The Importance of Stress and Fractures in Hydrofracturing and Stimulation Performance: A Geomechanics Overview*

Daniel Moos[1]

Search and Discovery Article #80255 (2012)**
Posted September 24, 2012

*Adapted from oral presentation at Geosciences Technology Workshop, Hydraulic Fracturing, Golden, Colorado, August 13-16, 2012

[1]Baker Hughes Inc., Palo Alto, CA (daniel.moos@bakerhughes.com)

Abstract / Summary

This article discusses the role of geomechanics in answering some of the key questions surrounding stimulation of shale plays and highlights some of the issues that a geomechanical analysis can help to address related to designing, conducting, monitoring, and predicting the results of stimulation. It also discusses some of the unanswered questions, for example, the relationship between the locations of microseismic events and the shape and size of the connected stimulated fracture network.

Study Results

- Low stress anisotropy.
- A single well developed, subparallel joint set.
- Narrow microseismic clouds were predicted and subsequently observed.
- Breakdown occurred a pre-existing fractures, and propagation occurred along those planes.
- Packers nucleated breakdown in some cases.
- Early production was best correlated to occurrence of pre-existing joint swarms.
- Frac from hard, quartz-rich units extends into adjacent TOC zones and modifies completion geometry to target joints.

- Operational success requires knowing both in situ stress and natural fracture, fault, and bedding patterns, and acting on that knowledge.
- Elastic properties are worth knowing, but not because they make good stress predictors.
- Hydraulically induced fractures can be contained by elastic properties contrasts, laminated bedding, or weak natural fractures.
- "Hydrofrac orientation" may not be a good predictor of stress orientation.

- Uncemented wells can break down due to stress, by opening transverse weak planes, or at nucleation points, e.g., packers.

Selected References

Franquet, J.A., A. Mitra, D. Moos, and A. Lacazette, 2011, Integrated acoustic, minerology, and geomechanics characterization of the Huron Shale, southern West Virginia, USA: Canadian Unconventional Resource Conference, 15-17 November 2011, Alberta Canada, 14 p. SPE-148411-MS. doi:10.2118/148411-MS

Rogers, S., C. MacBeth, E. Liu, and E. Angerer, 2003, Constraining models of fractured reservoirs using seismic anisotropy maps, for improved reservoir performance and prediction: 73rd Annual International Meeting of SEG, p. 1549-1552.

Rousel, N.P., and M.M. Sharma, 2011, Strategies to minimize frac spacing and stimulate natural fractures in horizontal completions: SPE Annual Technical Conference and Exhibition, 30 October-2 November 2011, Denver, Colorado, SPE 146104-MS, 16 p. doi: 10.2118/146104-MS.

Smith, A.L., 1987, Radioactive-scale formation: Journal of Petroleum Technology, v. 39/6, p. 697-706. SPE-145849-PA. doi:10.2118/14589-PA

Soliman, M.Y., L. East and J. Augustine, 2010, Fracturing design aimed at enhancing fracture complexity: SPE EUROPEC/EAGE Annual Conference and Exhibition, 14-17 June 2010, Barcelona, Spain, SPE 130043-MS, 20 p. doi:10.2118/130043-MS.

Vassilellis, G.D., C. Li, V.K. Bust, D. Moos, and R. Cade, 2011, Shale engineering application: The MAL-145 project in West Virginia, Canadian Unconventional Resource Conference, 15-17 November 2011, Alberta Canada, 19 p. SPE-146912-MS. doi:10.2118/146912-MS

The importance of stress and fractures in hydrofracturing and stimulation performance

A Geomechanics Overview

Presented at:

Hydraulic Fracturing: New Controversies and Key Plays

AAPG GTW, Golden, CO

August 15, 2012

Daniel Moos

Baker Hughes Technology Fellow

Typical steps in optimizing NPV

1. Sweet spot detection
2. Choosing lateral position
3. Determining the shape of the connected stimulated network (CSN)
4. Choosing completion type
5. Selecting stimulation points
6. Designing the stimulation schedule
7. Predicting and optimizing production behavior

BAKER HUGHES

Questions…

- What controls hydraulic fracture growth?
  - What controls "fracability?"
  - What dictates stimulated zone orientation?
  - What factors control wellbore breakdown?
  - What type of completion is best?
- What is the best position for a lateral well? For stages along a well?
  - Should the choice be based on TOC? Flow properties? Mechanical properties? Stress?
- What dictates the shape and properties of the region affected by stimulation?
  - What do μEQs mean? What is being changed / created? What can you learn?
  - Are pre-existing fractures good or bad? What about pre-existing faults?
  - What are the risk factors for "large" triggered μEQs?
- How can you maximize production?
  - Why might "choking" a well lead to higher long-term production?
  - What about re-fracturing?

And if flaws, stress, and mechanical properties control these processes…

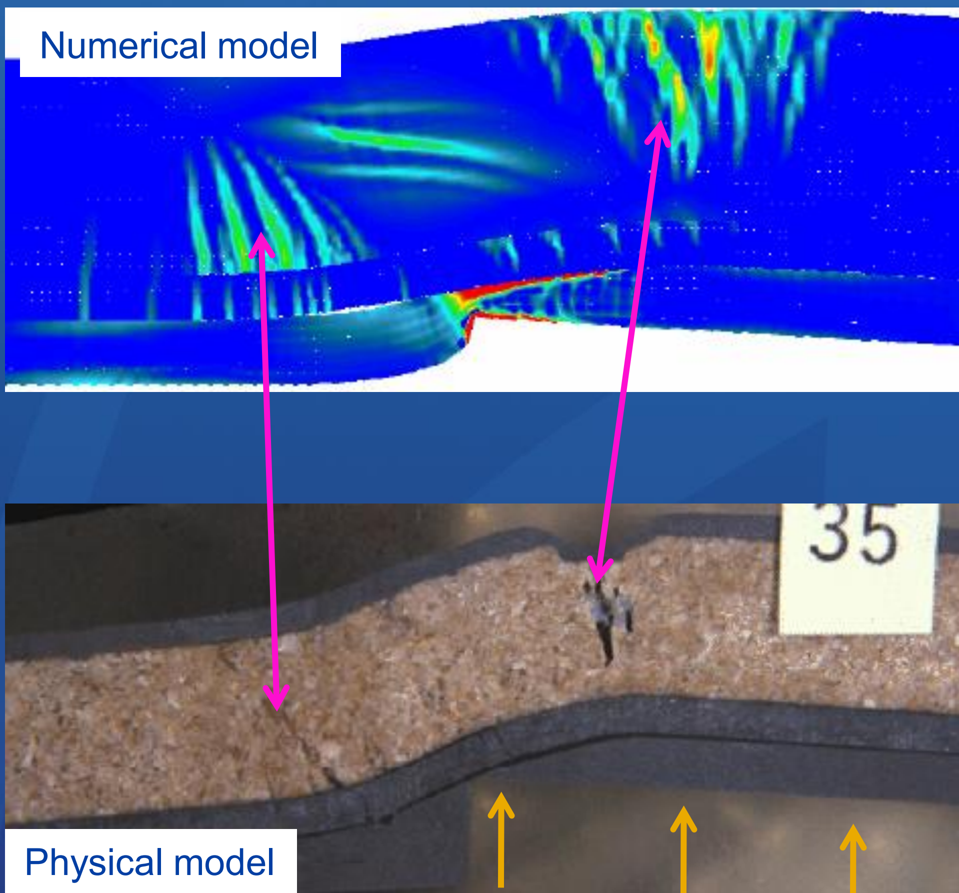
- How do you quantify stress?
- How do you identify and characterize natural fractures?
- Where they have similar effects, how can these be independently determined?
- How do you quantify mechanical properties?
- What does anisotropy mean?
  - Vertical:horizontal
  - Azimuthal

Overview

- A short definition of geomechanics and stress in the crust
- Controls on stimulation performance
  - Wellbore breakdown
  - Growth of the Hydrofrac
  - Growth of the Connected Stimulated Network (CSN)
  - Effects on production
- Determining and differentiating stress and structure
  - In situ stress
  - Natural fractures, faults, and bedding
  - Rock properties

Effects of Past Stresses

"Structural" Geomechanics



Figures courtesy H. Lewis and G. Couples, 2008

Structural modeling can determine:

- Locations and evolution of faults
- Fracture patterns
- Causative stress state

Curvature and coherence can be used to infer fracture patterns

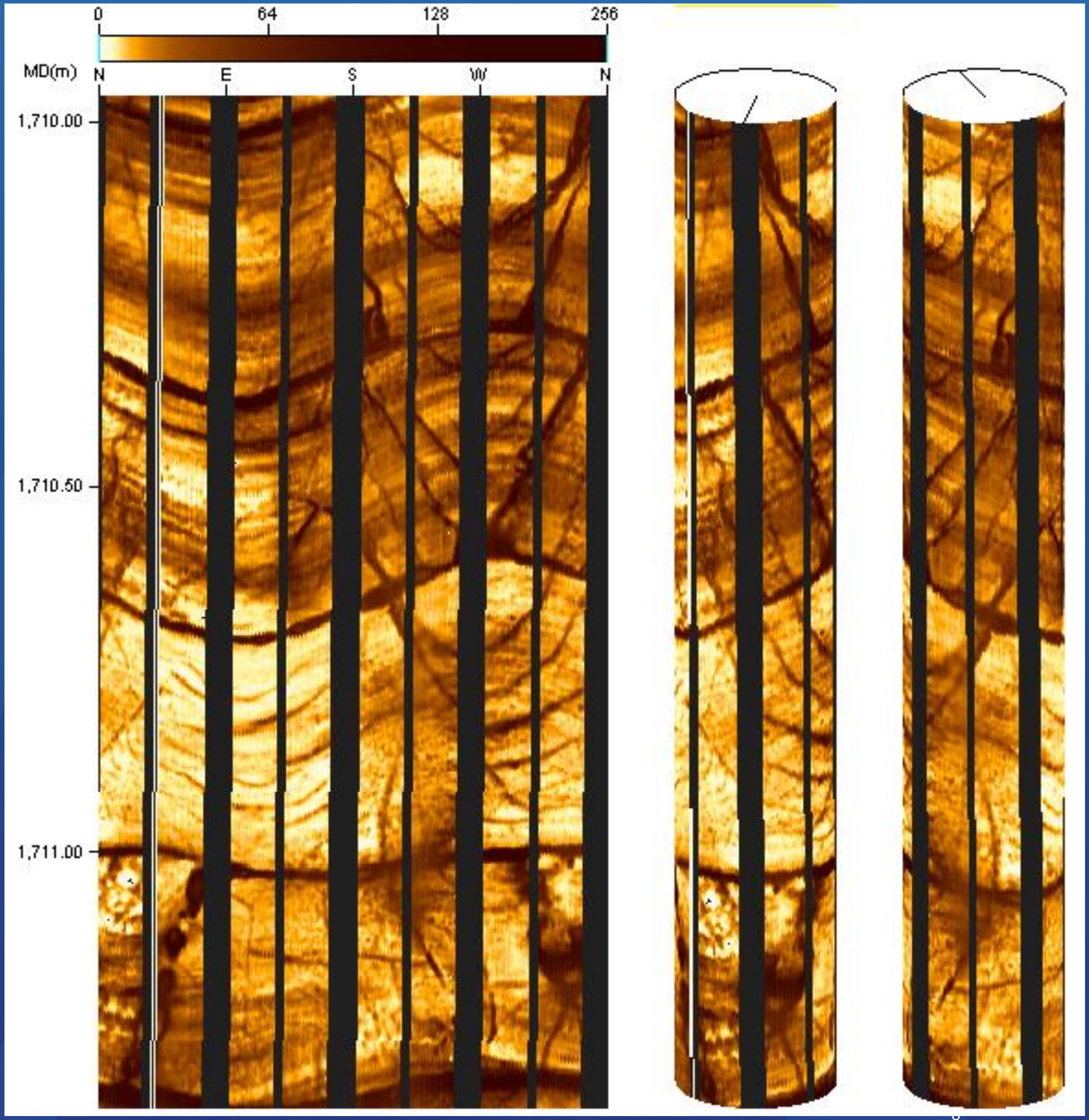
The stresses that created these structures may not still act today

It is generally impossible to predict present-day stresses from geological structure

The effect of today's stress on yesterday's structures can be non-intuitive

BAKER HUGHES

Fracture detection depends on well orientation



Fracture distribution can be derived from:

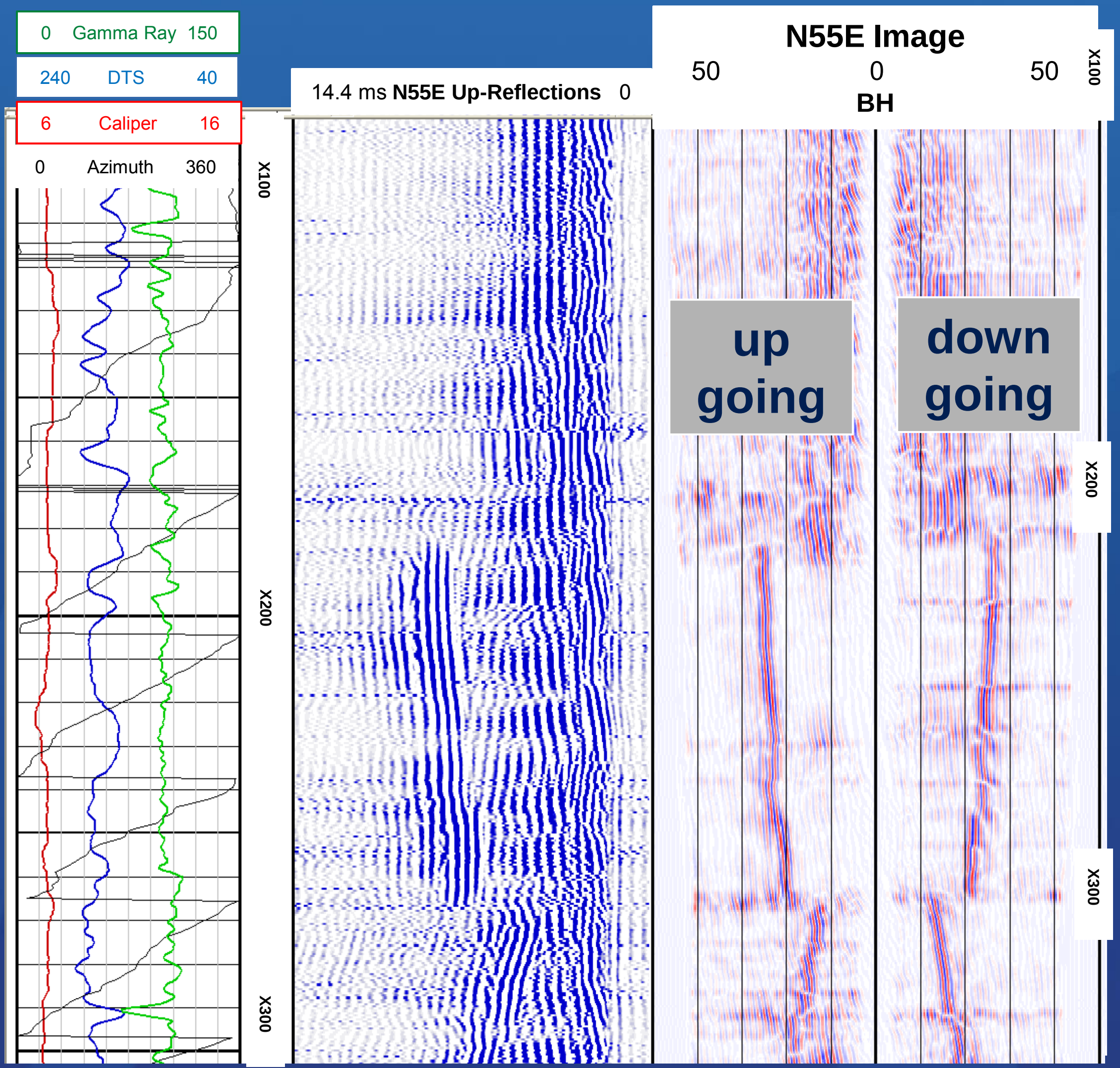
1. Core
2. Wellbore images
3. Seismic(?)

In core or wells, fracture distribution must be corrected for orientation bias*

*Fractures perpendicular to a well will be intersected more often

BAKER HUGHES

Seeing Fractures “beside” the well - Deep Shear Imaging



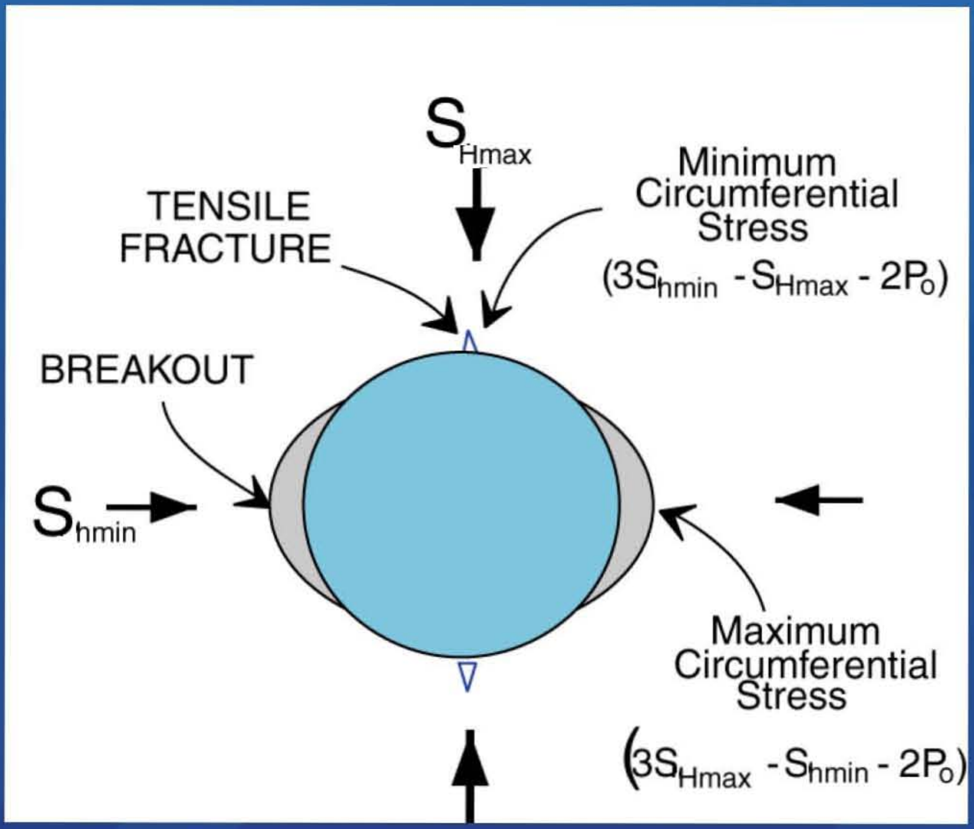
Deep shear imaging is ideal to detect fractures “beside” a well

These are the fractures that are under-sampled in image data

Not only are the fractures detectable, but also their orientation, size, and properties can be inferred

Effects of today's stresses

Stress-Induced Wellbore Failure



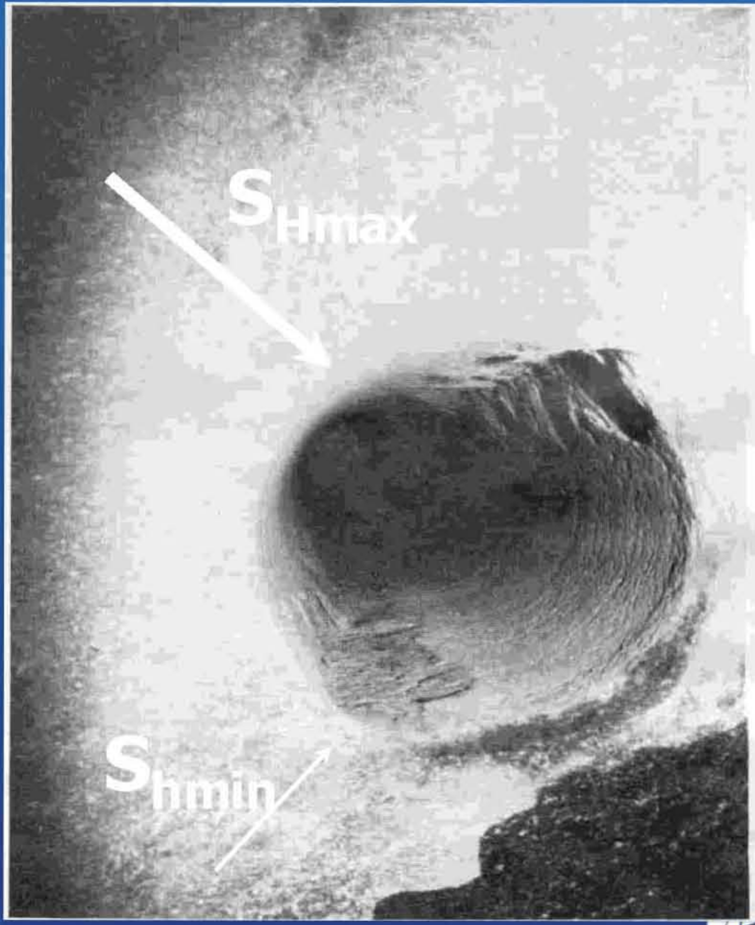


Figure 8.10 Example of wellbore breakout. (*Photo courtesy J. S. Bell, ISPG-EMR Calgary*)

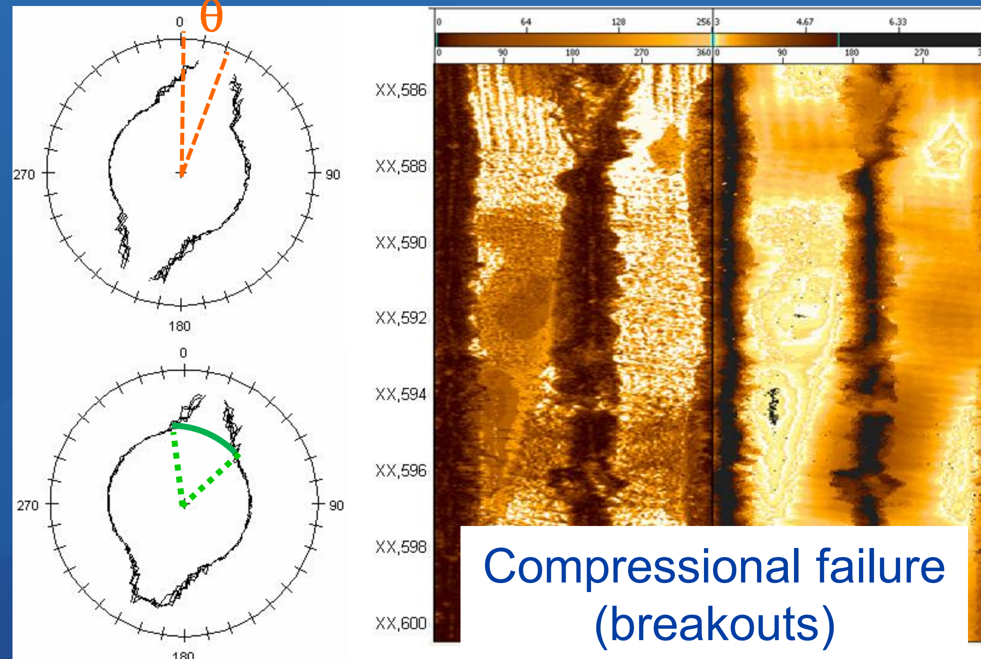
Quantifying stress magnitudes

- **Leakoff / minifrac / microfrac at several points along the well**
- **Wellbore failure using image logs**
  - Existence and widths of breakouts / tensile fractures (requires a rheological model and information about Pp and wellbore pressure)
  - Position around a deviated well / tensile fracture inclination (requires strength isotropy)
- **Acoustic moduli using cross-dipole acoustic data??????**
  - Requires differentiating stress-induced from structural anisotropy
  - Uses a lateral constraint / constant lateral strain / etc. model (requires unrealistic assumptions about how the earth behaves)
  - The alternative is non-linear elasticity and near-well modeling (requires precise information on parameters)
  - Near-well rotation of fast direction in deviated wells (new technique, US-8004932)

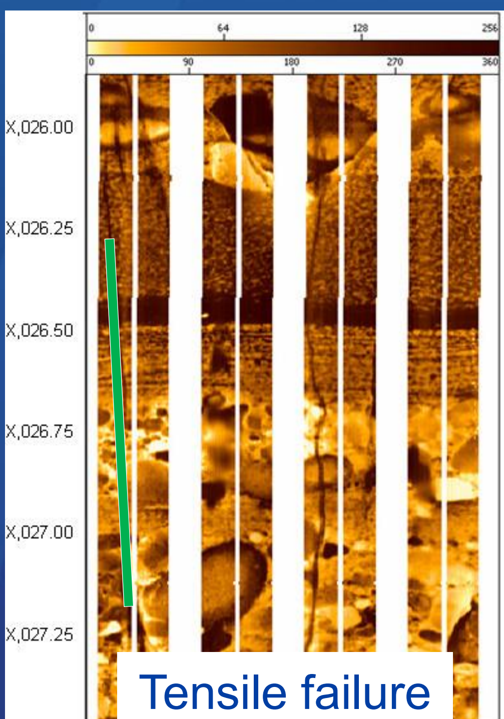
Stress from compressional and tensile failures

Breakout position ⇒ stress orientation (in deviated wells, also stress magnitude)

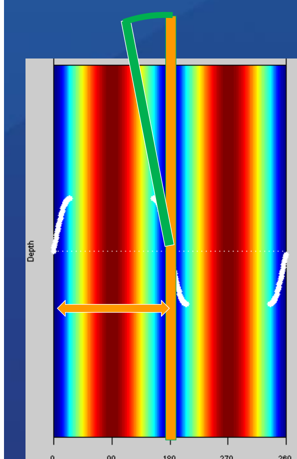
Breakout width ⇒ stress magnitude



Compressional failure (breakouts)



Tensile failure

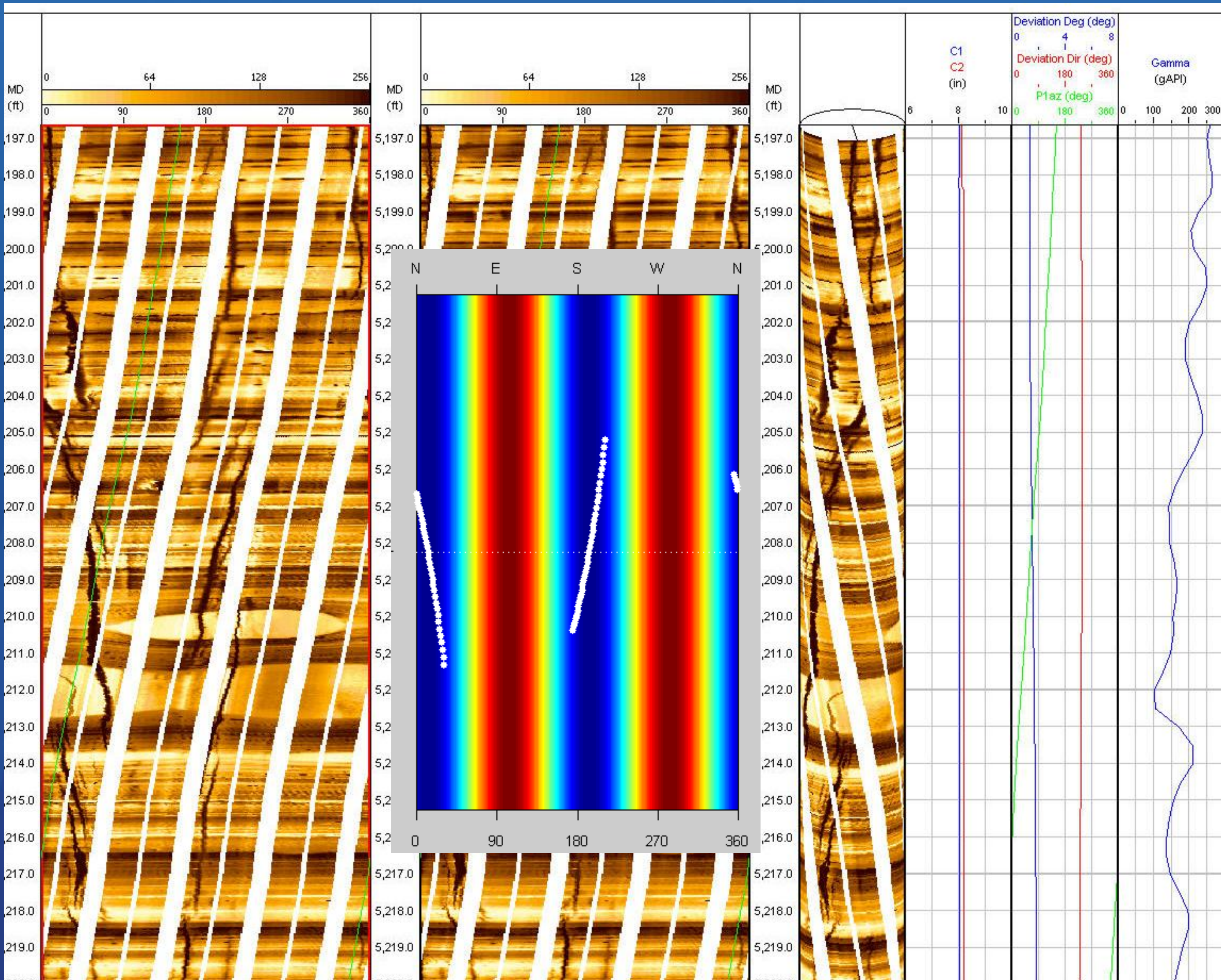


Tensile crack rotation ⇒ stress inclination, stress magnitude

Tensile crack azimuth ⇒ stress orientation (in deviated wells, also stress magnitude)

BAKER HUGHES

Inferring stress orientations and magnitudes from tensile fractures in the Barnett



Stress state:

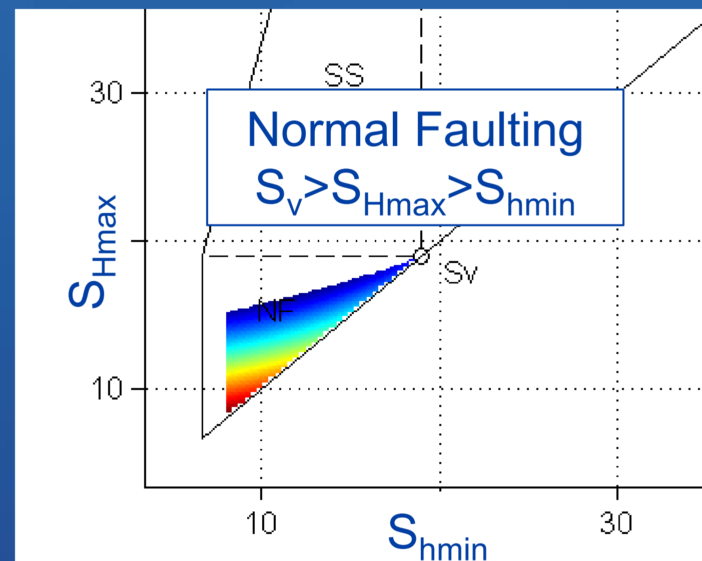
S_v=1.11 psi/ft
S_{Hmax}=0.7 psi/ft
S_{hmin}=0.6 psi/ft
P_p=0.47 psi/ft
aziSH=N13E

Using P_p 0.5 or 0.4 or S_{Hmax} 0.75 gave fractures that were too elongated

S_{Hmax} magnitude from breakouts in the lateral well

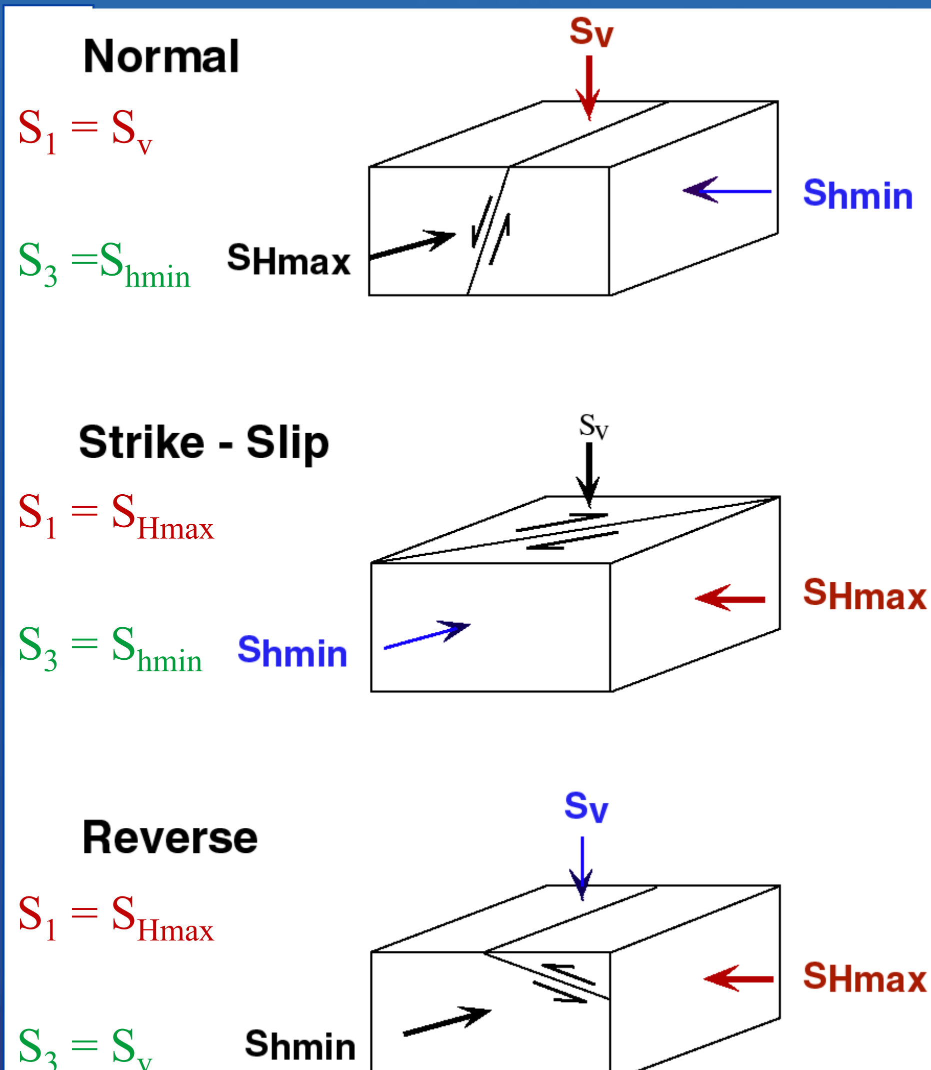
Well drilled towards S_{hmin}
Deviation angle 76

Breakouts on the sides of the well



Breakouts on the sides of a near-horizontal well require that $S_{Hmax} < S_v$

Stress Classification of Shale Plays



Shear fractures strike perpendicular to S_{hmin}
Mode I fractures vertical and parallel to S_{Hmax}

Shear fractures strike +/- 30 degrees to S_{Hmax}
Mode I fractures vertical and parallel to S_{Hmax}

Shear fractures strike parallel to S_{hmin}
Mode I fractures are horizontal

Low Stress…

Gulf Coast

Barnett…

US Northeast
US Rockies
California

Canadian Rockies

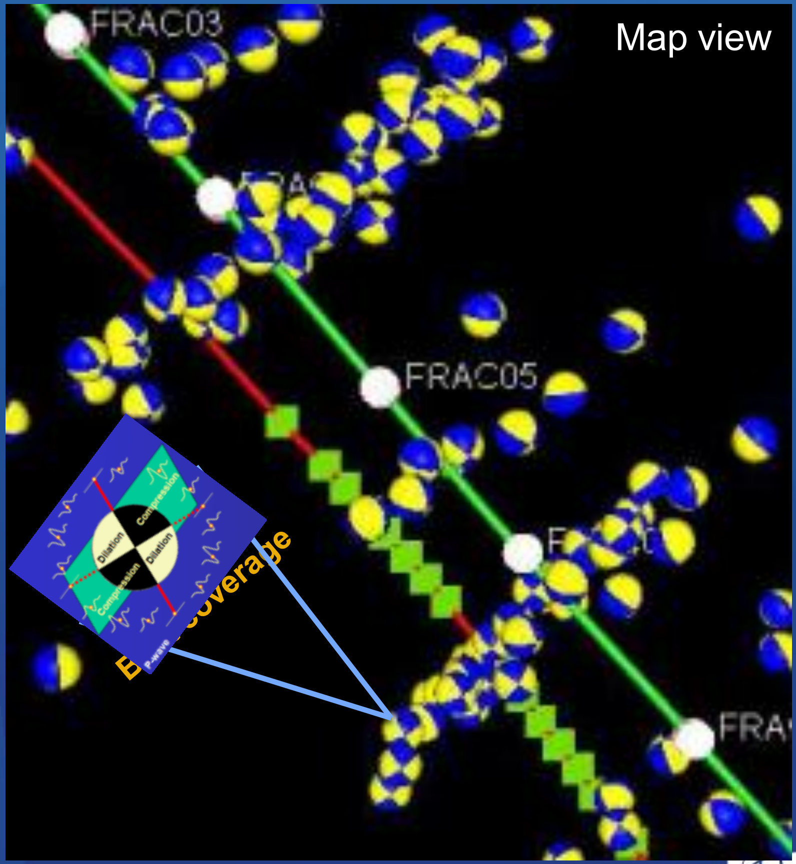
Central Australia
Shallow depths

High Stress…

Mechanisms to create a connected network

Generating an orthogonal network of hydrofracs

Creating shear slip on pre-existing fractures



BAKER HUGHES

Mechanisms to create a connected network

Generating an orthogonal network of hydrofracs

Low horizontal stresses and low stress bias is all that is required to allow creation of a wide network

Creating shear slip on pre-existing fractures

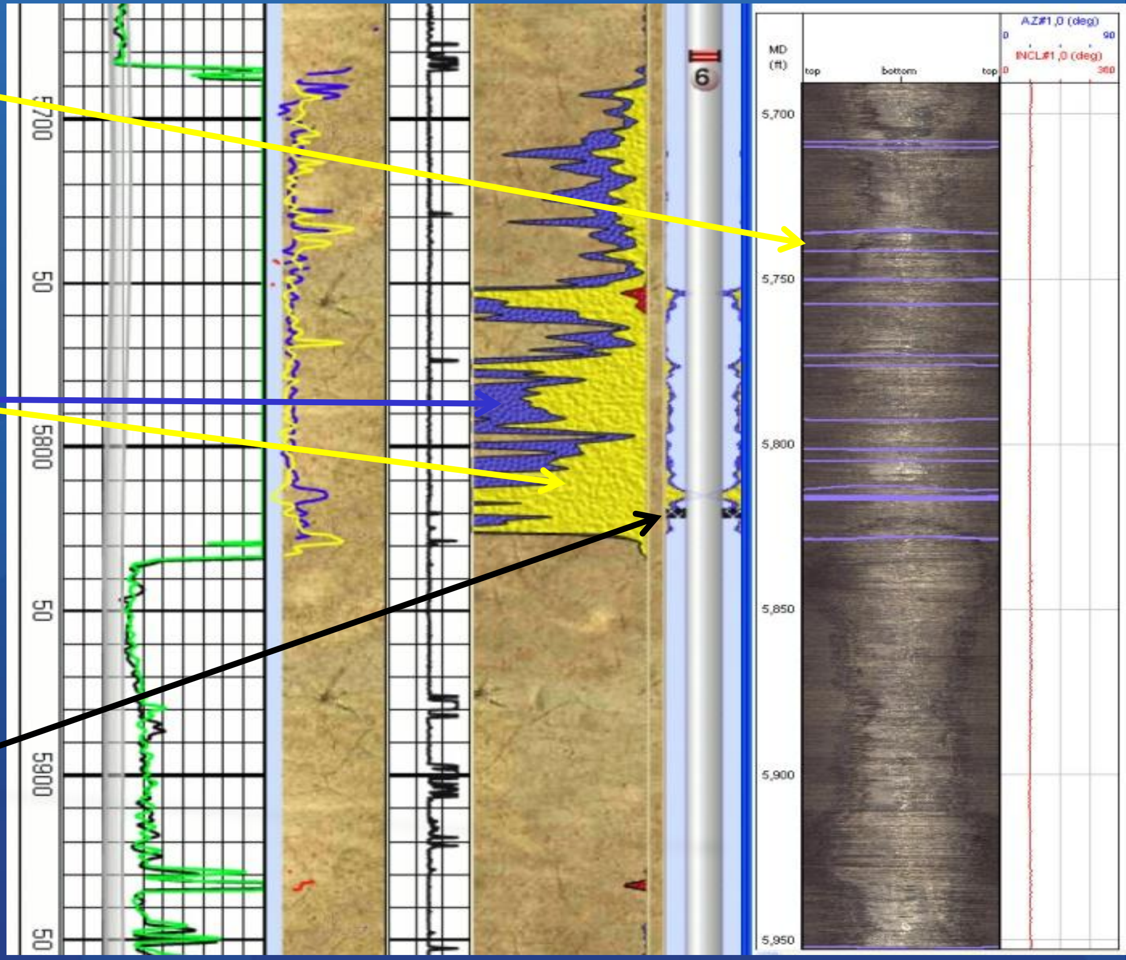
A variety of combinations of stress state and fracture patterns will allow creation of a wide network

Natural Fractures as Initiation Points

An optical image log showed natural fractures

Tracer data showed clear evidence of fluid entry from two stages (one on each side of the packers)

Packer was placed over a natural fracture cluster.



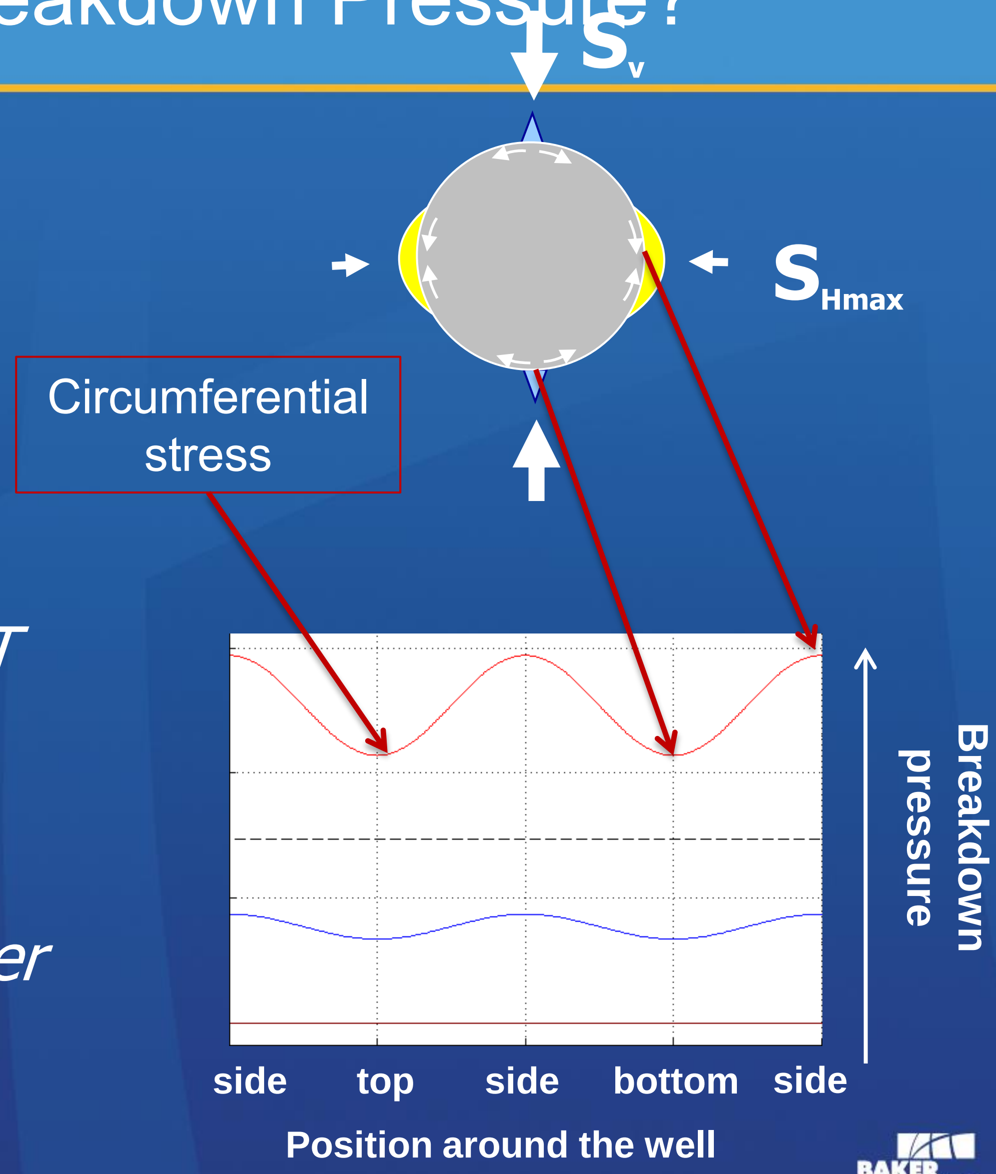
BAKER HUGHES

What Determines Breakdown Pressure?

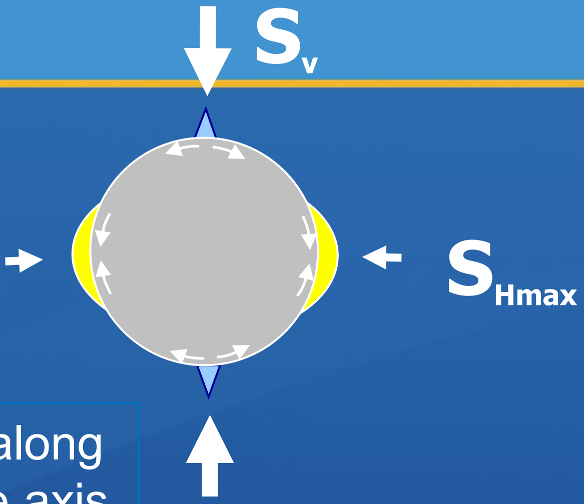
- The wellbore stress concentration
- Tensile strength

$$P_b = 3S_{Hmax} - S_v - P_p + T$$

Smaller S_{Hmax} causes easier breakdown

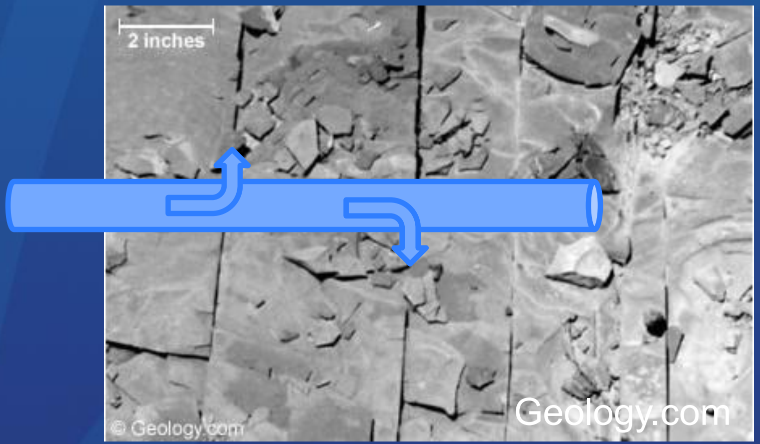


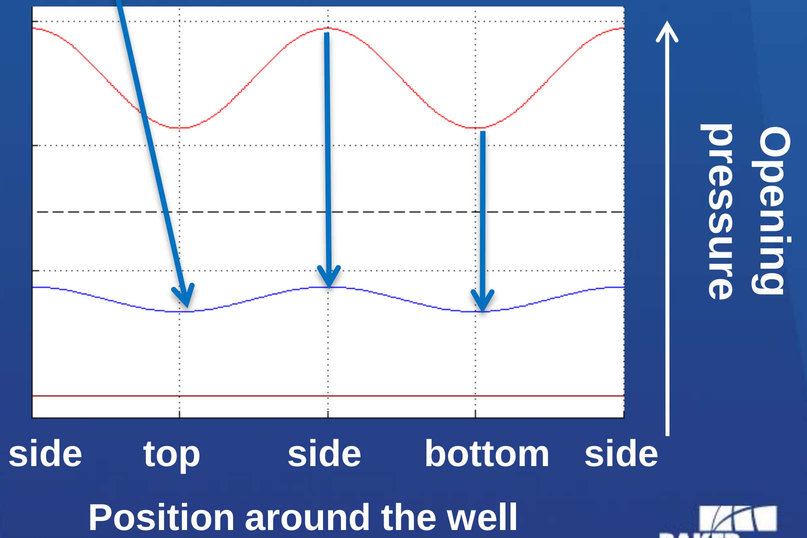
What Determines Breakdown Pressure?



- The wellbore stress concentration
- Tensile strength
- The presence of pre-existing weak joints or fractures can lead to early leakoff & lower breakdown pressure

Stress along wellbore axis





Fracture pressure (horizontal well towards S_{hmin})

- Four ways to break down a well
  - Create a new hydrofrac
  - Reopen a pre-existing tensile fracture
  - Open a transverse natural fracture
  - Cause shear slip on a pre-existing fracture

To create a new hydrofrac

$$P_b = T + 3S_{H\max} - S_V - P_p$$

To reopen a pre-existing tensile frac

$$P_{reop} = 3S_{H\max} - S_V - P_p$$

To "open" a transverse natural fracture

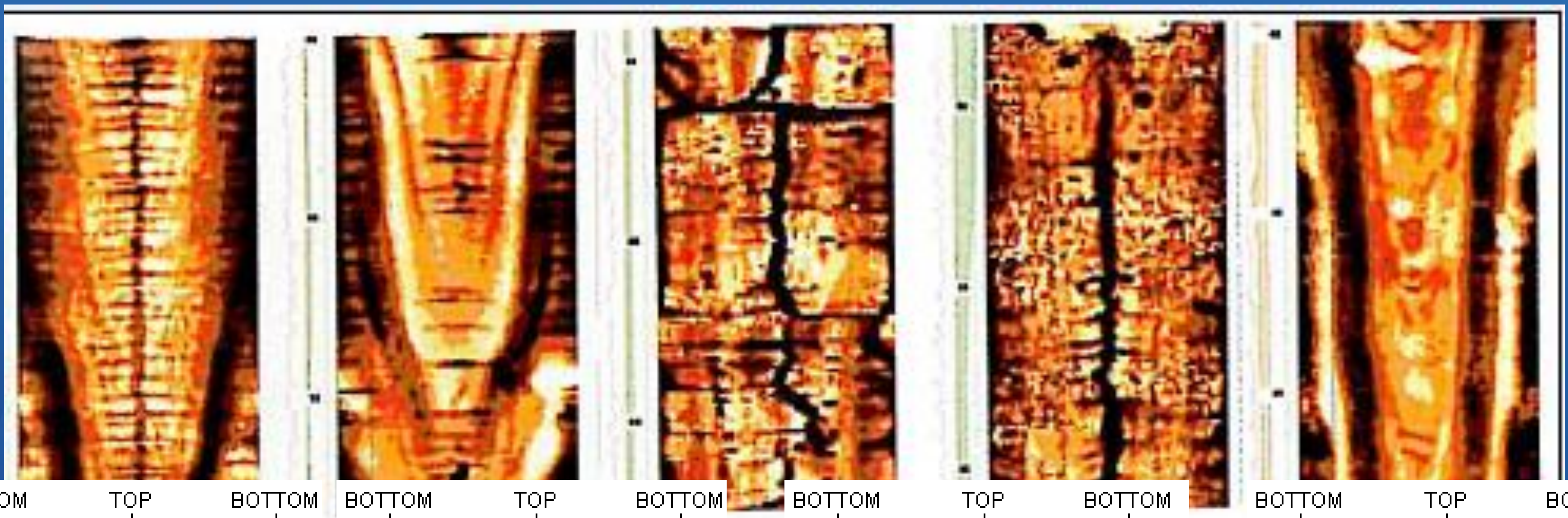
$$P_{opening} = T + S_{\text{hmin}}$$

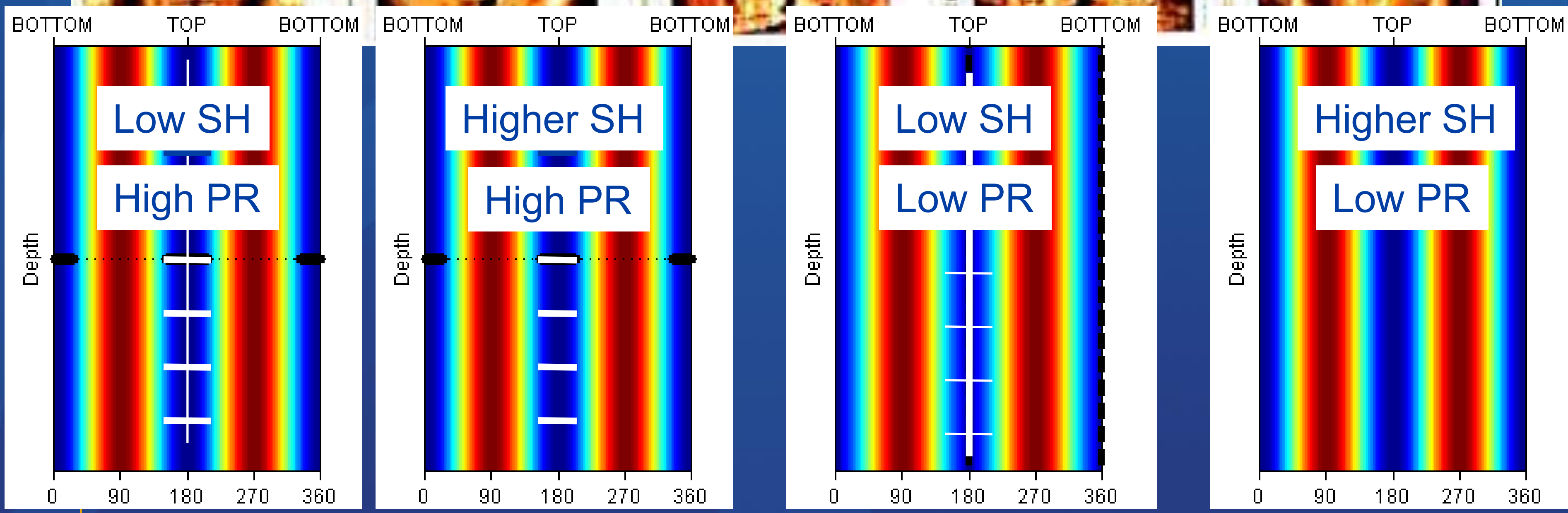
To cause shear slip

$$P_{slip} = S_{\perp} - \frac{\tau + S_o}{\mu}$$

BAKER HUGHES

New transverse fractures can be created while drilling



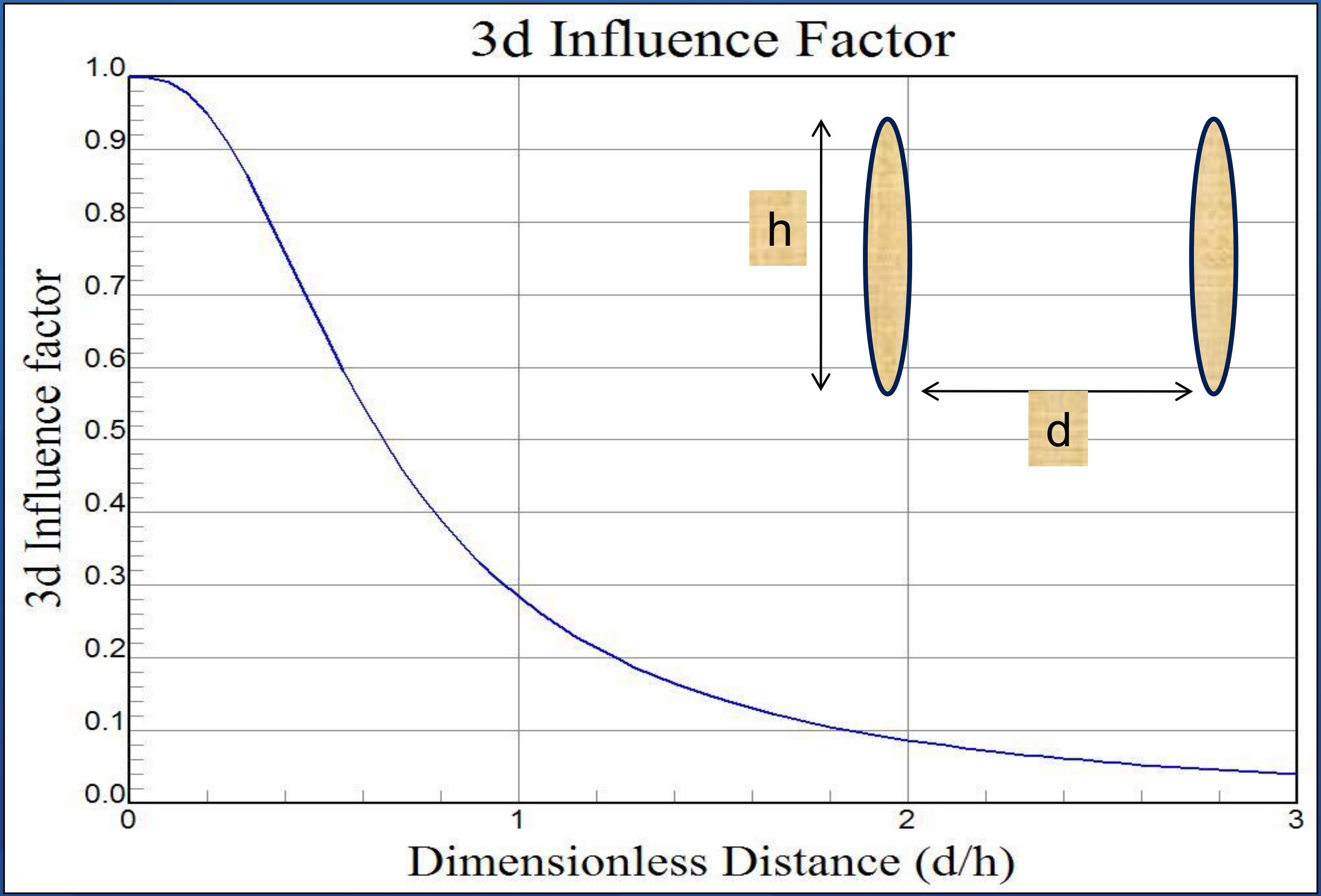


Breakdown pressure (well drilled towards S_{hmin})

- In open hole completions…
  - Breakdown is easier if S_{Hmax} is low
  - Pre-existing transverse fractures can open before creation of a hydrofrac
  - Isolation depends on appropriate location of packers

- Cased hole completions are better if…
  - S_{Hmax} is close to S_v and there are no transverse natural fractures
  - Pinpoint control of initiation points is required

Fracture interference and stage separation



Optimizing fracture spacing

SPE 130043 11

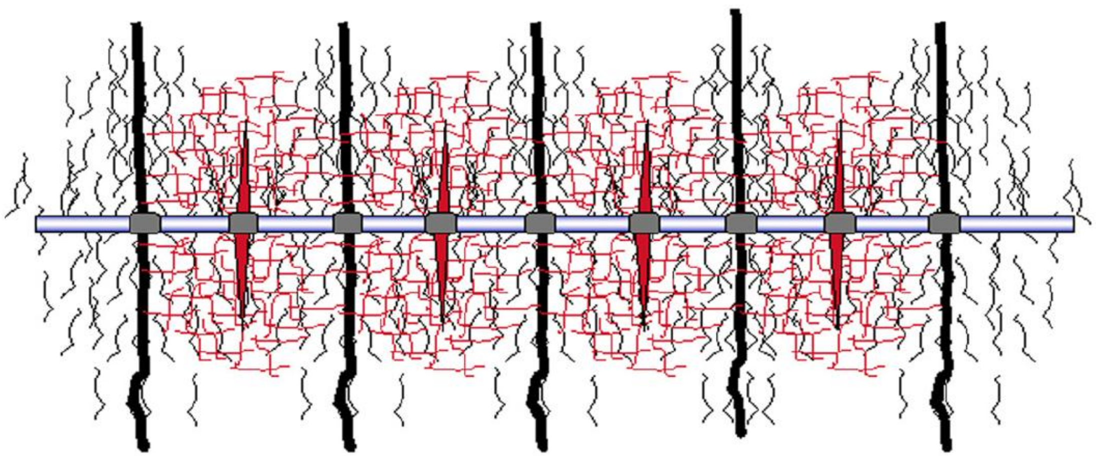


Fig. 9—Texas two-step fracturing method completion.

Alternating fractures can allow increased complexity
Soliman, SPE 130043

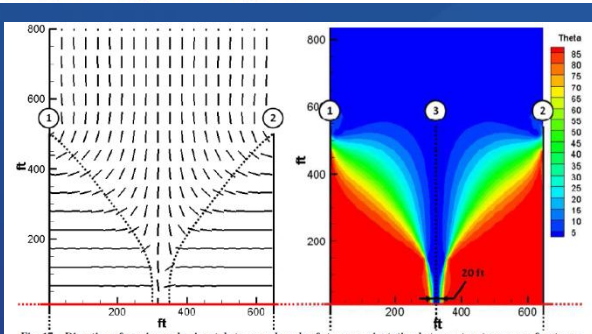


Fig. 17 – Direction of maximum horizontal stress and angle of stress reorientation between two transverse fractures spaced 650 ft apart (s_f = 325 ft, alternate fracturing sequence)

However, fractures can be "attracted" if too close to a previous fracture
Rousel, SPE 146104

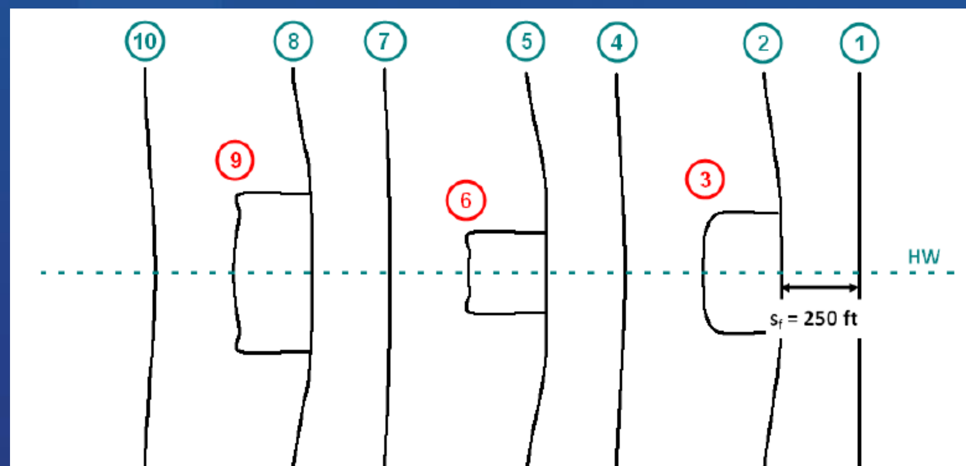
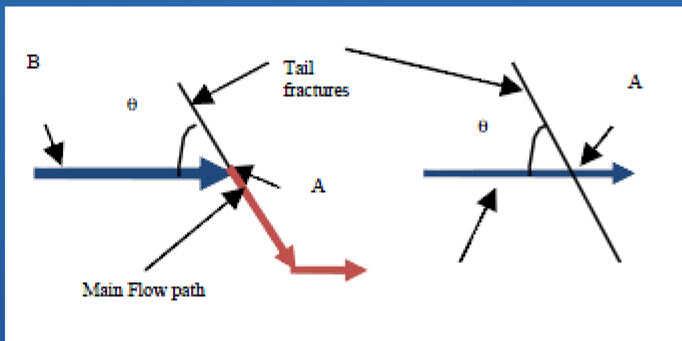
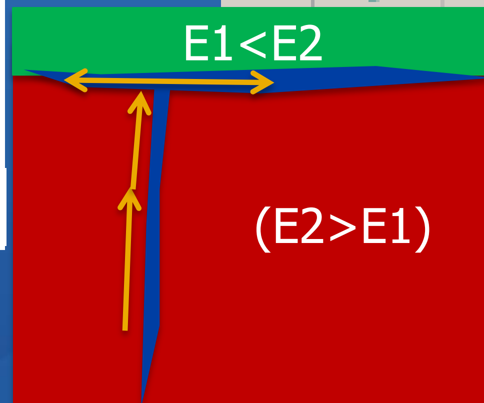


Fig. 10 – Trajectory of multiple consecutive transverse fractures spaced 250 ft apart

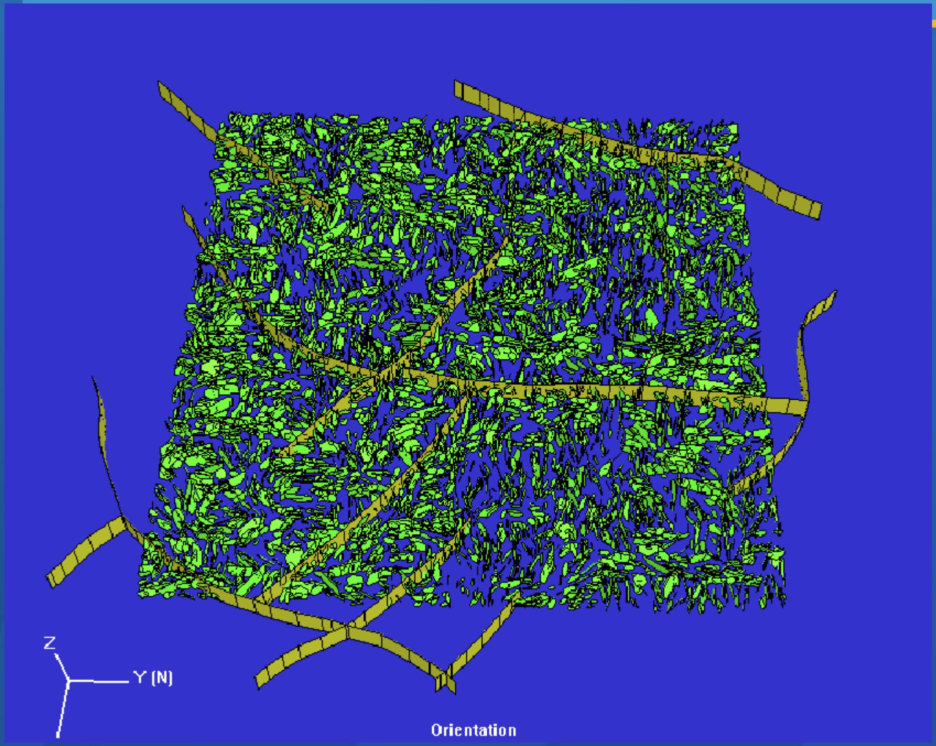
Hydrofracture Truncation & Complexity



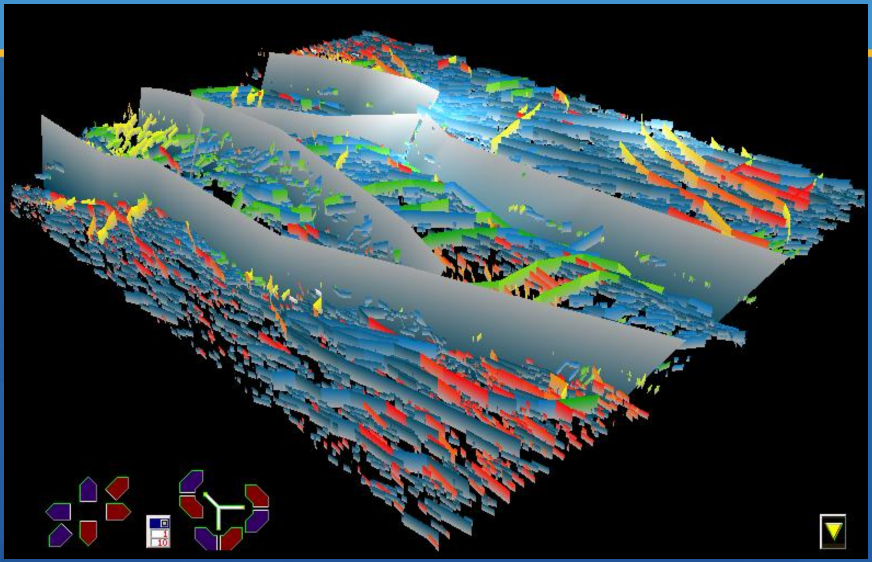


- Theoretical analyses predict that hydrofracs will stop at some fractures and at bedding interfaces
- Fracture propagation simulations that apply this model are being developed

Discrete Fracture Networks (DFN)



(Rogers, MacBeth, Liu, and Angerer, 2003)



(courtesy Badleys)

- A DFN is an artificial representation of the reservoir fracture network.
- DFN's are generated stochastically, conditioned with available data from boreholes image data, cores, (microseismic) and seismic.

BAKER HUGHES

Hydrofrac height growth

- Elastic properties contrasts – ratio of E to toughness determines likelihood of crossing a welded contact
- Weak planes cannot transmit stress into adjacent units – “T” fractures result
- Complexity can develop due to interactions with pre-existing weak or well oriented fractures
- Stress variations undoubtedly exist and will also affect fracture growth – an obvious example is the transition to reverse faulting at shallow depth

Natural Frac Truncation, Taughannock Falls, NY

http://www.cnyhiking.com/NYSP-TaughannockFalls.htm

Putting it all together in the Huron

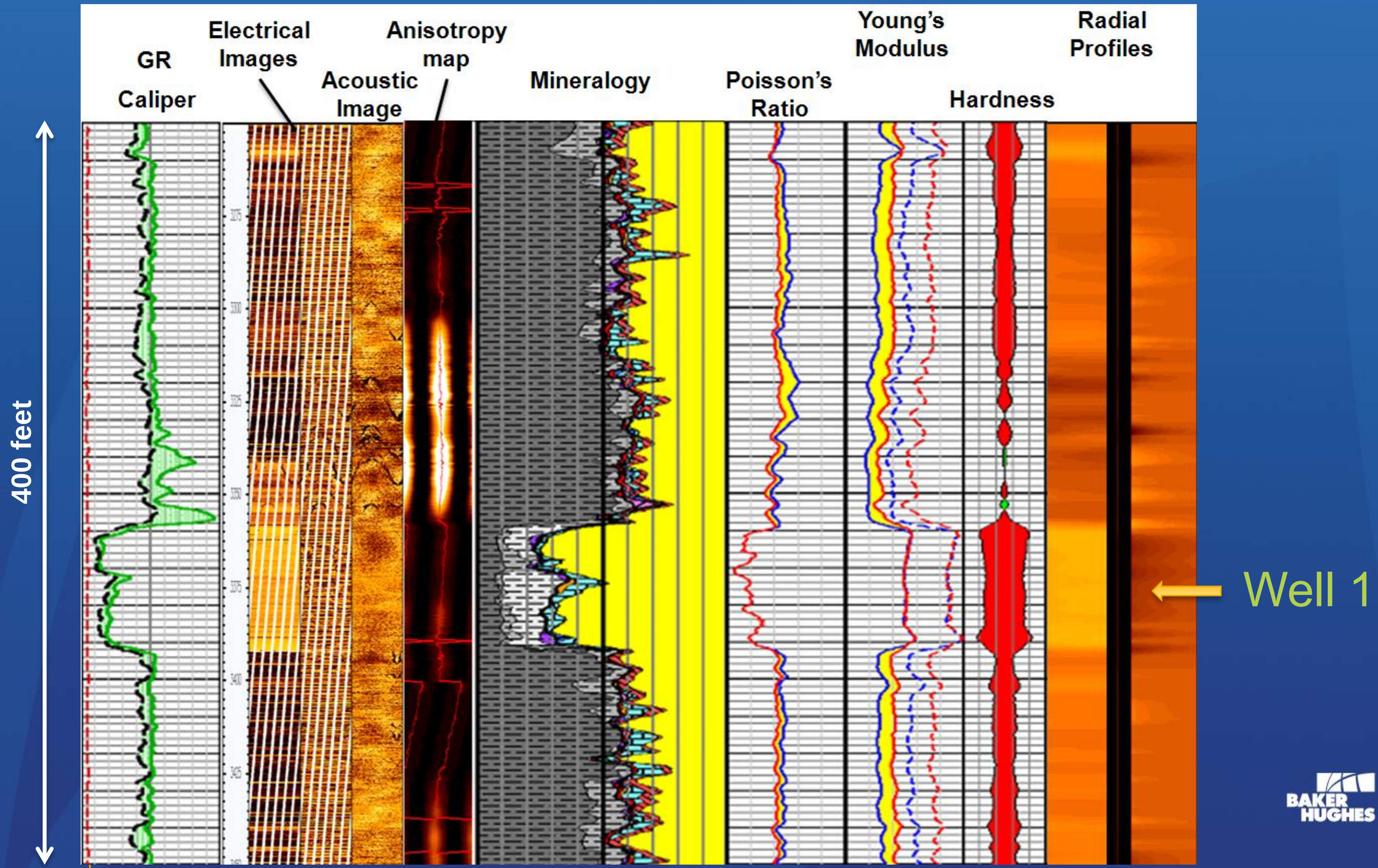
Further reading:

SPE-145849; SPE-148411;

SPE-146912

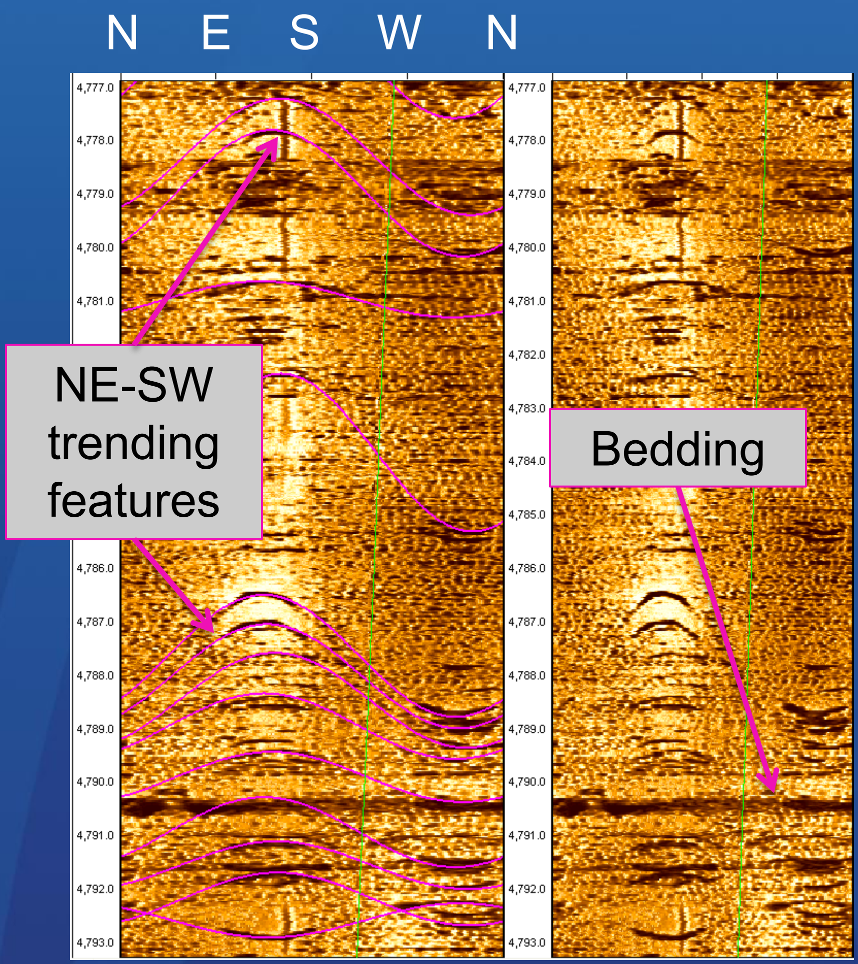
Advanced logging results – near Well 1

Geochemistry, stress, anisotropic elastic properties



Huron natural fractures– vertical well

Natural Fracture Analysis



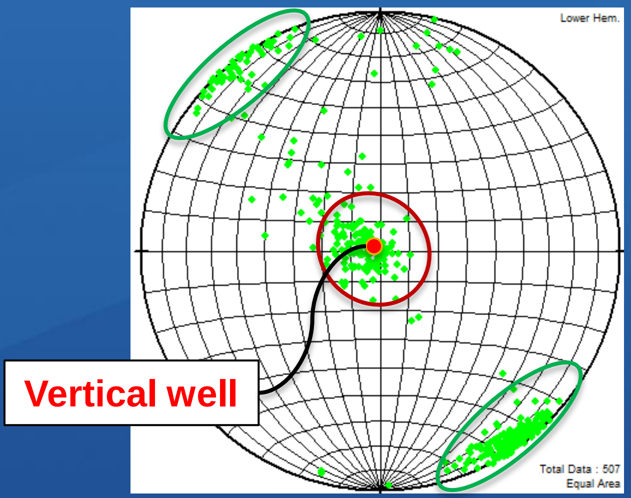
Acoustic Amplitude

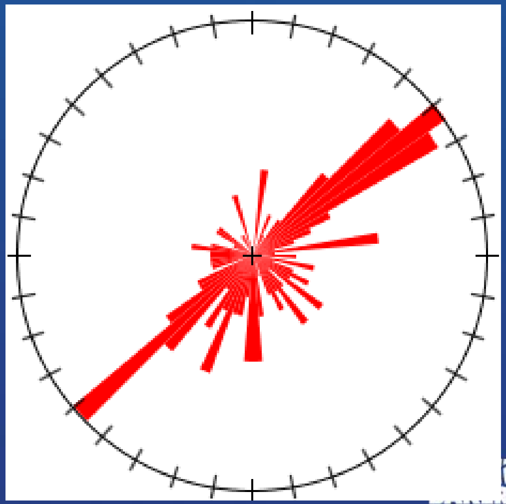
Bedding-related fractures

Near-vertical, NE-SW "joints"

Steep "joints" have NE-SW trends

Poles to fractures





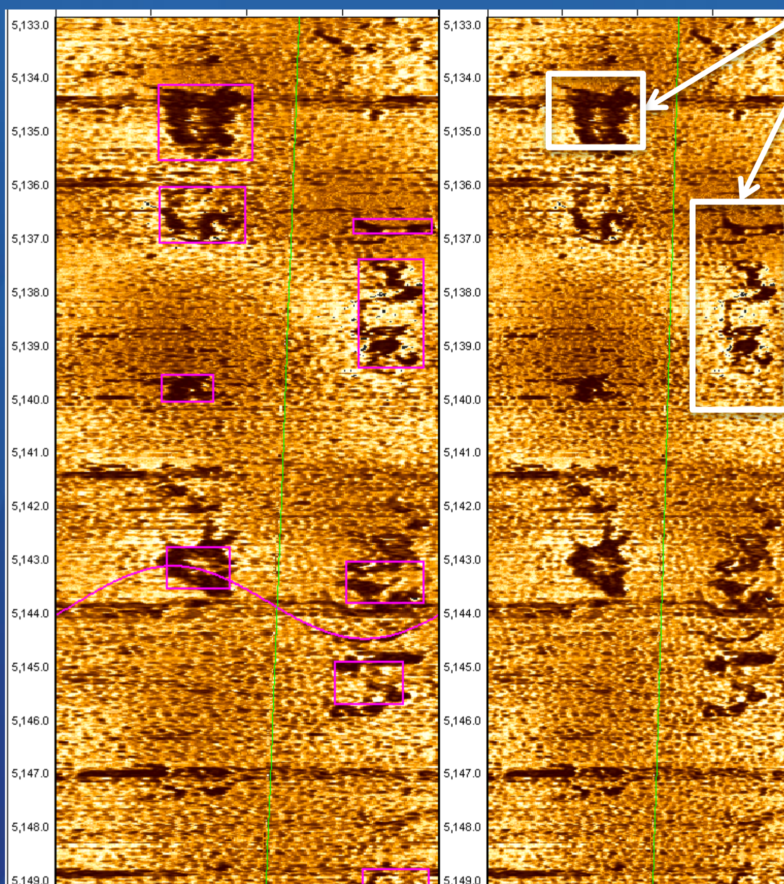
Fracture trends

Stress orientation from breakouts in the vertical well

Breakout Analysis

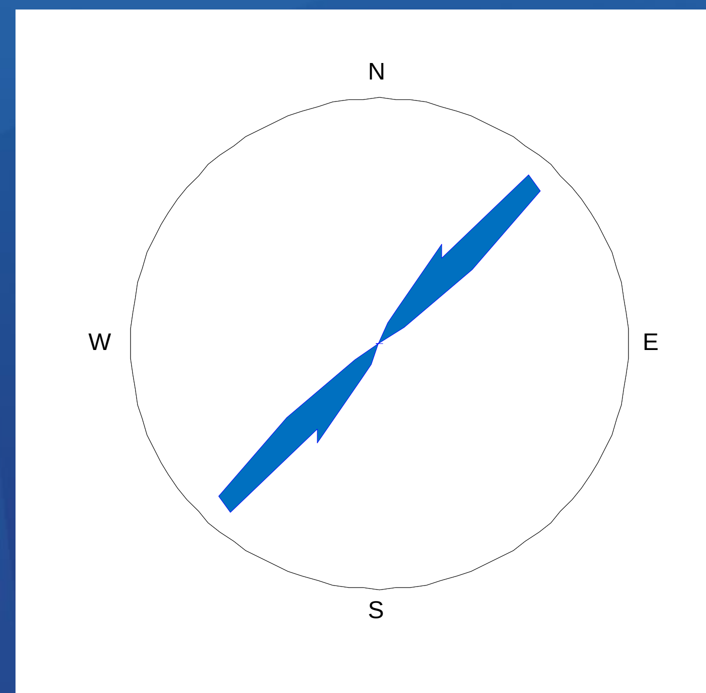
N E S W N

Breakouts appear as dark, non-reflective areas



Acoustic Amplitude

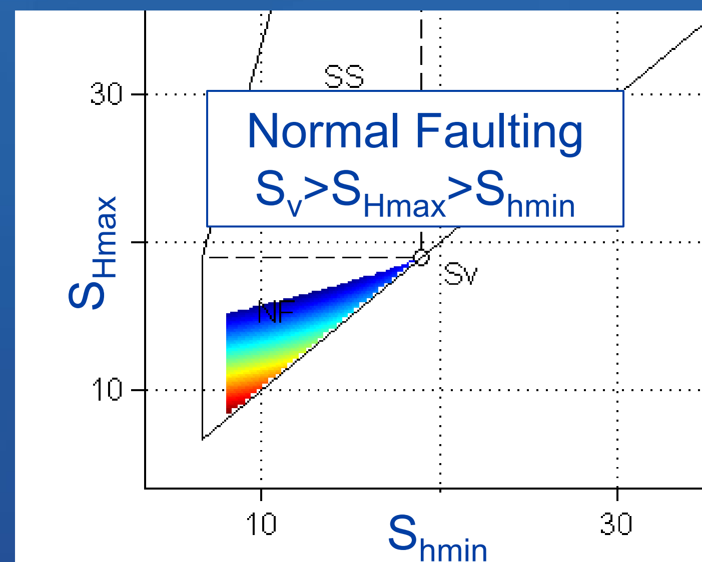
NE-SW S_{Hmax} orientation



S_{Hmax} magnitude from breakouts in the lateral well

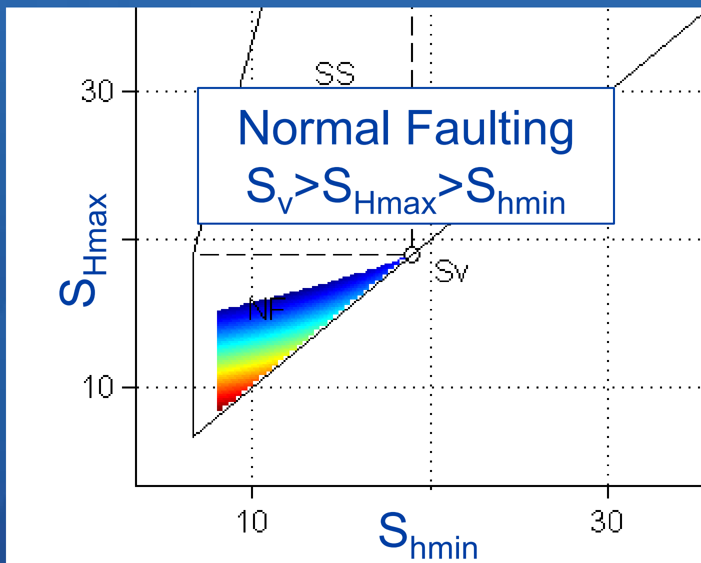
Well drilled towards S_{hmin}
Deviation angle 76

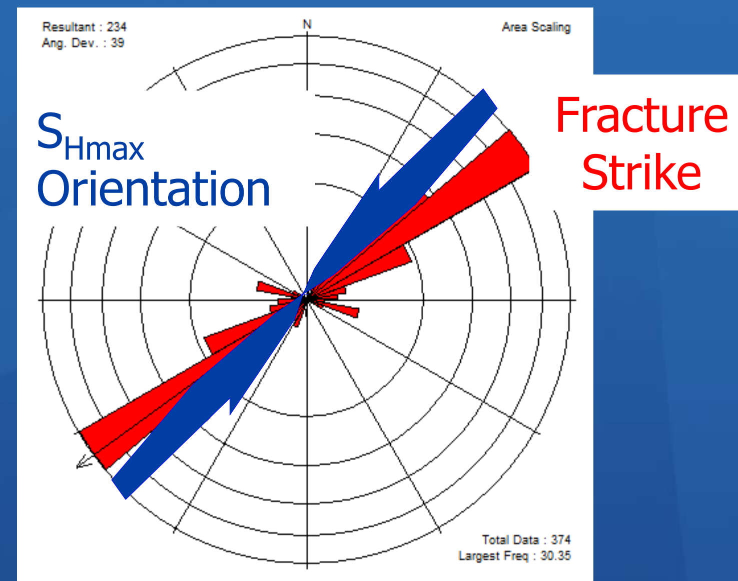
Breakouts on the sides of the well



Breakouts on the sides of a near-horizontal well require that $S_{Hmax} < S_v$

Predicting stimulated zone shape





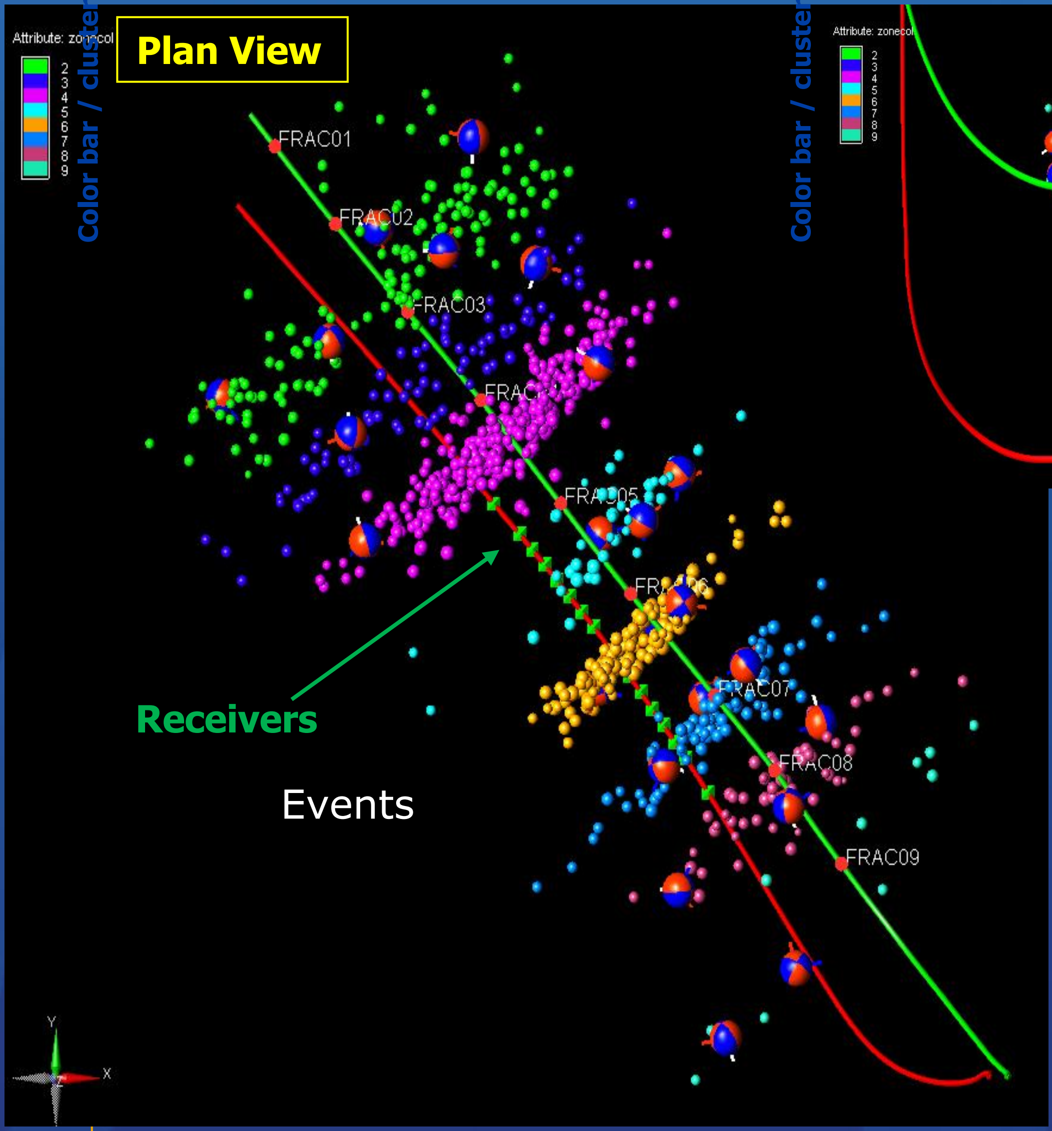
Low horizontal stress contrast suggests wide zones of microseismicity

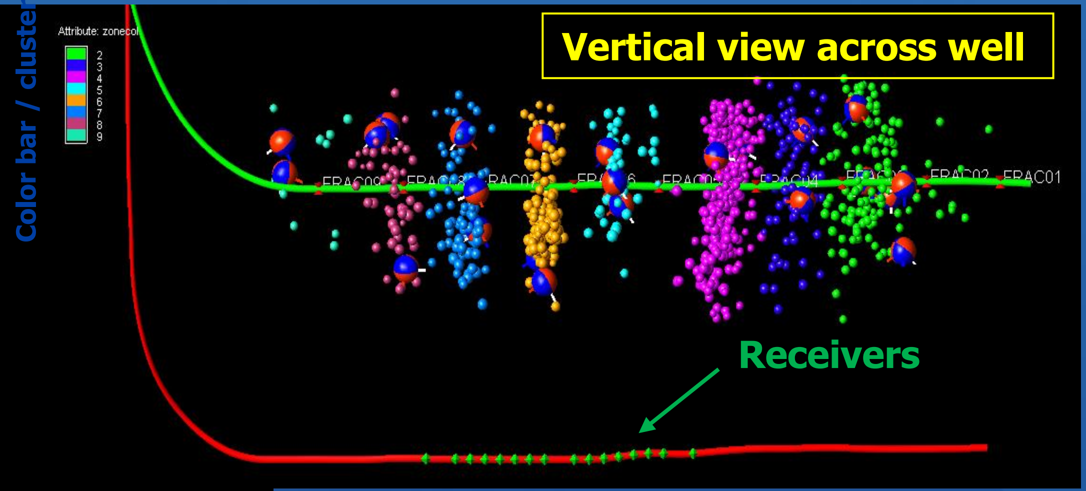
But there are no pathways for lateral growth of stimulated zones

Narrow microseismic clouds oriented NE-SW are predicted for this stress state and fracture pattern

High net pressures <u>may</u> widen stimulated zones

Microseismic observed zone shape





Observations:

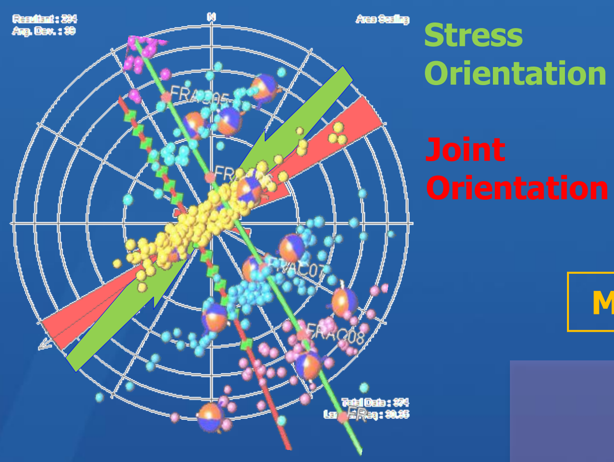
Narrow microearthquake zones

Zones oriented NE-SW

Wider zones at toe and heel?

BAKER HUGHES

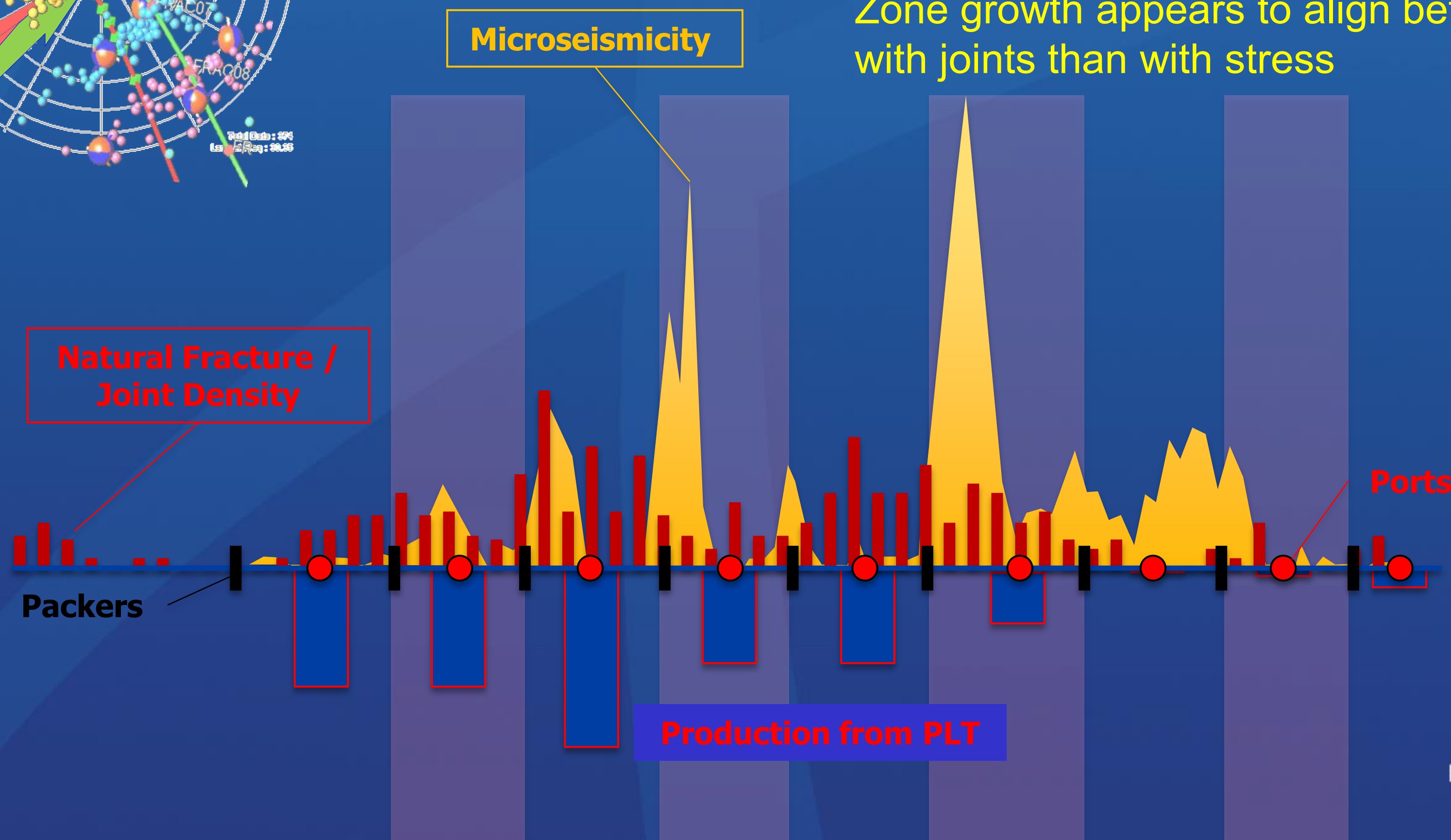
Frac, production and completion behavior



Fracs initiate away from ports

Production is poorly correlated to the number of events

Zone growth appears to align better with joints than with stress



BAKER HUGHES

Summary of study results

- Low stress anisotropy
- A single well developed, subparallel joint set
- Narrow microseismic clouds were predicted and subsequently observed
- Breakdown occurred at pre-existing fractures, and propagation occurred along those planes
- Packers nucleated breakdown in some cases
- Early production was best correlated to occurrence of pre-existing joint swarms

- Frac from hard, quartz-rich units into adjacent TOC zones, and modify completion geometry to target joints

BAKER HUGHES

Take away points for discussion

- Operational success requires knowing both in situ stress and natural fracture, fault, and bedding patterns, and acting on that knowledge
- Elastic properties are worth knowing, but not because they make good stress predictors
- Hydraulically induced fractures can be contained by elastic properties contrasts, laminated bedding, or weak natural fractures
- “Hydrofrac orientation” may not be a good predictor of stress orientation
- Uncemented wells can break down due to stress, by opening transverse weak planes, or at nucleation points, e.g., packers

BAKER HUGHES

Thank You…

Questions?

Discussion?