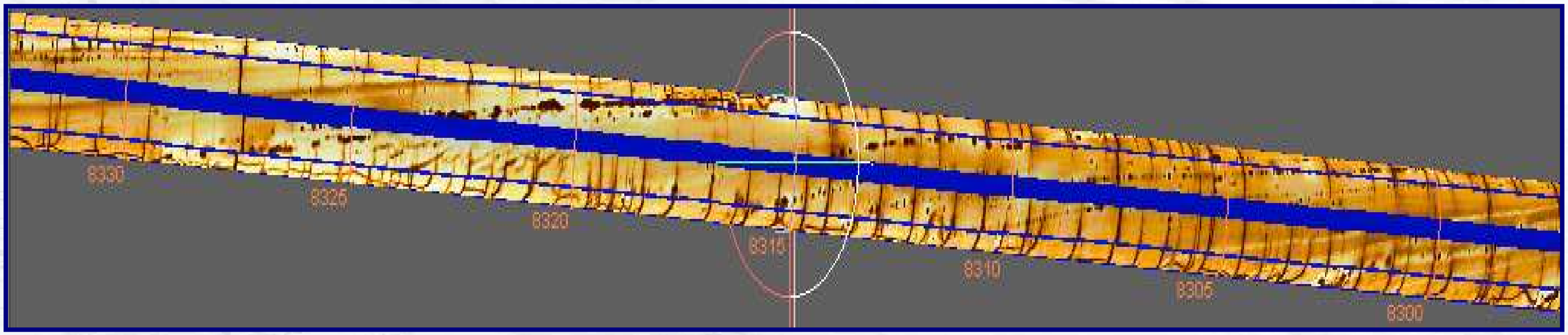
Horizontal Well Planning Within the Woodford and Other Gas Shales Within the Mid-Continent, USA



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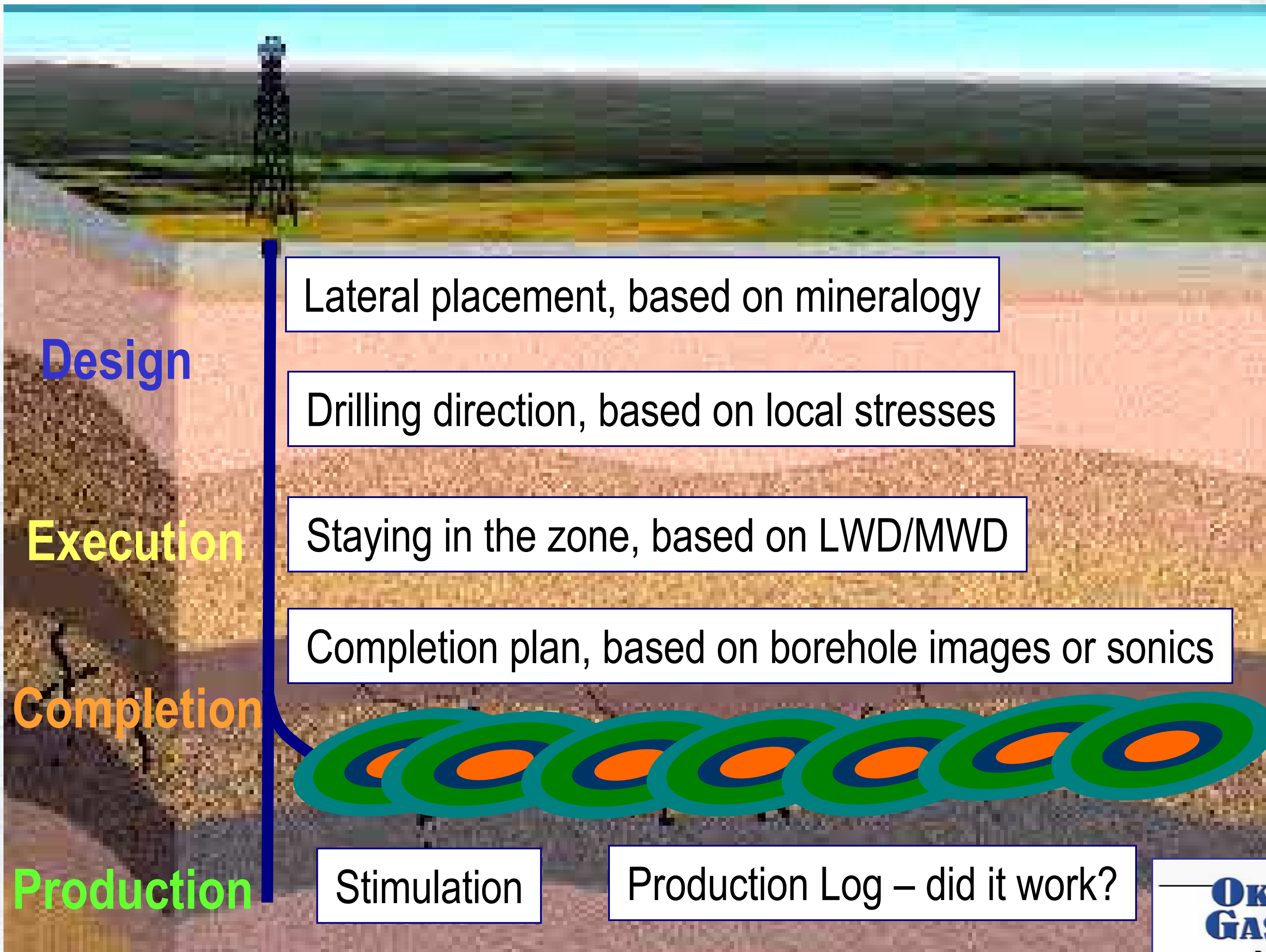
Hz Well Planning within Gas Shales – Key Topics



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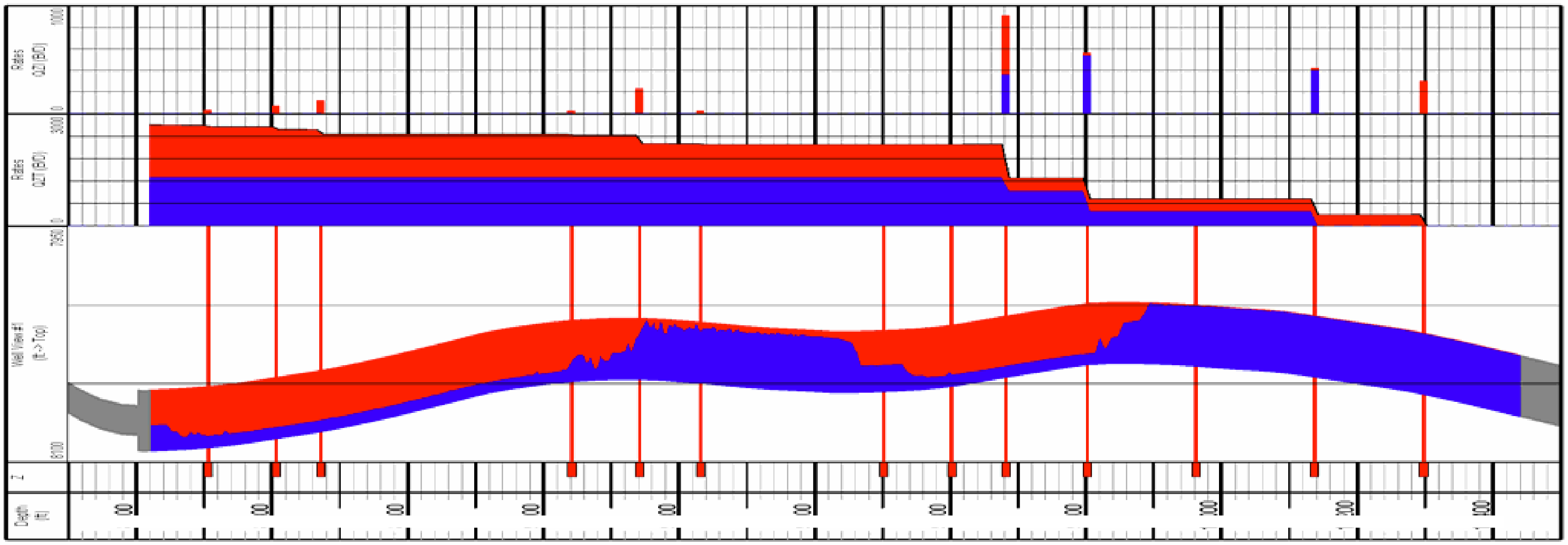
This is what we're seeing on production logs….

Woodford Shale Hz PL example



Flow Scanner* observations:

- contribution to gas production varies between perforation clusters
- 75% of water production is from 4 toe perforations (stage one)
- 20% of gas productions is from 4 toe perforations (stage one)

Wouldn't it be nice to have geologic information to explain these results?

Solution:

- operator plugged the four toe perforations and eliminated 80-85% of water production (1000 bwpd) with a minimal drop in gas production

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Intro to Horizontal Well Planning in Gas Shales

The key to success in horizontal well projects within gas shales is to set up, plan and execute an effective completion design

Step 1: Lateral placement – pilot hole evaluation

- Geochemical log (ECS) to quantify mineralogy and play potential
- Borehole images for structural dip, fracture, fault and stress analysis

Step 2: Drilling direction depends on local stress regime

- Borehole images or advanced sonic tools for stress orientations
  - Drilling fractures form parallel to present day maximum horizontal stress direction
  - Fast shear azimuth is parallel to present day maximum horizontal stress direction

Step 3: Completion planning – Hz well evaluation

- Borehole images or advanced sonic tools for rock stiffness
  - Resistive vs. conductive mineralogy on borehole images
  - Rock mechanical properties for fracture closure stress
- Borehole images for structural dip, fracture, fault and stress analysis
  - Dip changes may indicate folding or faulting (higher stresses)
  - Natural fractures enhanced system perm, may be related to faulting, can be good or bad
  - Drilling fractures help us predict hydraulic fracture initiation and geometry

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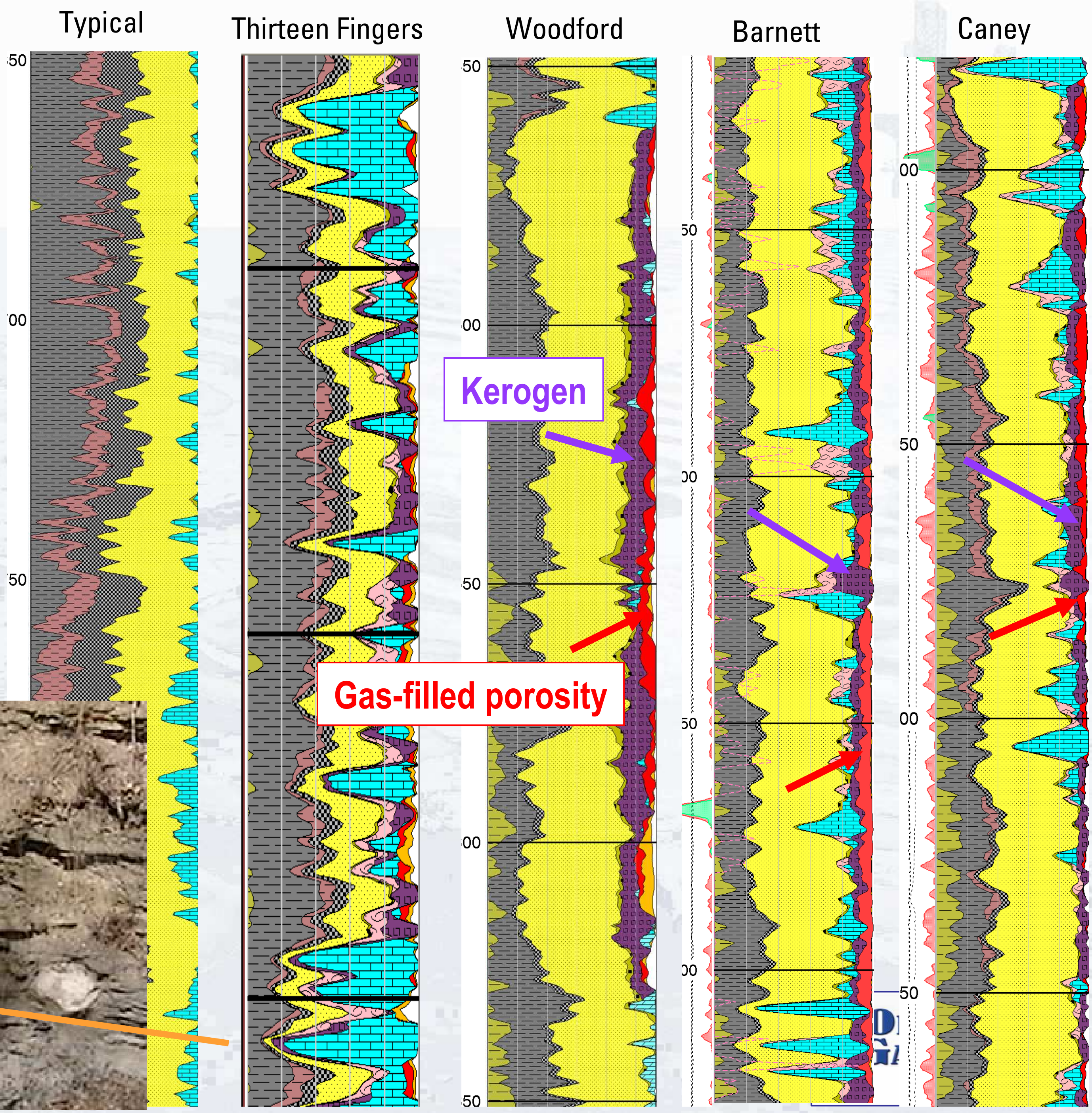
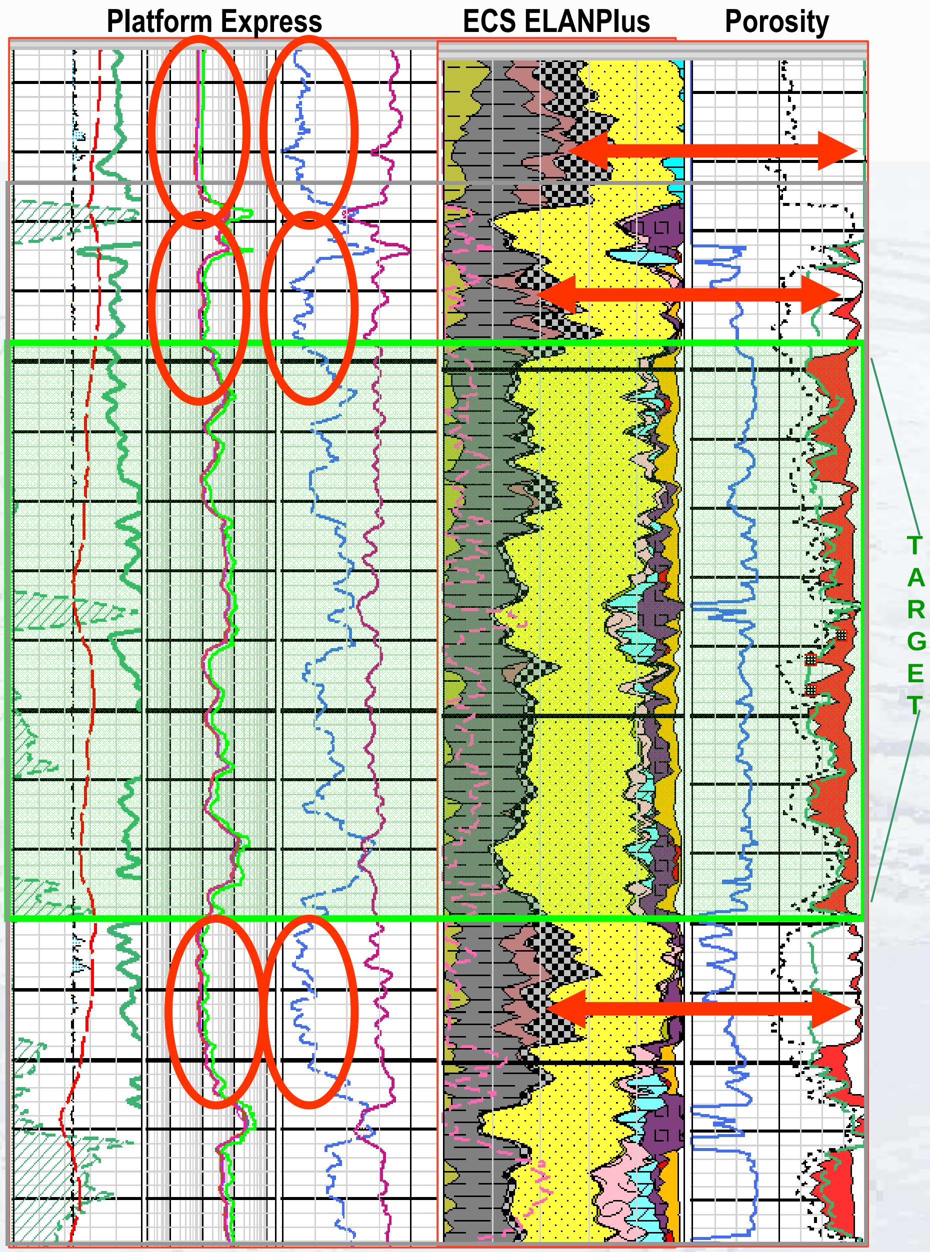
Shale Minerals

Gas Shales

- Quartz Rich
- Frequent Carbonates
- Illite Dominant Clay
- Chlorite Common
- Periodic Swelling Clays
- Pyrite Common
- Variable Kerogen



Reservoir Evaluation for Lateral Placement



Geochemically (ECS)-enhanced formation evaluation

- Quantitative mineralogy
  - High silica, low clay = better reservoirs and higher modulus
  - Swelling clays = big problems

Borehole images → FMI/OBMI/UBI

- Natural fractures
- Drilling-induced fractures
- Faults
- Bed orientation

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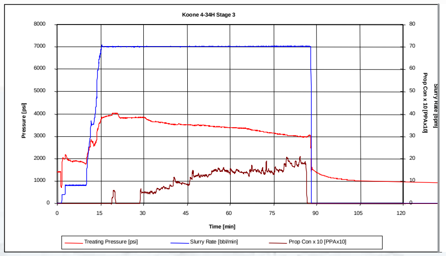
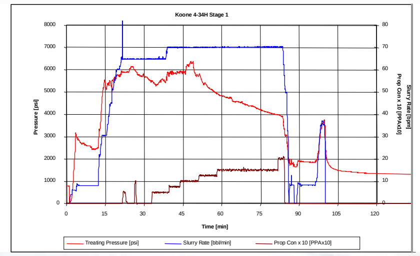
Mineralogy: Variable Characteristics = Variable Treatments

Siliceous rock

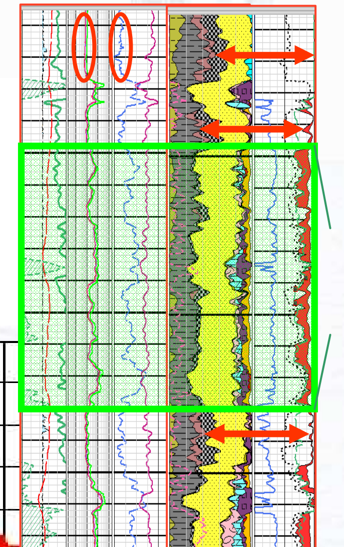


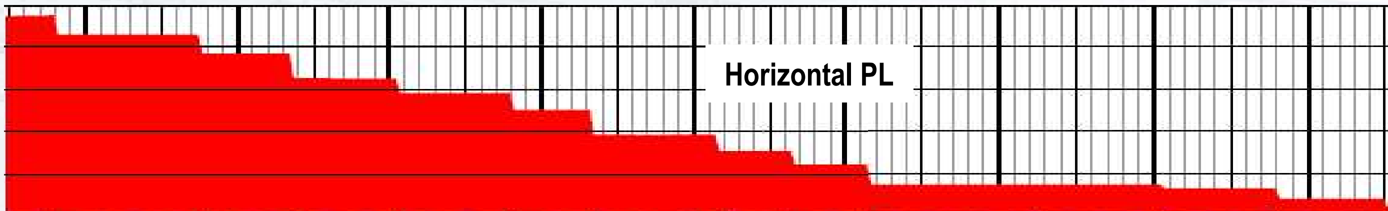
Treating Pressures

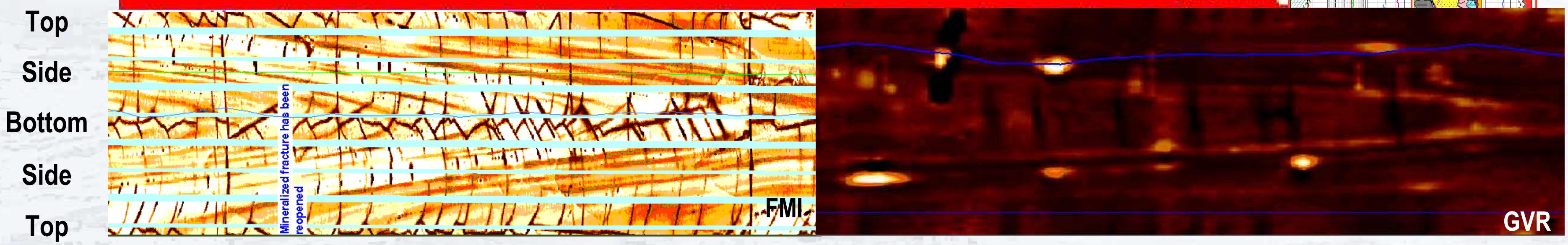
Clay-rich rock



Pilot Hole - ECS







Resistive Mineralogy

- siliceous and/or calcareous rock
- high stiffness (low frac initiation pressure)
- relatively good reservoir quality

Conductive Mineralogy

- clay-rich (argillaceous) rock
- low stiffness (high frac initiation pressure)
- very poor reservoir quality

Siliceous zones

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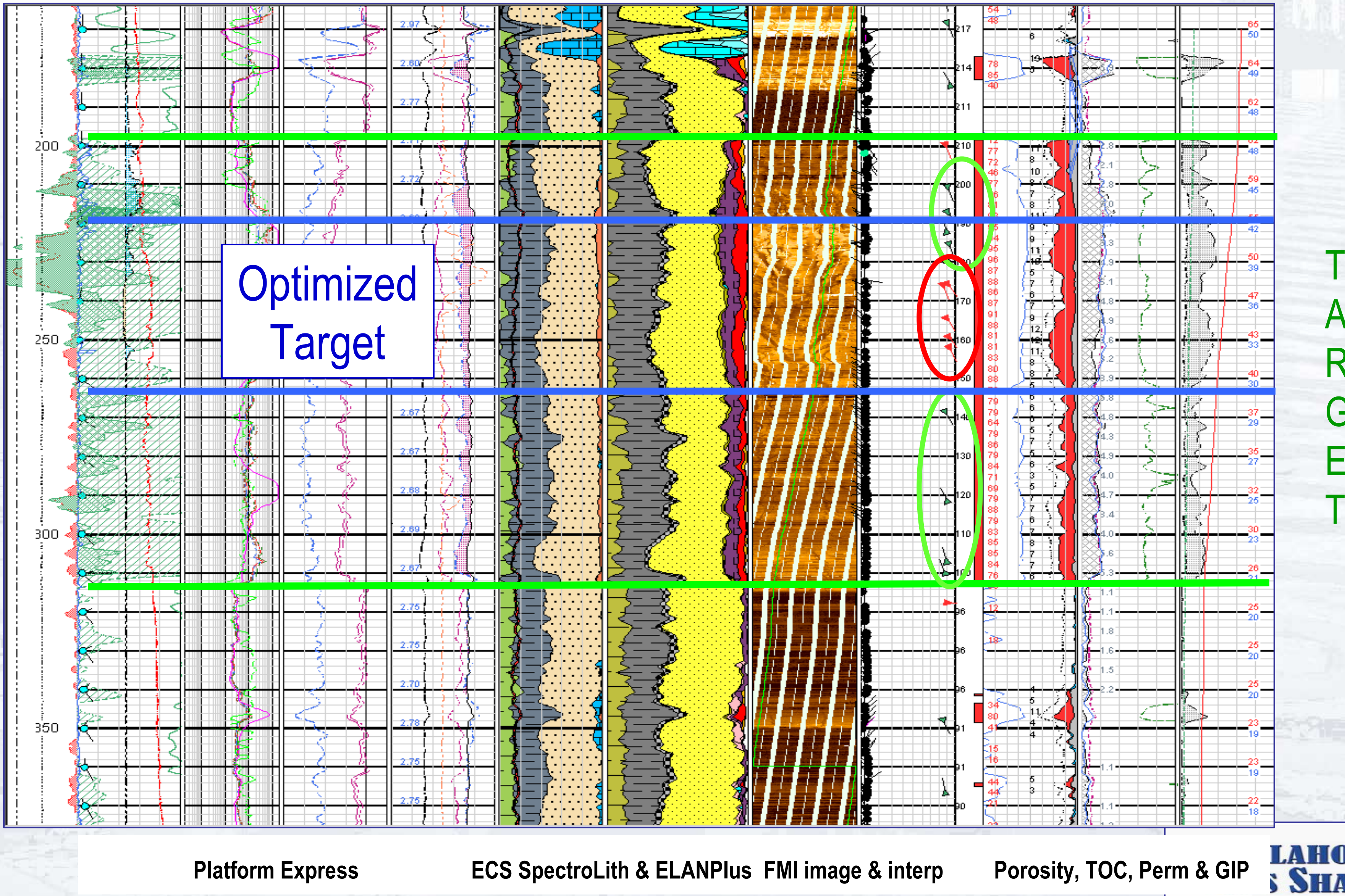
Pilot Hole Example – Lateral Placement



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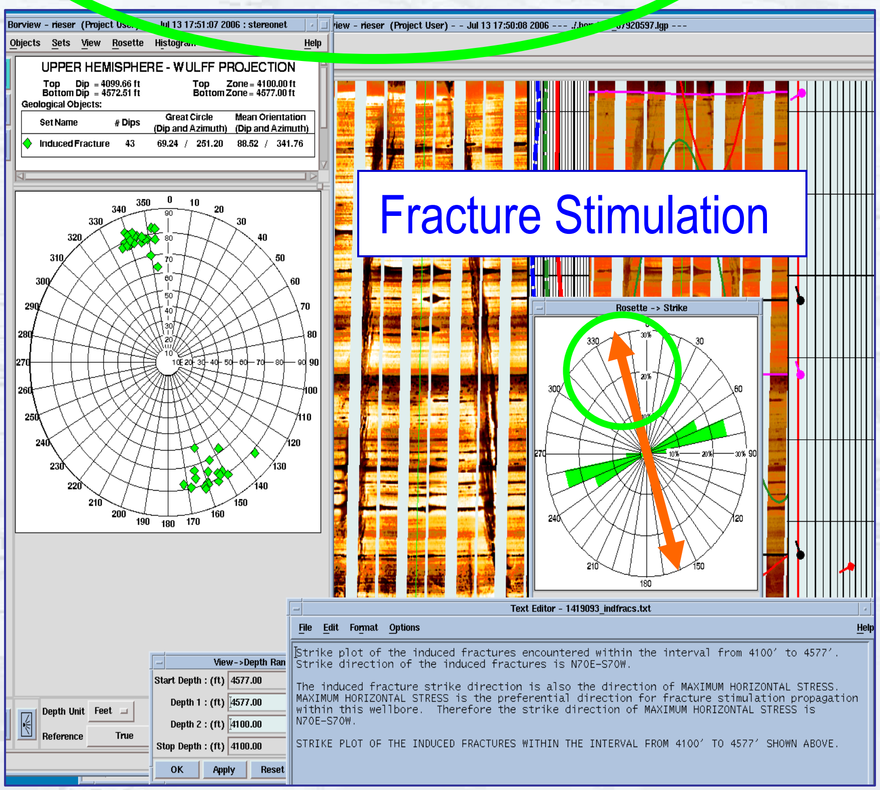
Pilot Hole Example – Orienting the well

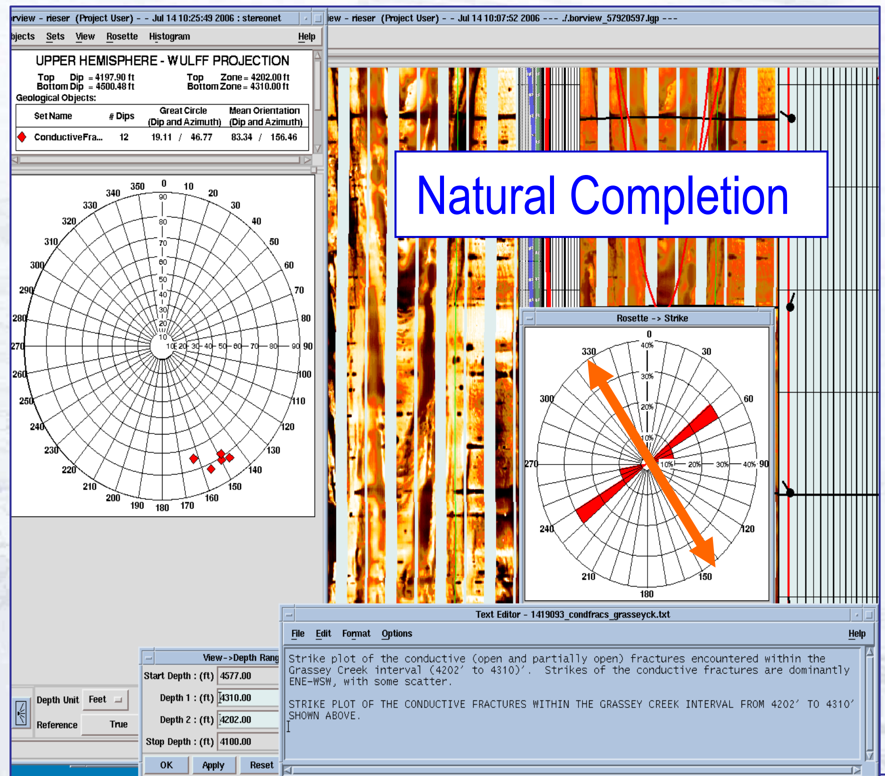
Drilling-Induced Fractures

- ENE-WSW
- Maximum horizontal stress

Natural Fractures

- ENE-WSW
- Important for natural completions





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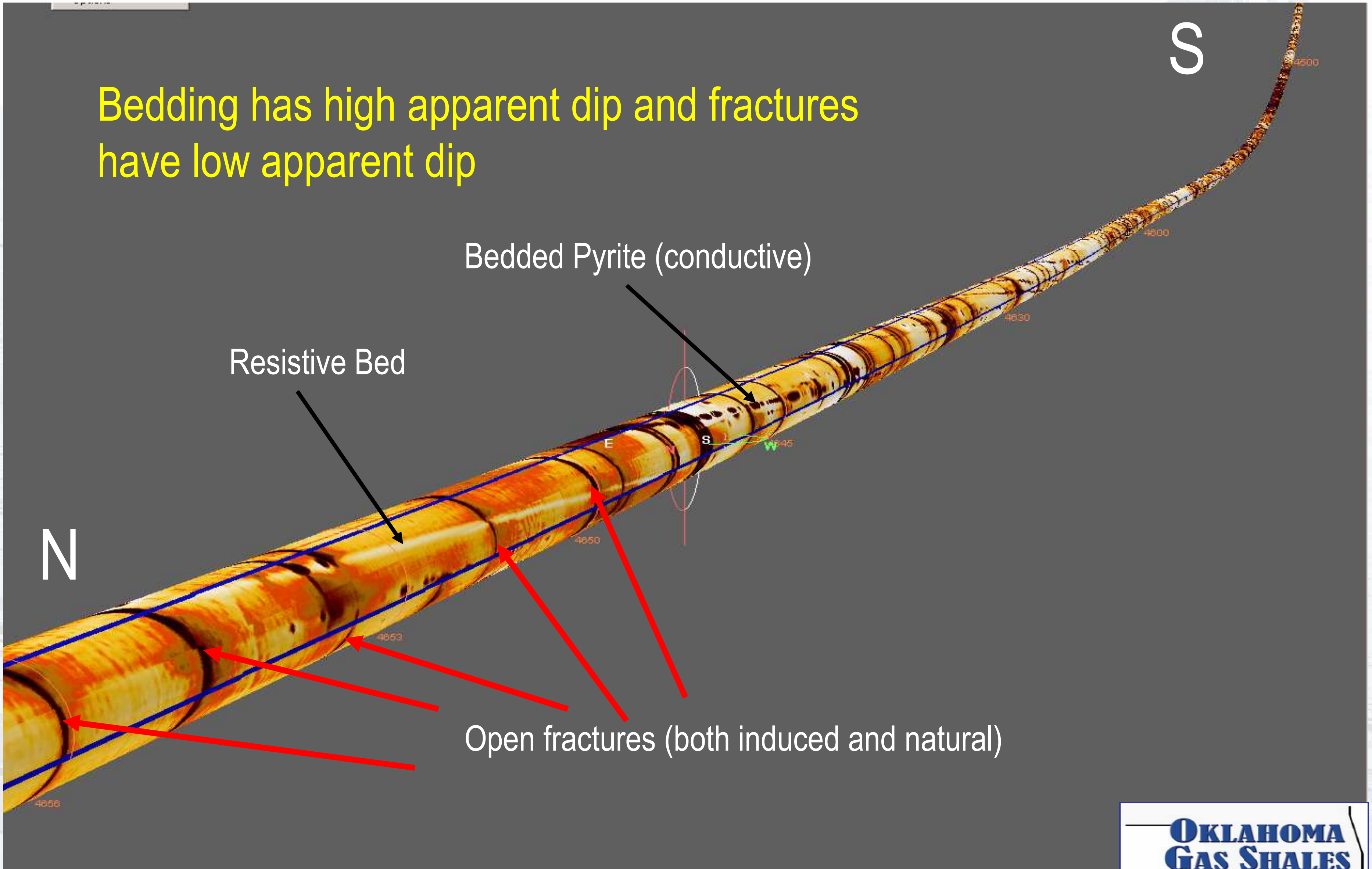
3D View of Horizontal Well – WellEye



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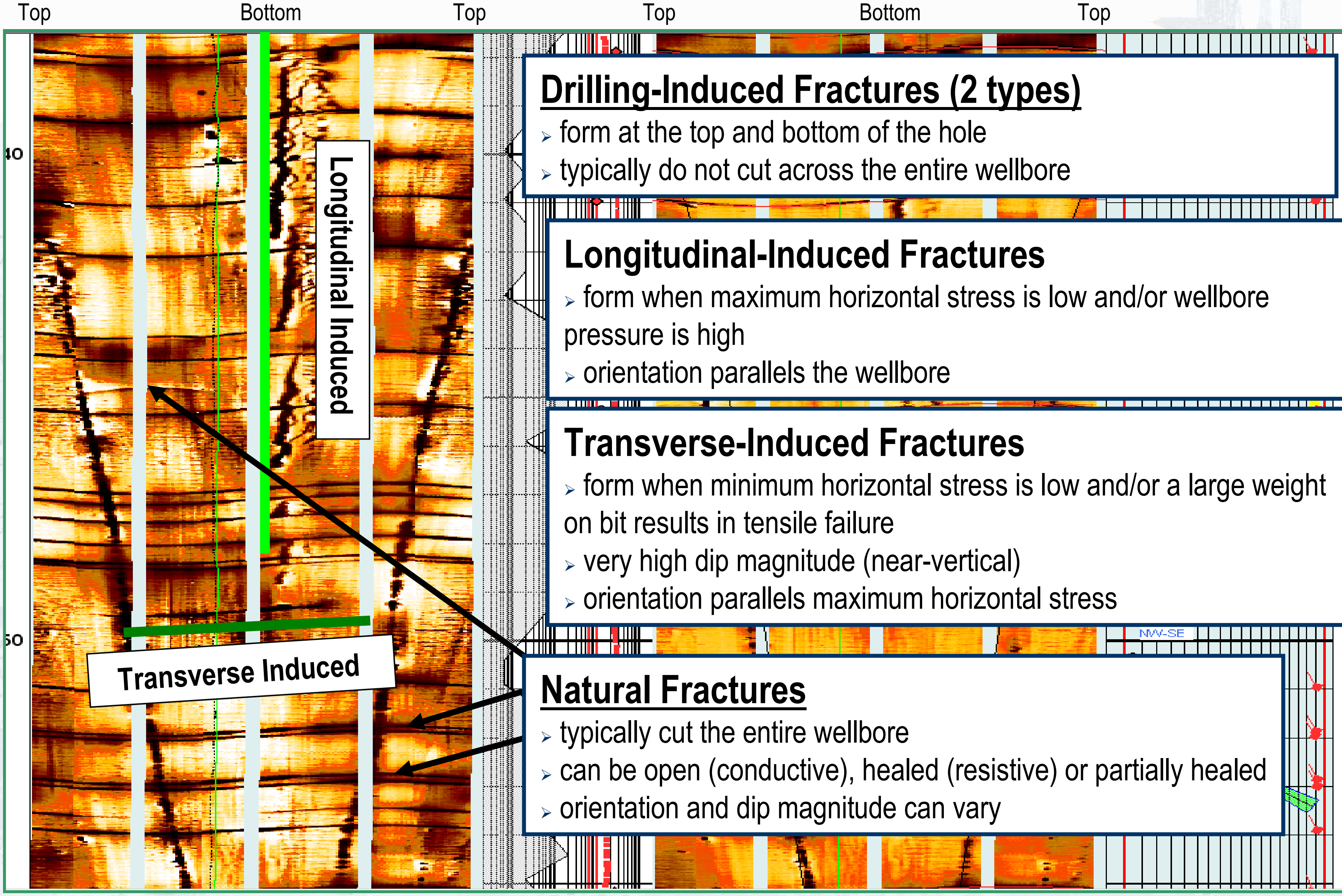
Horizontal Image Interpretation: Fracture Analysis



Drilling-Induced Fractures (2 types)

- form at the top and bottom of the hole
- typically do not cut across the entire wellbore

Longitudinal-Induced Fractures

- form when maximum horizontal stress is low and/or wellbore pressure is high
- orientation parallels the wellbore

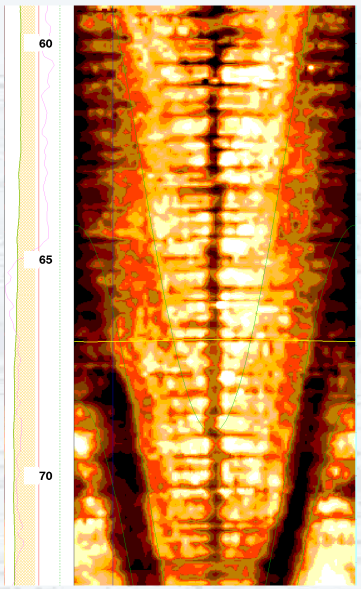
Transverse-Induced Fractures

- form when minimum horizontal stress is low and/or a large weight on bit results in tensile failure
- very high dip magnitude (near-vertical)
- orientation parallels maximum horizontal stress

Natural Fractures

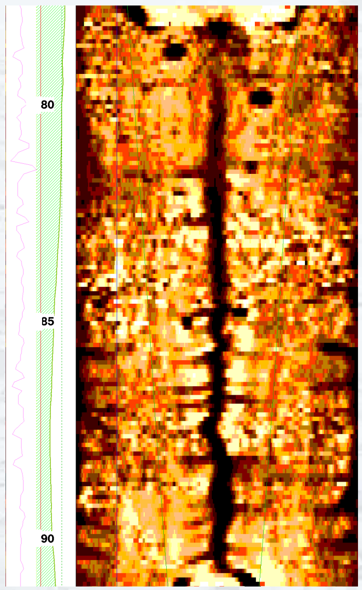
- typically cut the entire wellbore
- can be open (conductive), healed (resistive) or partially healed
- orientation and dip magnitude can vary

Stress Information in Horizontal Wellbores → Induced Fractures: Variable Characteristics = Variable Treatments



Transverse & Longitudinal

Overall low stress
&
isotropic stresses



Longitudinal only

Low maximum stress,
high minimum stress
(higher isotropic stress)

Transverse only

Low minimum stress,
Max >> Min stress
(stress anisotropy)

None

Overall high stress

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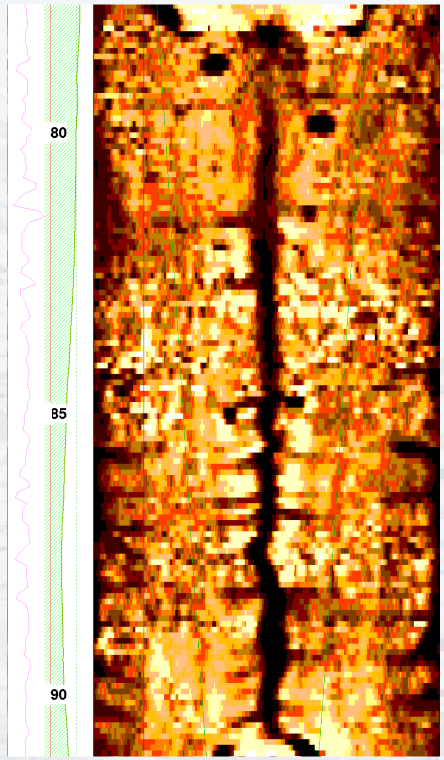
Stress Information in Horizontal Wellbores → Induced Fractures: Variable Characteristics = Variable Treatments

Transverse & Longitudinal

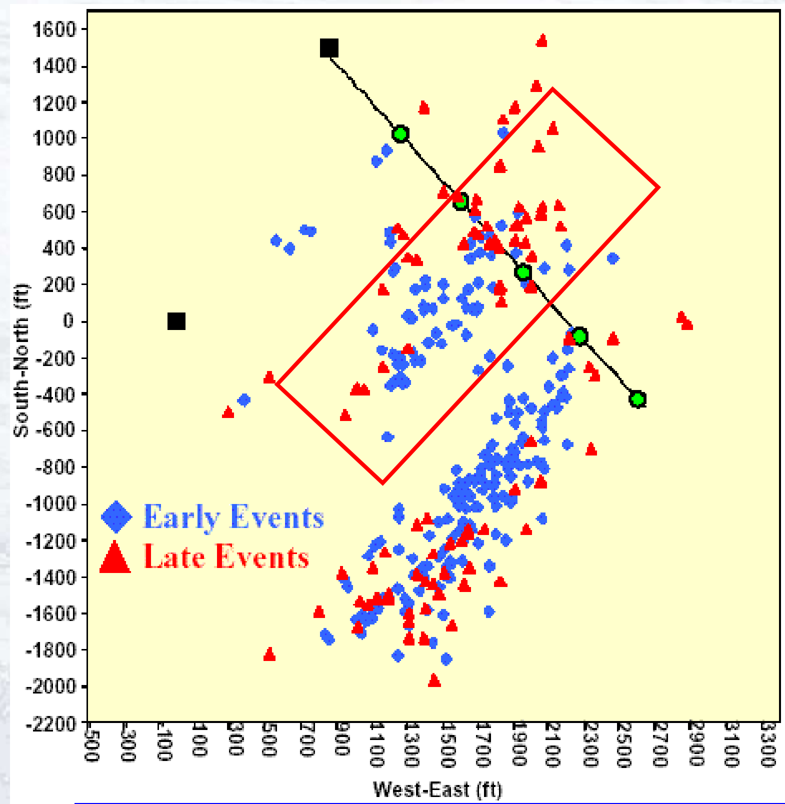
Overall low stress
&
isotropic stresses



Longitudinal only

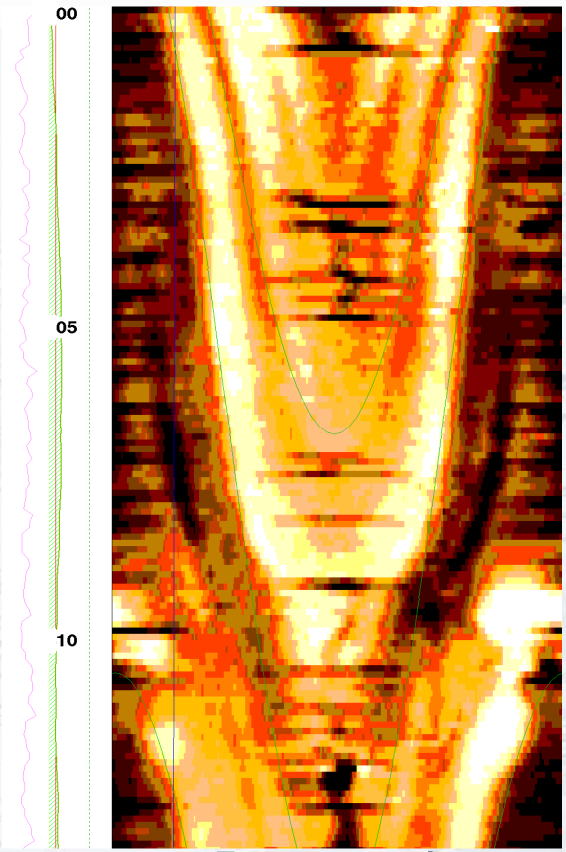
Low maximum stress,
high minimum stress
(higher isotropic stress)

Short & wide fracture fairway



Completion considerations:
- More spacing between perf clusters?
- More fluid for more frac length?

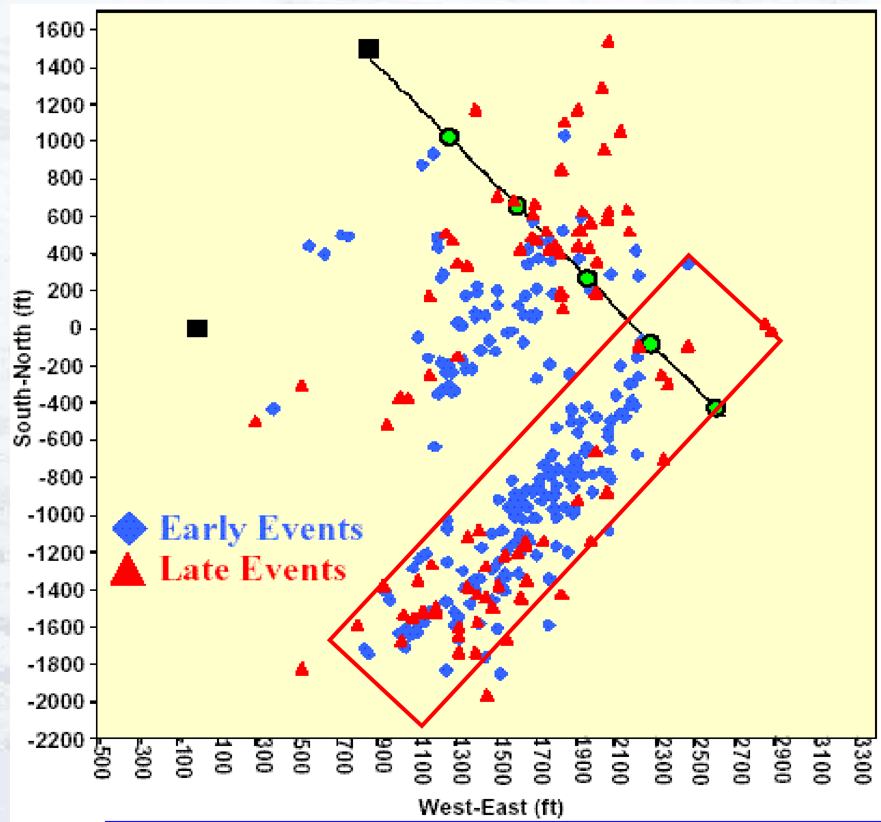
Stress Information in Horizontal Wellbores → Induced Fractures: Variable Characteristics = Variable Treatments



Transverse only

Low minimum stress,
Max >> Min stress
(stress anisotropy)

Long & narrow fracture fairway



Completion considerations:

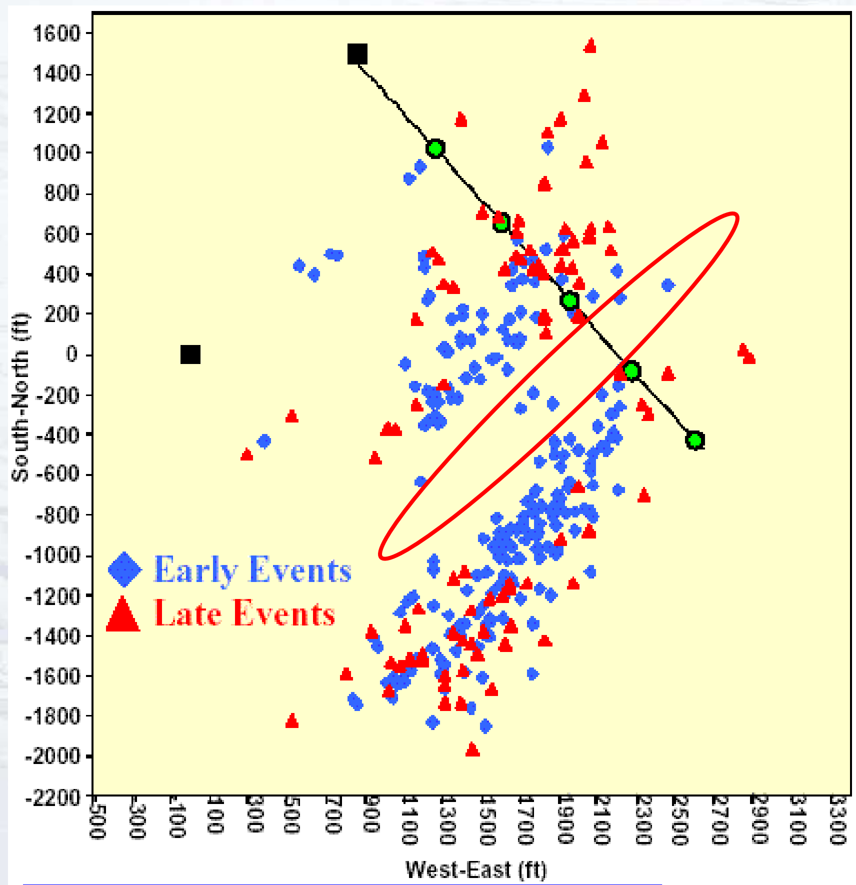
- Less spacing between perf clusters?
- Less fluid?

Stress Information in Horizontal Wellbores → Induced Fractures: Variable Characteristics = Variable Treatments

No induced fractures

Overall high stress

No Fractures



Completion considerations:
- Closely spaced perfs?
- Isolation of high stress intervals?

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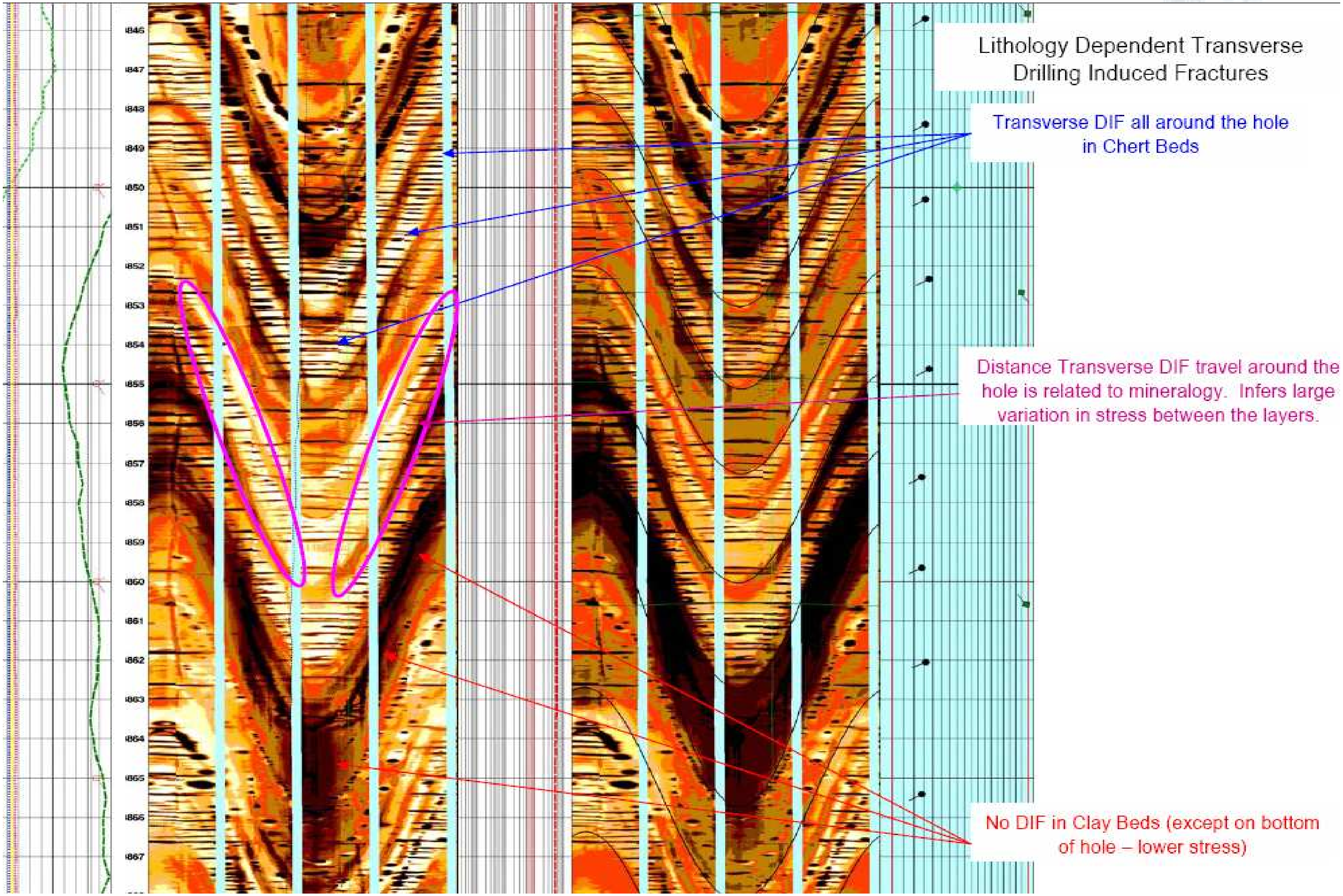
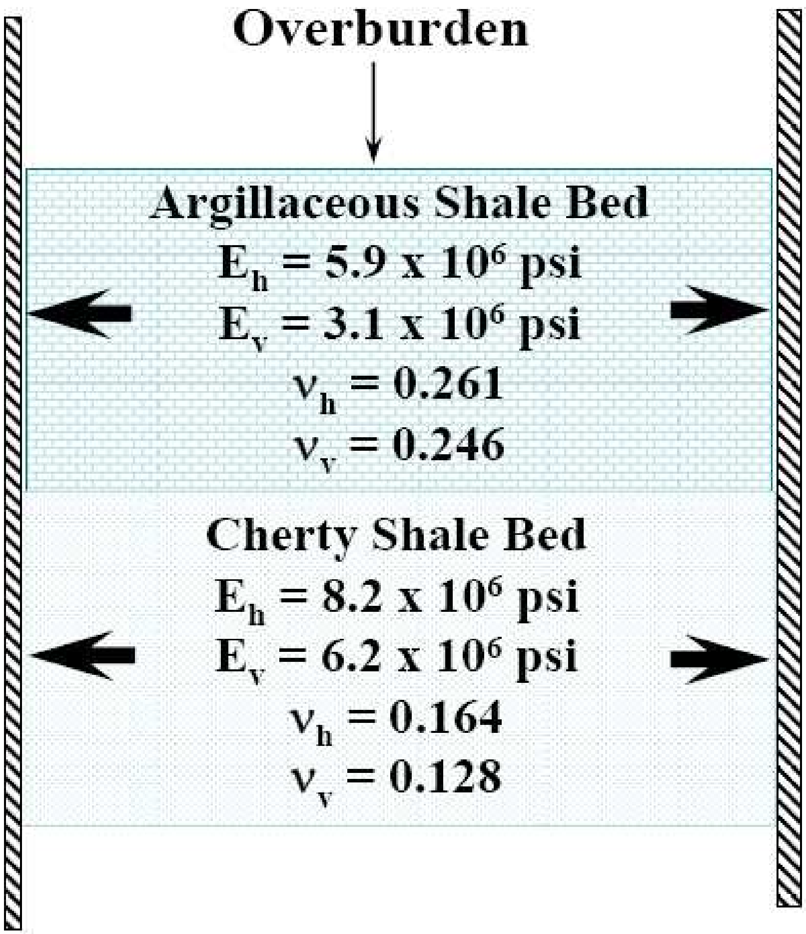
Horizontal Woodford Example



Impact of Mineralogy on Mechanical Properties and Stress



Anisotropic shale properties increases stress in argillaceous intervals

Assume:

$D = 7{,}500$ ft
$P_r = 0.49$ psi/ft
$\sigma_v = 1.10$ psi/ft
$\alpha = 1.0$

<u>Isotropic Stress</u>

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

<u>Anisotropic Stress</u>

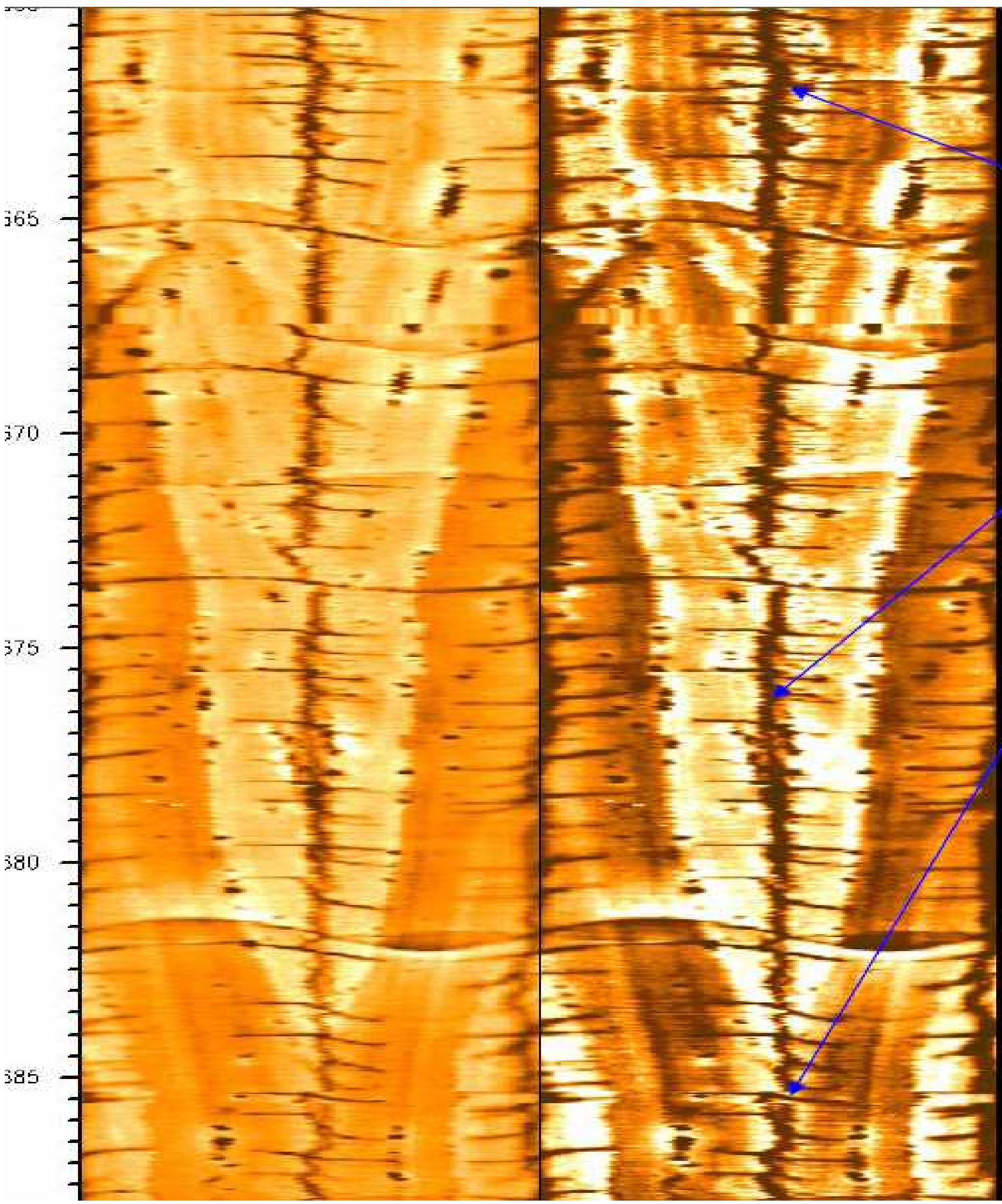
$$\frac{E_h}{E_V} \times \frac{\nu_V}{(1-\nu_H)} \times (\sigma_V - \alpha P_r) + \alpha P_r$$

Argillaceous Shale:
Isotropic: σ_h = 5,288 psi = 0.705 psi/ft
Anisotropic: σ_h = 6,573 psi = 0.876 psi/ft

Cherty Shale:
Isotropic: σ_h = 4,568 psi = 0.609 psi/ft
Anisotropic: σ_h = 4,605 psi = 0.614 psi/ft

Large stress contrast between beds

Barnett Example



For Comparison:
Lithology Independent Drilling Induced Fractures in Barnett Shale
(Ft. Worth Basin)

Distance Transverse DIF travel around the hole is independent of lithology

Much smaller Mechanical Properties Contrast than in Woodford Shale

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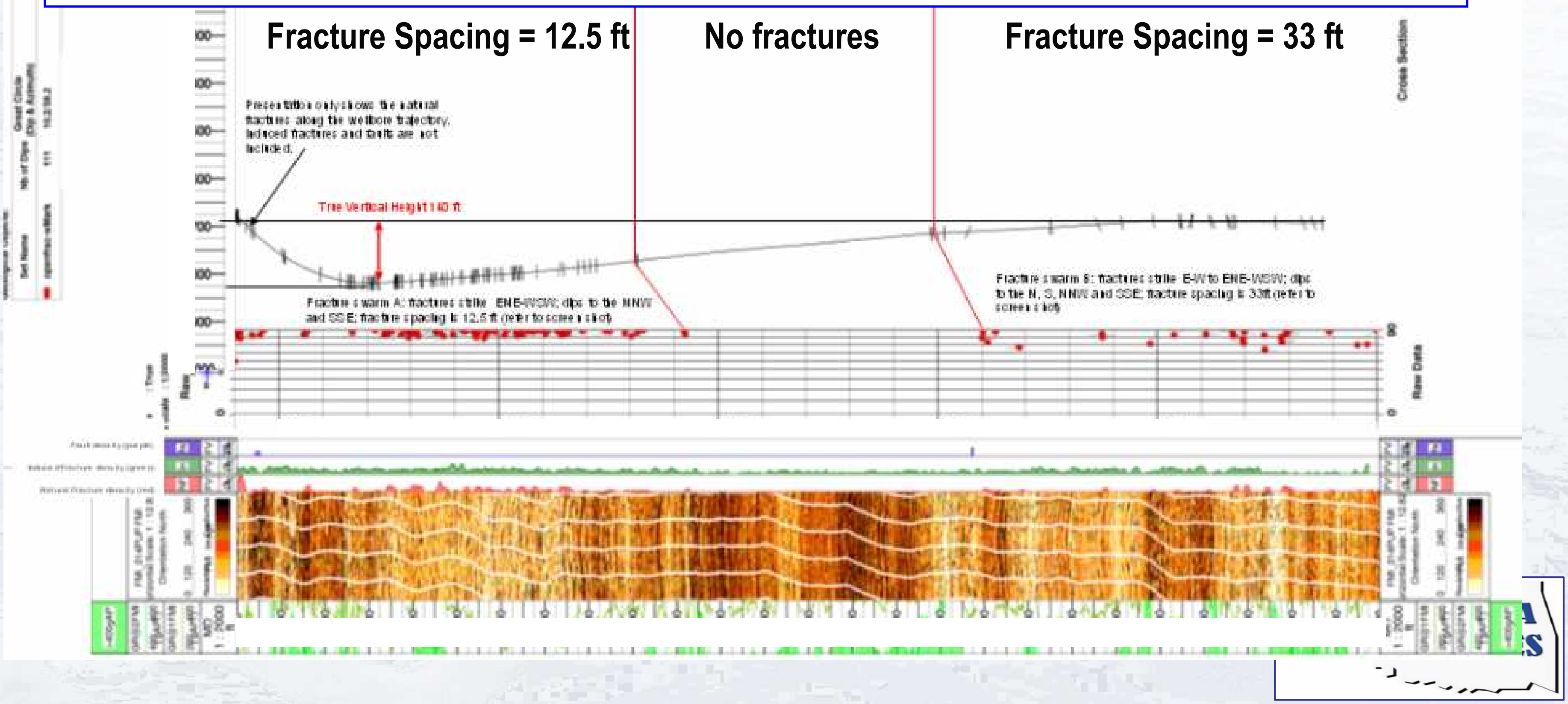
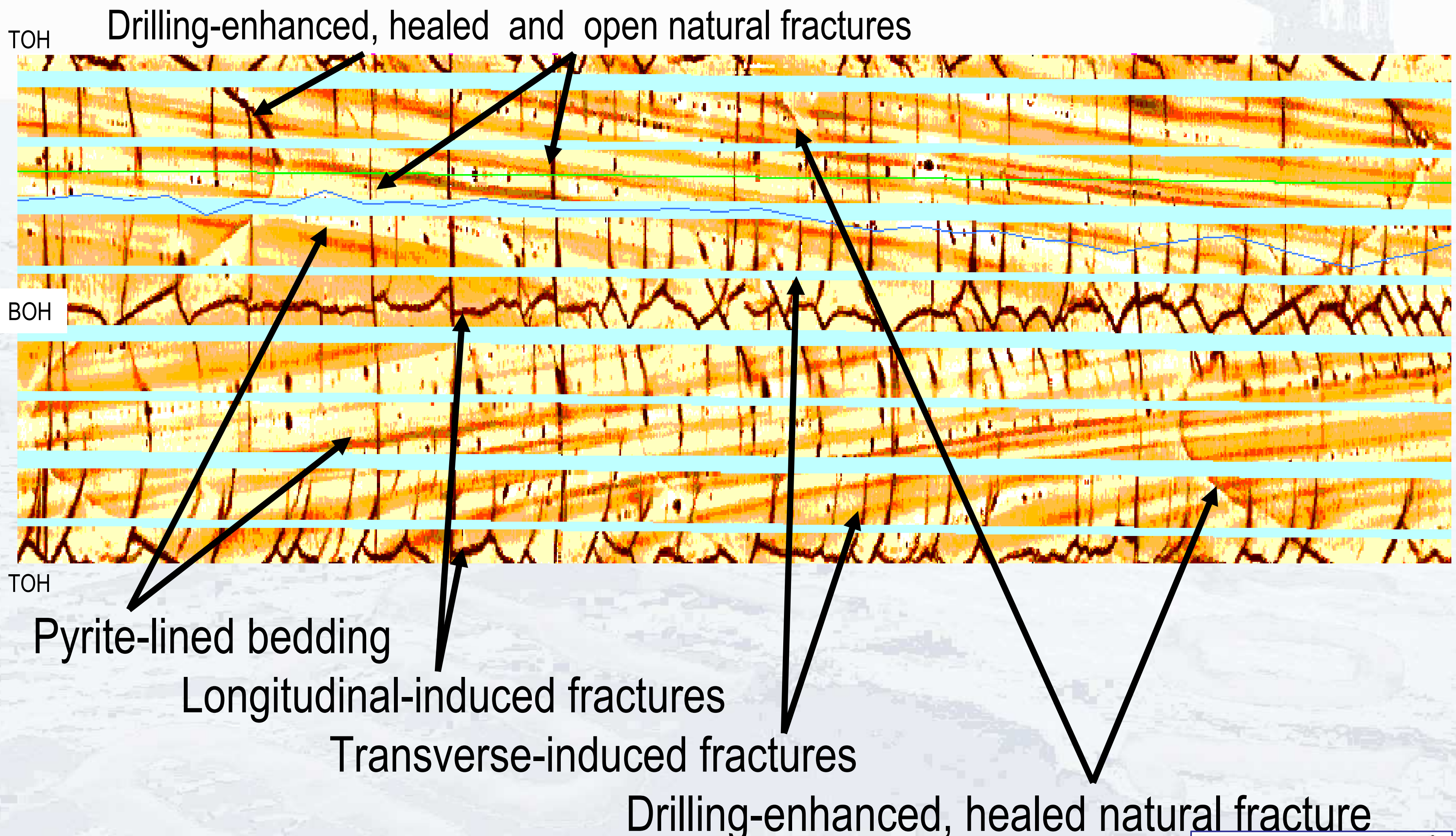
Natural Fractures:
Variable Characteristics = Variable Treatments

Completion considerations:

- as natural fracture spacing decreases, perf spacing can increase
- isolate intervals with significant differences in natural fracture spacing



Horizontal Image Interpretation Examples



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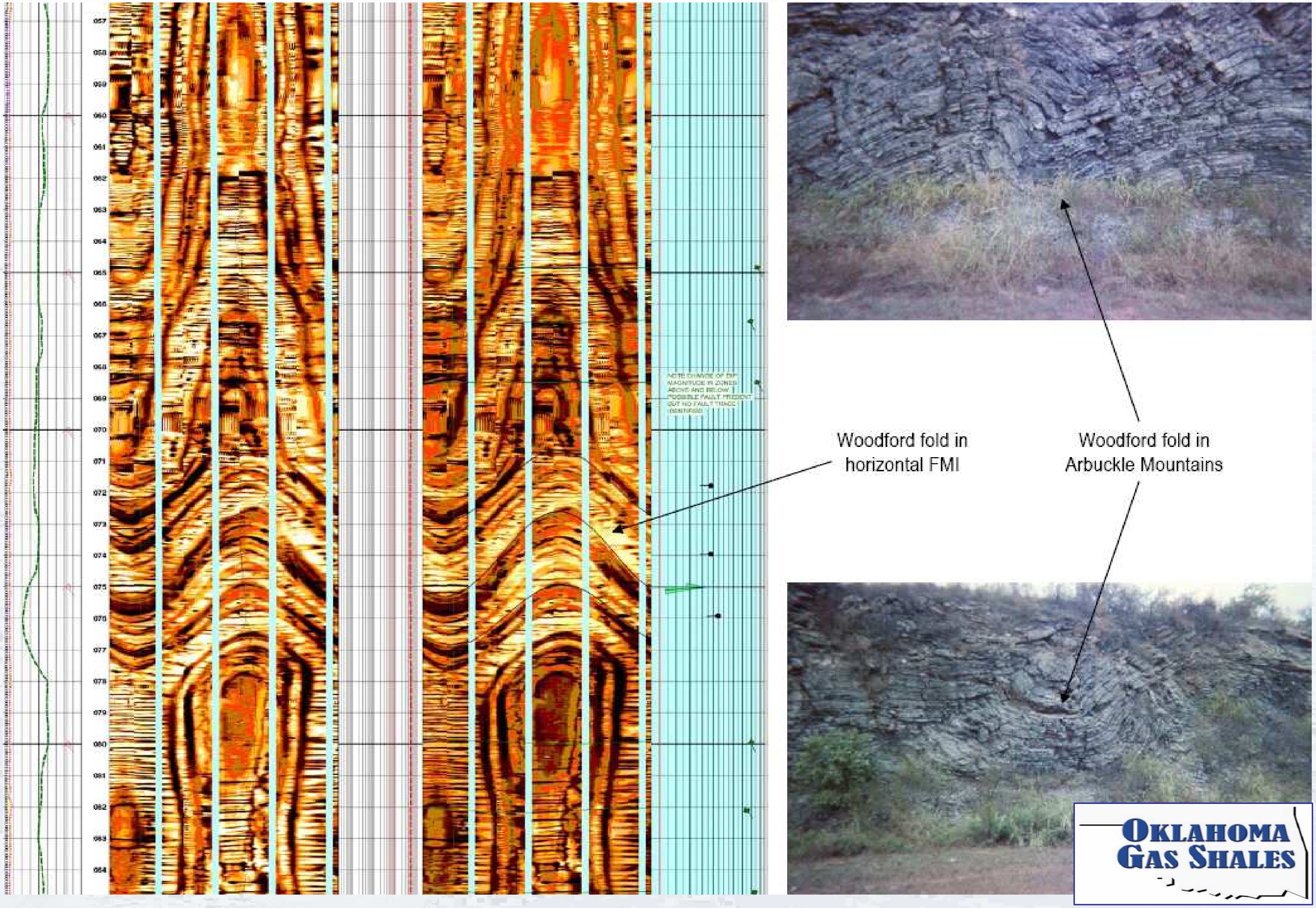
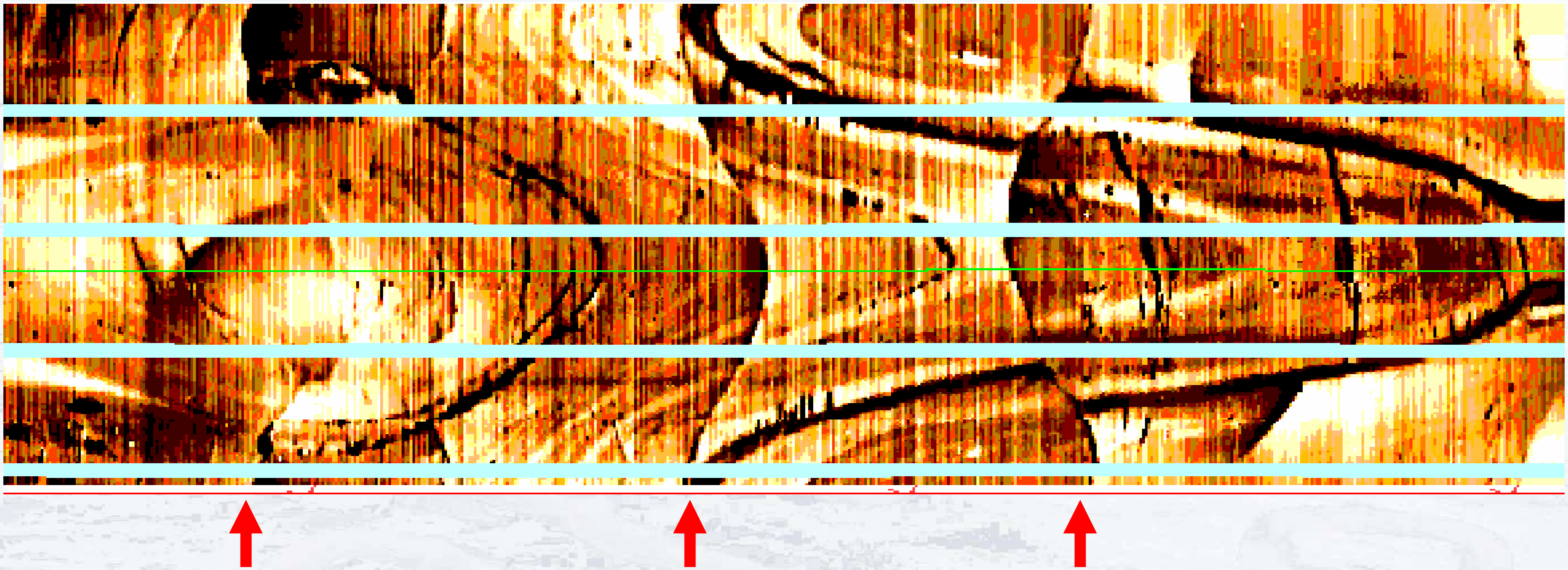
Horizontal Woodford Example



Horizontal Image Interpretation Examples

Sub-seismic faults



Potential Issues:

- wasted frac energy and inefficient reservoir stimulation
- can guide hydraulic fractures to water-bearing zones

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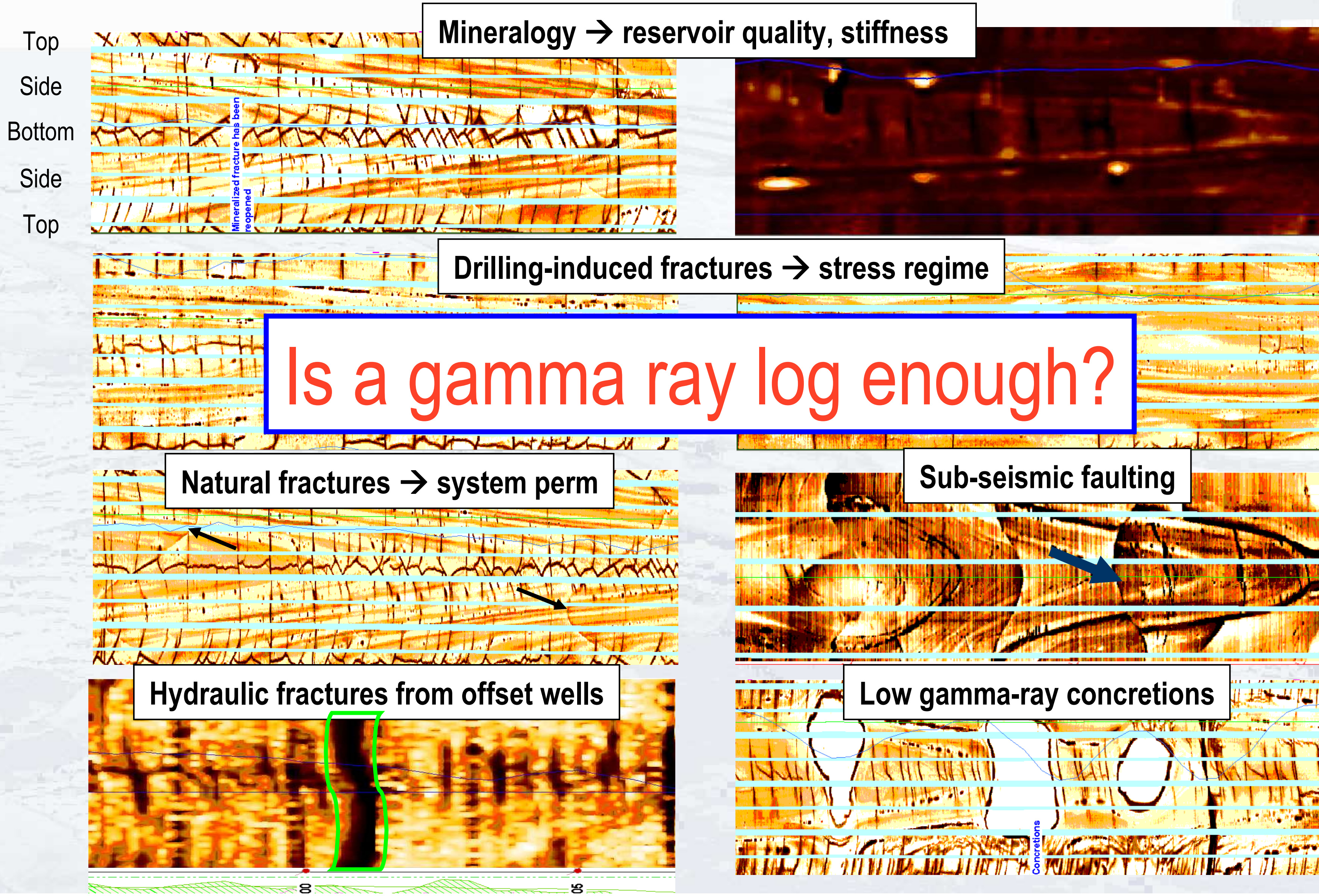
Wrap Up: Completion Planning/Prediction Summary
Variable Characteristics = Variable Treatments



Conclusions

- ✓ Geochemically-enhanced formation evaluation, advanced sonic measurements and/or borehole image analysis optimize horizontal well placement
- ✓ Borehole image and/or advanced sonic analyses define local stress regime and determine the optimal horizontal well azimuth
- ✓ Borehole image analysis can optimize the completion design

Oklahoma Gas Shales

Thank You!

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