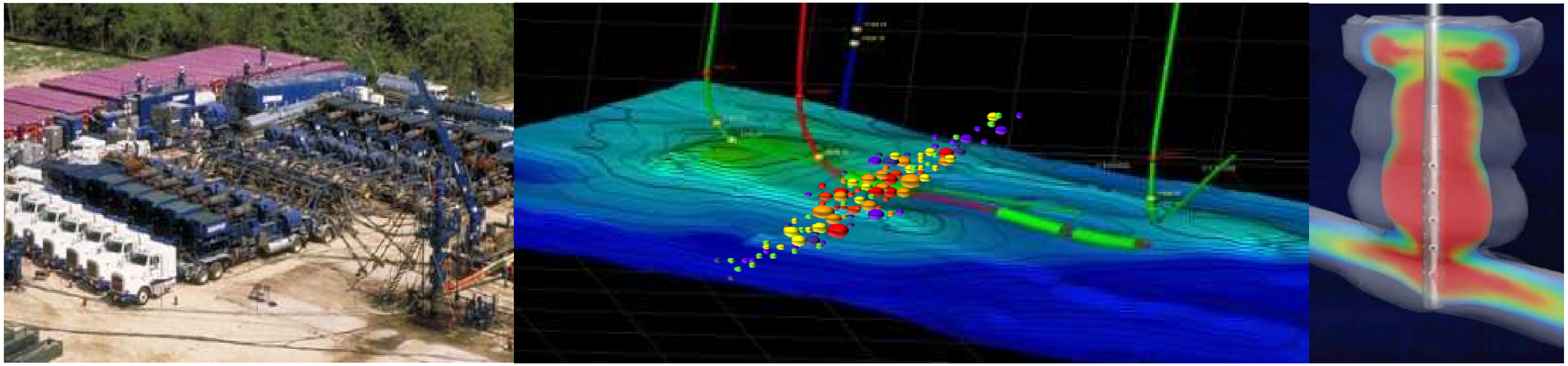


Geomechanic for Hydraulic Fracturing in Unconventional Reservoirs

Raul German Rachid
Production Stimulation Engineer
Schlumberger
Argentina Bolivia Chile

Agenda

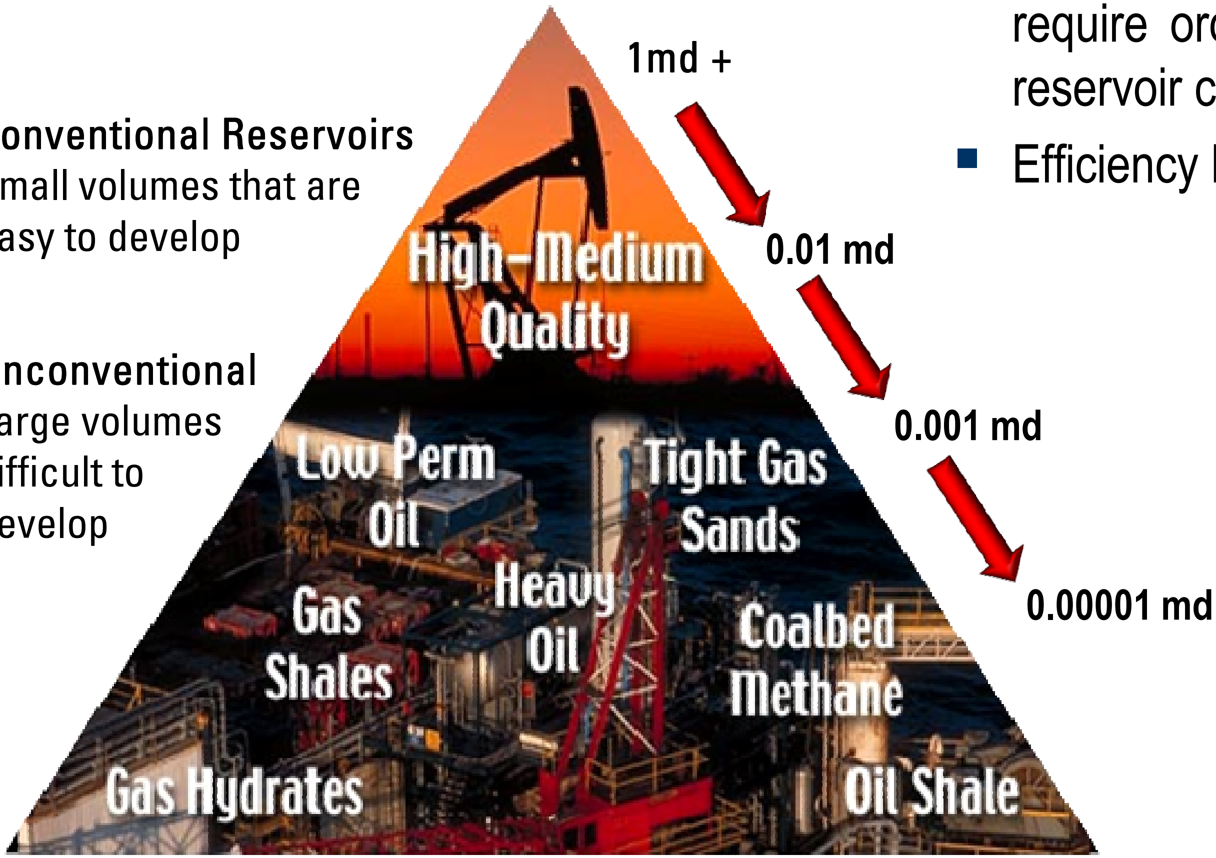
- Introduction to Unconventional Reservoirs
- Consequences of Heterogeneity and Lamination
- Stress Profile Modeling in Anisotropic Media
- Horizontal Wells
- Fracture Geometry Simulation
- Conclusions

Introduction to Unconventional Reservoirs

The Industry Challenge

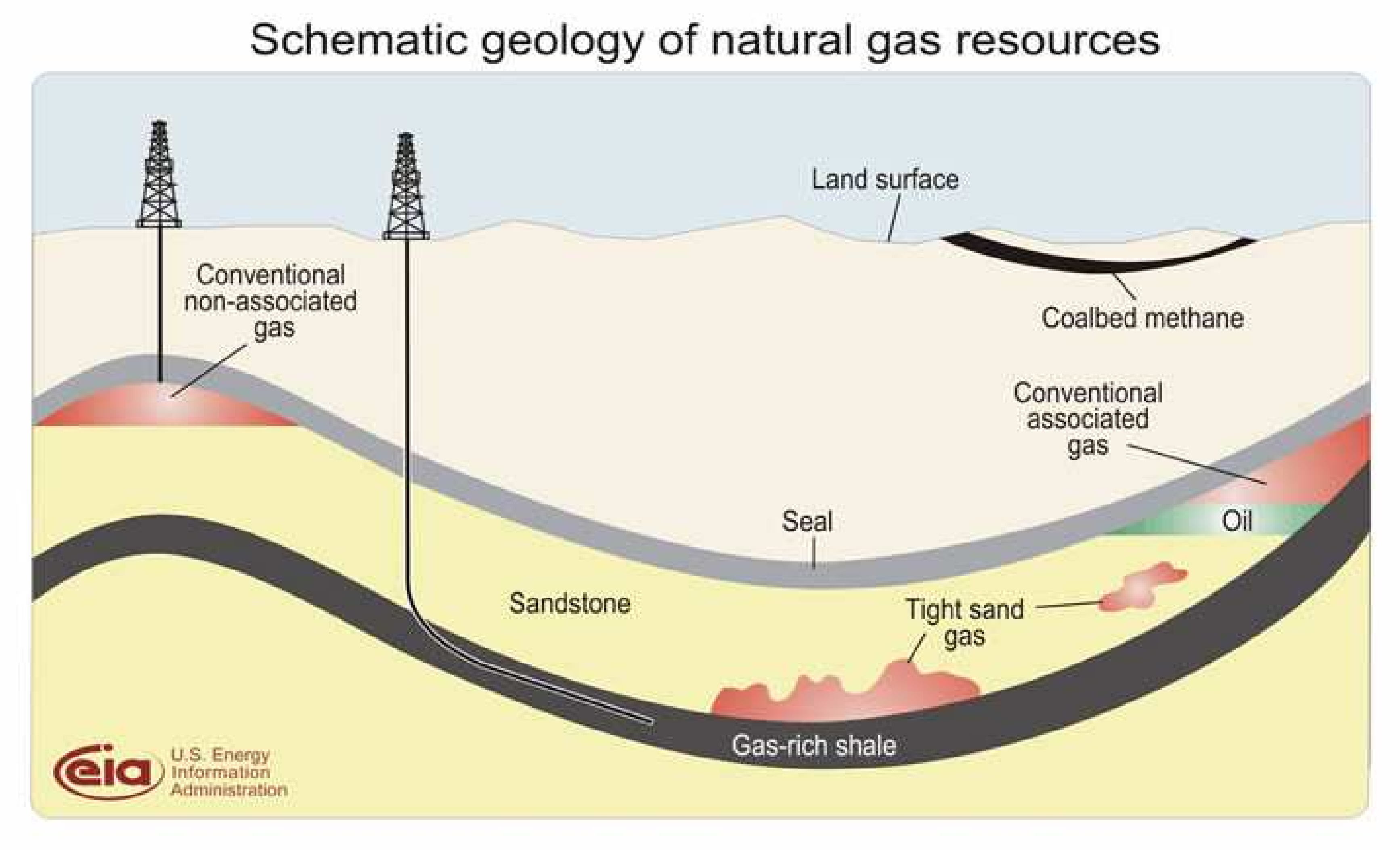
Conventional Reservoirs
Small volumes that are easy to develop

Unconventional
Large volumes difficult to develop



- Orders of magnitude reductions in perm require orders of magnitude increase in reservoir contact
- Efficiency key to economic success

Shales are unconventional reservoirs



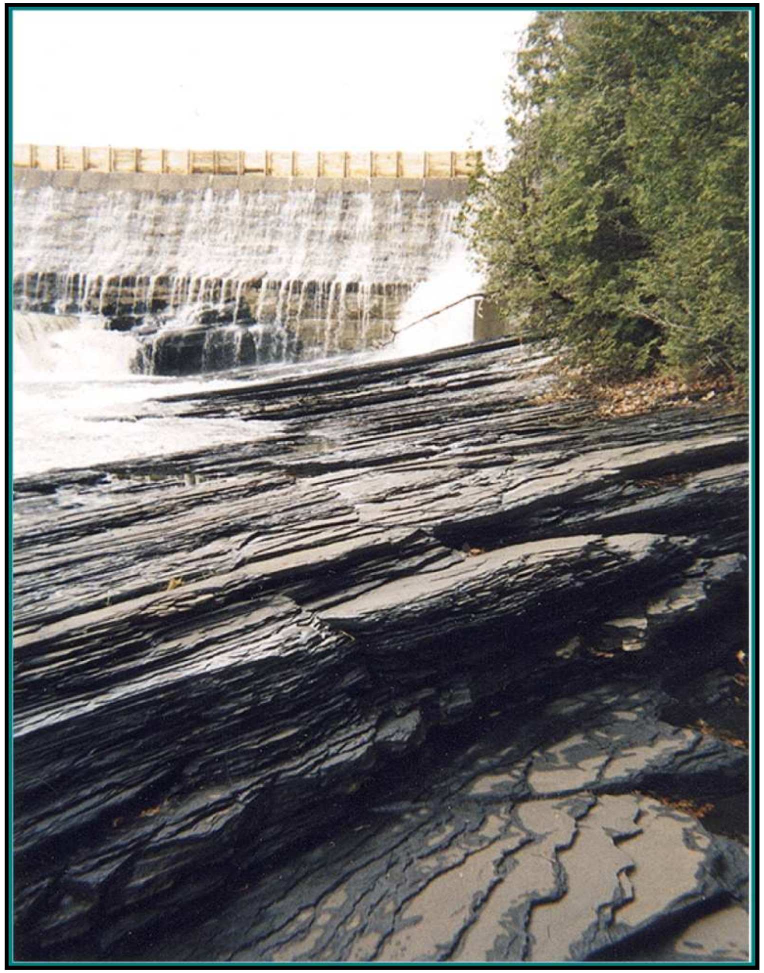
Shale Gas Introduction

What are they?

- Organic-rich shale
- Source rocks
- **Adsorbed** and **free** gas
- Very low permeability

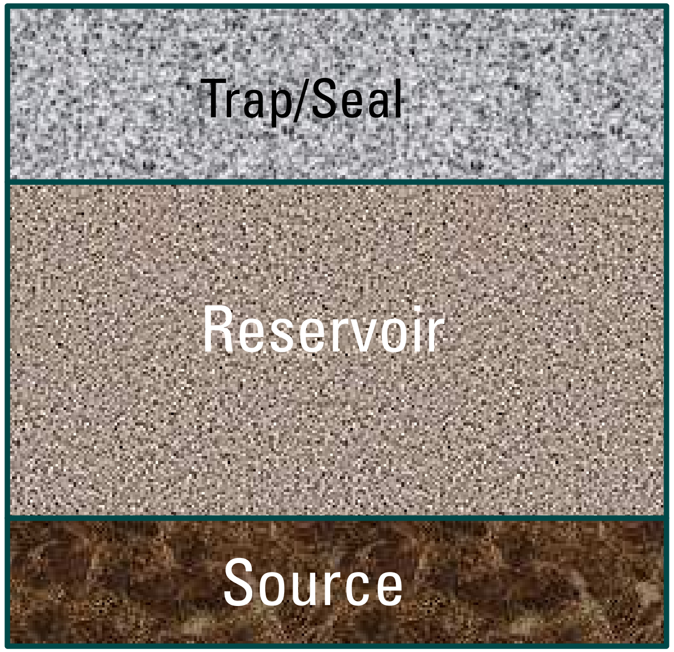
Common traits of gas shale reservoirs

- Abundant gas (20 to 400 BCF/mi^2)
- Large developments (economies of scale)
- Large and numerous hydraulic stimulations
- Long well life (60-year reserves common)



Trap, Reservoir & Source Rock

Conventional



Hydrocarbon leaves source and settles in the reservoir because it cannot pass the trap

Unconventional

Rock is too tight to let go of Hydrocarbon so source rock acts as the trap and the Reservoir

Heterogeneous Rock at Fine Scale

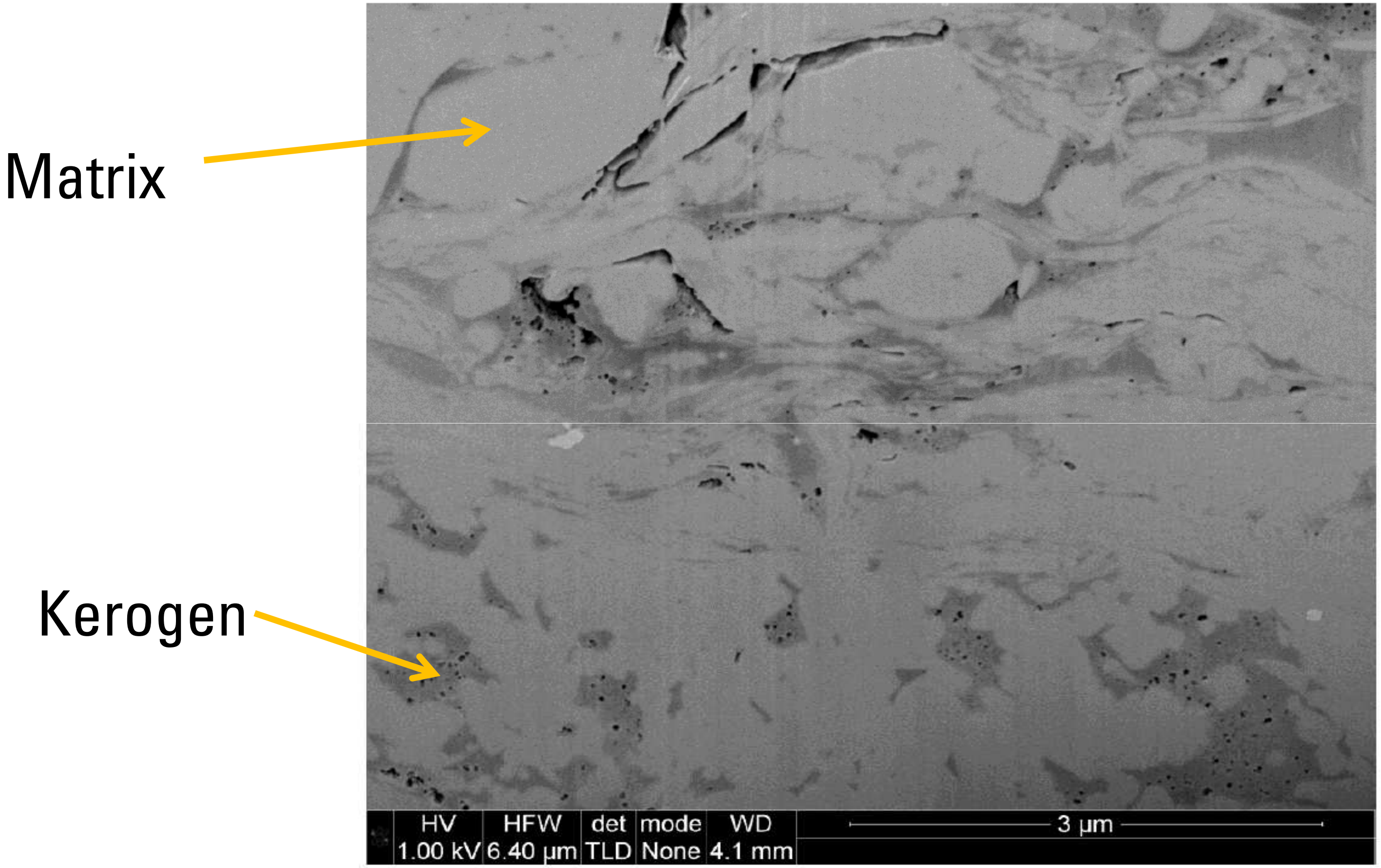
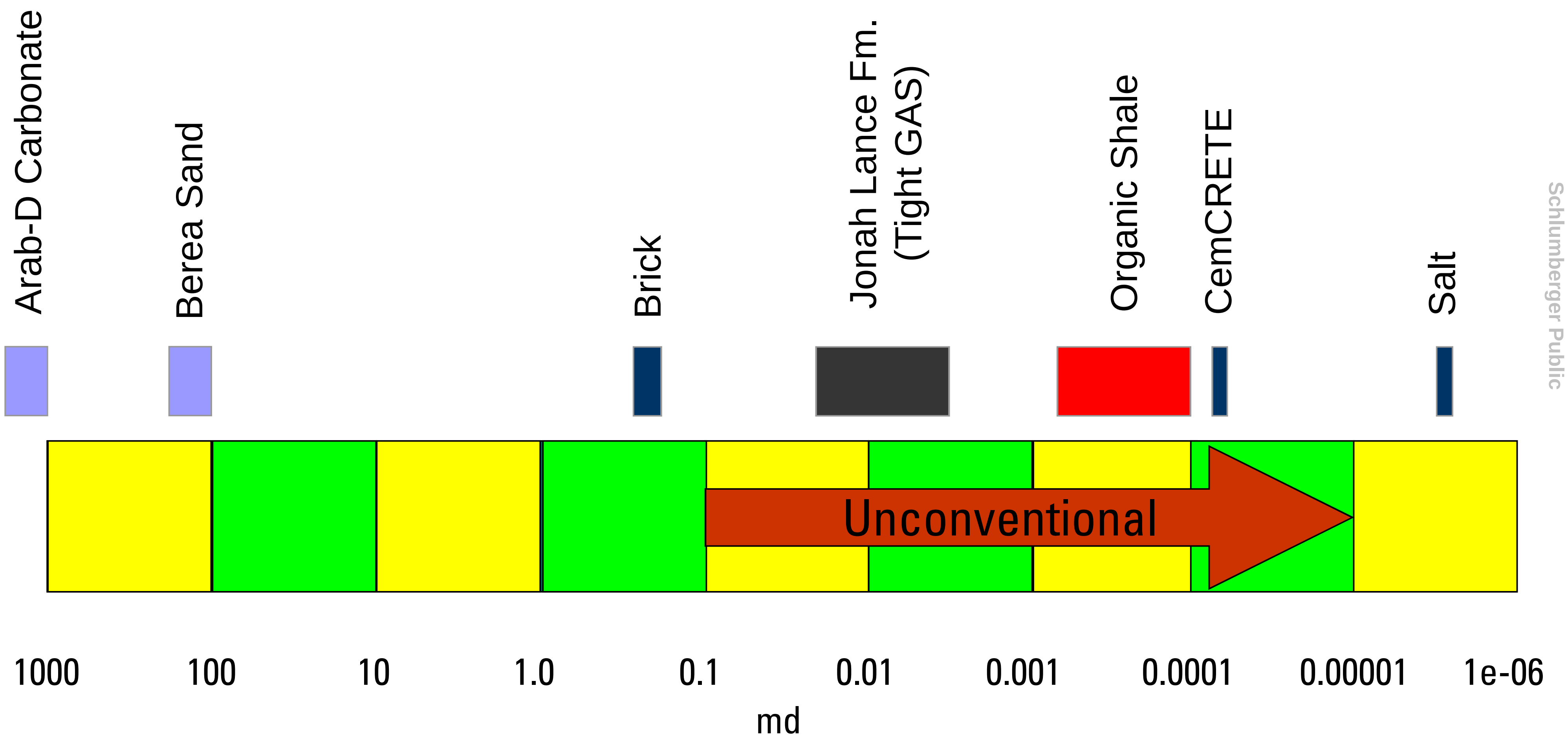


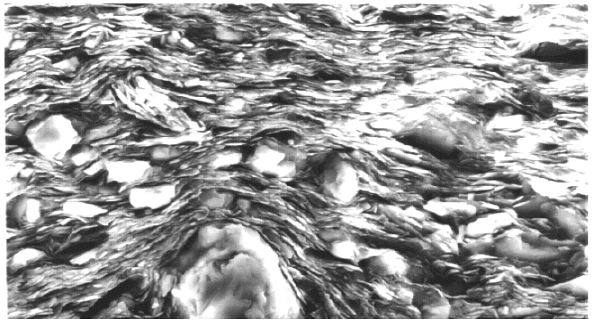
Fig. 3. 2-D FIB/SEM image showing porosity and kerogen within shale. Black depicts pore, dark gray is kerogen, light gray is matrix (clay and silica).

SPE 131772

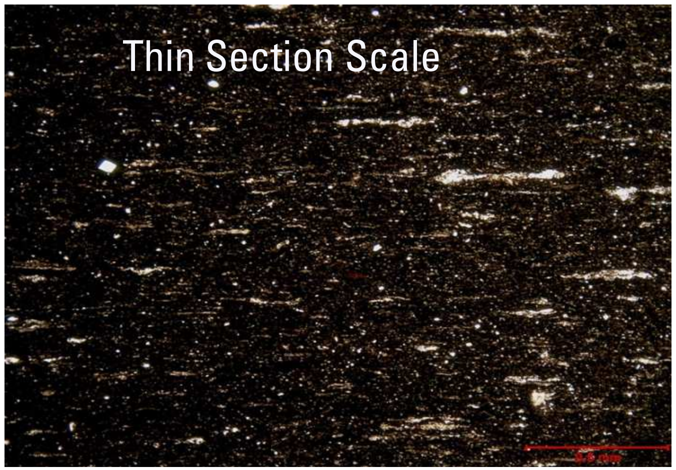
Shale in Perspective: Permeability

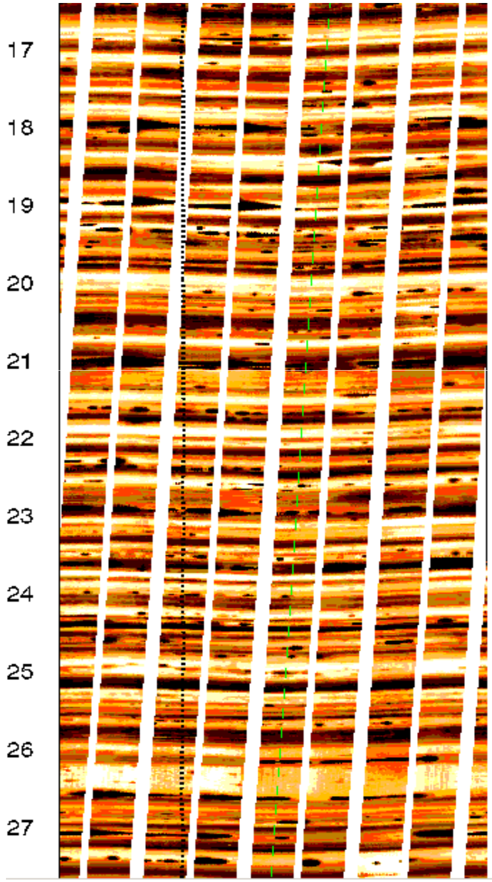


Mechanical Properties for Shales
The Consequence of Laminations

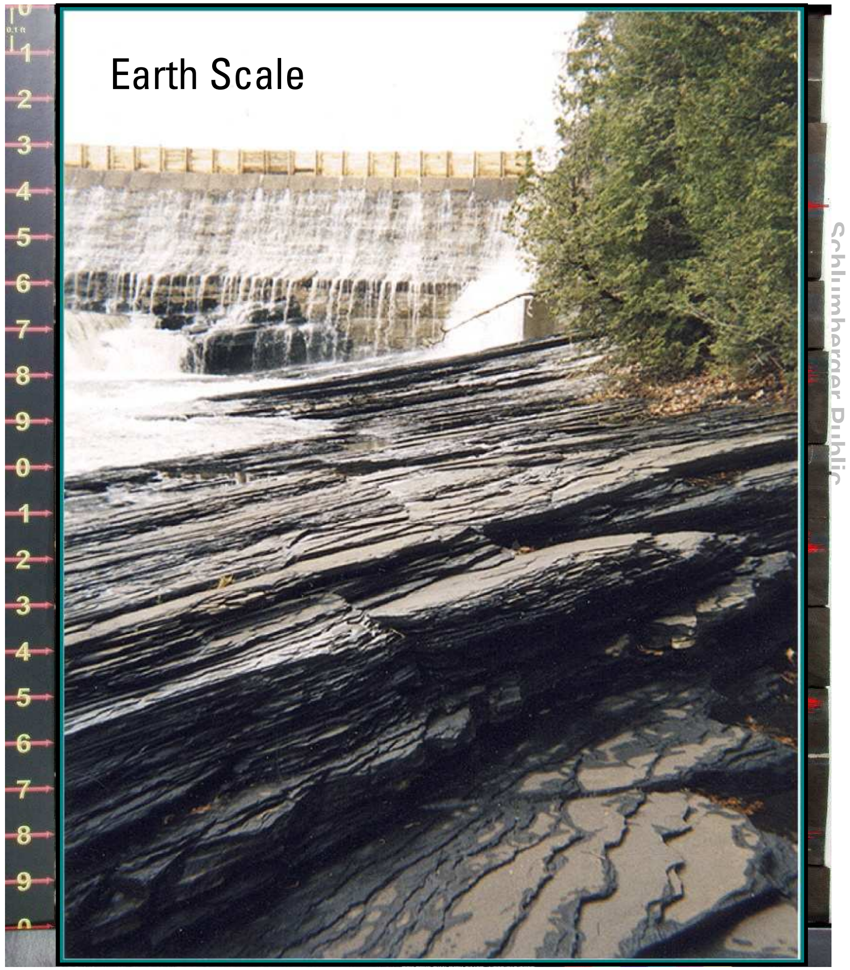


SEM Scale





Log Scale



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Unconventional Shale Gas Reservoirs

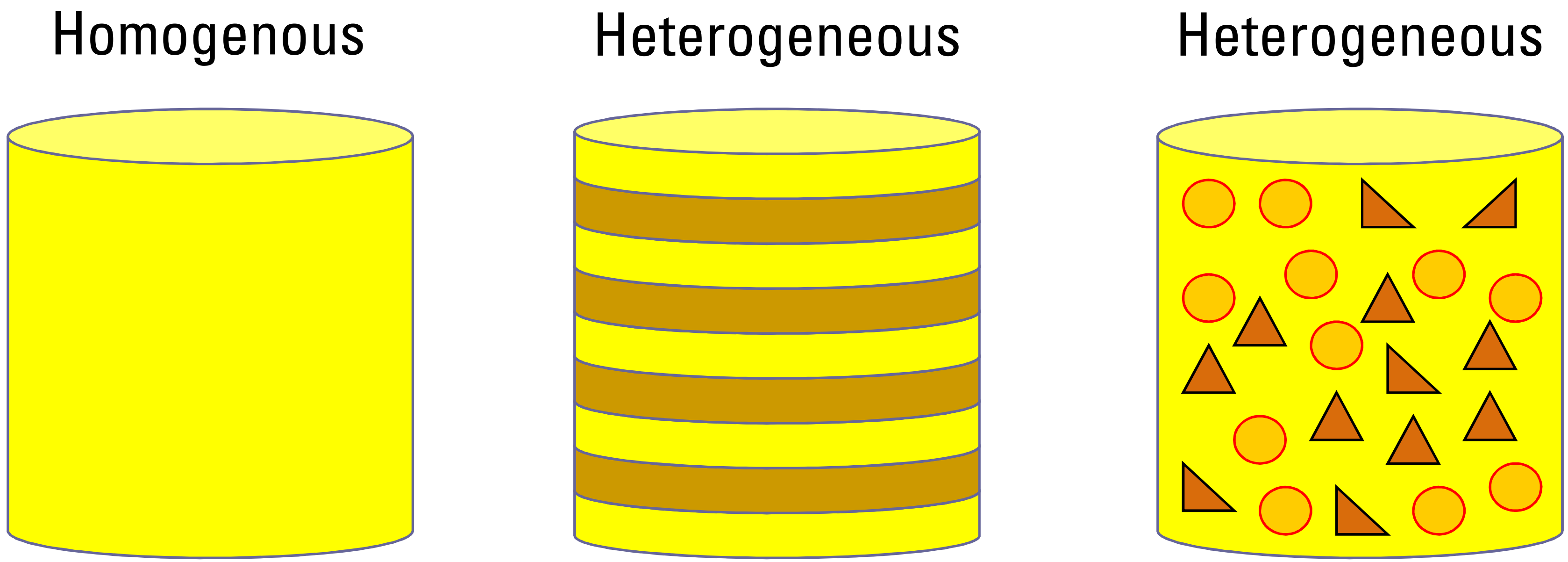
- Hydraulic fracture containment is often either unknown or perceived as uncertain.

- Traditional stress modeling in shale gas reservoirs has lead to inefficient fracturing or unexpected height growth.

- However by considering anisotropic rock properties……

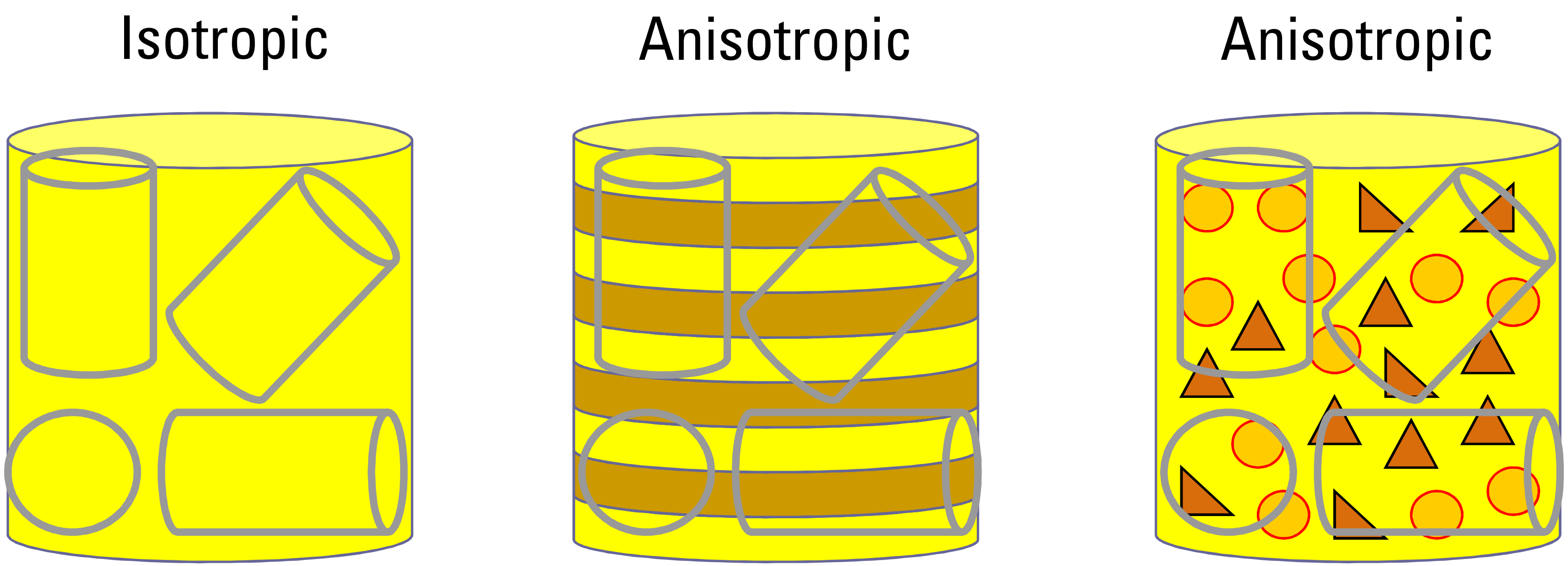
Heterogeneity

A heterogeneous material is one consisting of dissimilar or diverse constituents



Anisotropy

Anisotropy is defined as the variation of a property with the direction in which it is measured.



Evaluate using core, logs and seismic

What is a Transversely Isotropic medium?

Isotropic media

Same property in the 3 principal directions of space

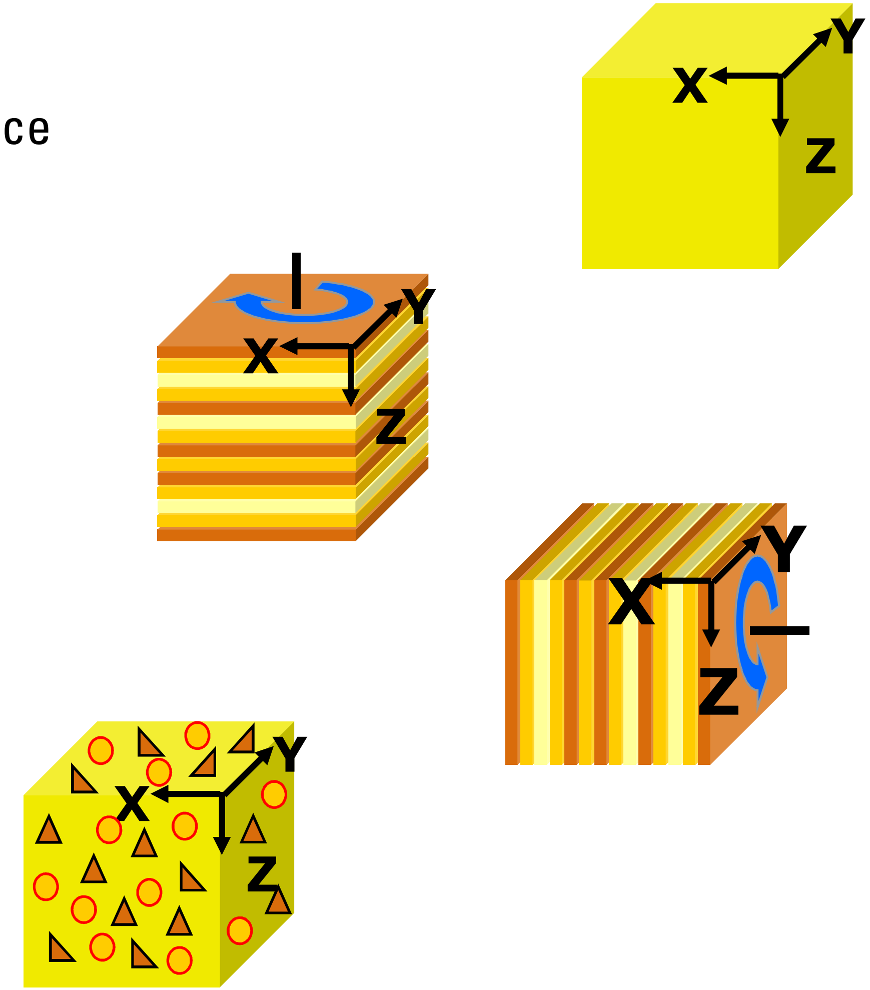
Transverse isotropic

Property is the same in 2 principal directions:

- TIV same property in horizontal plane
- TIH same property in vertical plane

Orthotropic

Property varies in 3 directions



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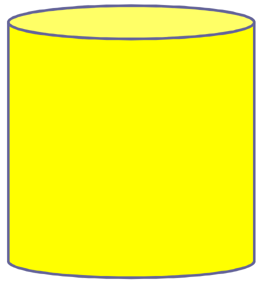
Stress Modeling of Shales

Jaeger and Cook – Fundamentals of Rock Mechanics (1979)

This is the case of a sedimentary rock with z-axis perpendicular to the bedding, and the increase of the number of elastic constants from two for the isotropic case to five is formidable. There is no great difficulty in handling many mathematical problems involving such materials, cf. Hearmon (1961), Savin (1961); the difficulty for practical purposes is in obtaining and using realistic values of the elastic constants.

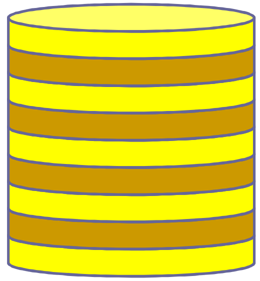
$$\sigma_h - \alpha P_p = \frac{v}{1-v}\left(\sigma_V - \alpha P_p\right)$$

Isotropic



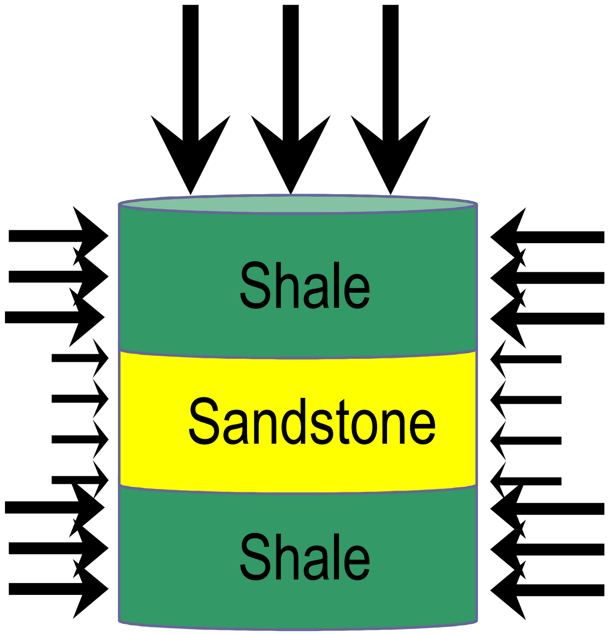
$$\sigma_h - \alpha P_p = \frac{E_h}{E_V}\frac{v_V}{1-v_h}\left(\sigma_V - \alpha P_p\right)$$

Transverse Isotropic

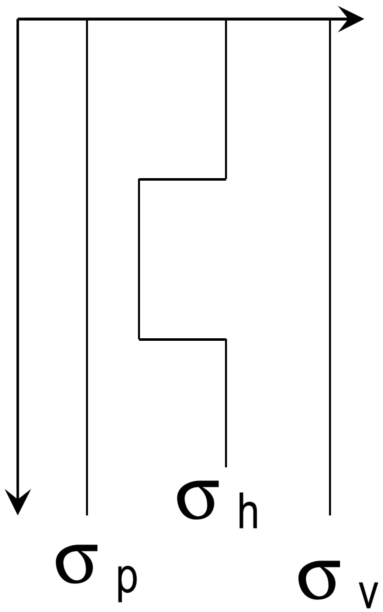


Traditional Stress Modeling: Isotropy

- σ vertical



Stress Profile



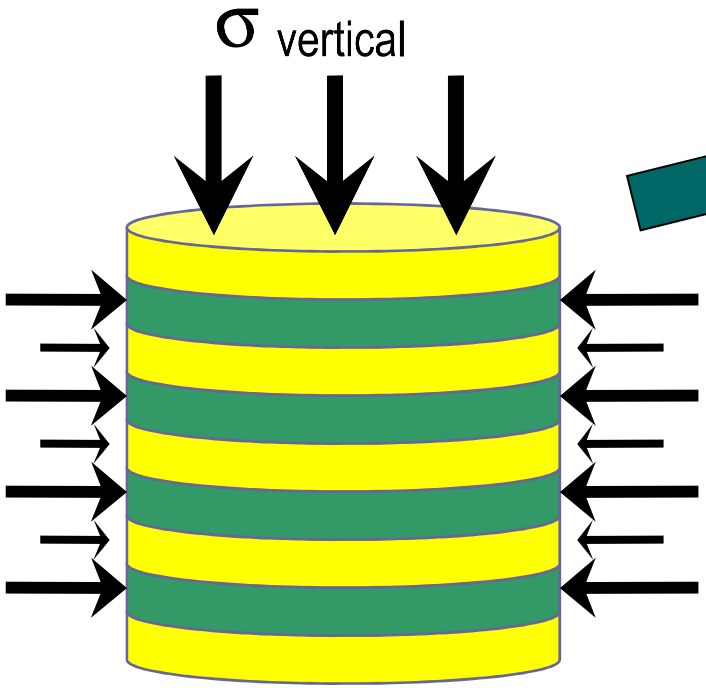
Isotropy assumes that:

Horizontal = Vertical

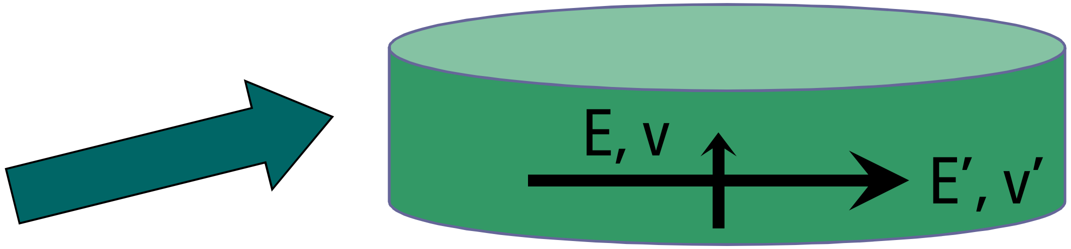
All conventional sonic tools !!

$$\sigma_h - \sigma_p = \frac{\upsilon}{1-\upsilon}\left(\sigma_v - \sigma_p\right) + tectonics$$

Stress Profiles in Anisotropic Rock



Laminated Shale which is the reservoir & source rock



Where:

- E = Young's Modulus <u>Vertical</u>
- v = Poisson's Ratio <u>Vertical</u>
- E' = Young's Modulus <u>Horizontal</u>
- v' = Poisson's Ratio <u>Horizontal</u>

$$\sigma_h - \sigma_p = \frac{Eh}{Ev}\frac{\upsilon v}{1-\upsilon h}\left(\sigma_v - \sigma_p\right) + tectonics$$

Vertically Anisotropic Formation – Impact on Frac Height

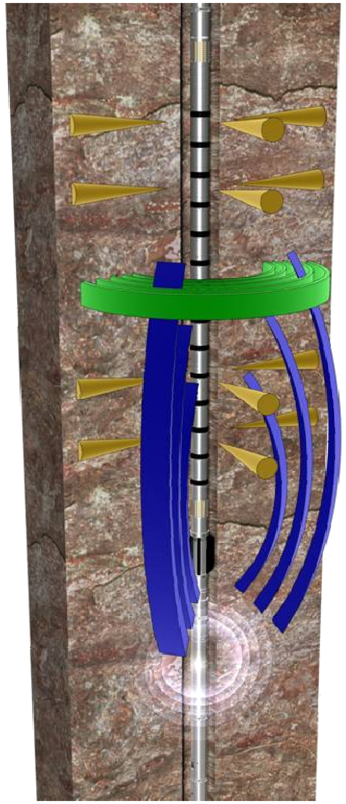
Isotropic Stress

$$\frac{\nu}{(1-\nu)}\times(\sigma_V - \alpha P_r) + \alpha P_r$$

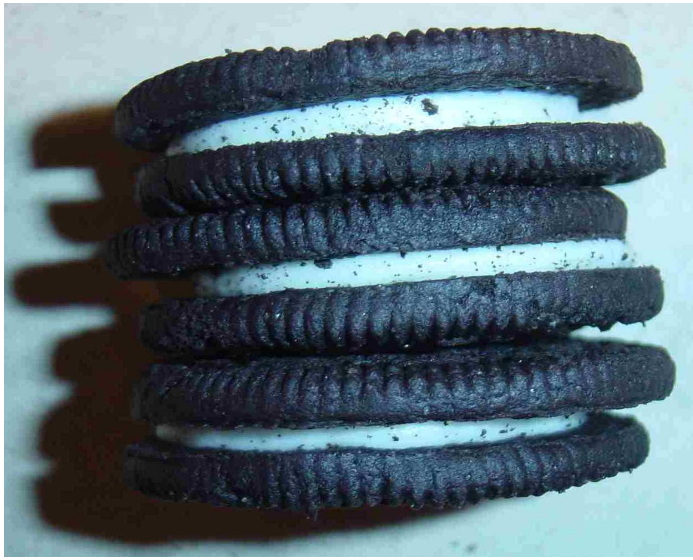
Anisotropic Stress

$$\frac{E_h}{E_V}\times\frac{\nu_V}{(1-\nu_H)}\times(\sigma_V - \alpha P_r) + \alpha P_r$$

Sonic Scanner

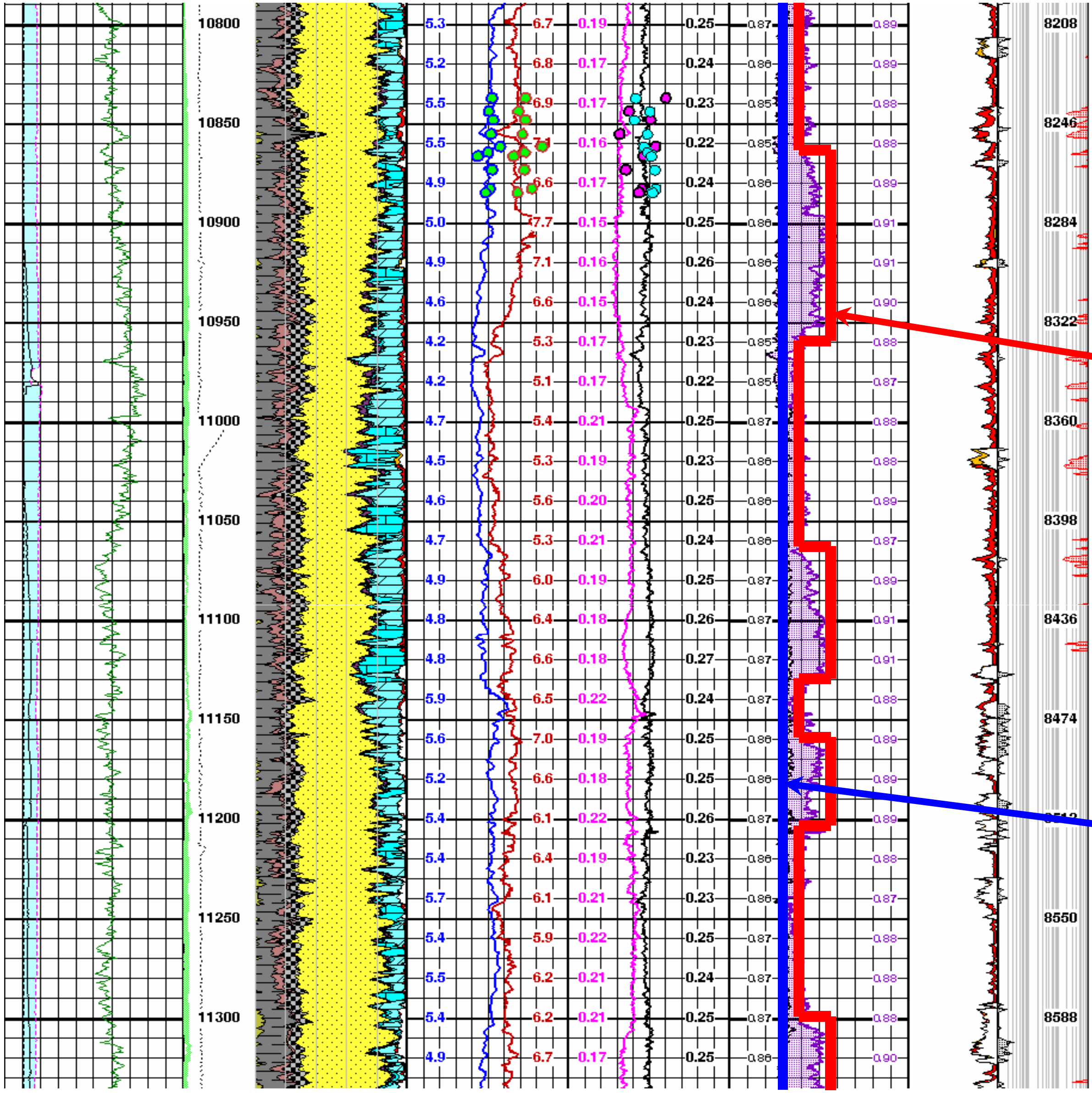


Leads to more accurate mechanical properties in laminated shales



Horizontal Young's Modulus (psi)			Vertical Young's Modulus (psi)			Horizontal Poisson's Ratio			Vertical Poisson's Ratio		
Average	Median	STD	Average	Median	STD	Average	Median	STD	Average	Median	STD
8.890E+06	9.034E +06	8.191E +05	4.598E+06	4.542E +06	2.179E +05	0.158	0.158	0.005	0.227	0.230	0.019
6.133E+06	6.135E +06	7.089E +05	4.091E+06	4.000E +06	3.102E +05	0.150	0.151	0.013	0.155	0.158	0.019

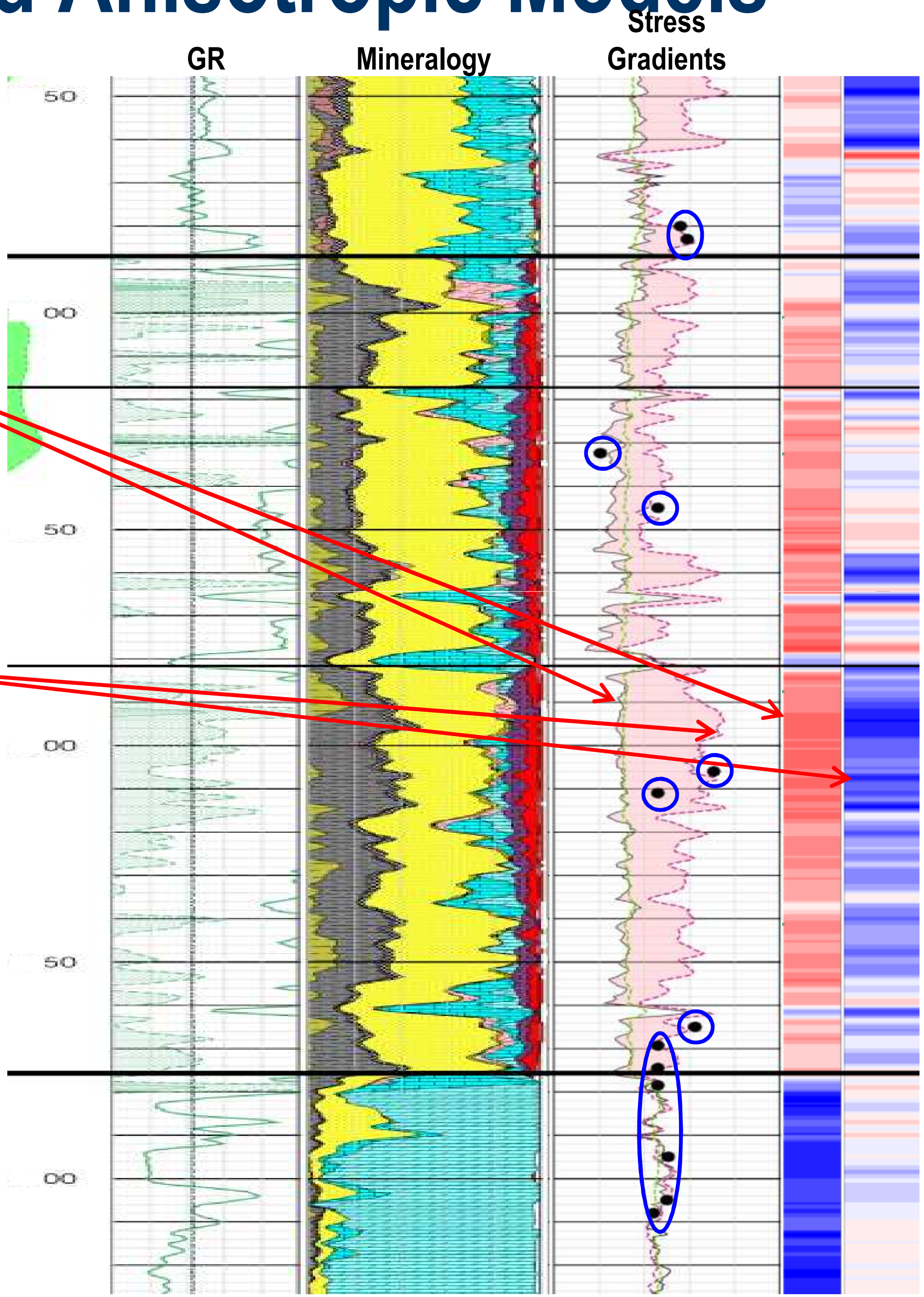
Staging the Stimulation



Anisotropic Stress Profile

Isotropic Stress Profile

Comparison of Isotropic and Anisotropic Models



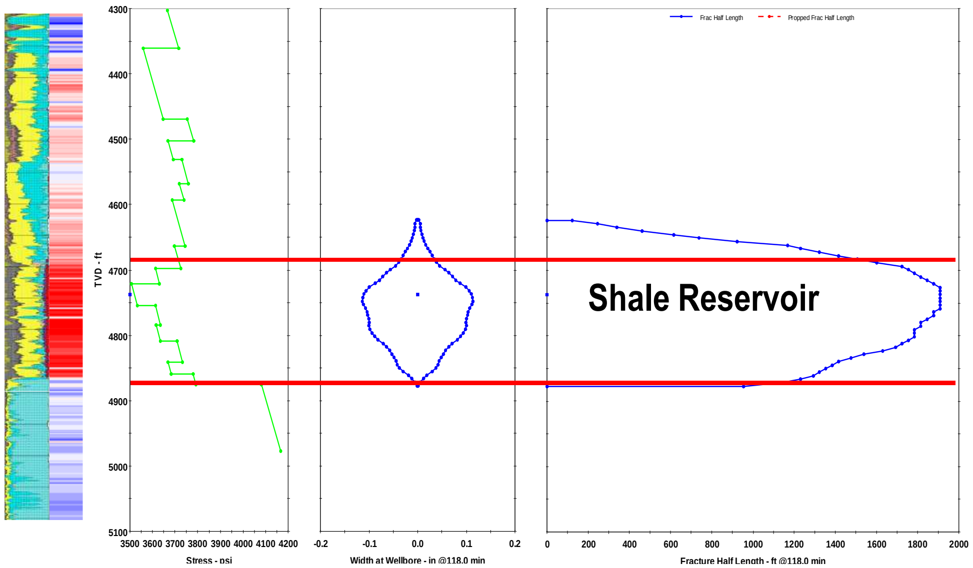
Low stress predicted in shales using conventional earth model in high clay volume rocks

Higher stress predicted in shales using anisotropic earth model in high clay volume rocks

Measured stresses via in-situ stress testing

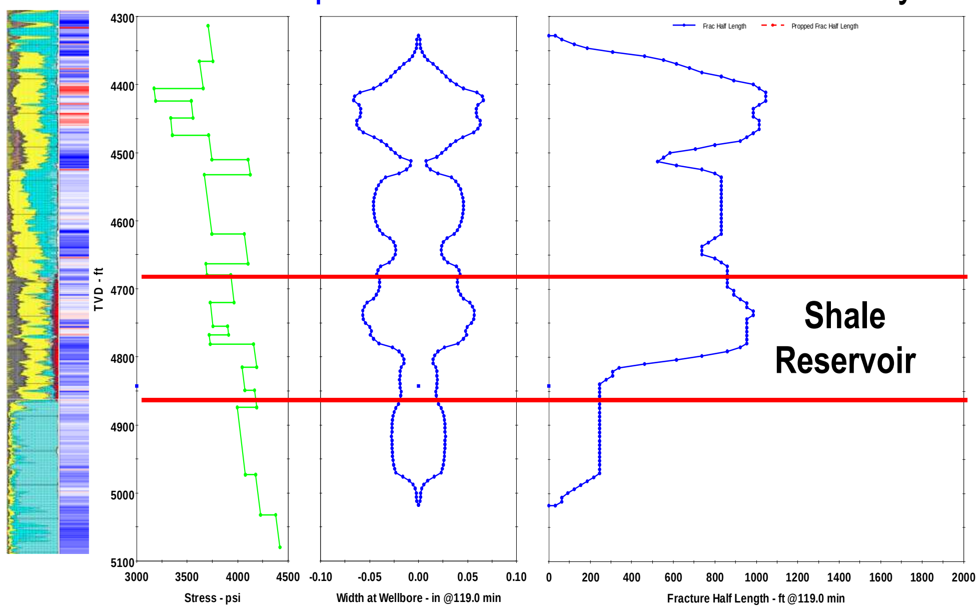
Impact of Anisotropic Stress Profile

Isotropic Stress Profile Fracture Geometry



Hydraulic fracture contained within the organic shale

Anisotropic Stress Profile Fracture Geometry



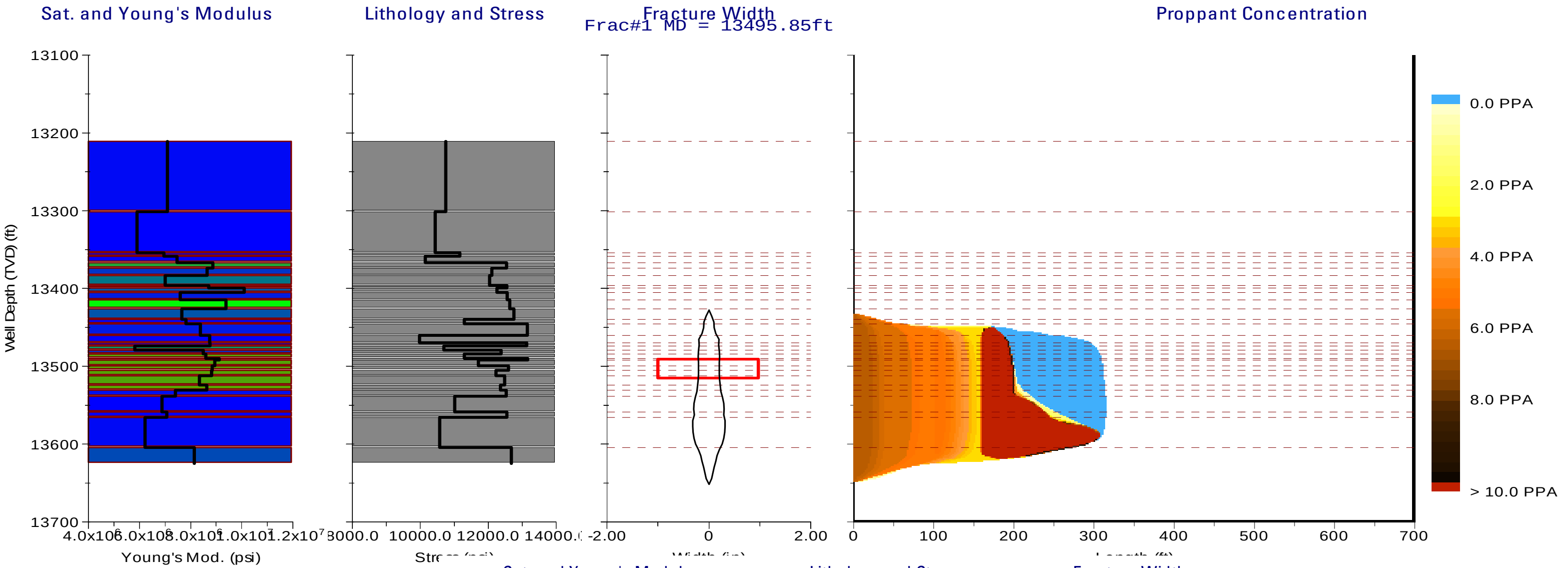
Hydraulic fracture grows above the organic shale

Best barriers for organic shales are conventional, high clay volume inorganic shales

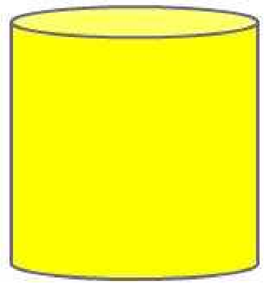
Fractures that grow out of zone will result in poor production regardless of the Reservoir Quality

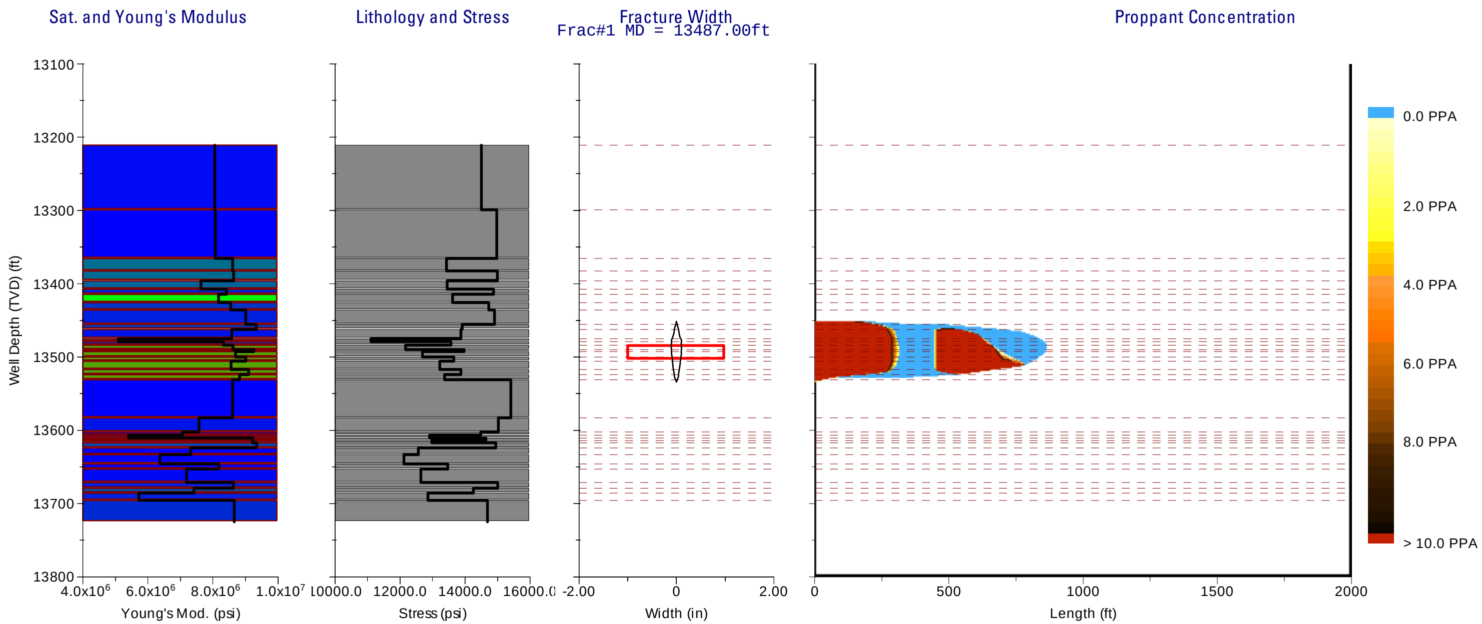
Impact of Stress model on hydraulic fracture

Isotropic Vs Anisotropic assumption

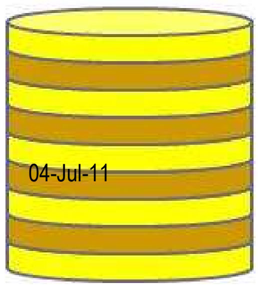


Isotropic





Transverse Isotropic



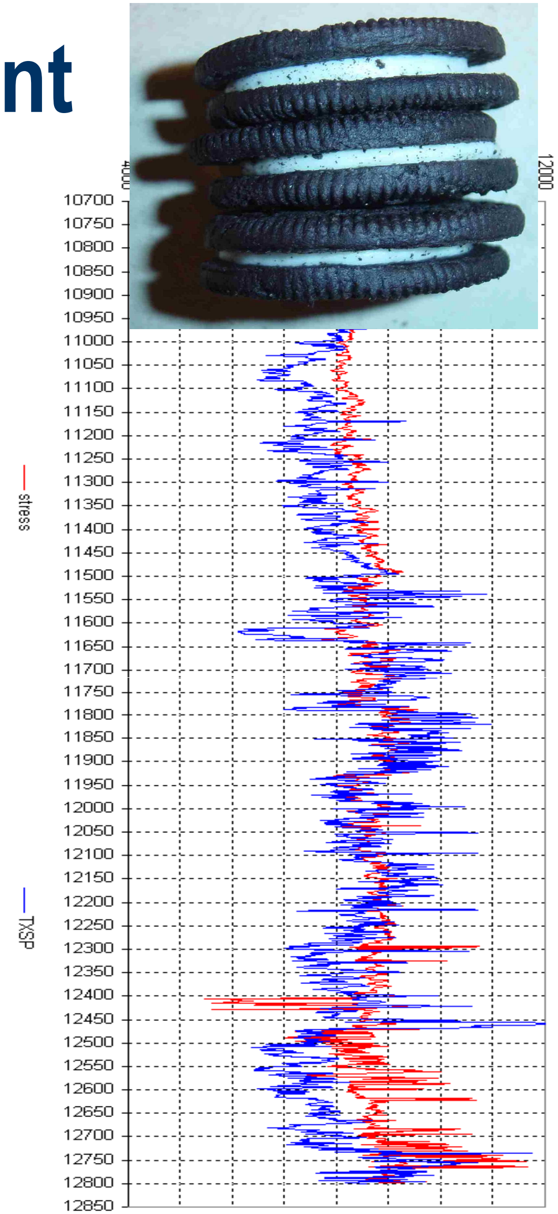
Anisotropy and Fracture Containment

Isotropic Blue (ν)

$$\sigma_h - \alpha P_p = \frac{\nu}{1-\nu}\left(\sigma_V - \alpha P_p\right)$$

Anisotropic Red (E_h, E_V, ν_h, ν_V)

$$\sigma_h - \alpha P_p = \frac{E_h}{E_V}\frac{\nu_V}{1-\nu_h}\left(\sigma_V - \alpha P_p\right)$$



Leads to more accurate mechanical properties in laminated formations

Completions Optimized with Integrated Geomechanical Approac

Integrated geomechanical and petrophysical analysis of
helps operator increase production by 500 Mcf/d

Challenge

Determine most effective stimulation treatment and avoid previous costly mistakes.

Solution

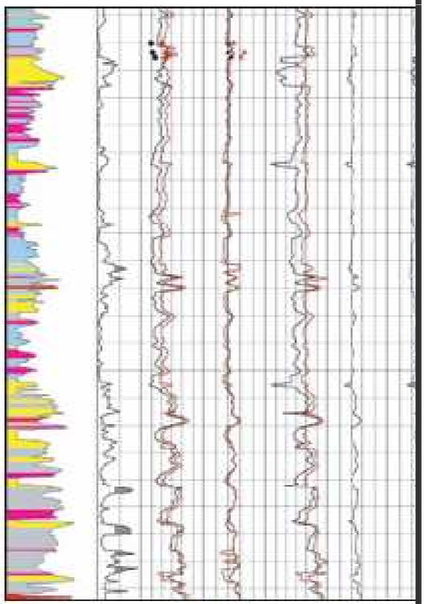
Apply formation evaluation by TerraTek* Geomechanics Laboratory Center of Excellence.

Results

Achieved better stimulation treatments and more economic completions, with an increase in production of 500 Mcf/d.

Reservoir evaluation disrupts fractured completion tre

Fracture growth out of the zone, potentially into wate
multiple completion opportunities for an operator in
most effective stimulation treatment for the completi
formation evaluation would need to be multifaceted a
and petrophysical properties determination with dow
goals were threefold: examine petrophysical data to d
geomechanical properties of the formation through a
the petrophysical evaluation, the comparison betwee
geomechanical properties, fluid-sensitivity tests, and
recommendation for completion.



Cluster analysis with anisotropic mechanical predictio

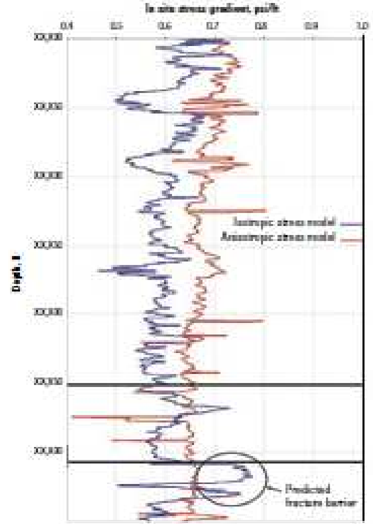
Integrated geomechanical and petrophysical analysis of core data helps operator increase production by 500 Mcf/d

Anisotropic stress model delivers fracture success

Schlumberger Data & Consulting Services, through its TerraTek Geomechanics Laboratory Center of Excellence, performed an evaluation of this Barnett Shale reservoir. Analysis gave the operator a detailed evaluation of this formation and a completion methodology designed for success. The completion methodology, designed for perforation placement avoiding laminated intervals, focused on more siliceous layers with low-closure stress. To avoid fracturing down into the water zone below the shale, analysis suggested perforating in intervals to promote upward growth.

With the analysis providing a full understanding of the reservoir, the operator incorporated a tapered proppant mesh throughout the course of the hydraulic fracture treatments. Key components of the evaluation methodology included the use of ECS* elemental capture spectroscopy sonde, FMI* fullbore formation microimager, ELANPlus* software, Sonic Scanner* acoustic scanning platform, Platform Express* wireline logging tool, and TerraTek core analysis to provide a complete characterization of the reservoir and its potential.

Processing mechanical properties with an anisotropic stress model is critical to predicting and mitigating proppant entry issues, as well as predicting fracture geometry. A thorough knowledge of the stress gradient and contrasts is vital to determining the optimum way to hydraulically fracture the reservoir. Detailed fluid sensitivity tests lead to the selection of the best fracturing fluids.



Where the simplified isotropic stress model incorrectly indicated a barrier, the anisotropic stress model revealed that there was none.

Complete analysis leads to solid completions

Combining all of these analyses with a perforation strategy helped the client avoid completion failures common in this reservoir, like fracture growth out of the zone, potentially into a water zone. The 3D anisotropic processing revealed that apparent fracture barriers in carbonate and high-clay intervals did not exist. Surface-passive microseismic monitoring of the hydraulic fracture treatment later confirmed this. The relevance of processing geomechanical data with an anisotropic stress model proved invaluable to the development of the reservoir.

Analysis of core data resulted in better placement for perforation clusters, optimized well trajectory for horizontal laterals, and enhanced production. This well, completed using TerraTek Geomechanics Laboratory Center of Excellence analysis, showed an average production increase of 500 Mcf/d.

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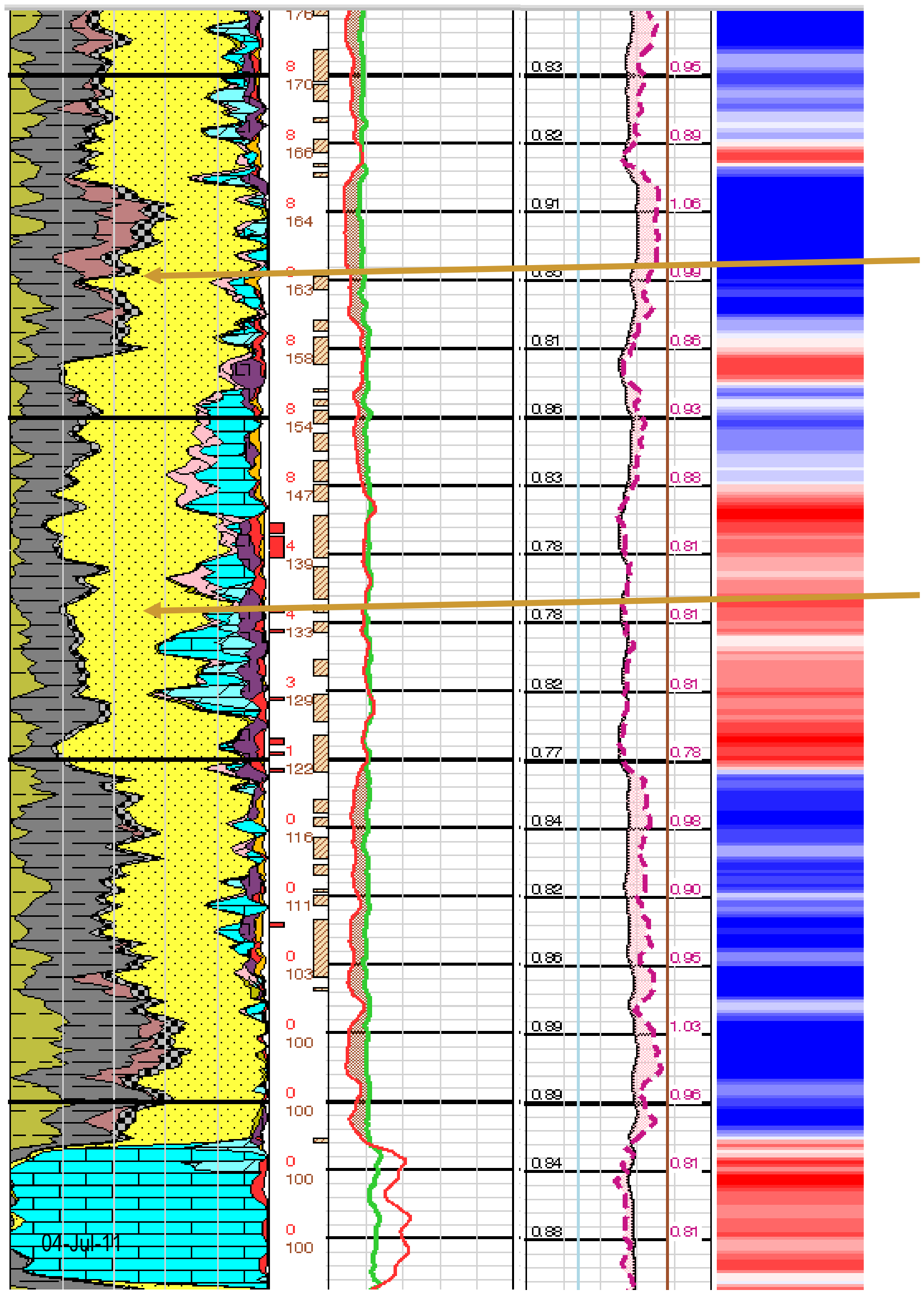
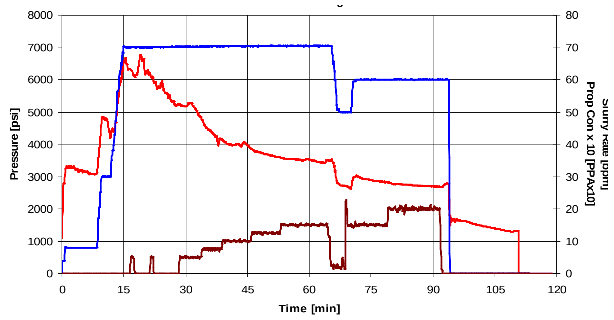
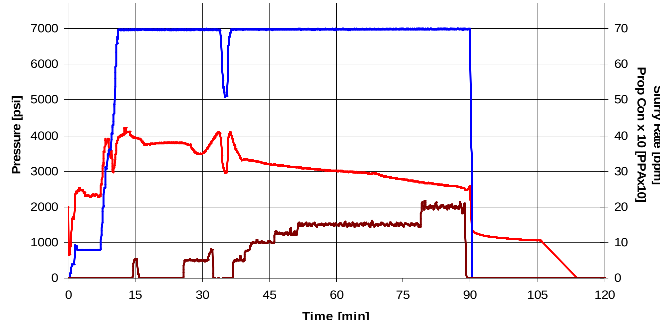
Intelligent performance is a mark of Schlumberger

Frac Breakdown Pressure







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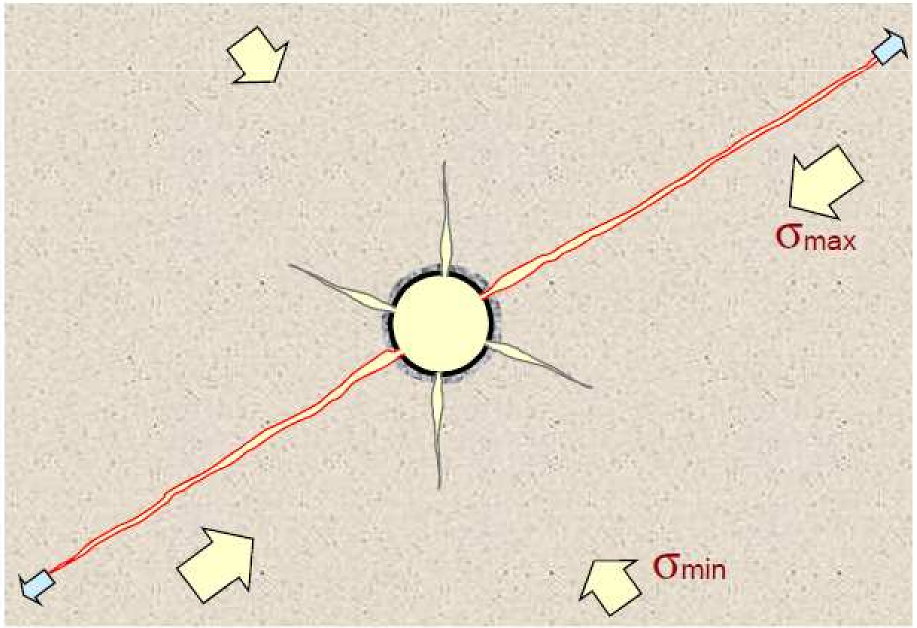
Unconventional Reservoir Fracturing Evaluation

Hydraulic Fracturing Direction

Hydraulic fracture direction

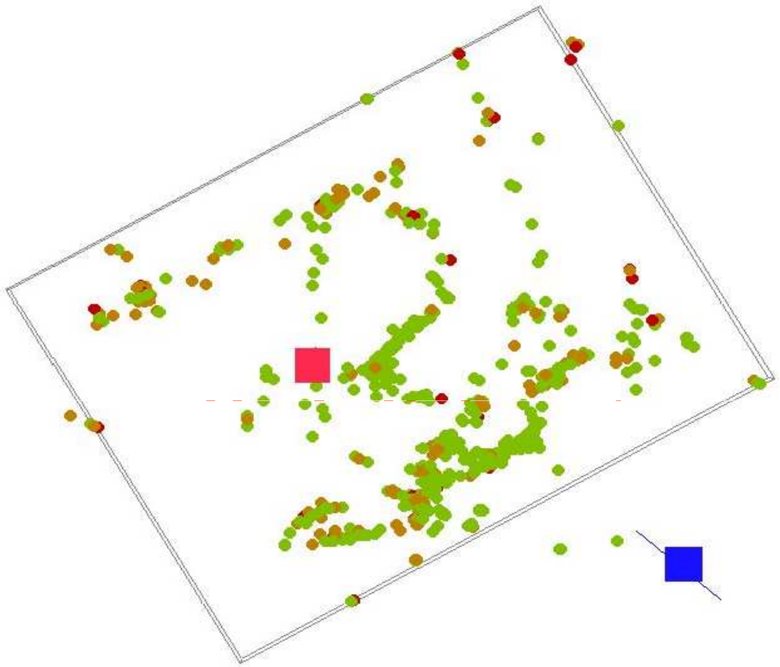
As the frac propagates, it always tries to grow in the plane perpendicular to the minimum stress direction in the formation (the preferred fracture plane, PFP).

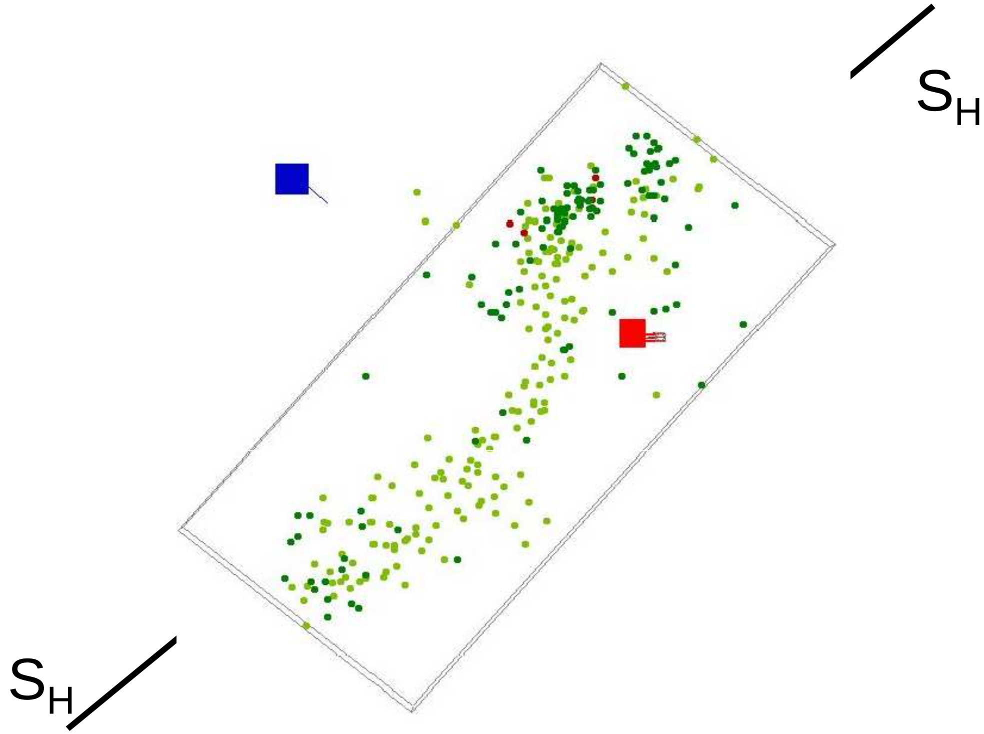


When the geometry and formation are favourable*, like this, it succeeds very simply.

(*well axis parallel to a principal stress; isotropic unfractured rock; good perforations.)

Hydraulic Fracturing Direction





- Low stress anisotropy
- Lower seismic anisotropy
- Wide fracture fairway

- High stress anisotropy
- Higher seismic anisotropy
- Narrow fracture fairway

Fracture Geometry Information from Horizontal Image Logs

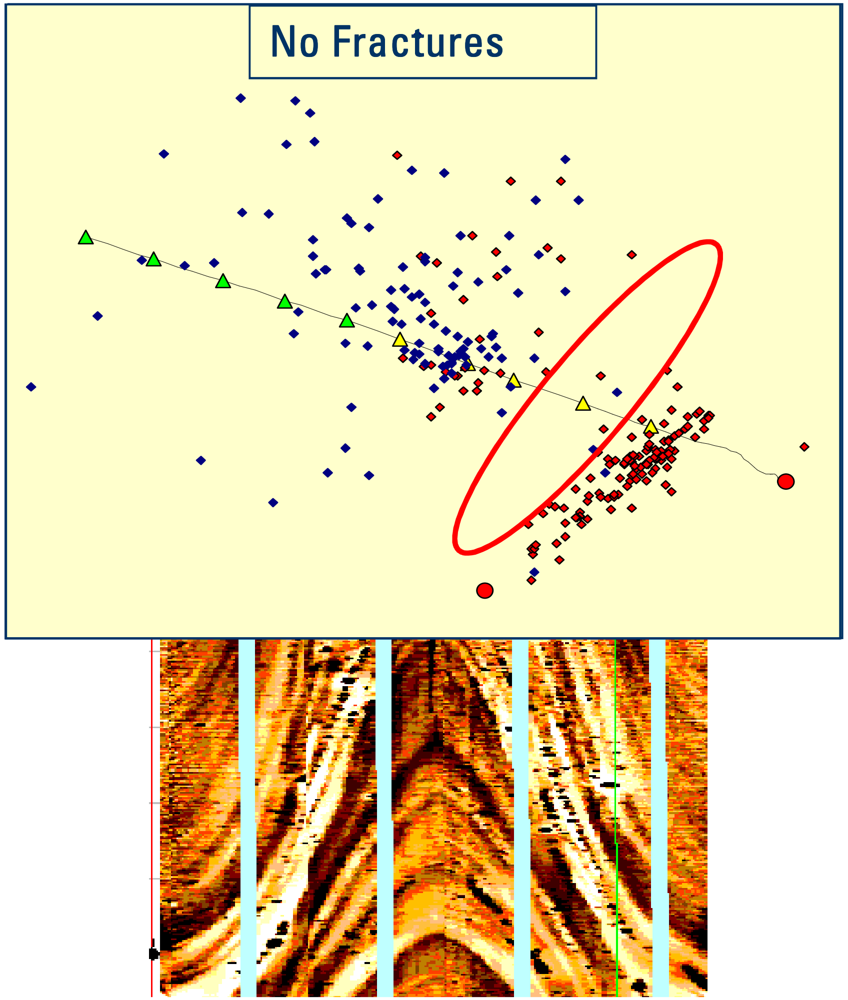
Variable Induced Fractures Infers Variable Stress

Transverse Fractures Only:

$\sigma_H >> \sigma_h$

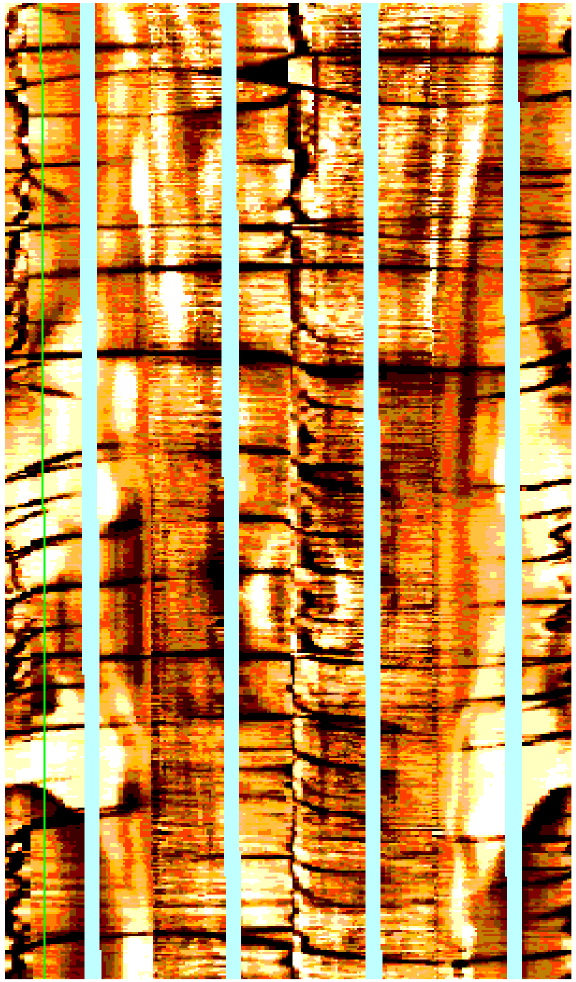
No Fractures:

High σ'



Long & Trans Fractures:

Low σ' & $\sigma_H \sim \sigma_h$



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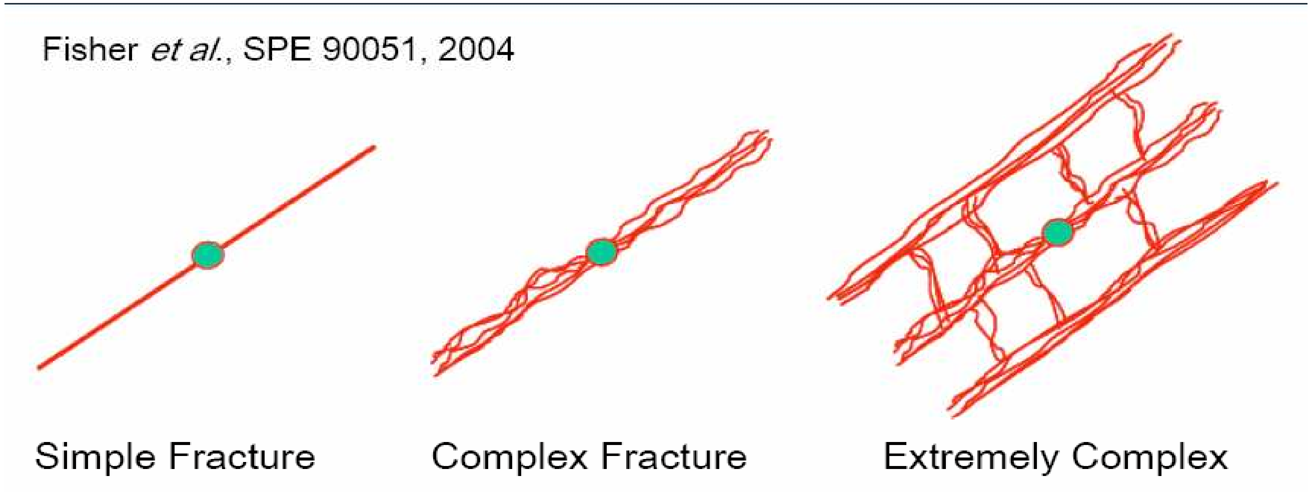
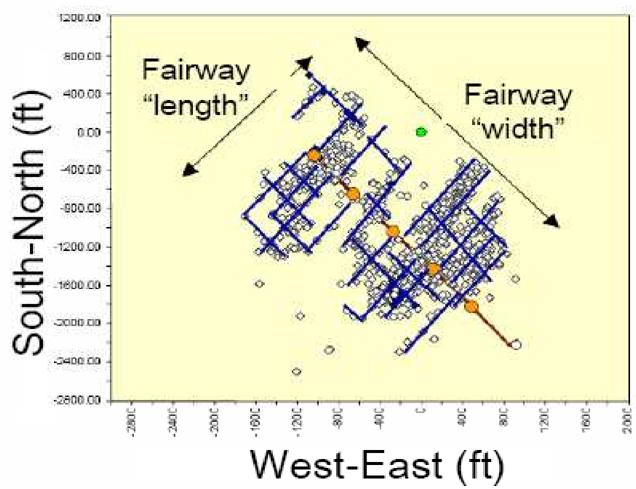
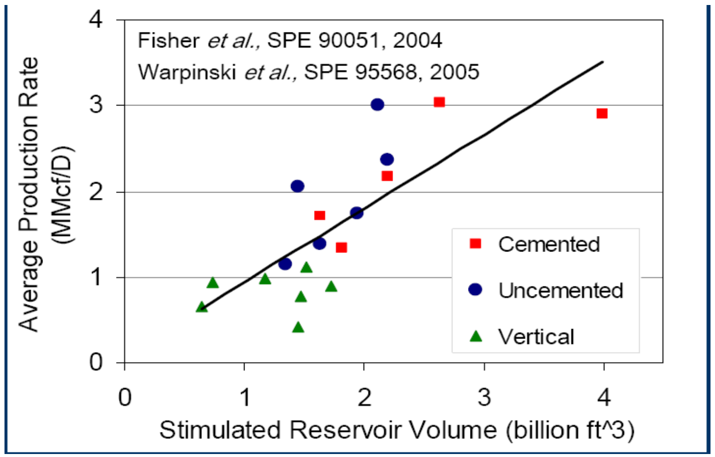
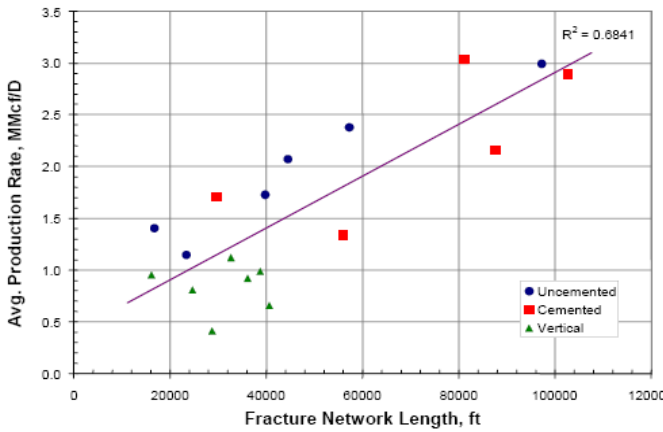
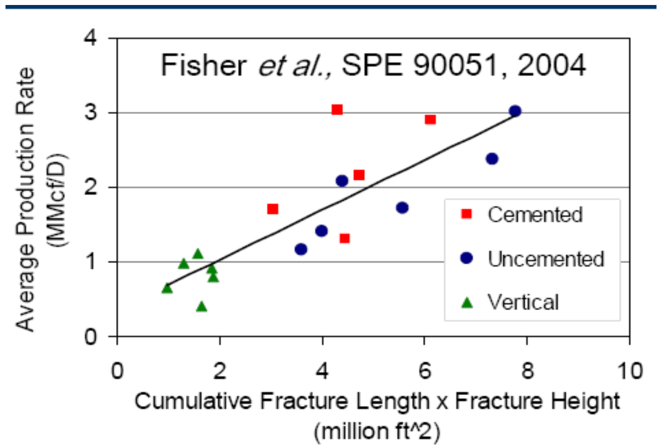




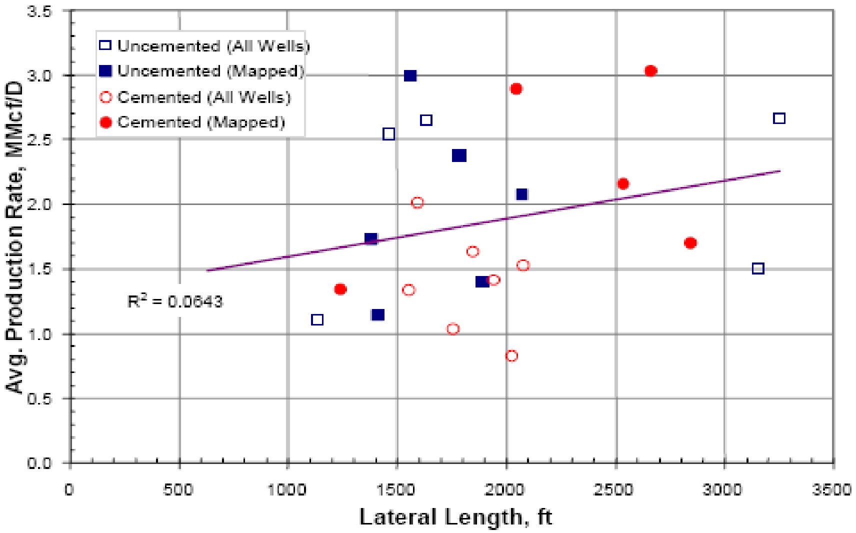


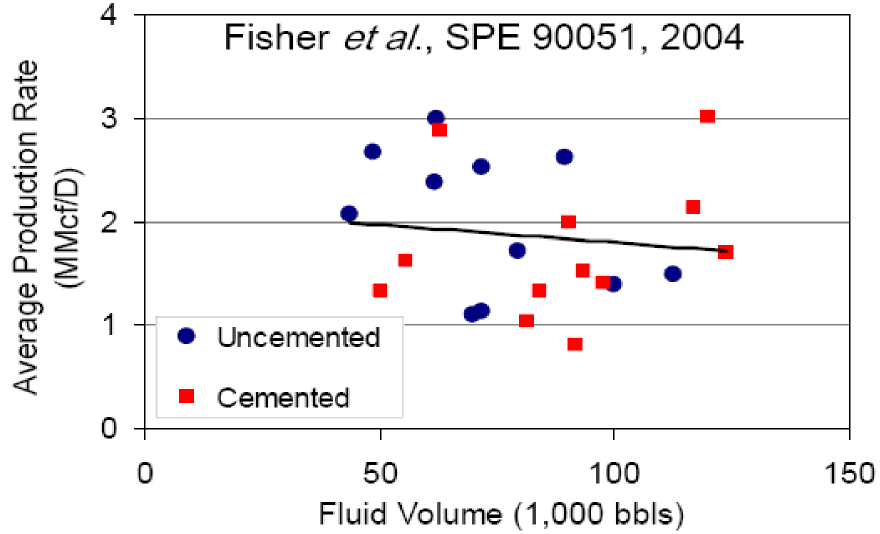


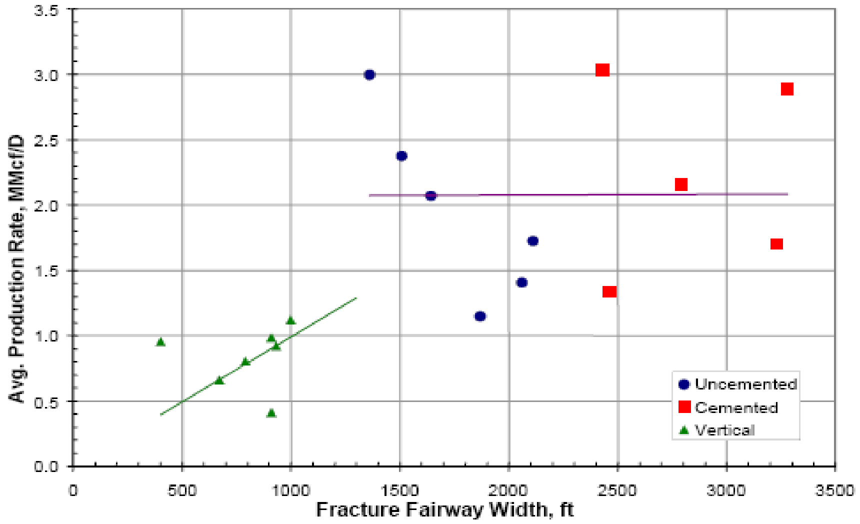


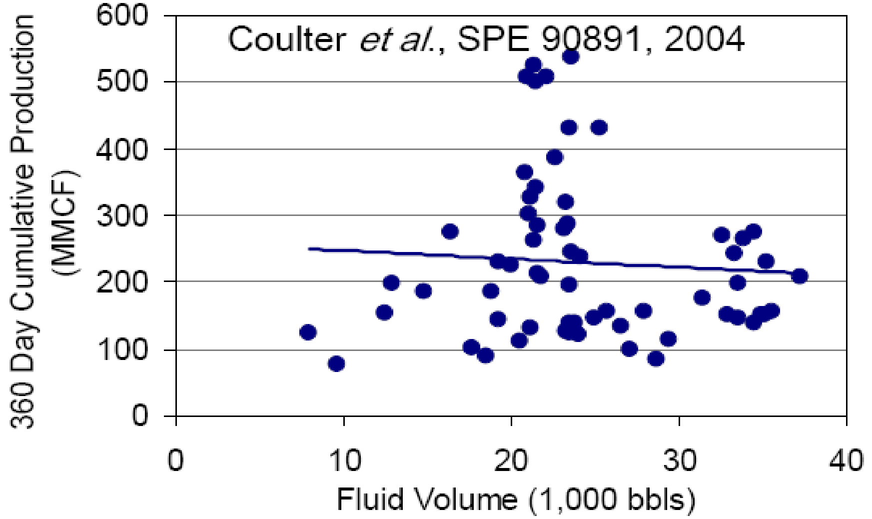
SRV or ESV

SPE-90051









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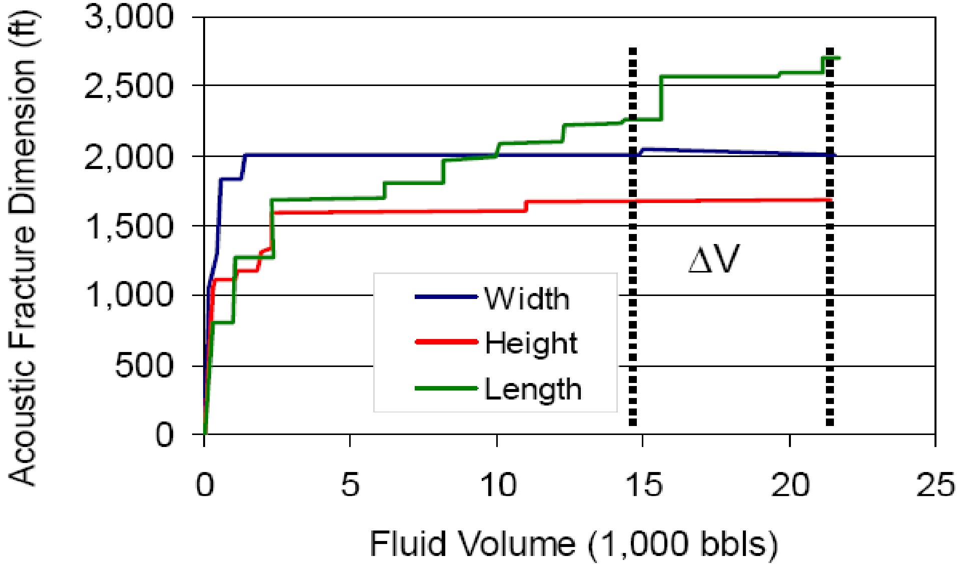
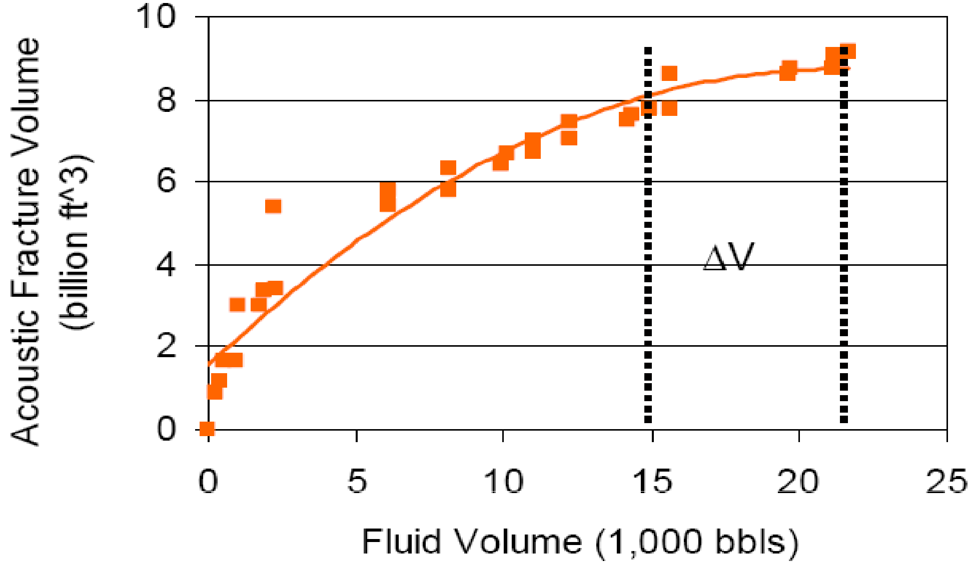
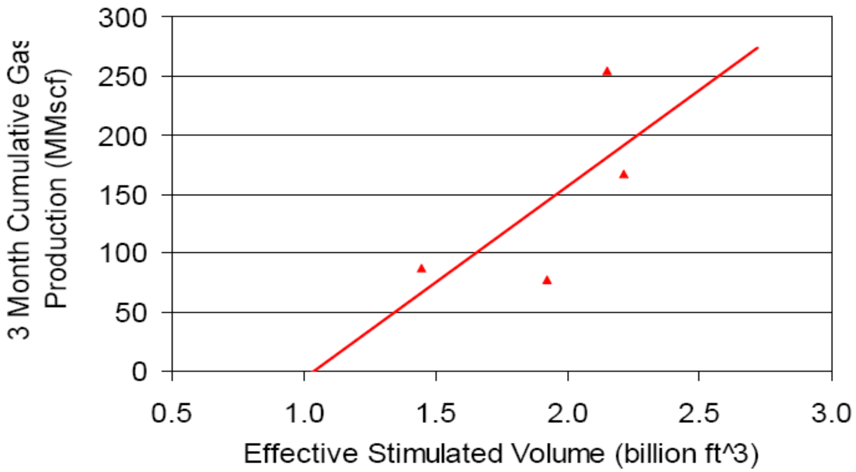
SPE-90051



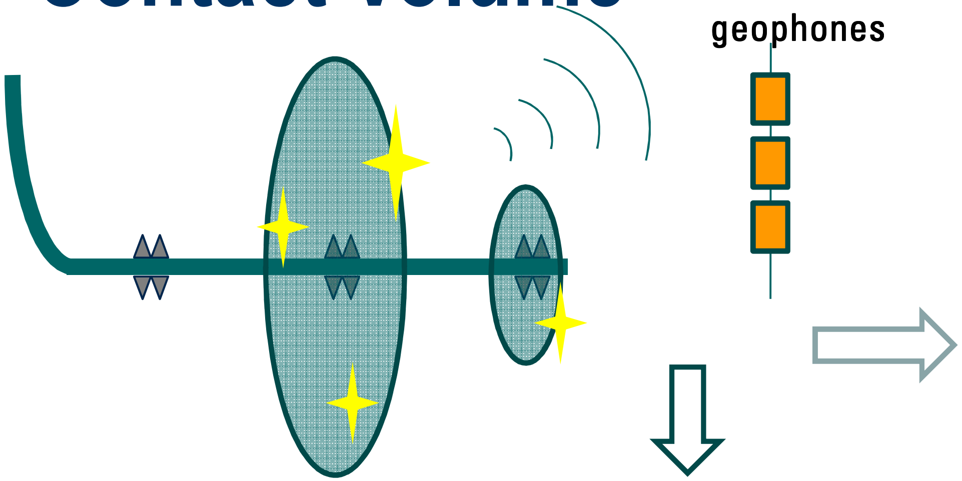


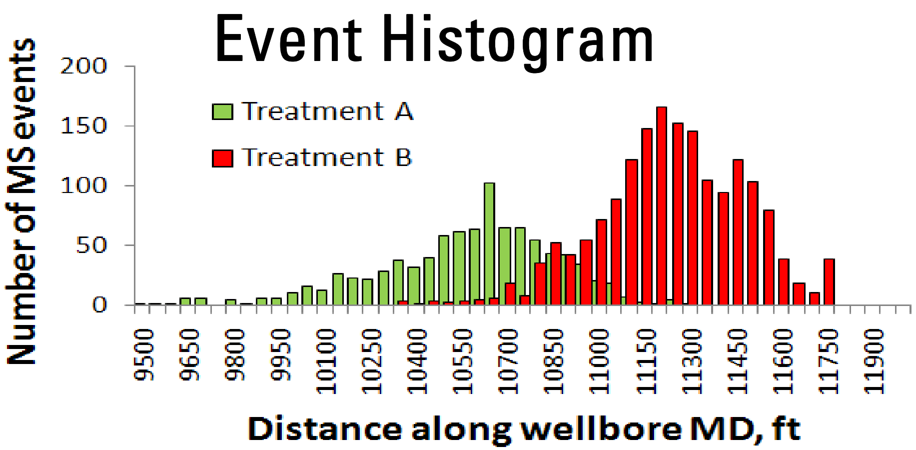


Effective use of the fracturing fluid

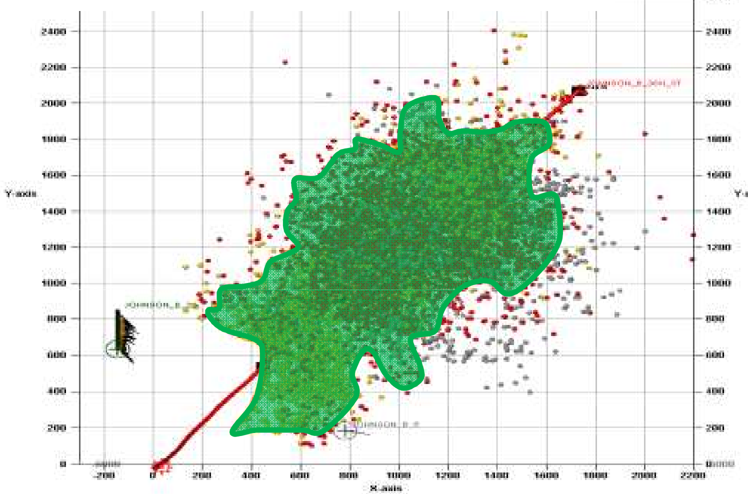
Volume optimization using the fracture acoustic volume for make real time decisions.

StimMAP* LIVE – Quantifying Contact Volume





Effective Stimulated Volume (ESV) density based algorithm



A Tool to make informed decisions

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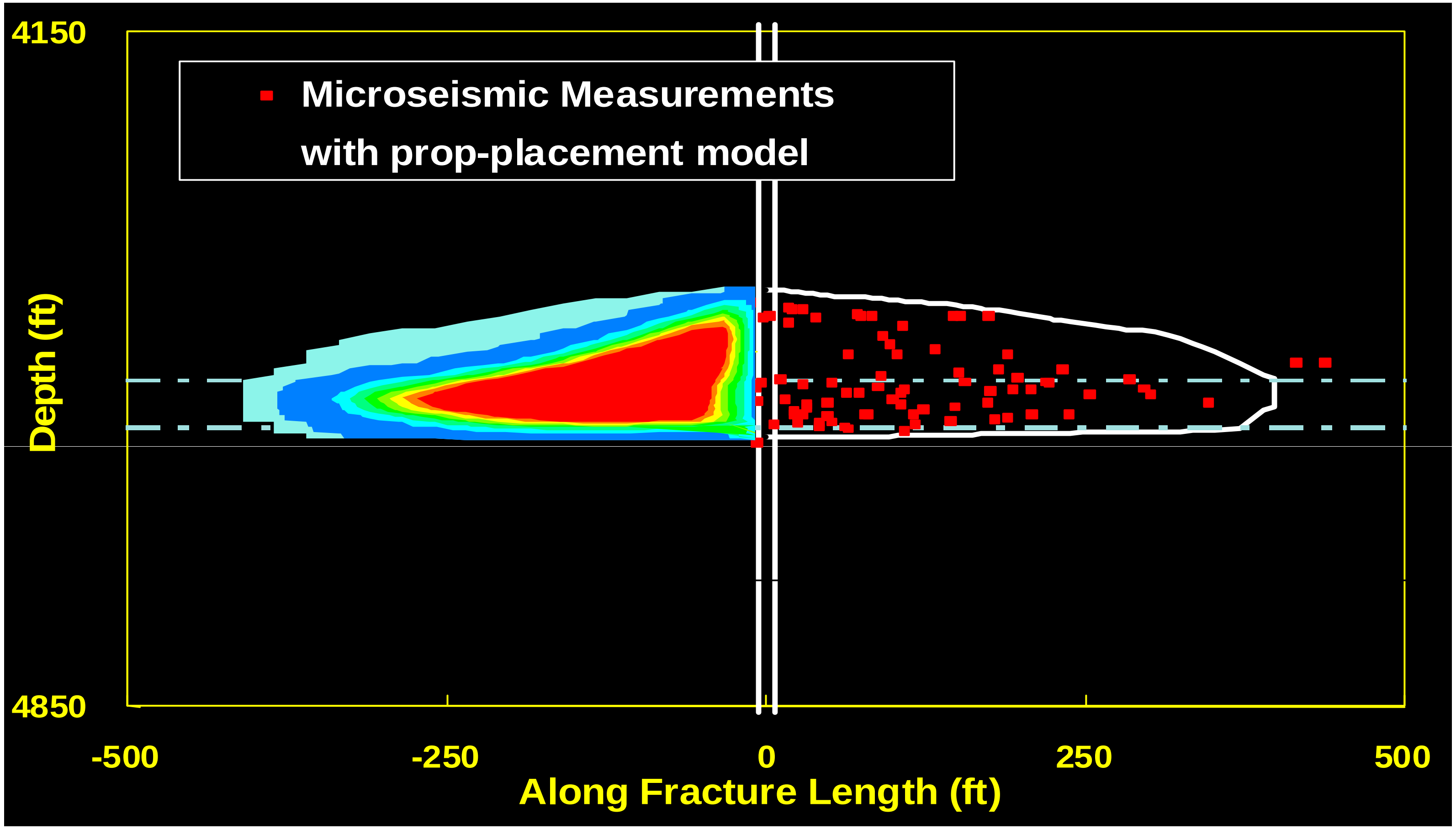
Hydraulic fracture mapping for evaluation



SPE 38575 (DOE-GRI MWX data)

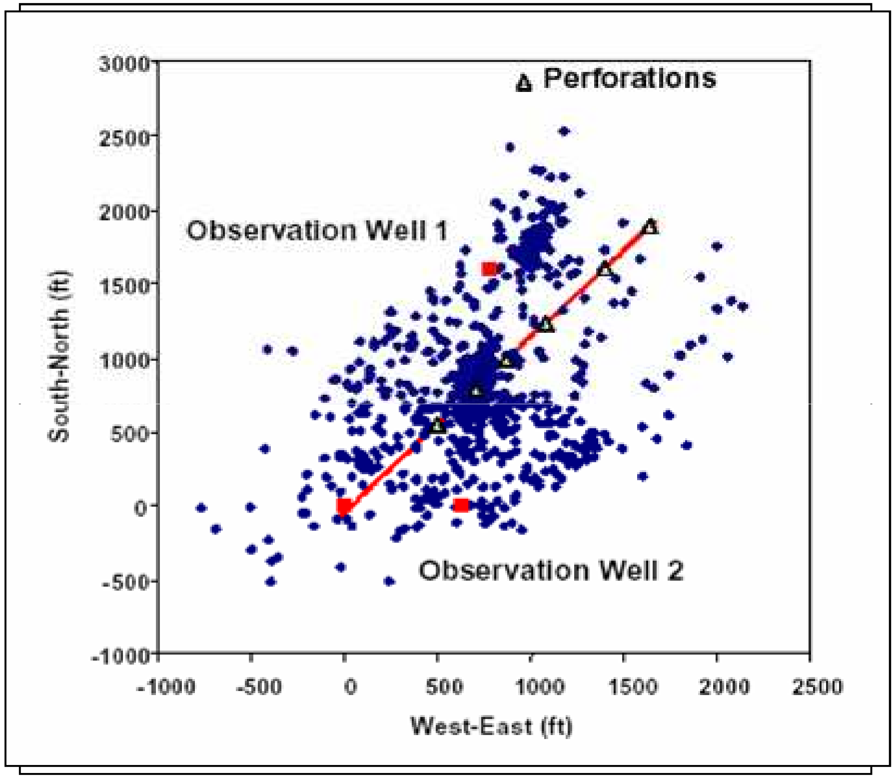
Fracturing Fluid Selection

Slickwater Fluids

- More ft^2/$
- Wider Fracture “Fairways”

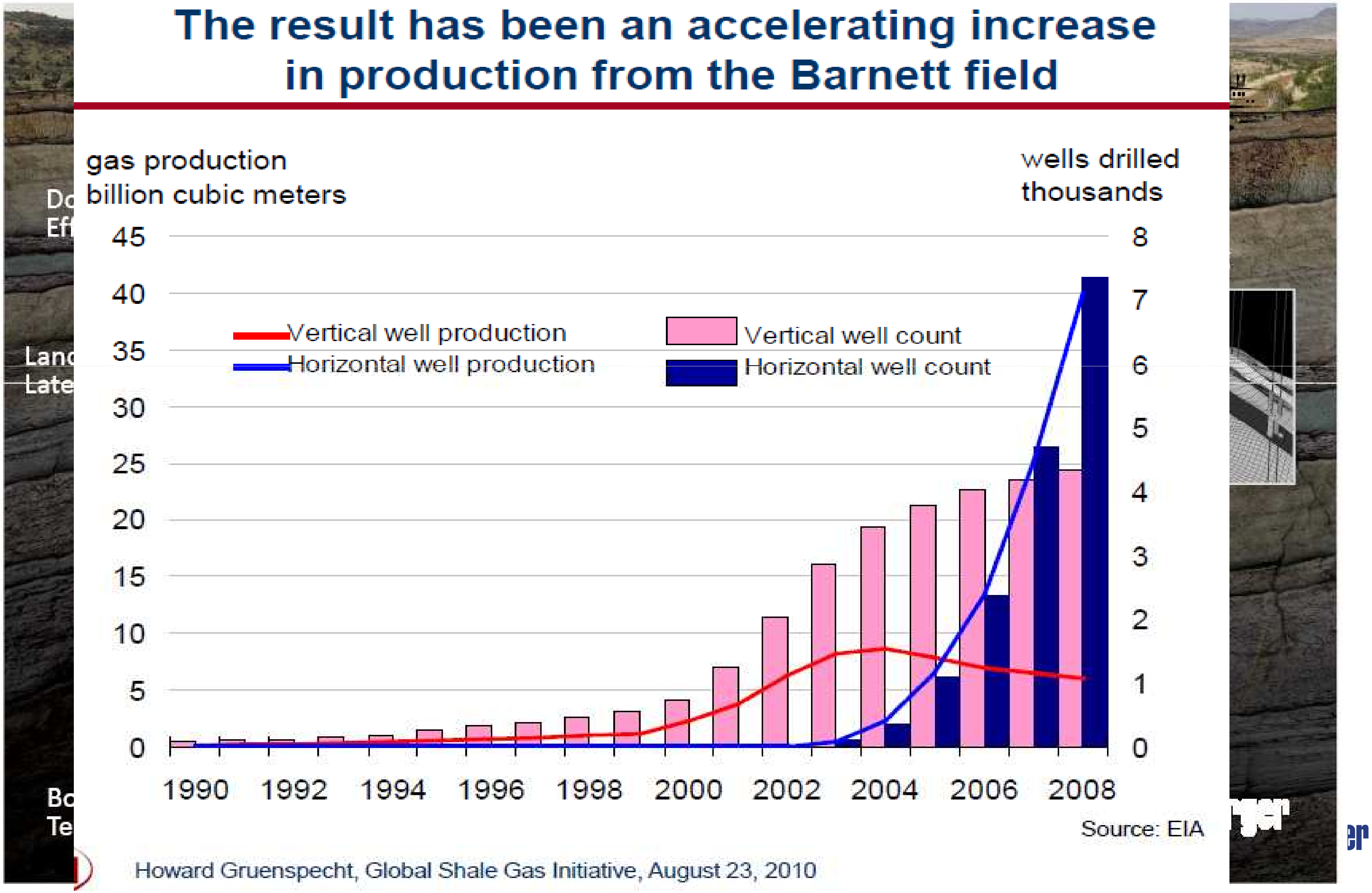
Geled fluids

- Frac Initiation



Horizontal Wells

Fracture Treatments – Increase Surface Area & Flow



Hydraulic Fractures In Horizontal Wellbores

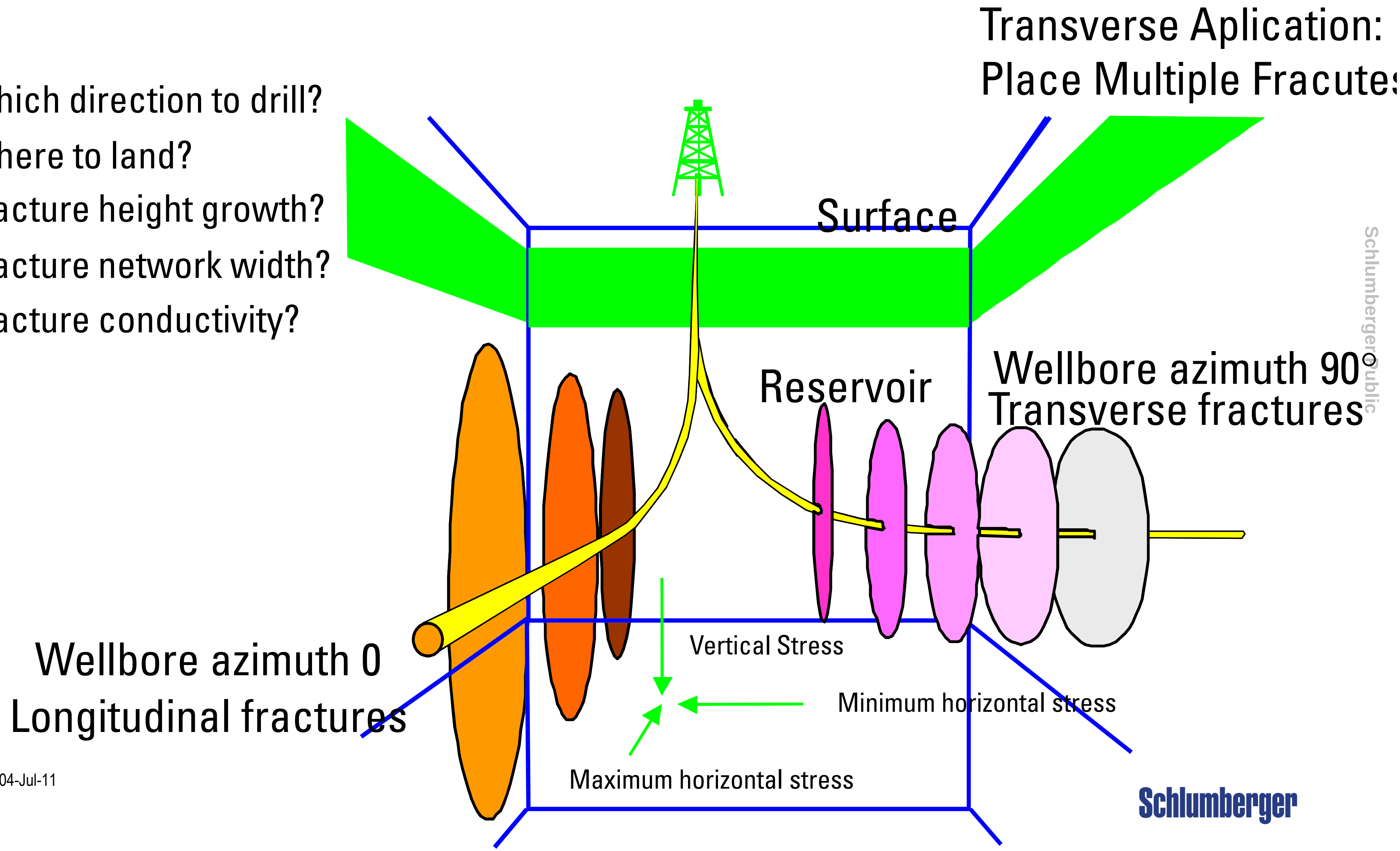
Which direction to drill?

Where to land?

Fracture height growth?

Fracture network width?

Fracture conductivity?



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Lateral Placement

Quartz Rich Shales

- Isotropic Behavior

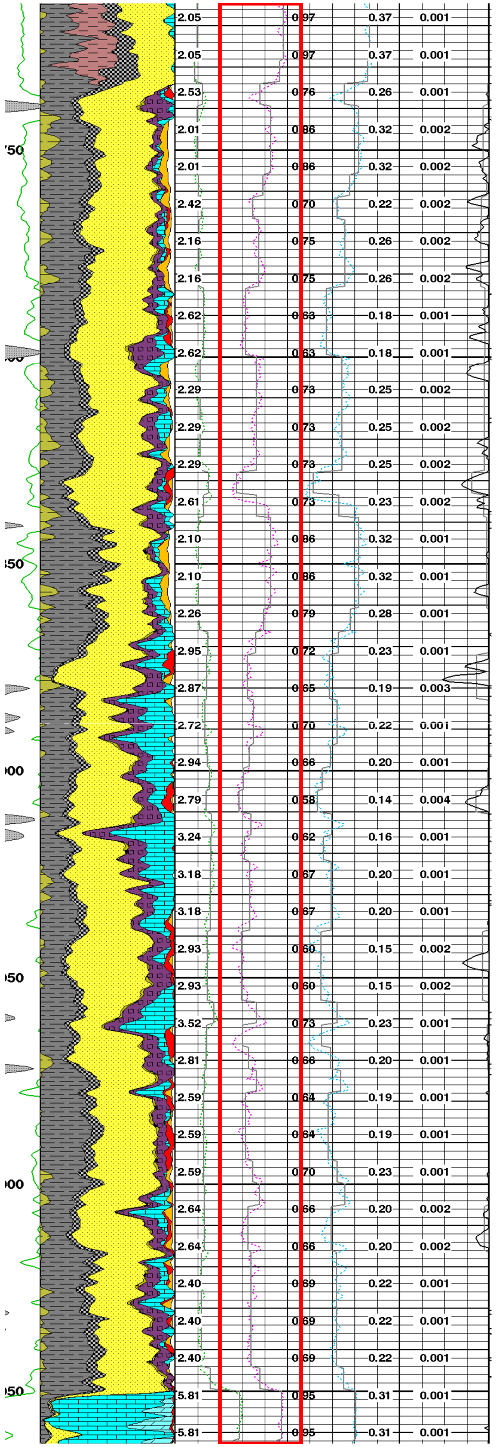
Bedding

- Lamination → Complexity

Drilling/Stimulation Efficiency

- Expanding Clays
- Oil Based Muds
- Borehole Breakout

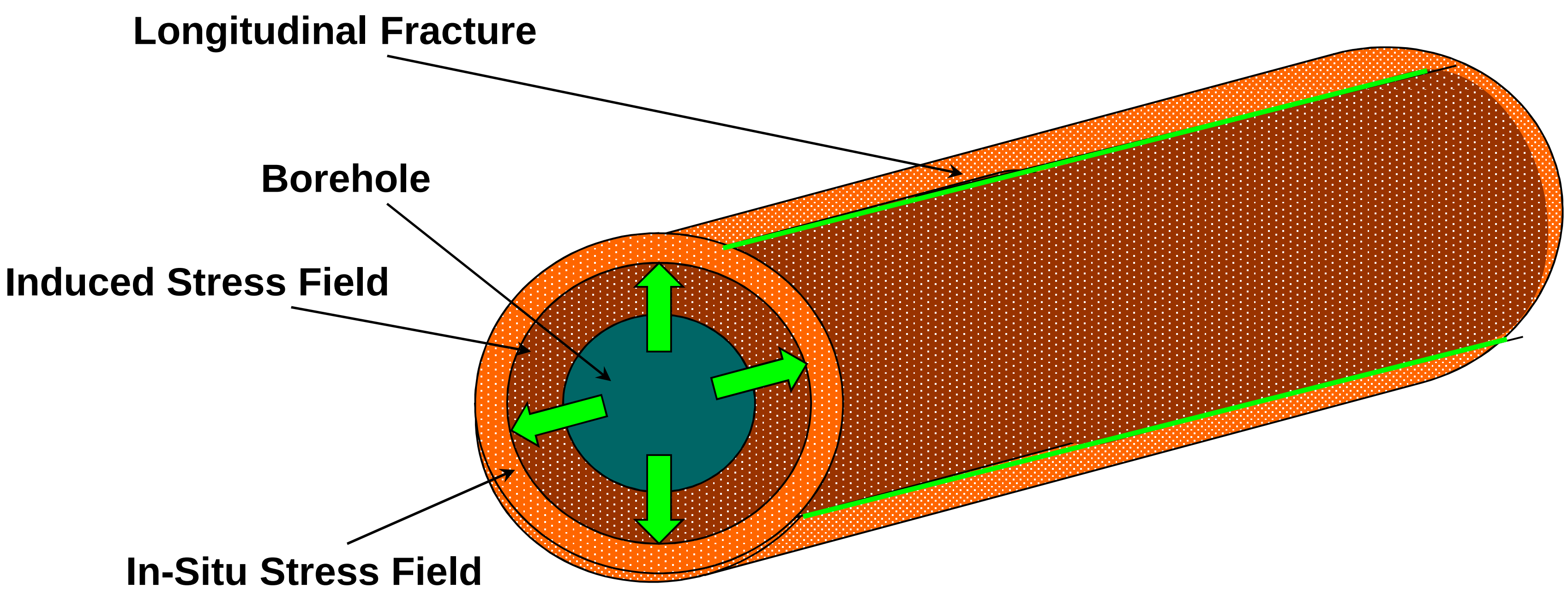
Closure Stress



Induced Stress due to a Horizontal Hole in σ_h Direction

Drilling Process can induce Tensile Stress

Potential Initiation of Tensile Fractures



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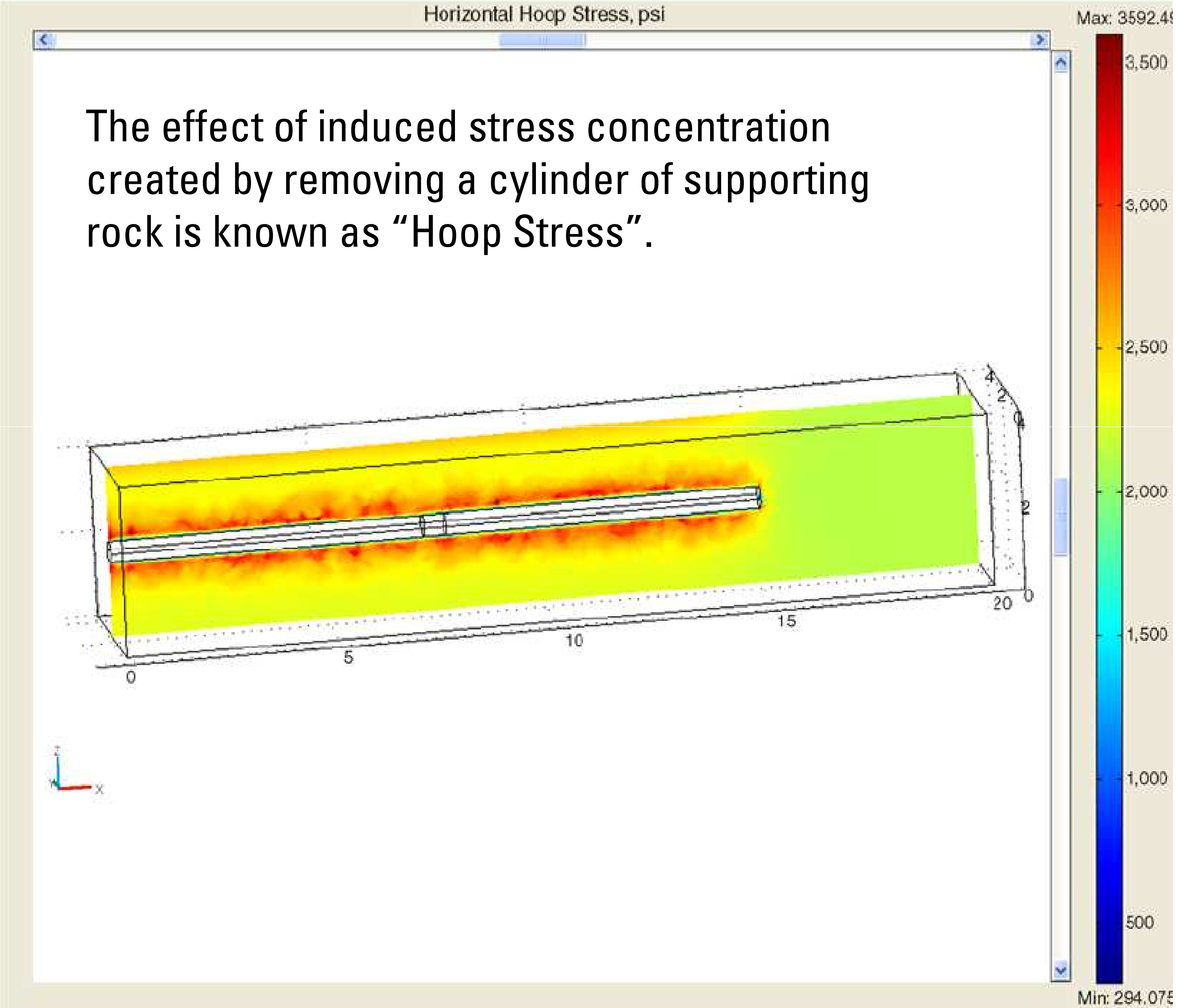
Factors Affecting Fracture Geometry

The effect of induced stress concentration created by removing a cylinder of supporting rock is known as "Hoop Stress".



Weijer 1994 – Fracture initiate longitudinal when OH drilled ⊥ to σ_{max}, then is reoriented to transverse .

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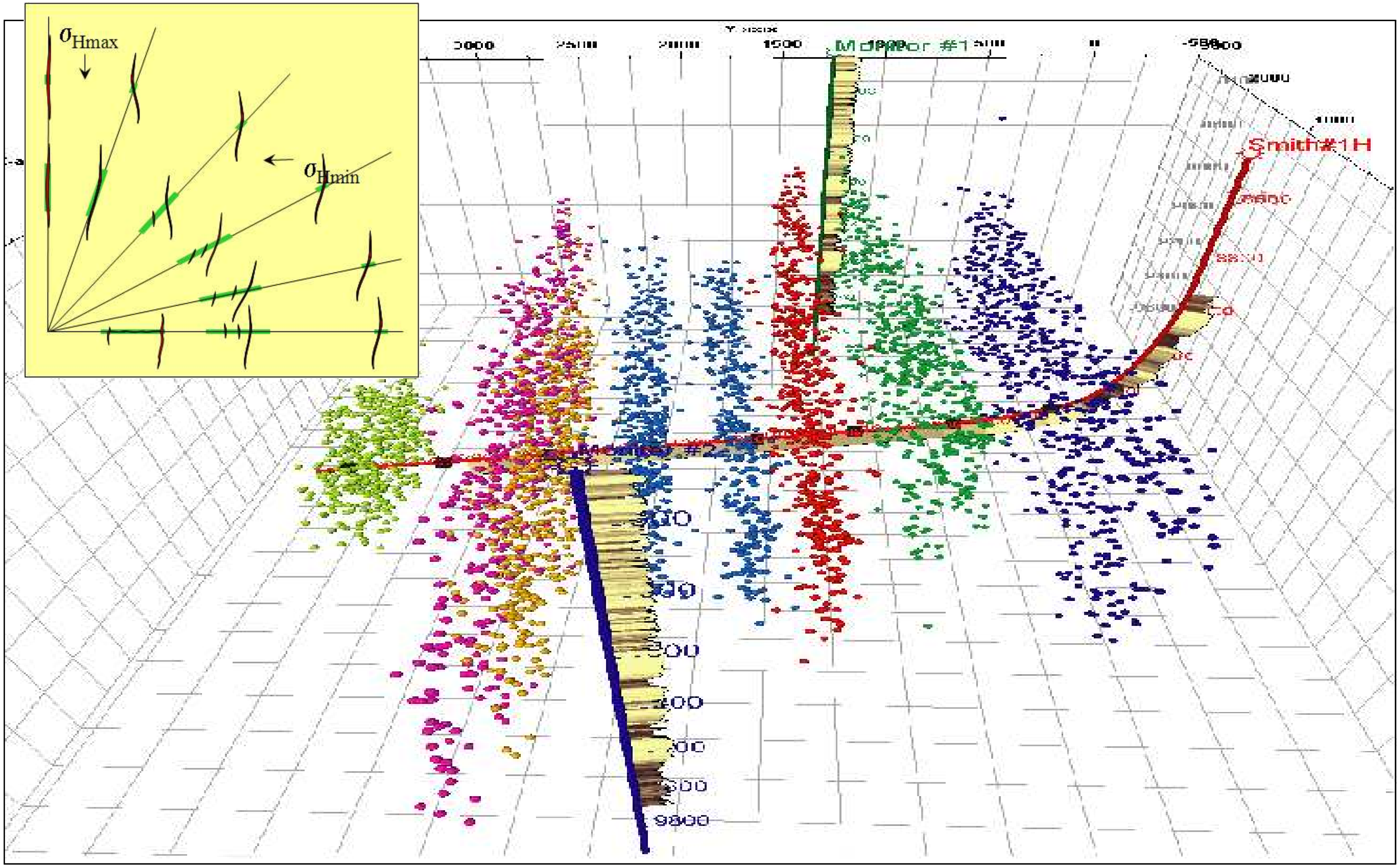
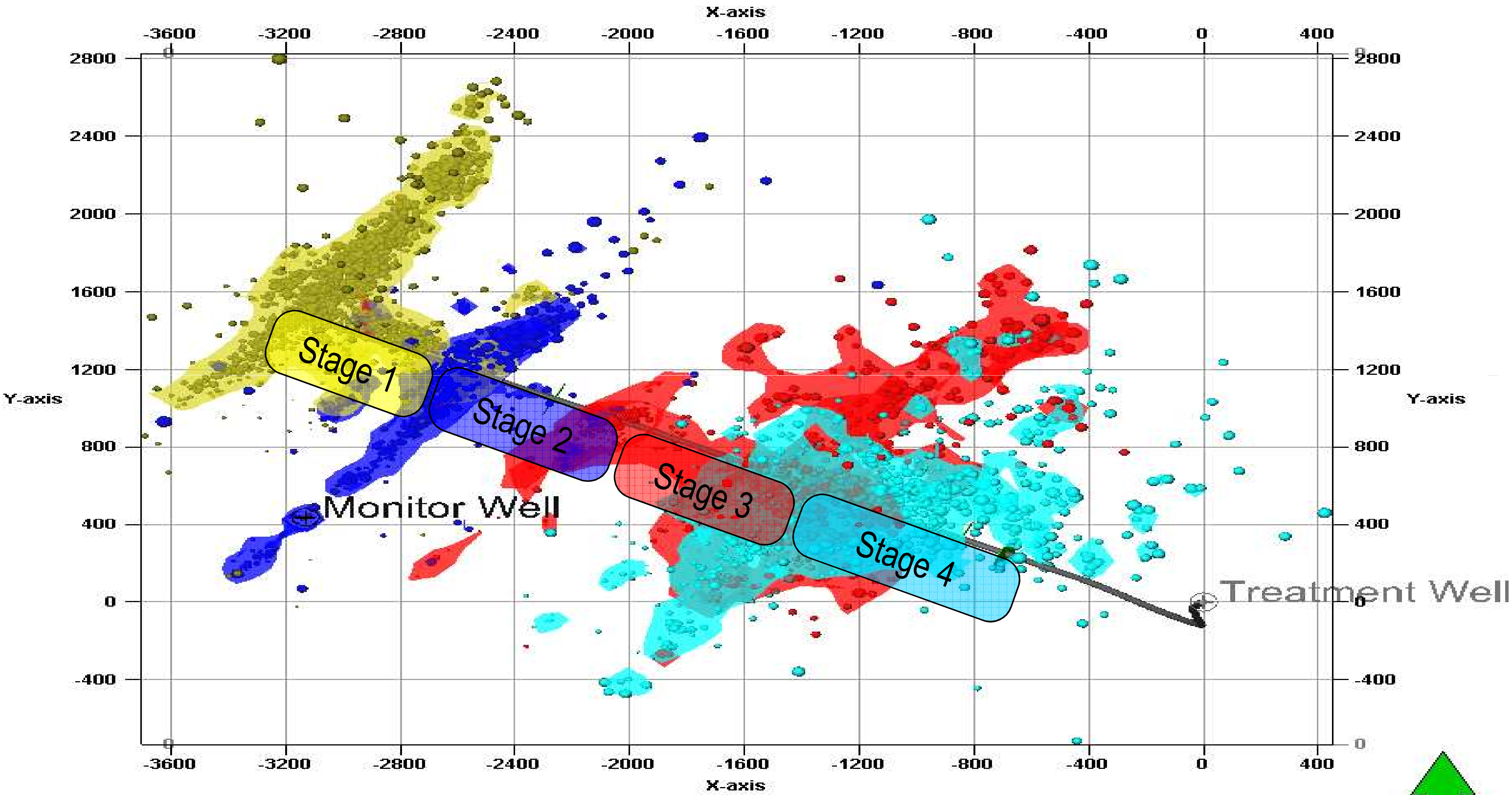
Microseismic Data and Fracture Orientation



SPE 110562



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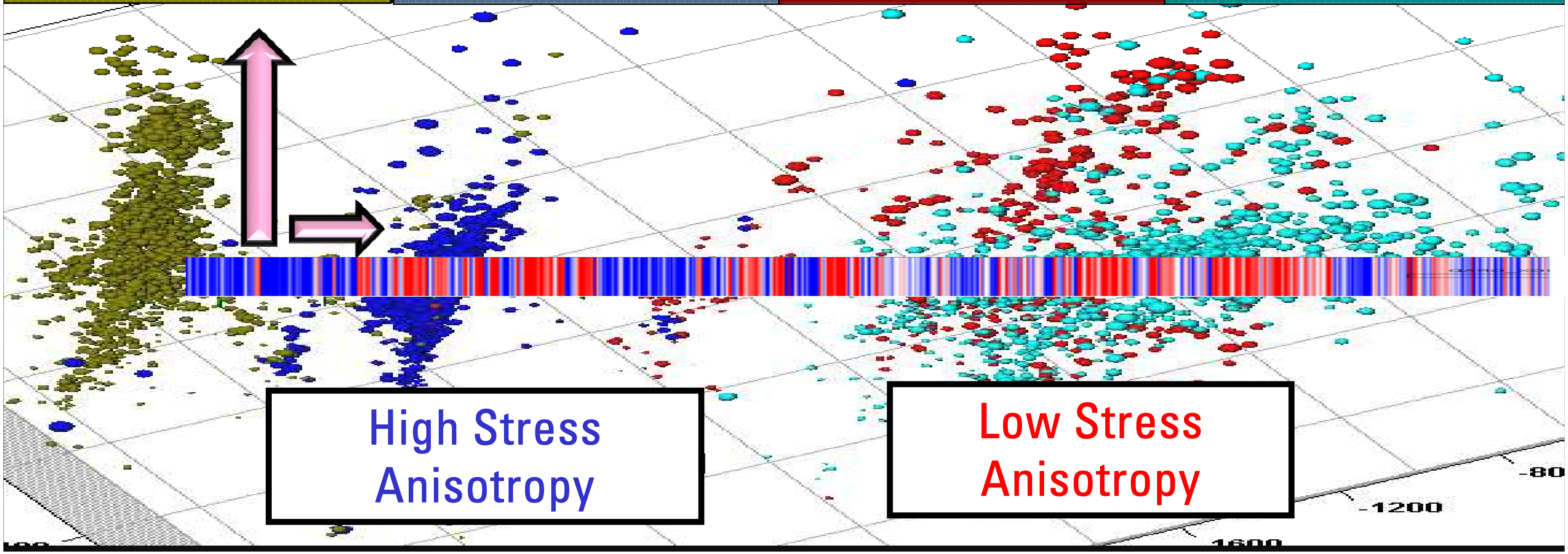
SPE 110562

Stage 1	Stage 2	Stage 3	Stage 4
$\sigma max_{avg} = .77$	$\sigma max_{avg} = .74$	$\sigma max_{avg} = .69$	$\sigma max_{avg} = .65$
$\sigma min_{ISIP} = .70$	$\sigma min_{ISIP} = .64$	$\sigma min_{ISIP} = .65$	$\sigma min_{ISIP} = .62$
$\sigma M - \sigma m = .07$	$\sigma M - \sigma m = .10$	$\sigma M - \sigma m = .04$	$\sigma M - \sigma m = .03$



Schlumberger

SPE 110562

Stage 1

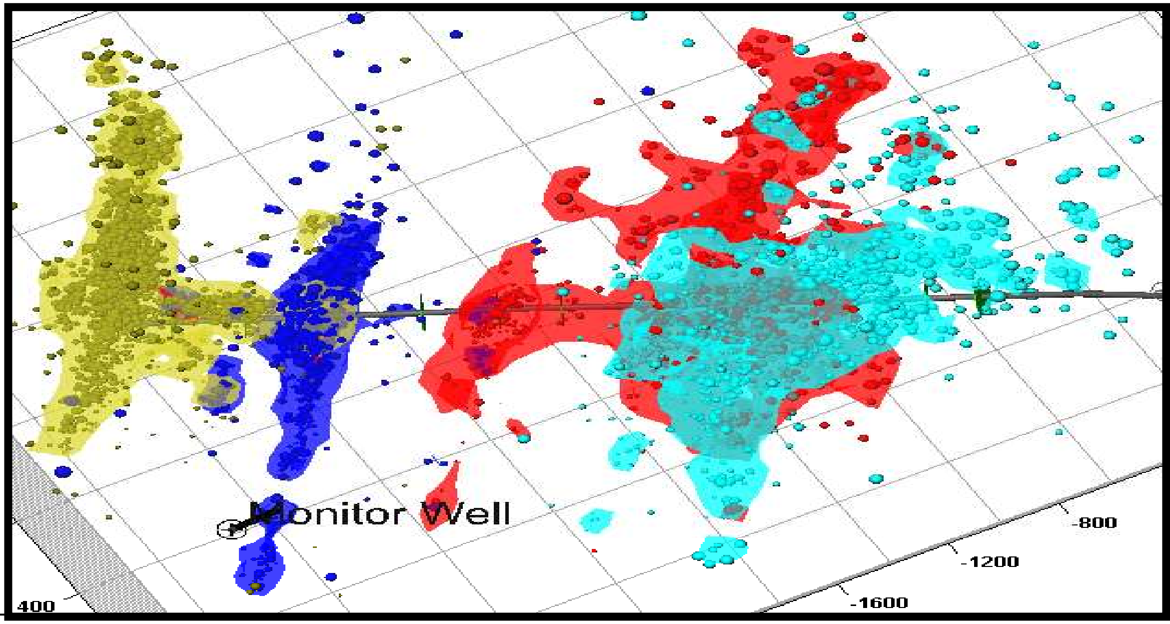
$\Delta P = -191$

$\sigma M - \sigma m = .07$

Stage 2

$\Delta P = 249$

$\sigma M - \sigma m = .10$



Stage 3

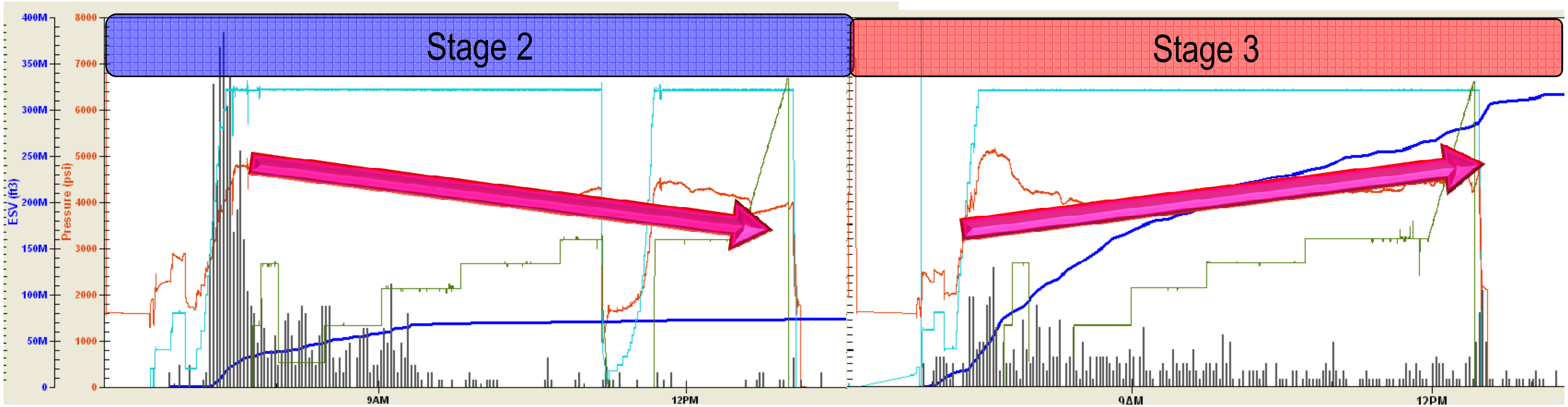
$\Delta P = 564$

$\sigma M - \sigma m = .04$

Stage 4

$\Delta P = 1109$

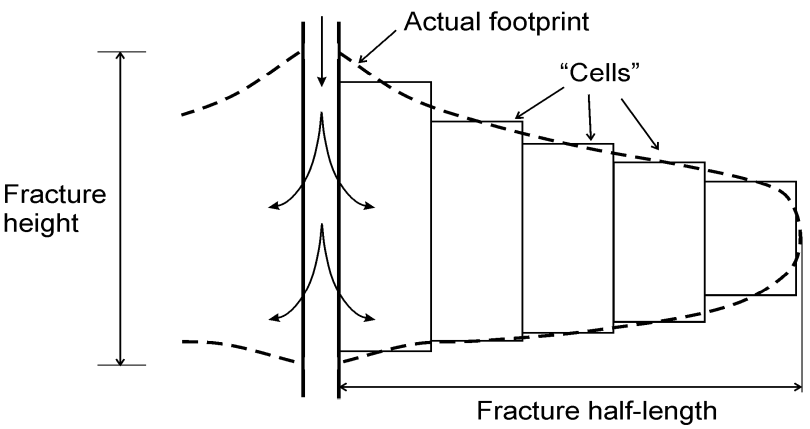
$\sigma M - \sigma m = .03$

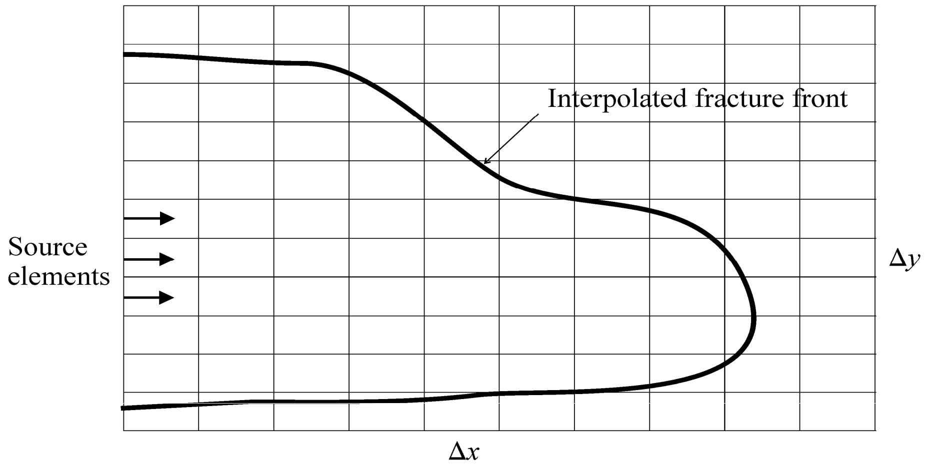


Hydraulic Fracturing Simulation

Fracture geometry modeling

Differences between pseudo 3-D and planar 3-D





Propagation and fluid flow are 1-D

Assumes fracture length >> height (plane-strain assumption)

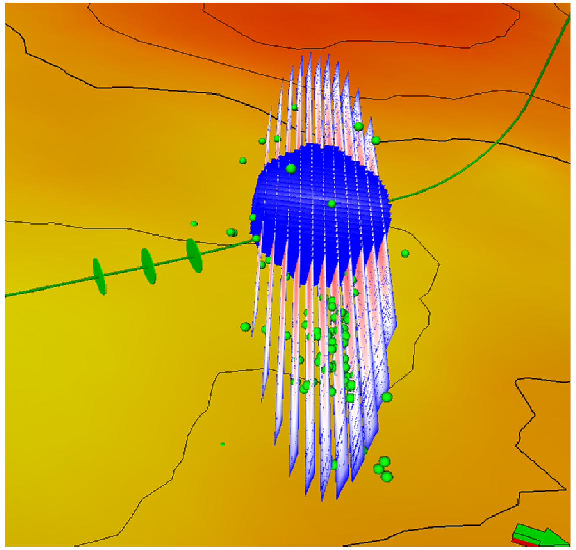
Propagation and fluid flow are 2-D

No assumption/restriction on the aspect ratio (length vs height)

Only constraint – fracture stays within one plane (no bending or turning)

Planar 3-D models are more accurate in layered reservoirs than pseudo 3-D, which will maximize benefit from petrophysical and geomechanical data

Unconventional Reservoir Simulator (Mangrove*)



What is it?

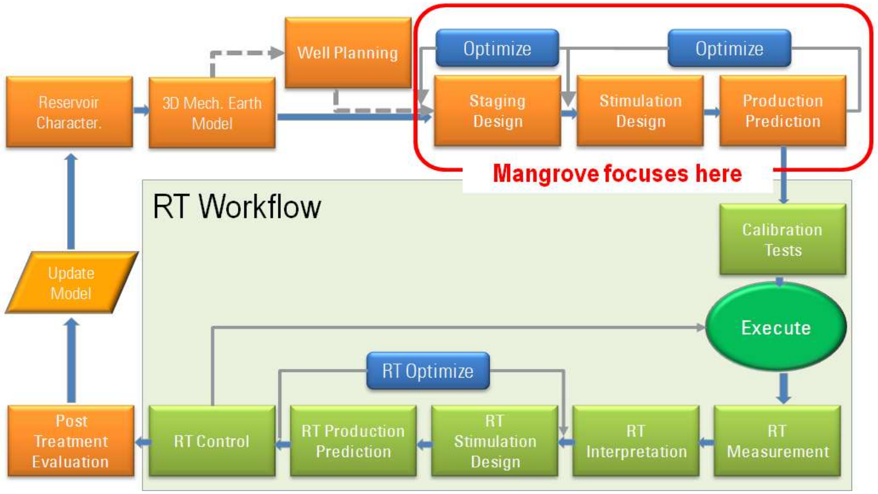
– Multi-stage stimulation design and evaluation software for conventional and unconventional markets
– Integrated in the overall oil field services' multi-disciplinary solutions; …petrophysics, G&G, geomechanics, reservoir engineering

How does it work?

– Implemented as a Plug-in for Petrel

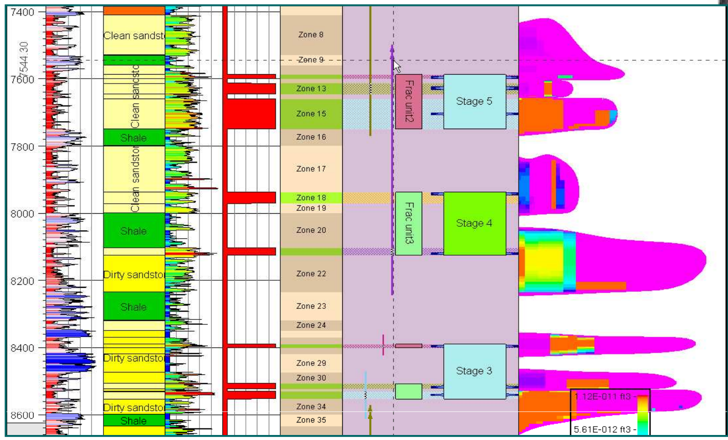
What is the value?

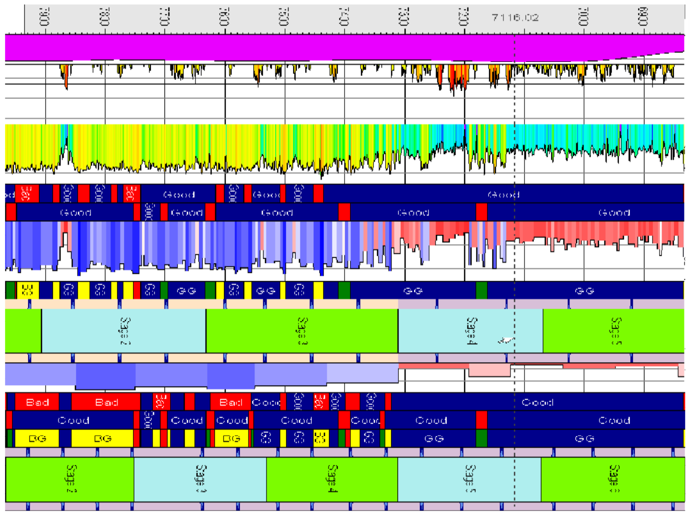
- Differentiate through technical solution rooted in reservoir characterization (measurements and interpretation), enabling reservoir centric stimulation design for specific environments
- Reorient for the global shift to unconventional reservoirs



Multi-staging Advisors

- **Tight Gas Sandstone & Pilot Shale** (Vertical)
  - 100 separate stacked sands over 3000 ft gross
  - Differential depletion
  - Starting point *AutoFRAC* (Denver)
- **Shale (Laterals)**
  - Laterals through heterogeneous rock
  - Ultra low permeability
  - Naturally Fractured





Completion challenges
- Consistent model
- Tedious process (2 days – 2 weeks)

Improved Efficiency, Consistency & Knowledge Dissemination

Simple facts About Reservoir Productivity

Good RQ + Good CQ = Good well
Good RQ + Bad CQ = Bad well
Bad RQ + Good CQ = Bad well
Bad RQ + Bad CQ = Bad well

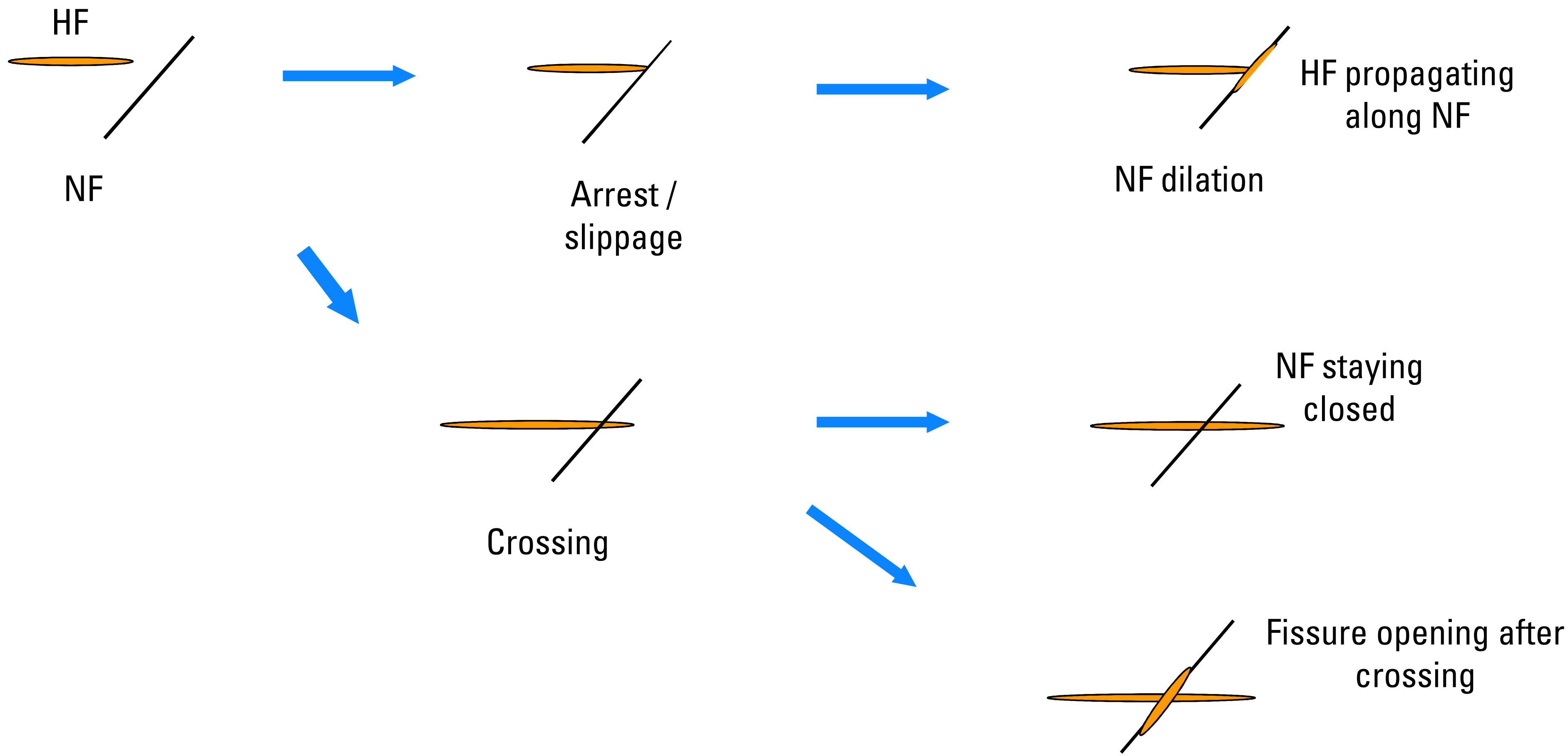
Reservoir productivity (on a well to well basis) depends strongly on reservoir quality and completion quality.

Reservoir quality can be measured and predicted (via logs) with high degree of confidence. However, it cannot be changed.

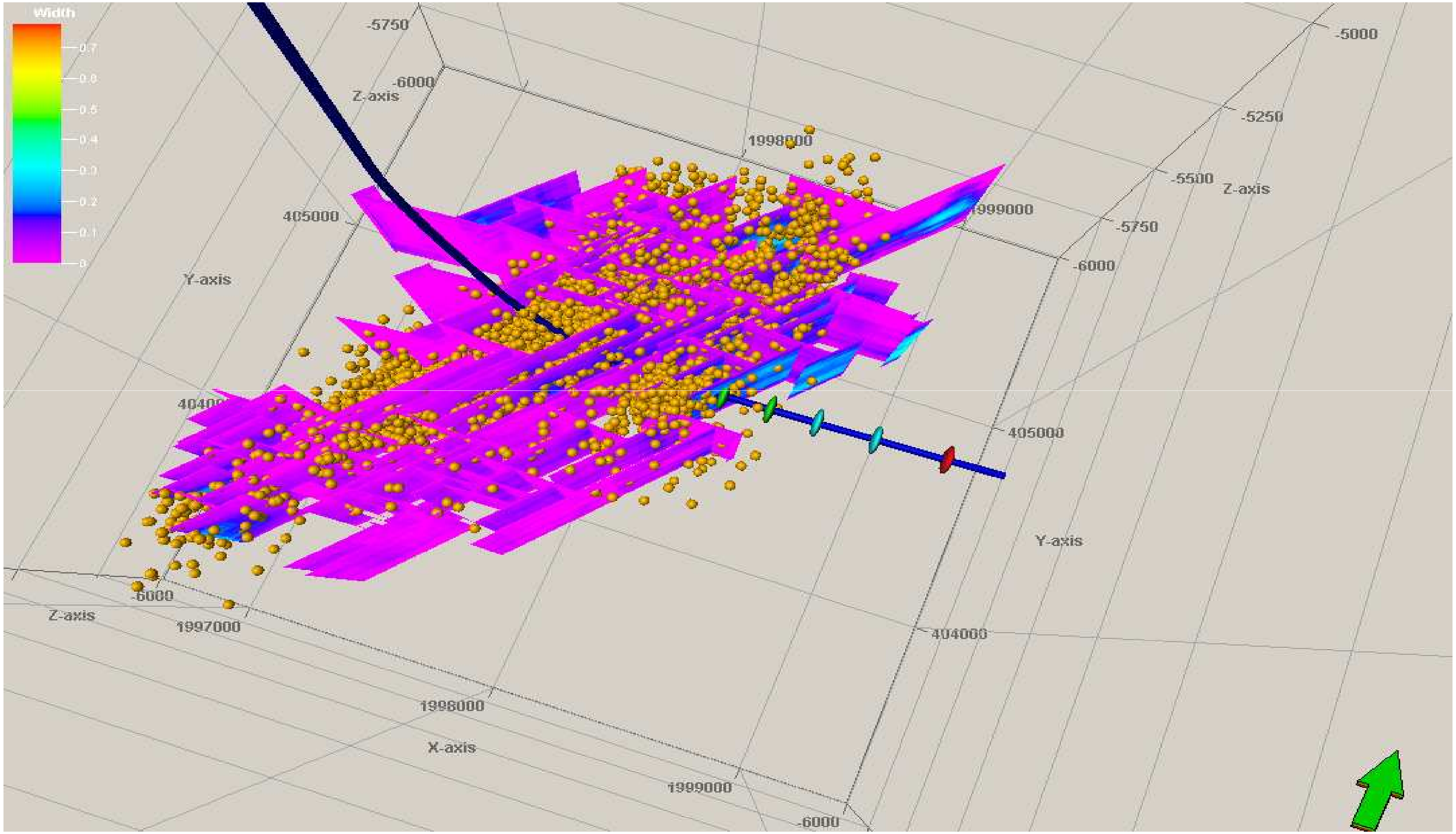
Completion quality is more difficult to predict, but is the property that potentially can be modified from bad to good.

Reservoir quality and completion quality change laterally and vertically as dictated by the large-scale reservoir heterogeneity.

HF-NF Interaction (Crossing Criterion)



Example of UFM Results with micro-seismic data

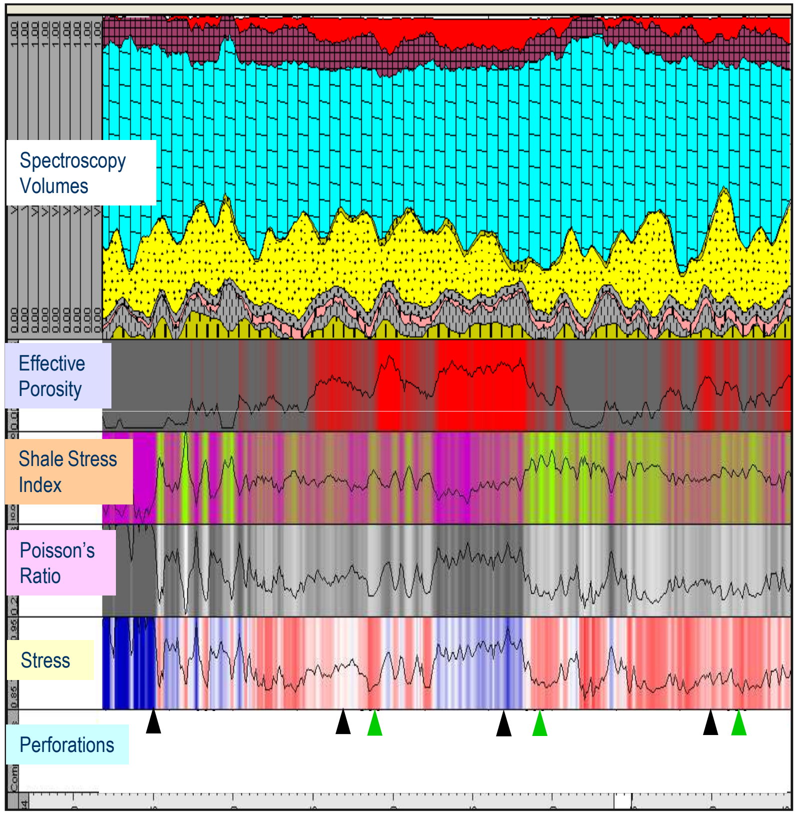


Integrating Reservoir & Completion Quality

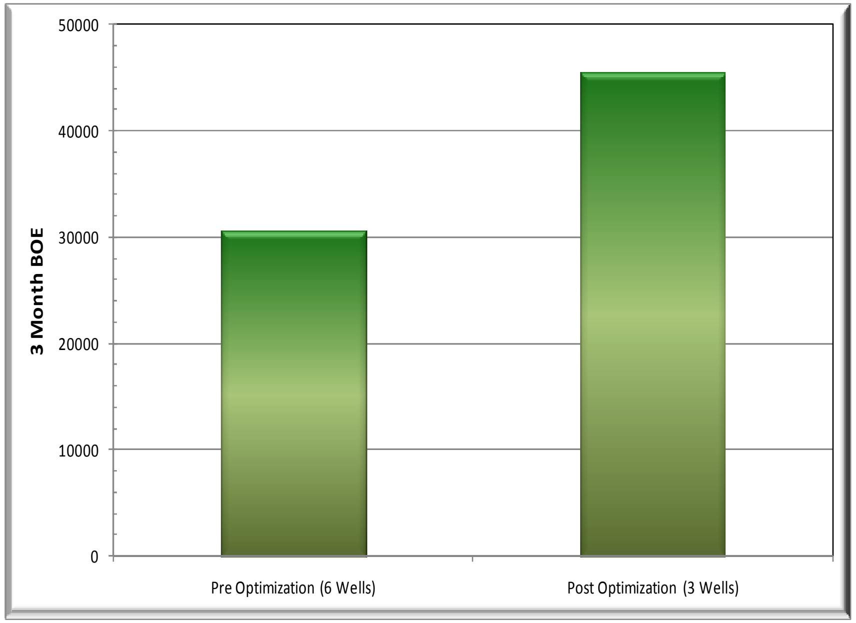
Examine Reservoir and Completion Quality.

Recommend stages with optimal properties. Variable number and lengths.

Recommend specific perforation location



- 33% increase in 3 month average cumulative BOE on new wells. Save $300k in frac costs
- New wells used Reservoir Quality and Completion Quality to optimize completions.



- Combined logs and core measurements for the reservoir and completion quality assessment.
- Reservoir Quality technology routine: Triple Combo-Spectroscopy (PEX-ECS/ EcoScope), Di-Electric Scanner, NMR
- Completion Quality technology routine: Borehole Images (FMI, RAB, LWD Density), Sonic Scanner/Mangrove*

Conclusion & Summary

- Unconventional Reservoirs require special consideration related to the heterogeneity.
- Conventional Isotropic stress models can lead to erroneous evaluations.
- Geomechanical Models are becoming more important in the process of the Reservoir completion.
- It's not *just* about technology, it's about integrating appropriate technology.

Questions or Comments?