N
Recommend for Optimization and Infill Drilling
0
-3%
Average % Difference
Utley, 2017
Wishbone Section
1 Mi
11N
10C
9N
3C
2N
1N
Recommend for Optimization and Infill Drilling
Fracture
Conductivity
0.5 md*ft
2 md*ft
52

Observed Factors Controlling Hydrocarbon Production & Drainage Areas Around Wells

Webinars

- Reservoir quality…
- Reservoir stimulation efficiency…
- Well spacing
- Faults as barriers and conduits…
- Fractures as conduits…
- Well landing position relative to geology…
- Offset producing wells

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Observed Factors Controlling Hydrocarbon Production & Drainage Areas Around Wells

Webinars

- Reservoir quality…
- Reservoir stimulation efficiency…
- Well spacing
- Faults as barriers and conduits…
- Fractures as conduits…
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As a consequence of

Geological Heterogeneity

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Value of 4D Seismic Integration

Webinars

- **Identify role of reservoir heterogeneity** (faults, fractures, lithofacies changes) on hydraulic fracture stimulation and hydrocarbon production
- **Determine optimum well spacing** for optimized reservoir drainage
- Useful for **planning infill well placement** around bypassed "un-depleted" reservoir intervals
- **Optimize stage placement** around geological features (faults and fractures and lithological changes in the reservoir
- **Validate** reservoir simulation models

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Summary

Webinars

Seismic monitoring techniques are successful at:

	Micro-seismic	4D seismic
– Highlighting **non-uniform stimulated intervals** within the reservoir	✓	✓
– Highlighting **non-uniform production** from unconventional reservoirs		✓
– Highlighting **bypassed pay** interval within the reservoir		✓
– Highlighting **well interference** with producing wells (**frac-hits**)	✓	✓
– Highlighting fault **barriers** and flow conduits within the reservoir		✓
– Predicting optimum **well spacing** for field development		✓
– Inferring maximum horizontal stress direction	✓	
– Validating hydraulic fracture and/or production simulation models		✓

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Webinars

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BACKUP SLIDES

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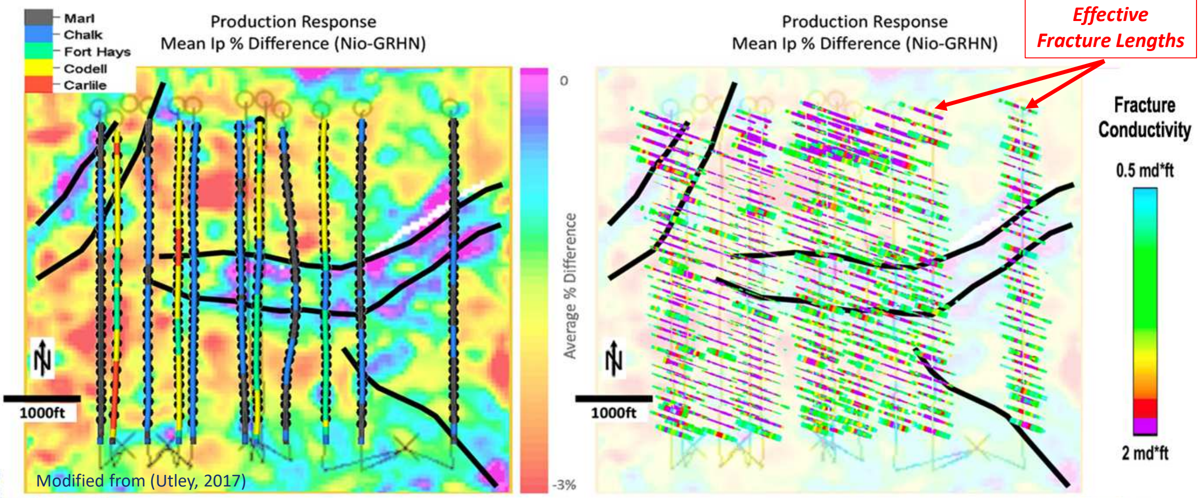
HF Efficiency & Production Controlled by Geologic Heterogeneity



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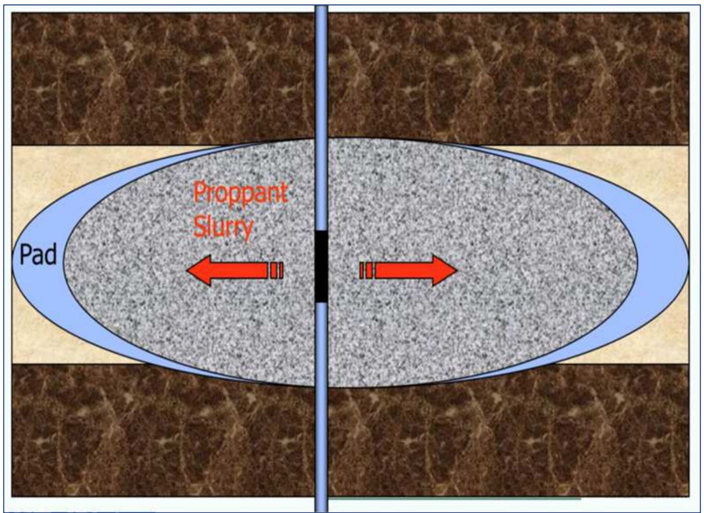
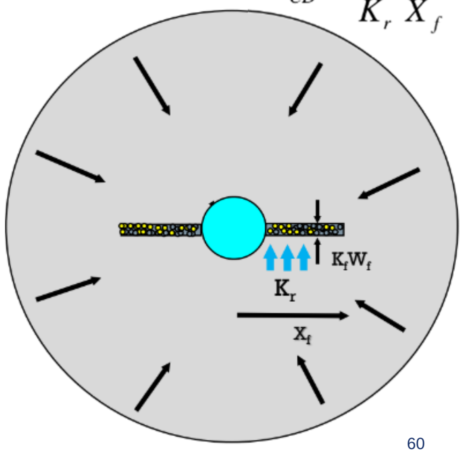
Fracture Conductivity



Effective Fracture Conductivity

Dimensionless Fracture Conductivity

$$F_{CD} = \frac{W_f \, K_f}{K_r \, X_f}$$



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Gas Saturation from History Matching

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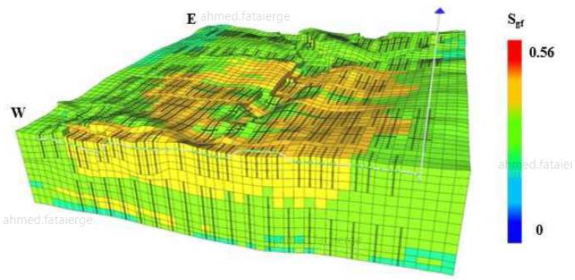

Figure 4-22 3D view of gas saturation distribution after two years of production

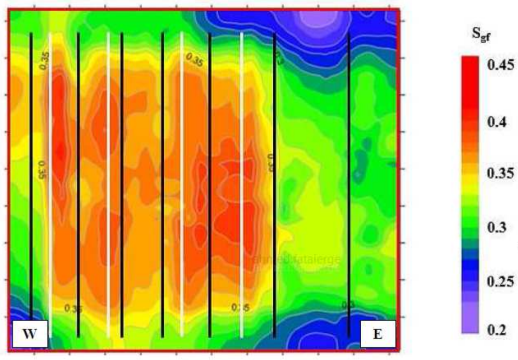

Figure 4-23 2D view of gas saturation distribution after two years of production.

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RA Tracer Analysis

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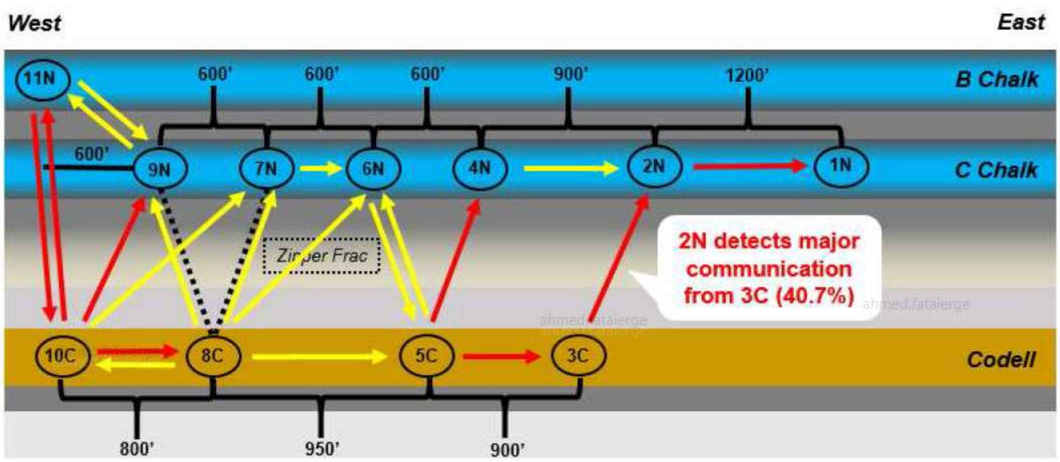

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3D Geomechanical Model Building

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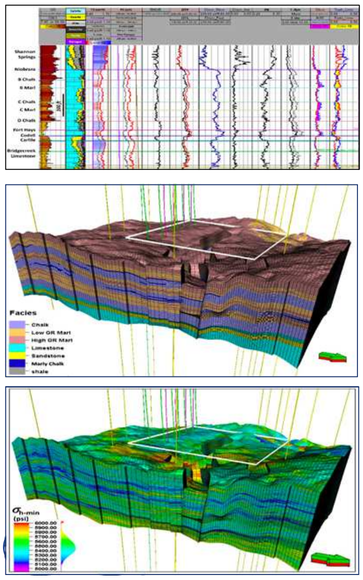

1D Petrophysical Analysis

Classify lithofacies based on unique petrophysical properties
Associate elastic moduli with different facies types

3D Geostatistical Modeling

Distribute elastic moduli from logs into **facies model**

Poisson ratio *(v)*
Young's modulus *(E)*
→ **Sequential Gaussian Simulation**

Overburden Pressure (P_{ob})
Pore Pressure (P_p)
Tectonic Strain (ε_x)
→ **Kriging**

$$3D\ \sigma_{h\,min} = \frac{v}{(1-v)}[\sigma_v - \alpha P_p] + \alpha P_p + \varepsilon_x E + \sigma_t$$

Volumetrically Calculate Magnitude of Minimum Stress

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Production P-impedance correlation with Gas Production

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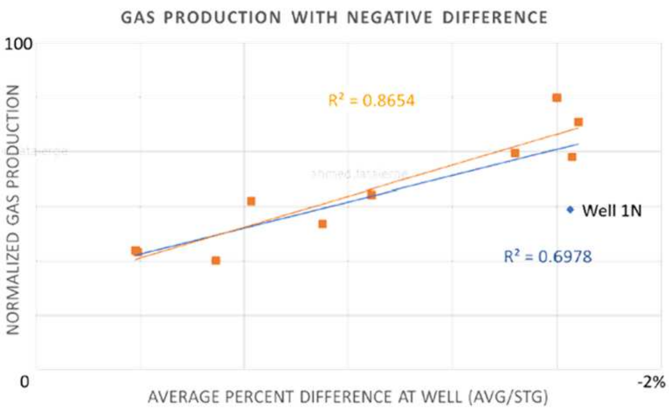

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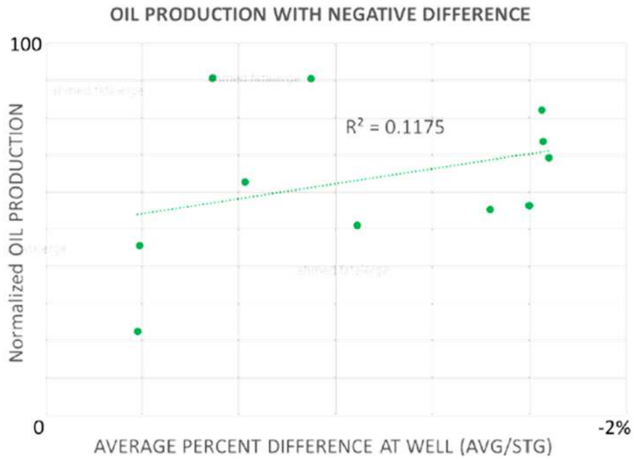
Production P-impedance correlation with Oil Production



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