

Stress vs. Strain Understandings and Misconceptions in their Application to Hydraulic Fracturing*

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Conclusions

- Measure what changes
- Start with a Road Map
- Natural fractures are rarely predicted.
 - Measure the 2nd and 3rd order curvature to identify local differential strain
 - 2nd and 3rd order complexity is sub-resolution of 3D Seismic
 - Identify the opportunity at hand; not all stages are equal
- Distribute properties that do not change
 - Lithofacies, Mechanical Properties
- Measure completion effectiveness
 - 80%+ in one stage? One stage away from a dry hole?
 - Retain connection to the completion
 - Compare results to your Road Map

Curvature is complex in faulted horizons.

Defining the mechanical unit to generate stress values at present is observed only in whole core.

Can geologic strain relax?

Reference

Ramsey, J.C., 1967, Folding and Fracturing of Rocks: McGraw-Hill, New York, 568 p.

Stress vs. Strain

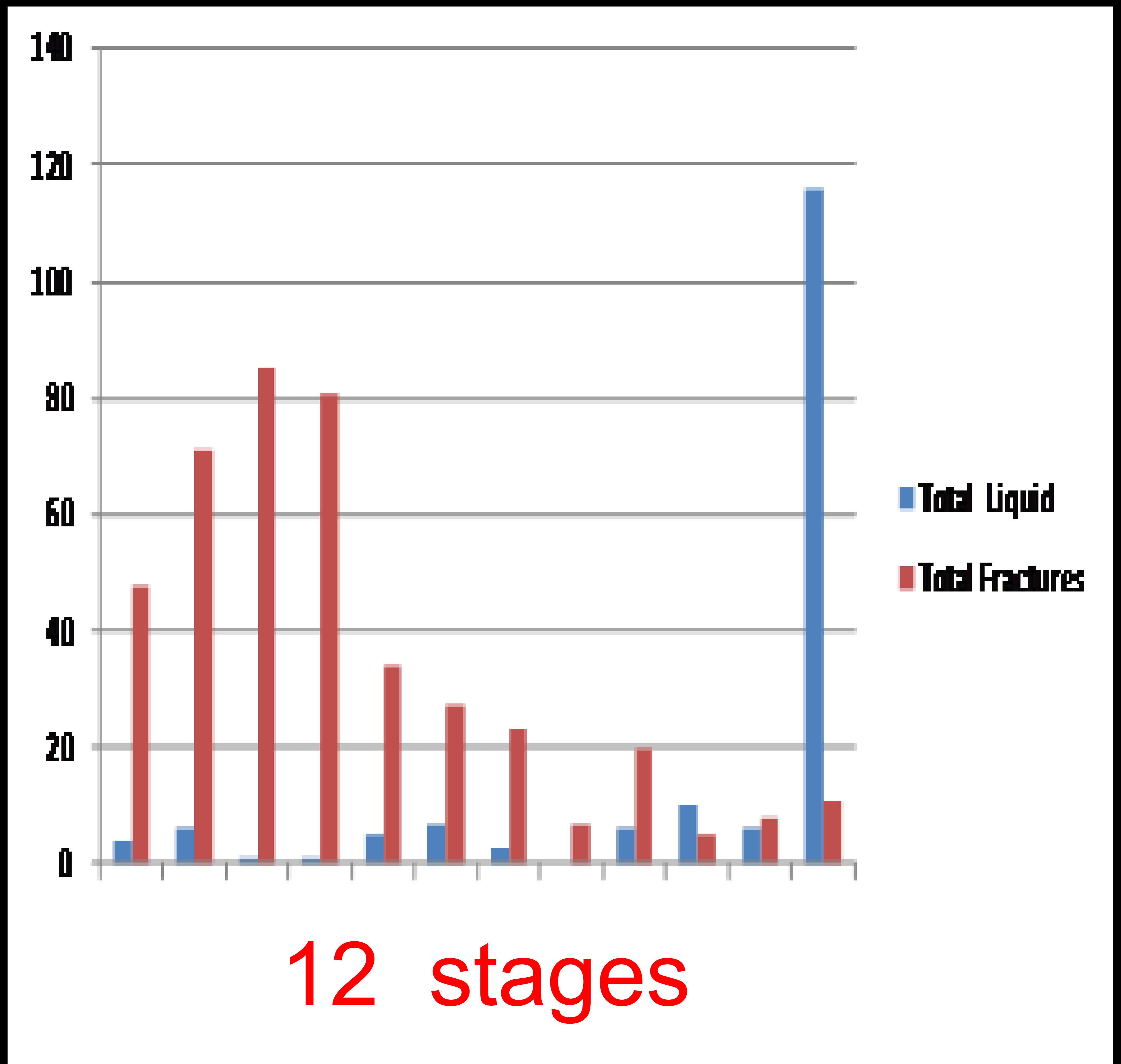
Understandings and Misconceptions in their Application to Hydraulic Fracturing

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Measuring “Stress”

Why are Mechanical Properties, Stress and Strain Important?

- Results: 125 horizontal production logs
- Multiple shale plays: ~ 1/3 perforation clusters contribute none or trace amounts to production
- Generating significant surface area is required
- Retaining the hard fought complexity connection to the wellbore



Is this a Problem?
Or , is this Opportunity?



- Most E&Ps are in the early stages of shooting and analyzing 3D seismic.
- Identify faulting and fracturing.
- When establishing leaseholds, E&Ps have consulted existing vertical well data, formation thickness, and resistivity, among other factors, and may target anticlinal structures in the hope of encountering natural fractures.
- Operators with the most experience and data to consult will have a leg up on the competition and produce more consistent results earlier in the play's evolution.

The Challenge...

Initial Assumptions

- Deeper water deposition implies simplified geological influence.
- Lack of completion complexity implies a “hydrocarbon farming” operation
- Natural fractures are required

Recent Understandings

- Structural complexity is high. Faults grabens, half grabens, longitudinally rotated fault blocks, transverse ramp and relay structures. These structures may generate significant local strain.
- Production results between wells and profile within a single well are highly variable
- Stimulation surface area may not remain connected to the borehole due to local strain

SPE: Horizontal Well Completions in North America Shales

"Data-Calibrated Optimization"

- **Best Practices - Legacy Shale, High Pressure, High Temperature, Permian Basin and Mid-Continent, Light Tight Oil Shale, Appalachian, Canadian**
 - *Well Performance Analysis*
 - *Multi-Method Microseismic*
 - *Understanding Critical Characteristics and Differences in Shales*
 - *Case Histories*
 - *Brittleness, Ductility, and Geomechanics*
 - *Optimizing Completion Designs*
 - *Interpreting Uncemented Multistage Hydraulic Fracturing Completion Effectiveness, and Comparison of Cemented versus Uncemented*
 - *Formation Evaluation and Reservoir Characterization with Logging-While-Drilling (LWD)*

What was missing? A roadmap of the reservoir.....

Measure What Changes

- Pilot Holes

- Traditional reservoir properties

- ✓Porosity, hydrocarbon, barriers, mechanical properties.

- Horizontal Wells

- ✓Measure the wellbore path.

- ✓Correlate the layers and their vertical reservoir properties

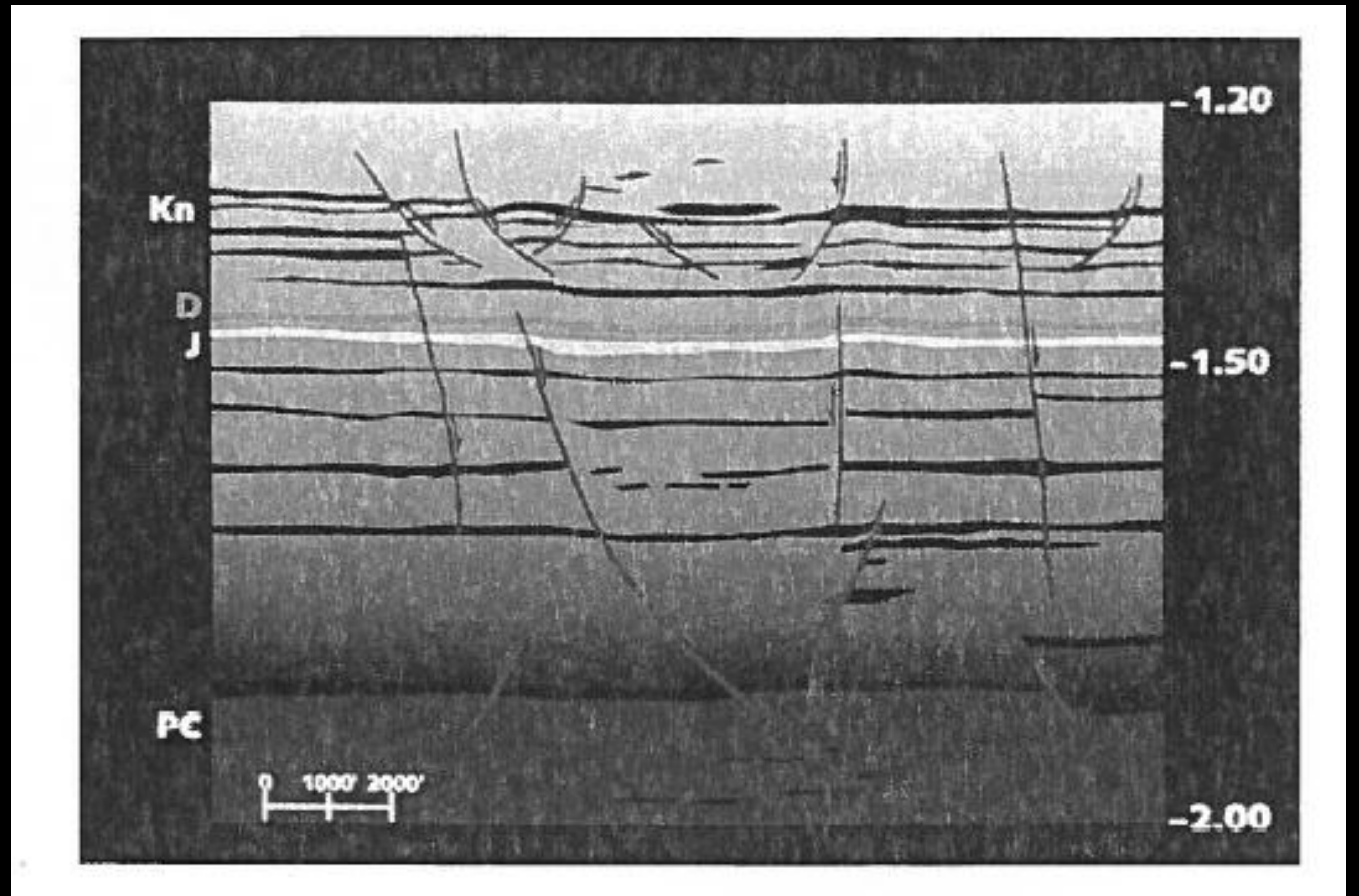
- ✓Measure the population densities, types, apertures and orientations of natural fractures and faults for each completion stage.

- ✓Identify zones of structural complexity that may have adverse reactions to retaining the completion to wellbore connection.

- ✓Measure any depositional or diagenetic variances with traditional logs if uncovered using pilot hole logs.

Geologic Strain

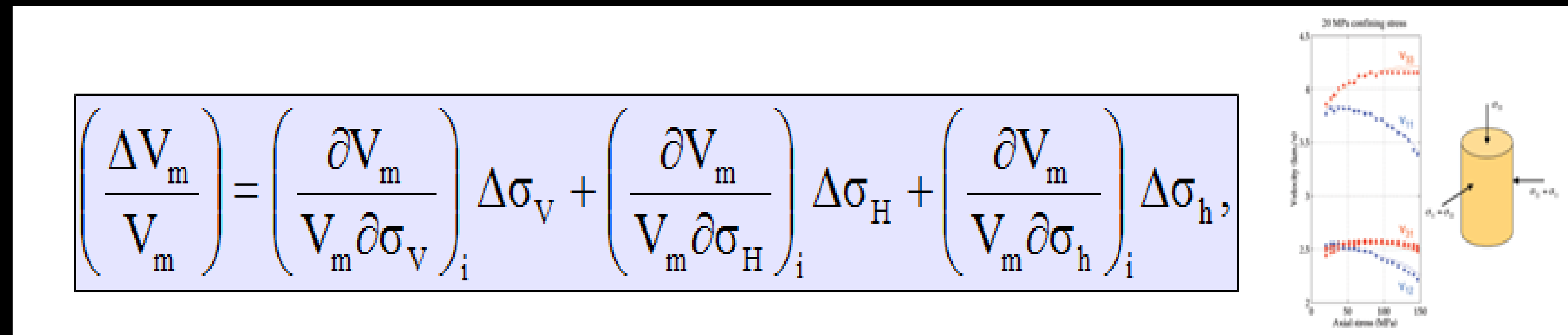
- Compressive
- Extension
- Basement Faulting
 - Horst /Graben
 - Rotated Fault Blocks
 - Relay Structures
- Geologic Uplift
- Plate Tectonics



From Sonnenberg

Quantify the Magnitude of Stress

- Needed for stress-sensitive rocks, (fractures, tectonic loads)



- Problem: “Acoustic measurements do not measure any change in matrix velocity vs. stress in most shales. Rather, they rely on fracture anisotropy.” T. Bratton
- Leaving the question : What about facies that have deformed but not exceeded rock strength and have formed natural fractures?

Structural Deformation

Natural Fractures:

Exceeding the rock strength.

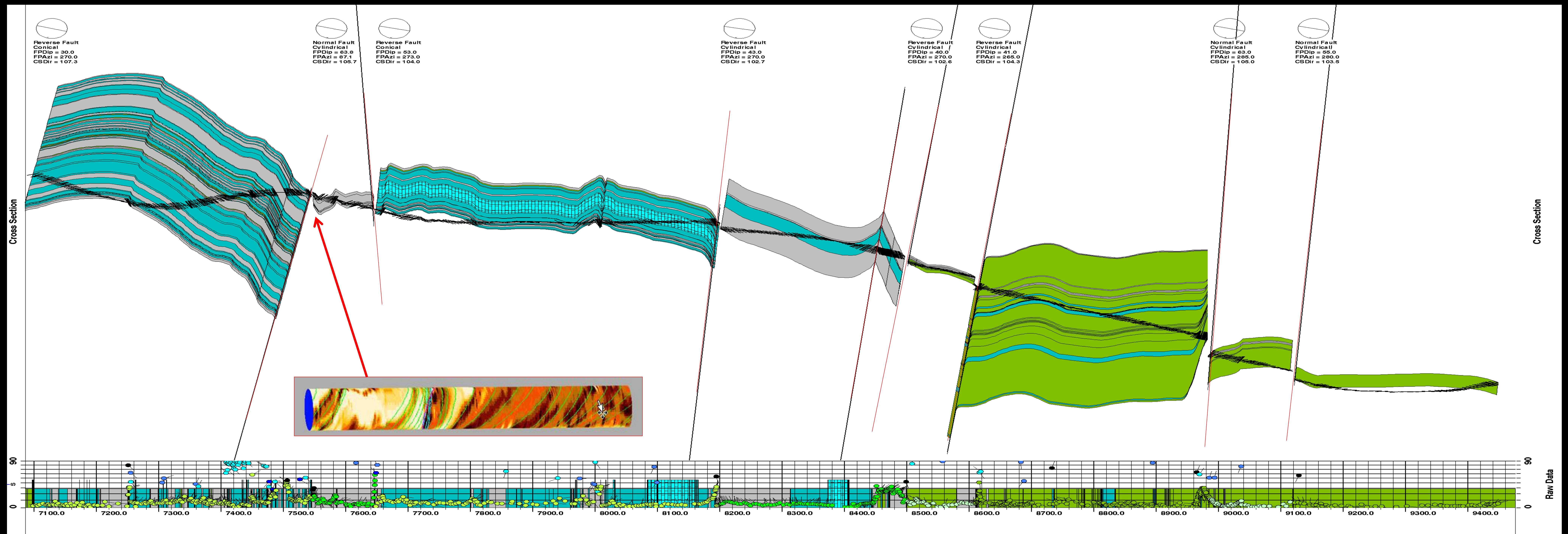
Curvature:

Generating Local
Differential Strain

Differential Strain:

relative change in size
or shape that has not
exceeded rock strength
and formed fractures.

Horizontal Road Map Continued



Observations: Numerous fractures both open and mineralized, eight faults with missing section and structurally deformed bedding dip data.

Interpretations:
Structural bedding is complex

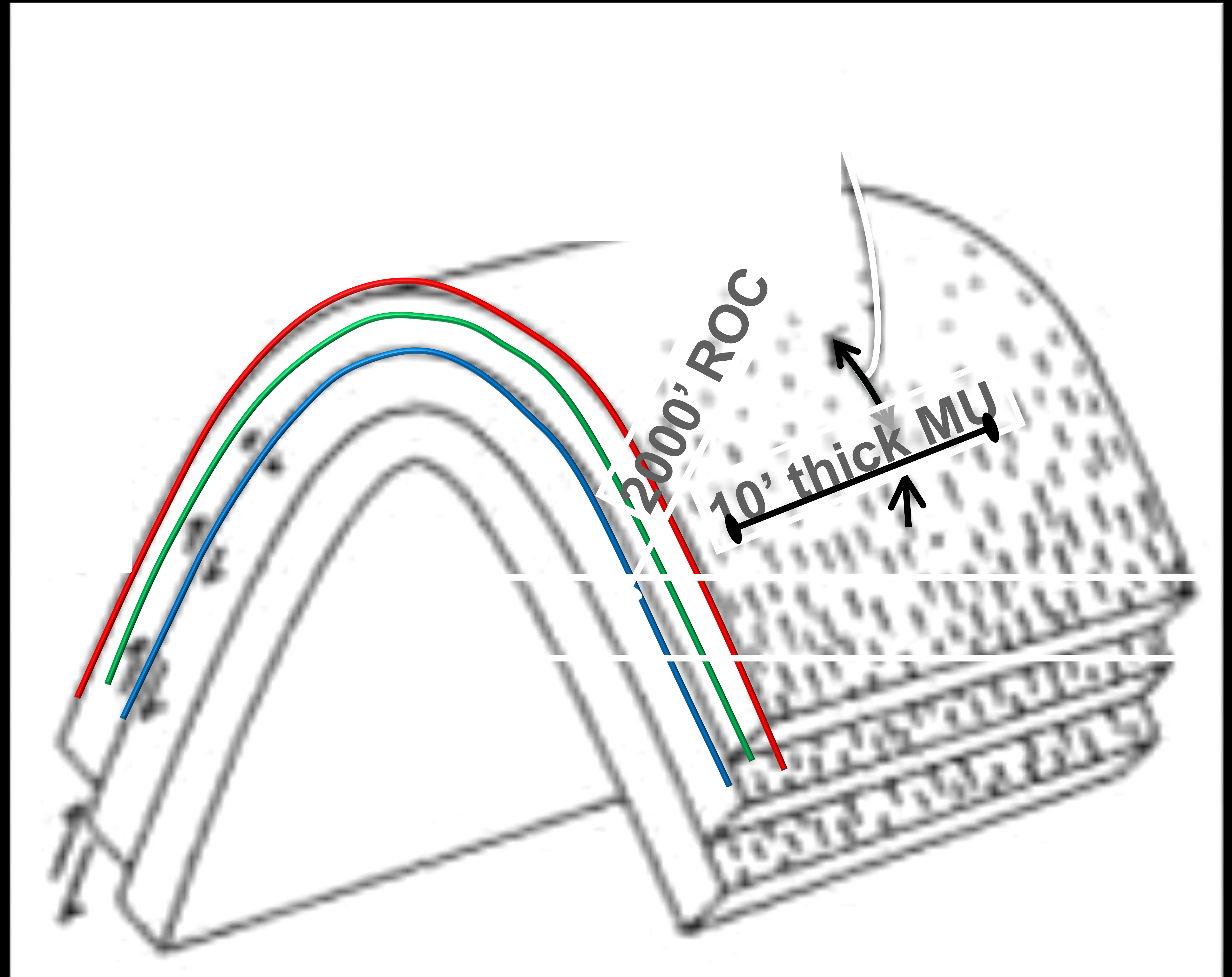
Mineralized fractures (cyan) NNW-SSE are not parallel to faults NNE-SSW.

Maximum horizontal stress from pilot hole data is WSW-ENE.

Structural Deformation – Why is it important!

Curvature → Strain

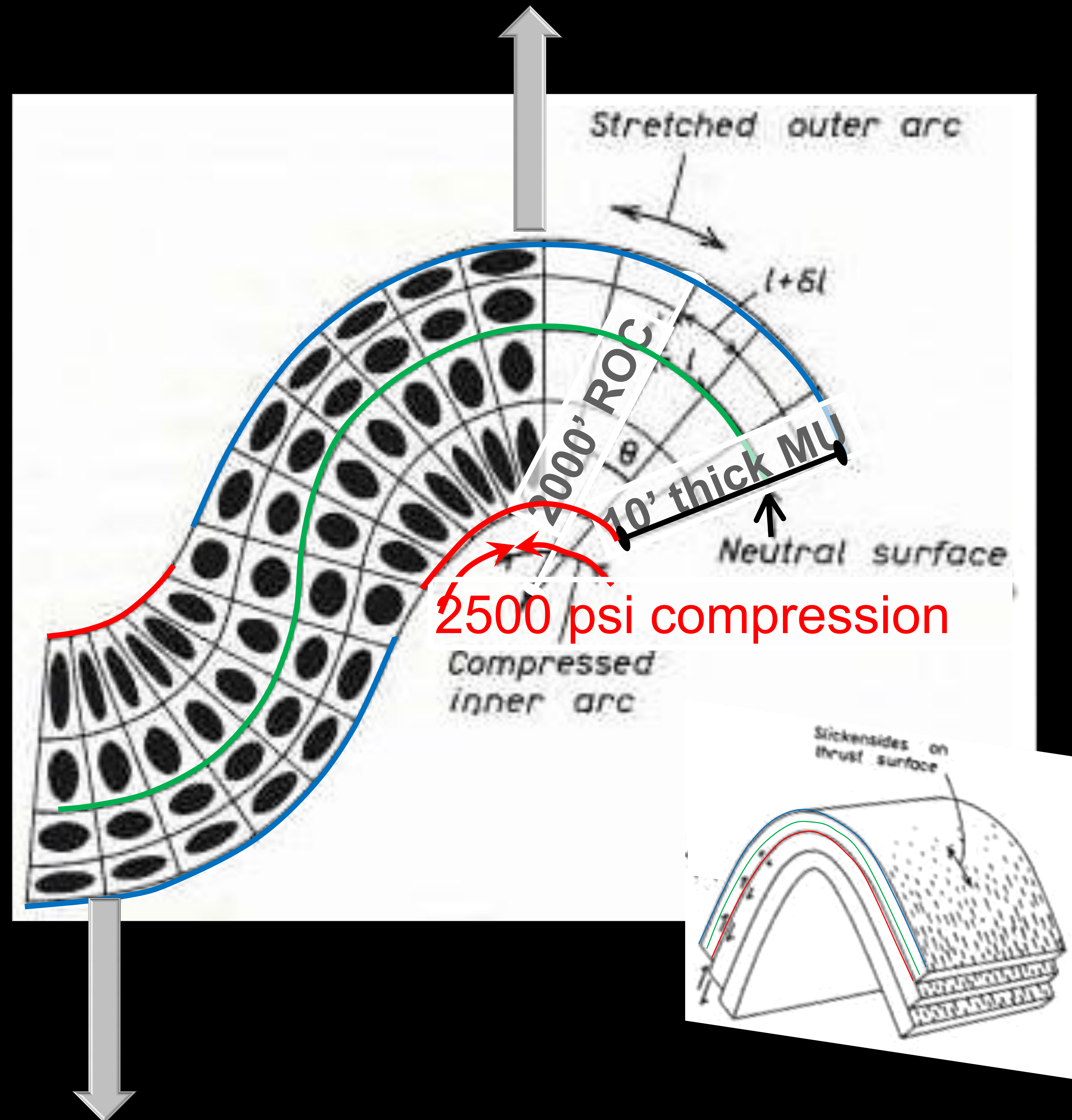
- Outer portion is “stretched” → extensional force
- Inner portion is “squeezed” → compression
- 10' thick mechanical unit and a 2000' radius of curvature generates strain ~ 2500 psi.



Structural Deformation – Why is it important!

Curvature → Strain

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Orders of Structural Curvature

1st Order:

- Vertical well tops
- No correlation to natural fractures

2nd Order:

- 3D seismic
- Some correlation to natural fractures

3rd Order

- Image displacement
- Correlation to natural fractures
- Potential to exceed rock strength and far field stress

Orders of Structural Curvature

1st Order

- Vertical
- No correction for fractures

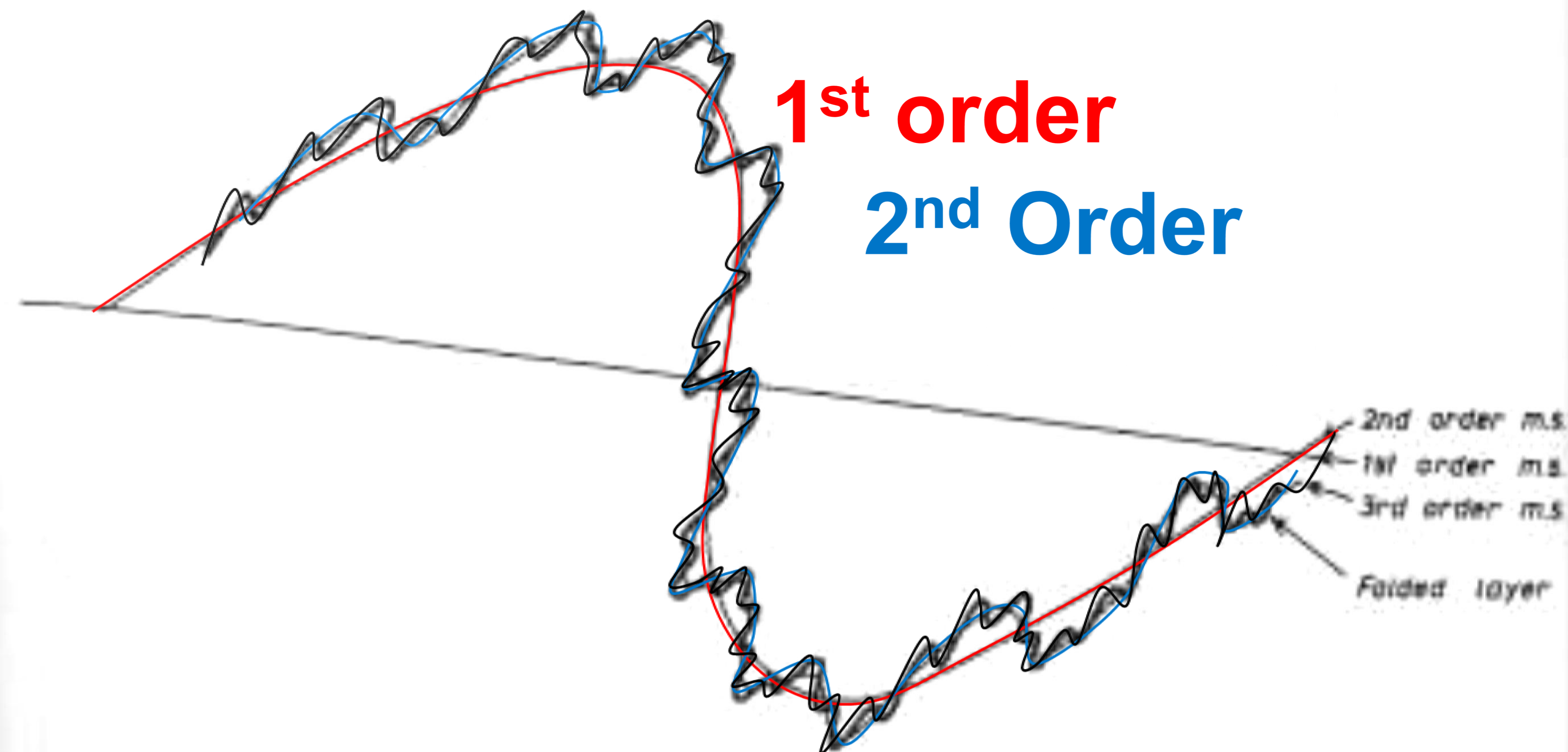


Figure 7-11

First-, second-, and third-order folds derived from the curvature of the median surfaces.

Measuring “Stress” Waveform Sonic Data

- Dt compressional and Dt Shear
 - Used to calculate Young's Modulus and Poisson's Ratio
=>Used to Calculate Layered Mechanical Facies Properties
 - Layered Mechanical properties can infer rock strength from changes in the elastic moduli of each facies
- Anisotropy
 - The azimuthal difference in velocity or energy around the borehole

Stress Indicators from Well Logs

If rock is insensitive to stress for velocity/energy, then where do the anisotropic differences originate?

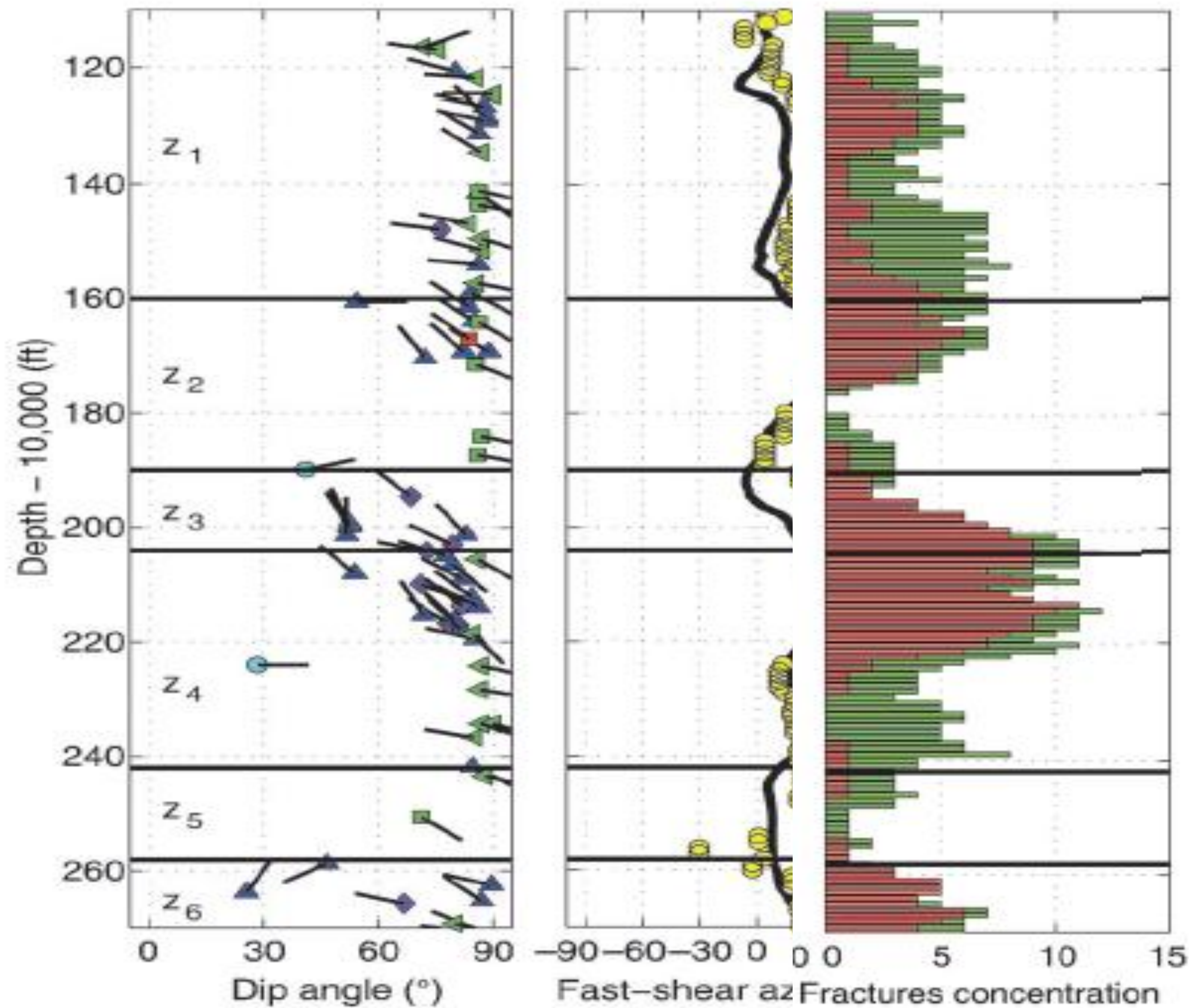
FracAniso* Forward modeling of fracture-induced sonic anisotropy using a combination of borehole image and sonic logs

Romain Prioul, Adam Donald, Randy Koepsell, Zakariae El Marzouki, and Tom Bratton

Fracture-based image interpretation can generate an anisotropy log curve and predict the orientations

- Causes of Anisotropy in Matrix challenged reservoirs?
- Natural Fractures, Induced Fractures, Breakout, Tool Eccentering

Predicting Sonic Anisotropy



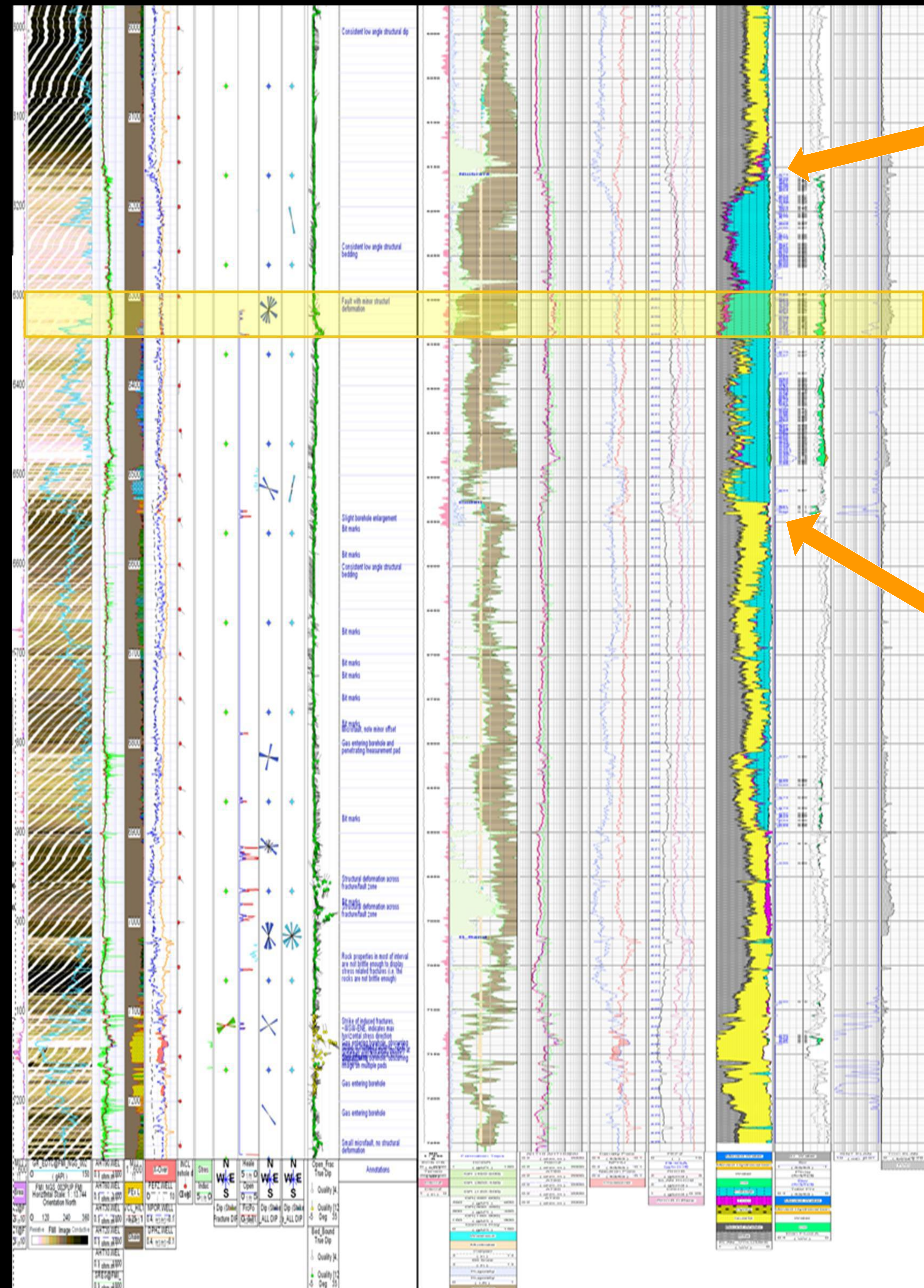
Case Study Example #1

Petrophysical Log Analysis – Pilot Hole

Traditional resistivity, density, neutron, PEF and GR.

Augmented analysis with
elemental capture.

Identifies target bench in the
reservoir with a 10' window.



Top
Niobrara

Niobrara
target

Base
Niobrara

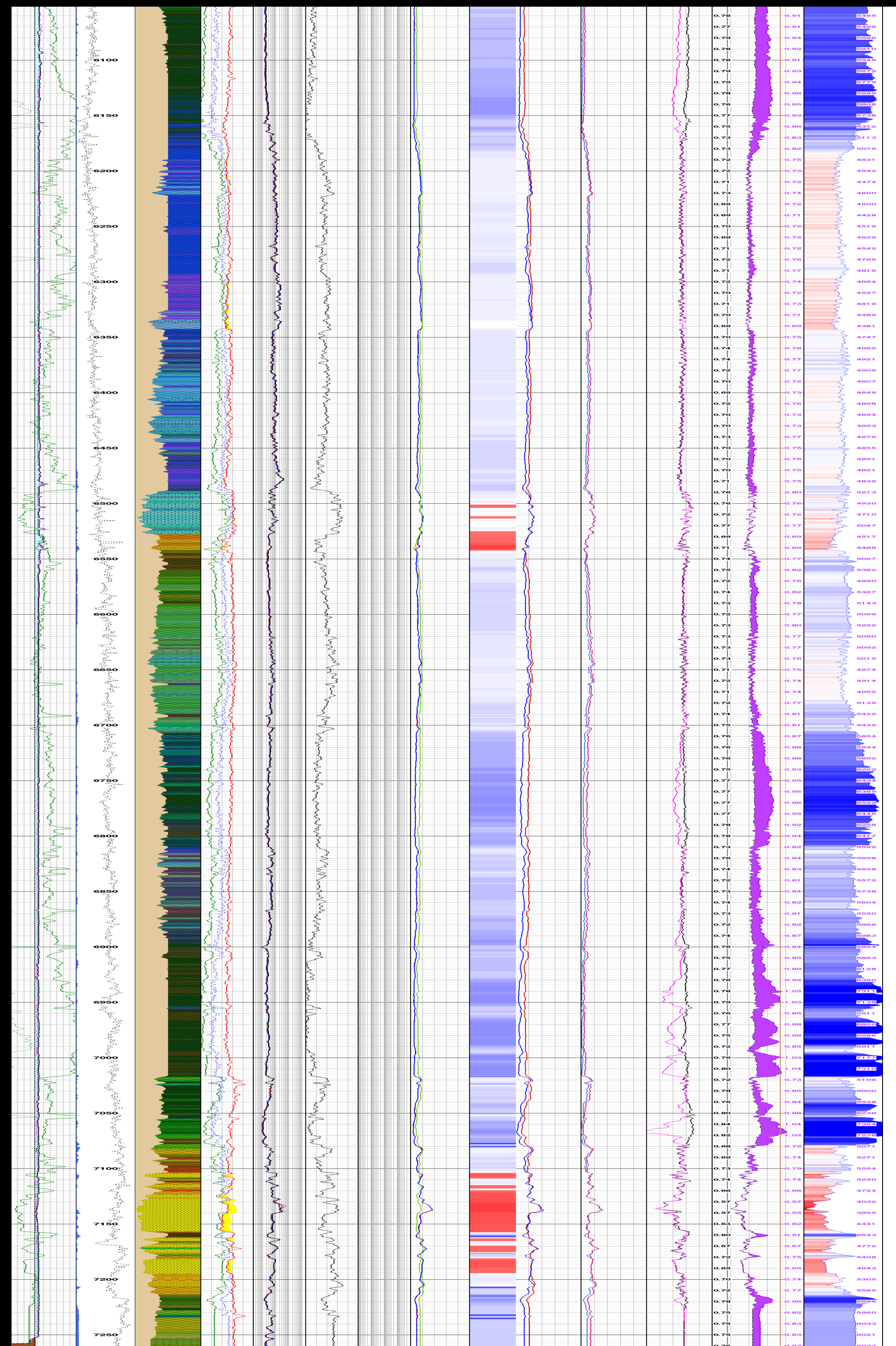
Case Study Example #1

Mechanical Properties Log– Pilot Hole

Minimum Horizontal Stress

Augmented analysis with elemental capture.

Identifies target bench in the reservoir with a 10' window.



Top
Niobrara

Niobrara target

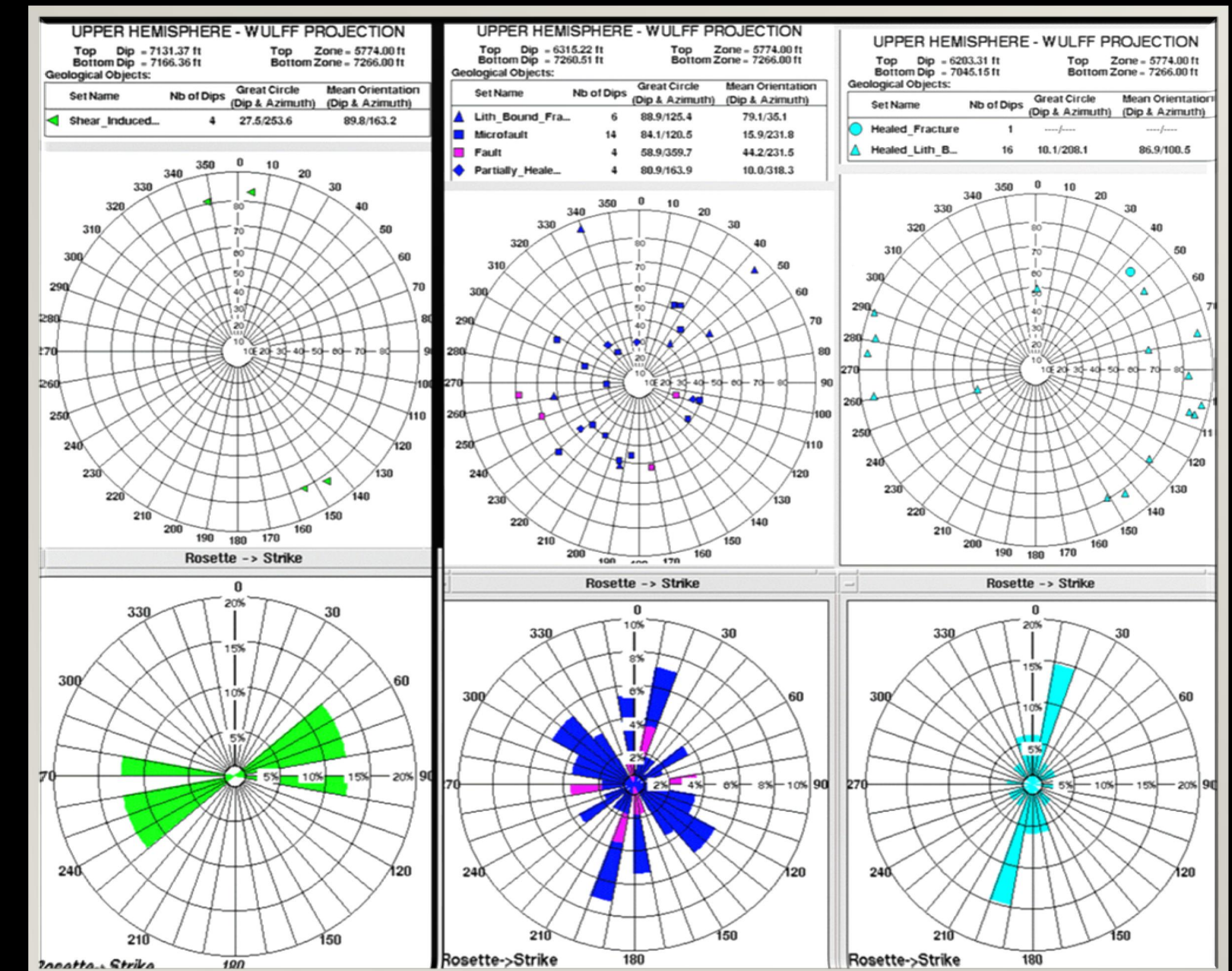
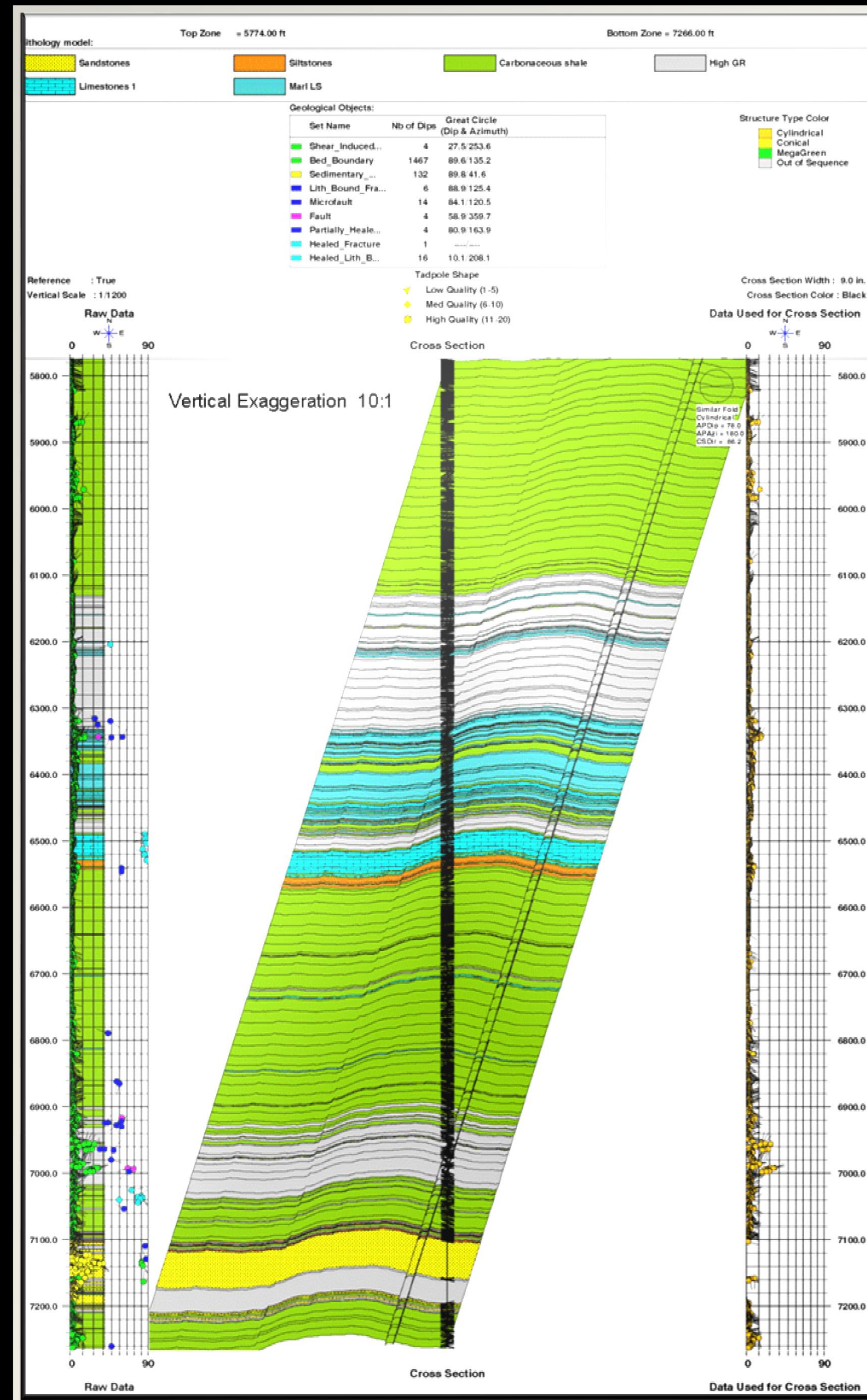


Base
Niobrara

Vertical Road Map

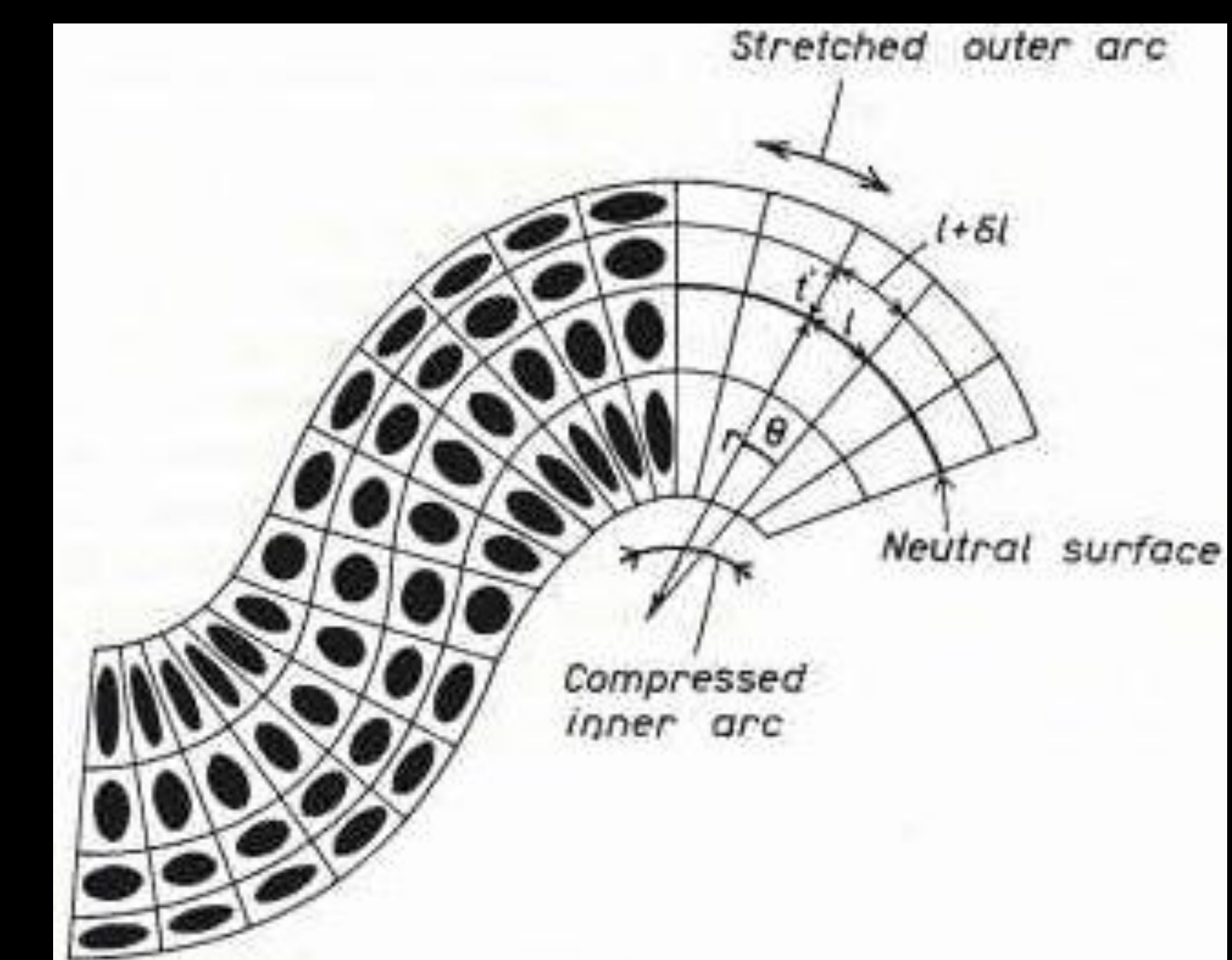
Key Findings

- 1) Structurally complex below the Niobrara. Faults below may propagate upwards.
- 2) Bottom half of Niobrara at present location is in subtle fold, with local curvature and local differential stress. Upper half of Niobrara is fault separated and in monocline structure where far field stress will dominate.
- 3) Well path somewhat mirror images structural dip.
- 4) Bedding azimuth rosette, vector plot and StrucView cross section all define the subtle structural fold and faulting.
- 5) Max horizontal stress orientation is WSW-ENE. $N53^\circ$.
- 6) Most of the open fractures are perpendicular to stress. Secondary population is mode 1 shear viable.
- 7) Most of the healed fractures are feasible for mode 1 shear complex propagation.
- 8) Some of the faults and micro-faults are viable for mode 1 complexity in hydraulic stimulation.

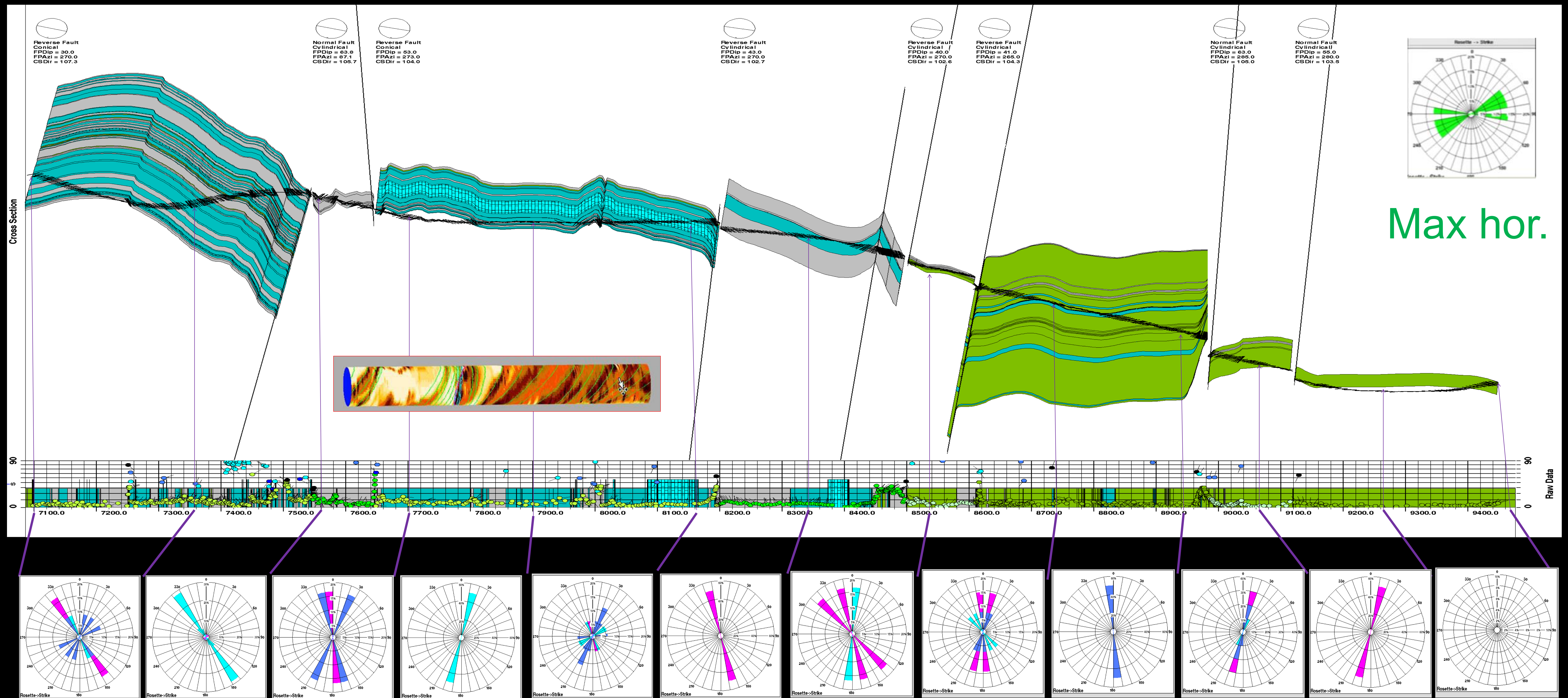


Induced Conductive Resistive

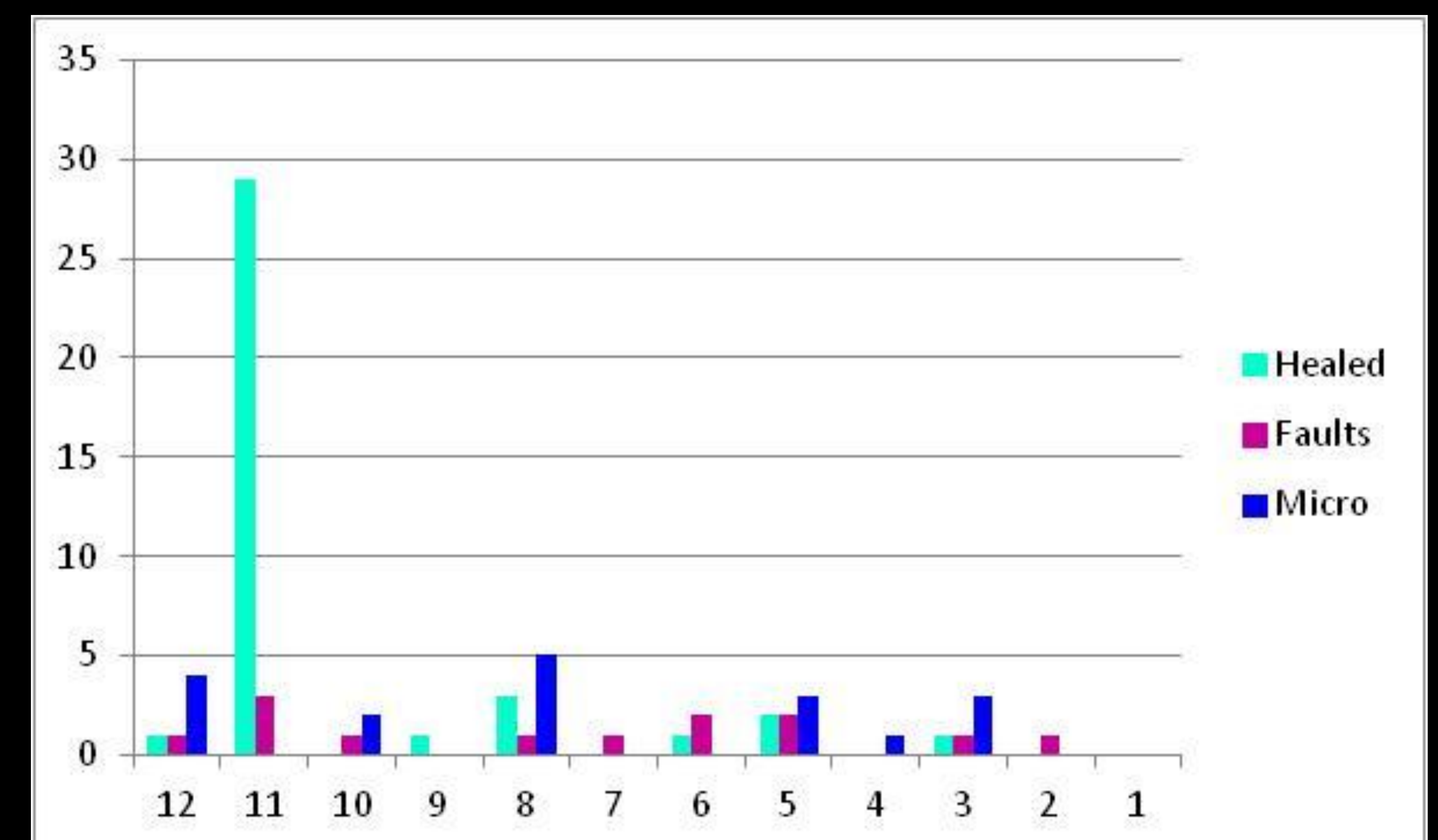
Pilot Hole Image Log



Road Map of a Horizontal Well



- Facies are derived from neural net GR and resistivity
- Curvature and fault-related strain modeled using bedding correlations
- ~200' stages modified using fracture, fault and facies changes.



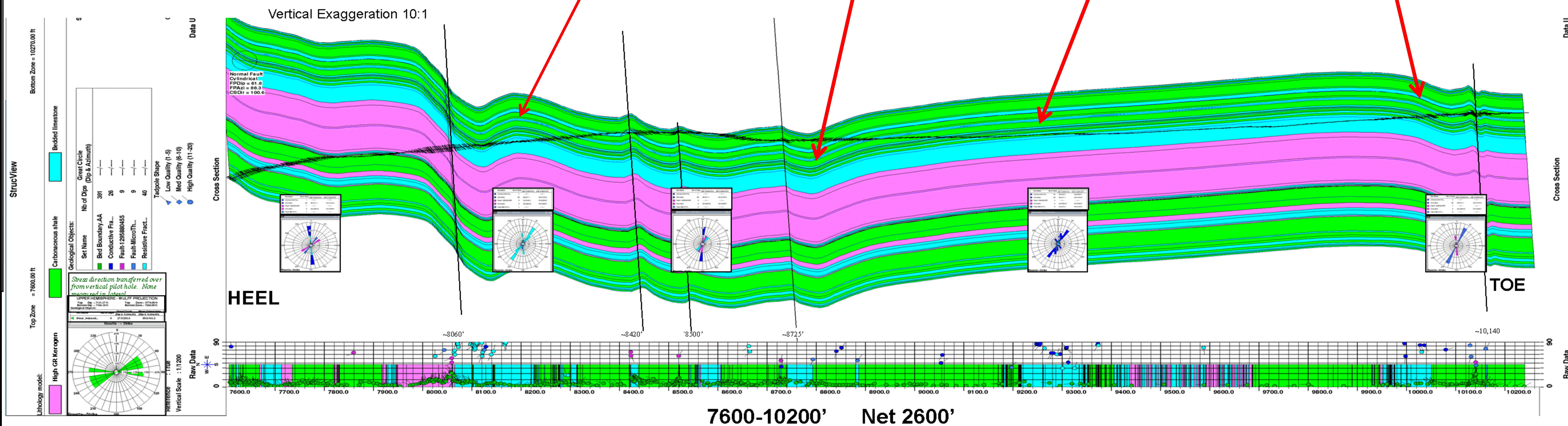
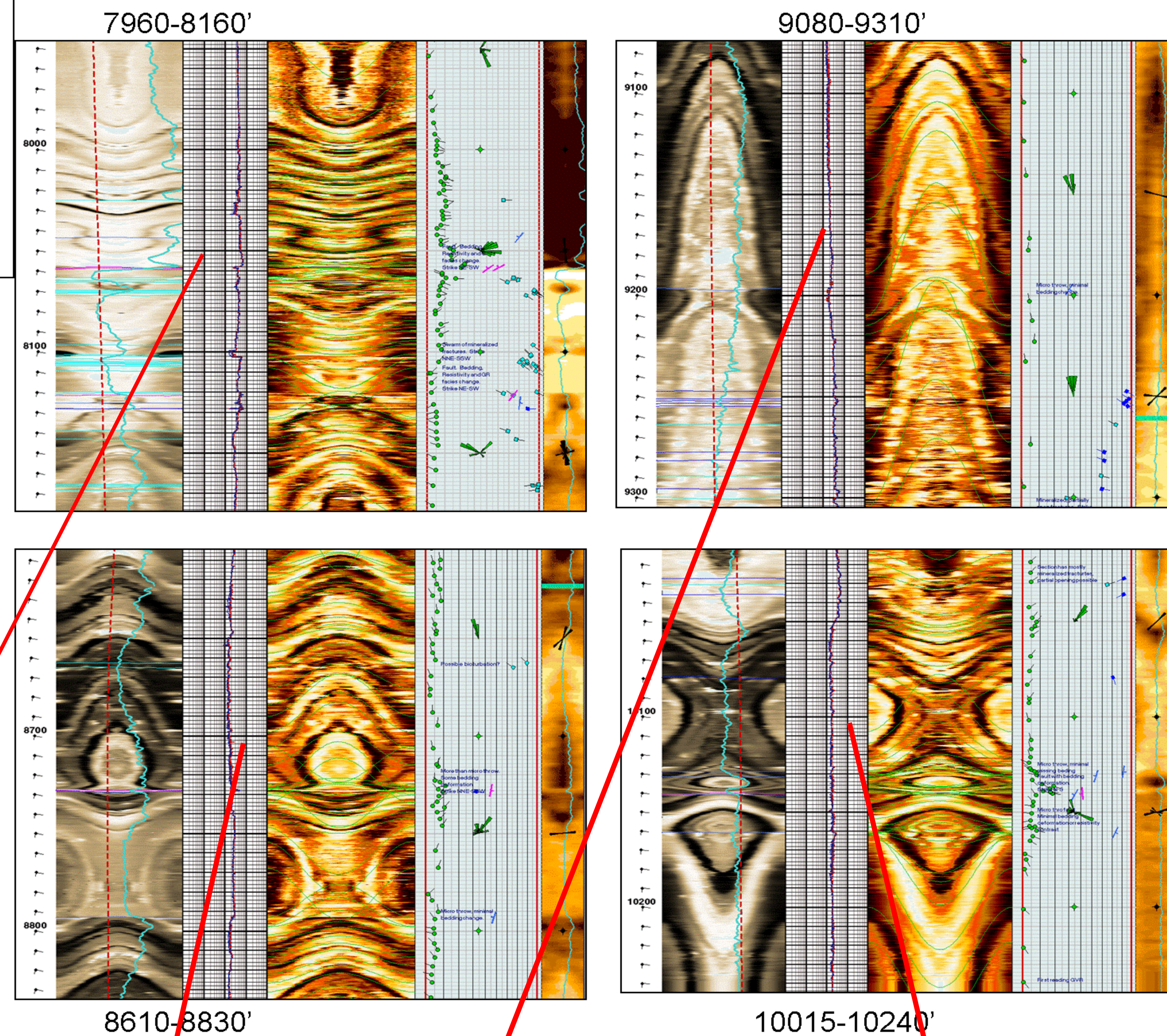
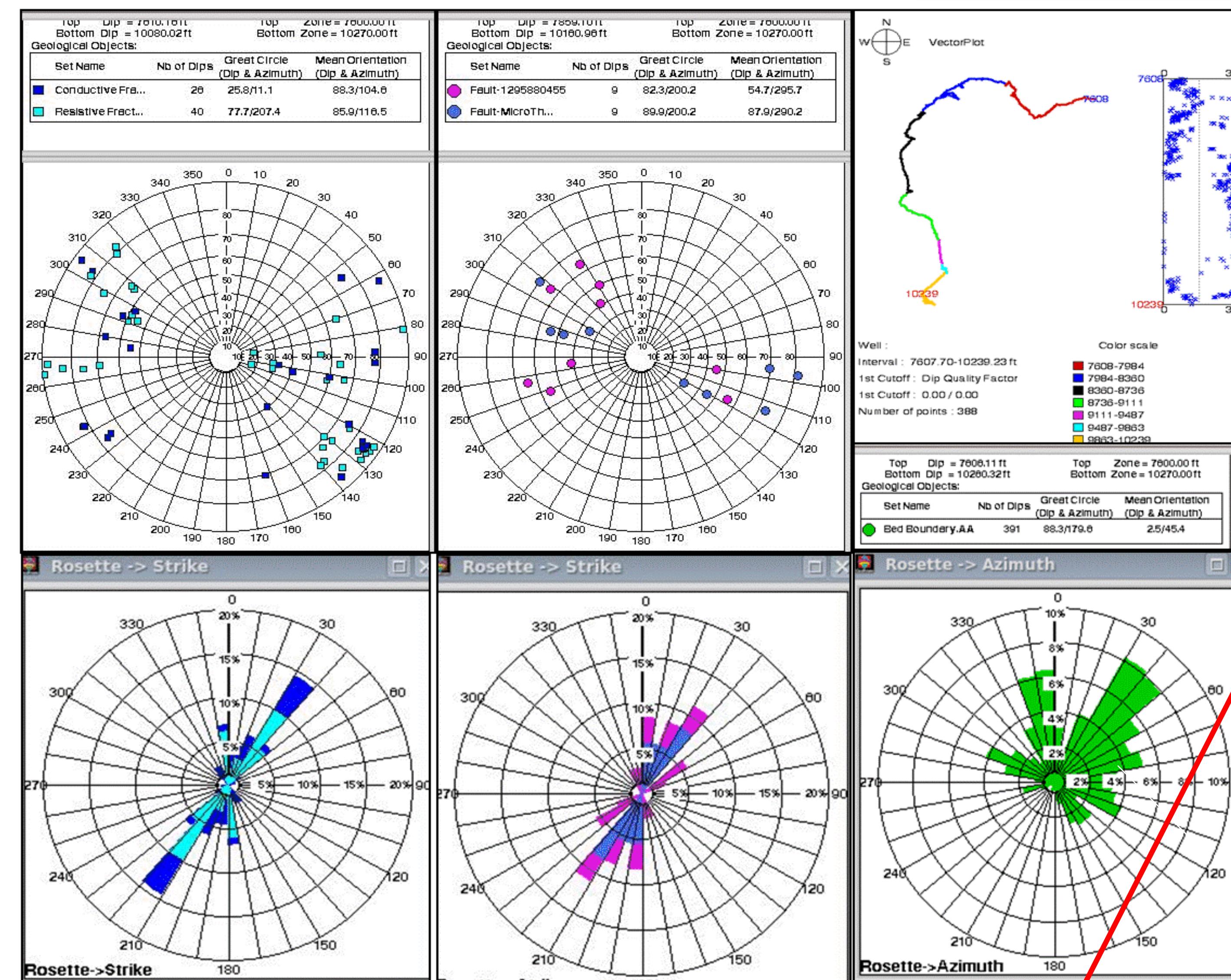
Fractures by Geologic Interval

Case Study #2

DJ Basin

MicroScope

SRI - Standard Resolution Image

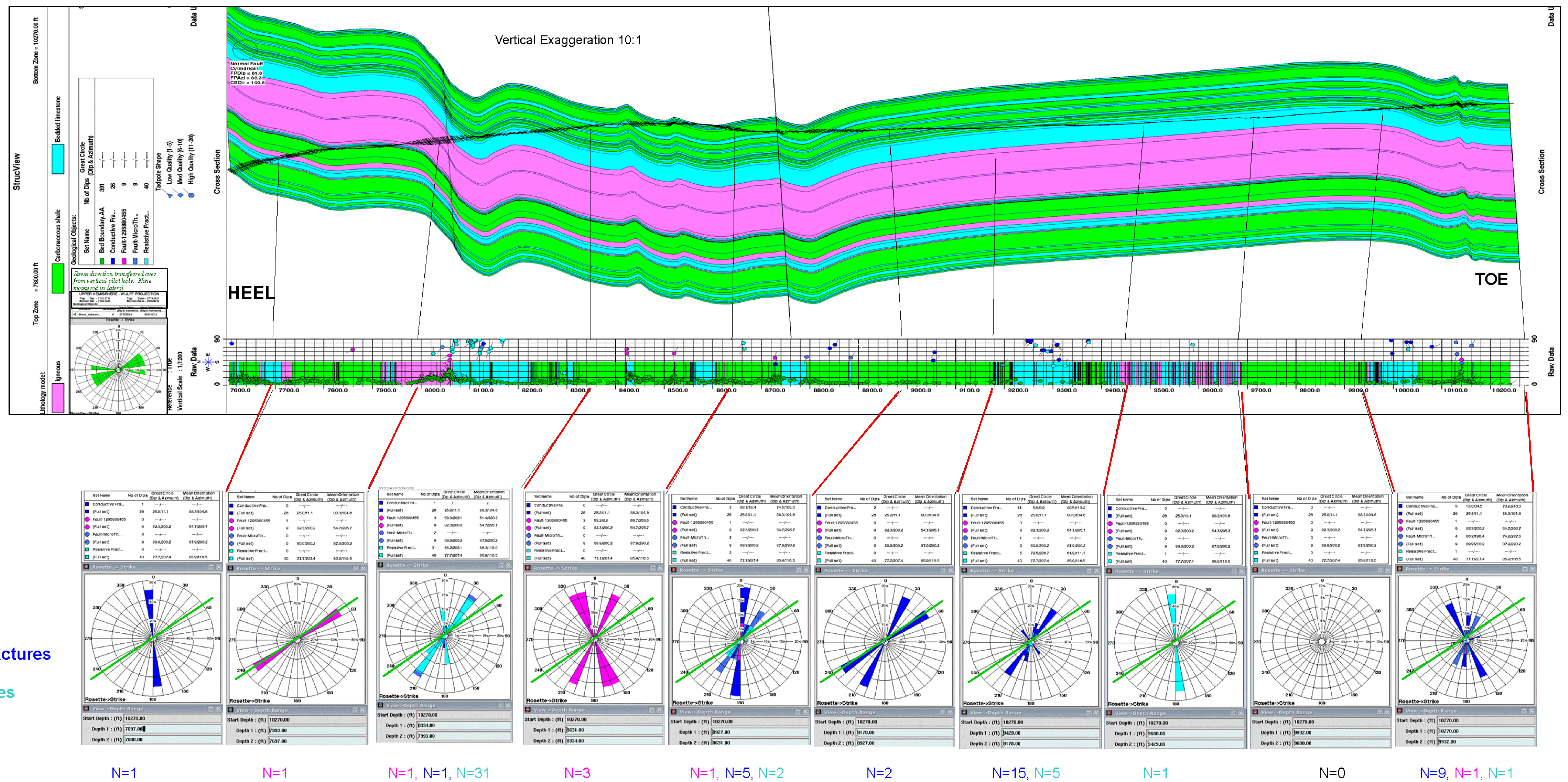


Fractures by Completion Stage

UHRI Case Study #2

Stereonets by Packer Stage: **Conductive Fractures**, **Faults**, **Healed Fractures**

Induced fracture stress orientation from vertical pilot hole FMI transposed onto natural fracture strike rosettes to understand the opportunity for parallel, perpendicular or shear by stage.



Conductive Fractures
Faults
Healed Fractures

Conclusions

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- **2 DISTRIBUTE PROPERTIES THAT DO NOT CHANGE**
 - Lithofacies, Mechanical Properties
- **3 MEASURE COMPLETION EFFECTIVENESS**
 - 80%+ in one stage? One stage away from a dry hole?
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Caveats

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Defining the mechanical unit to generate stress values at present is observed only in whole core

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Questions

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