Distinguished Lecturer Program

Primary funding is provided by

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Optimized Shale Resource Development using proper placement of Wells and Hydraulic Fracture Stages

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Society of Petroleum Engineers
Distinguished Lecturer Program
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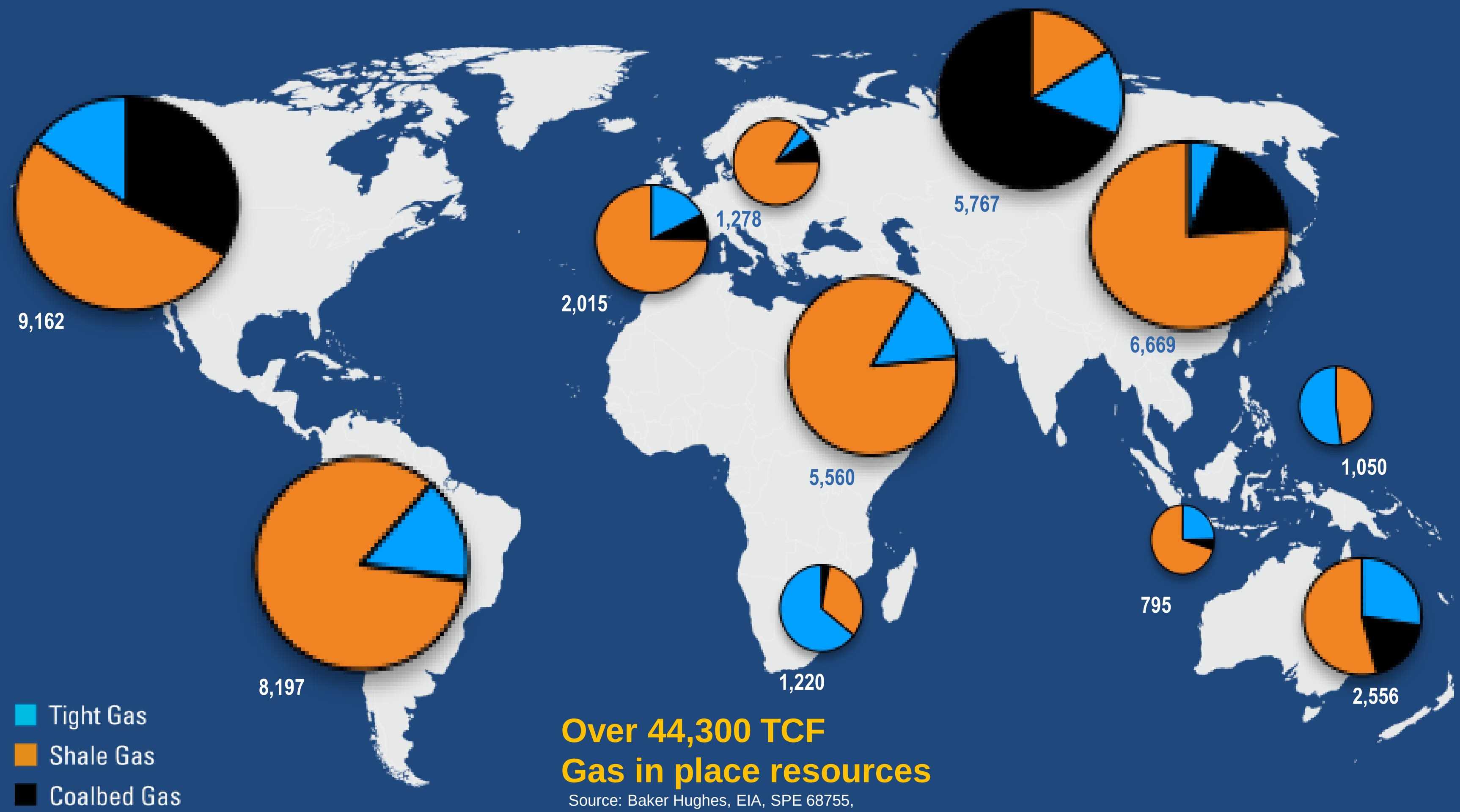
Outline

- Illustration of the Prize
- Present trend in Unconventional Reservoir Modeling and it's impact on production
- Challenges the industry face to enhance recovery factor while reducing cost per unit of hydrocarbon recovered
- Where should the future engineers focus?
  - What technologies are there and what are needed in the near future to ***optimally place wells*** for the enhanced recovery
  - What technologies are there and what the industry needs in the near future to decide the ***optimum placement of the hydraulic fracture stages***
- Illustrative field examples and the recommended way forward

Unconventional Gas Resource: A Global Phenomenon

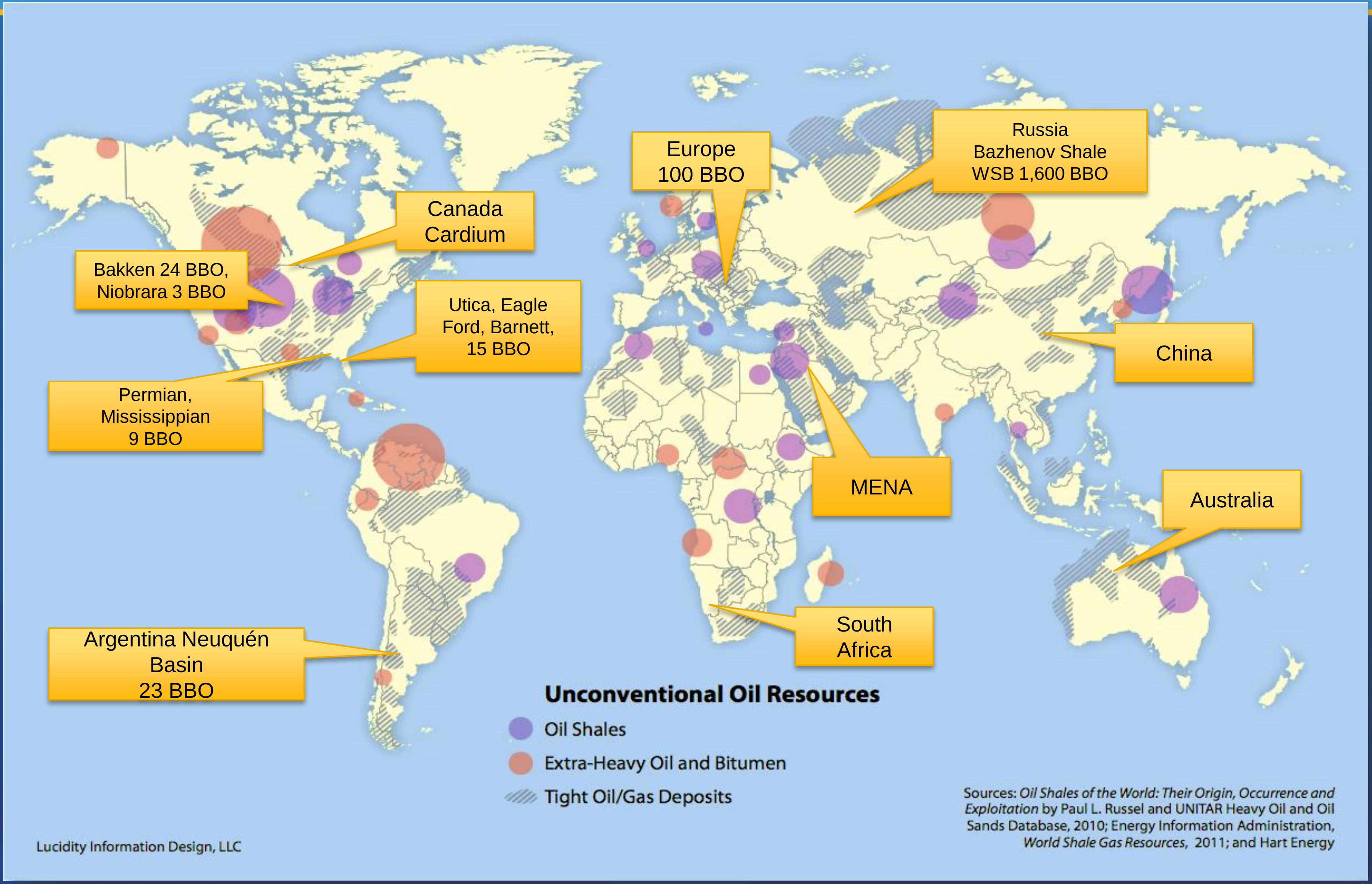


Pie size to scale

Over 44,300 TCF
Gas in place resources

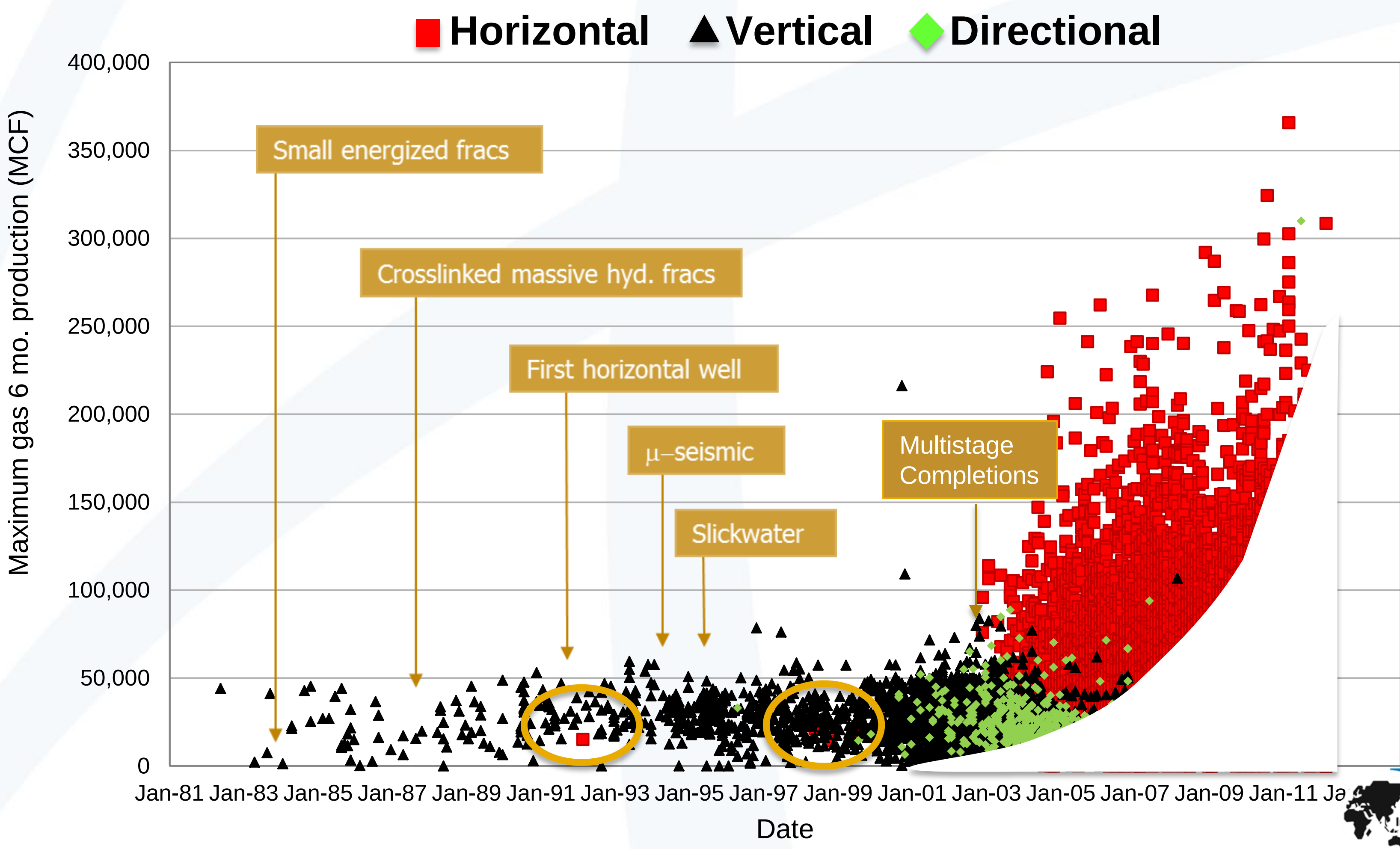
Source: Baker Hughes, EIA, SPE 68755, Kawata & Fujita from Rogner

Unconventional Oil Resources 2-3 Trillion Barrels



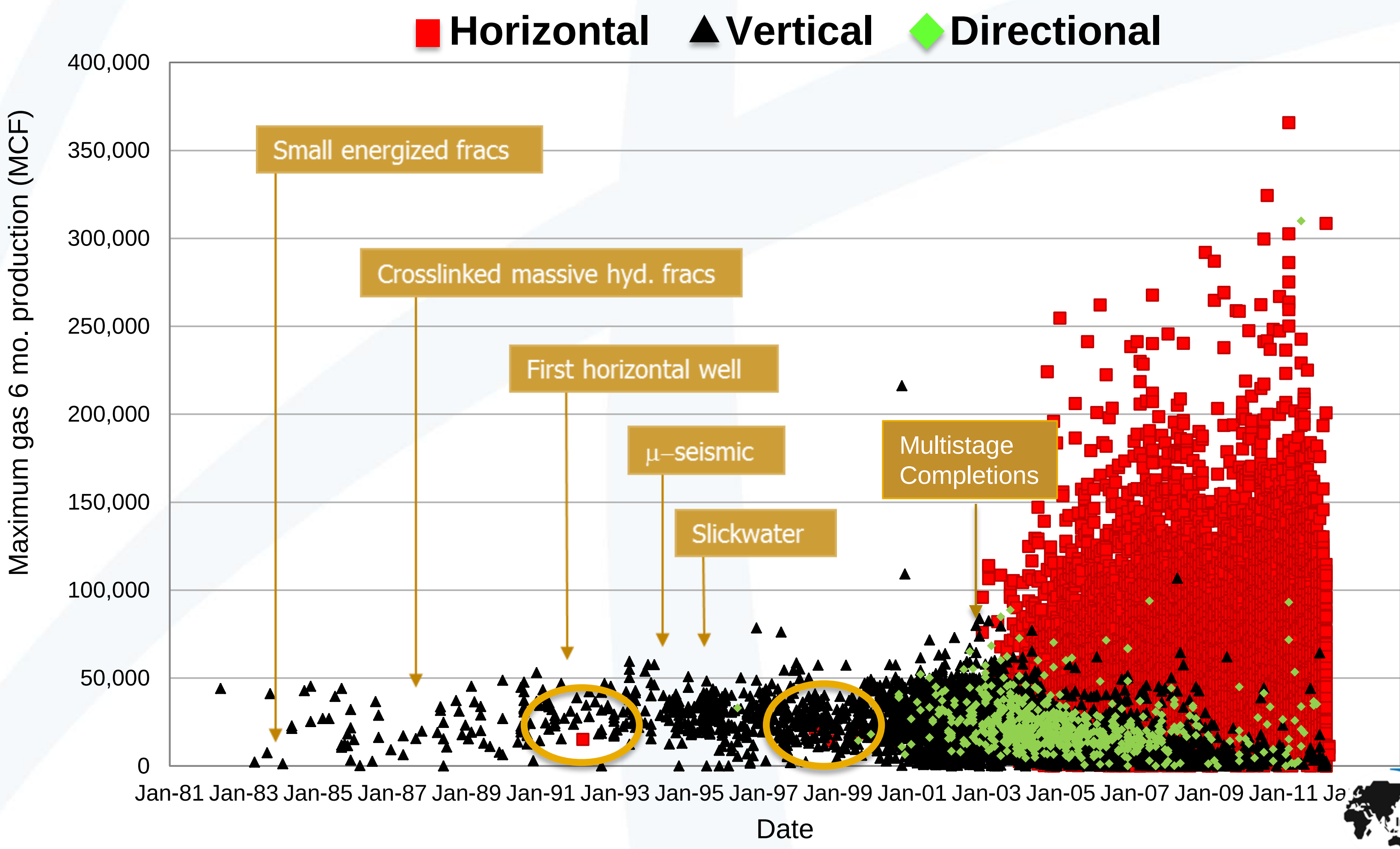
Unconventional Development – Learning Curve

Barnett Shale Development



Unconventional Development – Learning Curve

Barnett Shale Development



SPE International

A Closer Look at the "Shale Revolution"

70% of unconventional wells in the U.S. do not reach their production targets*

60% of all fracture stages are ineffective**

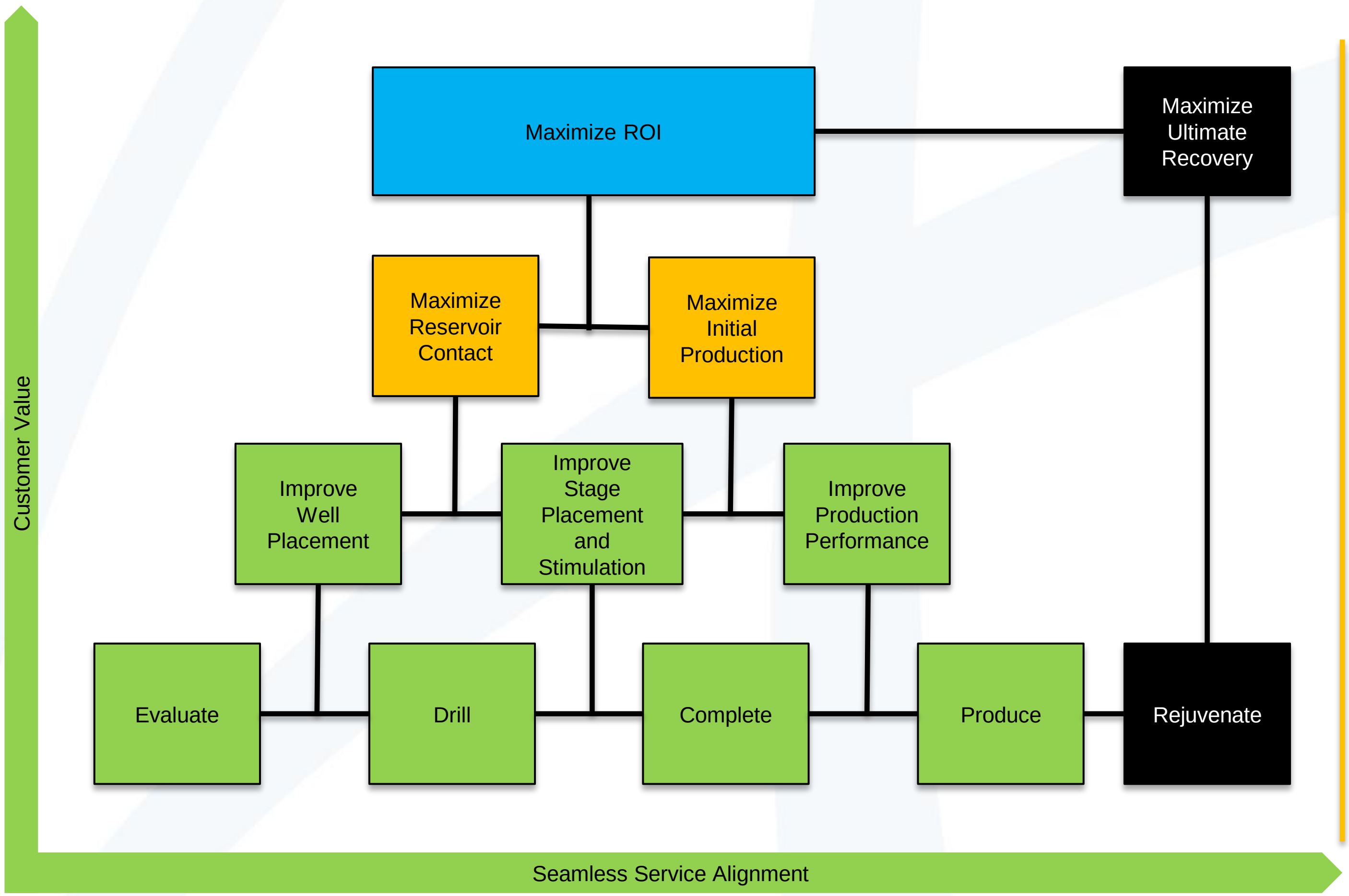
73% of operators say they do not know enough about the subsurface*

Efficiency and **Effectiveness** **are key for Proper Placement of Well and Frac Stage in Sweet Spots**

**Source: Welling & Company, 2012*
***Source: Hart's E&P, 2012*

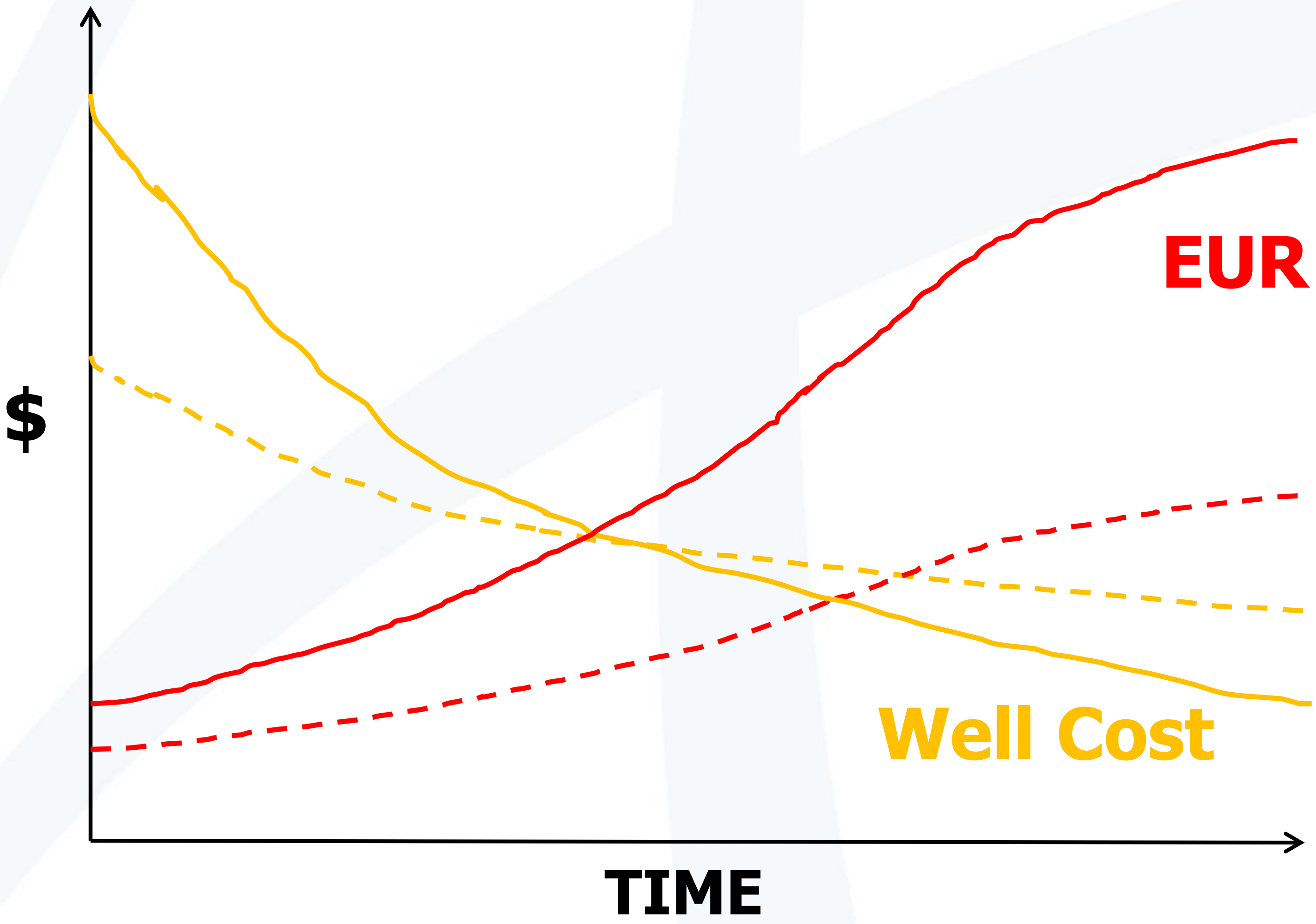
From Discrete Components To An Integrated Solution

Unconventional Market Segment

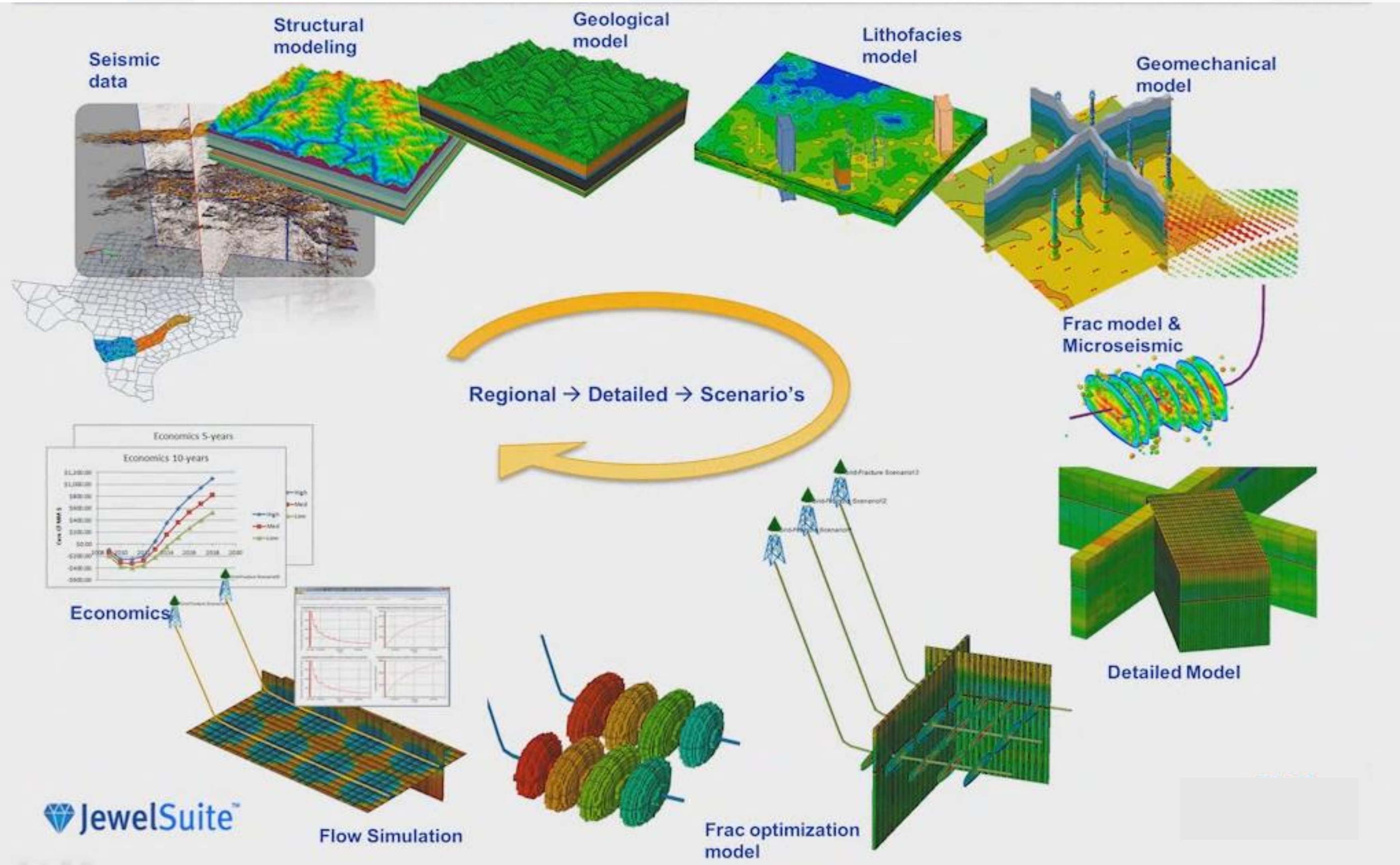


- **Identify sweet spots**
- **Predict performance /EUR**
- **Where to place wells:** Well placement, spacing, drainage area, lateral orientation, and length
- **Which Method of completion:** Open hole, cased hole,
- **Optimal Stimulation design:** Stage placement, number of stages, fluid, proppant, volume
- **Production management:** Flowback, managed rate of production

Low Cost vs Cost Efficient Development: Implications?



Unconventional Workflow: How is it Different?



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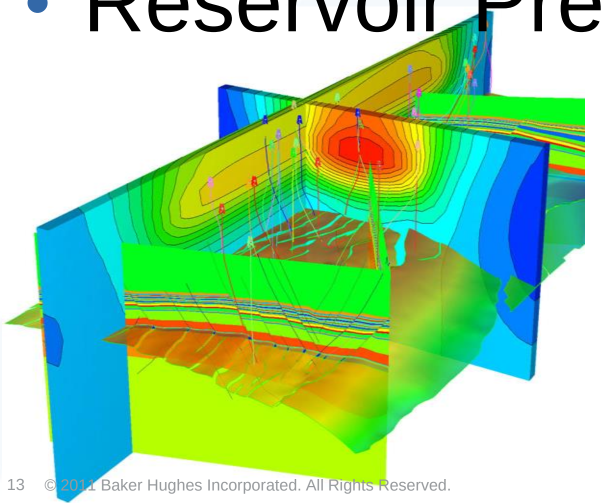
Moving from Conventional To Shales

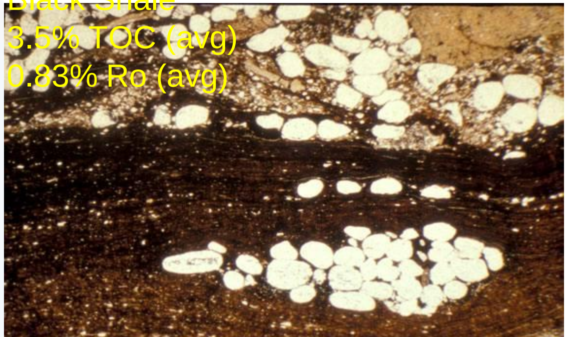
Conventional

- Porosity
- Saturations
- Permeability
- Resource Base
- Reservoir Pressure



Shales

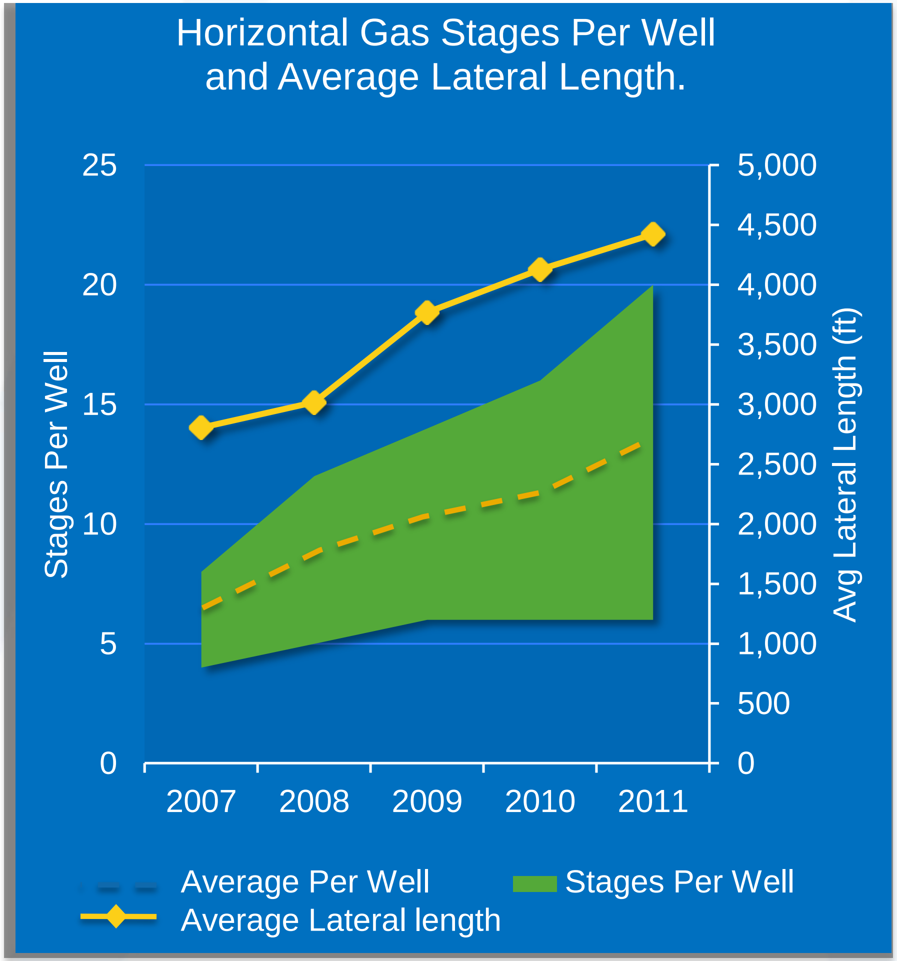
- Reservoir Pressure
- TOC
- Ro (Vitrinite Reflectance) / TM
- Permeability / NF
- Brittleness



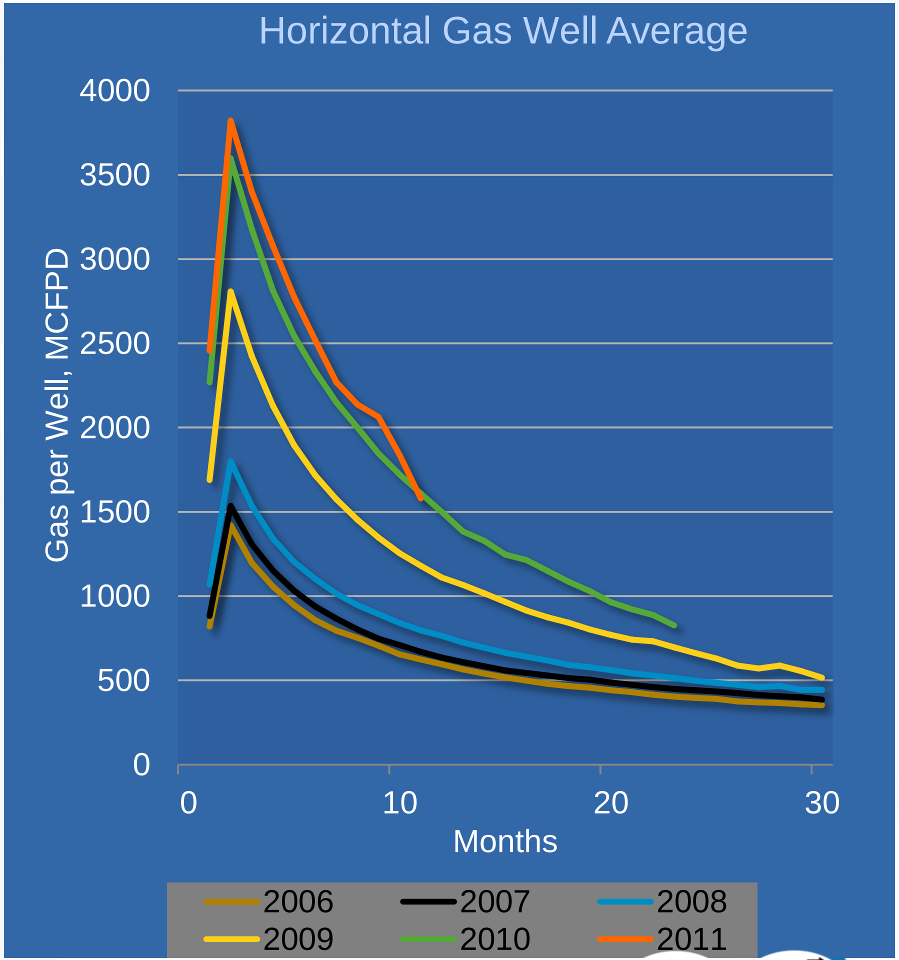
BAKER HUGHES

Technology Evolution and Production

Selected Unconventional Gas Basins, Onshore U.S.



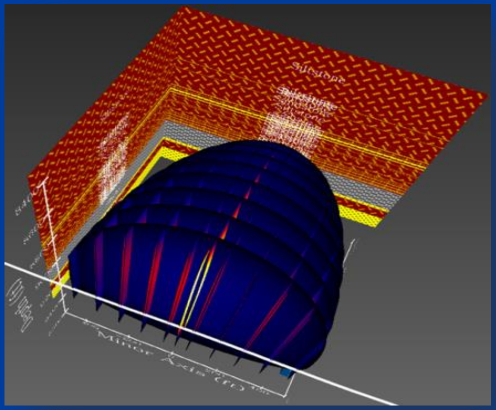
Source: BHI, HPDI, IHS, Company data



Source: HPDI

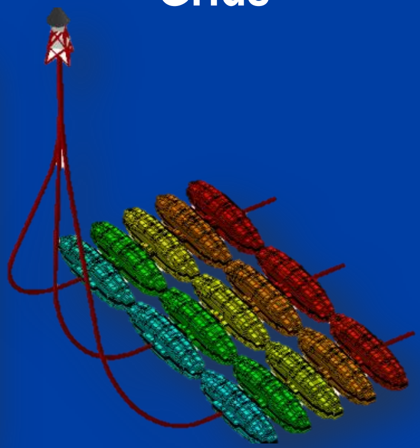
Three Key Elements To Avoid Sharp Production Decline

Hydraulic Fracture Model



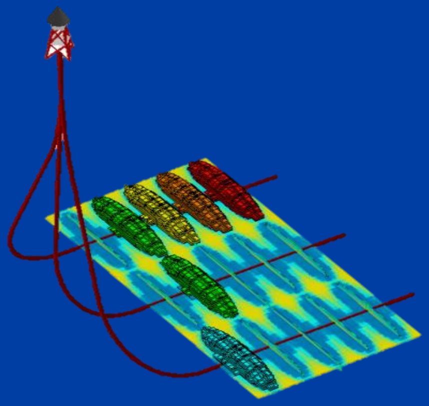
- Single well treatment
- Fracture grid representation
- Geometries and properties

Reservoir Fracture Grids



- Multiple wells and stages
- Fracture refinement
- Various scenarios

Reservoir Flow Model

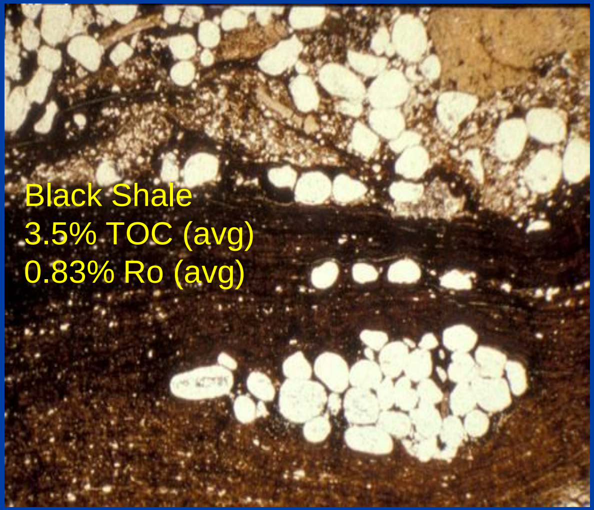


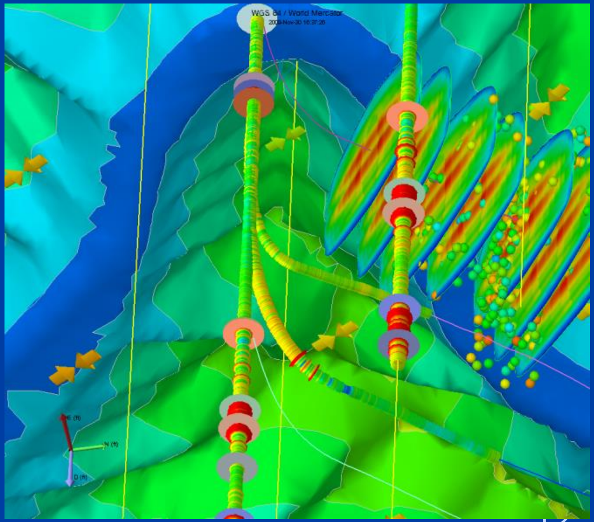
- Fit-for-purpose flow simulator
- Dec curves
- Drainage Scenarios

STIMULATION PERFORMANCE: *REDUCE THE SHARP PRODUCTION DECLINE*

Shale Reservoir Analysis

- Conventional **reservoir modeling & analyses** not effective for shale
- **Shale reservoirs require** new approaches to Analysis & Forecast
- **An integrated** "shale engineering" **approach is required to** plan wells, stimulate & forecast long-term production **for economic evaluations**

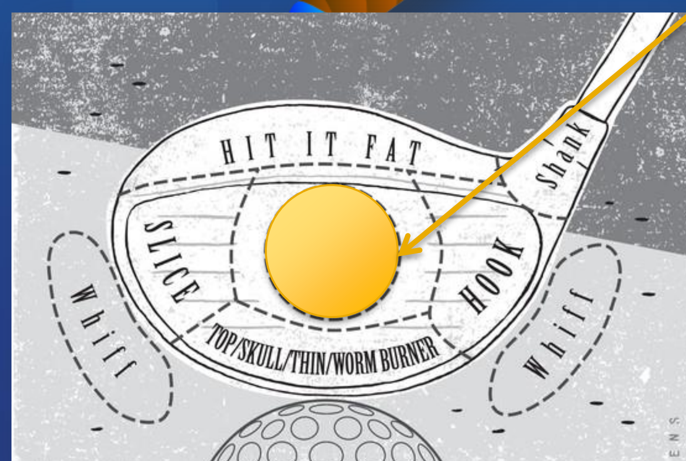




- SWEET SPOTS: Well and Frac Stage Locations

What is a “Sweet Spot”?

- The “Sweet Spot” is where the maximum power is generated with the least amount of effort and vibration .
- The Sweet Spot is important in these sports because we don’t all have perfect swings.
- What does this have to do with unconventional resources?



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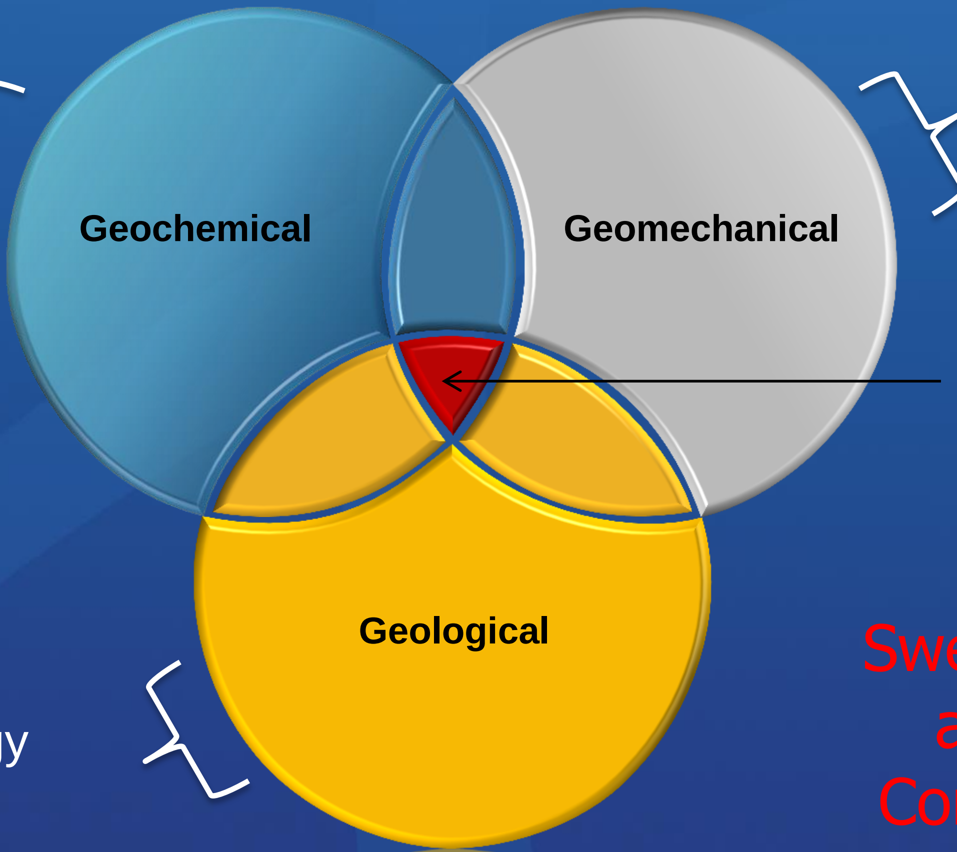
Unconventional Resources Sweet Spot Characteristics

A "Sweet Spot" or "Core" represents the concurrence of several favorable parameters such as:

TOC
Kerogen Type
Fluid
Thermal Maturity
Depositional Environment
(Litho-facies)

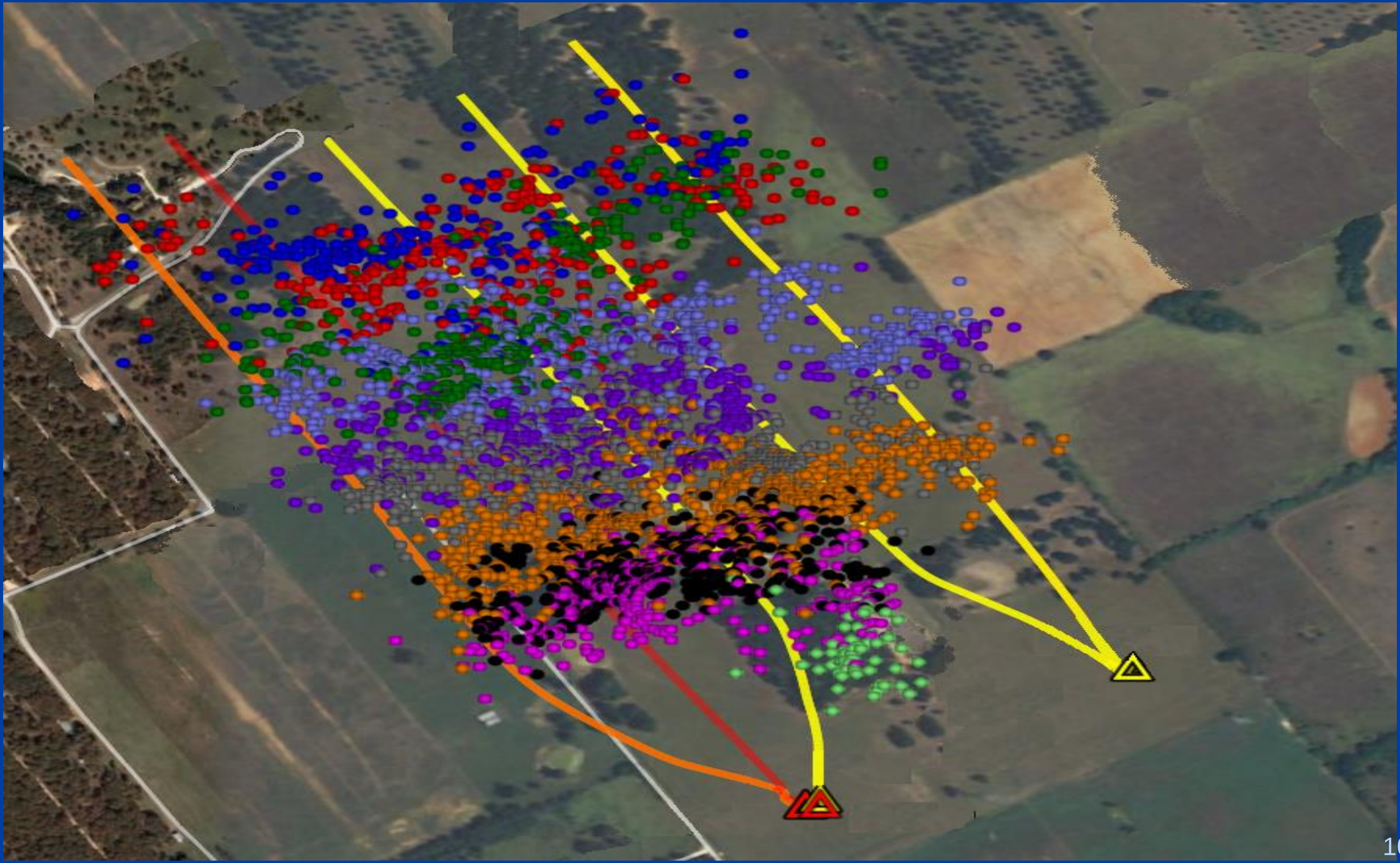
Anisotropy
Stress Regime
Fractures
Faulting
Brittleness
(Fracturability)



Depth
Thickness
Lithology/Mineralogy
Porosity
Pressure
(Continued Producibility)

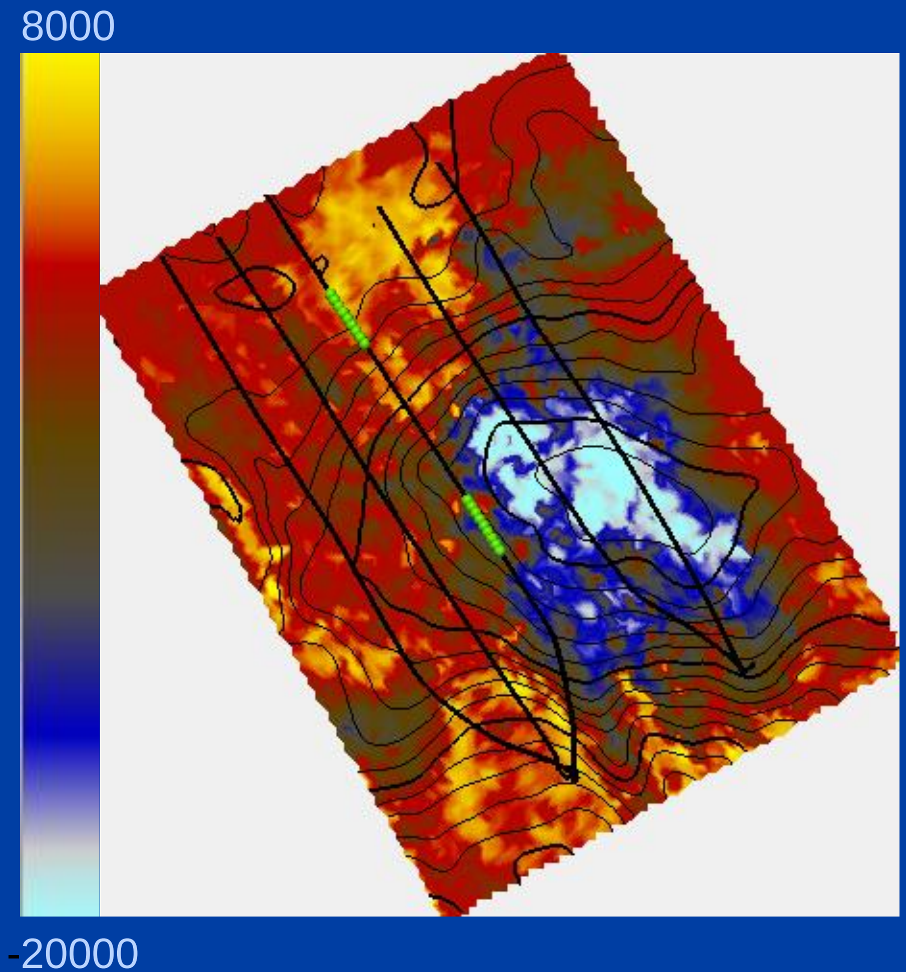
Sweet Spots are not Contiguous

Can we Identify Optimal Areas For Reservoir Stimulation Before Drilling and Frac'ing?

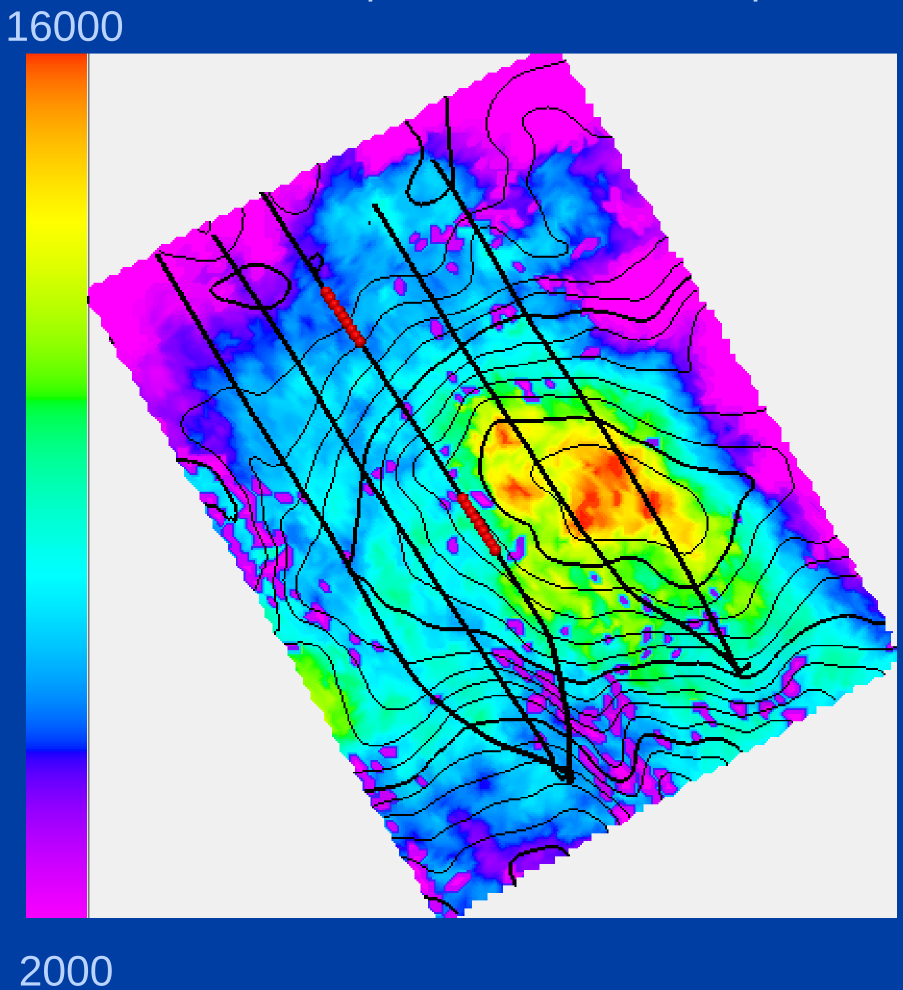


Attribute Analysis + Lithofacies = Sweet Spot Identification

Actual Amplitude Formation Top

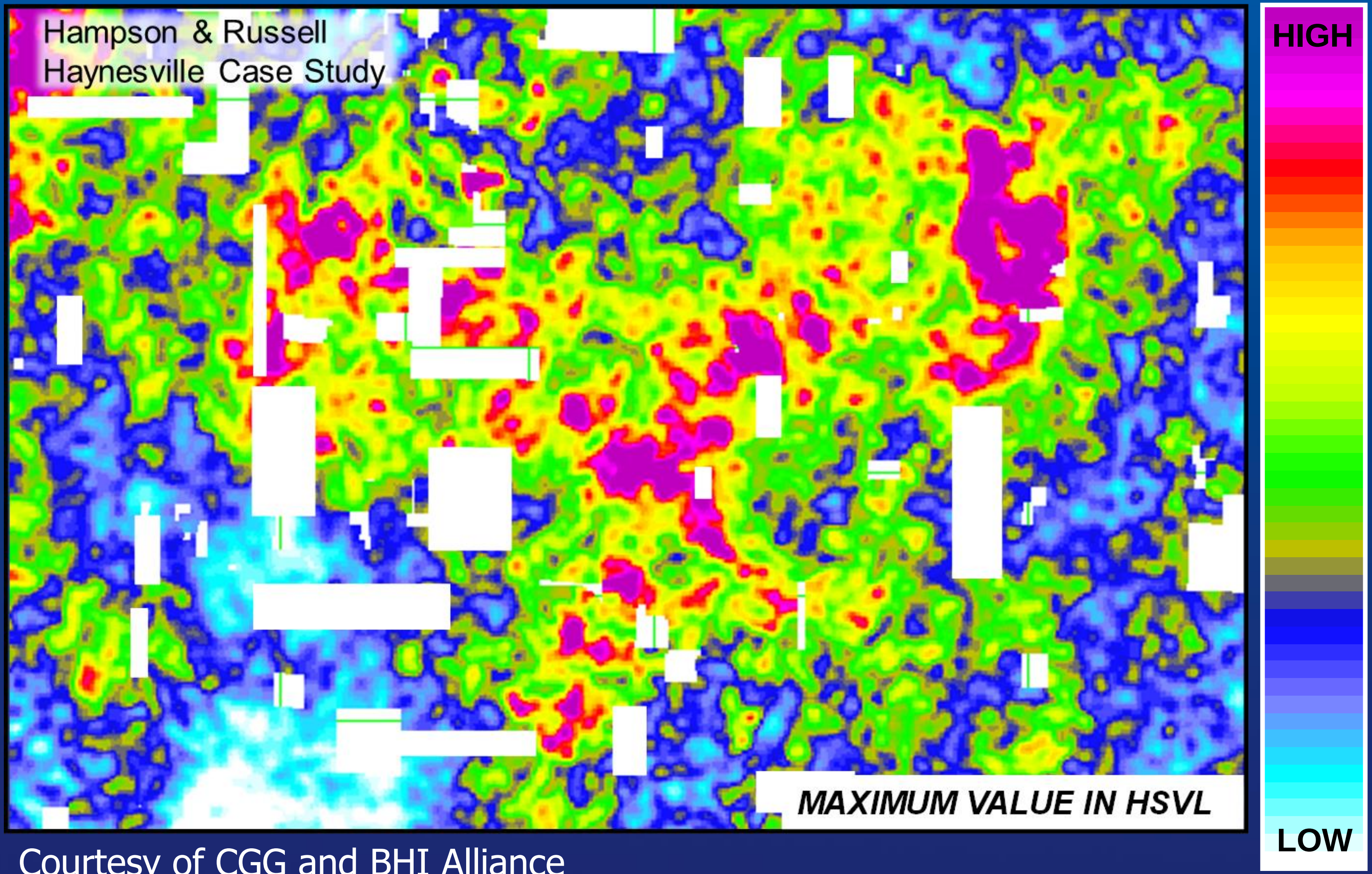


RMS Amplitude Formation Top



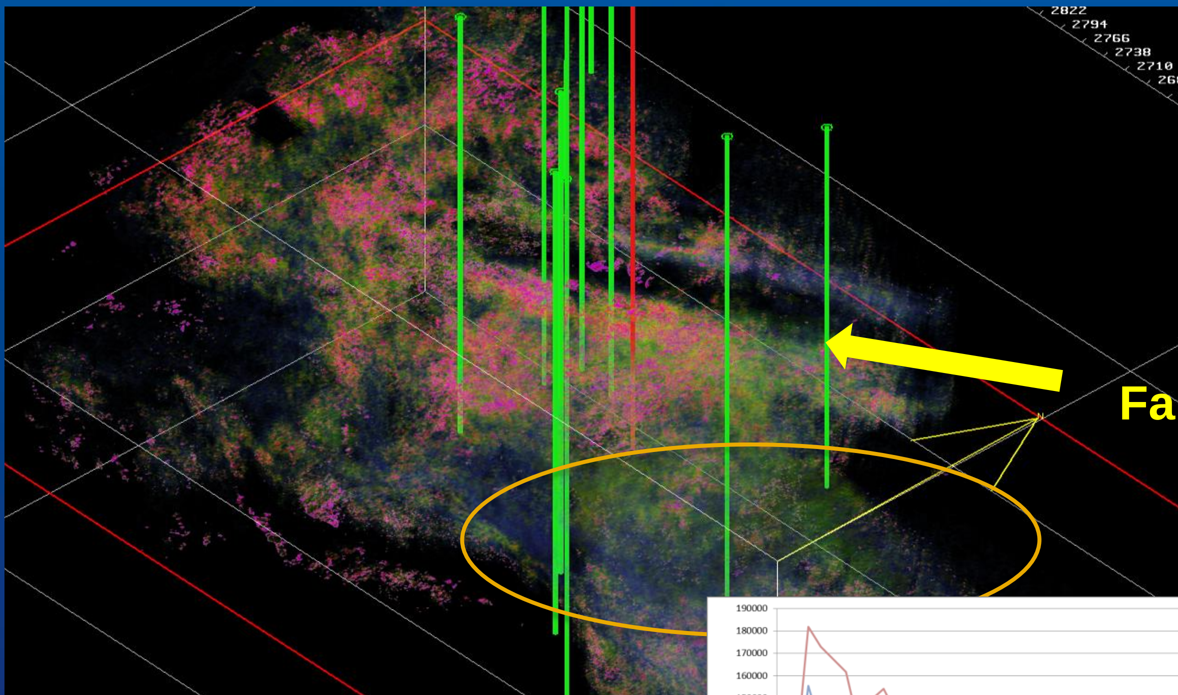
Location of LPLD events are correlative with amplitude anomalies

Multi-Attribute Prediction of TOC (WPCTOC)

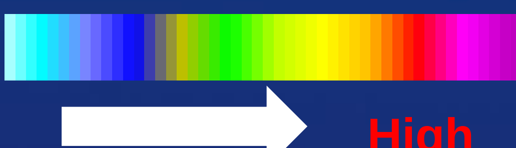


Courtesy of CGG and BHI Alliance

Locating Areas of High TOC in Seismic Volume

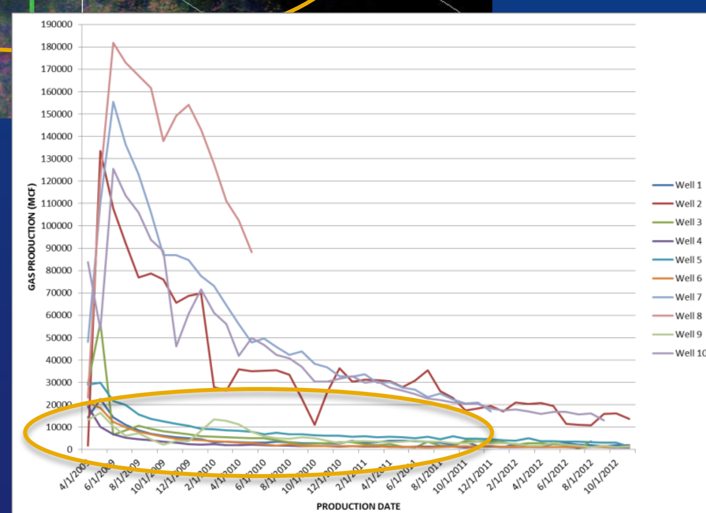


Fault



Probability

High



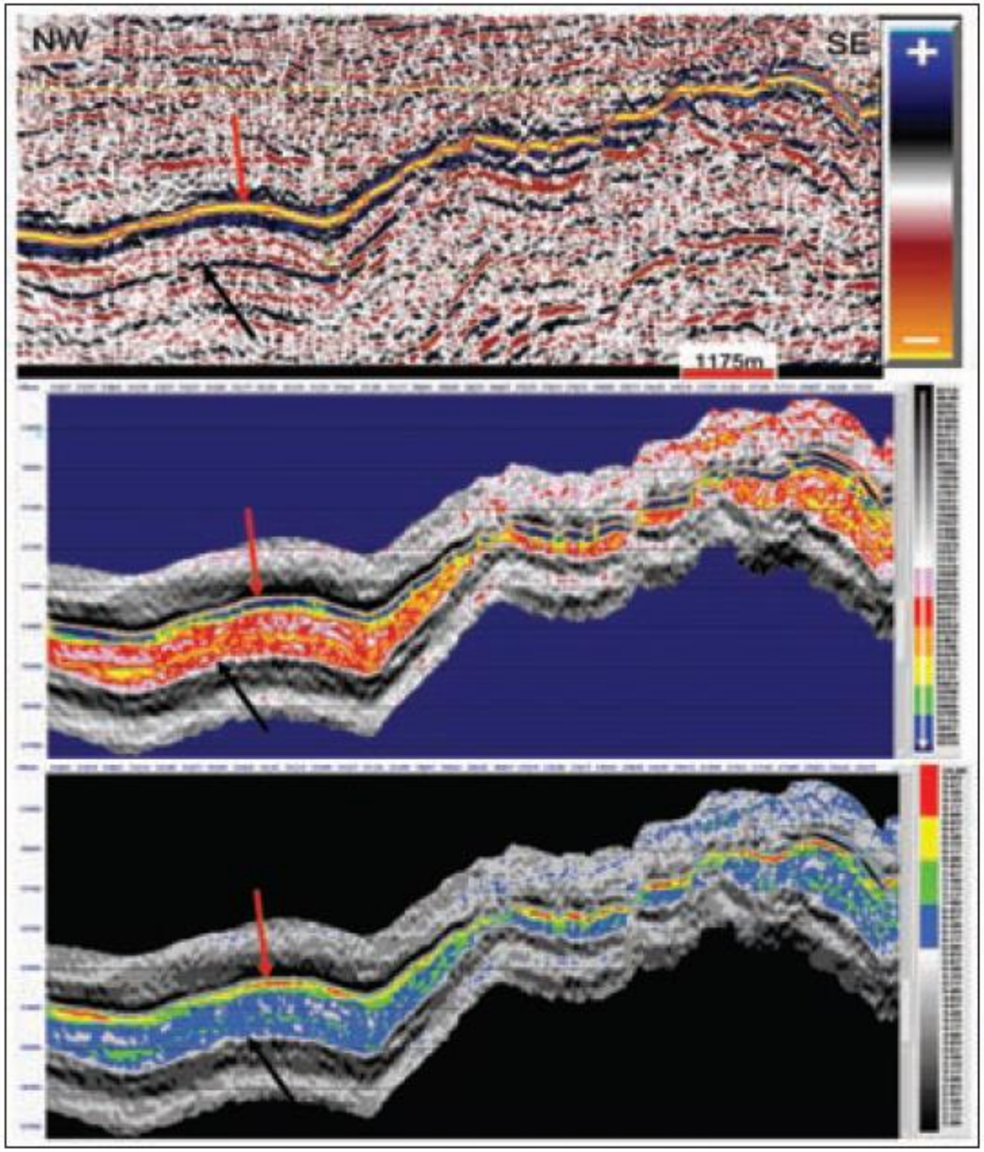
Volumetric View of TOC with well penetrations

Multiple uneconomic wells

Several TOC rich areas yet to be exploited

Courtesy of CGG and BHI Alliance

TOC (Total Organic Content) Vs. Acoustic Impedance



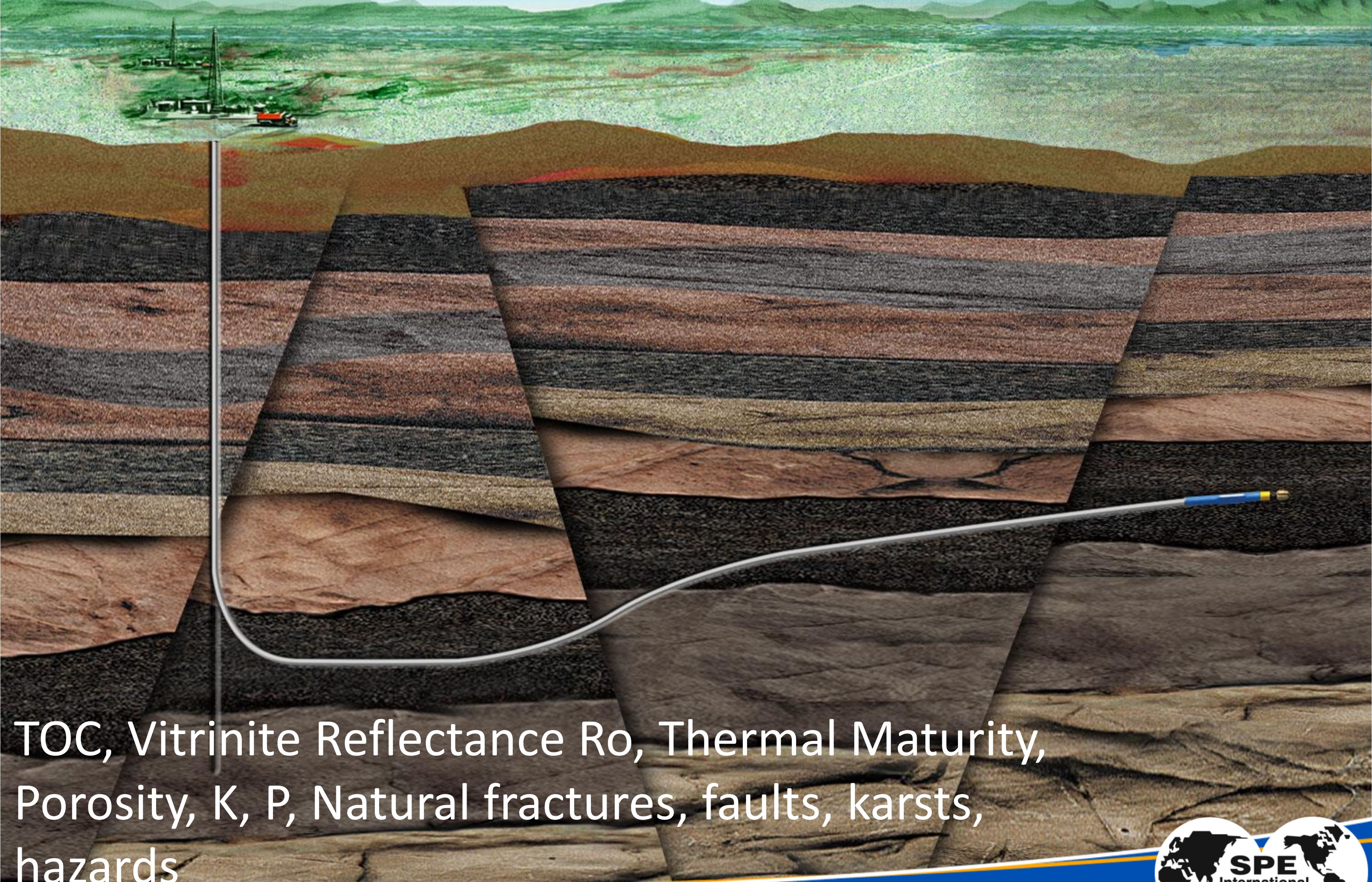
Lower Acoustic Impedance = Higher TOC and Natural Fractures

Pictured here (from top), near stack seismic section, Acoustic Impedance section and TOC section through the northern calibration well. The red arrows point at the top of the Spekk Formation and the black arrows point at the base. In the middle Acoustic Impedance section, the acoustic impedance is lower within the Spekk Formation than in adjacent strata, apart from in the shallowest part where the low impedances are due to the shallow depth and not due to organic content. A trend from very low acoustic impedances in the upper part (blue colors) to higher acoustic impedances further down (red and pink colors) is clearly seen within the Spekk Formation. TOC content greater than 6 percent TOC is highlighted in bright colors in the lower figure.

Graphics courtesy of Statoil Research Center

Source: AAPG Explorer. Dec 2009

Vertical Pilot Well: The start

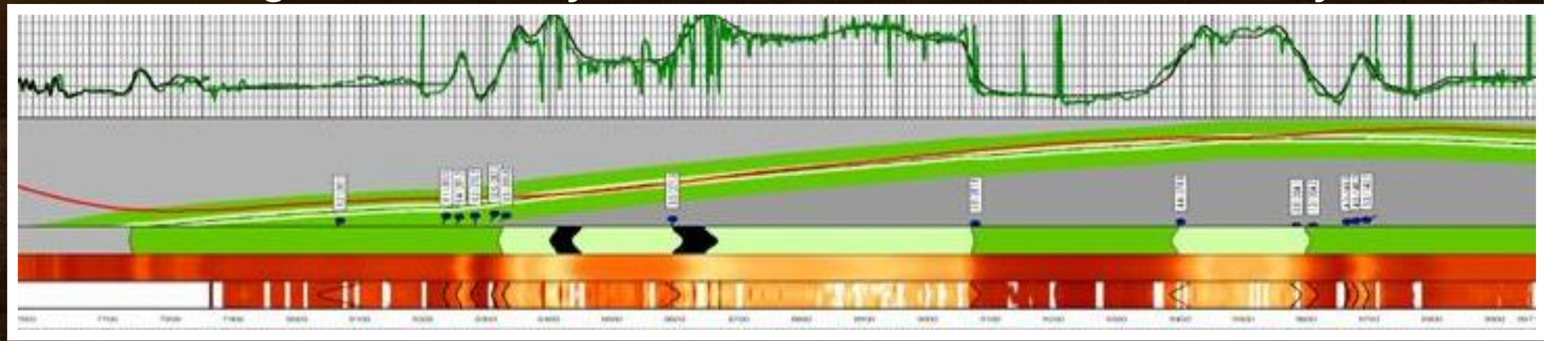


TOC, Vitrinite Reflectance Ro, Thermal Maturity, Porosity, K, P, Natural fractures, faults, karsts, hazards

Moving from Pilot wells to development wells

Reservoir Navigation Services - RNS (Azimuthal Resistivity & Gamma Images)

Armstrong Co., Pennsylvania – Marcellus Case History



Target for Lateral
High TOC = only 15ft Thick

Well Trajectory Planned
- Seismic
- Shale Analysis
- Offset Well Data

Monitored LWD GR
- Up and Down
- To determine if well approaching formation top or bottom / correct

Follow the high TOC, Ro, BI and Pp path

Evaluating the Resource and Production Potential

Resistivity / Density /Neutron						
20 Formation Lithology	Spectroscopy	Micro-seismic	Imaging	Large Diameter Coring	Deep Reading Shear Acoustic	Nuclear Magnetic Resonance
• Geochemistry • Lithology • Mineralogy • Total organic carbon	• Lithology • Mineralogy • Th/U for Carbon classification	Image correlation with lithology and facies	Fracture detection	Core analyses	• Geomechanical properties from Wellbore and away from wellbore	• Porosity • Indepen-dent measure of total organic carbon

Logging and Core analyses can identify:

- Fomation with producible source rock hydrocarbon
- Optimum formations to drill horizontal laterals
- Optimall placement of frac stages
- Potential barriers for frac containment
- Mineralogy key component integrated with Geomechanics

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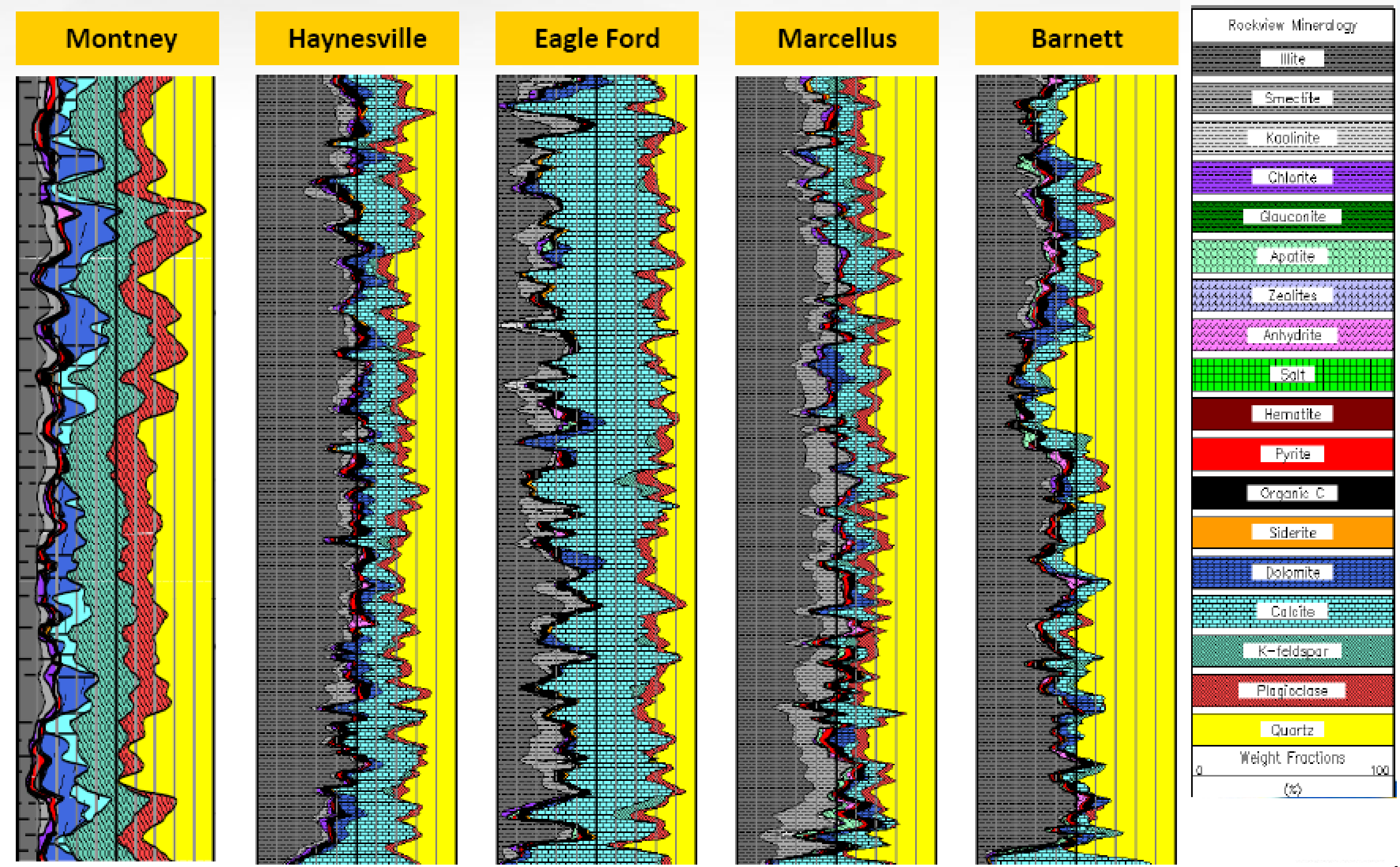
Mineralogy Varies in Shale Reservoirs



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Wellbore Imaging: Fractures, Faults & Geohazards

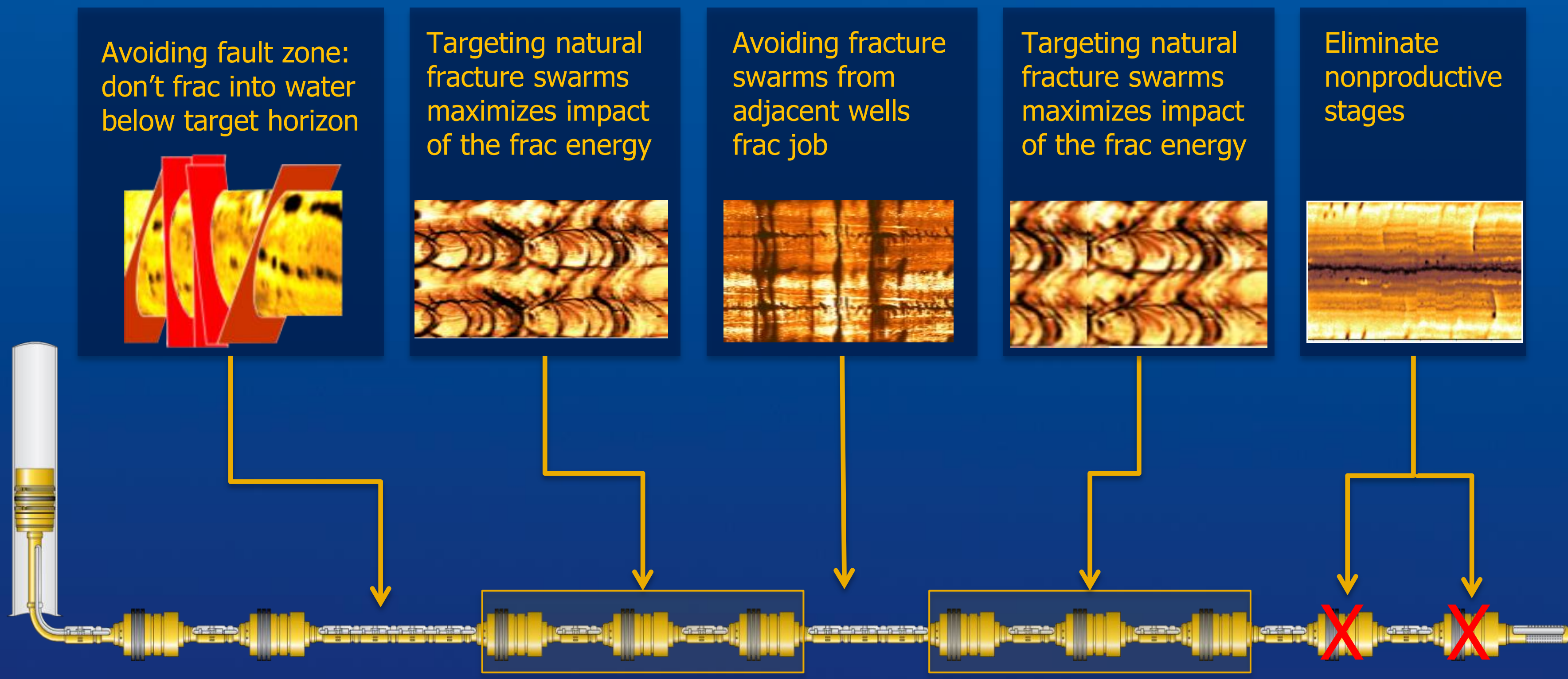
WBM Imager

Acquire high-resolution resistivity formation i

OBM Imager

Acquire high-resolution microresistivity images in oil-based mud system

High-definition LWD Imaging to Optimize Completions

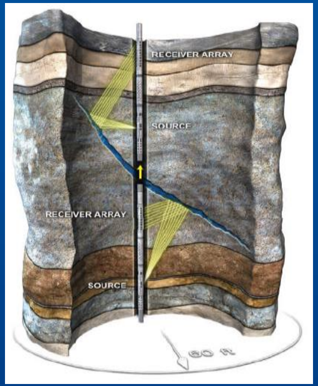


Case Histories Show Production Increases above 20 % and above 10% in EUR

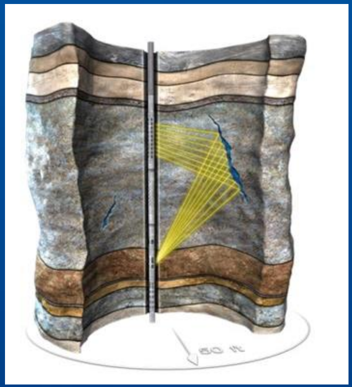
Deep Shear Wave Imaging (up to 70m away)

- Methodology
  - Filtering direct waves
  - Reflected wave stacking
  - Reflector strike inversion
  - Fullwave data migration

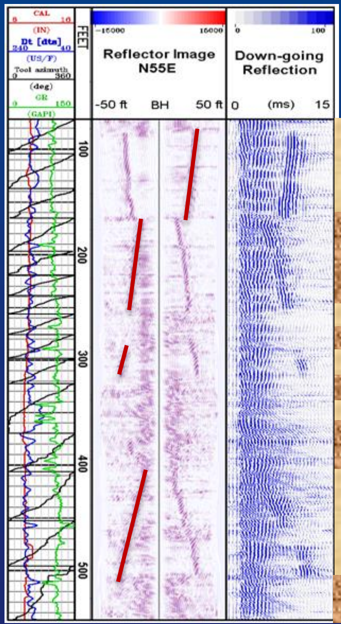
Imaging fractures that intersect the well

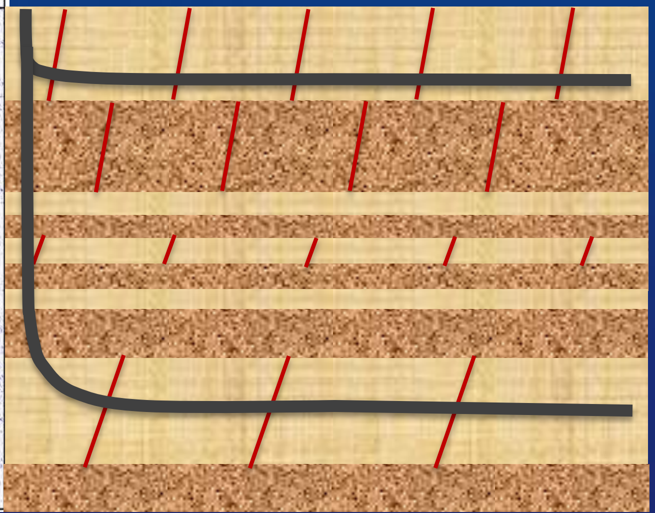


Imaging fractures that do not intersect the well

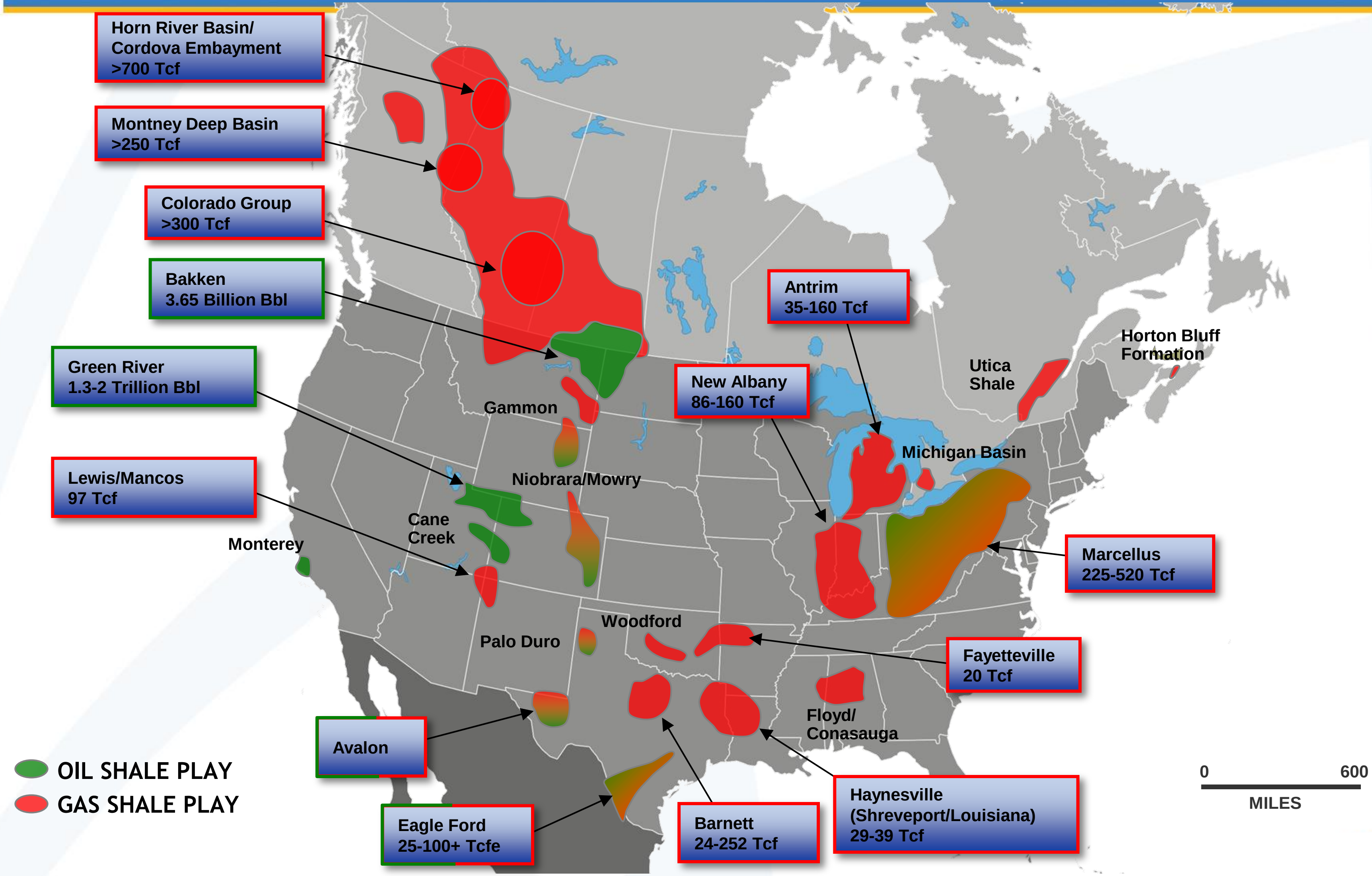


- Benefits
  - Illuminate natural fractures up to 70 m away.
  - Identify mechanical strata
  - Placing laterals





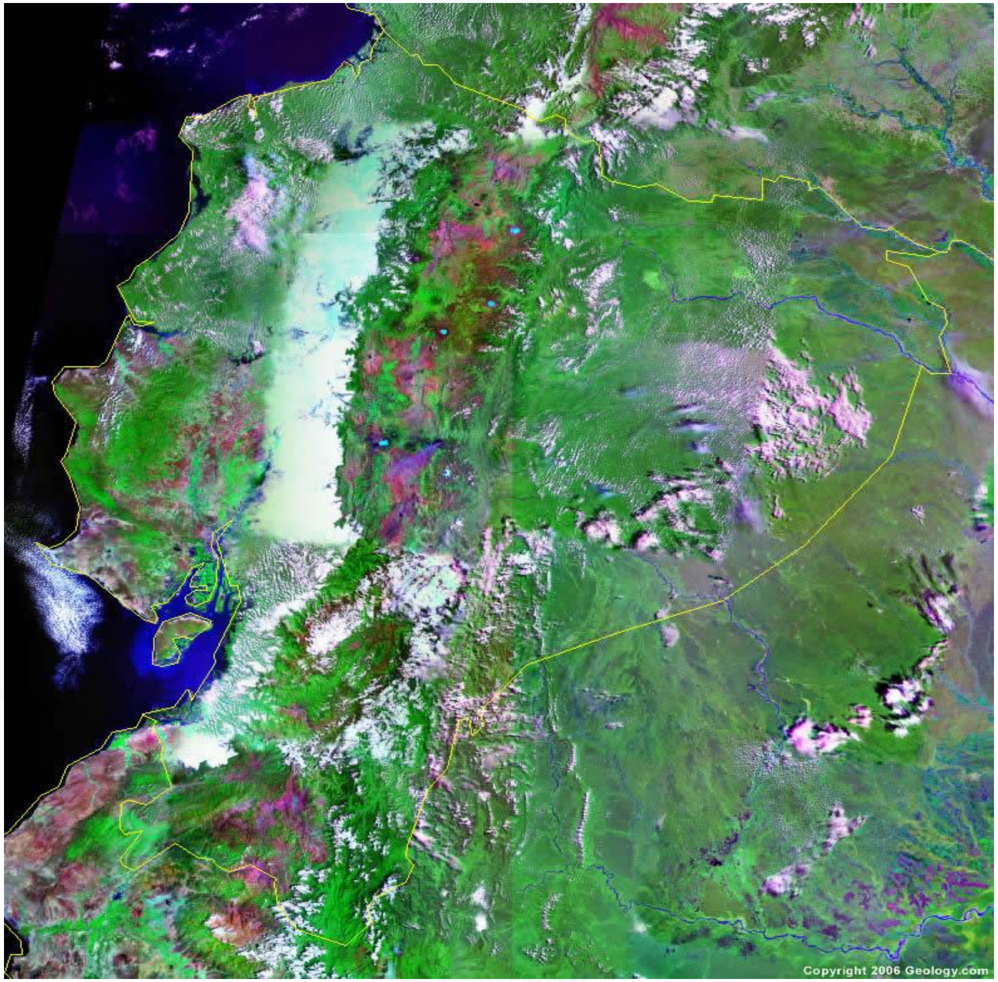
The Next 5-10 Years
~100,000 Wells, 1-2 Million Hydrofracs



How Do We Optimize Resource Development?

Outside North America?: The Next 5-10 Years? Wells, ? Hydraulic fracs

Eastern Hm
UK
Poland
Russia
Turkey
Saudi Arabia
Kuwait
India
China
Indonesia
Australia
Croatia

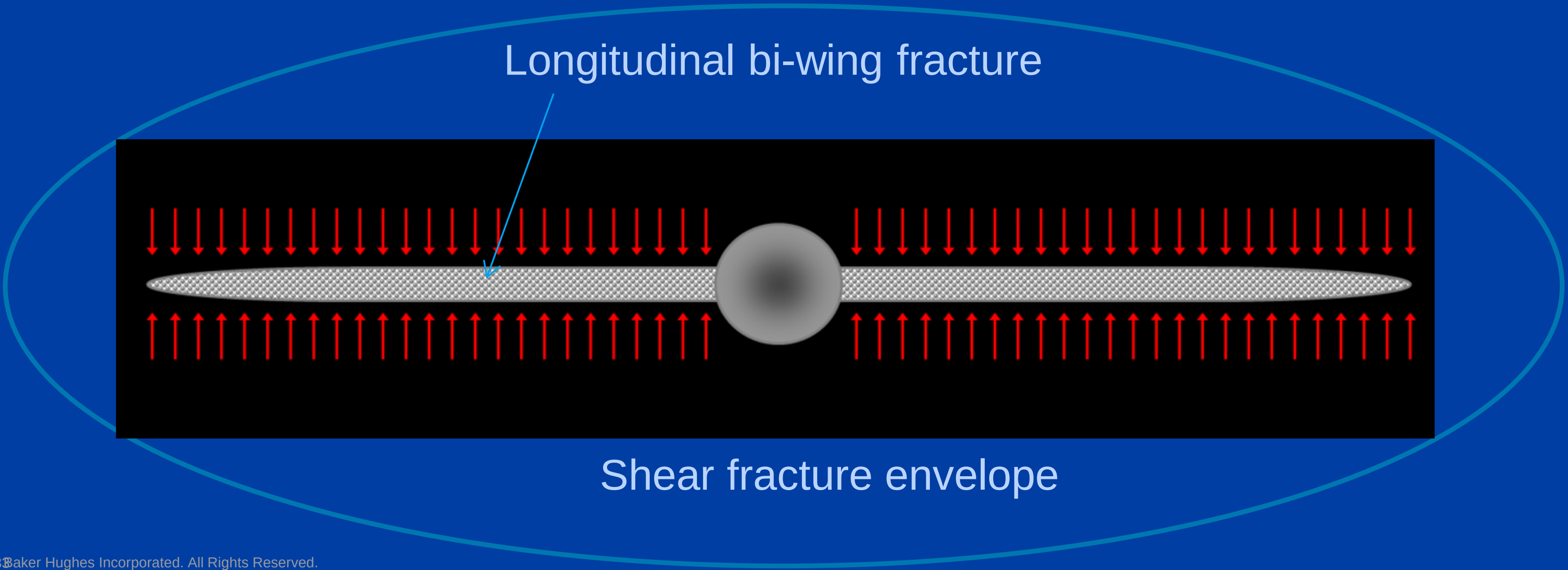


Western Hm
Argentina
Mexico,
Colombia
Venezuela
Ecuador
Brazil

How Do We Optimize Resource Development?

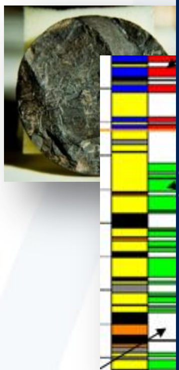
Production from Nano-Darcy Rocks?

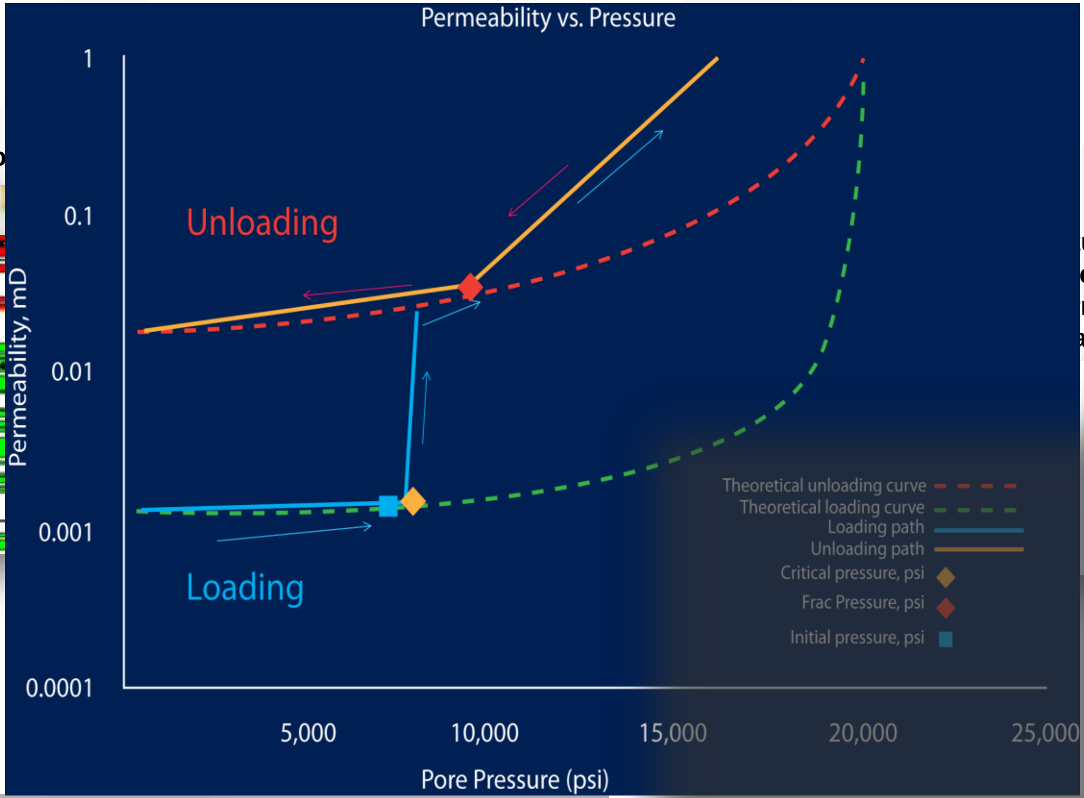
- Shale Resource has typically permeability in the nano-Darcy range
- Gas / hydrocarbon may move in order of few feet in a year!!
- What mechanism is there then to produce hydrocarbon from such low permeability rocks?
- Creation of a stimulated reservoir volume that has both longitudinal and shear fractures



From Natural Shale to the Artificial Reservoir

Logs and co





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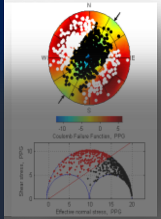
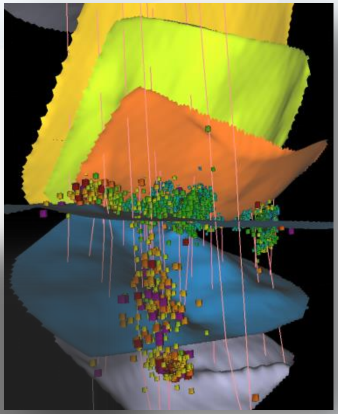


Microseismic Re-processing



Benefits

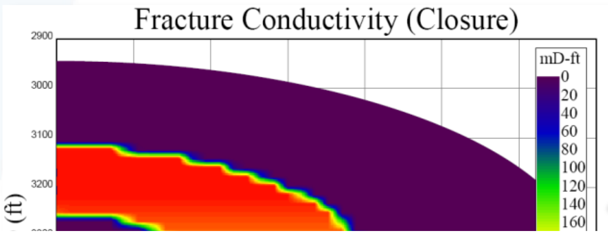
- Enhancing reservoir understanding
- Exploiting modern technology

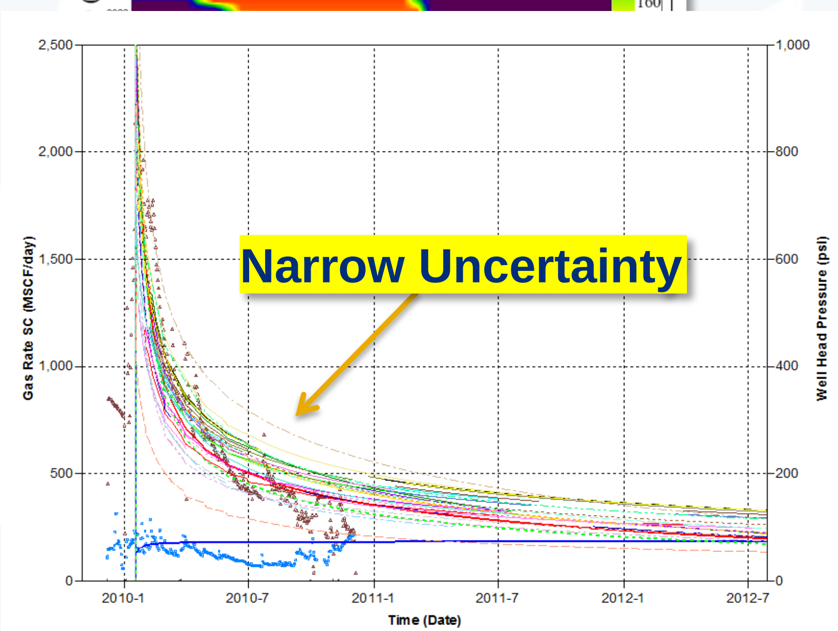
Shale Engineering Predictive Model

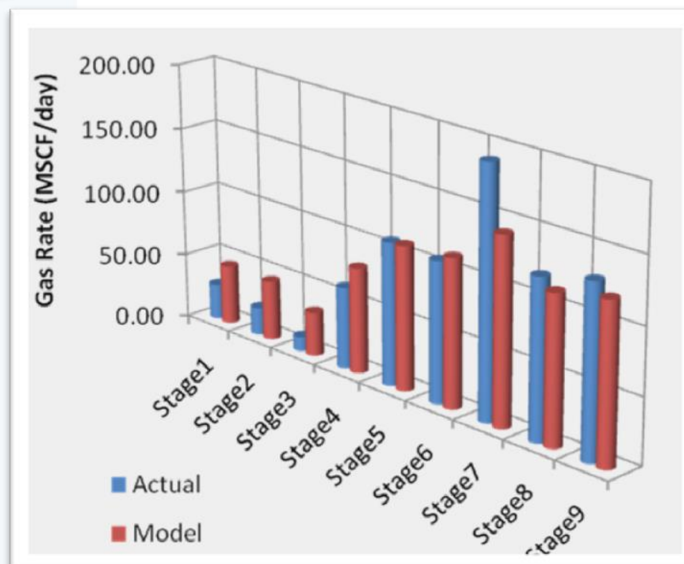
Matched production history and production logging

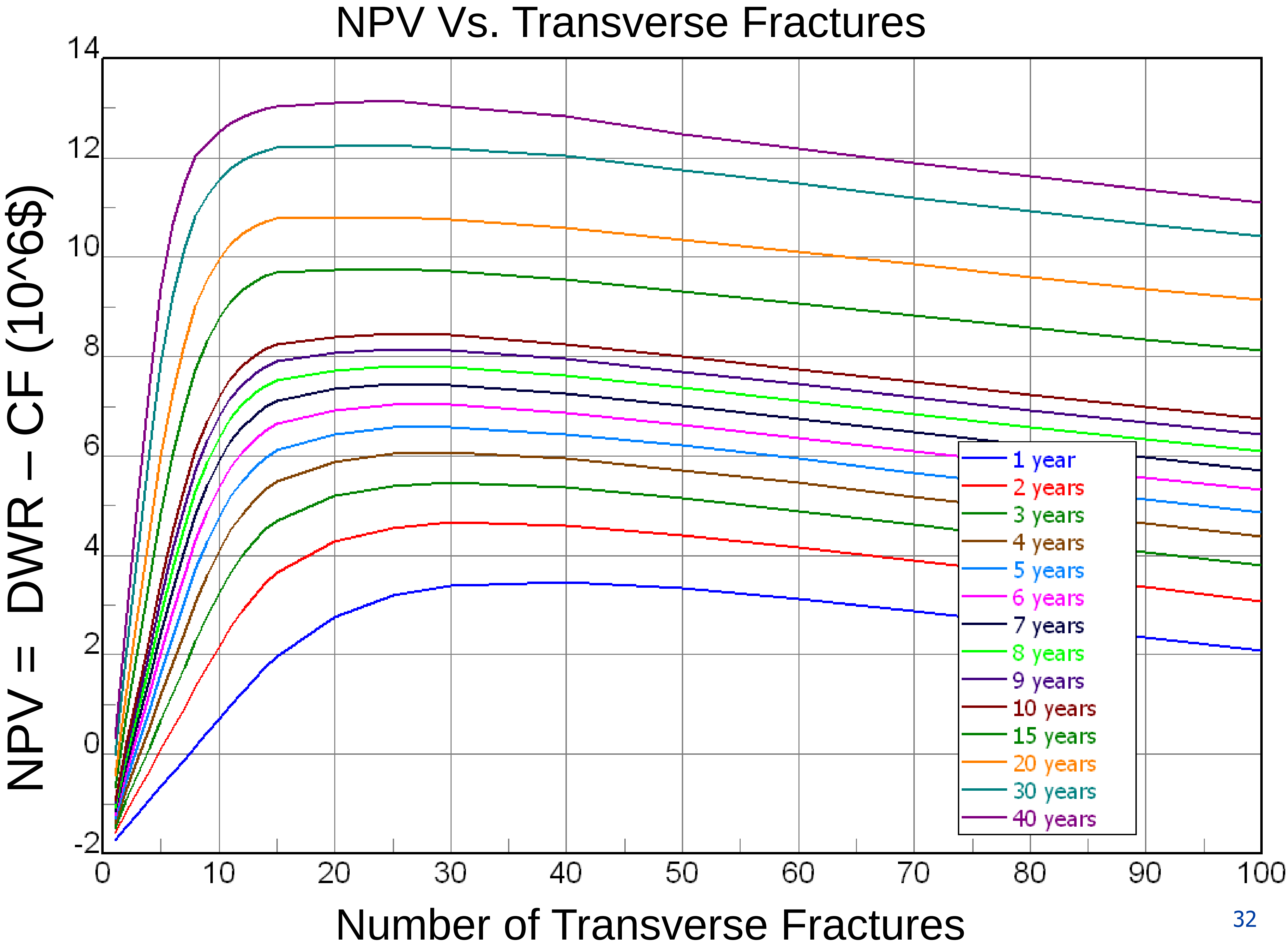
- ✓ **Frac stage contribution match**
- ✓ **Proppant placement match**
- ✓ **Well History match**

Pressure Drop, psi

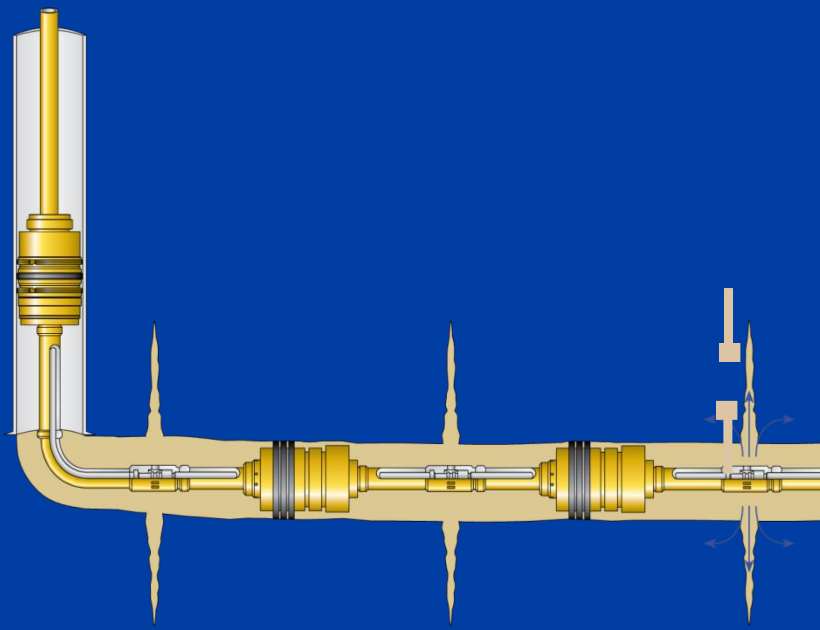


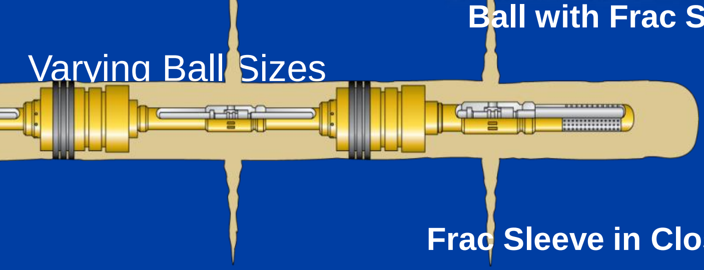





NPV Vs. Transverse Fractures
NPV = DWR – CF (10^6$)
Number of Transverse Fractures
14
12
10
8
6
4
2
0
-2
0
10
20
30
40
50
60
70
80
90
100
1 year
2 years
3 years
4 years
5 years
6 years
7 years
8 years
9 years
10 years
15 years
20 years
30 years
40 years

Ball Activated Sleeve Open / Close Completion System

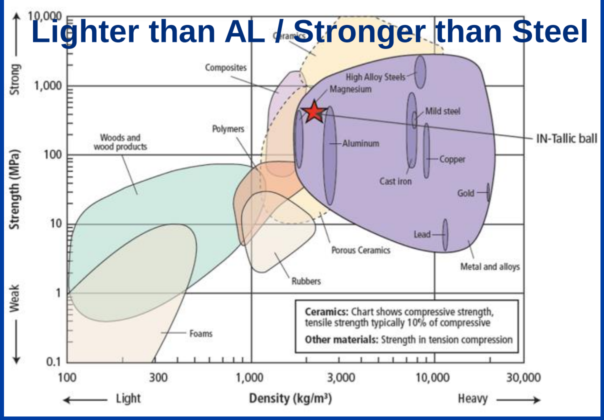




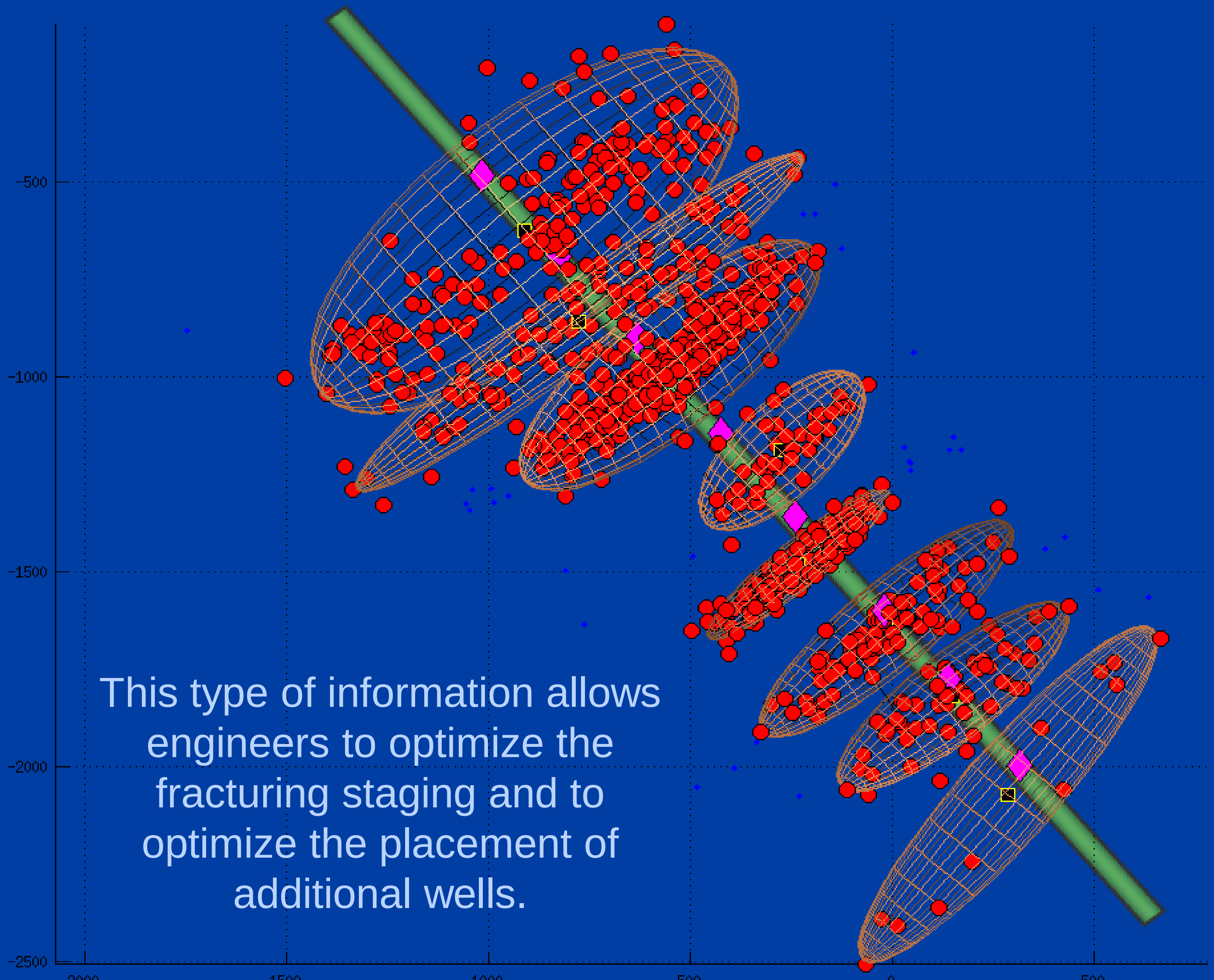
Varying Ball Sizes

Ball with Frac Sleeve Open

Frac Sleeve in Closed Position

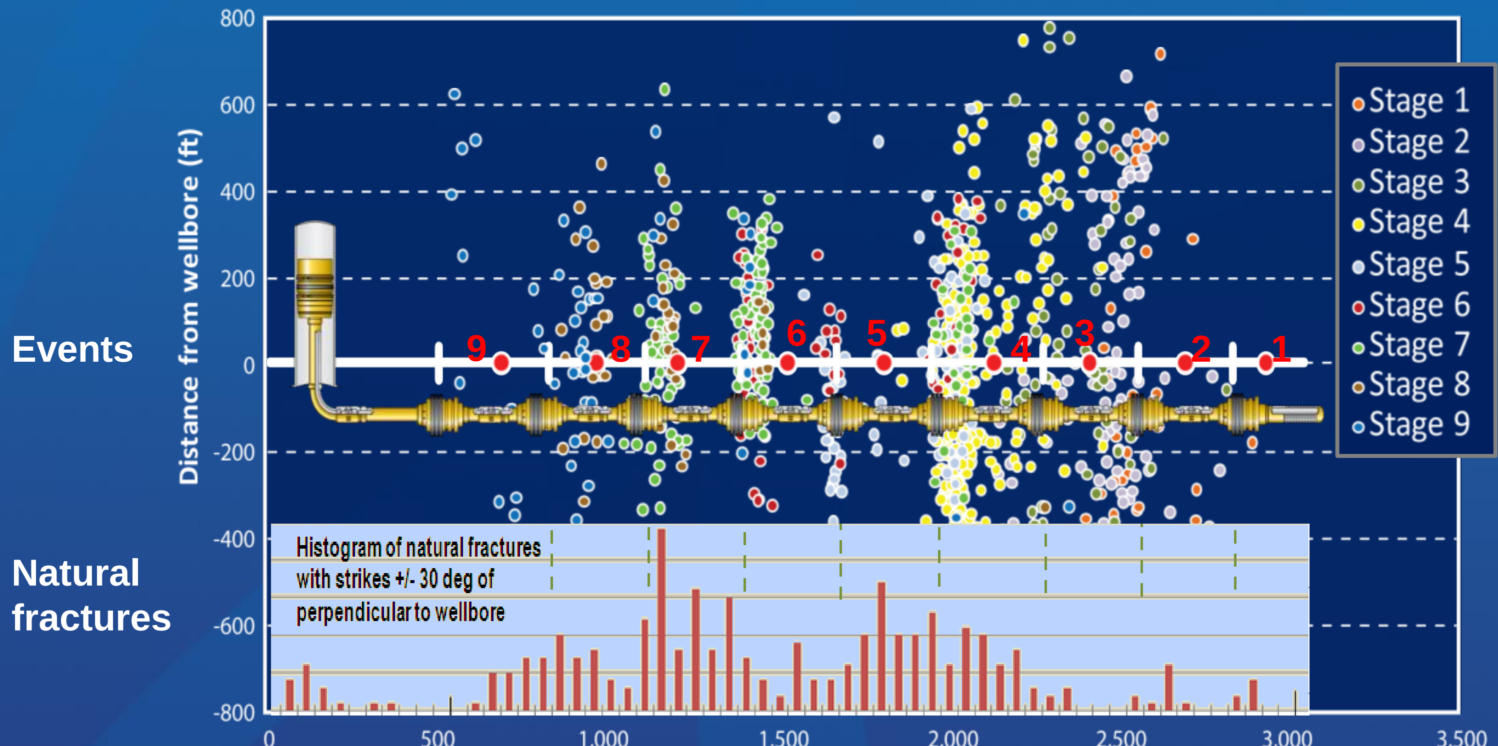


Extend and orientation of fractures created

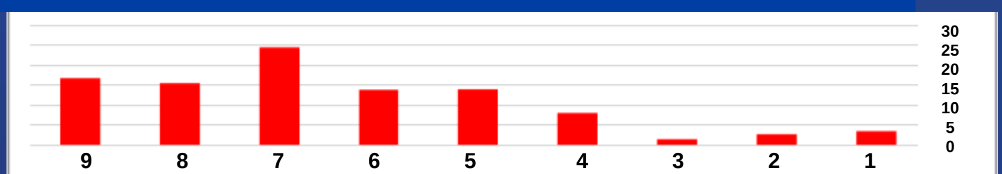


This type of information allows engineers to optimize the fracturing staging and to optimize the placement of additional wells.

Relating stage contributions to production:
Impact on Field Development Plan

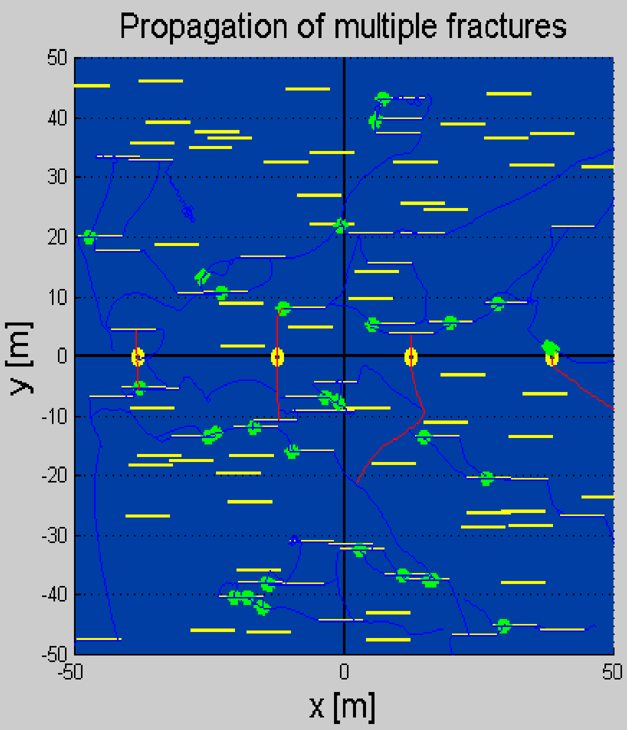


B-values								
-	0.98	-	1.01	-	1.92	2.27	1.92	-

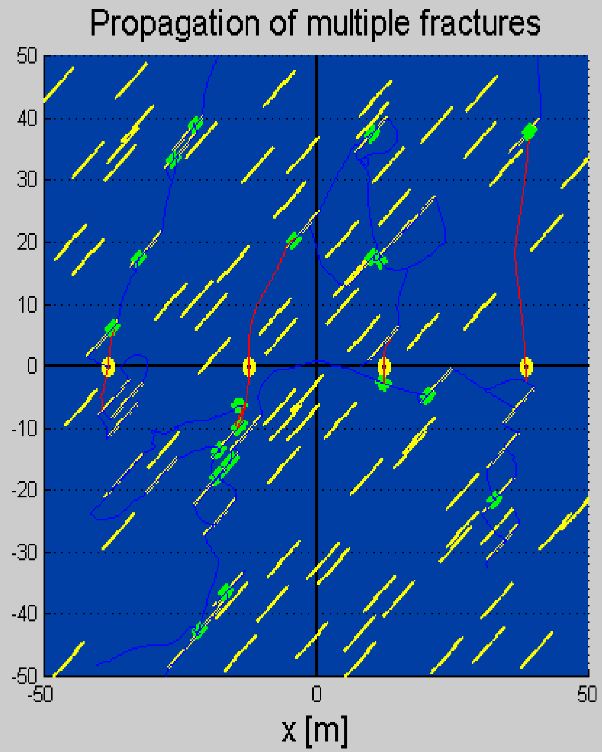


Rates measured by PLT 5 months later

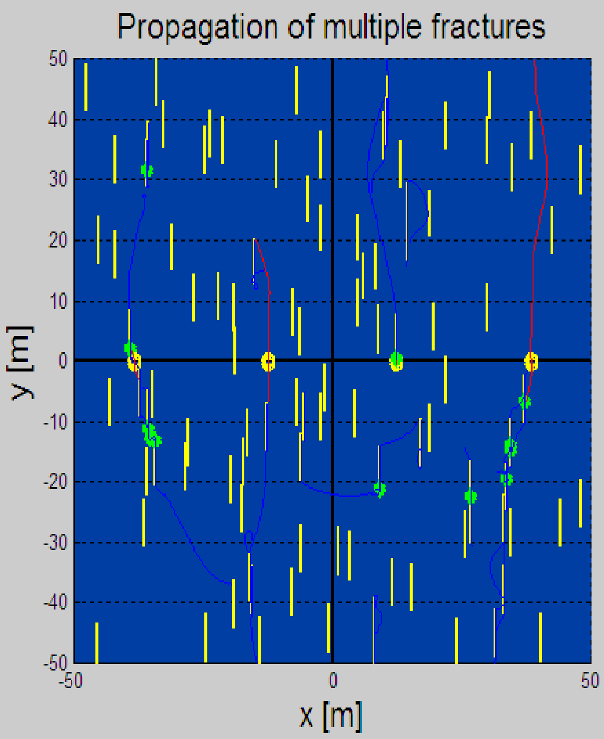
Fracture Mechanics Based Model



σh = σH, NF 100 EW (90º)

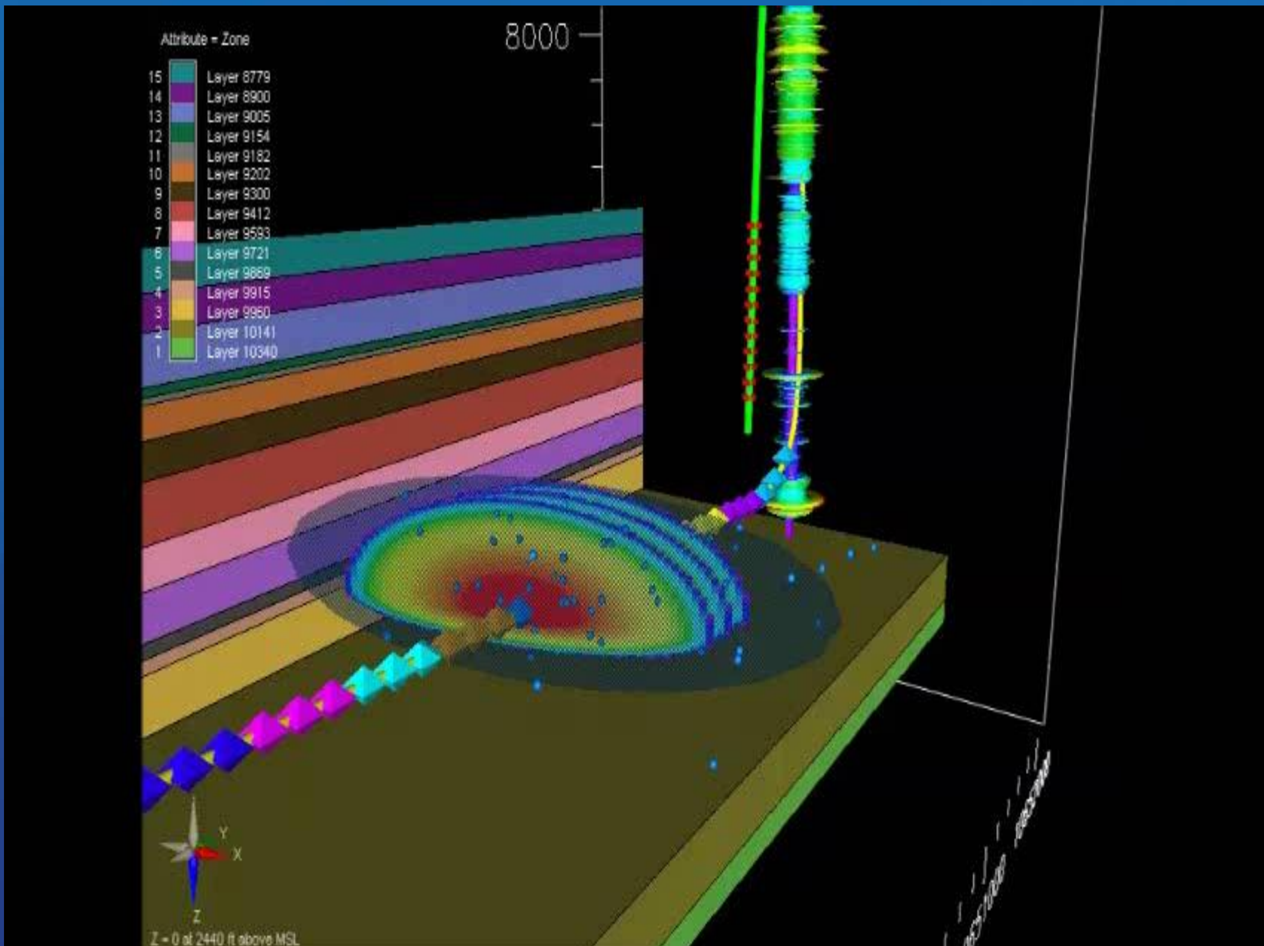


σh = σH, NF 100 NS (45º)



σh = σH, NF 100 NS (0º)

Integrated Display



- Well Logs
- Layers
- Fracture Model
- Events
- Real-Time “SRV”

Concluding Remarks

- Shale resource is not contiguous and no two Shale basins are the same
  - Sweet spot identification is going to be critical (seismic attribute + Lithofacies) for well placement
  - Different shales will require different set of attributes and the associated lithofacies
- Geometric placement of hydraulic fracture stages needs to be replaced by shale productivity based parameters
  - Capitalize on the presence of natural fractures at the well bore as well as away from the wellbore
  - Avoid faults and geohazards

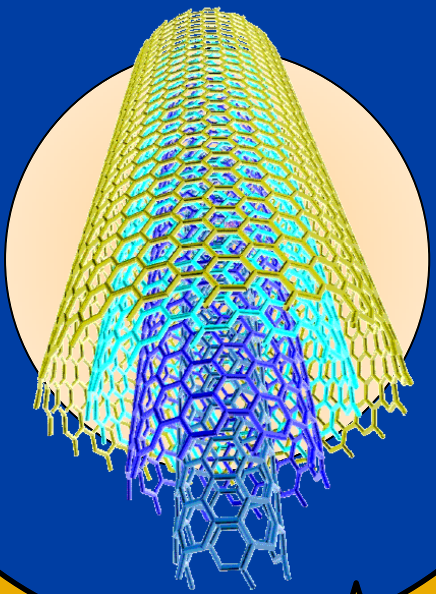
Shale Technology: A Look Ahead

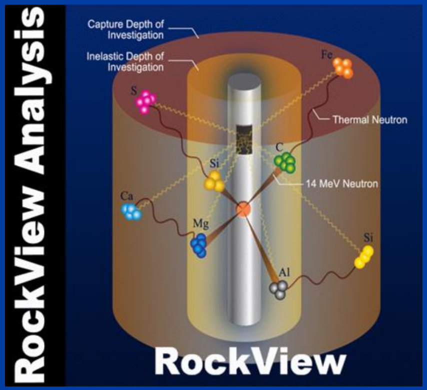
- Nanotechnology: An Enabler for Multiple Oil & Gas Applications

XMACsm

Production Enhancement

Reservoir Assessment





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