Optimizing Production from Unconventional Reservoirs

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Senior advisor

PETRO.AI ResFrac

SPE Argentine Petroleum Section
December 1, 2022

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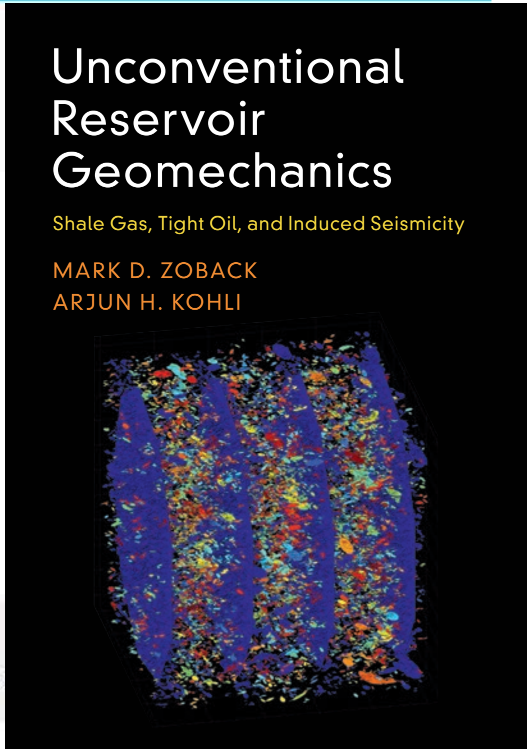

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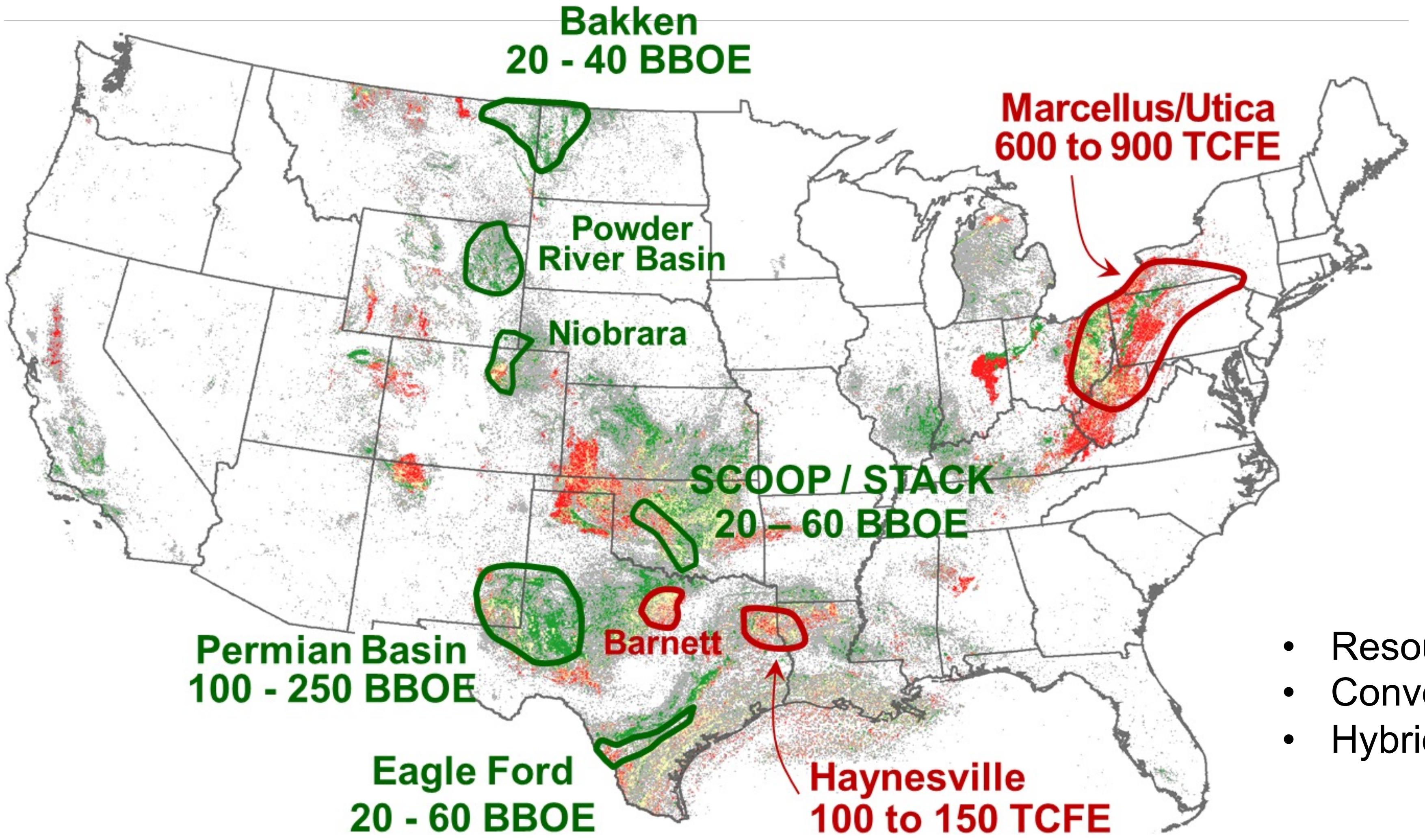
Mark D. Zoback

Benjamin M. Page Professor of Geophysics at Stanford University • Stanford University

Arjun H. Kohli

Research Scientist and Lecturer in the Department of Geophysics at Stanford University • Stanford University

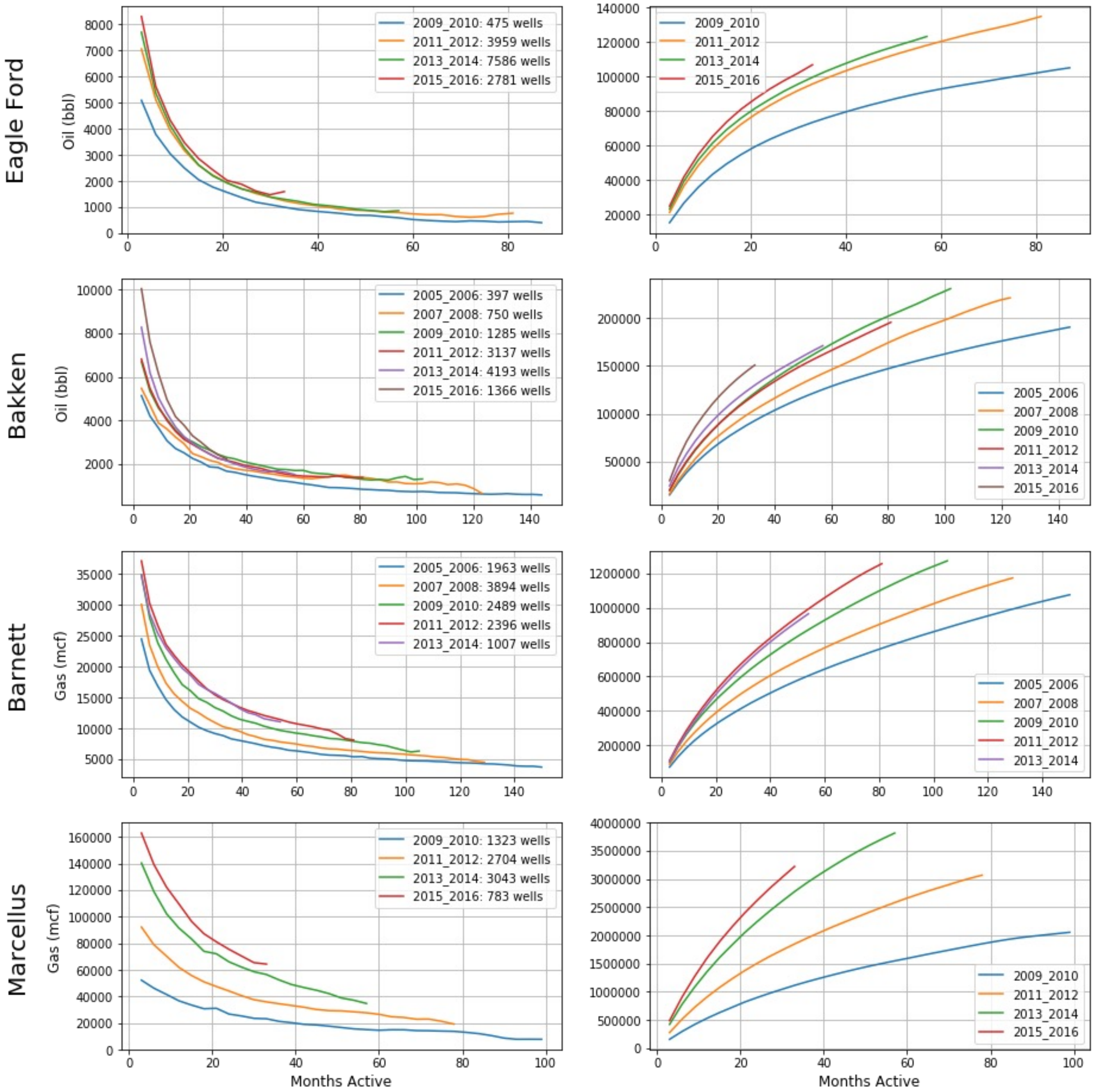
Unconventional Oil and Gas Reservoirs are World Class "Discoveries"



- Resource Plays
- Conventional Unconventionals
- Hybrid Plays

Courtesy Greg Leveille, ConocoPhillips

Rapid Reduction in Rate of Production | Modest Increase in Cumulative Production

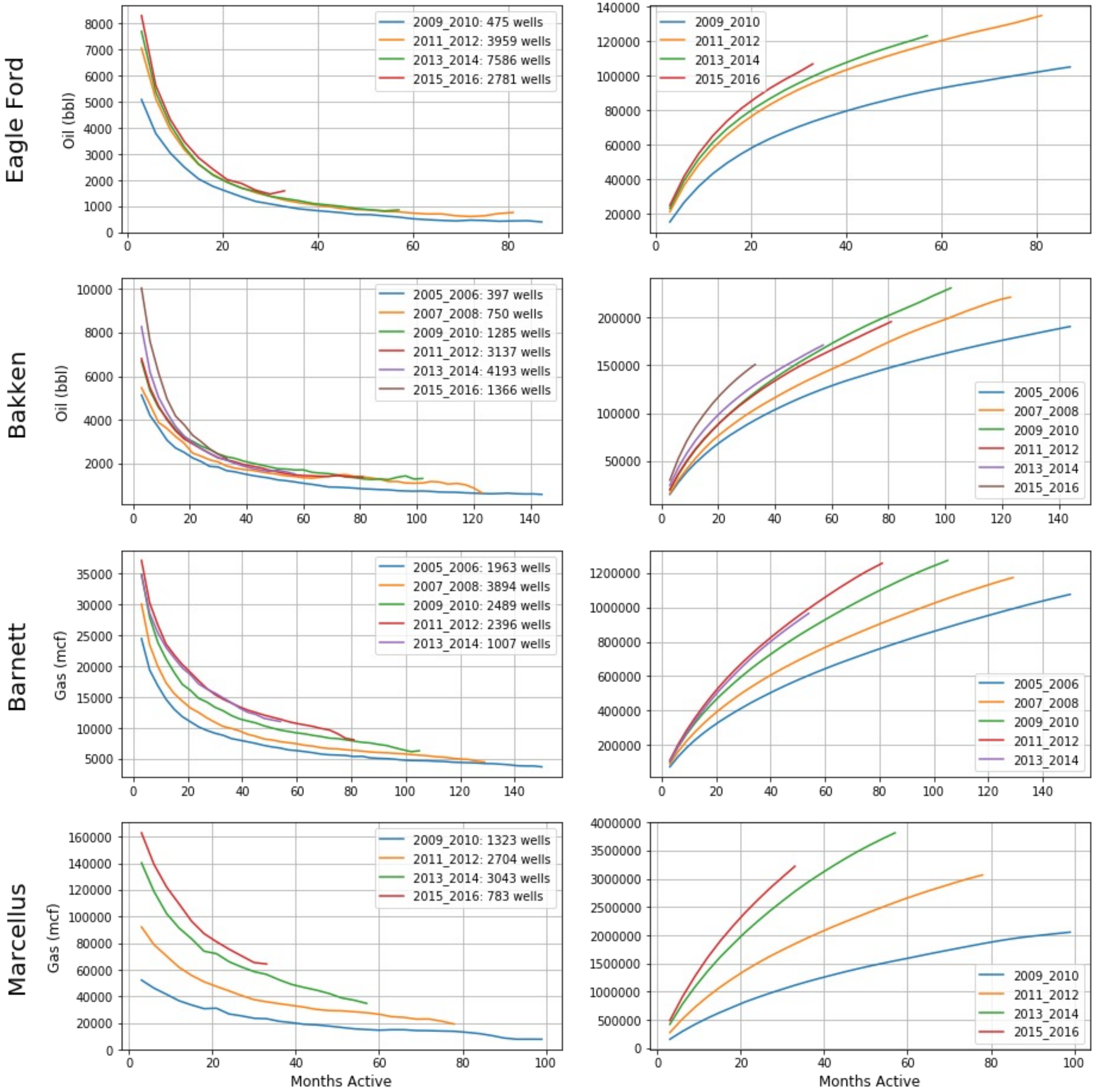


2009-2016	~40%
2009-2016	~40%
2005-2016	~50%
2005-2014	~100%

Fig. 1.12
With corrected average cumulative production per well

Rapid Reduction in Rate of Production

Modest Increase in Cumulative Production



2009-2016 ~40%

2009-2016 ~40%

2005-2016 ~50%

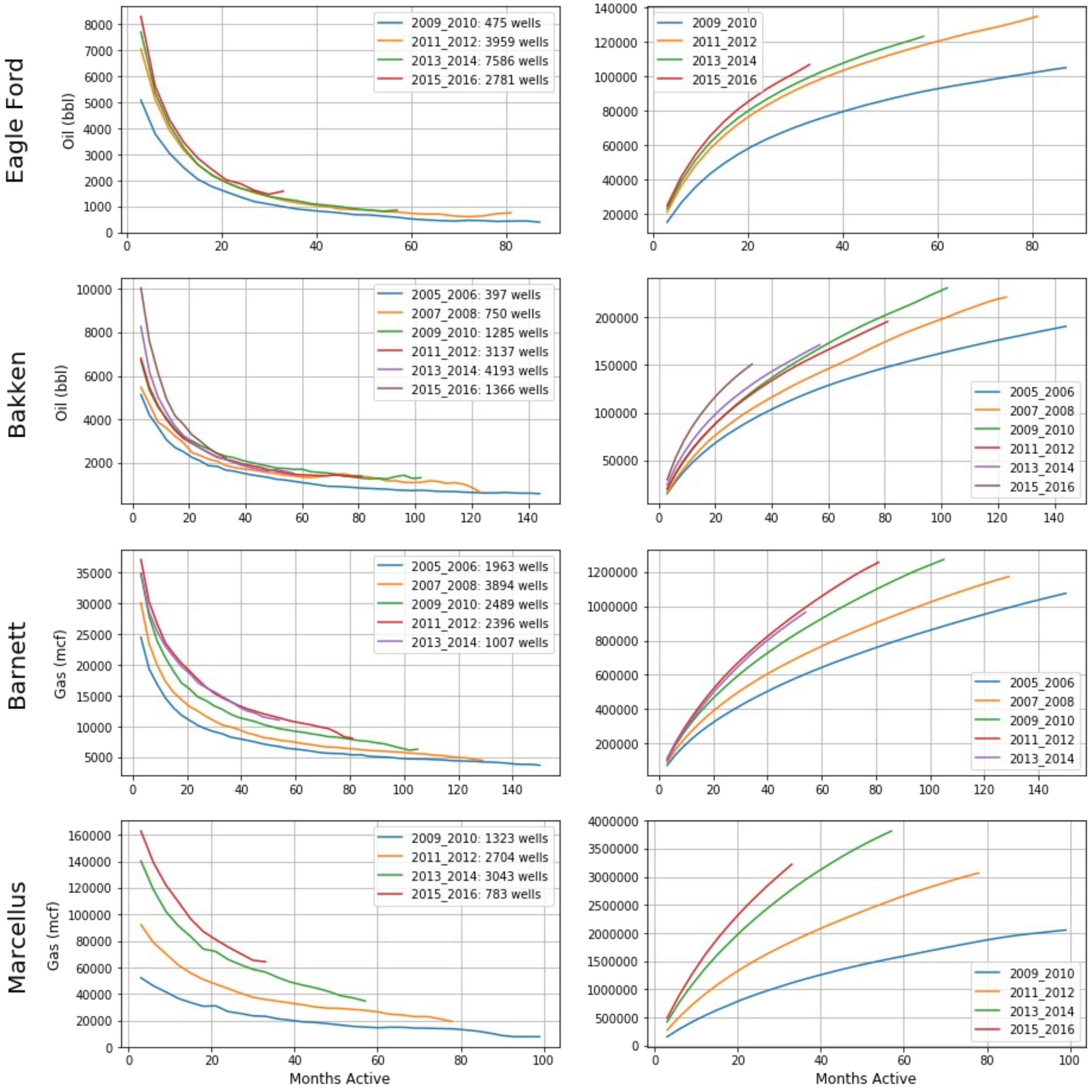
2005-2014 ~100%

Economics Complicated
- Resource Price
- Operational Efficiency
- Level of Effort

Fig. 1.12
With corrected average cumulative production per well

Rapid Reduction in Rate of Production

Modest Increase in Cumulative Production



2009-2016 ~40%

2009-2016 ~40%

2005-2016 ~50%

2005-2014 ~100%

Economics Complicated
- Resource Price
- Operational Efficiency
- Level of Effort

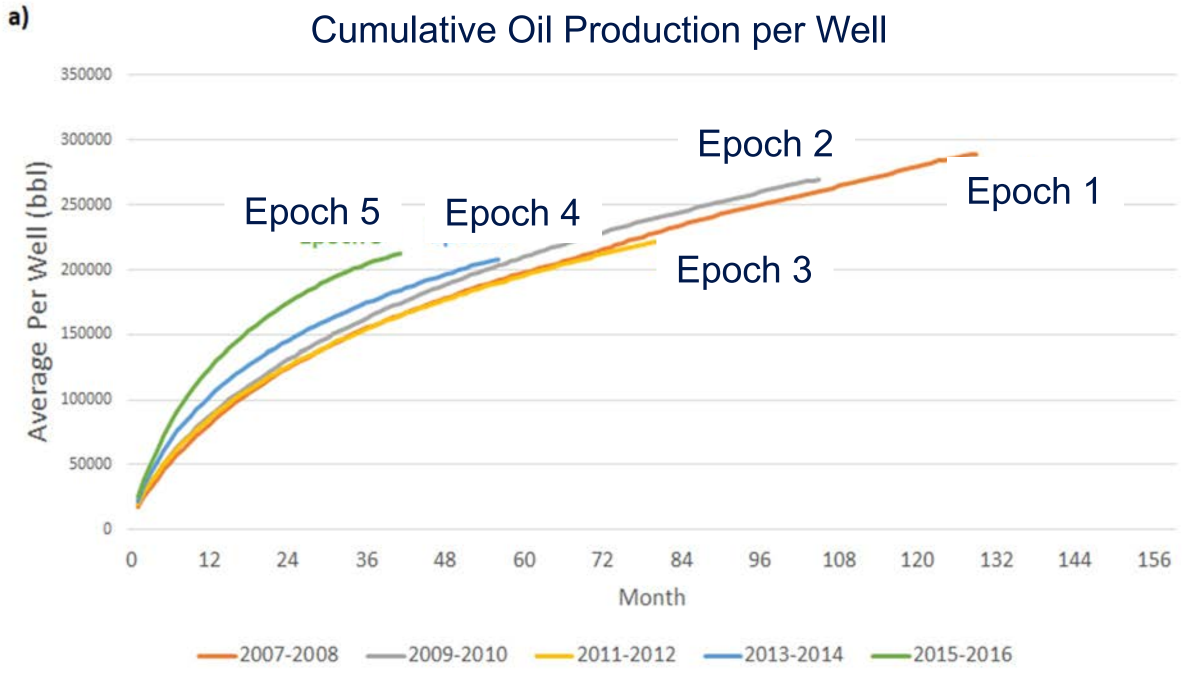
After > 300,000 Wells
- RF Dry Gas ~25%
- RF Tight Oil 2-10%
- Many Uneconomic Wells

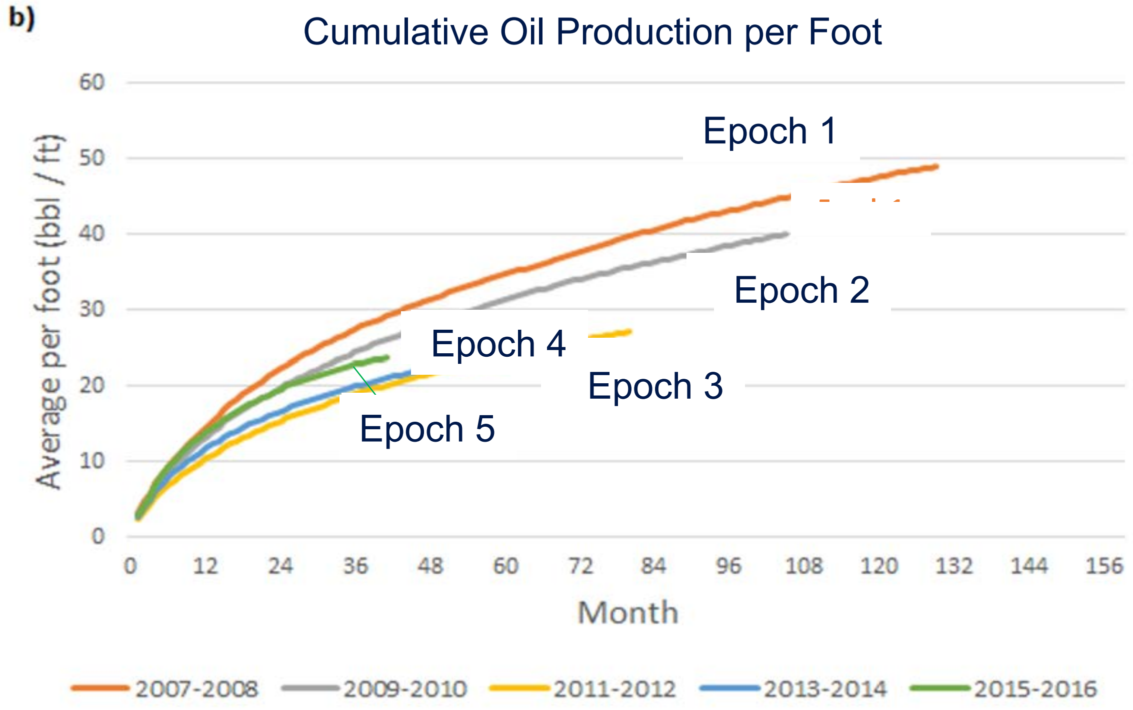
CapEx for Drilling and Completion ~ $80B/year

Fig. 1.12
With corrected average cumulative production per well

Bakken Production Data 2007-2016

- On a per well basis, cumulative oil production has shown a steady increase in time
- On a per foot basis, there has been a decline in production through time





Rostami, Boness and Zoback, URTeC 2813, 2020

Three Topics

- Get the Stress Right (You Can’t do Geomechanics Right With the Wrong Stress State).
    - Lessons from North America
    - Drilling Horizontal Wells in the Correct Direction (Bakken Example)

- Optimizing Well Placement When Exploiting Stacked Pay
    - Lithologically-Controlled Variations of the Least Principal Stress with Depth and its Impact on Multi-Stage Hydraulic Fracturing
    - Modeling Hydraulic Fracture Growth (ResFrac)
    - Optimizing Drainage Area (Petro.ai)

- Shear Faulting and Its Affect on Production Stimulation
    - Importance of Microseismic Events
    - Pad-scale Faulting Which Can *Hijack* Hydraulic Fracture Stages

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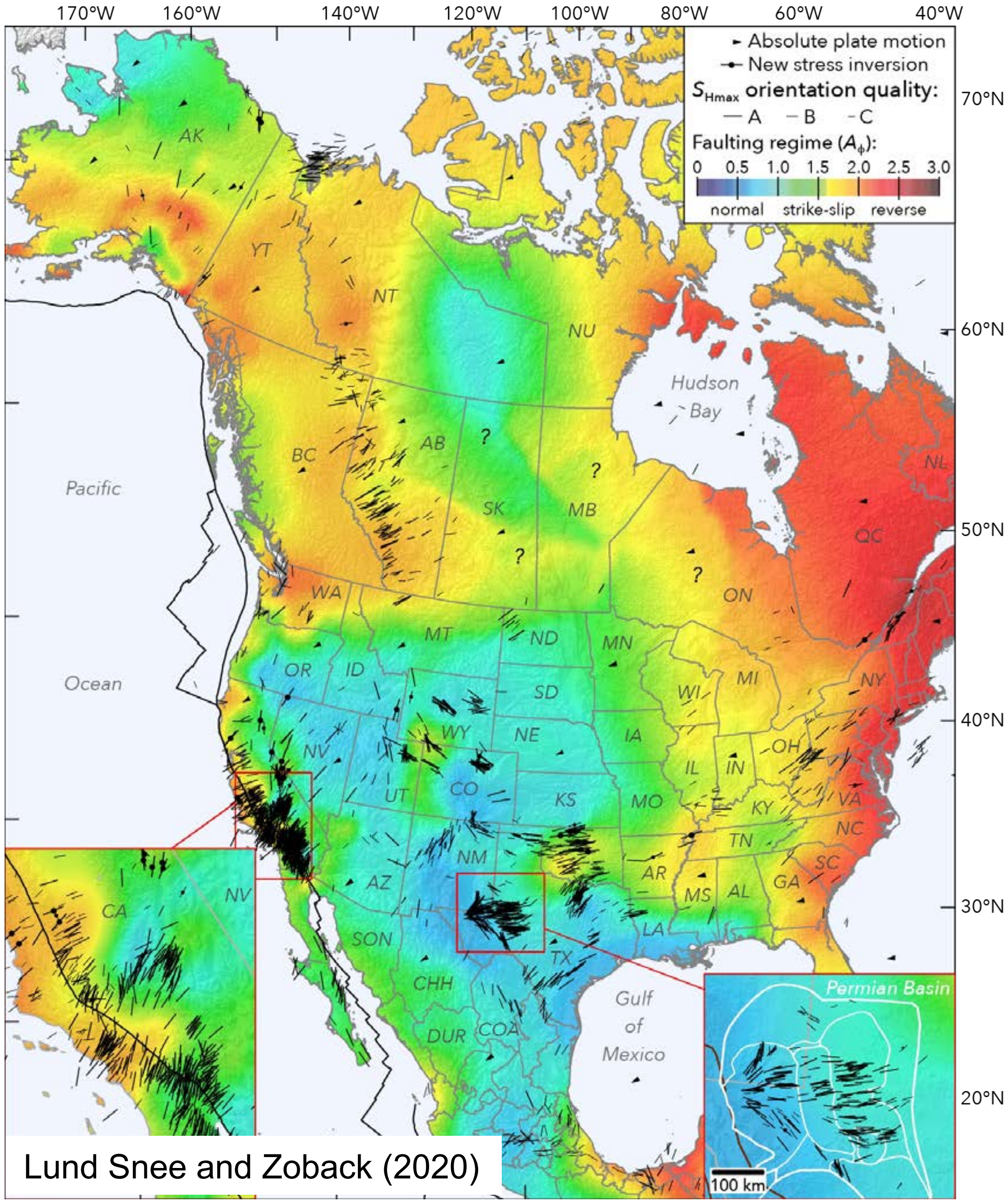
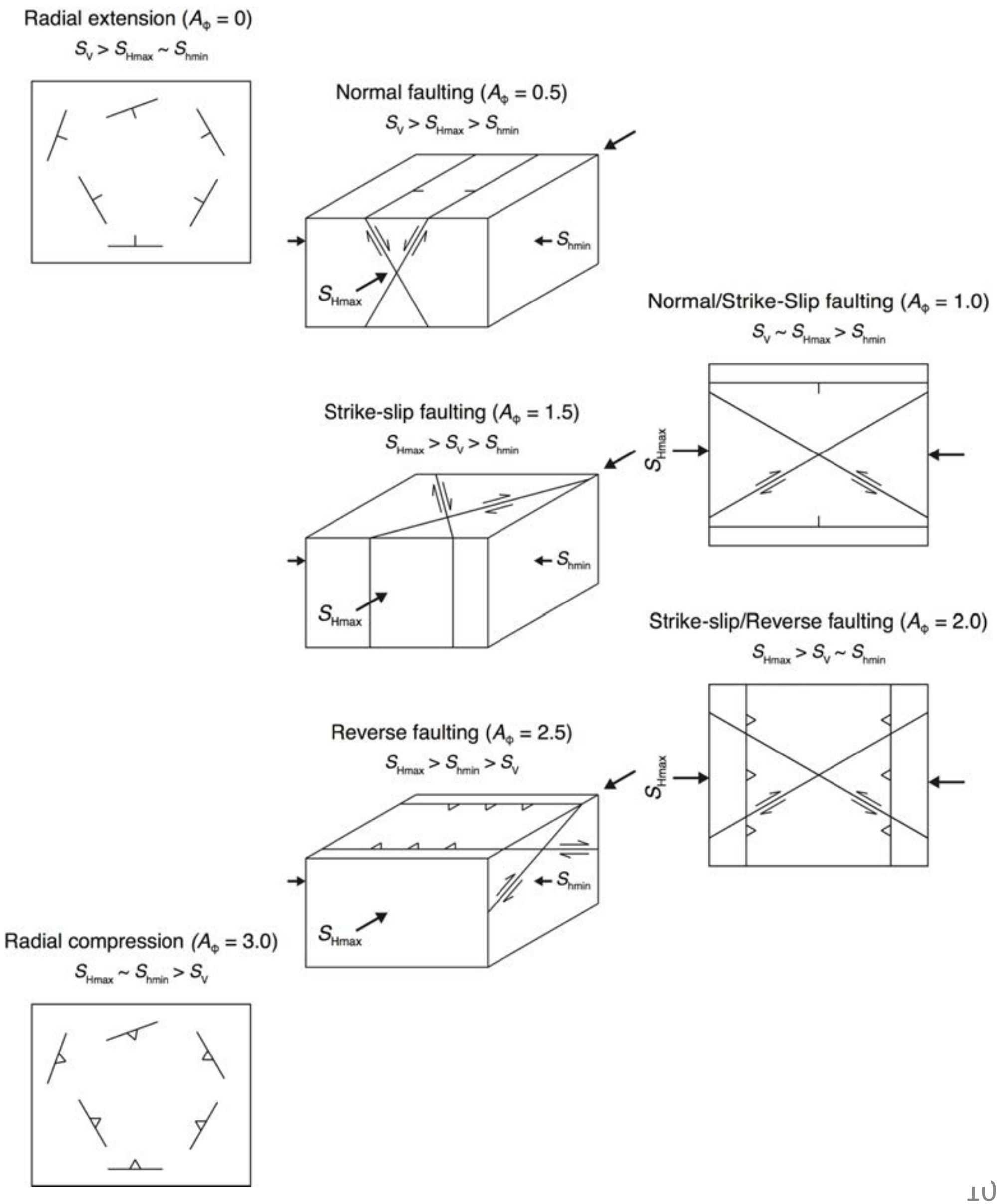
1. Stress Orientation
2. Variation of S_3 (S_{hmin}) with Depth

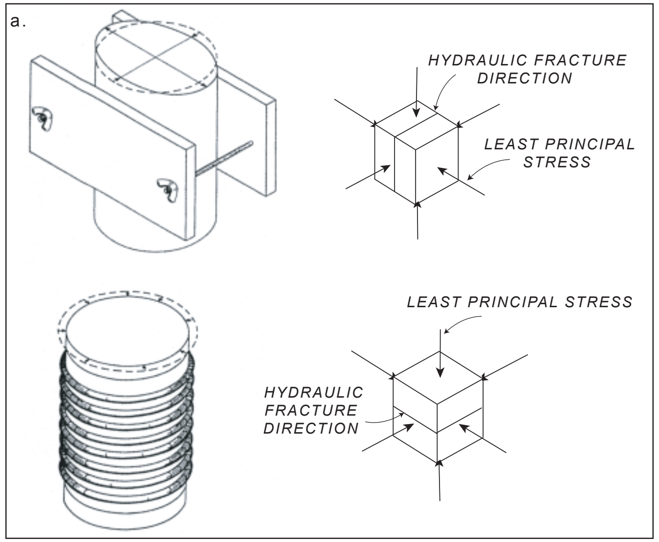
Anderson Faulting Theory Revisited

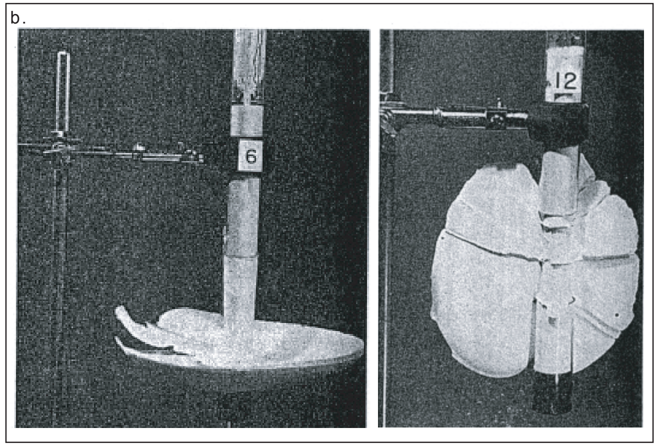


Lund Snee and Zoback (2020)



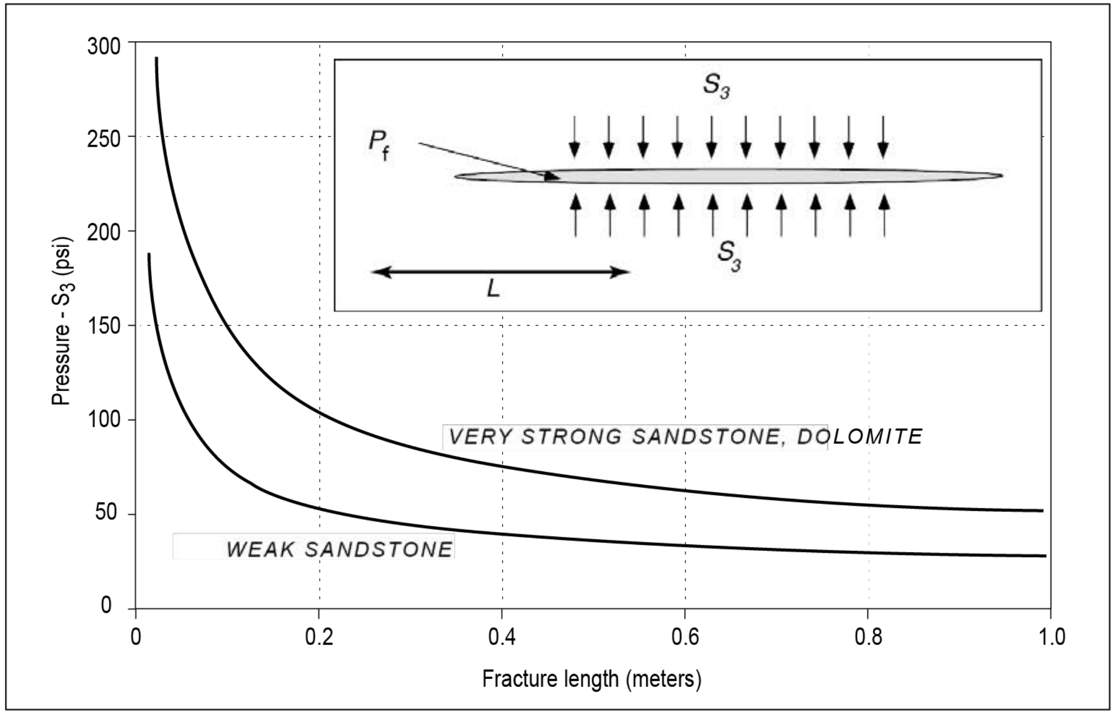
Hydraulic Fractures are <u>ALWAYS</u> Controlled by the Magnitude and Orientation of the Least Principal Stress (Usually S_{hmin})





Hubbert and Willis (1957)

Once hydraulic fractures are propagating, rock strength is reatively unimportant



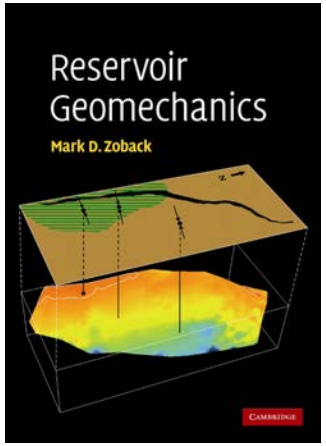
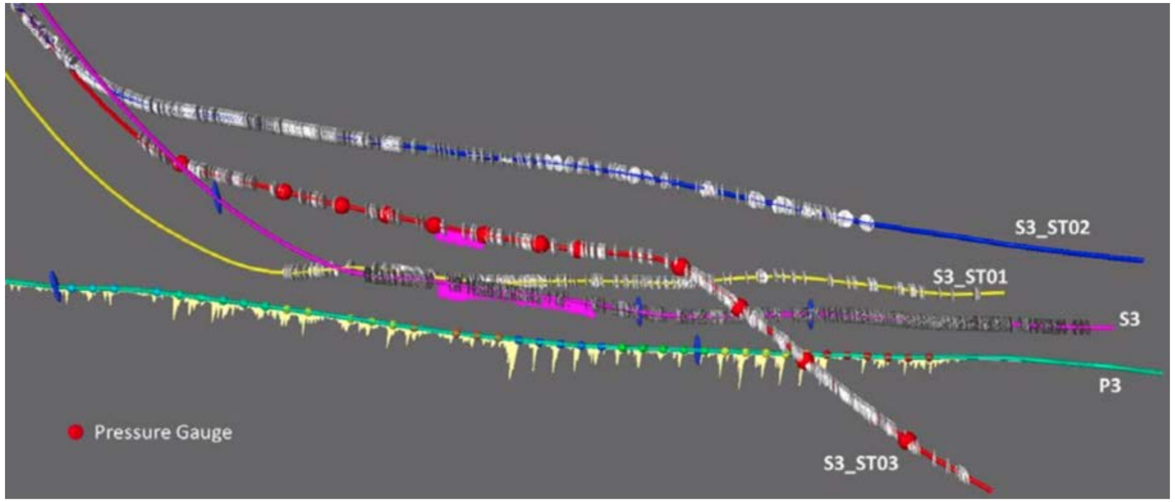
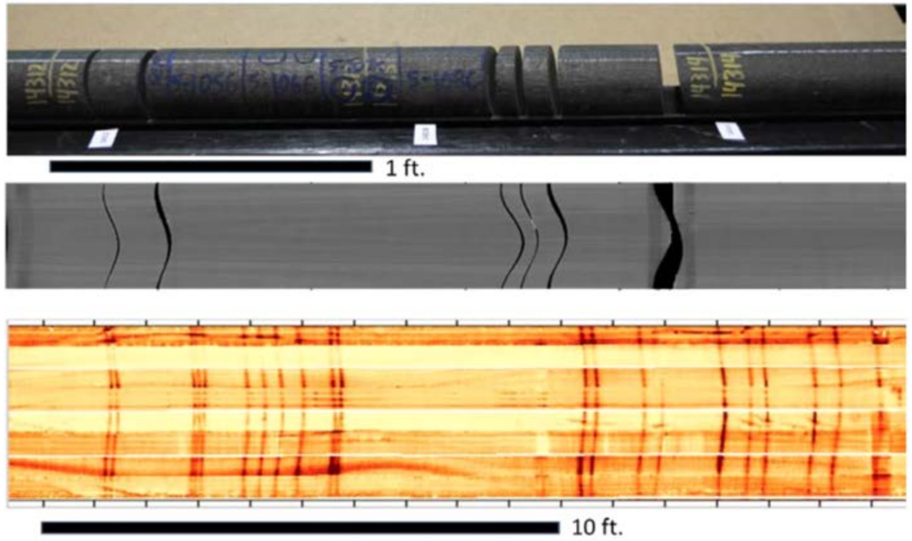


Fig. 4.21 page 122

Many Hundreds of Planar Hydraulic Fractures Propagating Normal to S_{hmin}





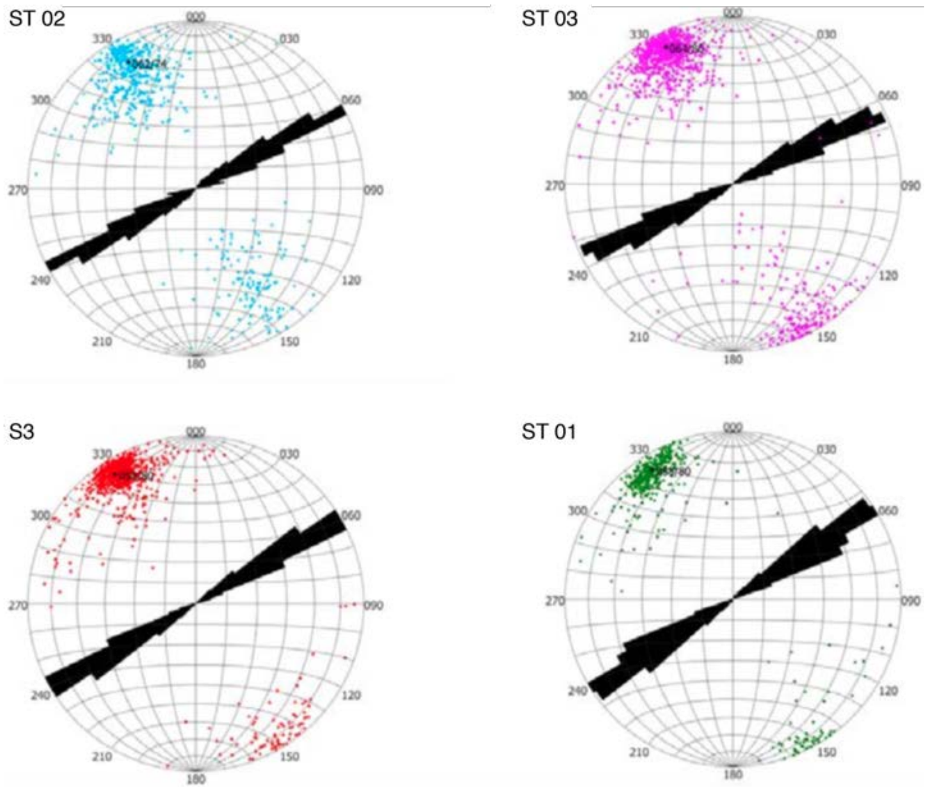


Fig. 8.8, 8.9

Eagle Ford Drill Through/Core Experiment

25 times more hydraulic fractures than perforation clusters

Raterman et al. (2019)

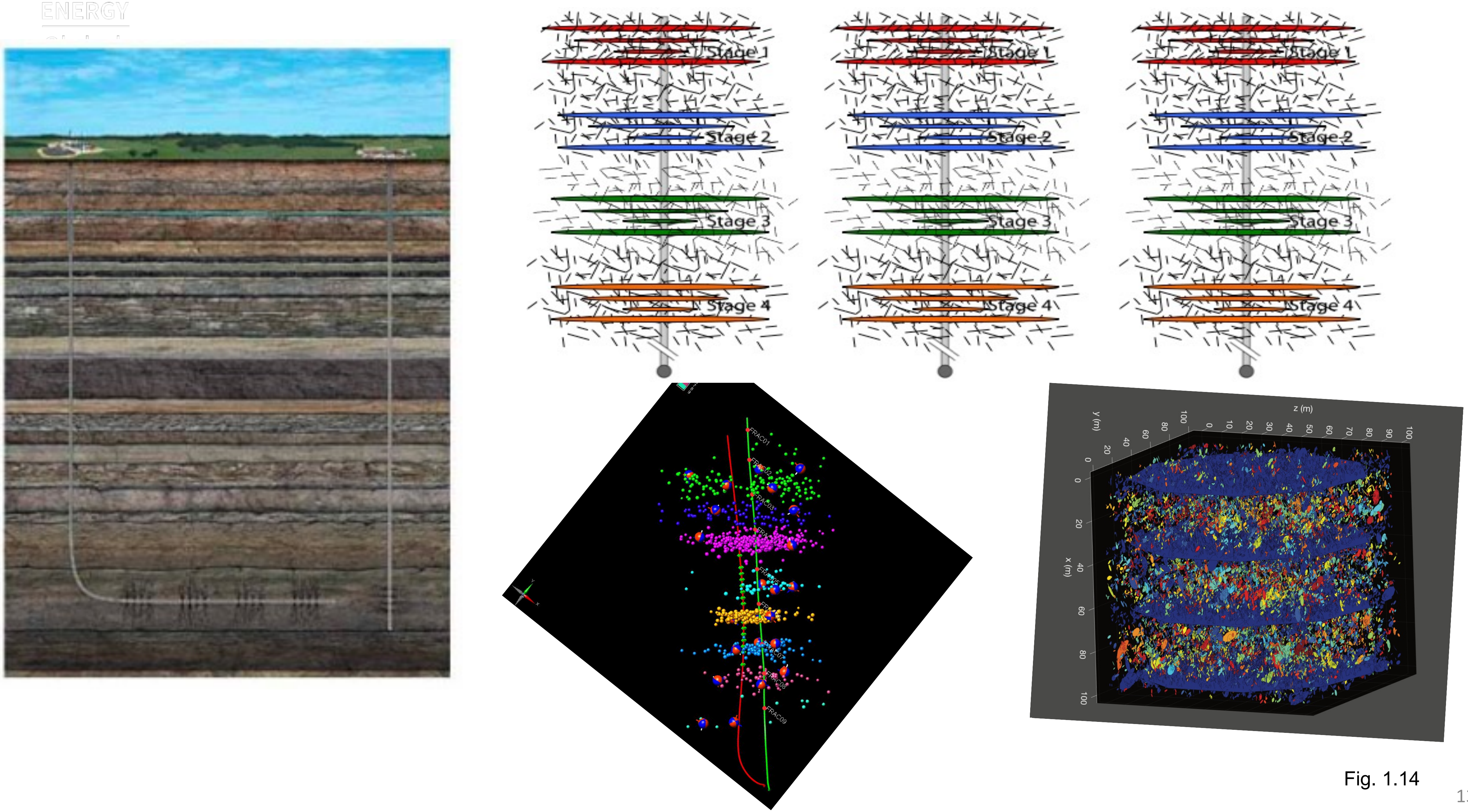

Stage 1
Stage 2
Stage 3
Stage 4
Stage 1
Stage 2
Stage 3
Stage 4
Stage 1
Stage 2
Stage 3
Stage 4
FRAC01
FRAC09
z (m)
y (m)
x (m)

Fig. 1.14

URTeC: 2813

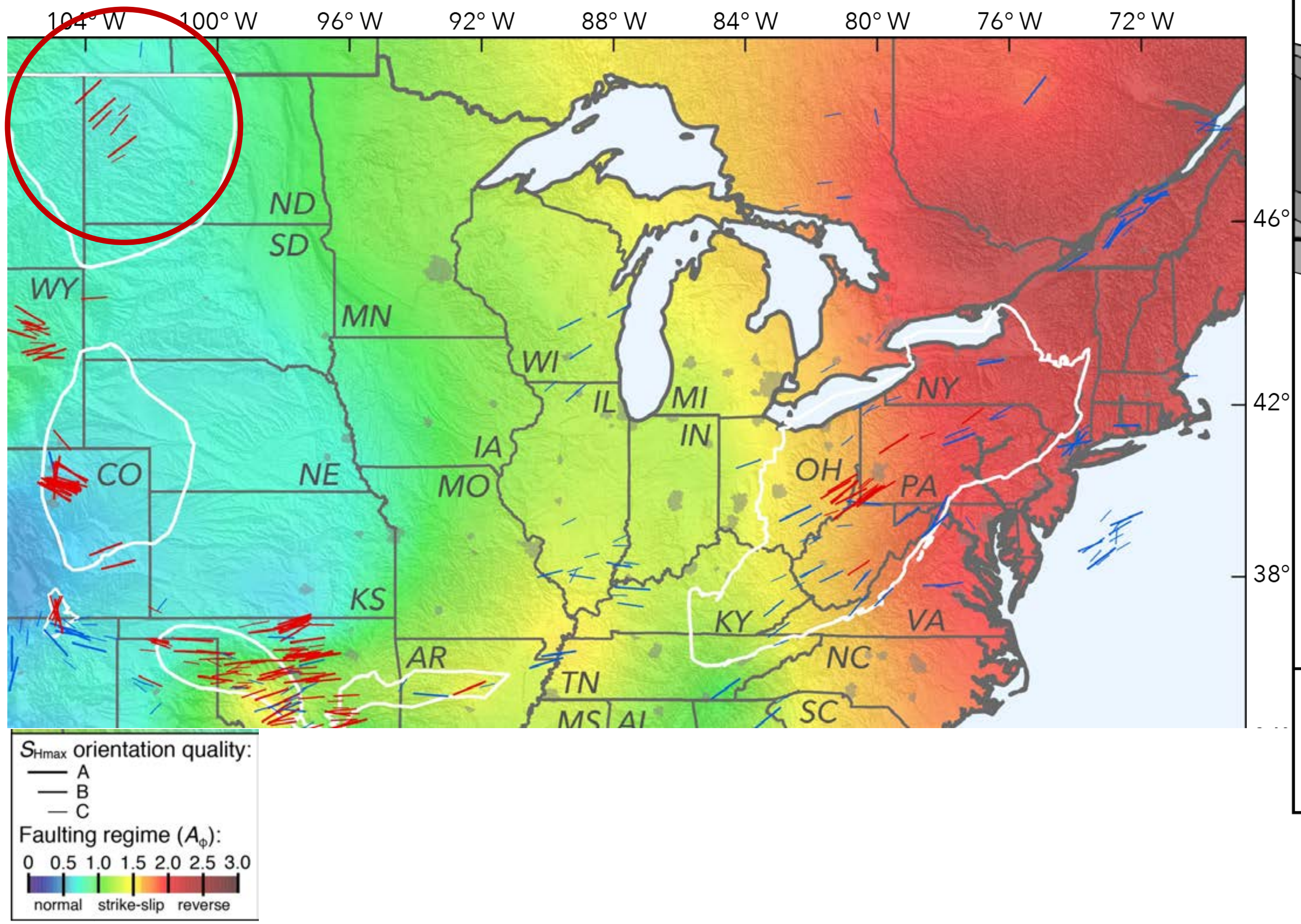
Significance of Well Orientation on Cumulative Production From Wells in the Bakken Region

Erfan Rostami*, Naomi Boness, Mark D. Zoback

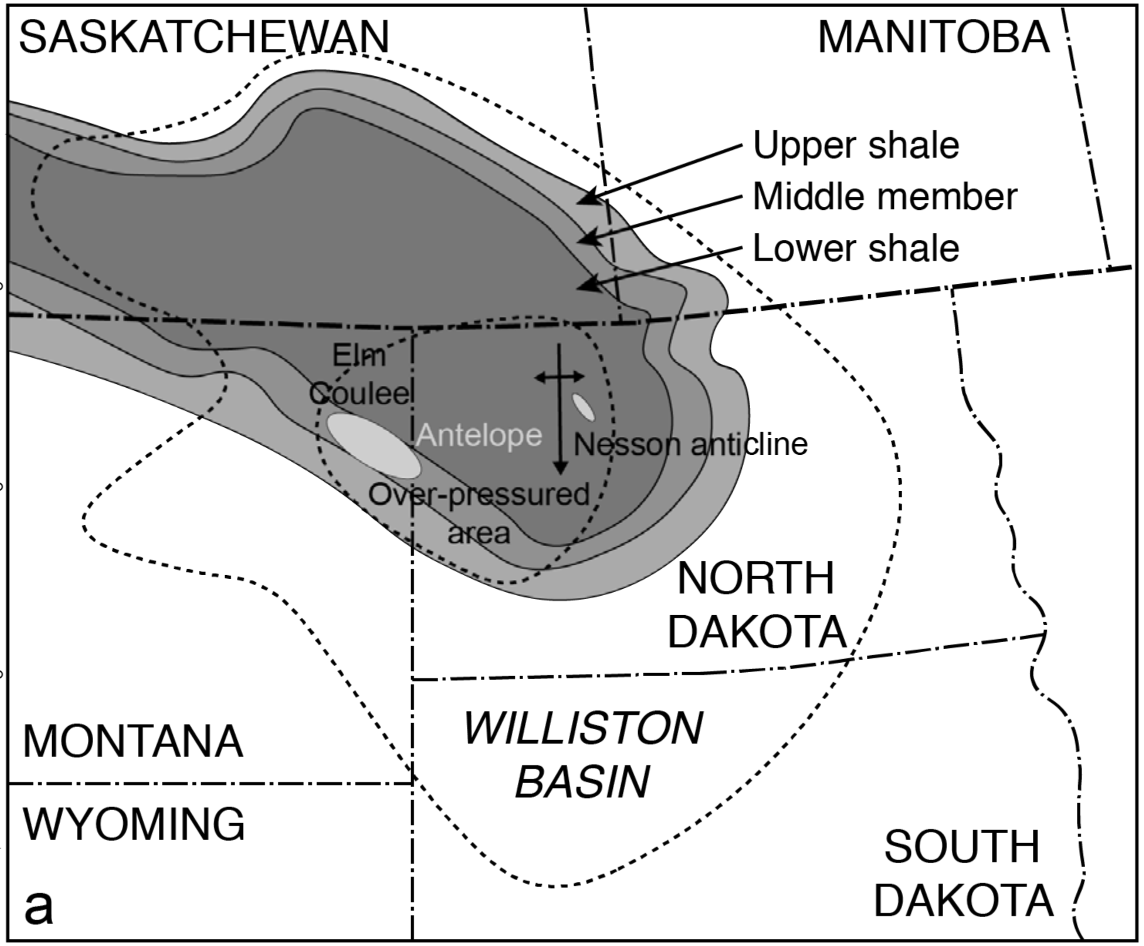
Abstract

We conducted a comprehensive analysis of approximately 7000 horizontal wells drilled in the Middle Bakken formation between 2007 and 2016 to assess the impact of well orientation on cumulative production. While it is common practice to drill horizontal wells “on-azimuth”, that is, in the direction of the minimum horizontal stress (S_{hmin}), there is a diversity of well orientations in the Bakken. S_{hmin} is consistently oriented N42°W throughout the production area. Our analysis clearly demonstrates that wells drilled in the direction of S_{hmin} (“on-azimuth”) produce more barrels per foot than wells in other directions, both in the core area and across the entire Bakken play. However, the amount of uplift gained from drilling on-azimuth wells decreases as the field matures, which we hypothesize is due to depletion. We found that the relationship between production and well orientation is consistently observed, regardless of the amount of proppant used. An economic analysis indicated that for wells of equal length, it is clearly beneficial to drill wells in the direction of S_{hmin}. However, wells in the direction of S_{hmin} are consistently shorter in length than off-azimuth wells, and it is generally more efficient to drill longer laterals on a given leasehold. Nevertheless, using the average oil price at the time the wells we studied were drilled, we find that the shorter wells in the on-azimuth direction have a significant economic uplift of several million dollars per well relative to the longer wells drilled in the off-azimuth direction.

Bakken



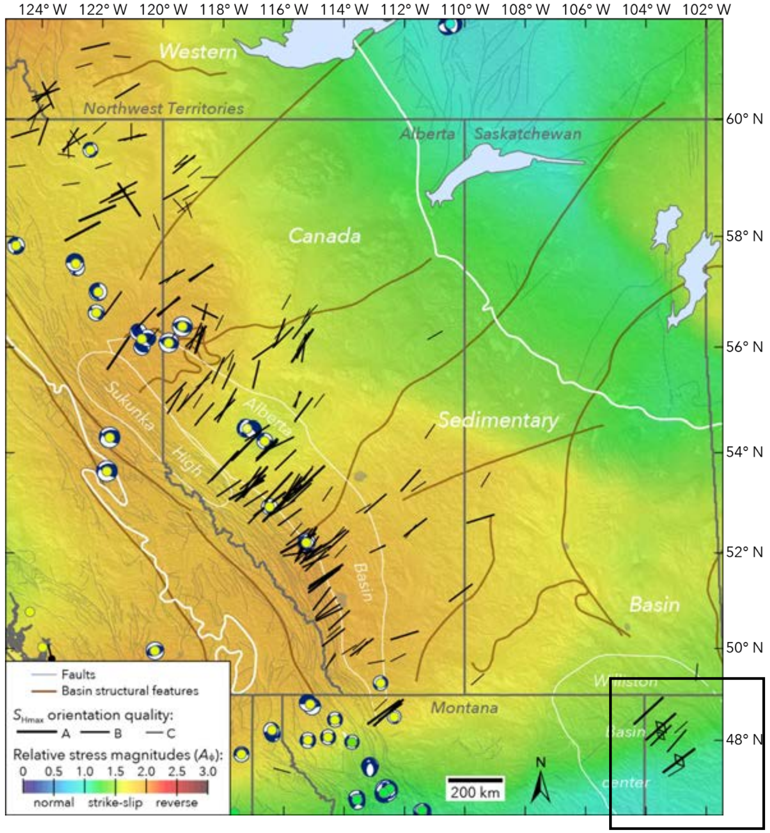
Bakken

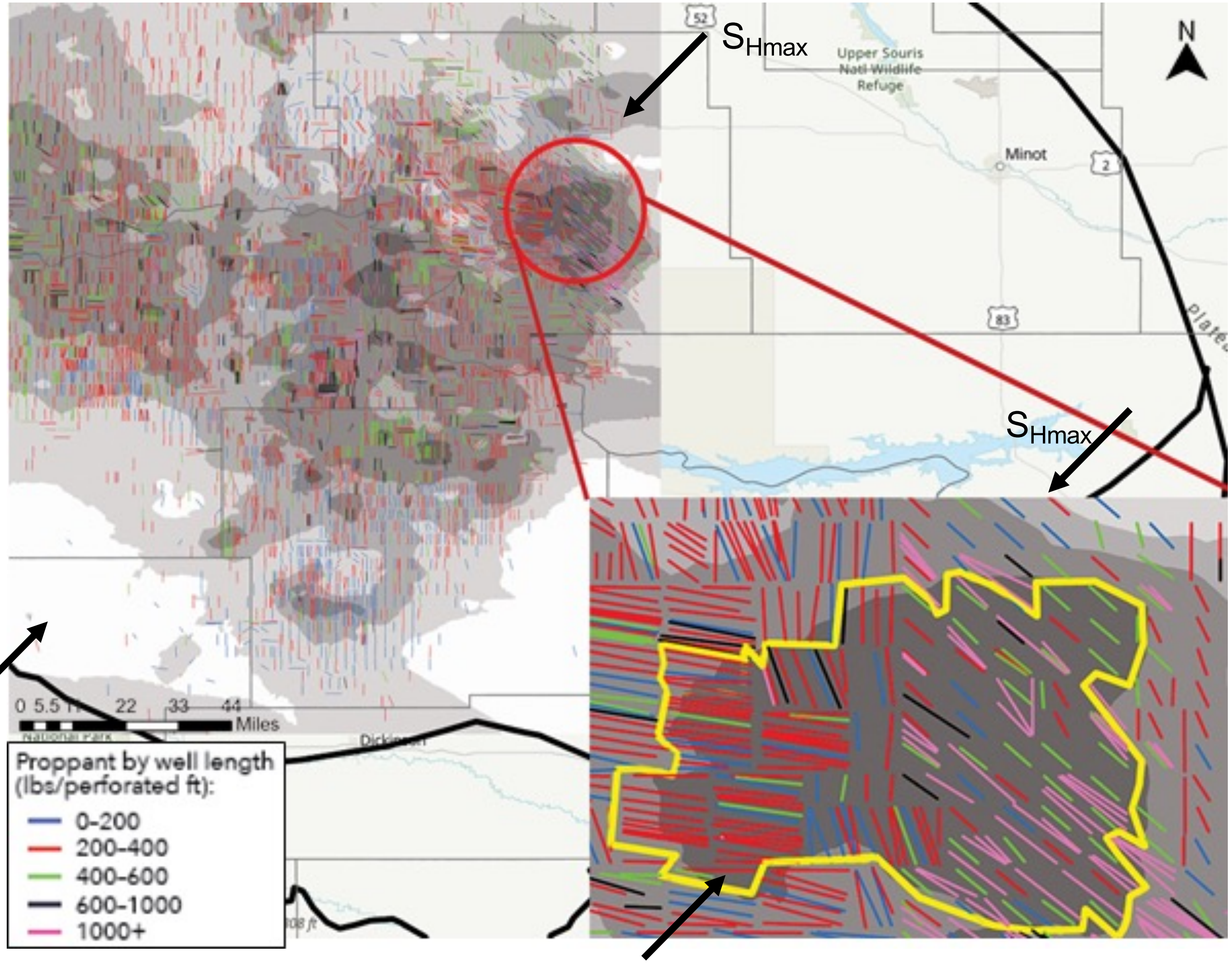


"Well Orientation Doesn't Matter?"

Lund Snee and Zoback (AAPG 2021)

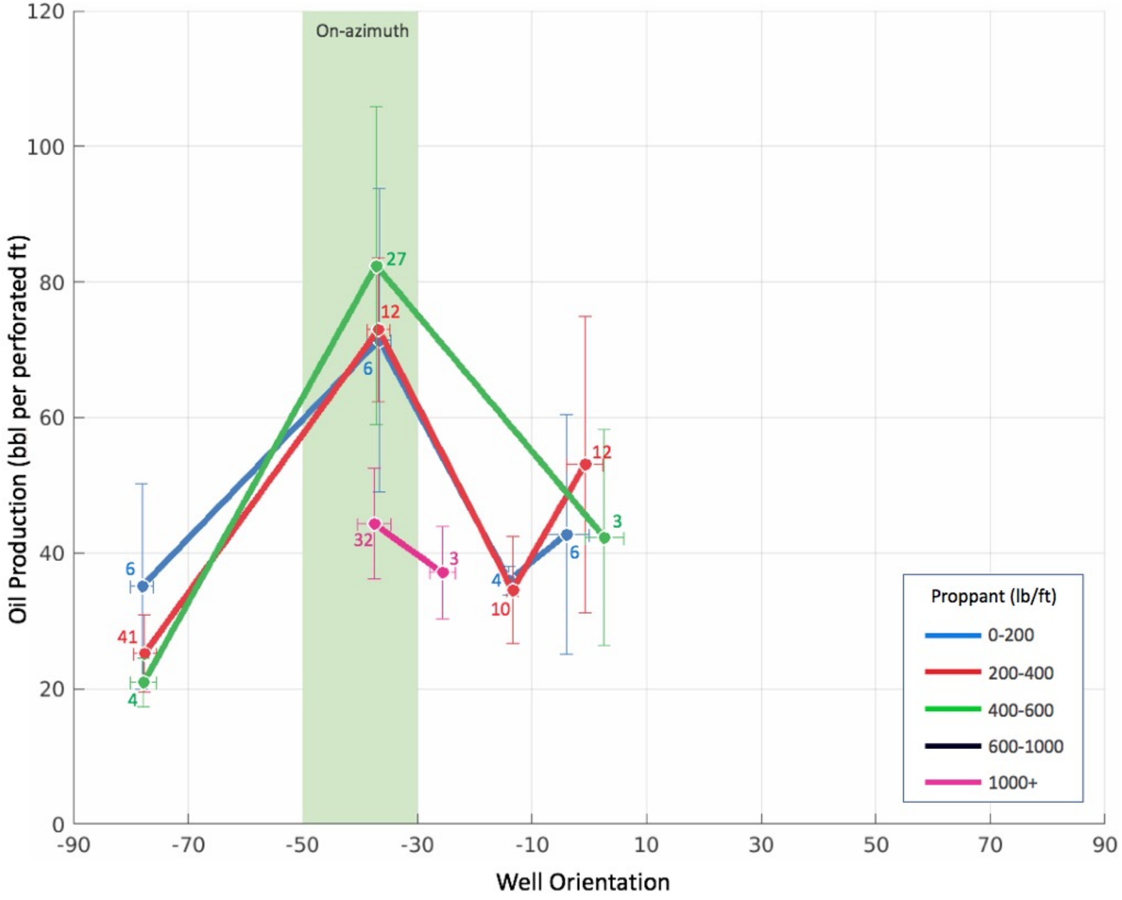
Well Orientation Study in the Core Area of the Bakken



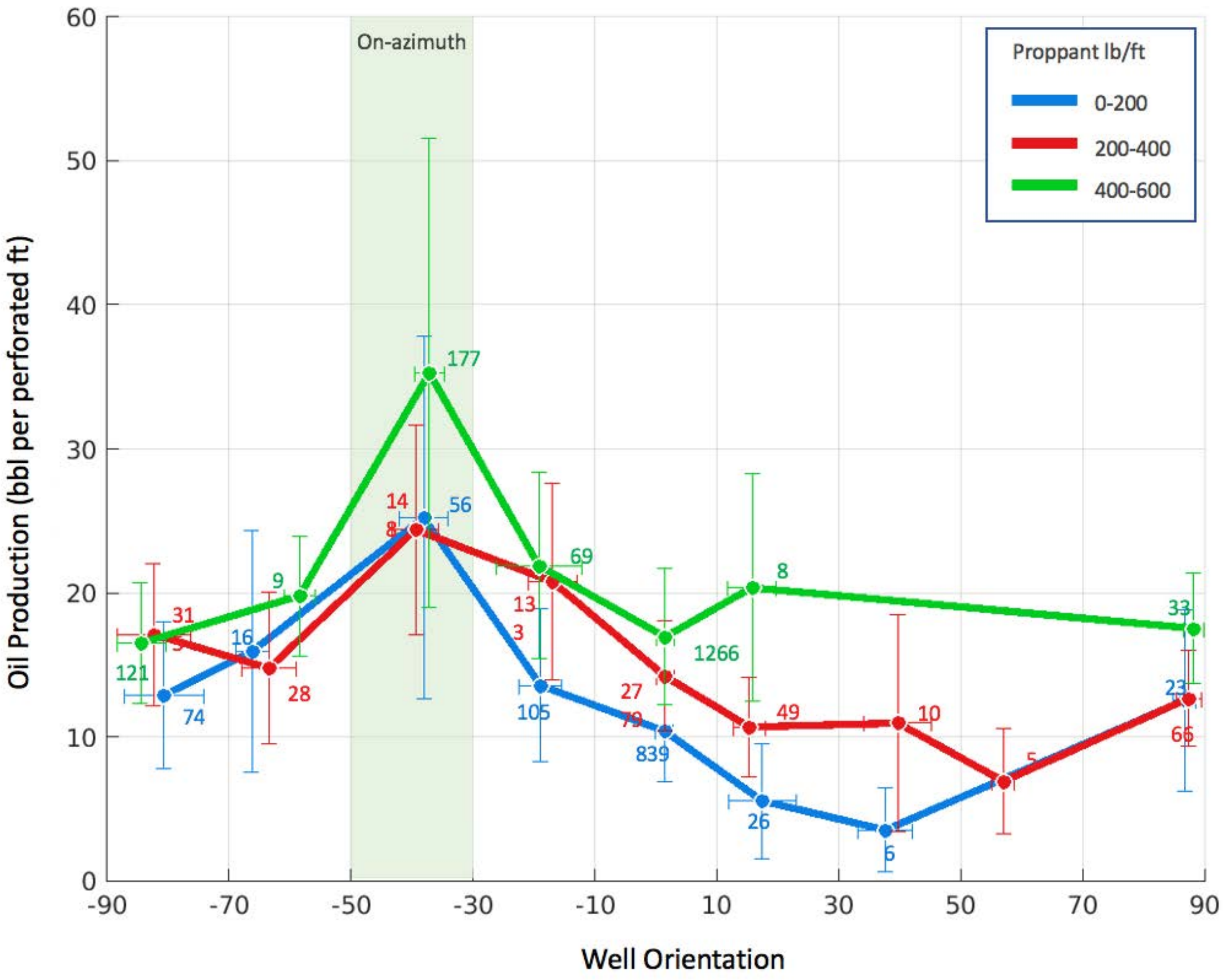


Rostami, Boness and Zoback (URTeC, 2020)

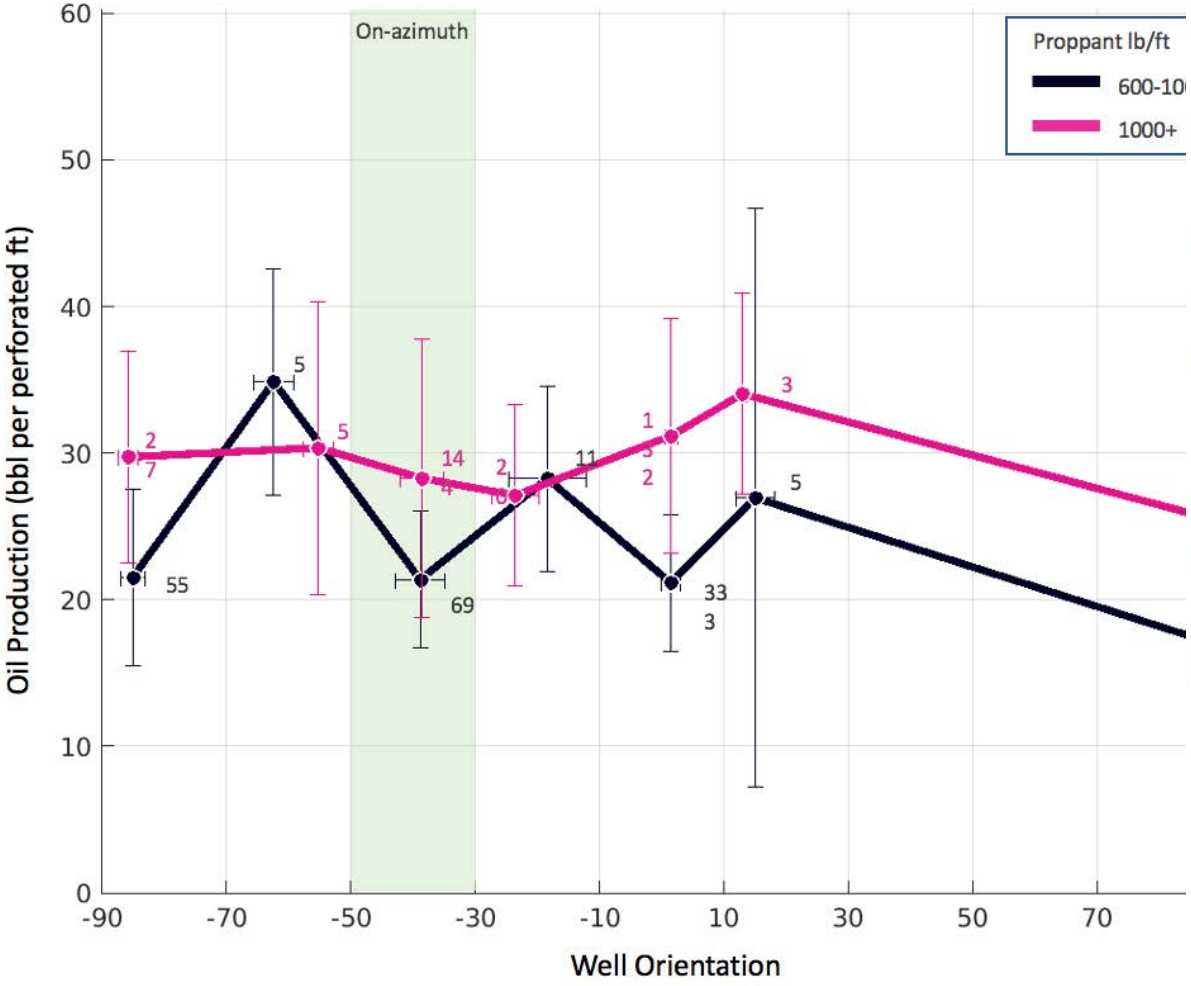
Bakken Core Area
176 wells (all epochs)



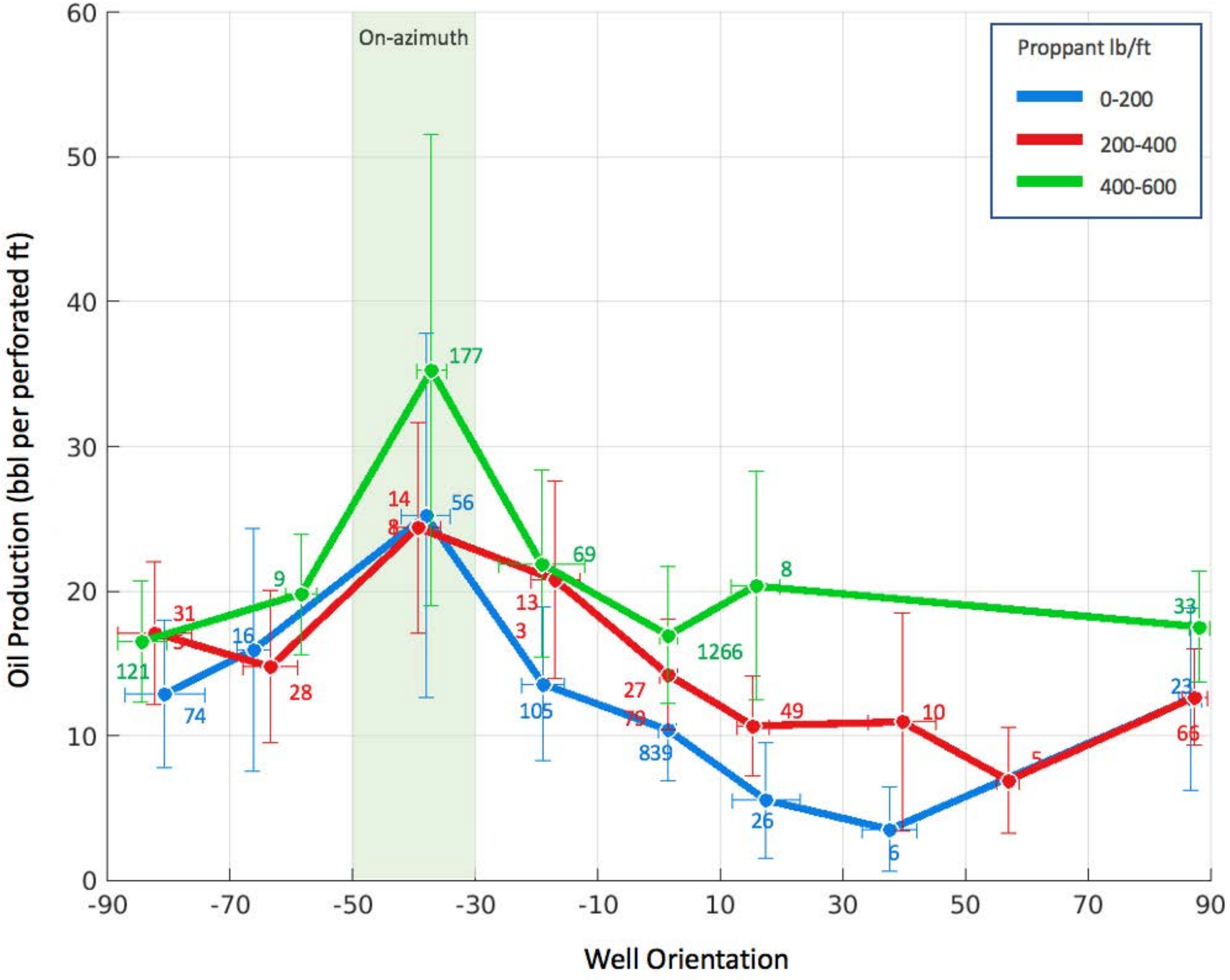
Entire Bakken Play
~7000 wells (first 3 epochs)



Entire Bakken Play
~7000 wells (last 2 epochs)



Entire Bakken Play
~7000 wells (first 3 epochs)



Permian Basin

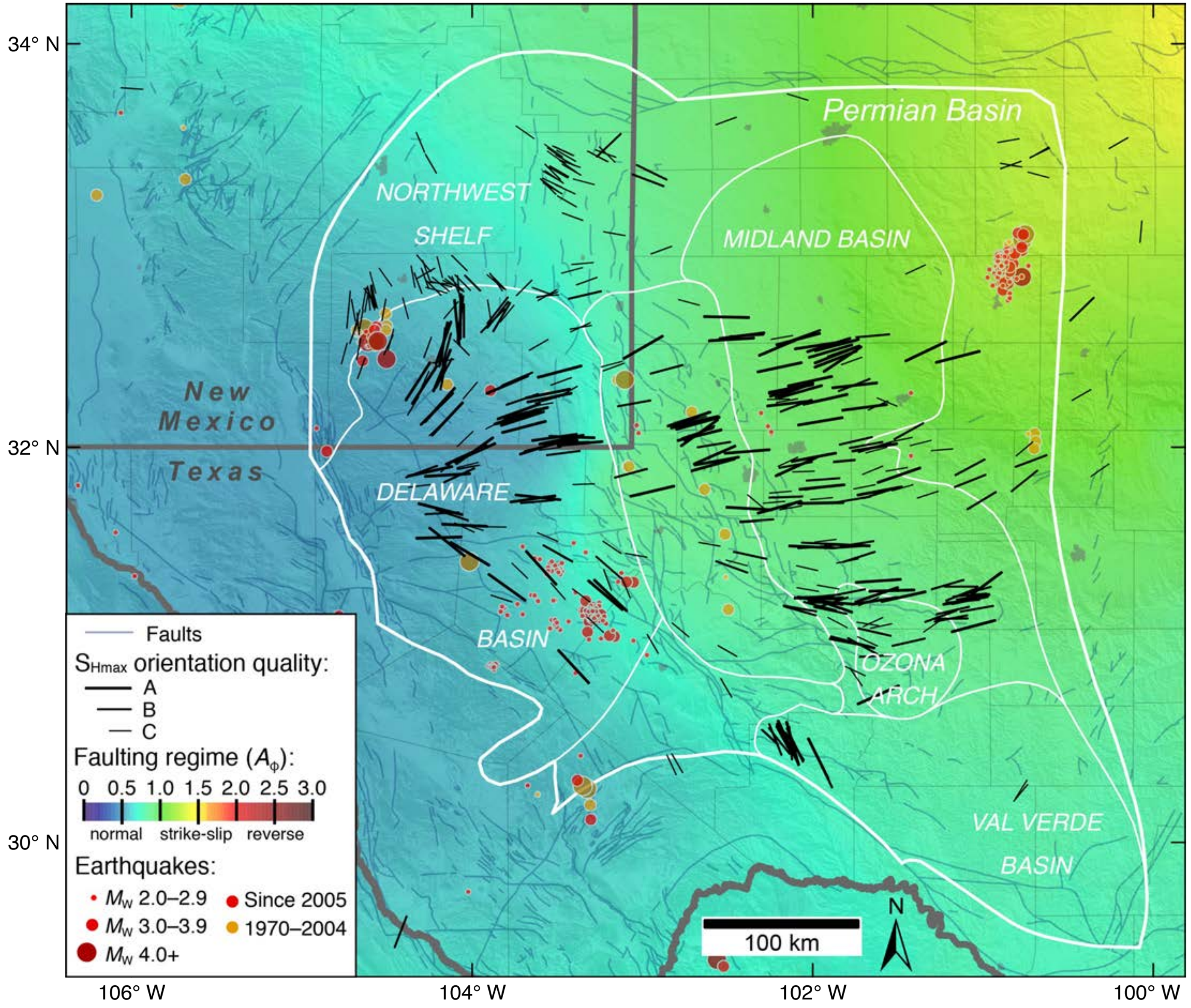
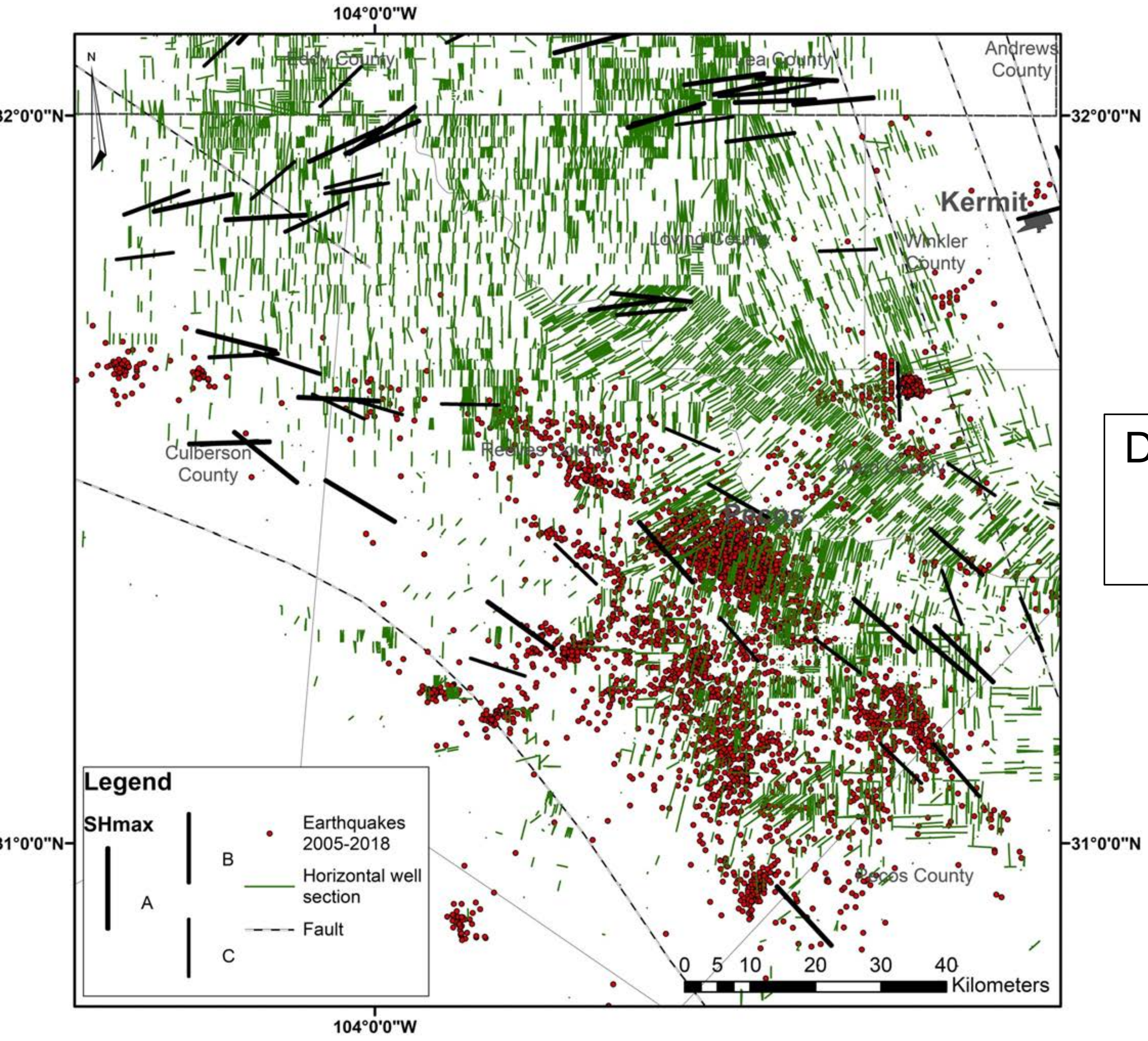


Fig. 7.3

Lund Snee and Zoback (2017)



Delaware Basin – HF-Induced Normal Faulting

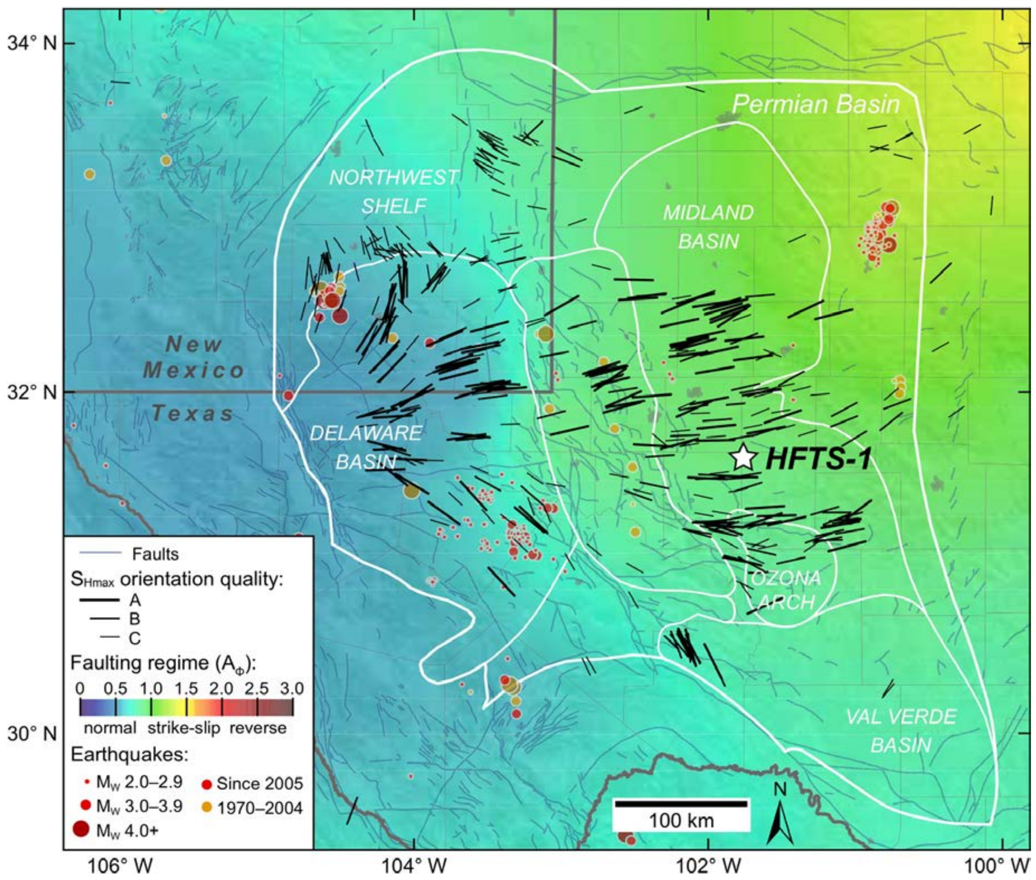
Many Wells NOT Drilled in Direction of S_{hmin}

Three Topics

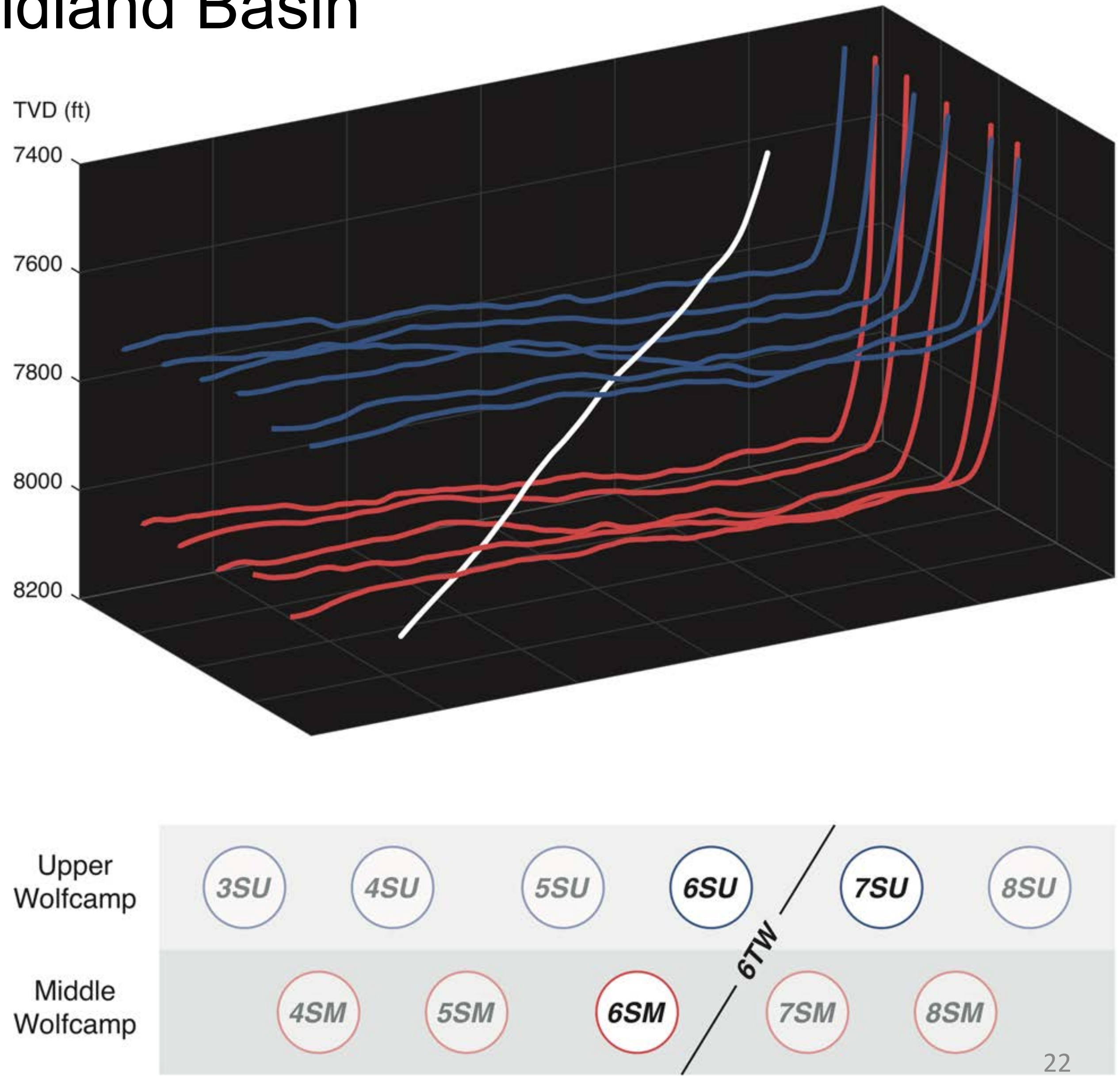
- Get the Stress Right (You Can't do Geomechanics Right With the Wrong Stress State).
    - Lessons from North America
    - Drilling Horizontal Wells in the Correct Direction (Bakken Example)

        1. Stress Orientation
        2. Variation of S_3 (S_{hmin}) with Depth

HFTS 1 - Midland Basin

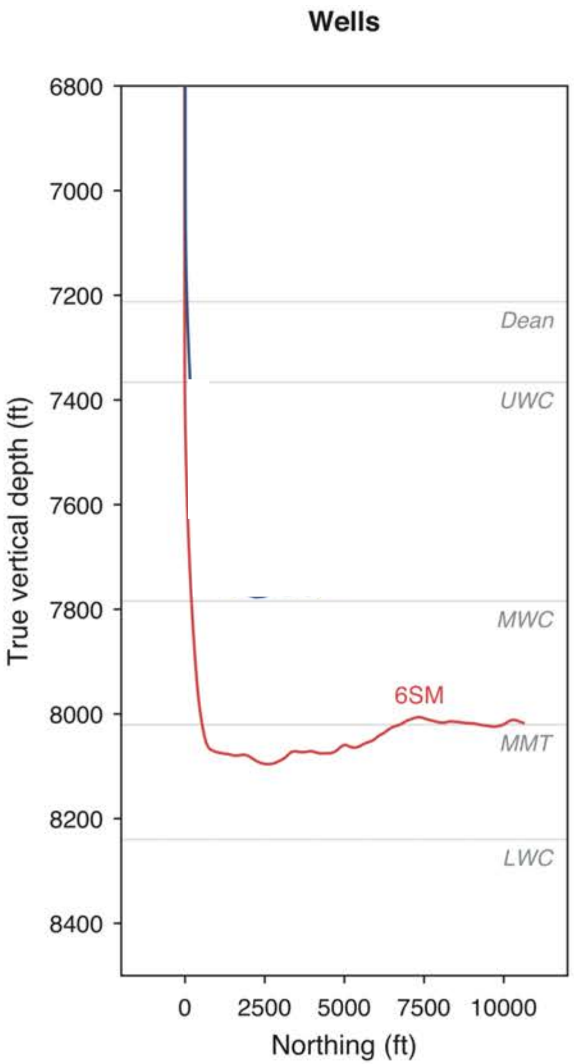


Lund Snee & Zoback (2018)

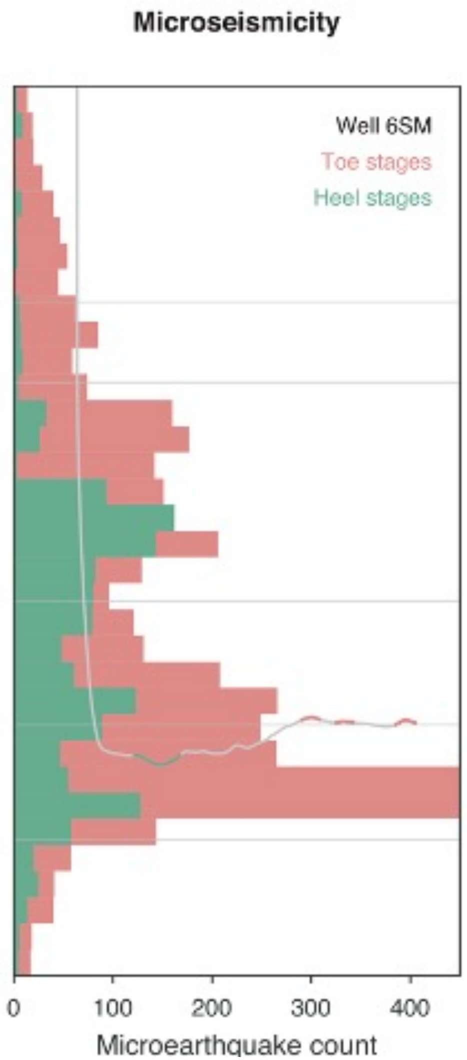


Kohli and Zoback (accepted, 2021)

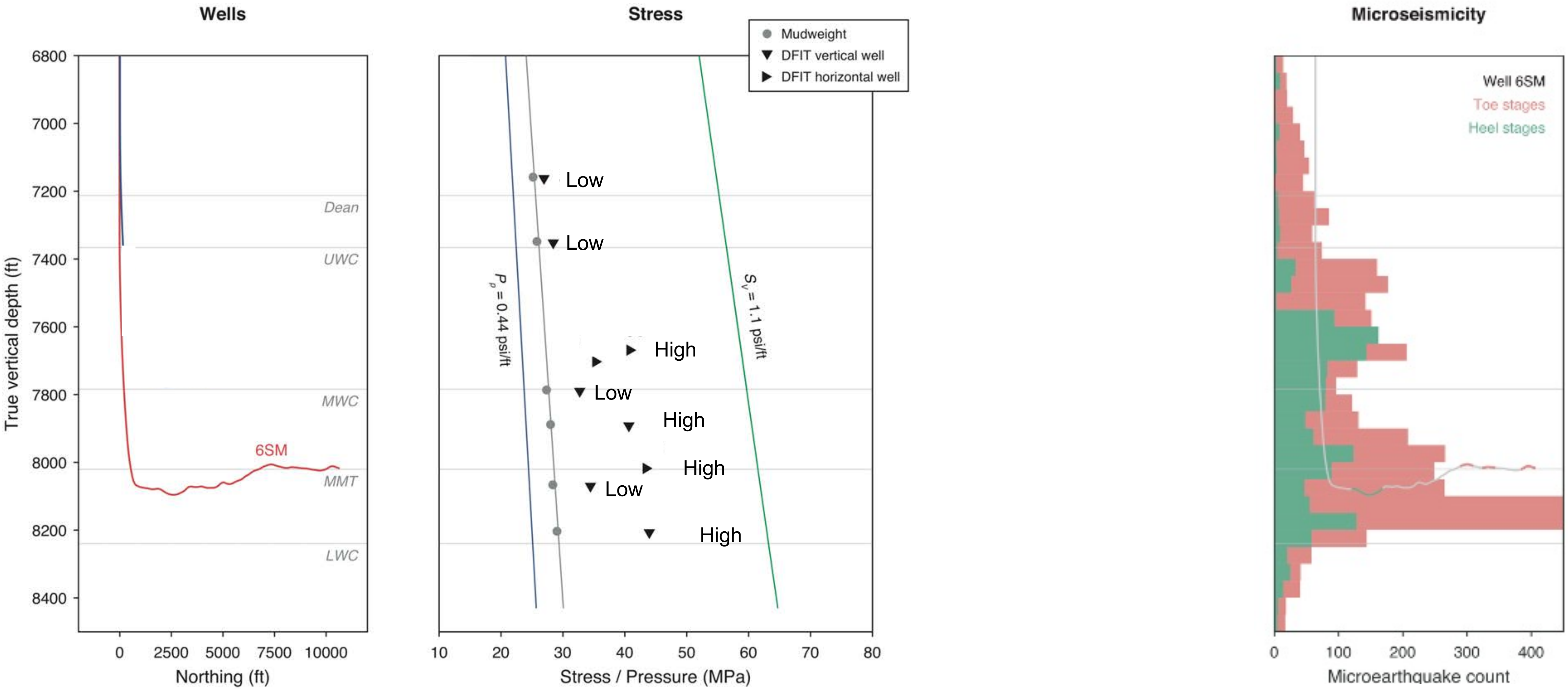
Variation of S_{hmin} With Depth



Why is the Microseismic Response of Toe Stages and Heel Stages in 6SM so Different?



Variation of S_{hmin} With Depth



Woodford Formation – Layer-to-Layer Stress Variations

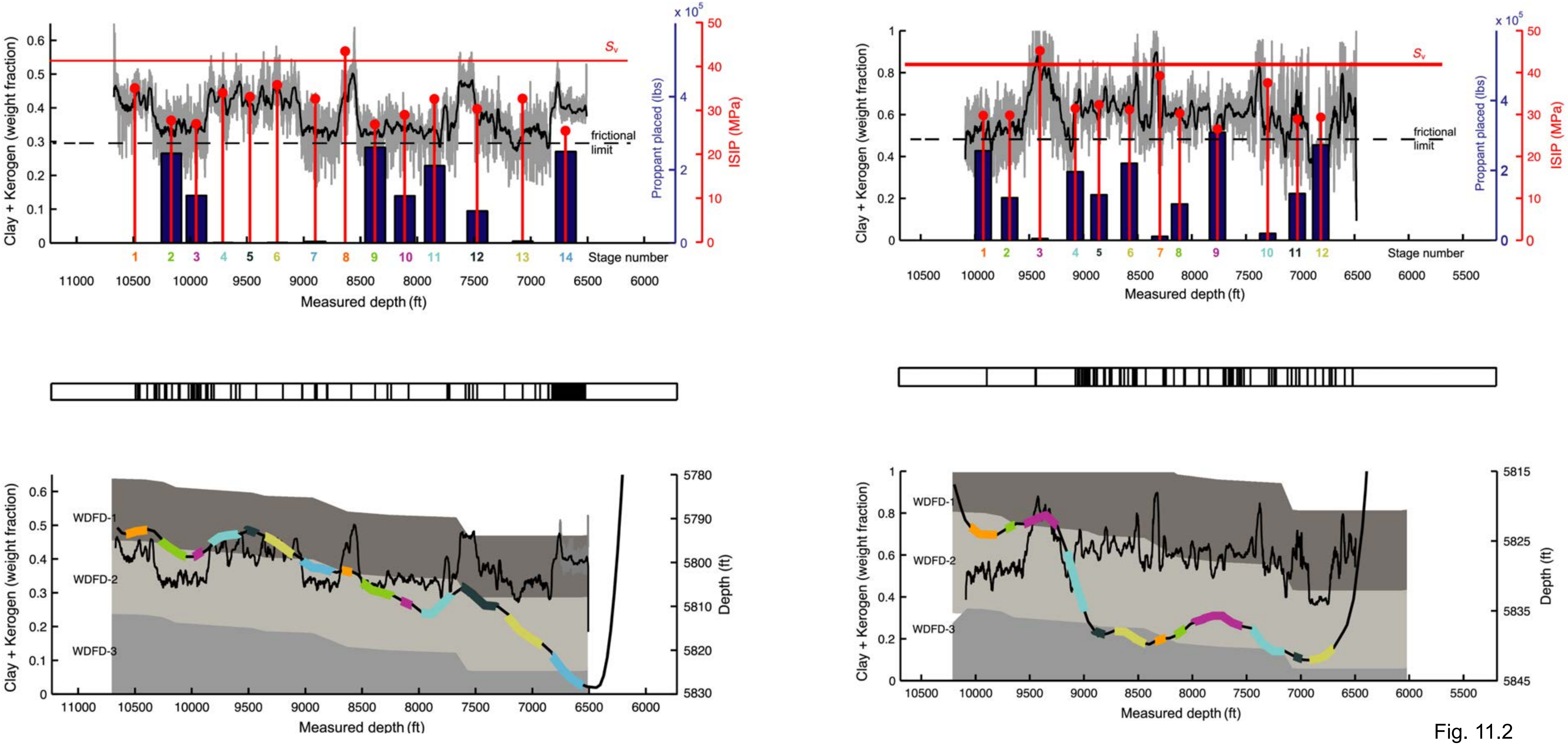
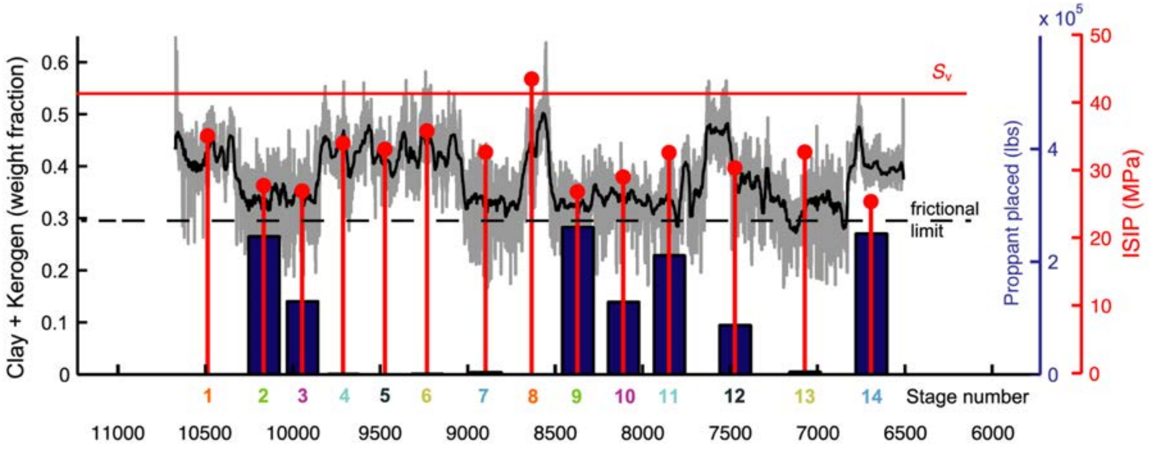
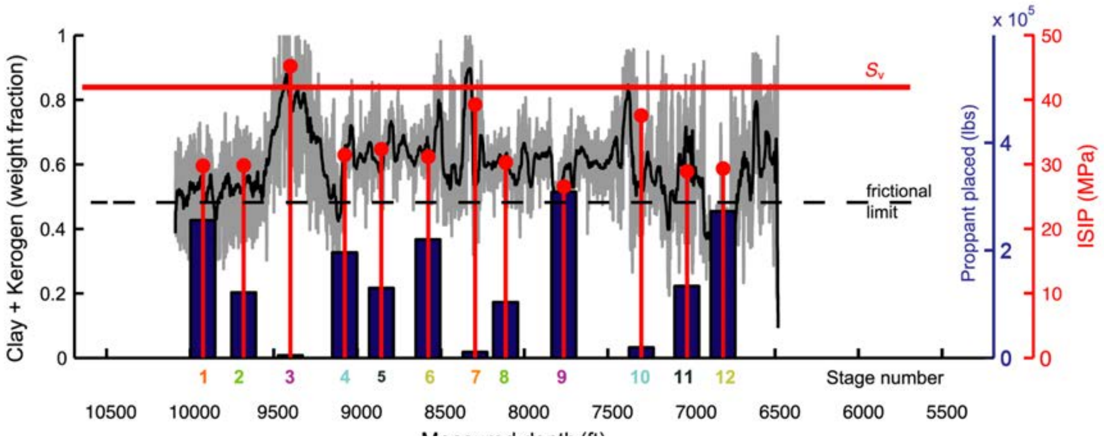


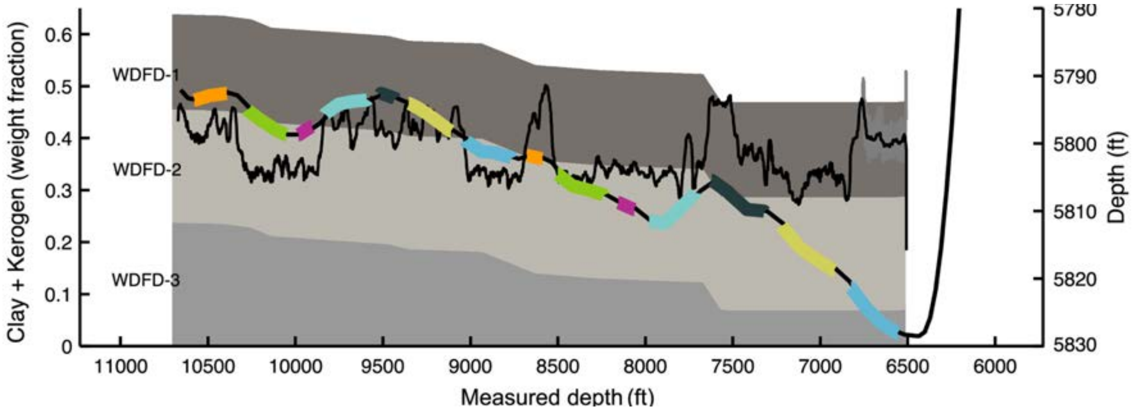
Fig. 11.2

Woodford Formation – Layer-to-Layer Stress Variations





What Looks Like Lateral Complexity is Simply Layer-to-Layer Stress Variations - Controlled by Lithology and Sampled by Well Path



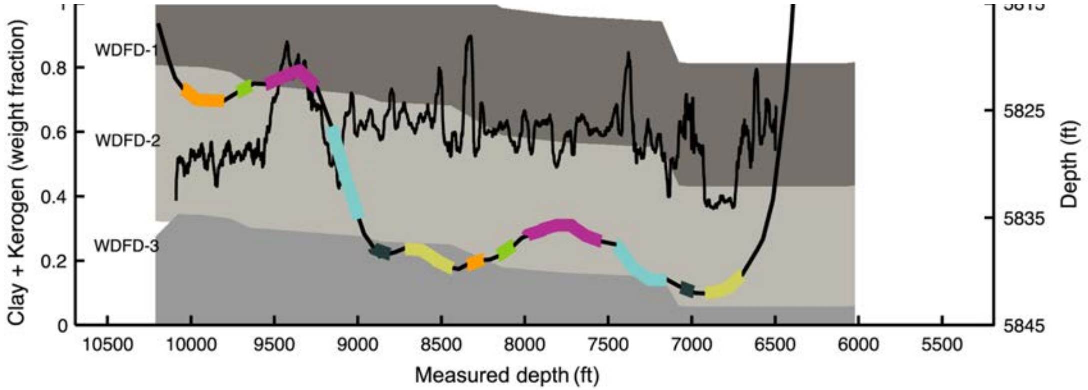


Fig. 11.2

Layer-to-Layer Stress Variations Caused by Viscoplastic Stress Relaxatior

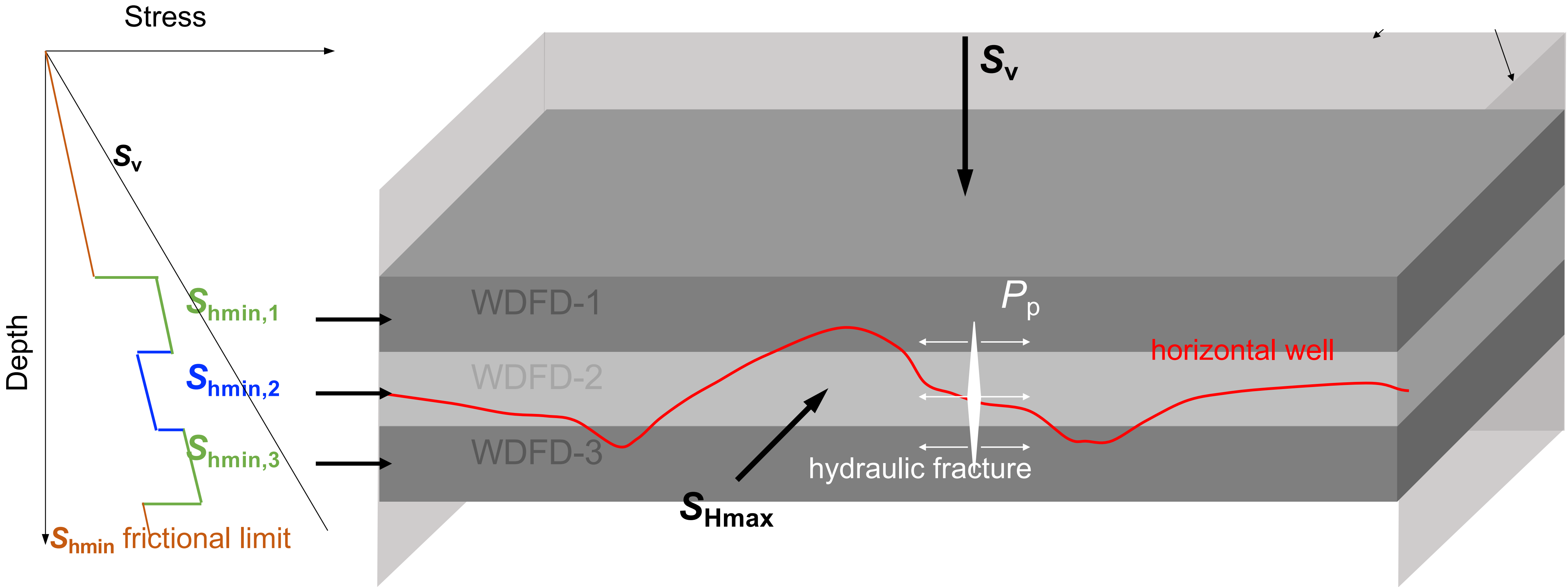


Fig. 11.13

What Looks Like Lateral Complexity is Simply Layer-to-Layer Stress Variations - Controlled by Lithology and Sampled by Well Path

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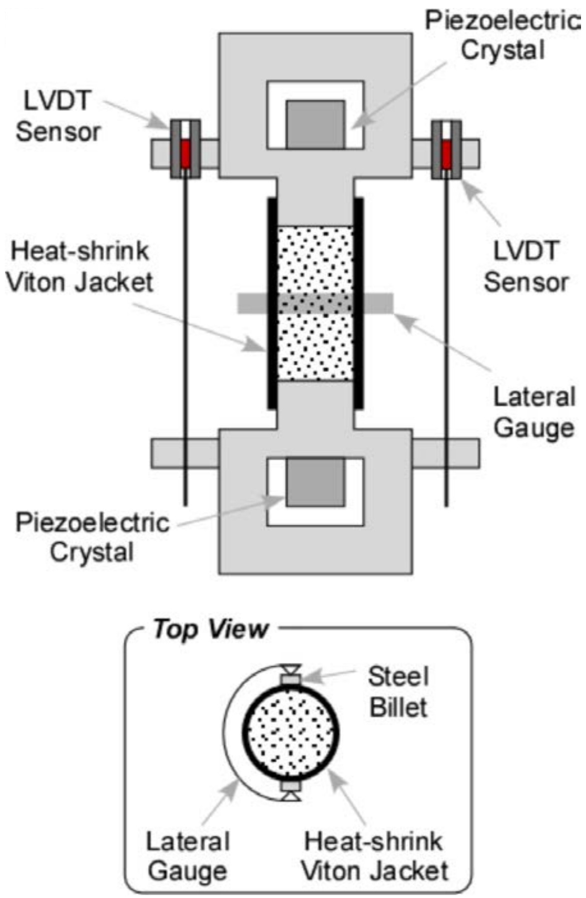


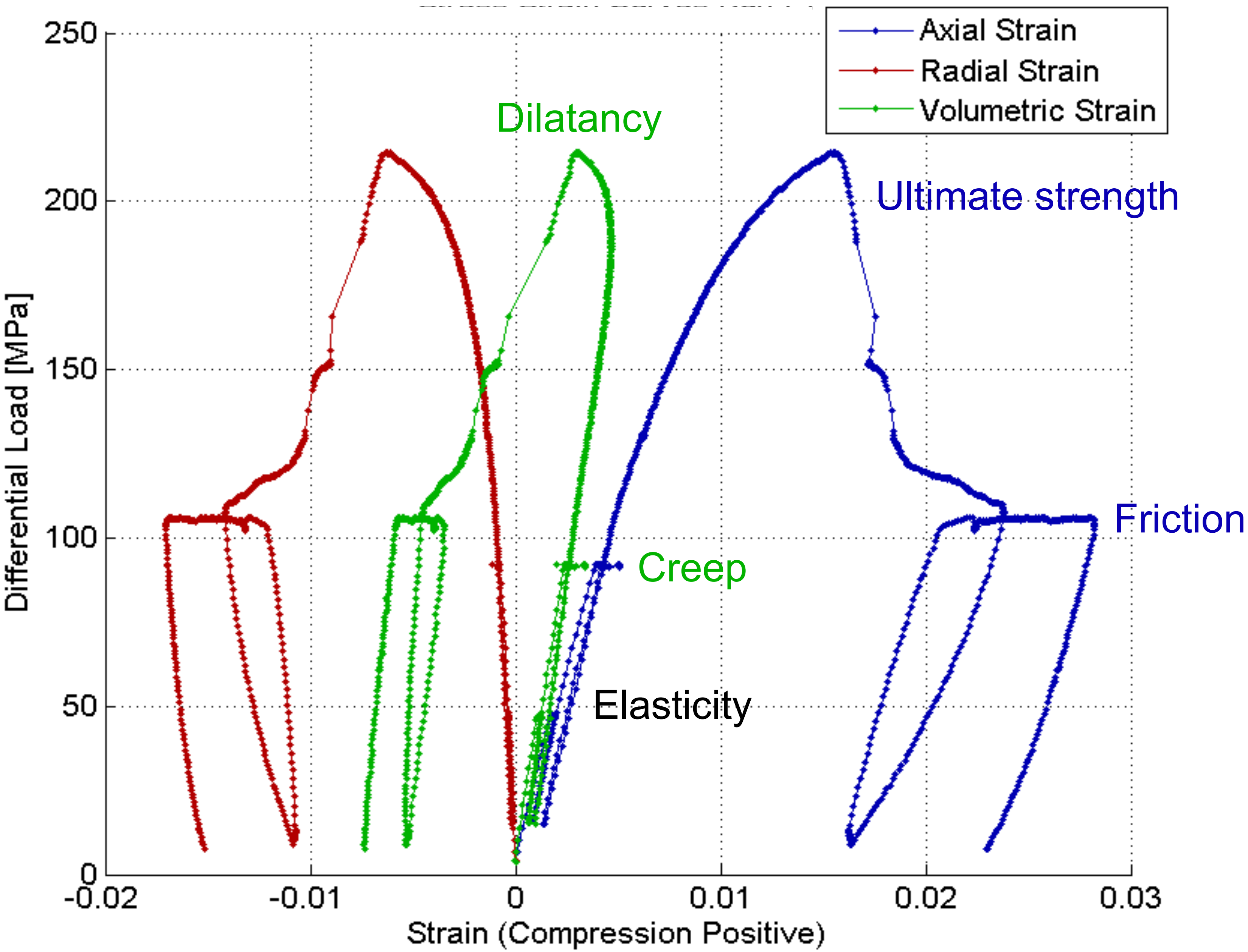
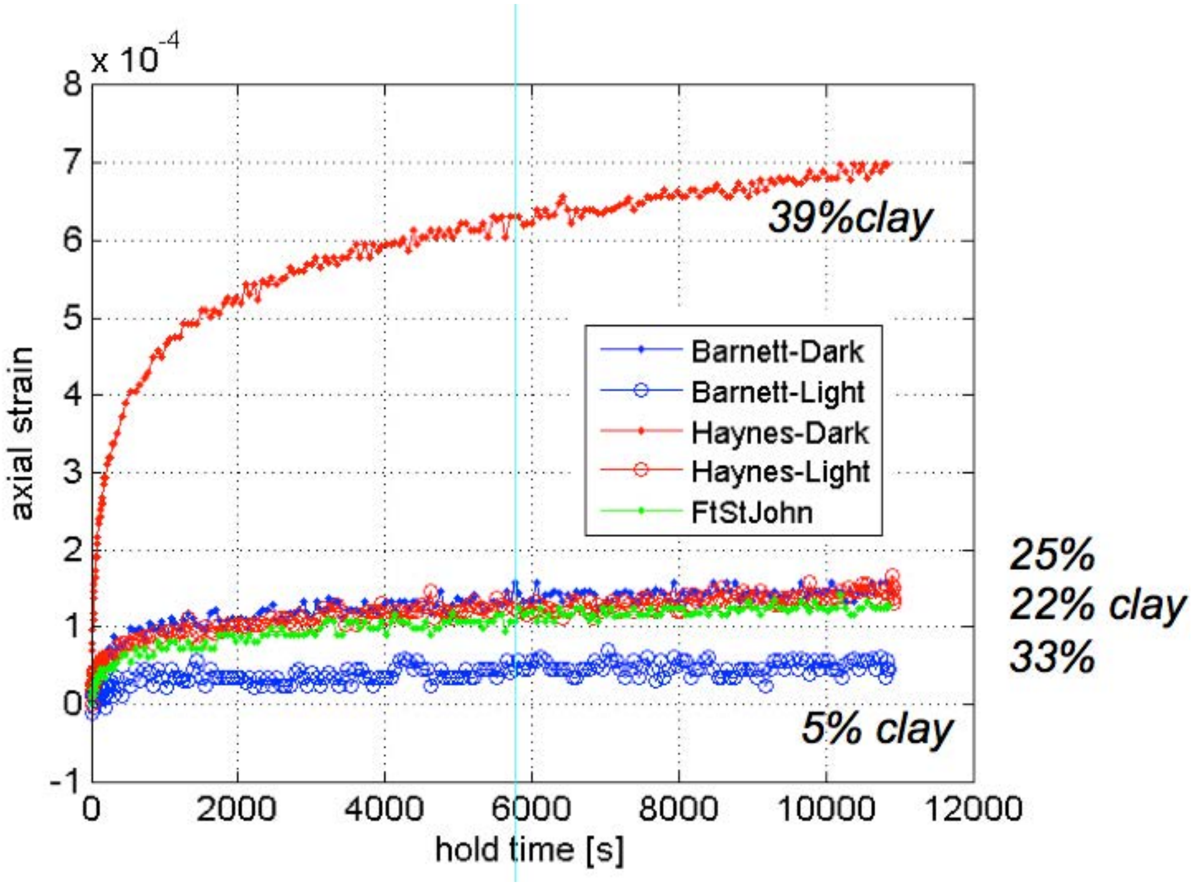


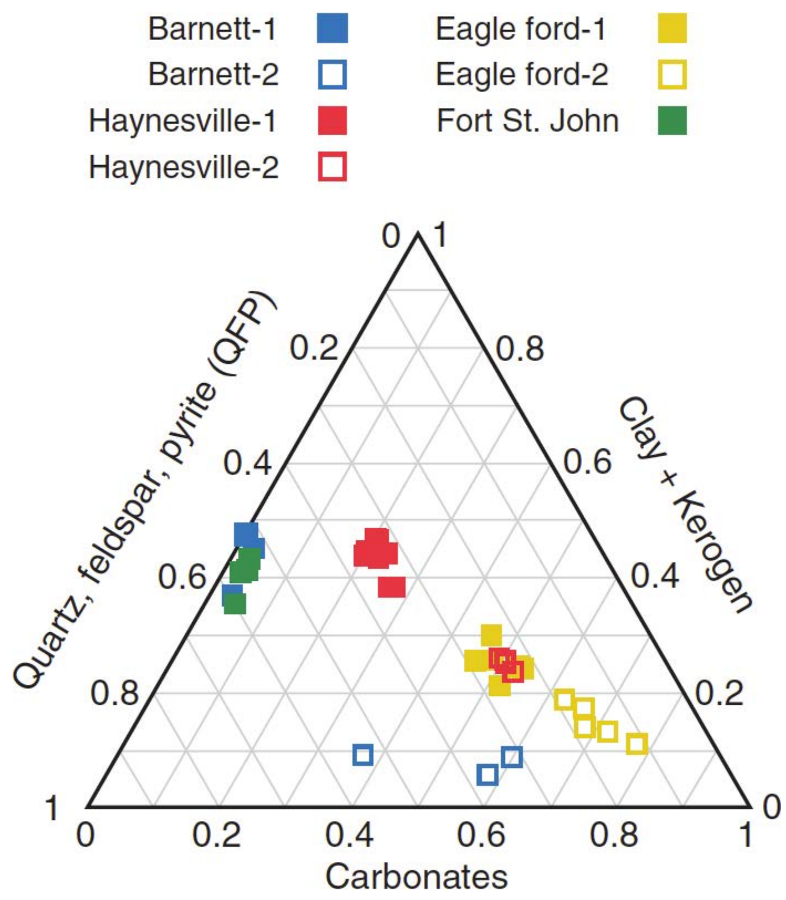
Fig. 3.1

Sone (2012)

Ductility → Viscoplasticity → Stress Relaxation

Stress Relaxation → Increase in Frac Gradient





Sone and Zoback (2013b)

Time-dependent Deformation (Creep)

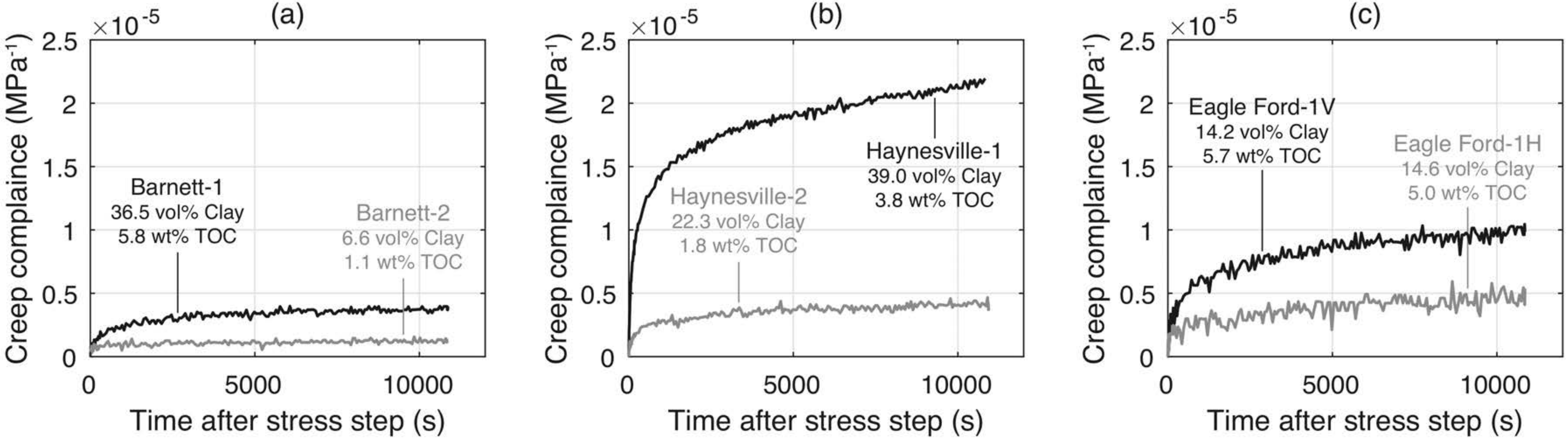


Fig. 3.7

- Creep compliance – 3 hr axial creep strain normalized by applied differential stress
- Samples from different reservoirs show different creep at similar clay + TOC
    - Similar to elastic properties, creep depends on both composition and microstructure

Time-Dependent Deformation (Creep)

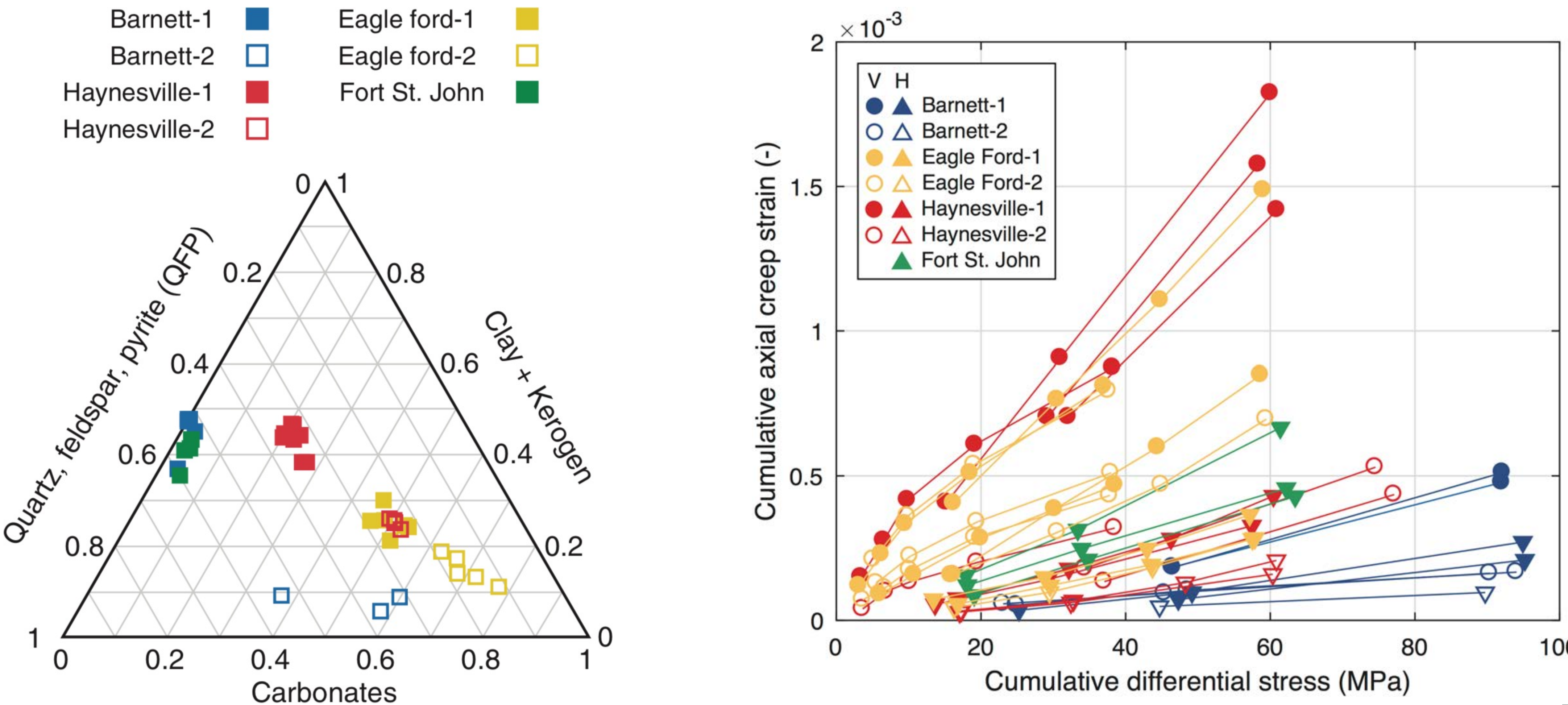


Fig. 3.6

Long Term Creep Experiments - Creep Constitutive Law

Short term experiments (3 hr) suggest logarithmic behavior

$$\varepsilon_{creep}(t) = A\log(t)$$

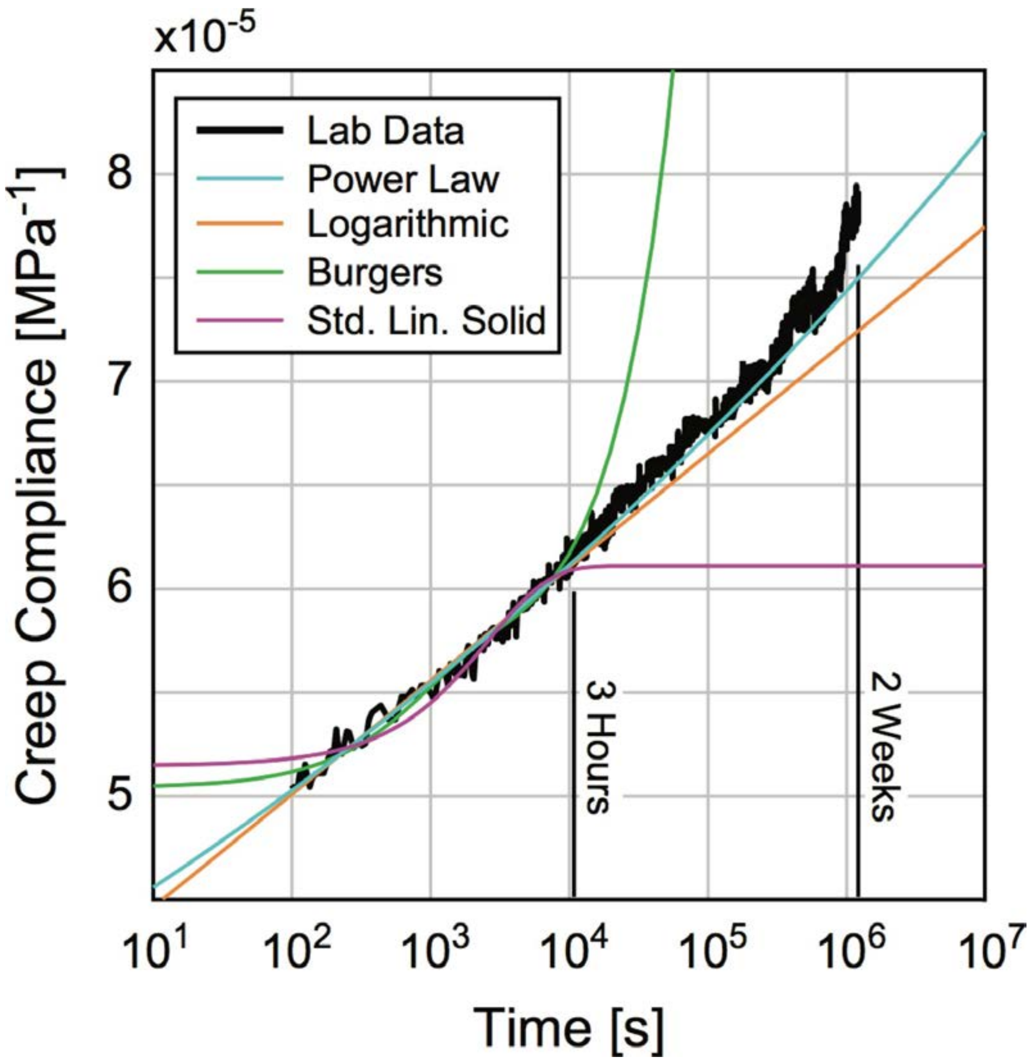
Longer term experiments better fit by a power law

$$\boxed{\varepsilon_{creep}(t) = Bt^n}$$

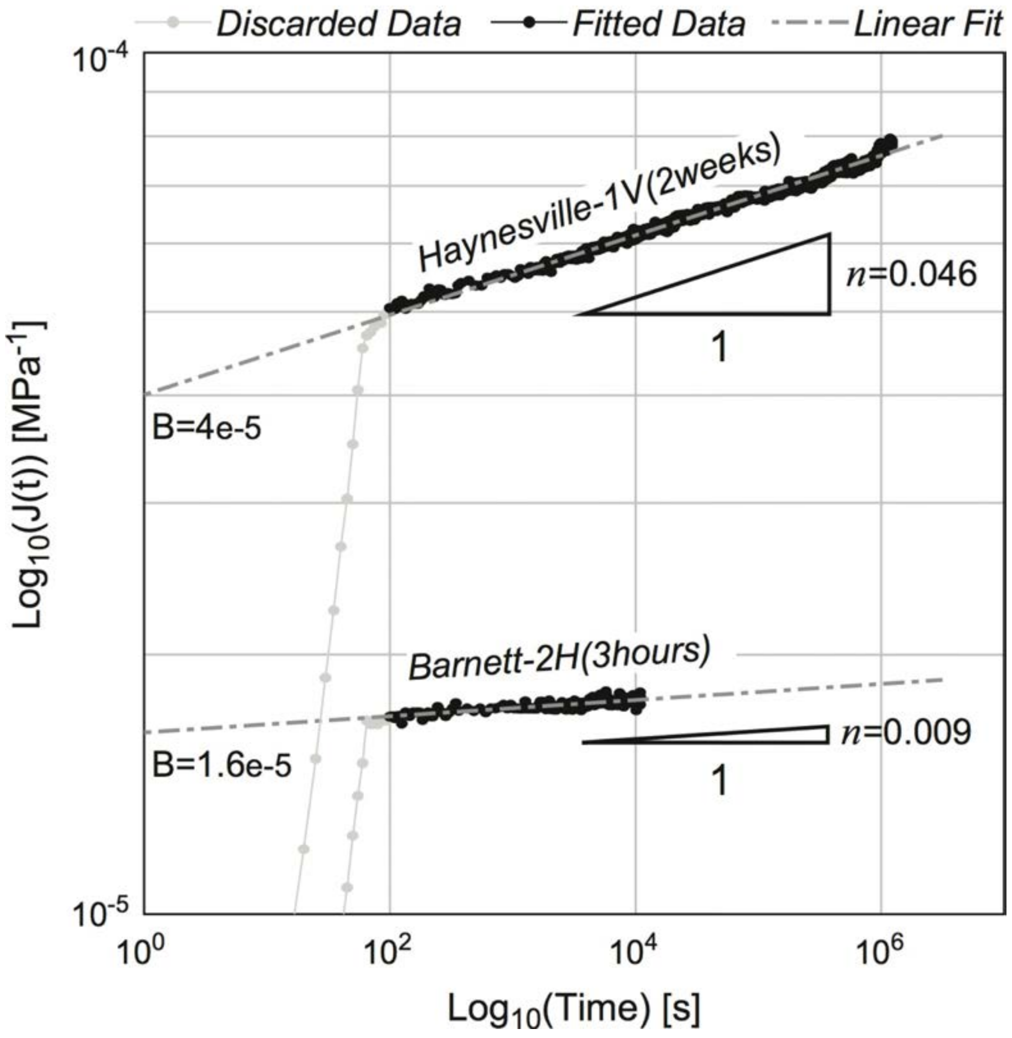
Power law describes both elastic and creep response

$$J(t) = \frac{\varepsilon}{\sigma} = Bt^n$$

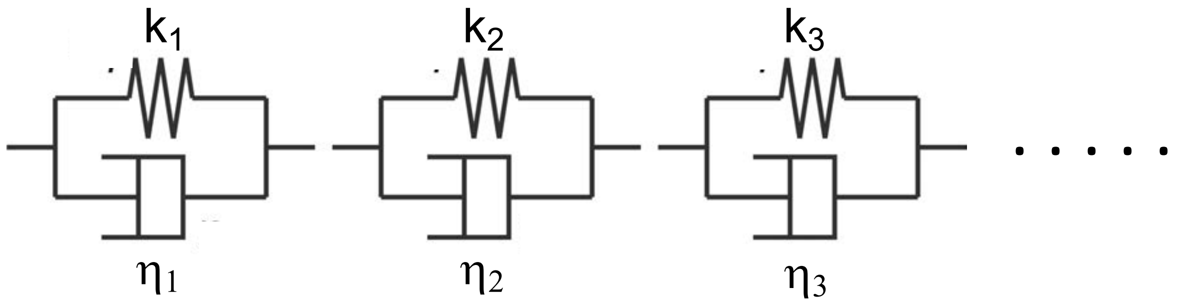
$$\log J(t) = \log B + n\log t$$



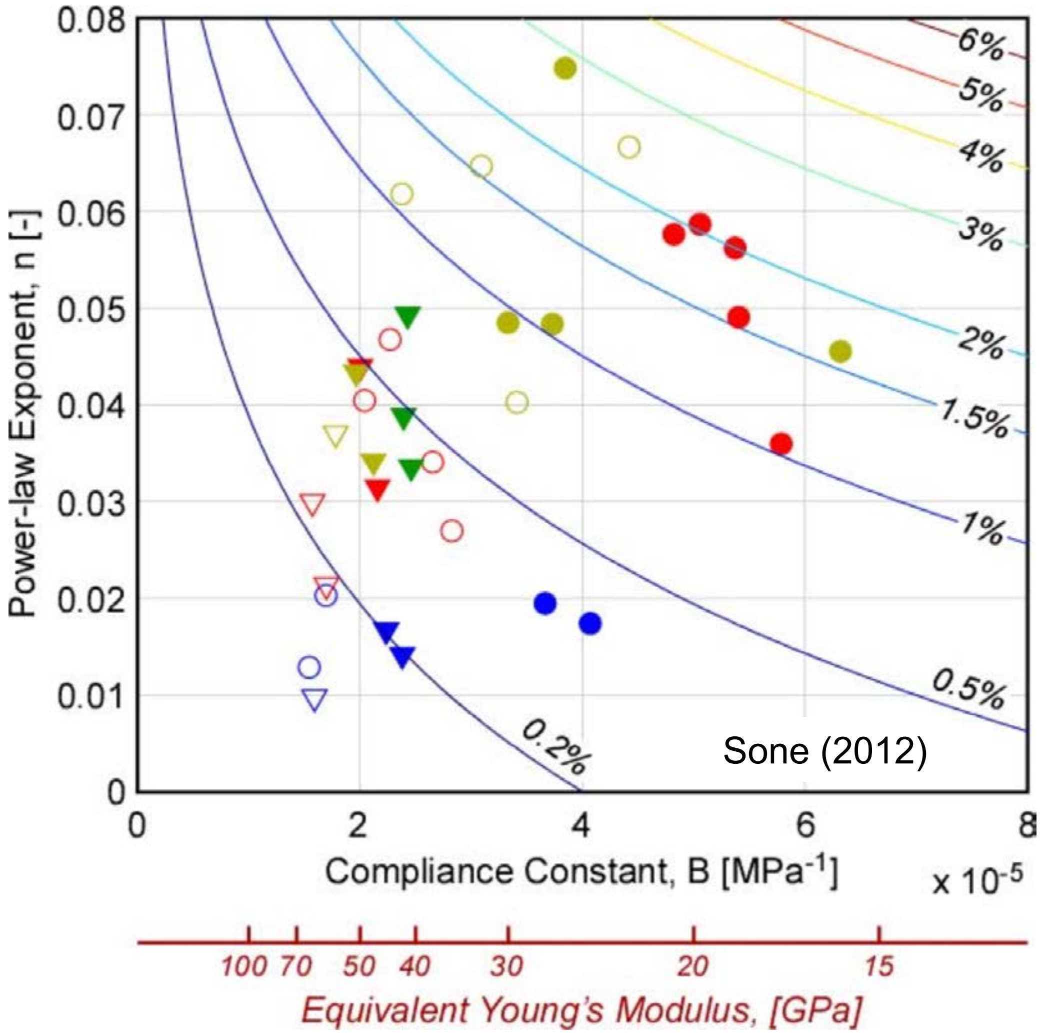
Viscoelastic Power Law



- In log-log space, creep strain is linear with time
- Separate elastic (grey) and creep (black) responses
- Model parameters have simple interpretations
    - *B* describes the elastic compliance
    - *B^{-1}* correlates with Young's modulus
    - *n* describes the time-dependent response
- Power law model equivalent to Kelvin model in series



Reality Check 1. – Creep Strain Over Geologic Time



Are strain predictions from lab measurements reasonable over geologic time?

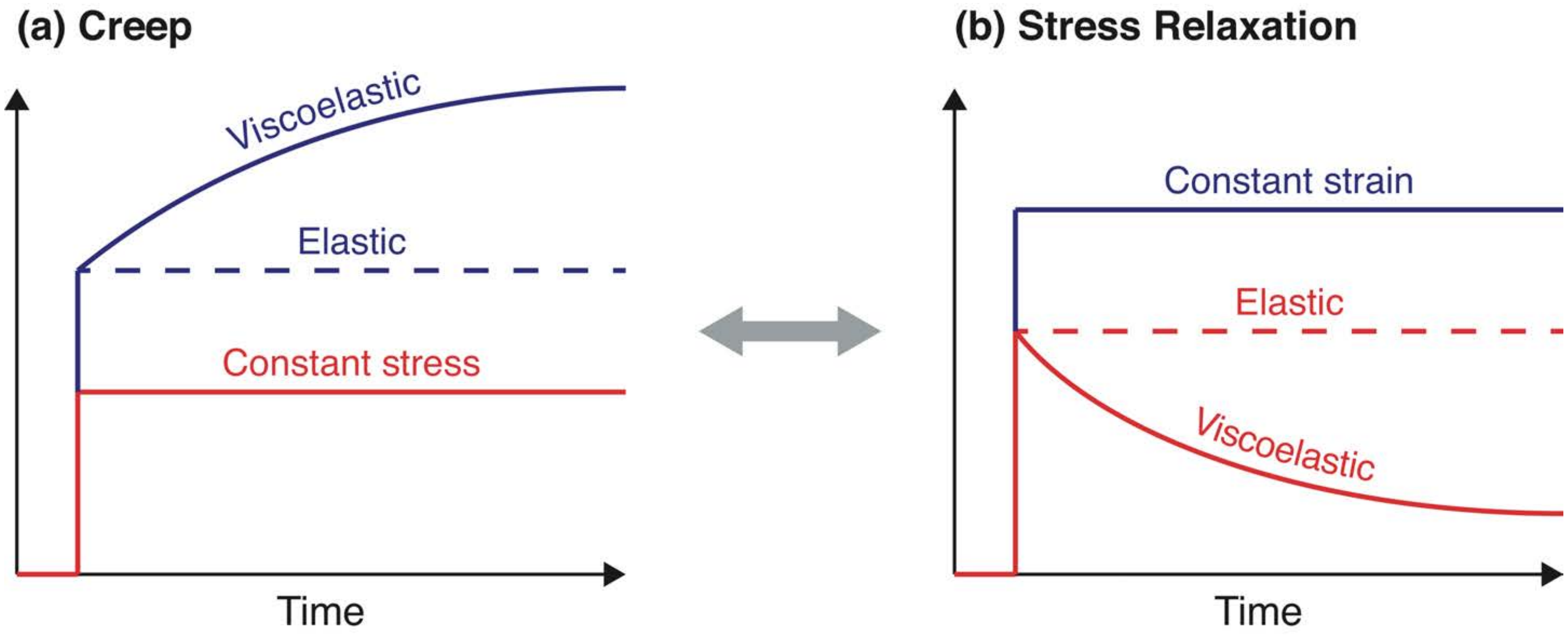
Contours – % axial strain over 100 Ma under 50 MPa

Axial strain ranges from ~0.1 – 3%

Creep is accommodated by pore/crack compaction

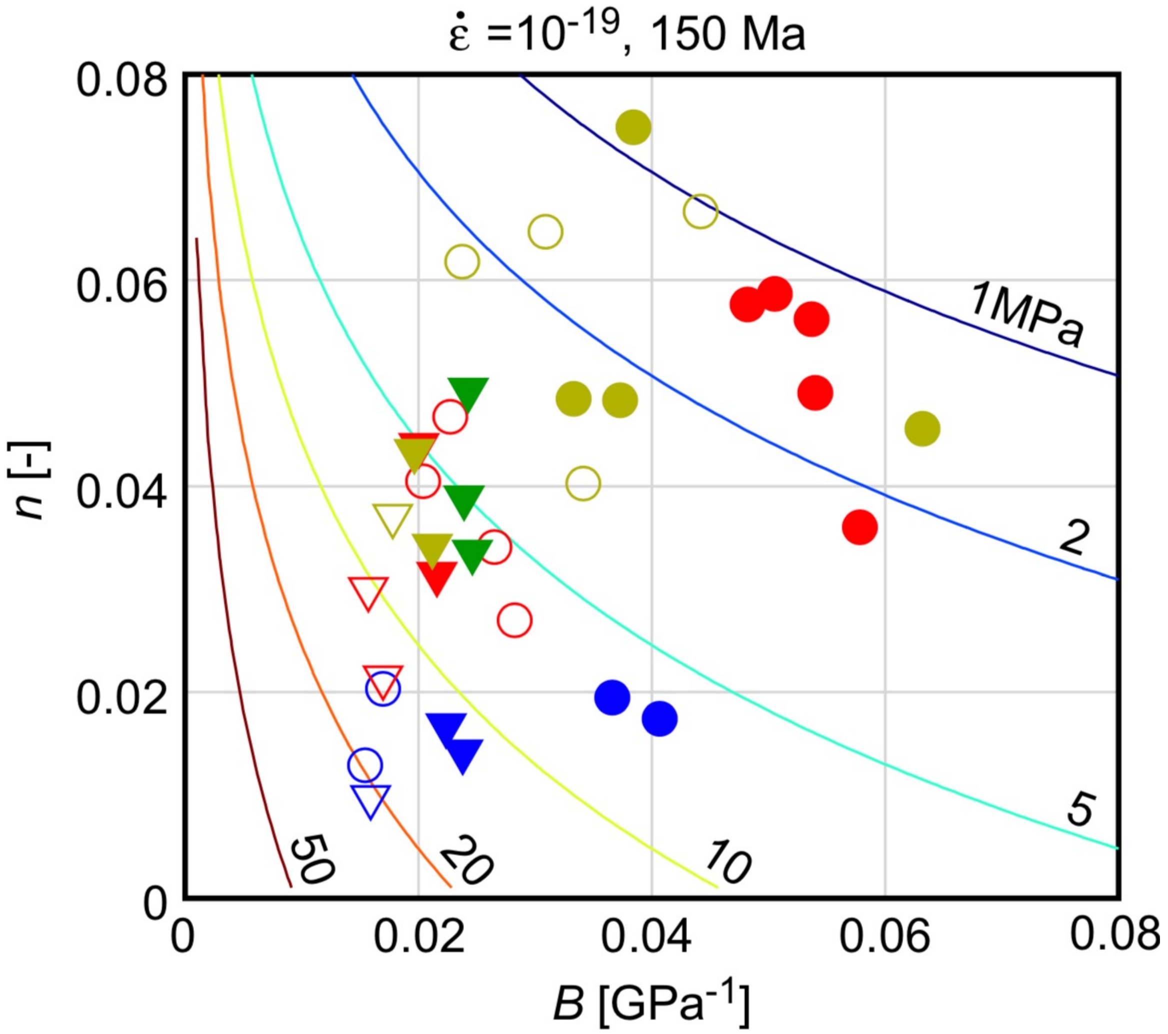
- ~10% reduction in porosity over geologic time

Linear Viscoelasticity



- Linear viscoelastic materials exhibit creep or stress relaxation (*i.e.*, constant stress or constant strain)
  - Creep and stress relaxation are inherently related
  - The relationship may be described analytically by the principle of linear superposition

Reality Check 2 - Differential Stress Over Geologic Time



Are lab measurements reasonable over geologic time?

Contours – Differential stress for constant strain rate

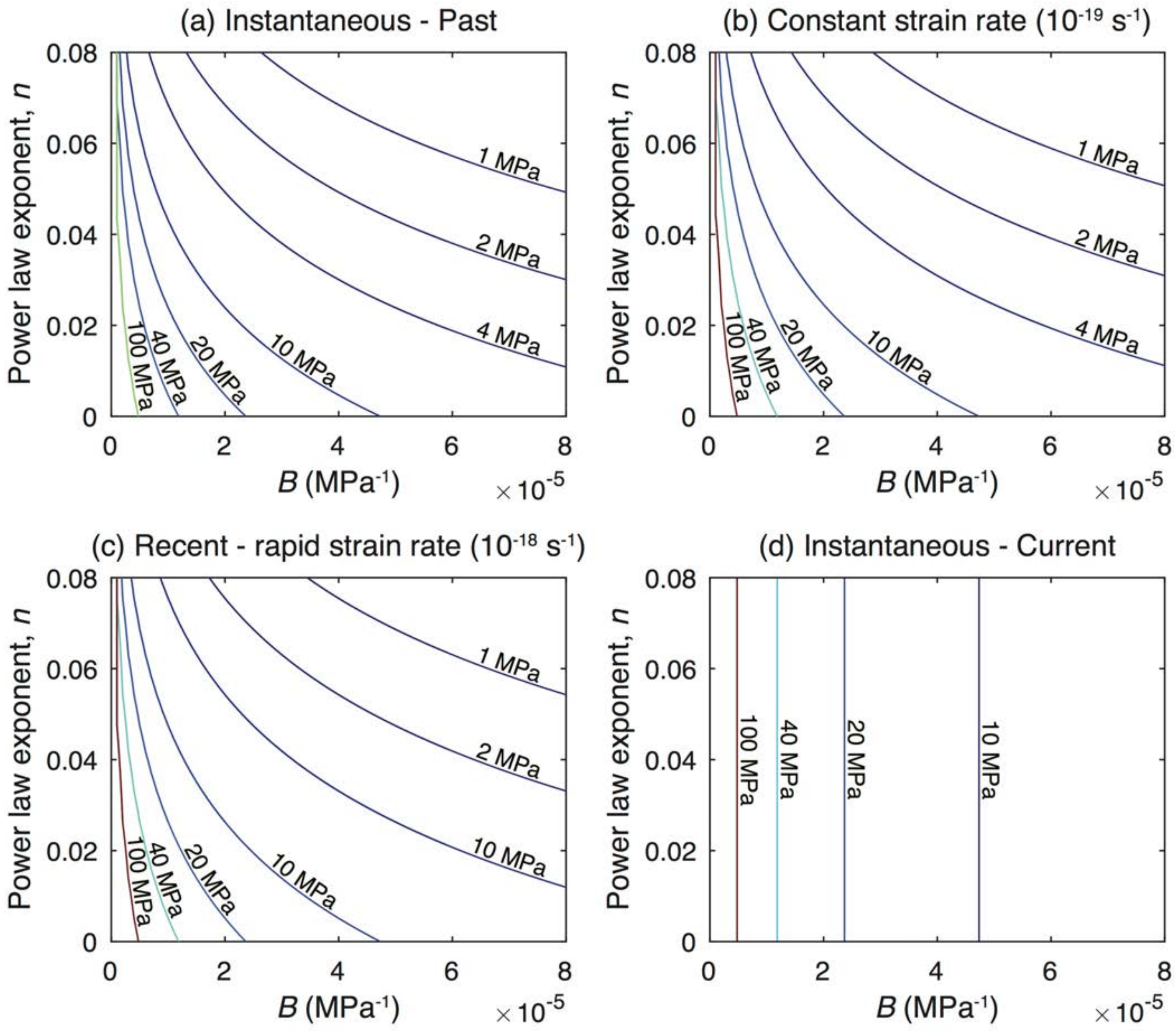
Low values of *n* imply large differential stress
→ Relatively stiff, strong rocks

For given *n*, stiffer rocks show greater differential stress
→ Less important at greater values of *n*
→ Elasticity of ductile rocks is less important

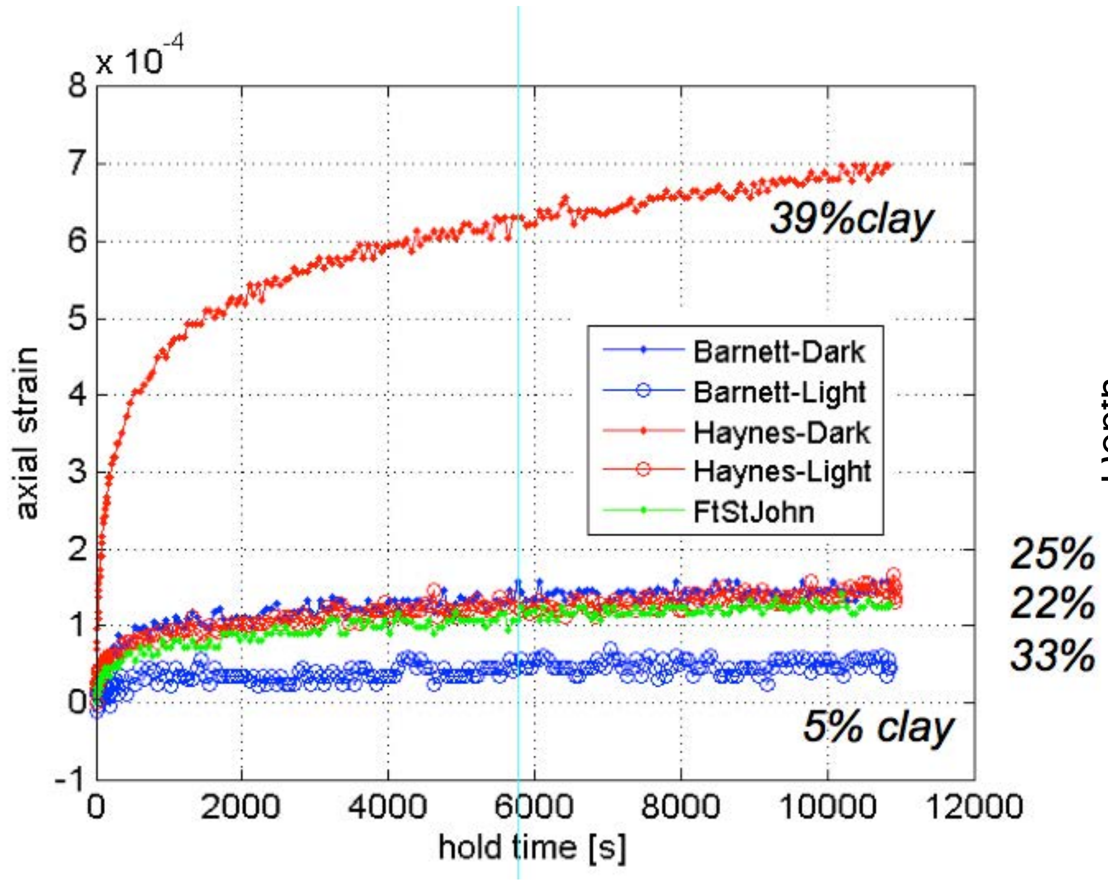
Detailed Geologic Loading History Does Not Matter

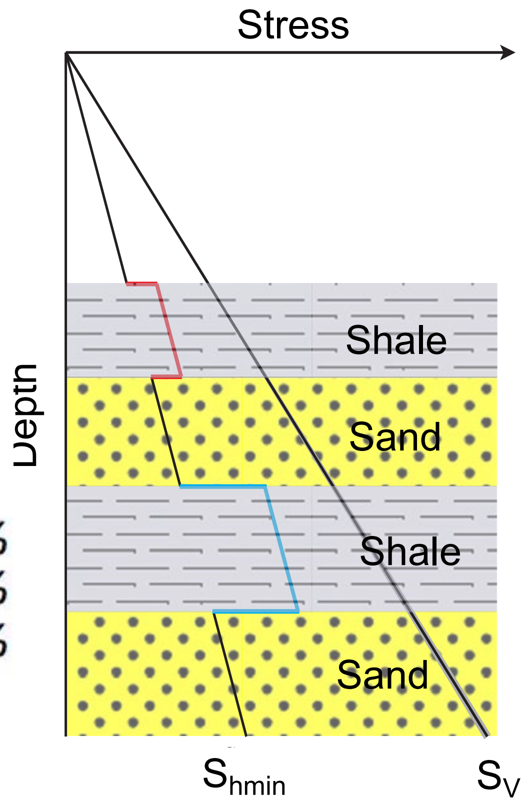
Constant total strain

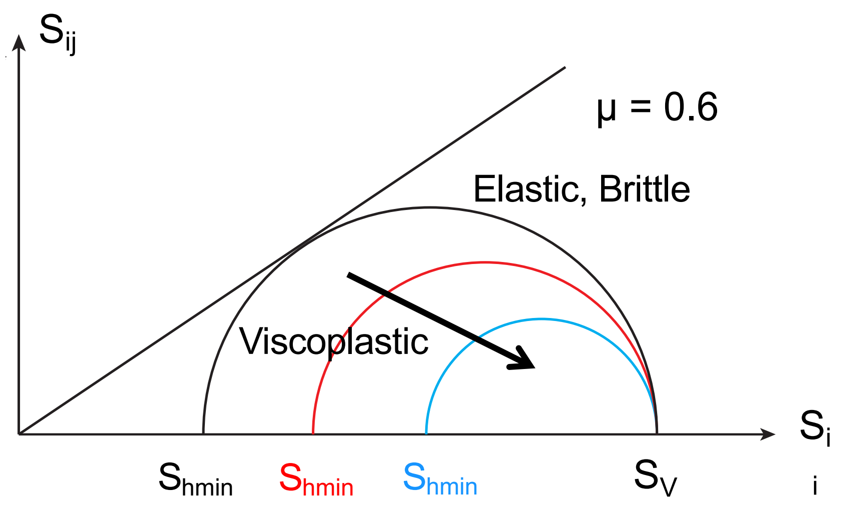
$\dot{\varepsilon}_0 t^{-n}$



Stress Relaxation Results in a More Isotropic Stress Field S_{hmin} Increases In Normal Faulting Environments







Sone and Zoback (2013)

Complete Stress Relaxation in Shales and Mud Stones

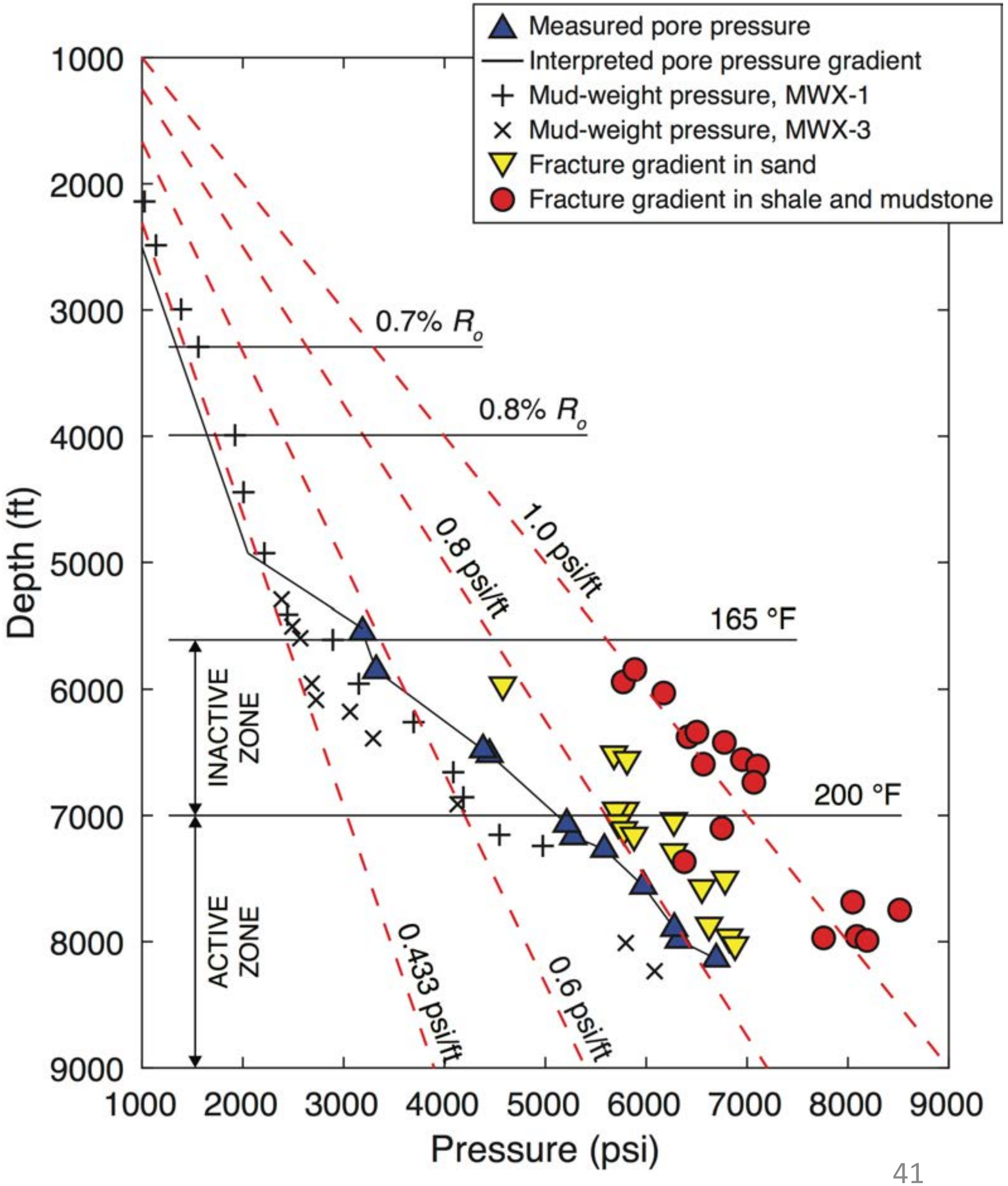
Multi-Well Experiment (MWX)

- Western Colorado – Piceance Basin (1981-1988)
  - Tight gas reservoirs (k = 1-10 μD)
  - 3 vertical wells spaced hundreds of feet apart

- Normal faulting ($S_v > S_{Hmax} > S_{hmin}$)

- Hydrocarbon generation in active zone
  - P_p exceeds hydrostatic (overpressure)
  - Fracture gradient in sands increases with P_p

- Fracture gradient in shales very close to S_v (1.1 psi/ft)
  - Essentially total stress relaxation (high ductility)
  - Shale units likely act as frac barriers

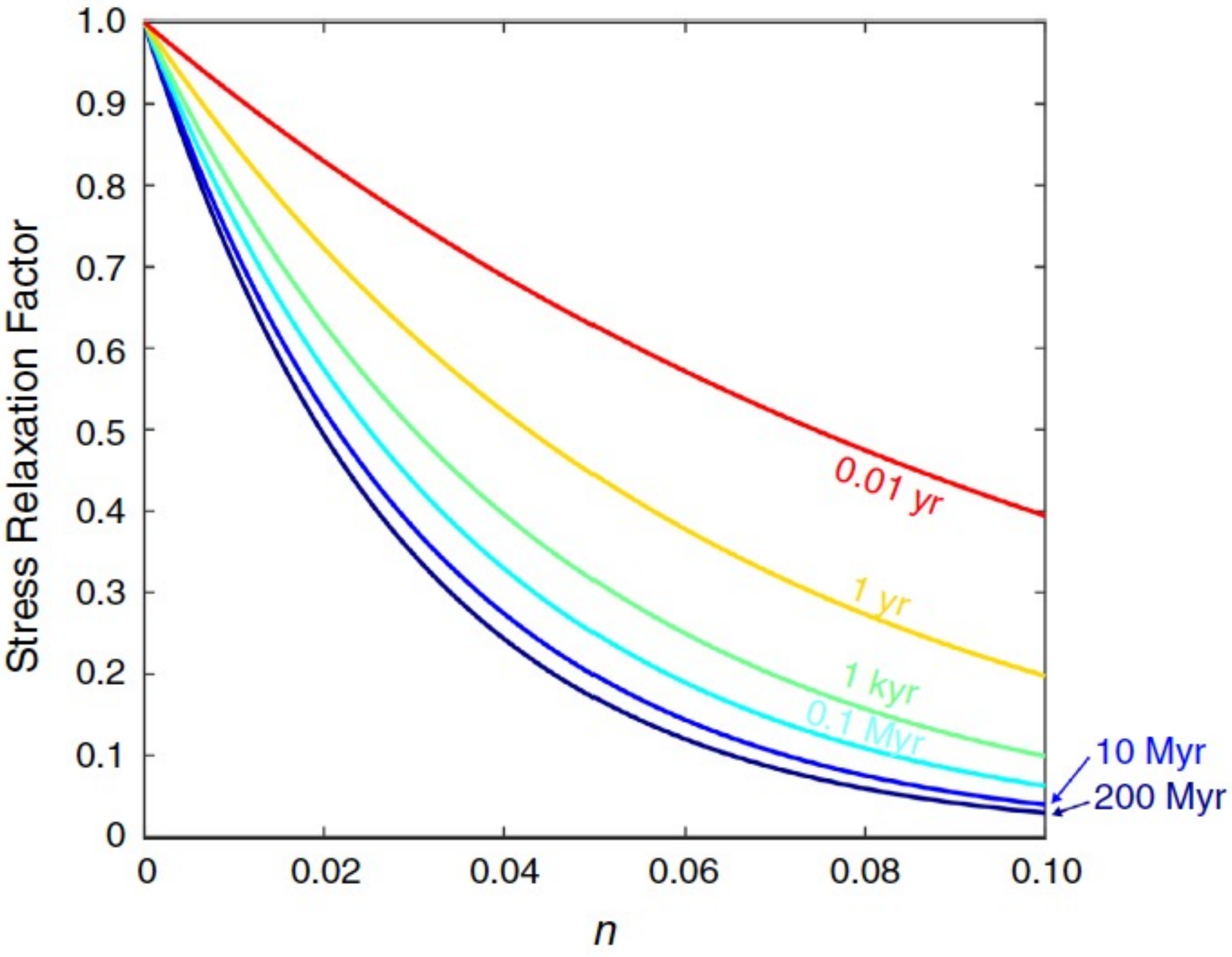


Stress Relaxation Happens Fast (Geologically)

$$\boxed{\sigma(t) = \dot{\varepsilon}\frac{1}{B(1-n)}t^{1-n}}$$

Normal Faulting

$$S_V - S_{hmin}(t) = \dot{\varepsilon}_0 \frac{E}{1-n}t^{-n}$$



Ma and Zoback (*SPE Jour.*, 2020)

WDFD 1 – Complete Stress Relaxation

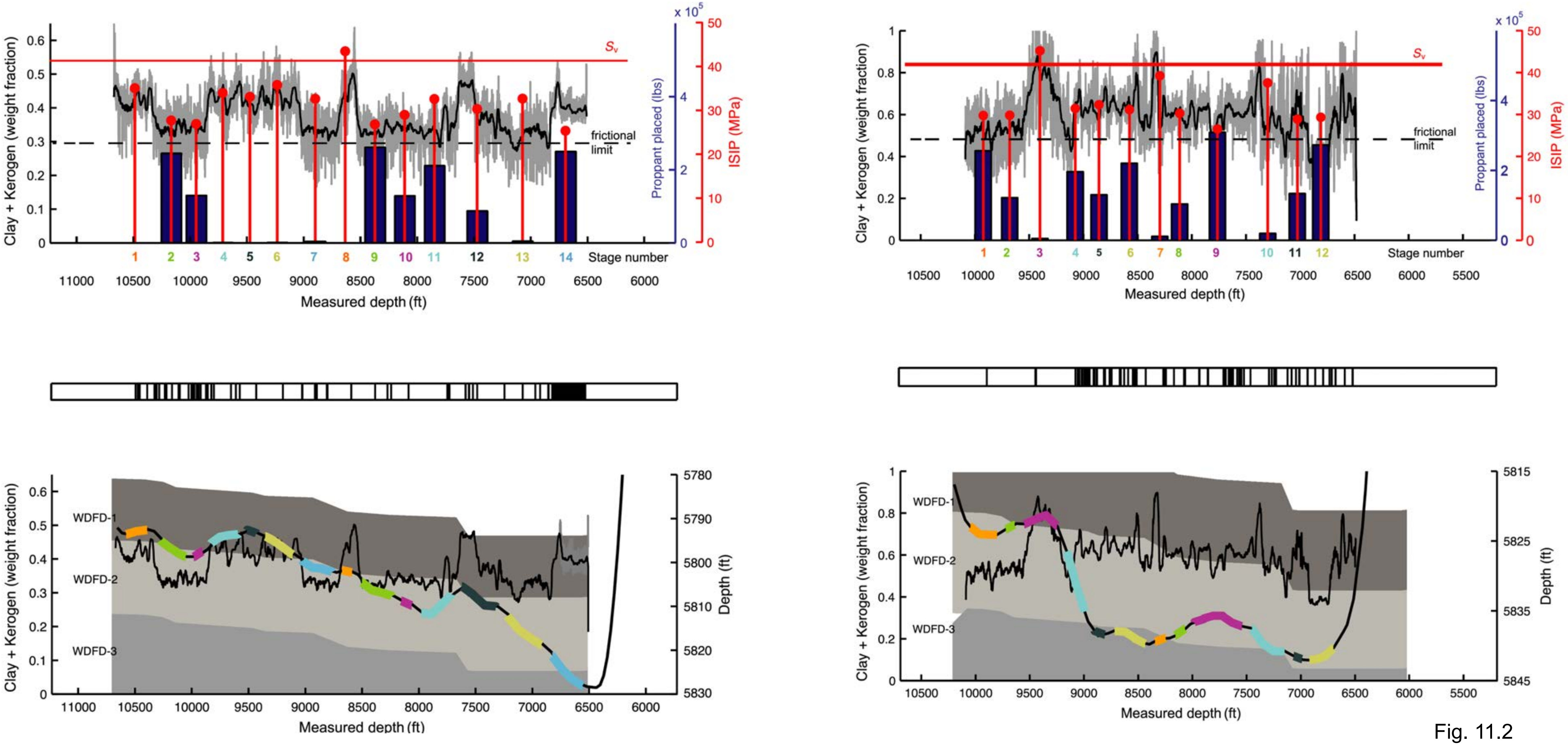
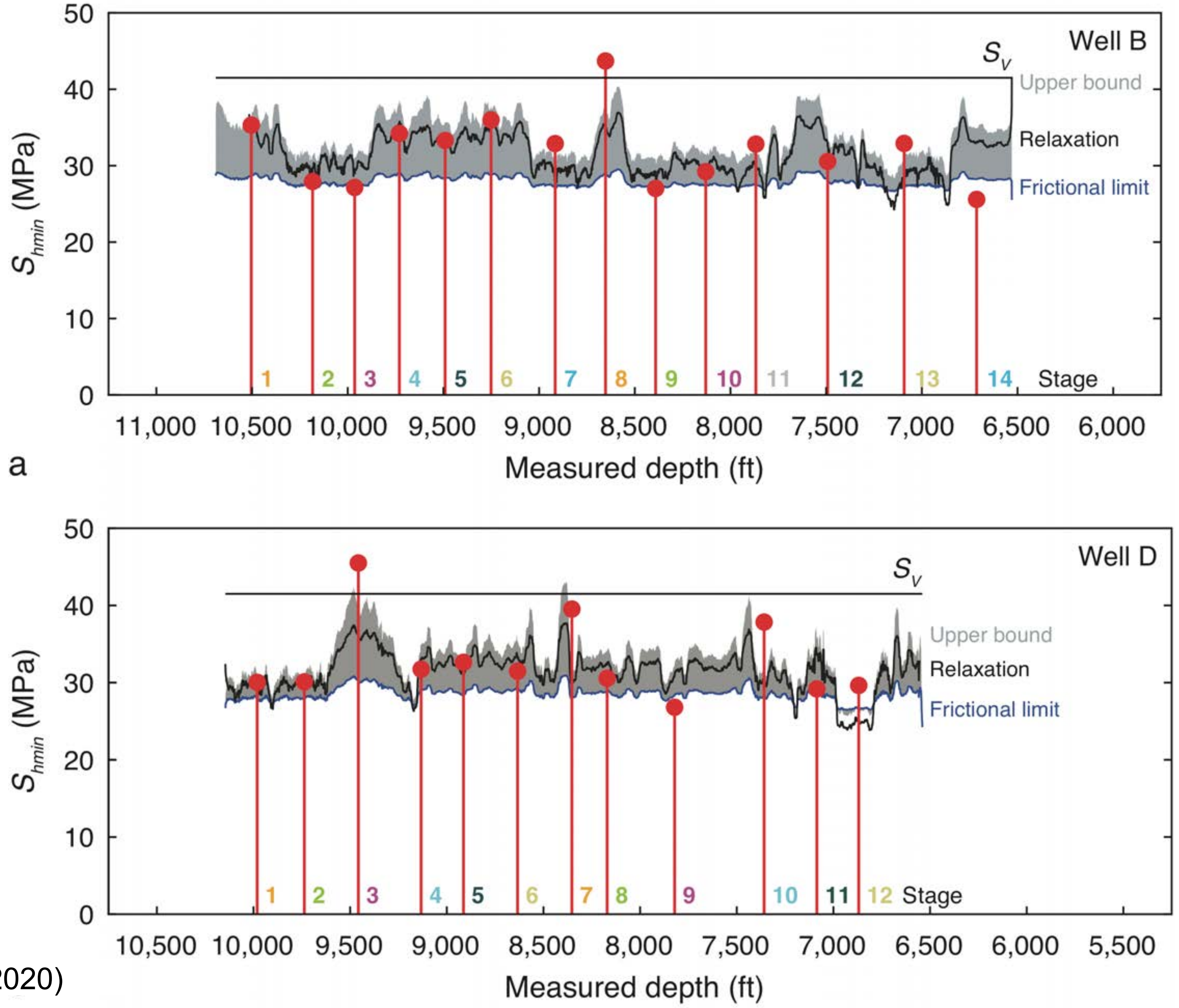


Fig. 11.2

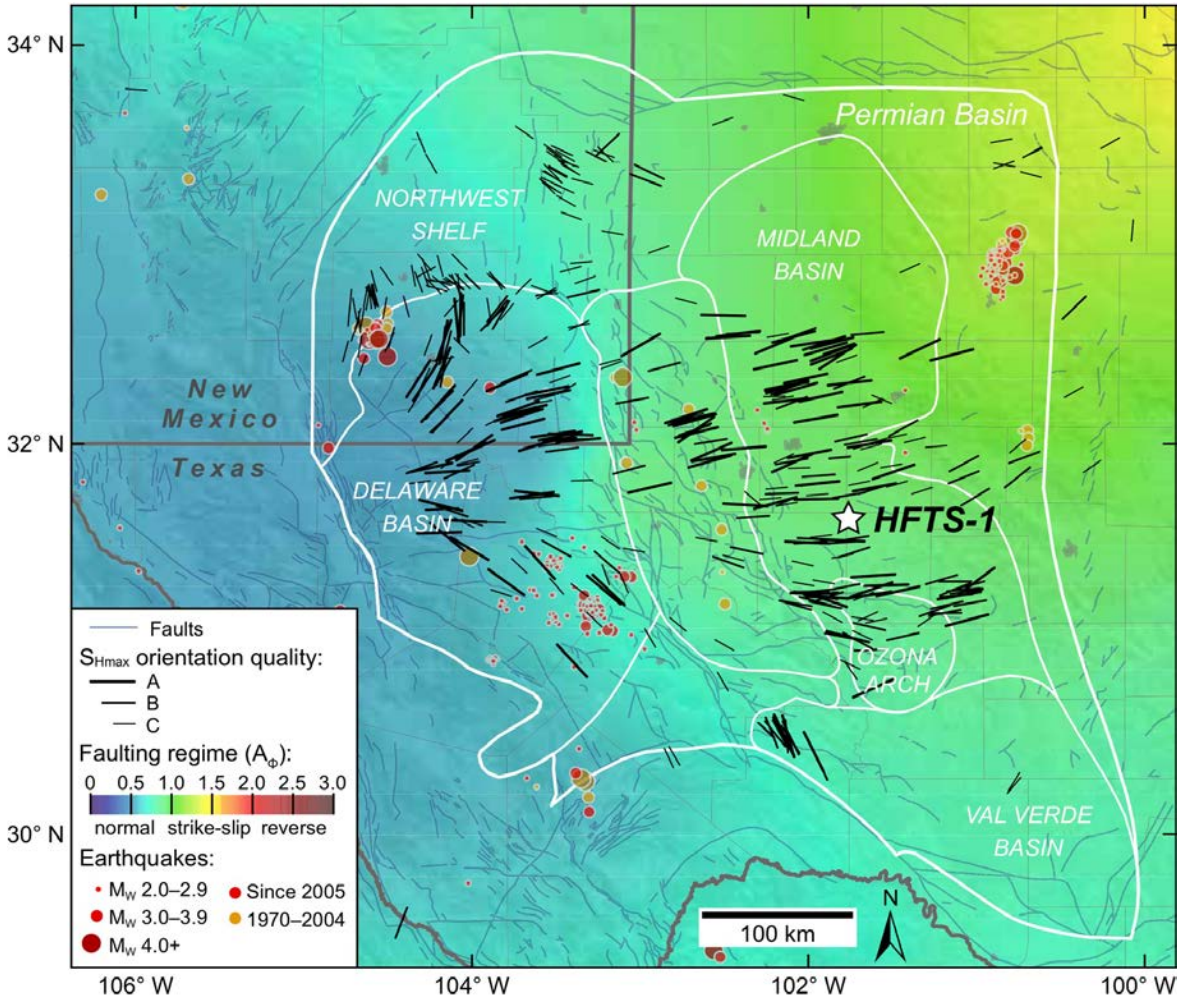
Ma and Zoback (*Geophysics,* 2017)

Modeling Stress Changes by Estimating “n” From Young’s Modulus

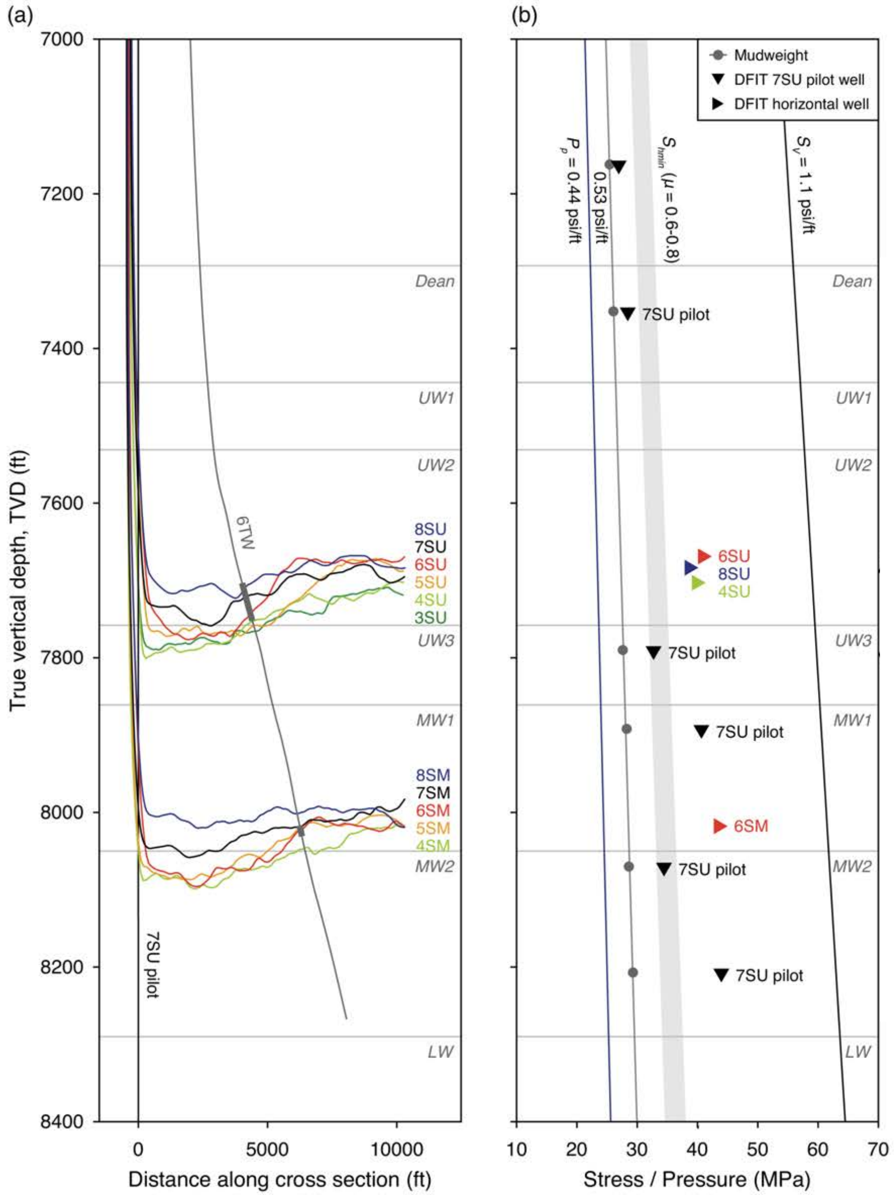


Ma and Zoback (*SPE Jour.,* 2020)

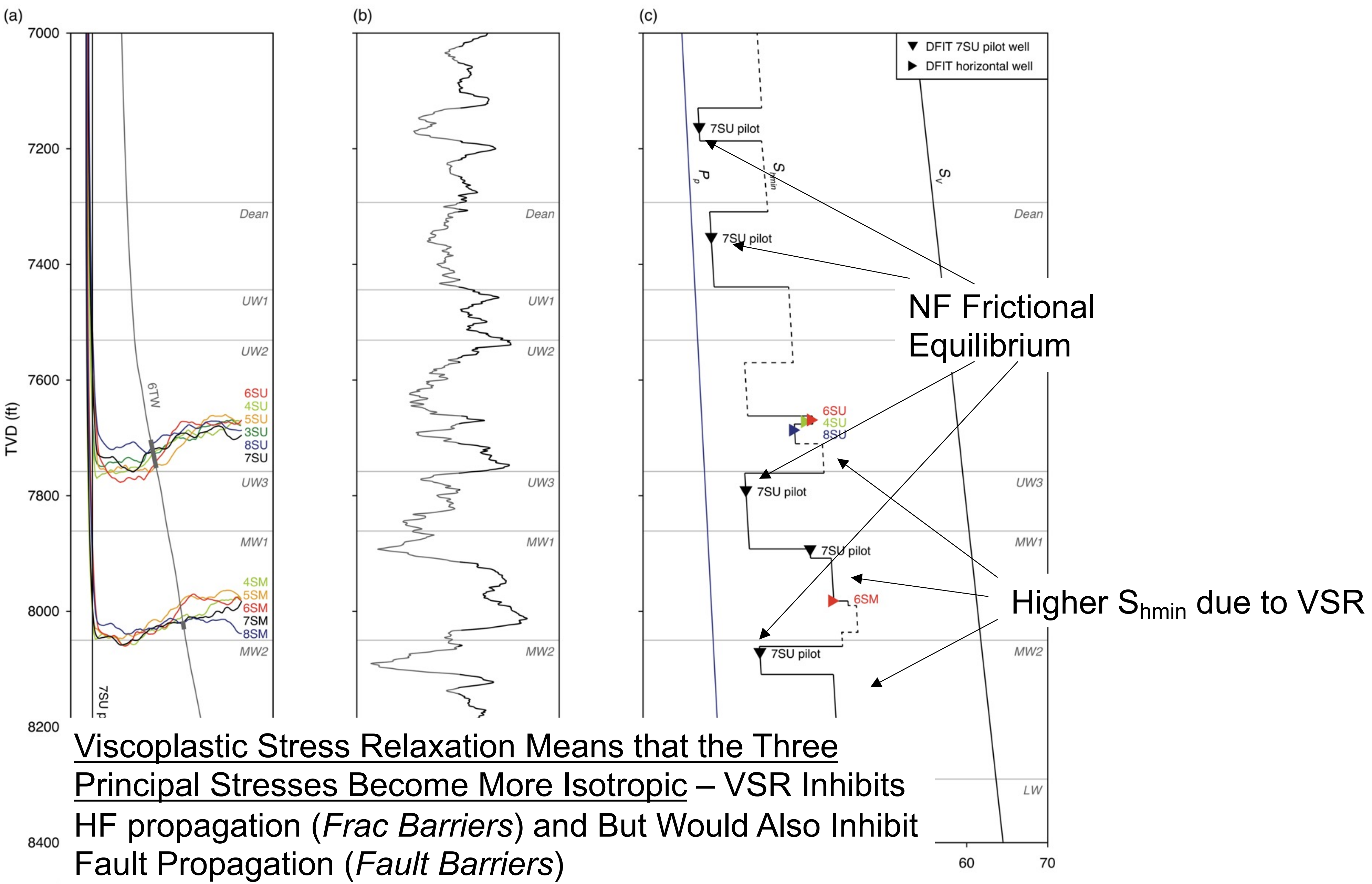
HFTS 1 –Measured Stress Magnitudes



Lund Snee & Zoback (*AAPG Bull.*, 2022)

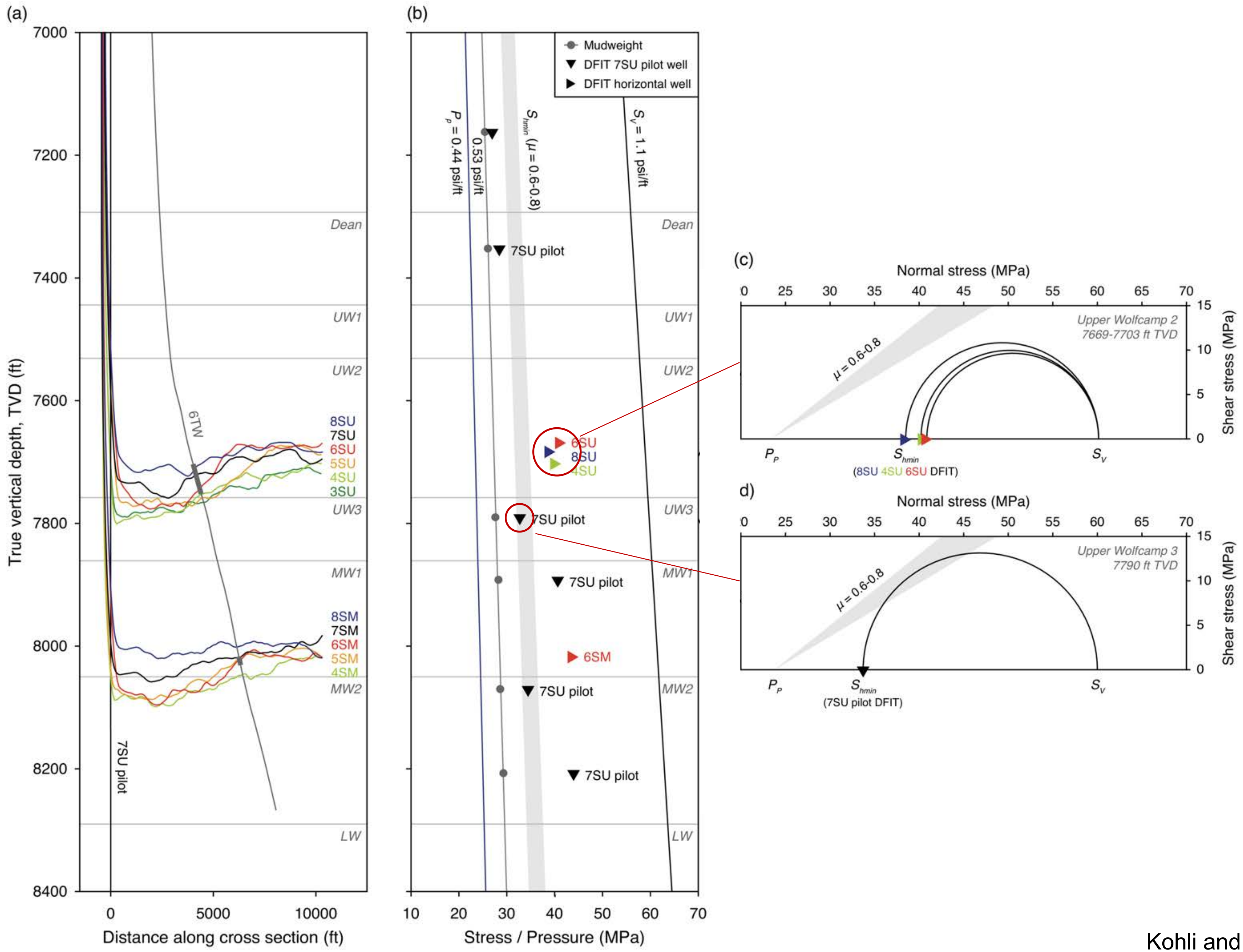


Kohli and Zoback (*Energies*, 2021)

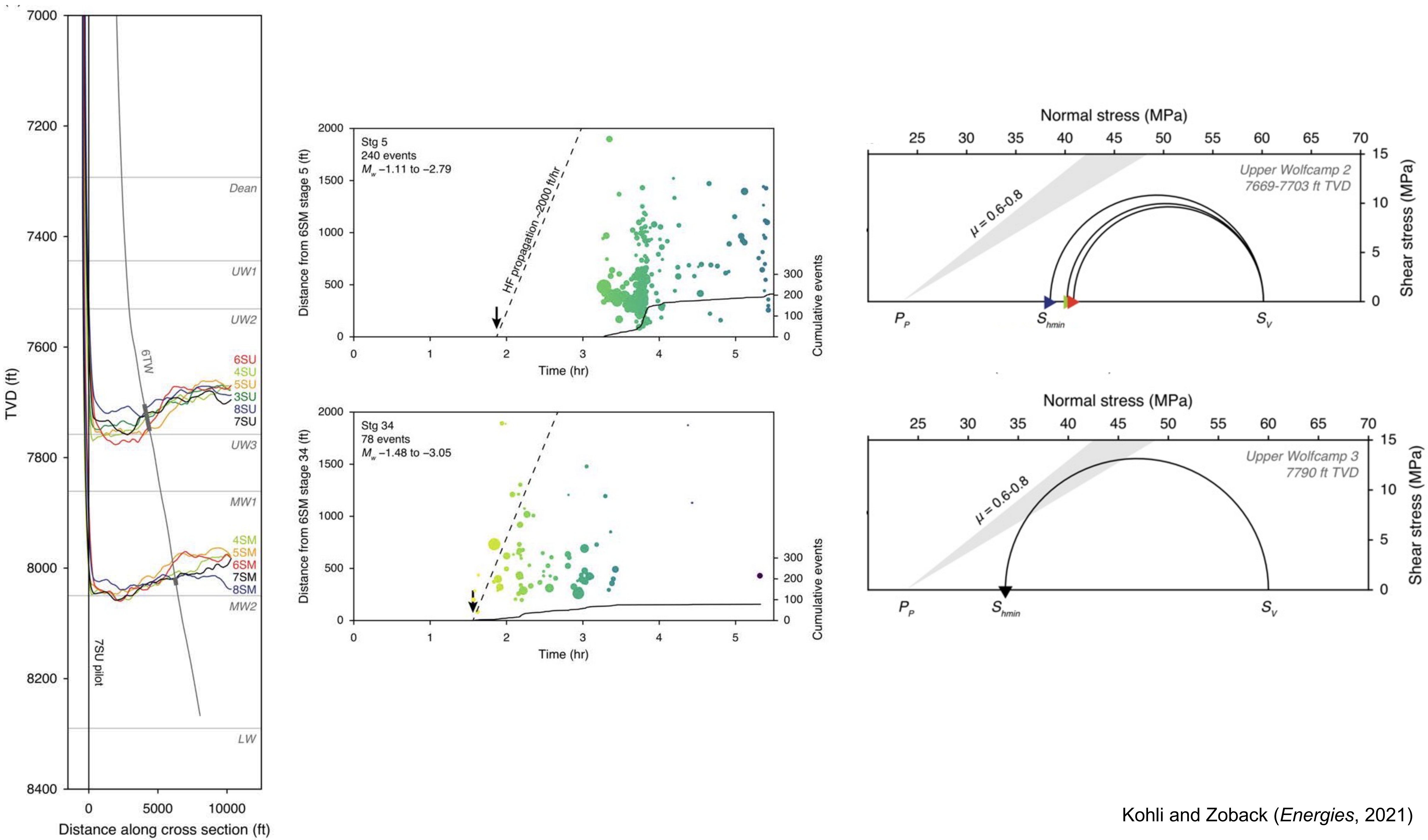


<u>Viscoplastic Stress Relaxation Means that the Three Principal Stresses Become More Isotropic</u> – VSR Inhibits HF propagation (*Frac Barriers*) and But Would Also Inhibit Fault Propagation (*Fault Barriers*)

Kohli and Zoback (*Energies*, 2021)



Kohli and Zoback (*Energies*, 2021)



Kohli and Zoback (*Energies*, 2021)

GEOPHYSICS, VOL. 87, NO. 3 (MAY-JUNE 2022); P. MR105–MR116, 14 FIGS.
10.1190/GEO2021-0429.1

Predicting variations of the least principal stress with depth: Application to unconventional oil and gas reservoirs using a log-based viscoelastic stress relaxation model

Ankush Singh[1] and Mark D. Zoback[2]

UNCONVENTIONAL RESOURCES TECHNOLOGY CONFERENCE
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URTeC: 3722883

Lithologically-Controlled Variations of the Least Principal Stress with Depth and Resultant *Frac Fingerprints* During Multi-Stage Hydraulic Fracturing

Mark Zoback*[1], Troy Ruths[2], Mark McClure[3], Ankush Singh[3], Arjun Kohli[1], Brendon Hall[2], Rohan Irvin[3], and Malcolm Kintzing[4], 1. Stanford University, 2. Petro.ai, 3. ResFrac, 4. Henry Resources

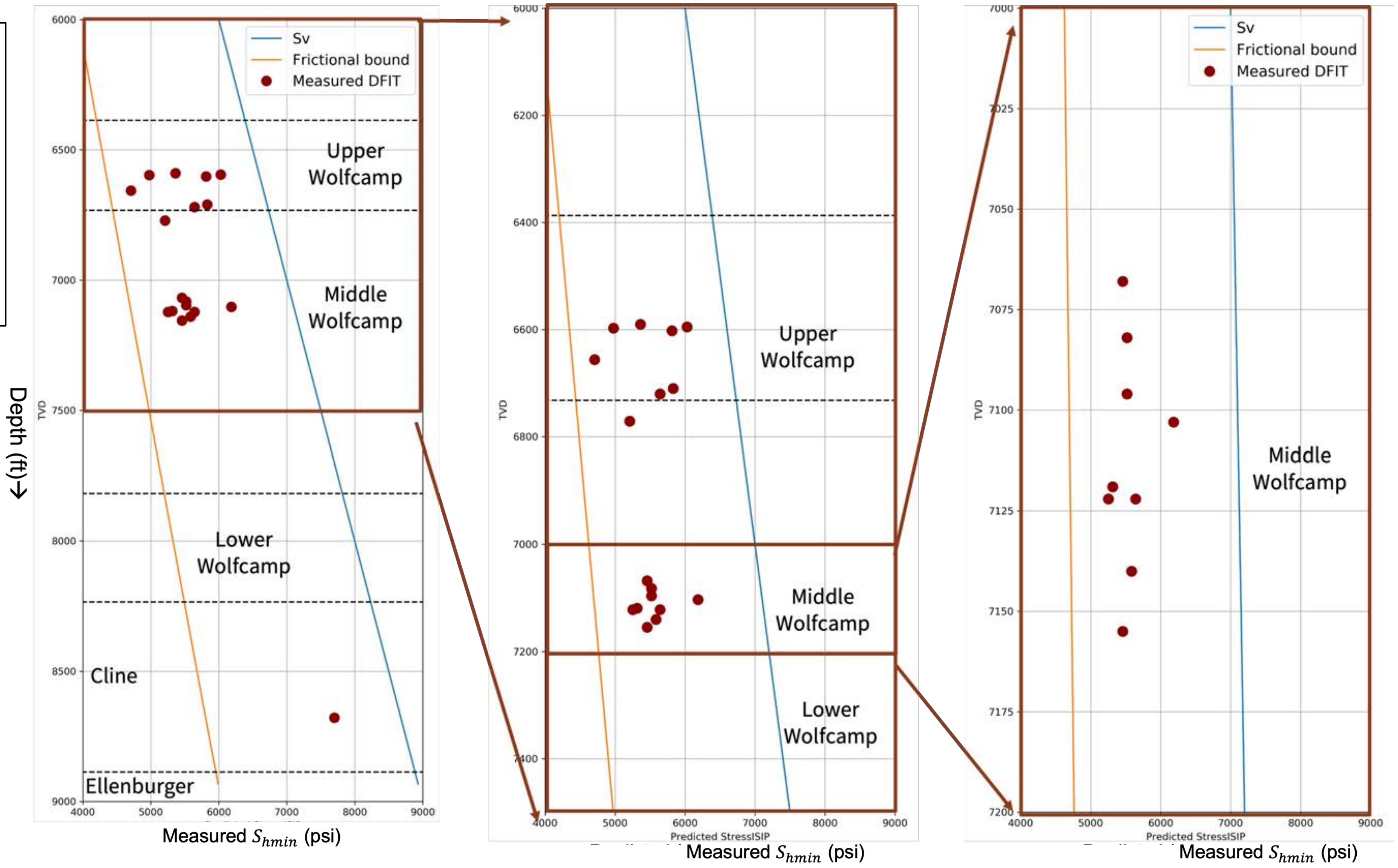
This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Houston, Texas, USA, 20-22 June 2022.

Measured S_{hmin} Variations With Depth

Midland Basin Pads*

- 7 Wells in Upper WCMP
- 9 Wells in Middle WCMP
- 1 Well in Cline
- 1 DFIT in toe of each well

* Proprietary Data Set



Singh and Zoback (*Geophysics,* 2022)

Predicting Variations of the Least Principal Stress With Geophysical Logs and a Few S_{hmin} Measurements

$$S_1 - S_3 = \epsilon_0 E_{horz} \frac{t^{-n}}{1-n}$$

$$\kappa(S_v - S_{hmin}) = \epsilon_0 \frac{t^{-n}}{1-n} E_{horz}$$

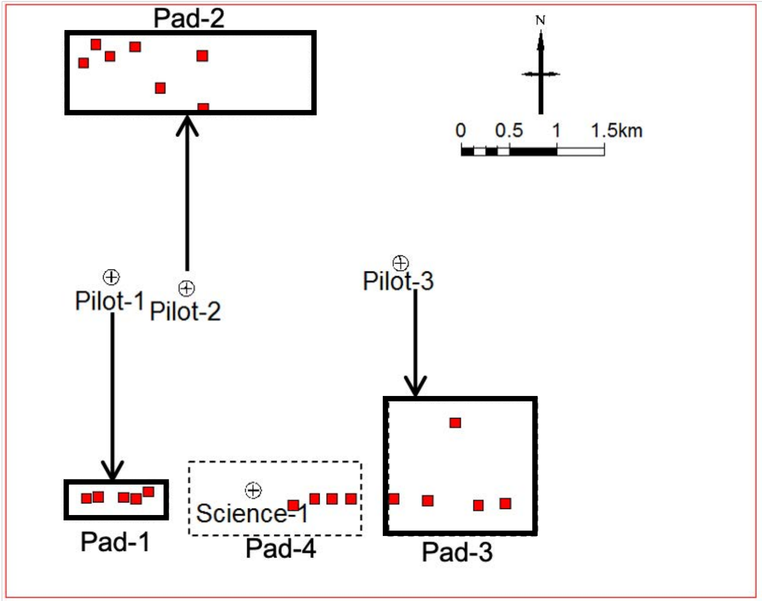
$$S_v - S_{hmin} = \epsilon_0 \frac{t^{-n}}{\kappa(1-n)} E_{horz}$$

$$S_v - S_{hmin} = n_{\epsilon t}^{*} E_{horz}$$

$$n_{\epsilon t}^{*} = f(v_{clay}, v_{calcite}, v_{quartz}, GR, \rho, \Omega, \phi)$$

Singh and Zoback (*Geophysics,* 2022)

S_{hmin} Profile is Computed by Fitting $n^*_{\epsilon t}$ as a Function of Well Logs



Step 1: **Fit**

Fit $n^*_{\epsilon t} = f(v_{clay}, v_{calcite}, v_{quartz}, GR, \rho, \Omega, \phi)$

Minimize:

$$RSS_{\text{linear}} = \sum_{i=1}^{n}\left(y_i - \beta_0 - \sum_{j=1}^{p}\beta_j x_{ij}\right)^2$$

$$RSS_{lasso} = \sum_{i=1}^{n}\left(y_i - \beta_0 - \sum_{j=1}^{p}\beta_j x_{ij}\right)^2 + \lambda\sum_{j=1}^{p}|\beta_j|$$

$$RSS_{ridge} = \sum_{i=1}^{n}\left(y_i - \beta_0 - \sum_{j=1}^{p}\beta_j x_{ij}\right)^2 + \lambda\sum_{j=1}^{p}\beta_j^2$$

Step 2: **Predict**

Predict $n^*_{\epsilon t}$ as a function of depth (z) and calculate:

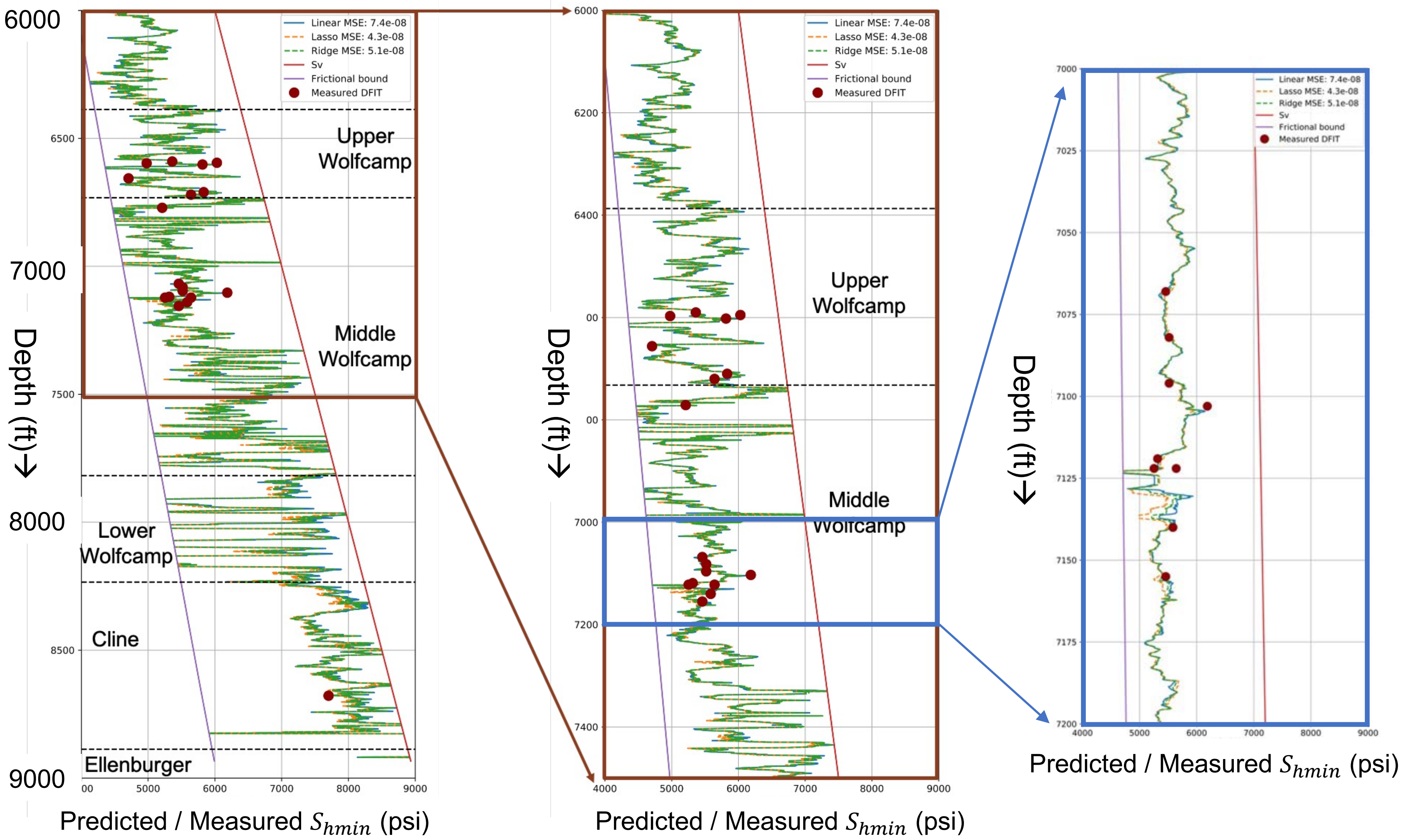
$$S_{hmin}(z) = S_V(z) - n^*_{\epsilon t}(z)E_{horz}(z)$$

Step 3: **Use geological constraints**

Use S_V and frictional bounds to constrain the stress profile

Singh and Zoback (*Geophysics*, 2022)

VSR Predicts 17 S_{hmin} Measurements ($R^2 \approx 0.9$)



(Singh and Zoback, *Geophysics*, 2022)

Why is This Important?

- Get the Stress Right (You Can't do Geomechanics Right With the Wrong Stress State).
    - Lessons from North America
    - Drilling Horizontal Wells in the Correct Direction (Bakken Example)

- Optimizing Well Placement When Exploiting Stacked Pay
    - Lithologically-Controlled Variations of the Least Principal Stress with Depth and its Impact on Multi-Stage Hydraulic Fracturing
    - Modeling Hydraulic Fracture Growth (ResFrac)
    - Optimizing Drainage Area (Petro.ai)

- Shear Faulting and Its Affect on Production Stimulation
    - Importance of Microseismic Events
    - Pad-scale Faulting Which Can *Hijack* Hydraulic Fracture Stages

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Lithologically-Controlled Variations of the Least Principal Stress with Depth and Resultant *Frac Fingerprints* During Multi-Stage Hydraulic Fracturing

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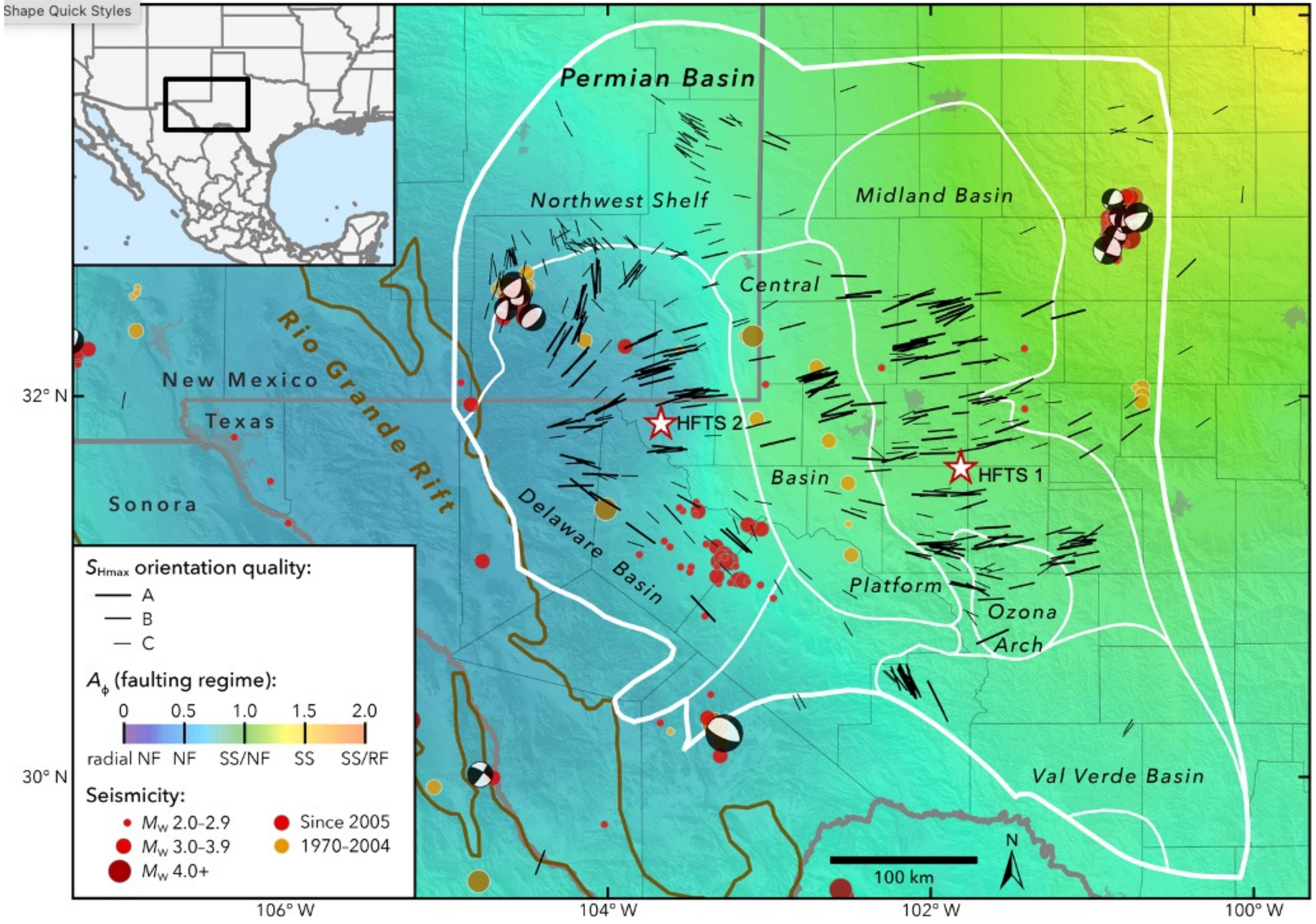
Stanford University, Petro.ai, ResFrac, Henry Resources



Lund Snee and Zoback (*AAPG Bull*., 2022)

Frac Fingerprints?

In gun barrel view, frac fingerprints refer to the pattern of vertical and horizontal hydraulic fracture propagation resulting from the position of a frac stage with respect to the magnitude of S_{hmin} at the depth of the stage and in the layers above and below it.

Illustrations of Frac Fingerprints

- Midland Basin A – 9 Well Pad
- Midland Basin B – 17 Wells, 3 Pads
- HFTS 1 – 11 Wells
- HFTS 2 – 6 Wells, 2 Parent, 4 Child
- Midland Basin C - 5 Well Pad informed by analysis of production data from surrounding pads

Three Topics

- Get the Stress Right (You Can't do Geomechanics Right With the Wrong Stress State).
    - Lessons from North America
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- Optimizing Well Placement When Exploiting Stacked Pay
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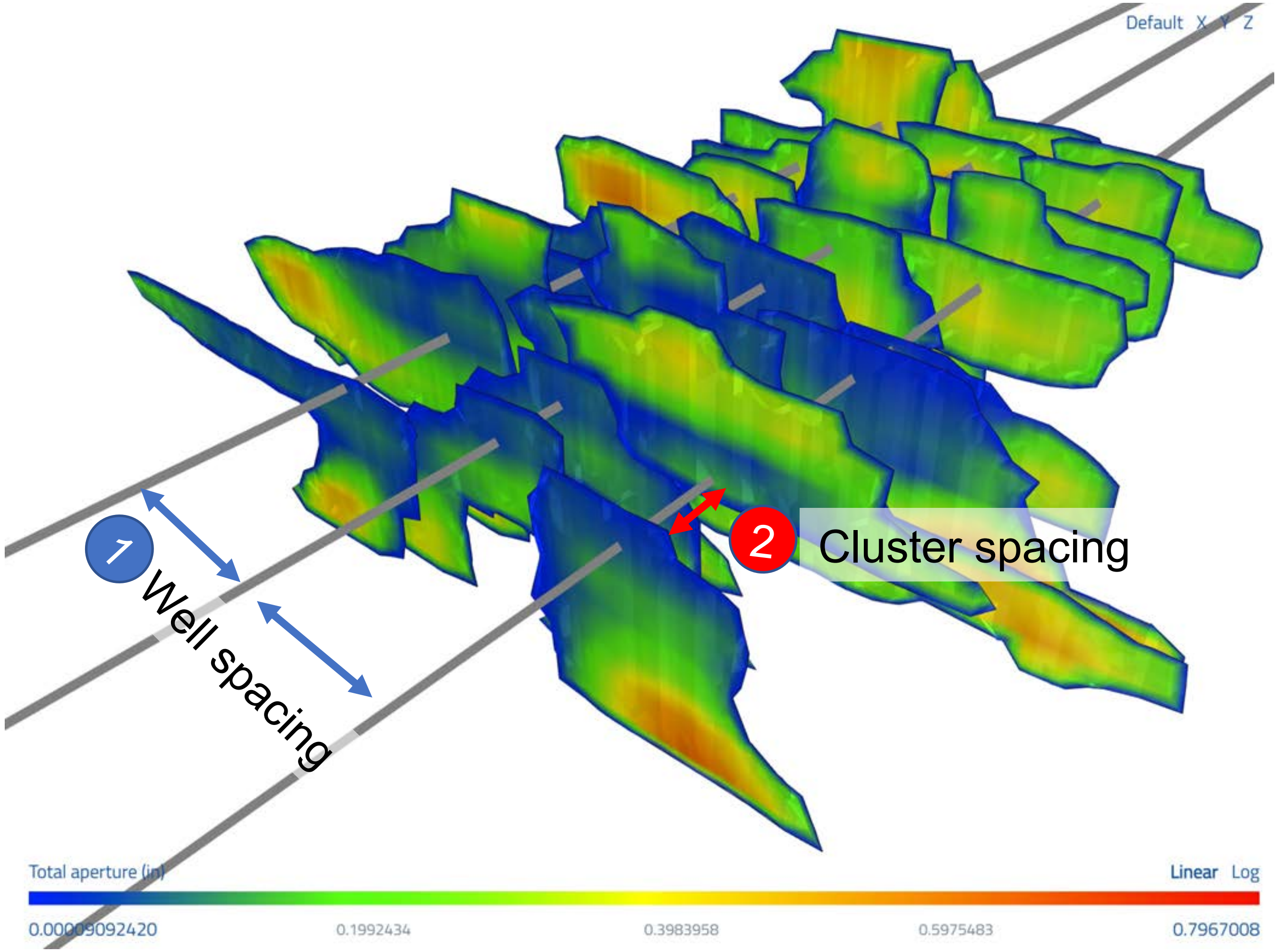
    - Pad-scale Faulting Which Can *Hijack* Hydraulic Fracture Stages

Coupled-Physics Unveils Parameter Dependencies

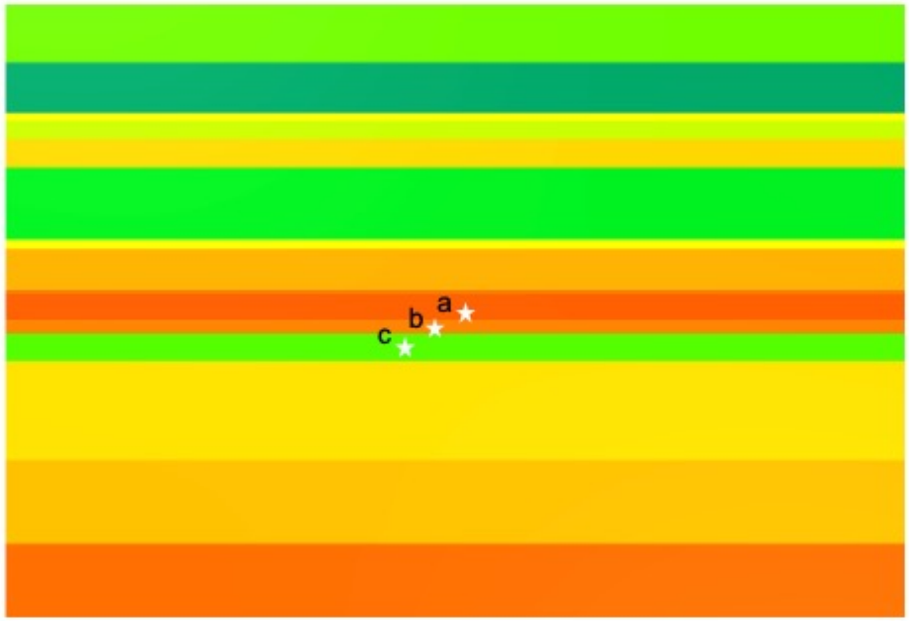


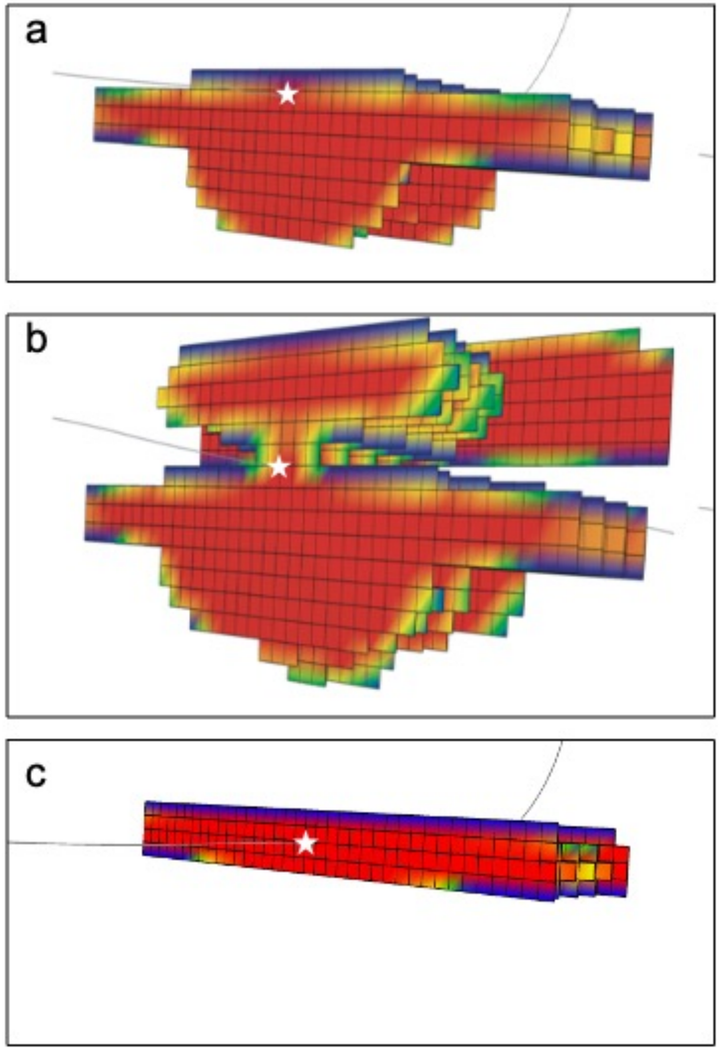
3 Proppant loading

ResFrac

HFTS 1 –Hydraulic Fracture Modeling

S_{hmin} Profile from Kohli and Zoback (2021)





Stage Near the Toe of one Well

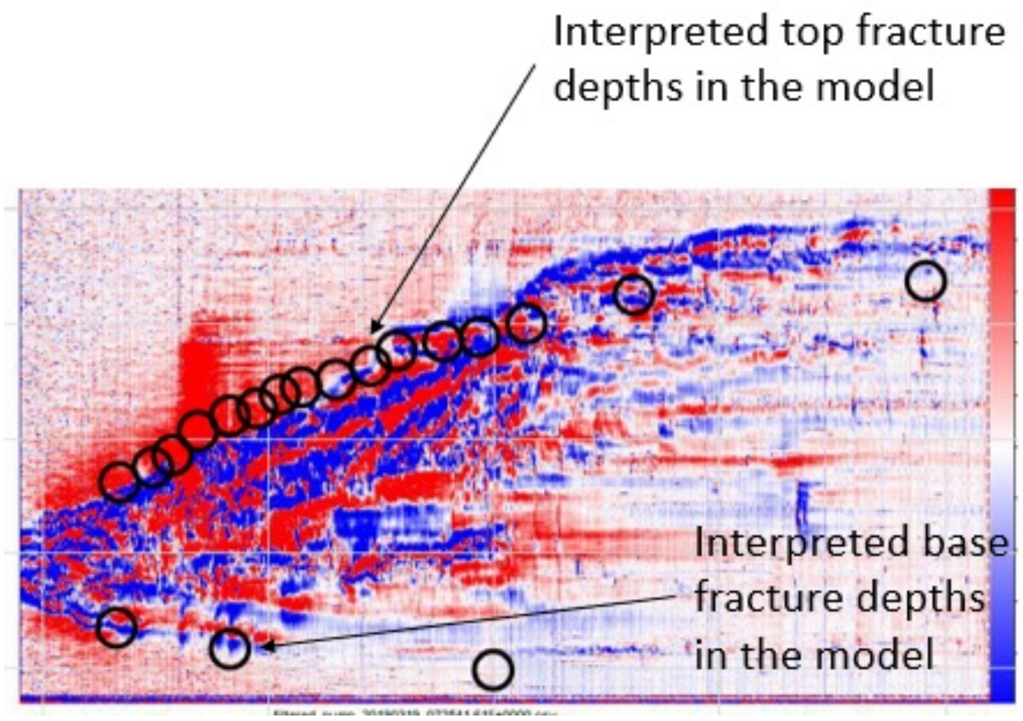
Stage Near the Heel of the Same Well

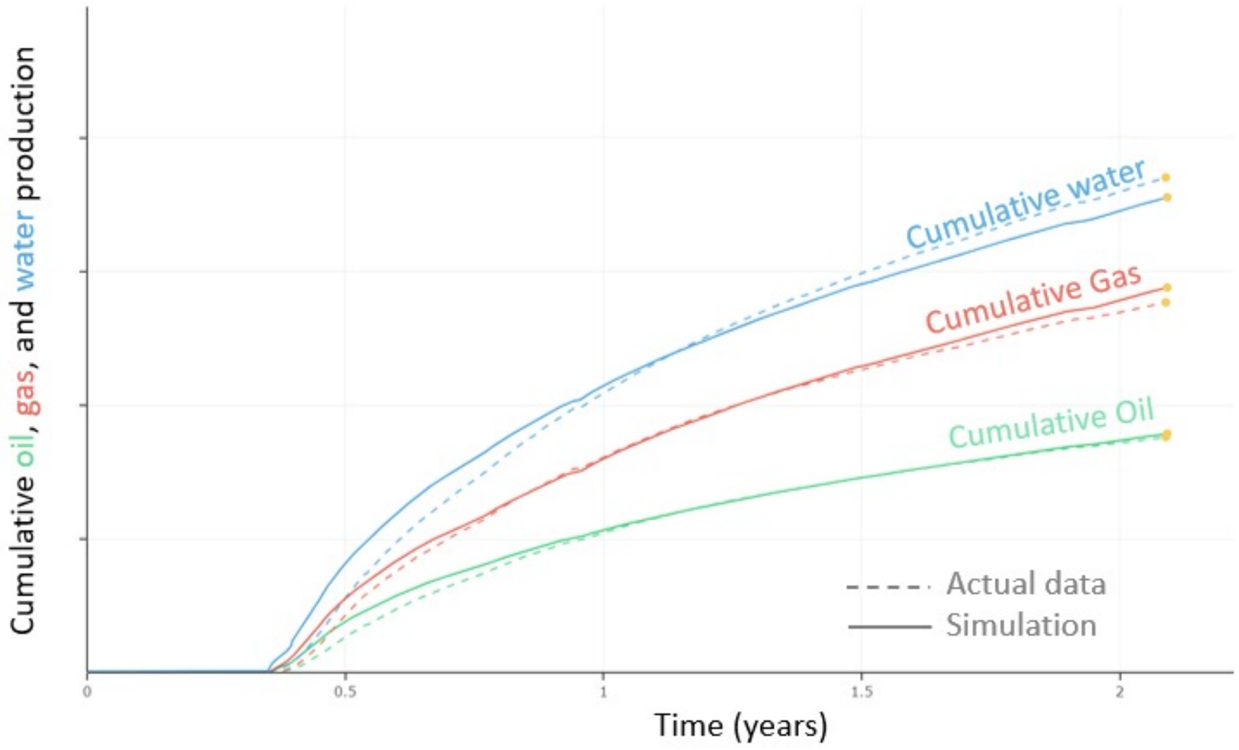
Hypothetical Stage Slightly Deeper Than Heel Stage

ResFrac

Color represents propped aperture

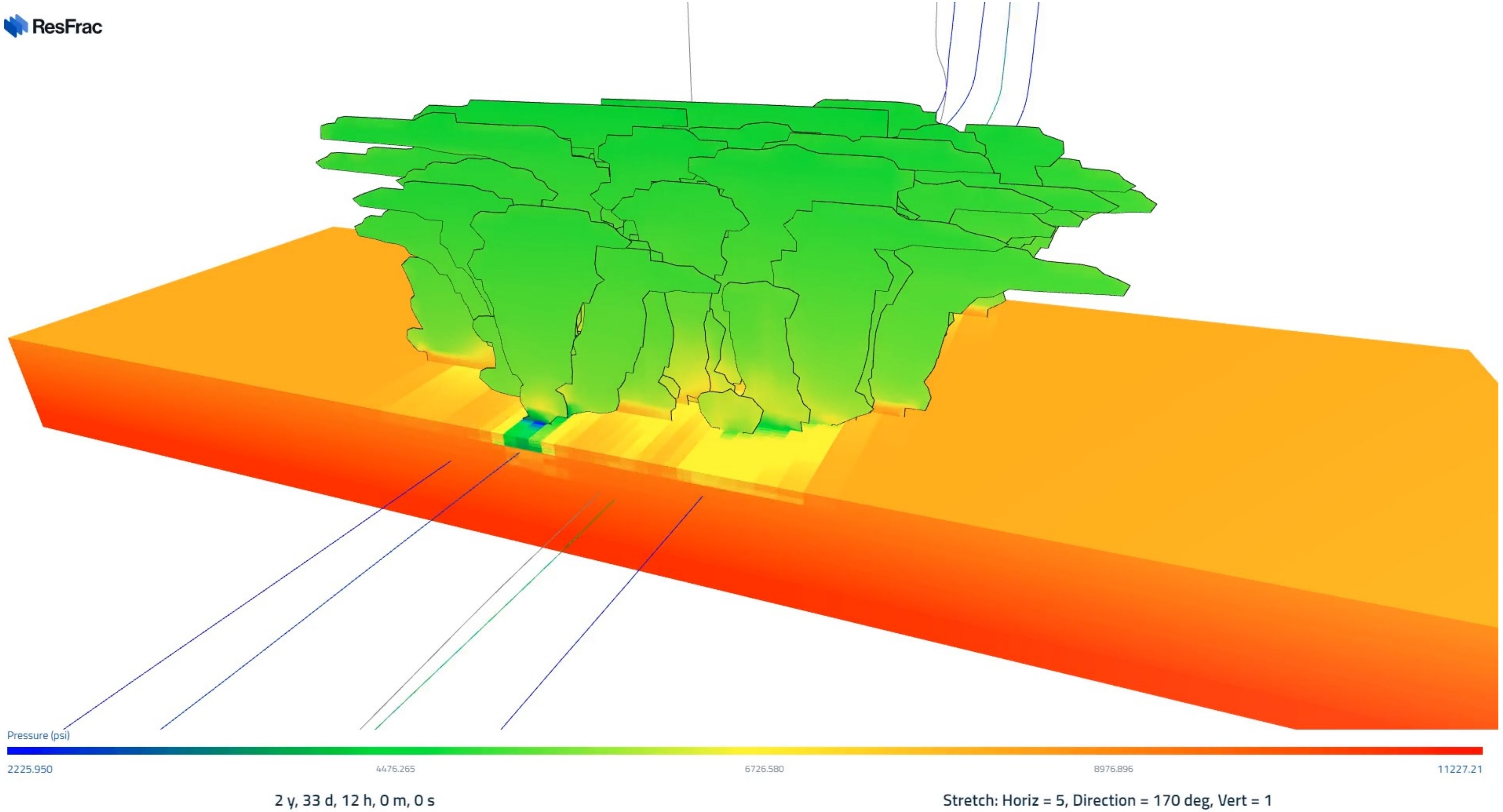
HFTS-2 Model Calibrated to all Available Diagnostics





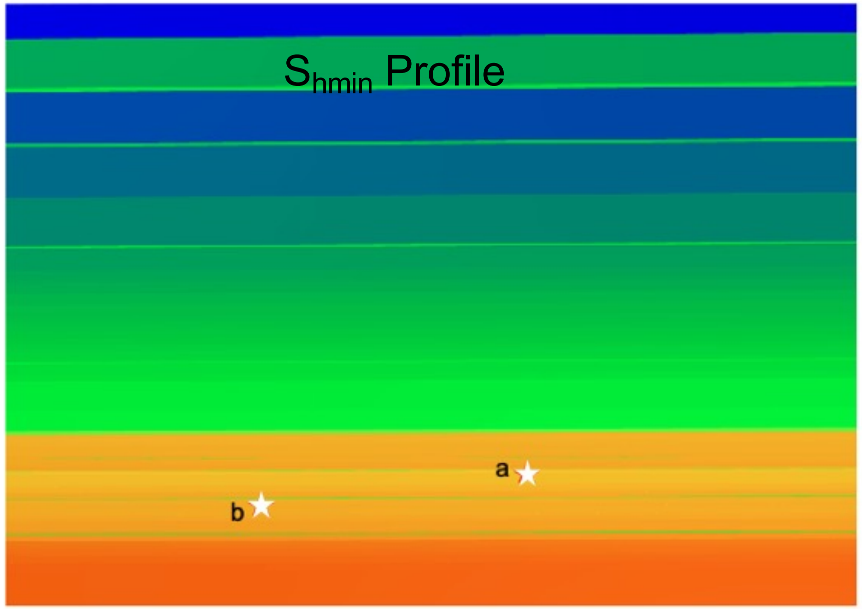
Pudugramam et al., 2022

HFTS-2 model (video)

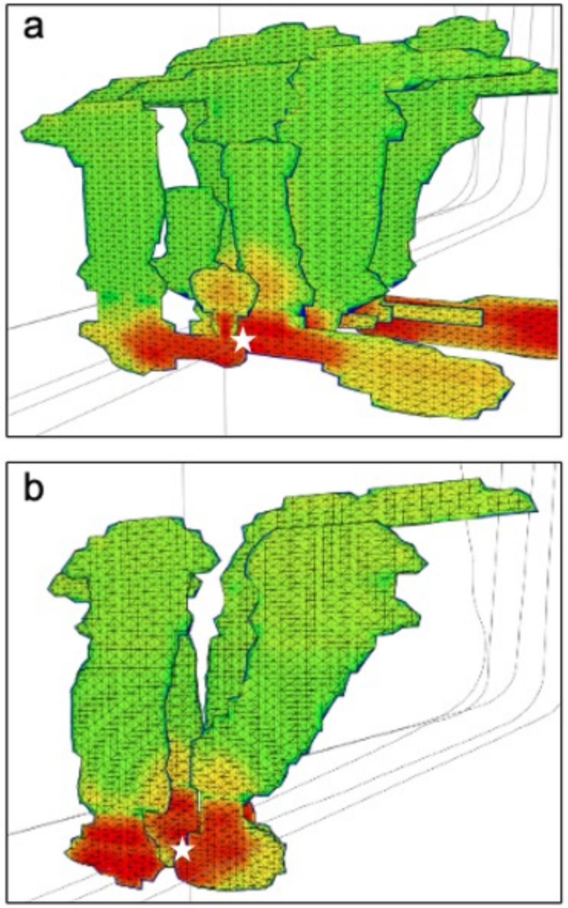


Pudugramam et al., 2022

HFTS 2 –Hydraulic Fracture Modeling



- Constrained by fiber data (pronounced vertical growth)
- Production data



Two Stages in Two Different Wells at Two Different Stratigraphic Depths

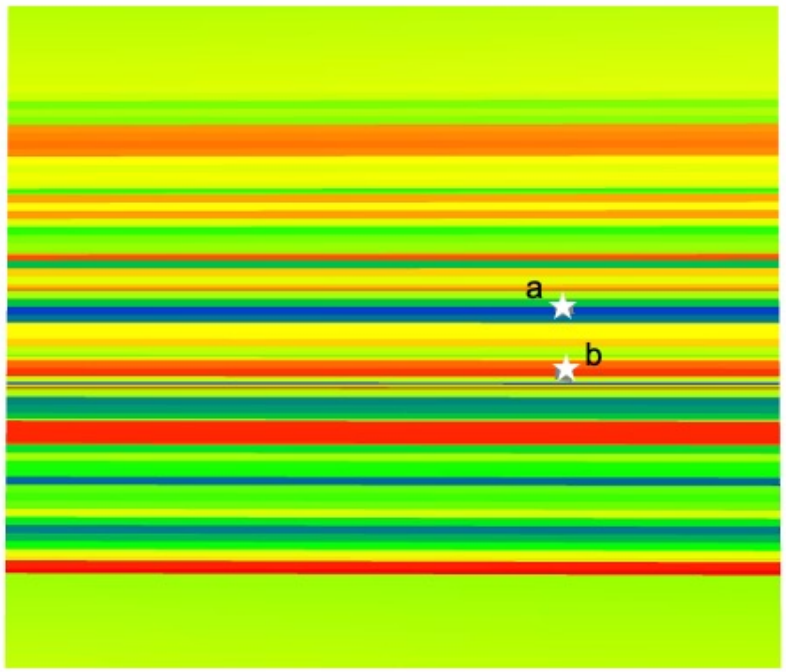
Color represents propped aperture

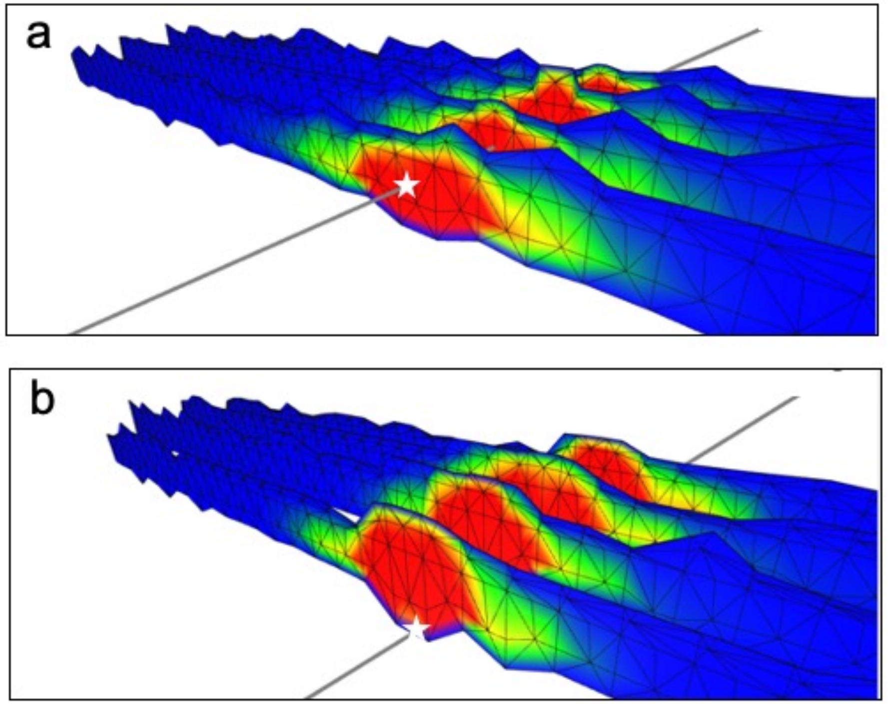
(from Pudugramam et al., 2022)
URTeC: 3723620

ResFrac

Midland Pads* –Hydraulic Fracture Modeling

S_{hmin} Profile from Singh and Zoback (2022)





Two Stages in Two Hypothetical Wells at Different Stratigraphic Depths

Color represents propped aperture

ResFrac

Three Topics

- Get the Stress Right (You Can't do Geomechanics Right With the Wrong Stress State).
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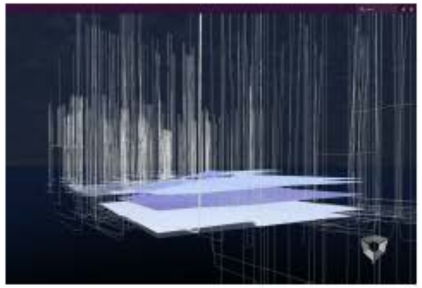
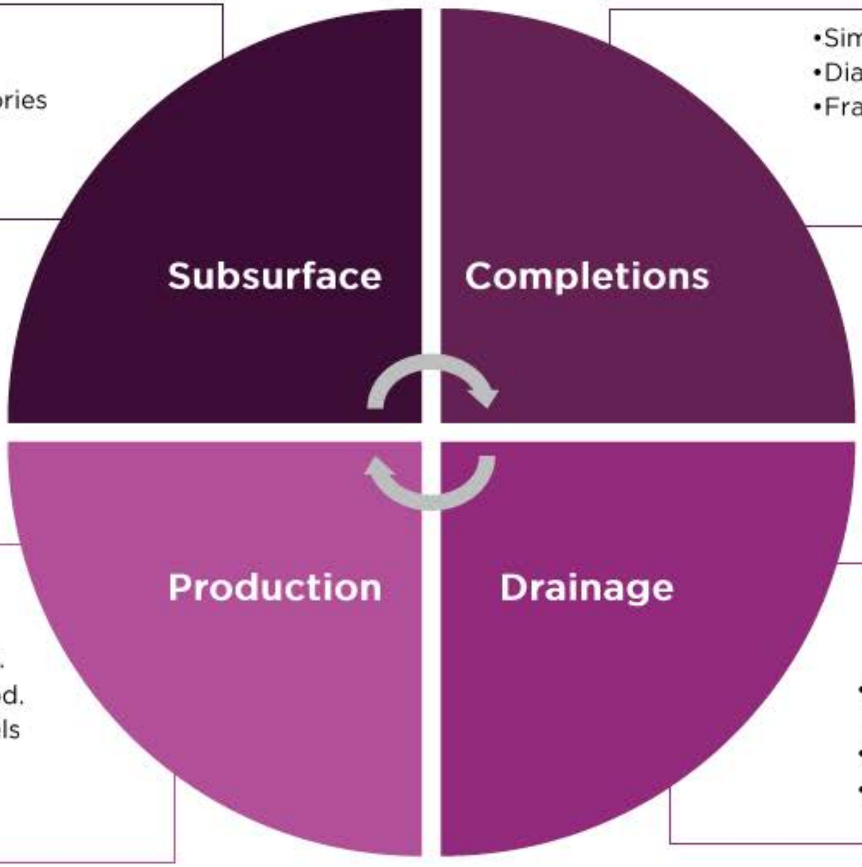
  - Importance of Microseismic Events
  - Pad-scale Faulting Which Can *Hijack* Hydraulic Fracture Stages

The Power of Connected Models

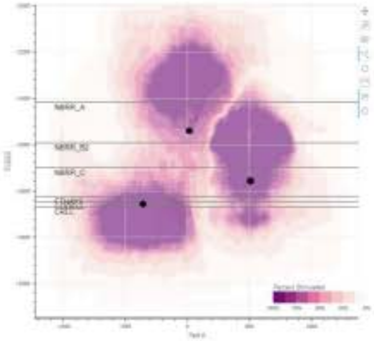
Data Driven Models, Constrained by Physics, Incorporating Your Unique Geology

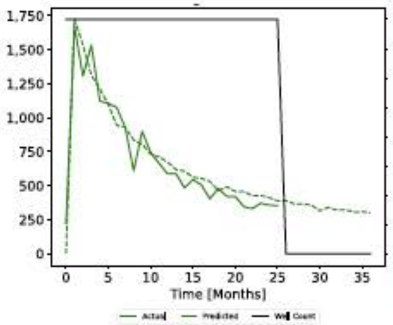


- Internal Grids
- Internal Logs
- Public Trajectories



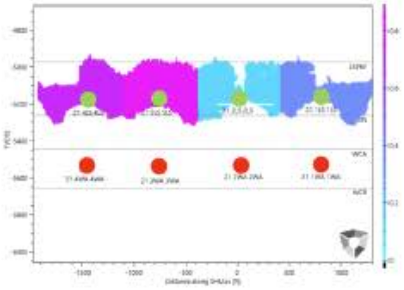
- Simulators
- Diagnostics
- Frac Van Data





- Internal Daily Prod.
- Public Monthly Prod.
- Arps Decline Models
- Price Forecasts
- Costs (AFEs, WIs, etc.)

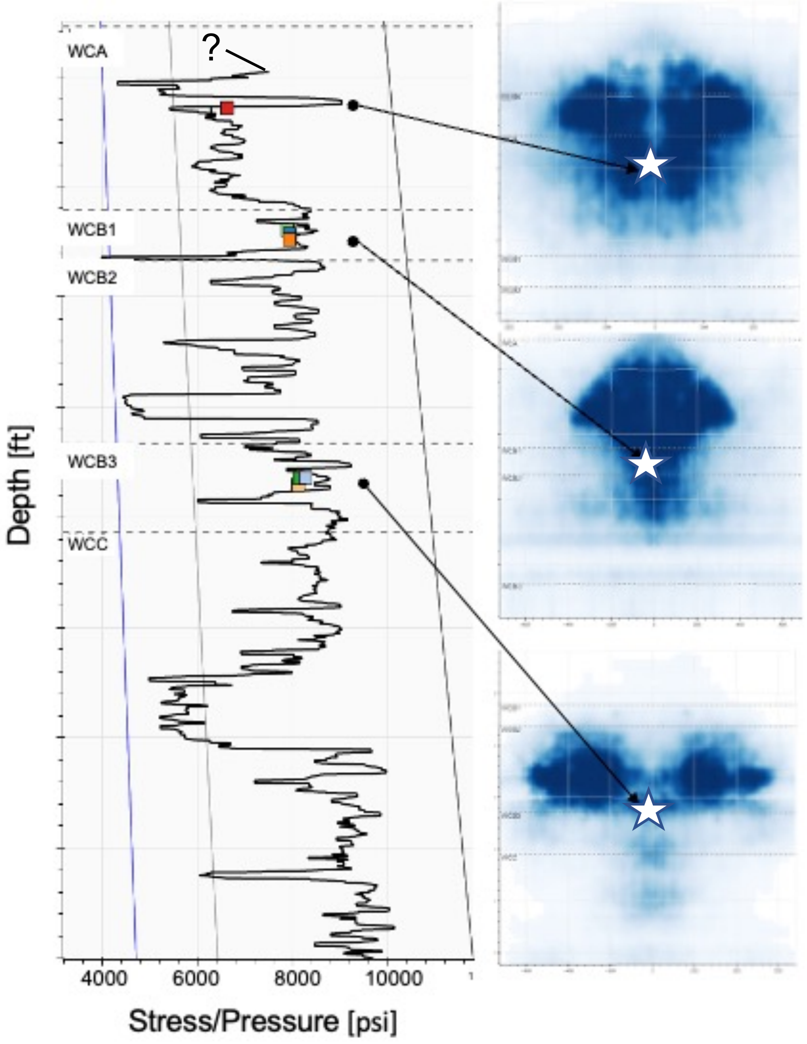
- Parent/Child Interaction
- Vertical Containment
- Oil Fingerprint



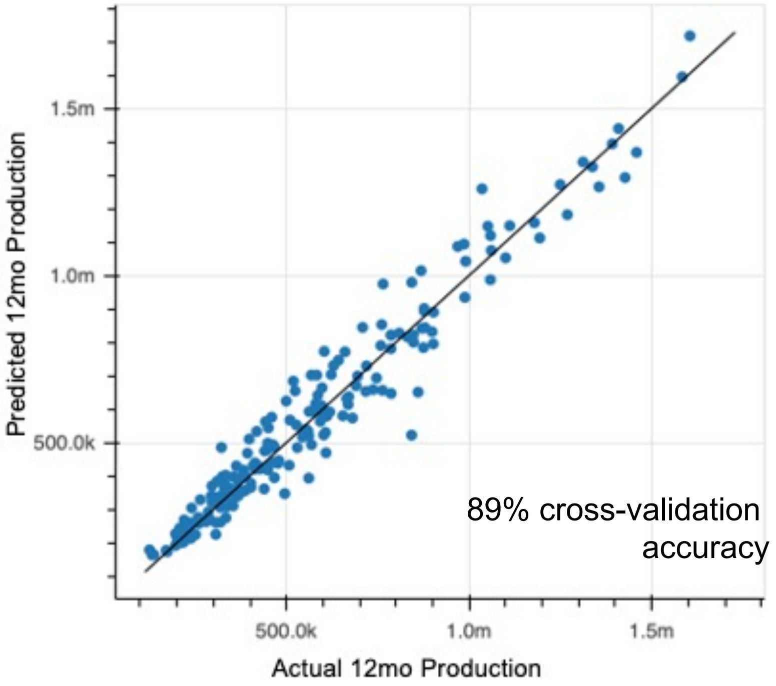
PETRO.AI

Midland Basin – Drainage Volumes Estimated from Stress Profile and ML Analysis of Production from 196 Surrounding Pads

Fingerprints Illustrate Drainage Volumes



Methodology Considers 10's of Thousands of of Potential Geomechanically-Constrained Drainage Volumes



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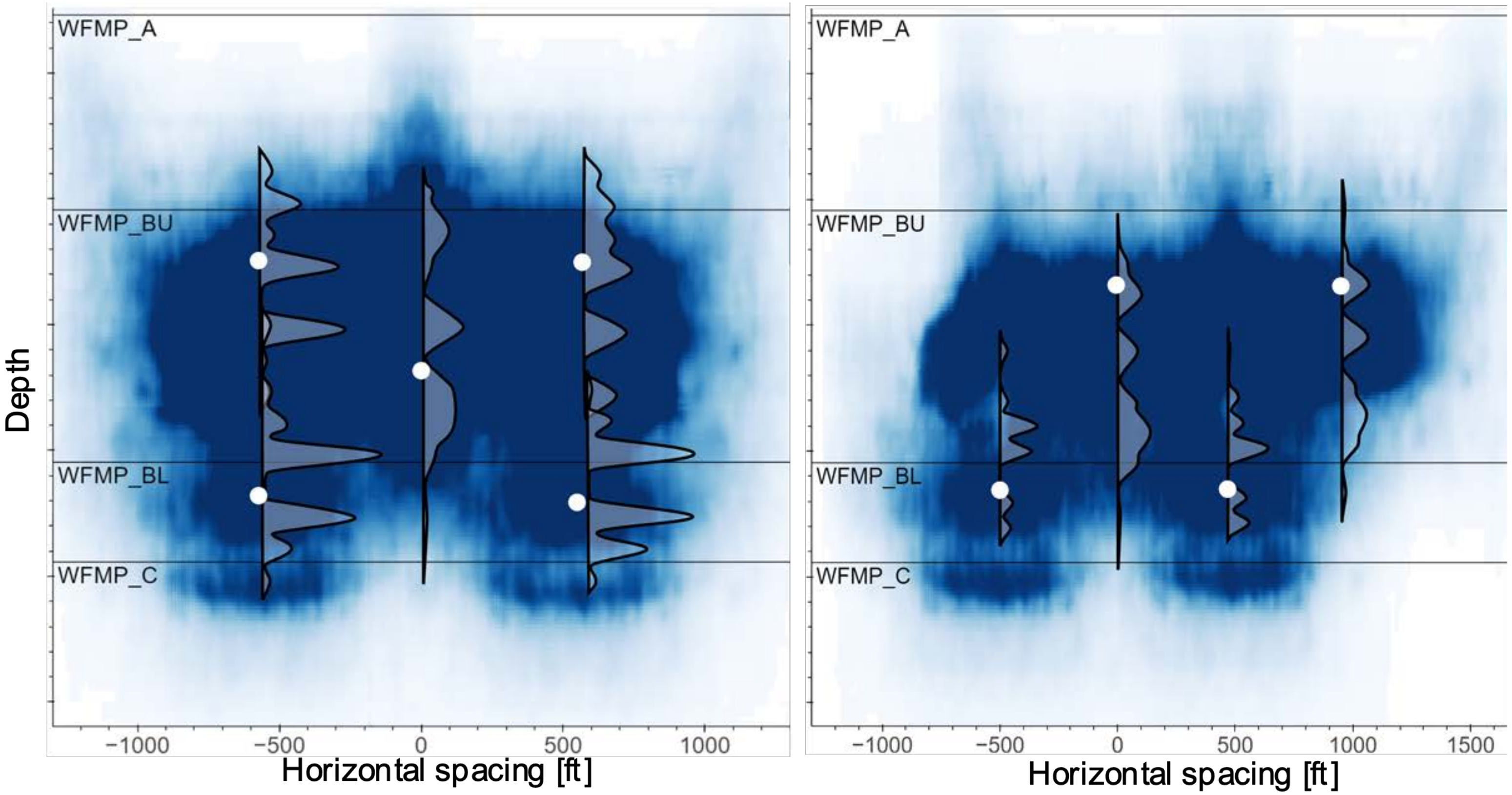
Midland Basin – What Controls Production?

Predicted 12 Month Cum. Production From 4 Wells is Almost Equivalent to 5 Well Pattern (But Much Better Economics)

Predicted Drainage Volumes from 5 Wells (12 Month Cum. Production) Are Consistent with Independent Geochemical Hydrocarbon Signatures (Ge et al., SPE-209145-MS, 2022)

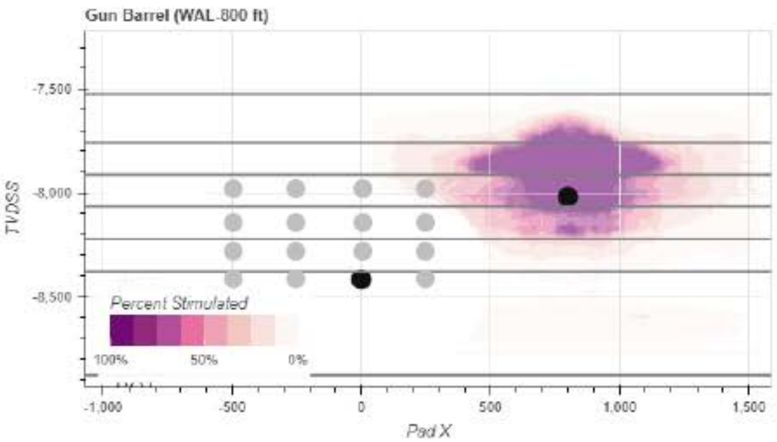


PETRO.AI

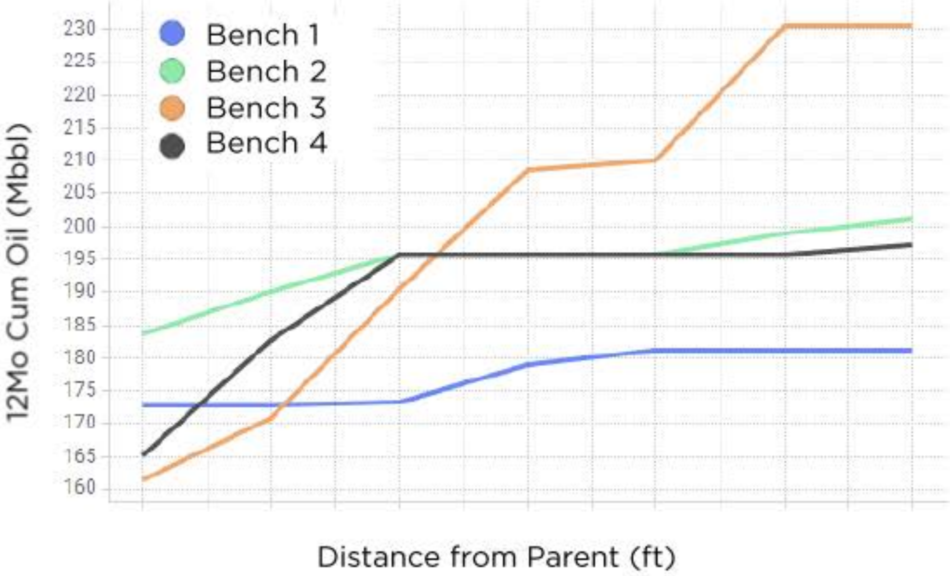
Child Well Degradation Analysis

Impact of Parent Wells is reduced outside of #### ft for wells in Bench 2, #### ft for Bench 3 offset horizontally from Parent Well

- **Goal: quantify effect of parent well on child well performance to determine optimal offset in Bench 2, Bench 3 and Bench 4 for a Bench 1 parent**
- Created scenarios with a parent well (Bench 2) and an offset child well in 100' increments
- One child well in each bench analyzed independently
- Results are shown for the child well
- For child wells offsetting parent in Bench 3, child affects are minimal when spaced > ###' horizontally in Bench 2 and Bench 3. Bench 1 wells mostly unaffected by Bench 4 parent well



Gun Barrel with frac fingerprint for various child well spacings



Predicted 12Mo oil for child well offset from parent at different spacings and landing zones

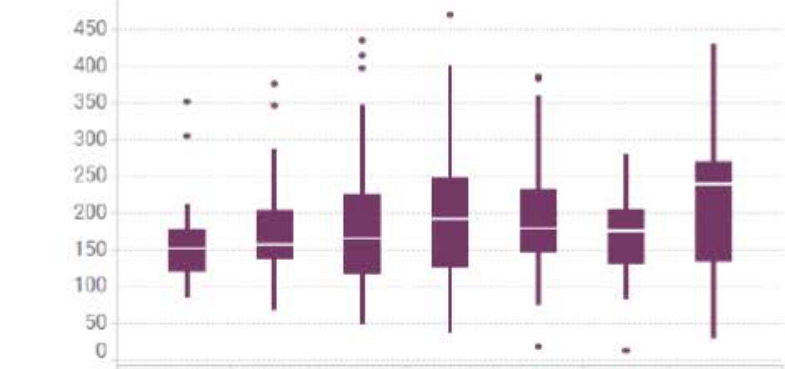
Optimal Well Spacing Different for Different Benches

PETRO.AI

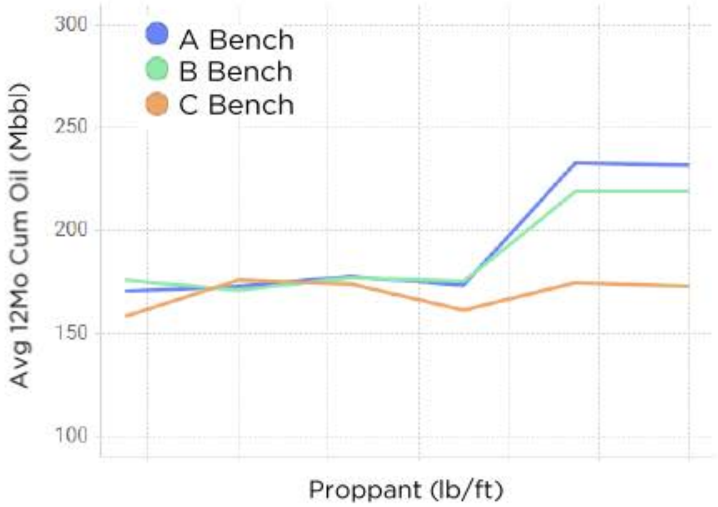
Proppant Sensitivity Analysis

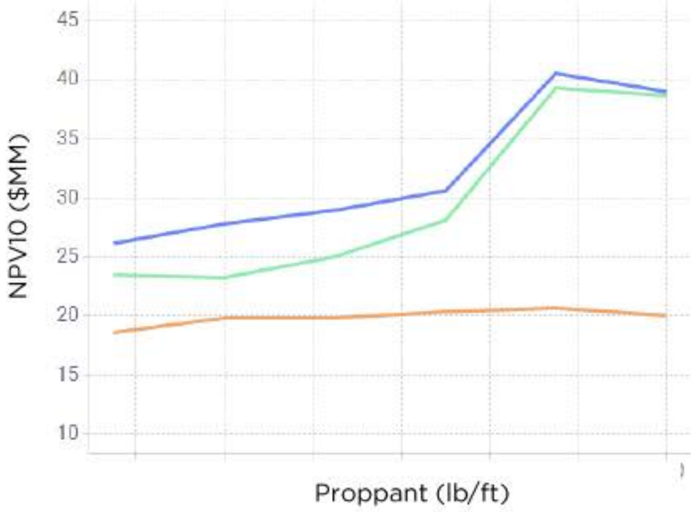
12-Mo. Cum. Oil Increases with More Proppant, but NPV Rolls Over

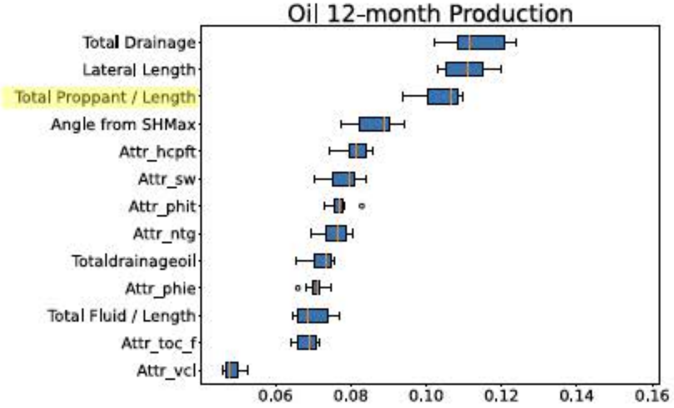
- Generated sensitivities of proppant intensities in 250 lb/ft increments
- Model predicts relatively similar 12-month cum. oil values between #### and #### lb/ft, increasing at #### lb/ft
- Slight NPV degradation predicted at #### lb/ft
- Proppant loading is 3rd most important feature for predicting 12-month oil cum. production



Count	17	46	52	74	119	23	23
Median	152	156	165	192	179	175	240



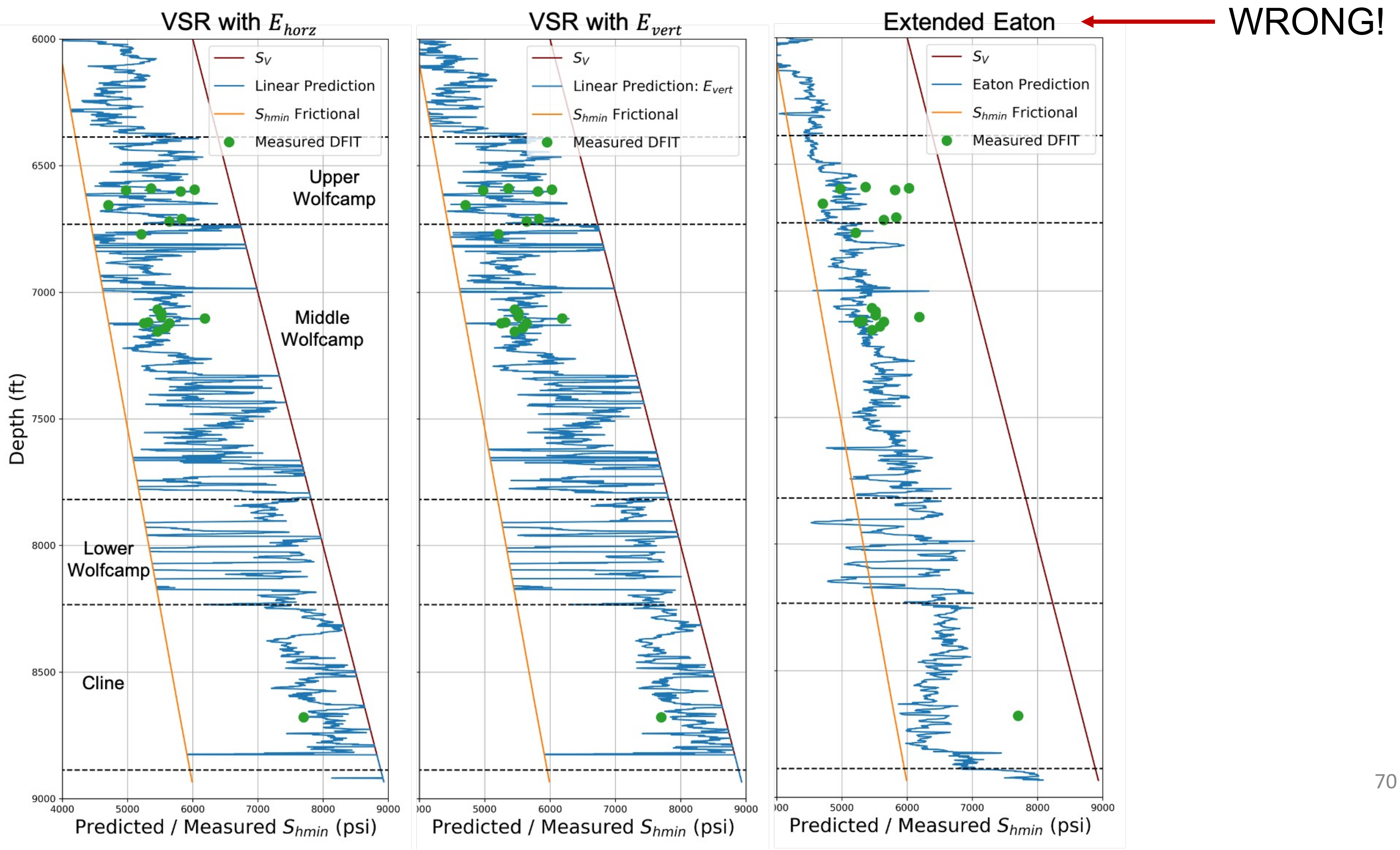




Proppant Sensitivity Different for Different Benches

PETRO.AI

Getting the Stress Right is Critical for Optimization



ResFrac

Three Topics

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    - Modeling Hydraulic Fracture Growth (ResFrac)
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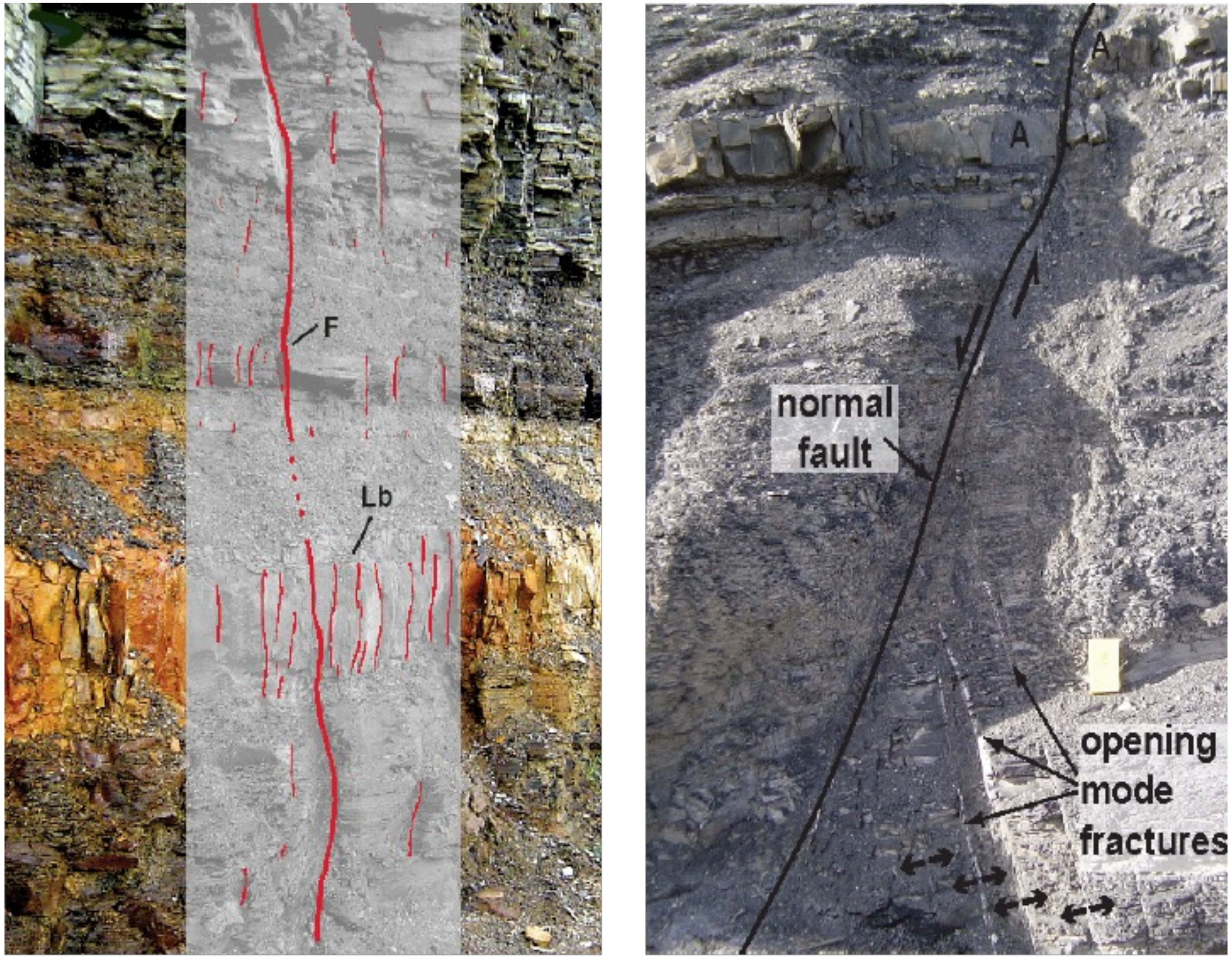
- Shear Faulting and Its Affect on Production Stimulation
    - Importance of Microseismic Events
    - Pad-scale Faulting Which Can *Hijack* Hydraulic Fracture Stages

Fractures and Faults at Many Scales

Fractures (any planar discontinuity – usually opening mode)



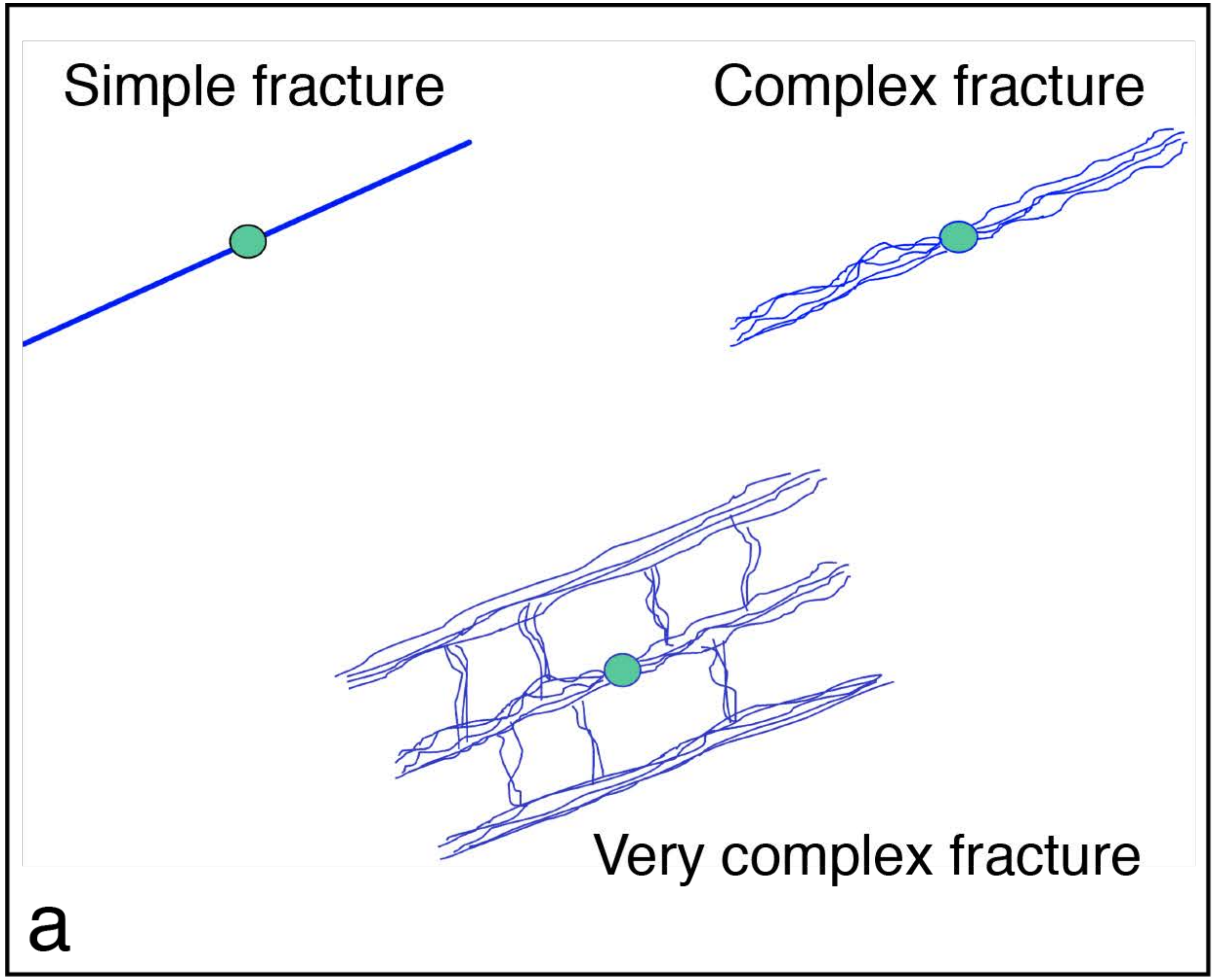
a
Fractures in New Albany Shale (Eastern Tennessee)

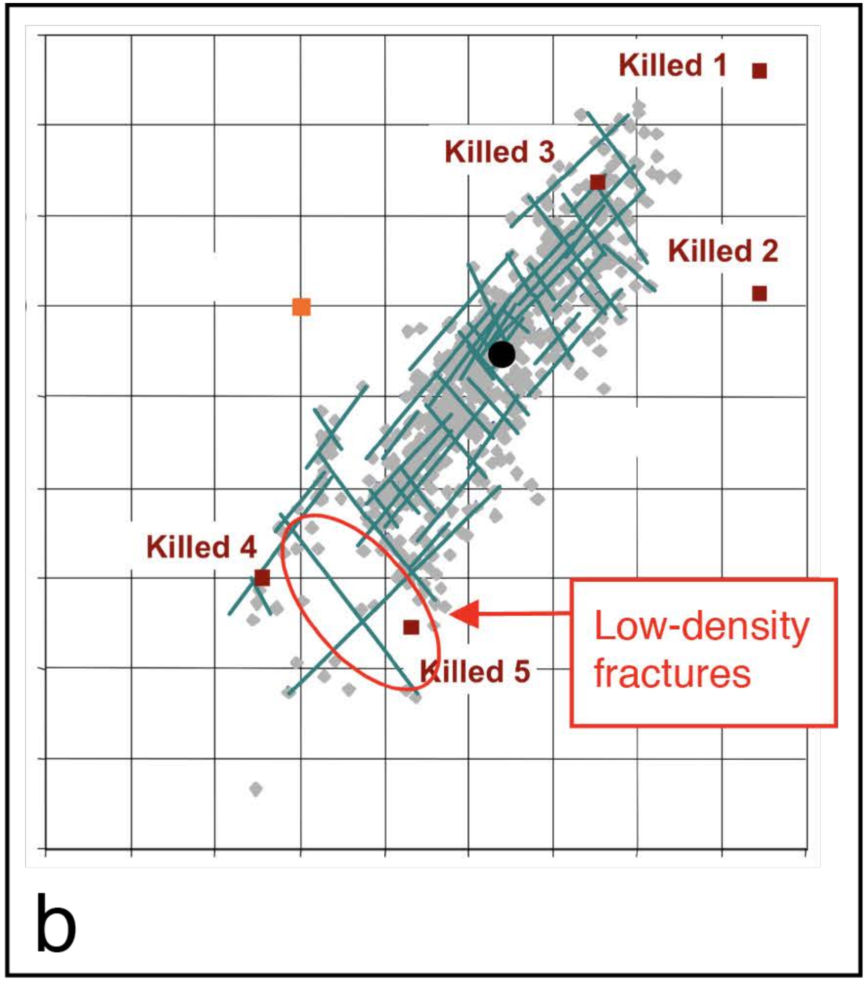
b
Fault and fractures in Vaca Muerta Shale (Argentina)

Faults (fractures that have moved in shear)

Fig. 7.20

A Critically Important, Early Study in the Barnett Shale
(Taken One Step Too Far)



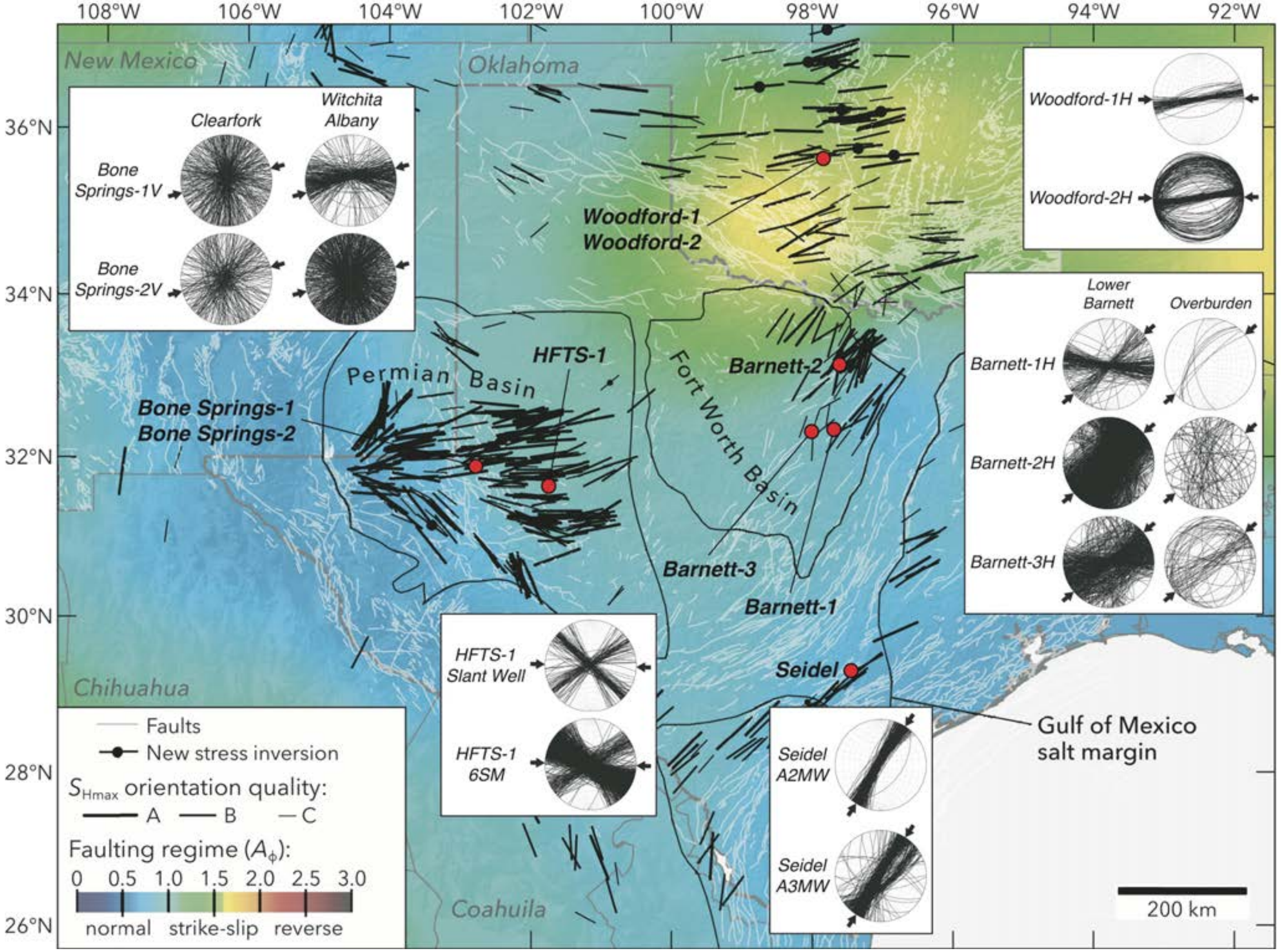


Fisher et al. (2002)

Fig. 7.21

Observations of Naturally Occurring Fractures In Horizontal Wells

The fact that the pre-existing fractures DO NOT occur in orthogonal sets parallel and perpendicular to S_{Hmax} and S_{hmin} is critical to the success of stimulation



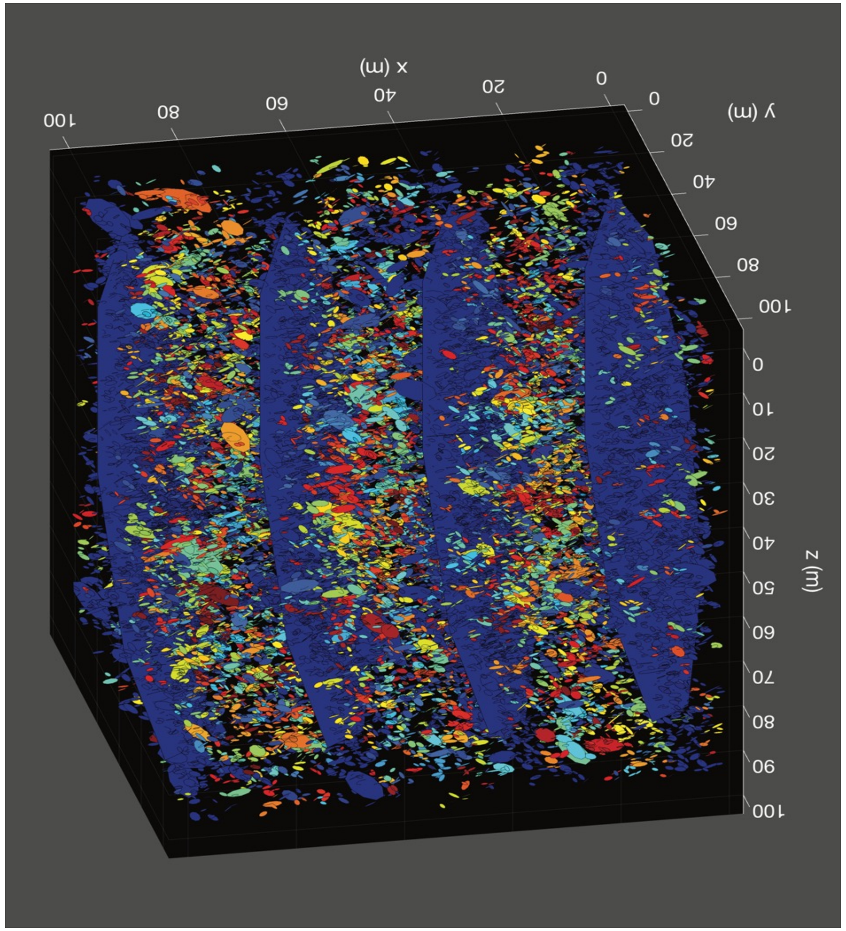


Fig. 7.22

Fig. 7.22

Three Topics

- Get the Stress Right (You Can't do Geomechanics Right With the Wrong Stress State).
    - Lessons from North America
    - Drilling Horizontal Wells in the Correct Direction (Bakken Example)

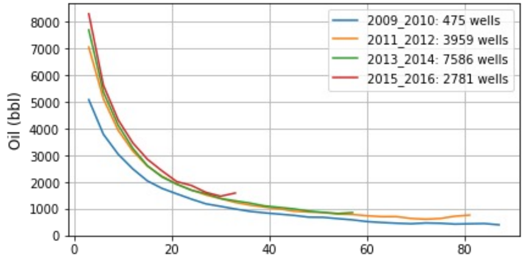
- Optimizing Well Placement When Exploiting Stacked Pay
    - Lithologically-Controlled Variations of the Least Principal Stress with Depth and its Impact on Multi-Stage Hydraulic Fracturing
    - Modeling Hydraulic Fracture Growth (ResFrac)
    - Optimizing Drainage Area (Petro.ai)

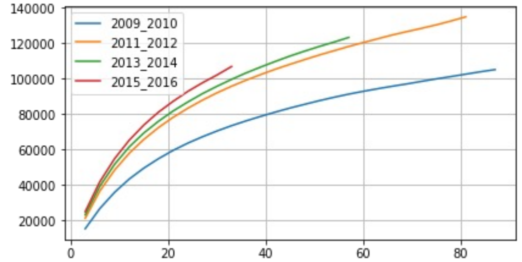
- Shear Faulting and It's Affects on Production Stimulation
    - Importance of Microseismic Events
    - Pad-scale Faulting Which Can *Hijack* Hydraulic Fracture Stages

Rapid Reduction in Rate of Production

Modest Increase in Cumulative Production

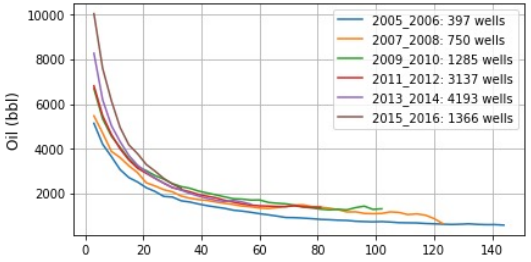
2009-2016 Eagle Ford

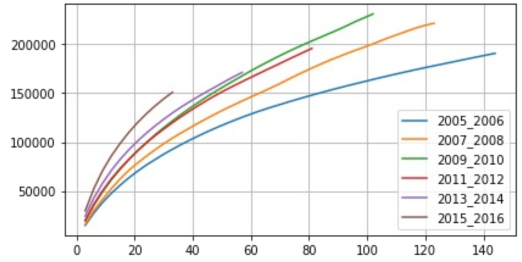




~50%

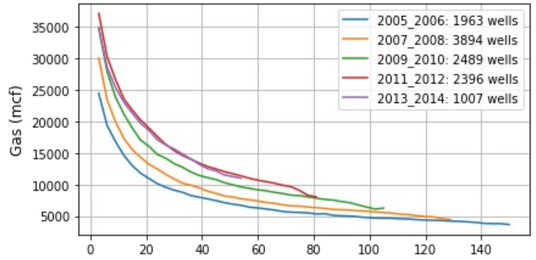
2009-2016 Bakken

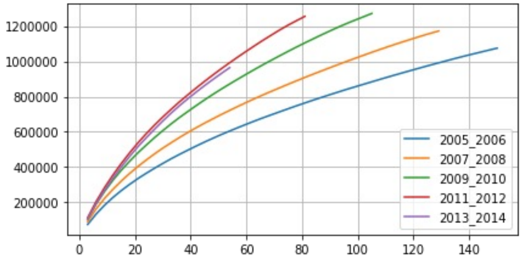




~50%

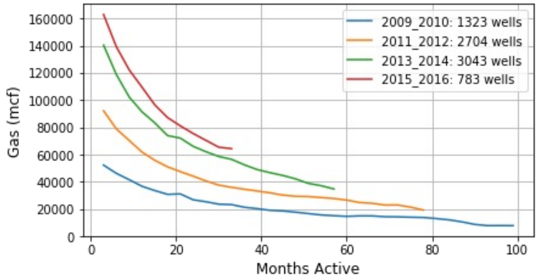
2005-2016 Barnett

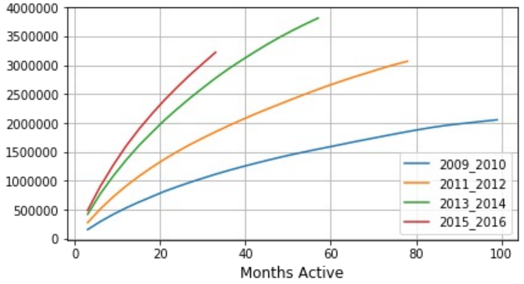




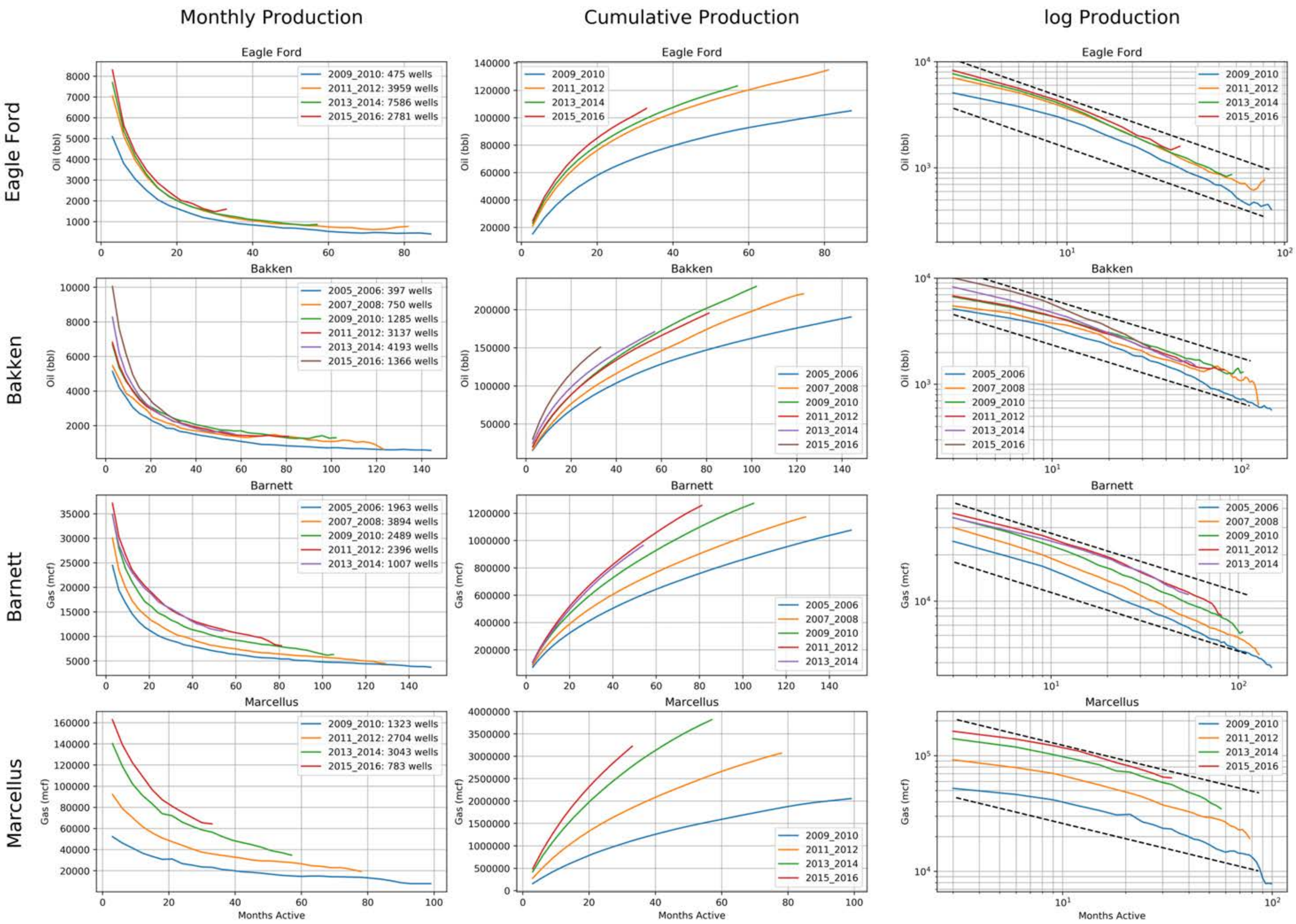
~50%

2005-2014 Marcellus





~100%



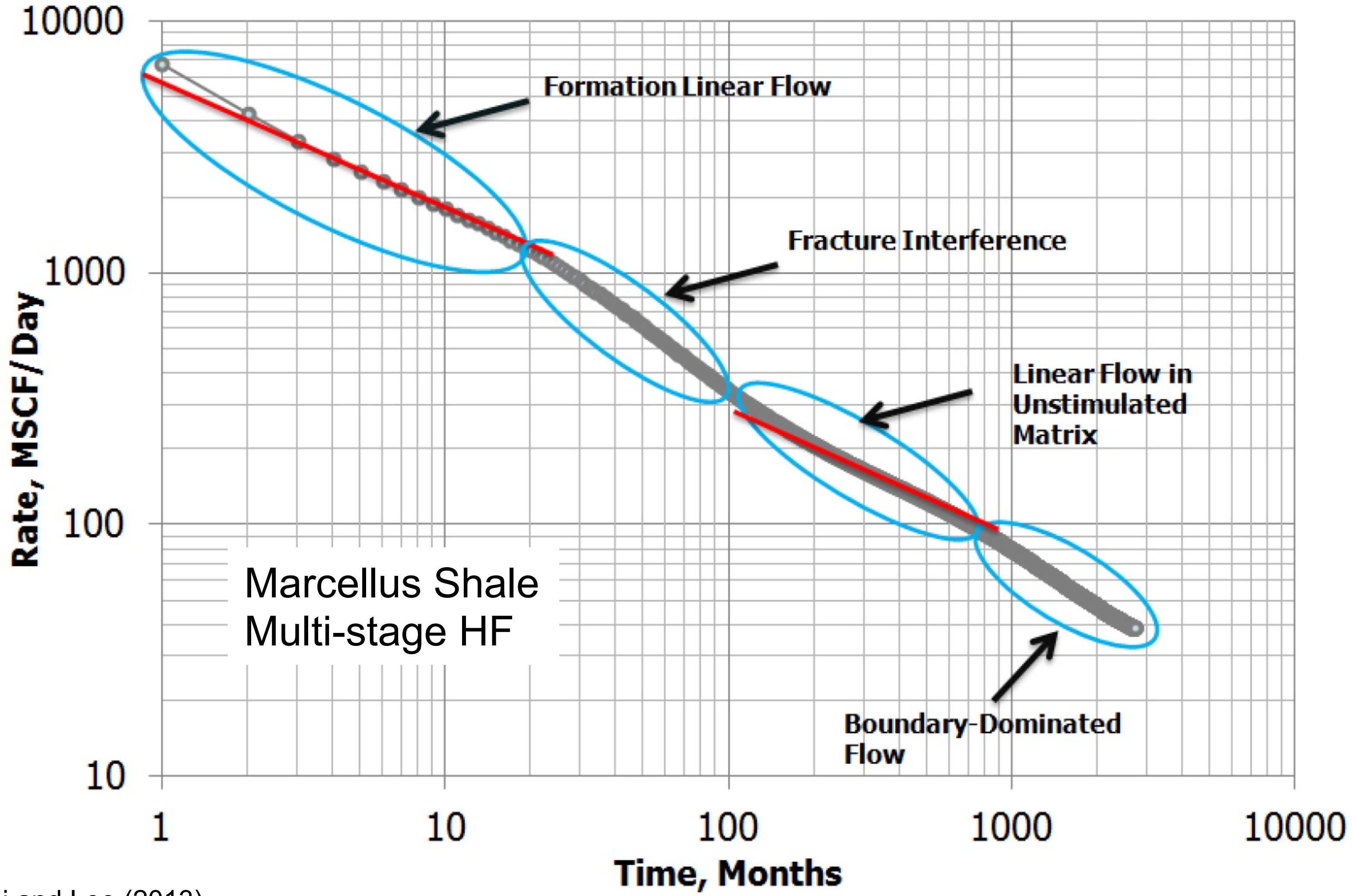
$q \propto t^{-1/2}$

Fits data well for ~ 2-3 years

All data, 3 years
b=1.99, R^2=0.98

Implies linear flow with constant permeability

Decline Curve Analysis to Predict Performance of Shale Gas Reservoirs



Joshi and Lee (2013)

Arps (1945) Hyperbolic decline

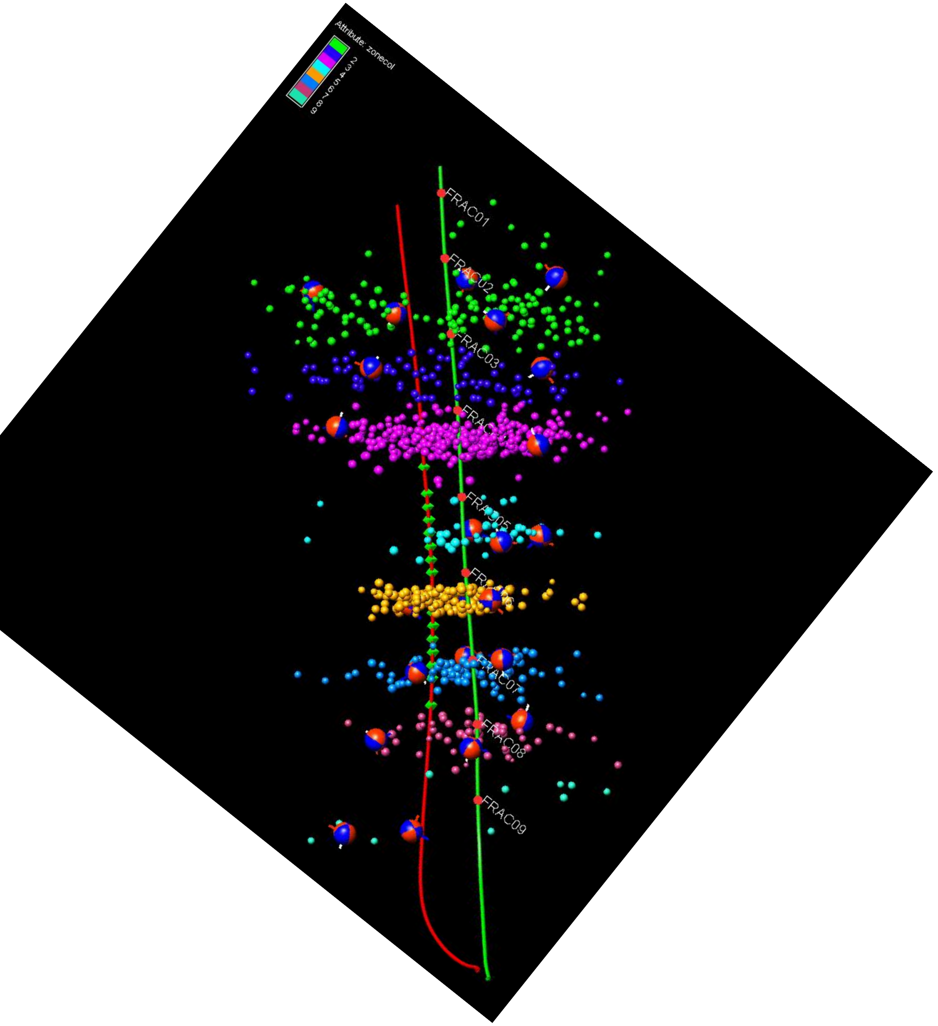
$q=q_i(1 + D_i t)^{-1/b}$

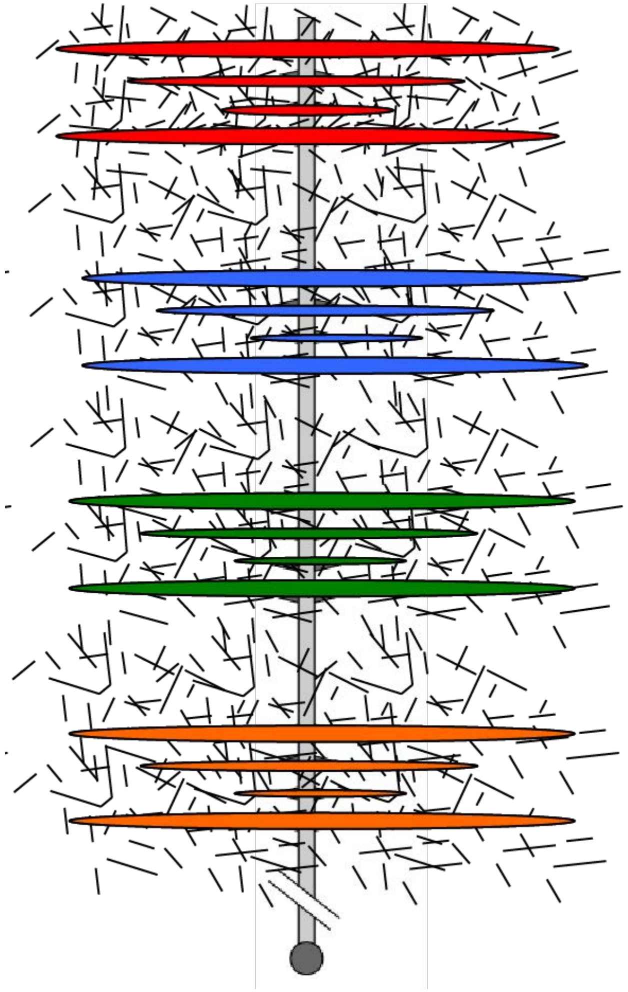
For linear flow b=2 (red line) – works well for the first 2 years of production

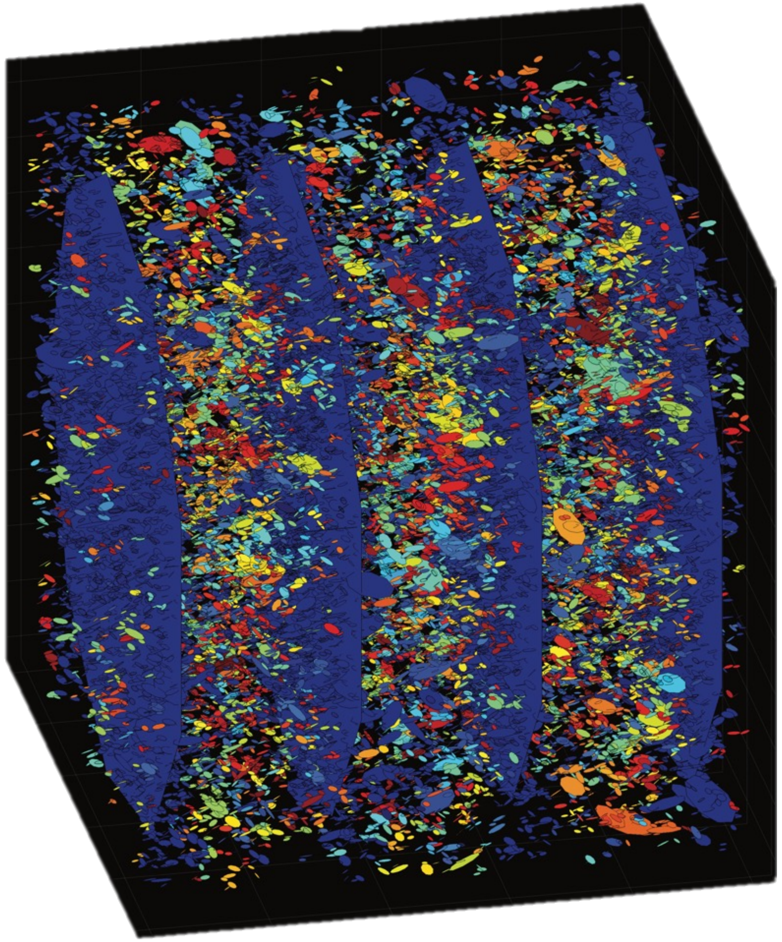
Fracture interference steepens slope

q_i initial flow rate (volume/time)
D_i initial decline rate (1/time)

Linear Flow Into Planar Hydraulic Fractures and Fracture/Fault Planes Associated with the Cloud of Microseismic Events







GEOPHYSICS, VOL. 84, NO. 6 (NOVEMBER-DECEMBER 2019); P. B461–B469, 8 FIGS.
10.1190/GEO2018-0545.1

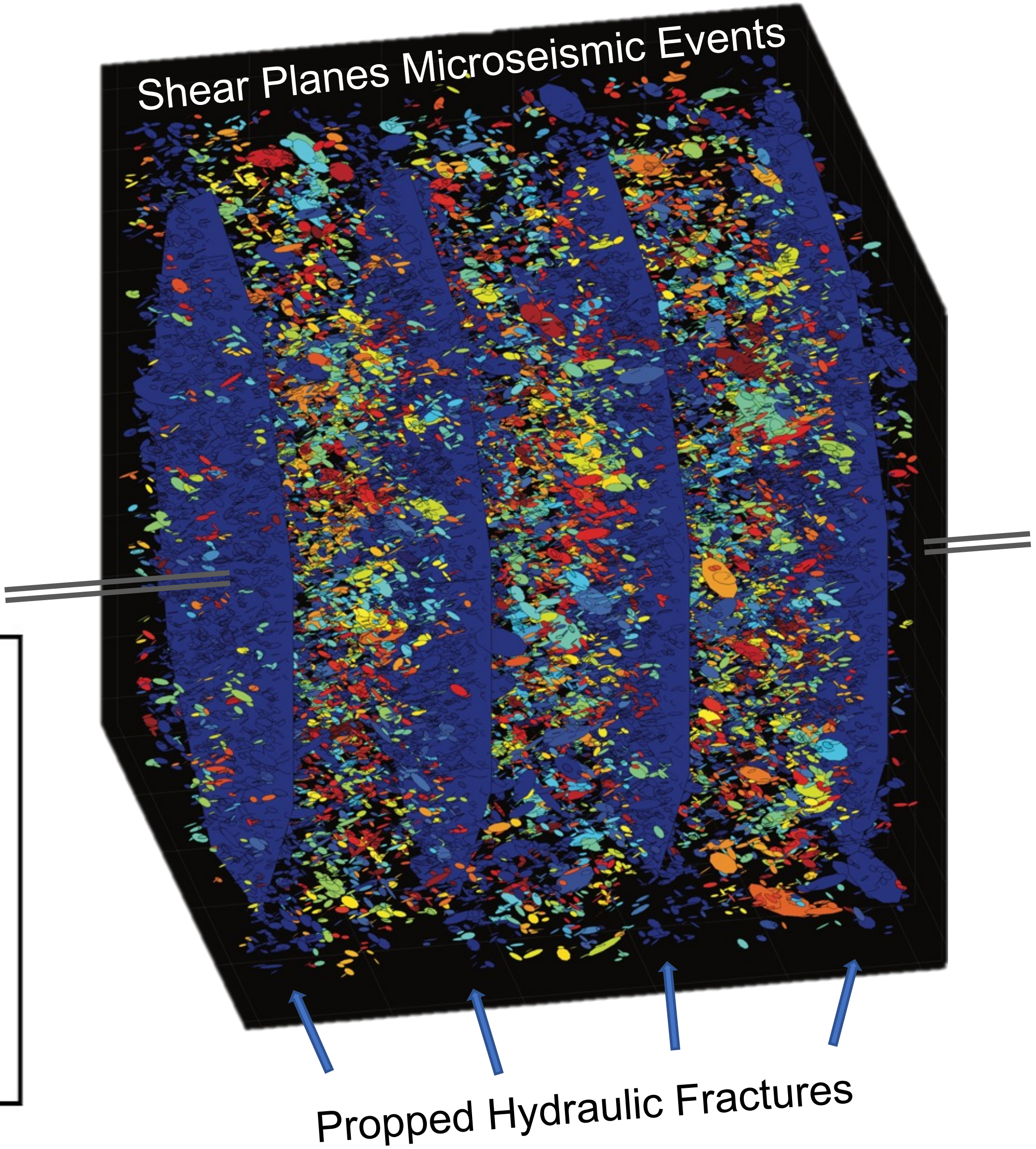
Case History

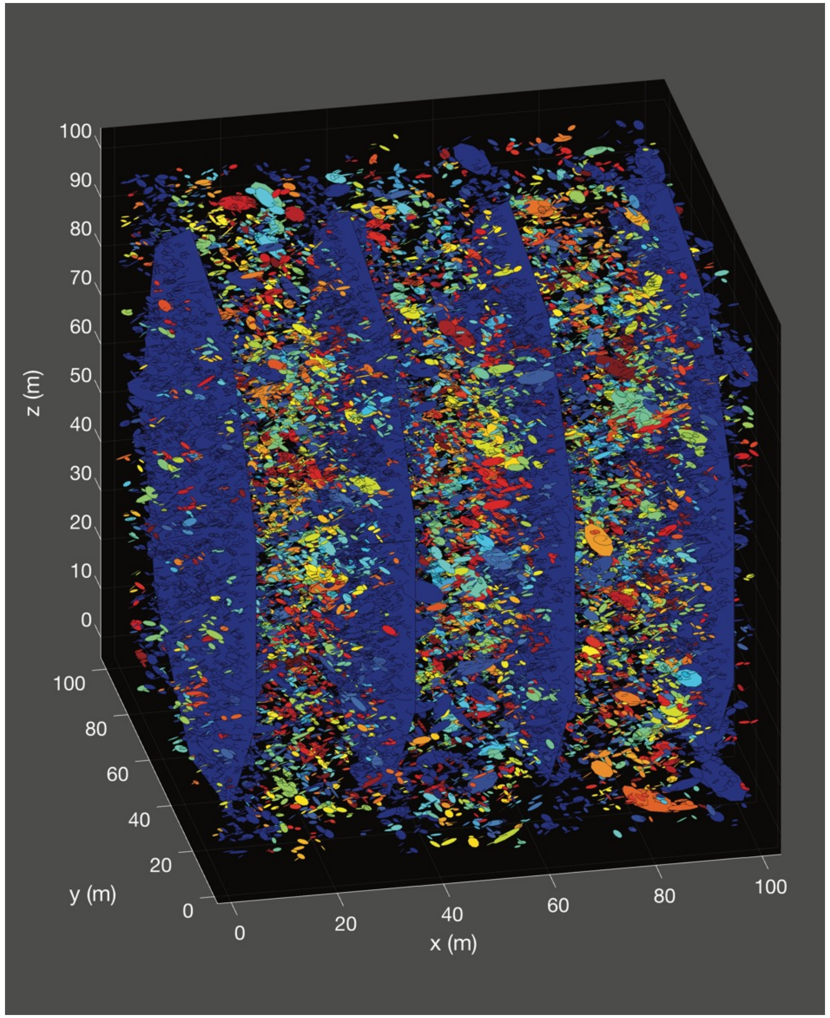
The relation between stimulated shear fractures and production in the Barnett Shale: Implications for unconventional oil and gas reservoirs

Alex Hakso[1] and Mark Zoback[1]

ABSTRACT

Economic production from extremely low permeability unconventional reservoirs is accomplished through multistage slick water hydraulic fracturing, which generates opening-mode hydraulic fractures and induces shear slip on preexisting fractures in the surrounding formation. We have addressed the critical contribution of the stimulated shear fracture network on production. We found production decline curves from tens of thousands of wells in four unconventional plays in the U.S. (two oil and two gas). These data indicate that during the early years of production: (1) Production is dominated by linear flow from the extremely low permeability matrix into much more permeable fracture planes, (2) the rapid decrease in production rates is a natural consequence of pressure depletion in the matrix within several meters of the more permeable planes, and (3) the cumulative area of permeable fracture planes created during stimulation is an important factor affecting cumulative production. Using data from two case studies in the Barnett Shale, we estimate the area of the fracture network from the microseismicity generated during hydraulic fracturing operations. The data from one study demonstrates that the cumulative area of the shear fracture network is needed to match production data. With data from the other case study, we demonstrate that the relative fracture area created during each stage correlates well with the relative stage-by-stage production determined from distributed temperature sensing.





Linear flow

Flow rate $$q = \frac{1}{2}\frac{\alpha}{\sqrt{t}}$$

where $$\alpha = A\left(\frac{P_r^2 - P_{bhf}^2}{P_s}\right)\sqrt{\frac{c_g \phi_m k_m}{\pi \eta}}$$

sometimes called an $A\sqrt{k}$ model

1-D Linear Flow into Permeable Planes

Diffusion time for flow

$$\tau = \frac{l^2}{\kappa} = \frac{\left(\varphi B_f + B_r\right)\eta l^2}{k}$$

B_f Compressibility fluid
B_r Compressibility rock
l distance
k matrix permeability
η viscosity
~ 0.3 cp oil
~ 0.03 cp gas

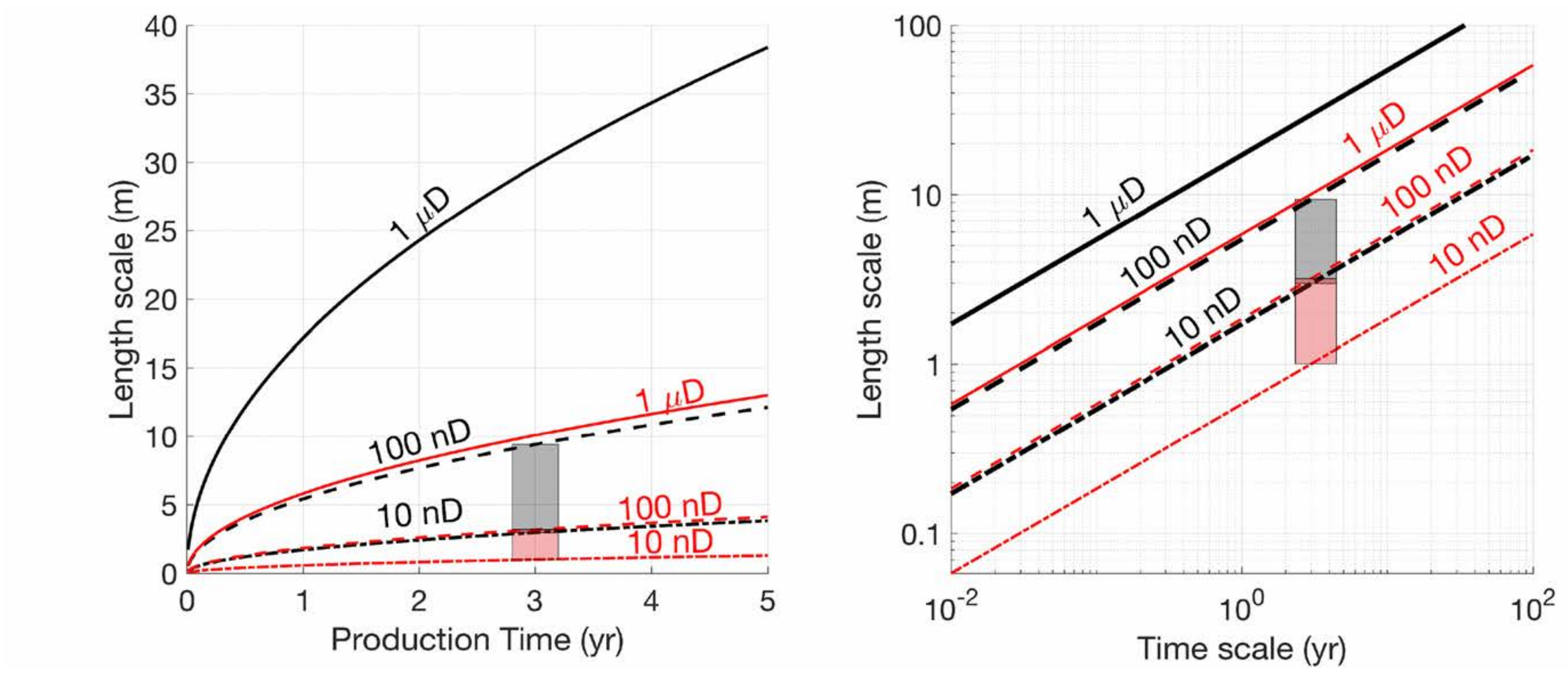
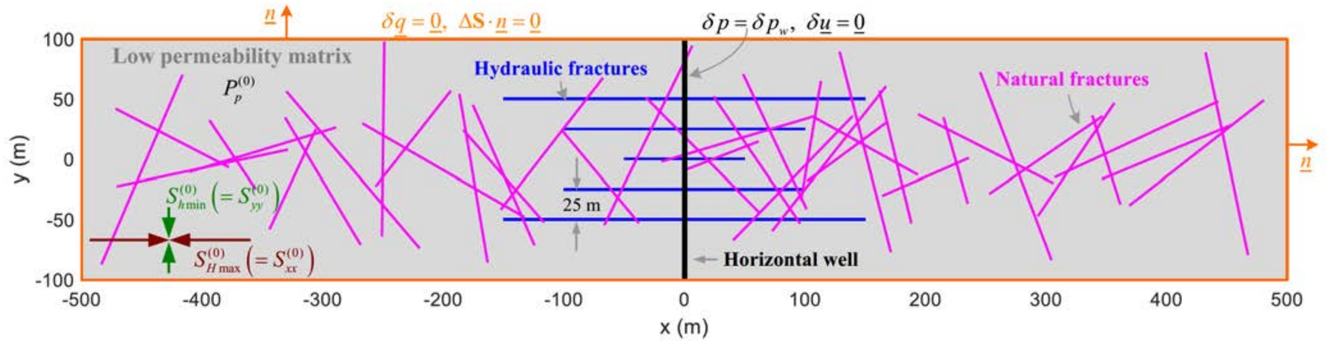


Fig. 12.2

Visualizing Production and Depletion

Fully-Coupled 2D Poroelastic Model Set Up



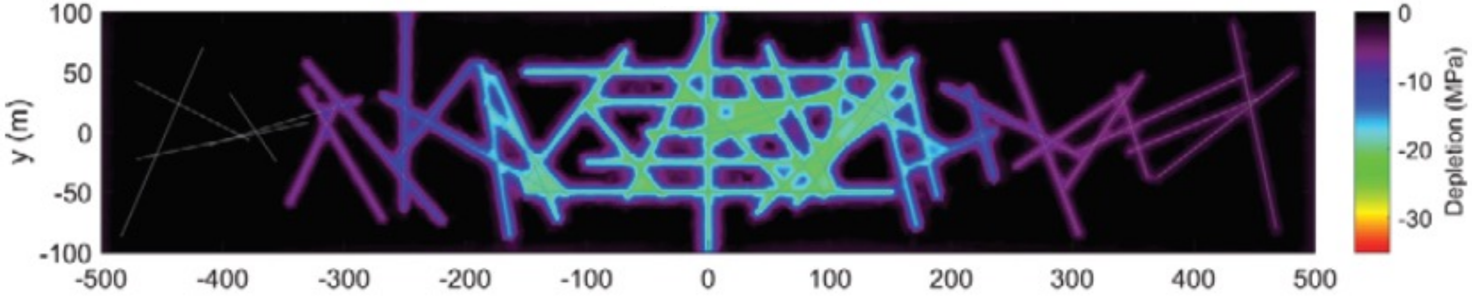
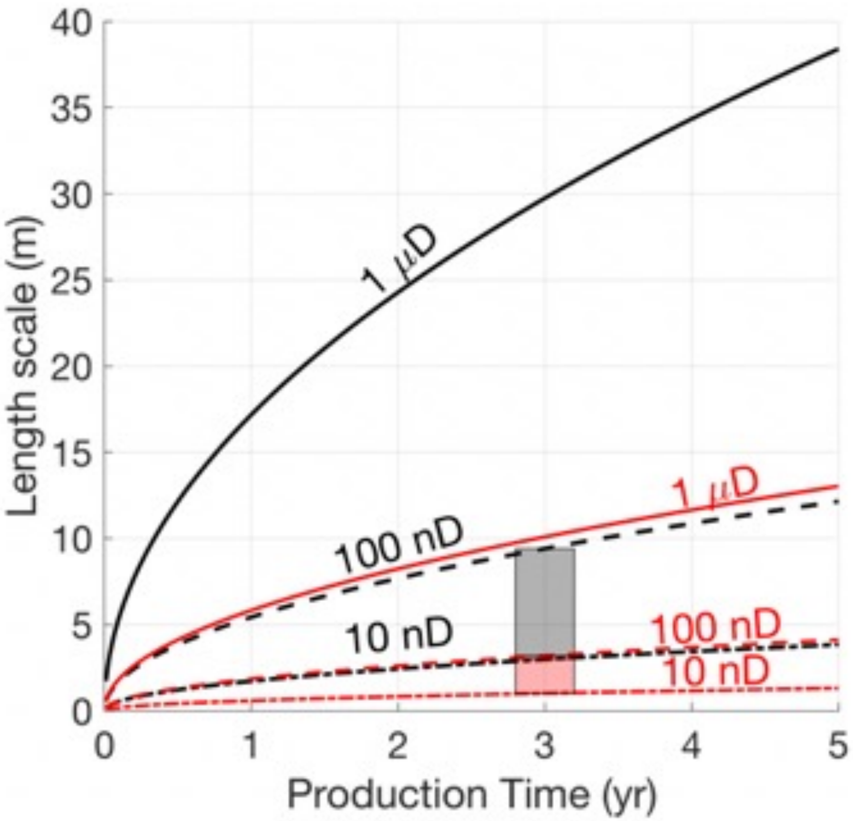
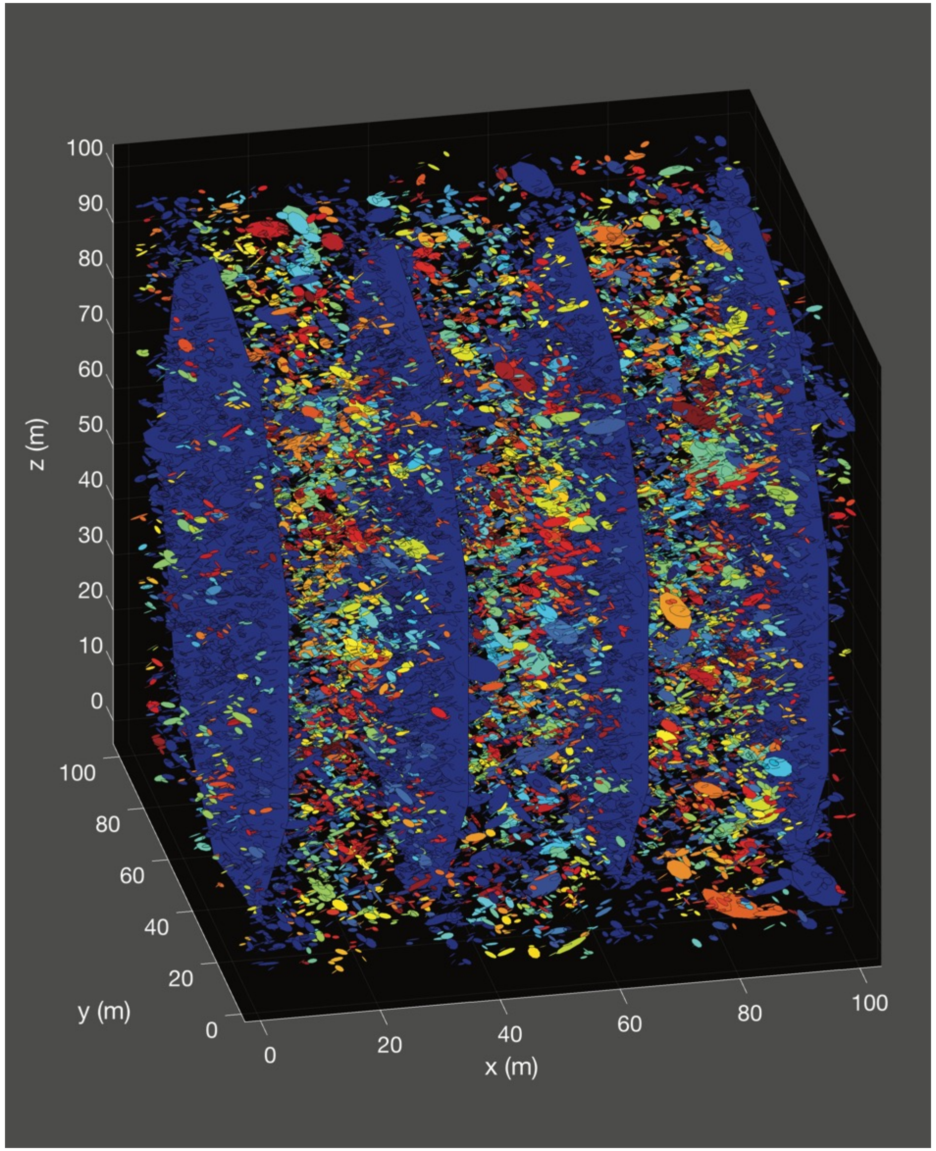


Fig. 12.10 and Jin and Zoback (2019)

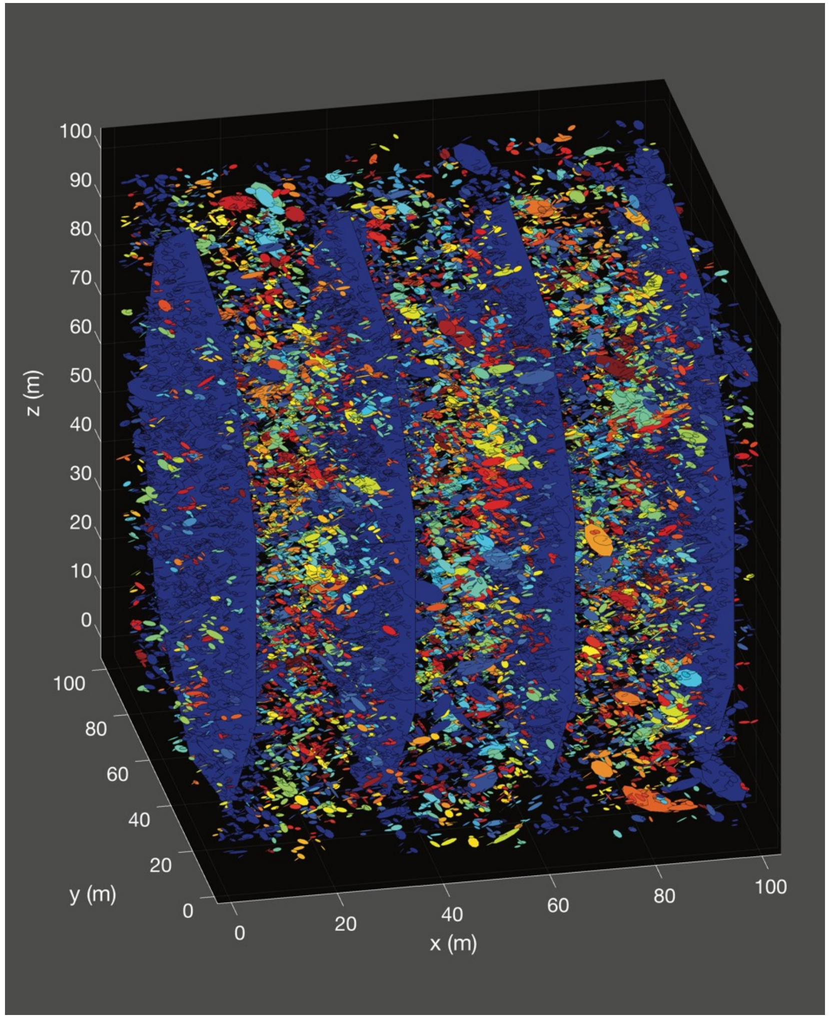


- Depth 7000 ft, Sv ~ 7000 psi
- Produced for 2 years
- Bottom Hole Pressure 1000 psi
- Laboratory-Determined Permeability ~10-100 nd



Why is Shear Stimulation Important?

- Creation of surface area during stimulation is critical for successful production
- Linear flow into all HF’s from matrix within ~10 m would recover approximately 3% of gas in place
- Linear flow into all HF’s and the stimulated fracture network accesses ~25% of the gas in place



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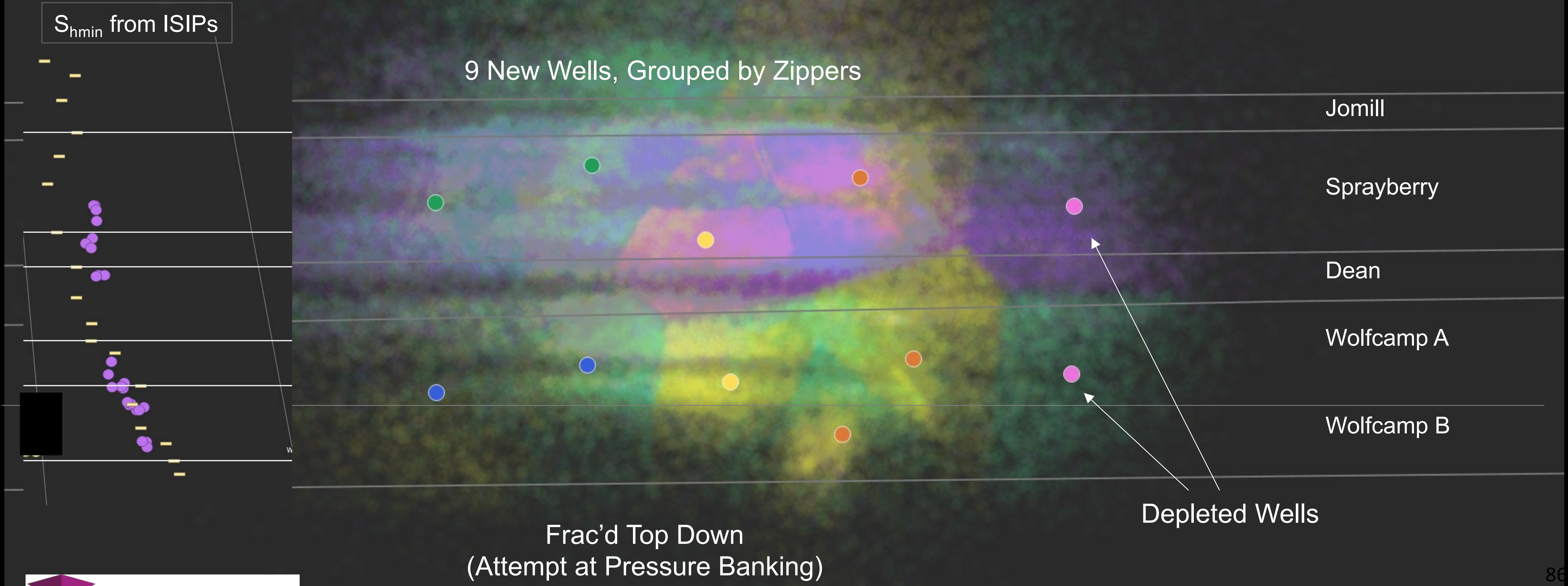
sometimes called an $A\sqrt{k}$ model

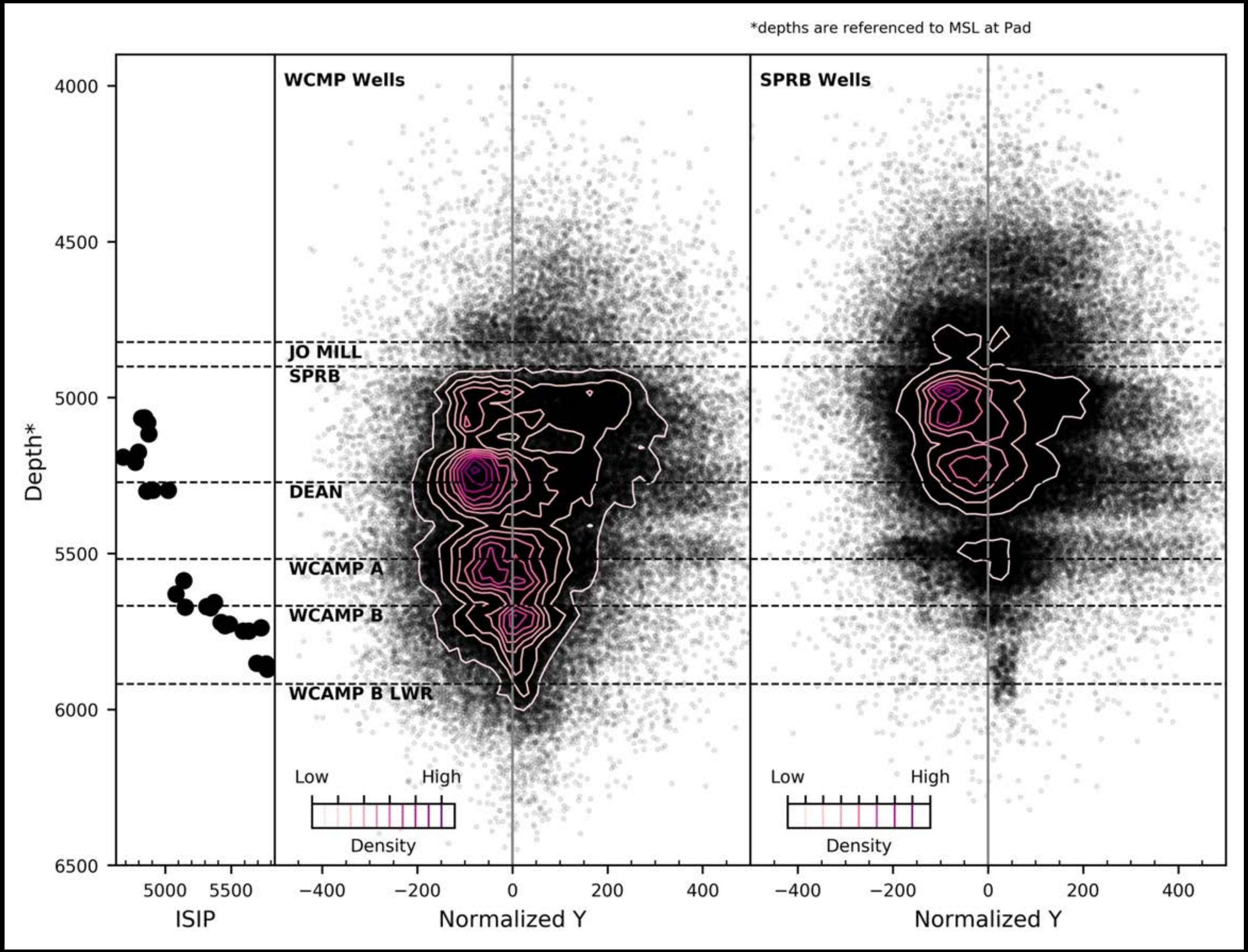
<u>One should consider flow into both the hydraulic Fractures and the shear fracture network</u>

Midland Basin Tank Development Science Pad



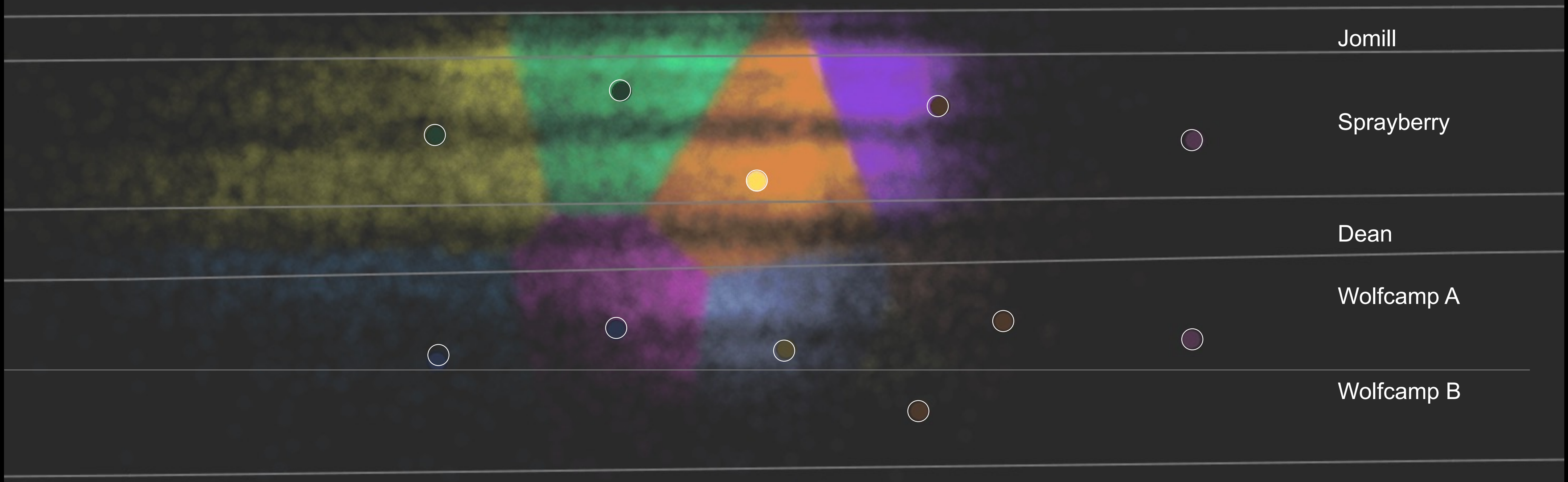
PETRO.AI

Midland Basin Tank Development
Apportioning Microseismic Events to Nearest Each Well



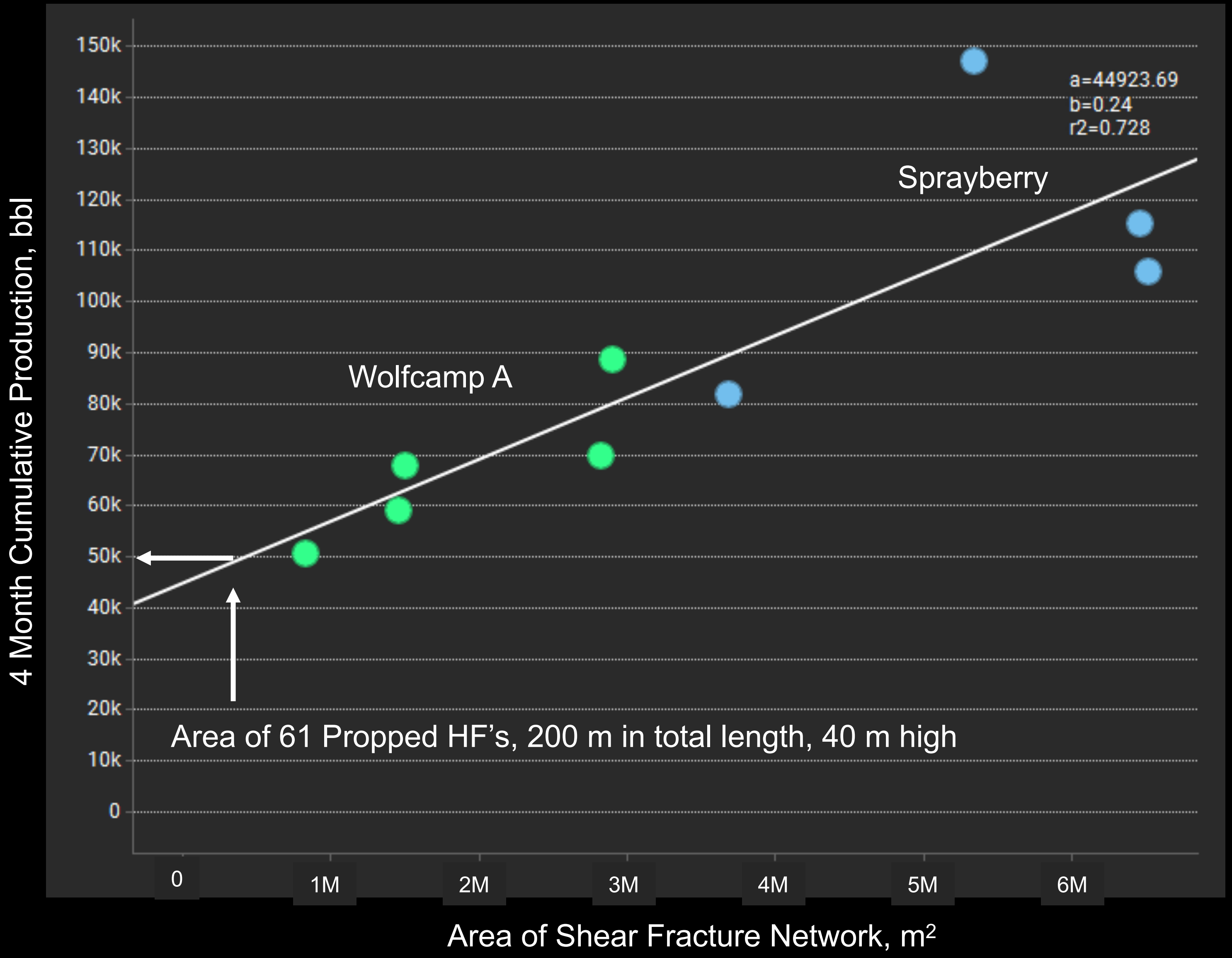
PETRO.AI

Midland Basin Tank Development
Apportioning Microseismic Events to Nearest Each Well



PETRO.AI

Cumulative 4-Month Oil Production vs. Fracture Surface Area Colored by Zone



According to Operator, Sprayberry wells are "normally" not as good as Wolfcamp wells in this area.

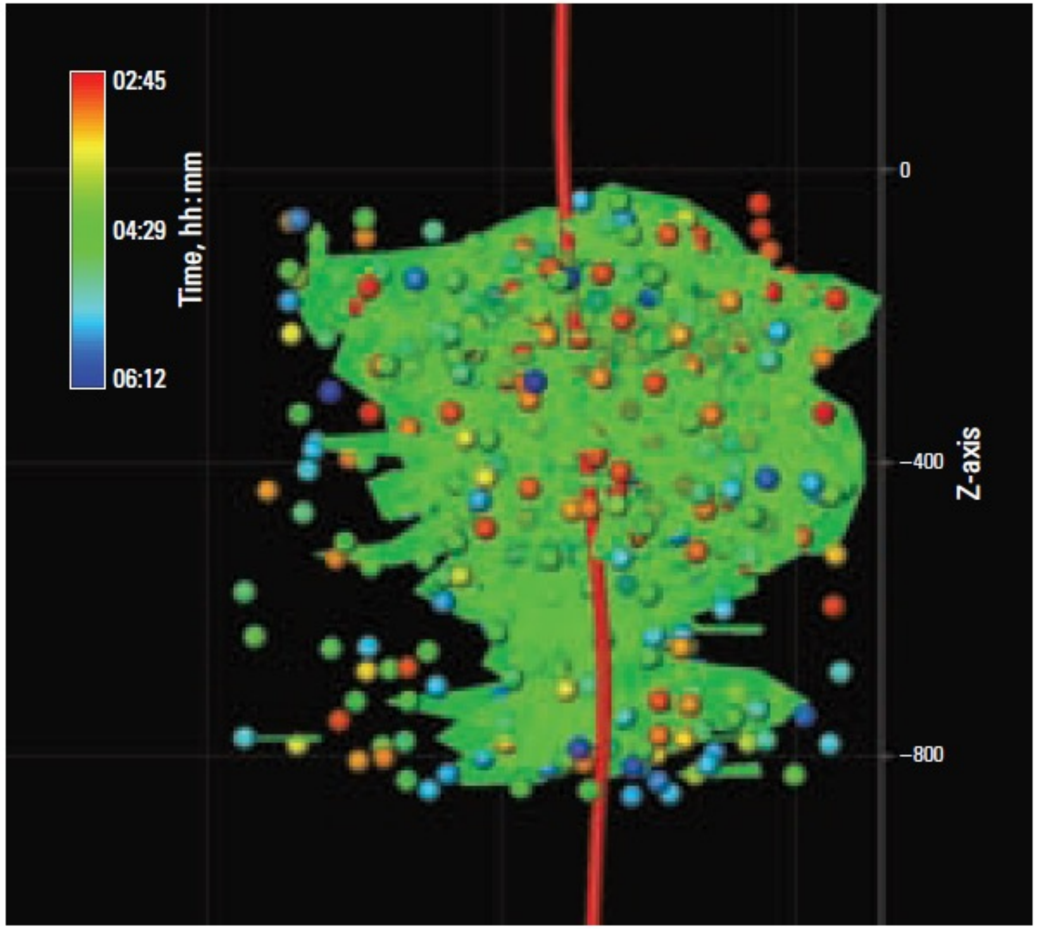
It is clear here that the Sprayberry wells are the best because they were stimulated multiple times

Are Microseismic Events Associated With Hydraulic Fracturing Stimulation Important for Production?

Take Away Messages

- Recognizing that many factors affect successful stimulation of unconventional reservoirs, induced shear on interconnected pre-existing (often mineralized) fractures creates a permeable interconnected fracture network
- The surface area of the interconnected fracture network can be as important for production as that of the surface area of the propped hydraulic fractures themselves
- If there is significant aseismic shear, there would be even more surface area created in the stimulated fracture network.
- If there are few pre-existing fractures, maximizing propped area of the hydraulic fractures is more critical than ever

Why Doesn't the SRV Explain Production?



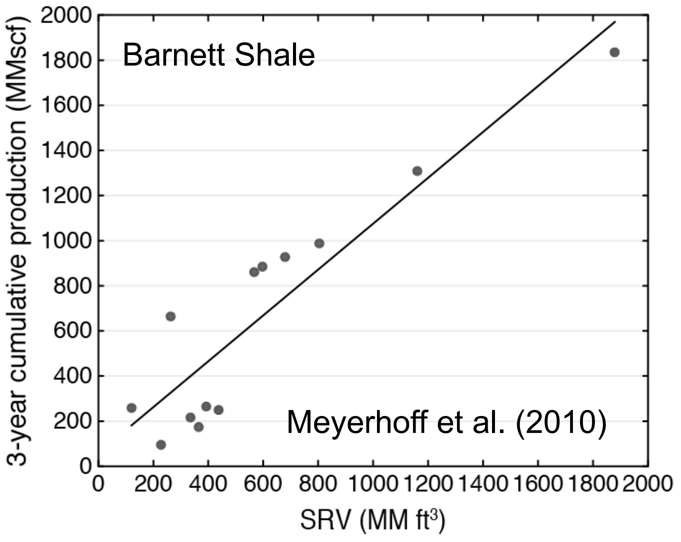
Stimulated Rock Volume

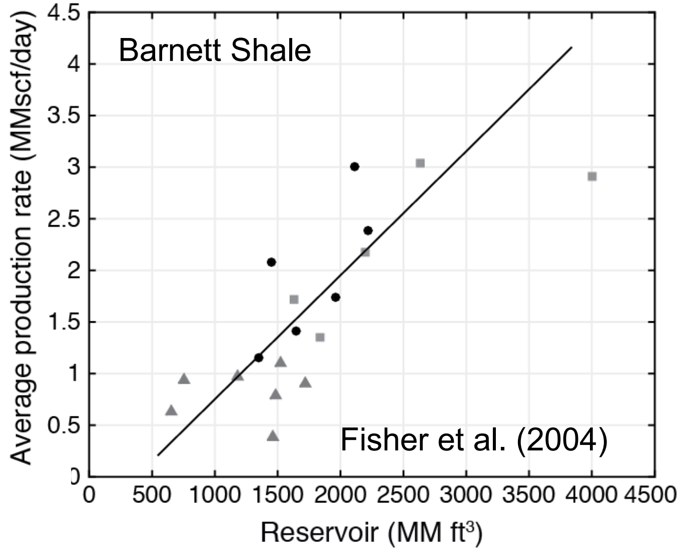
SRV Significantly Overpredicts Production (~8 x in one case study)

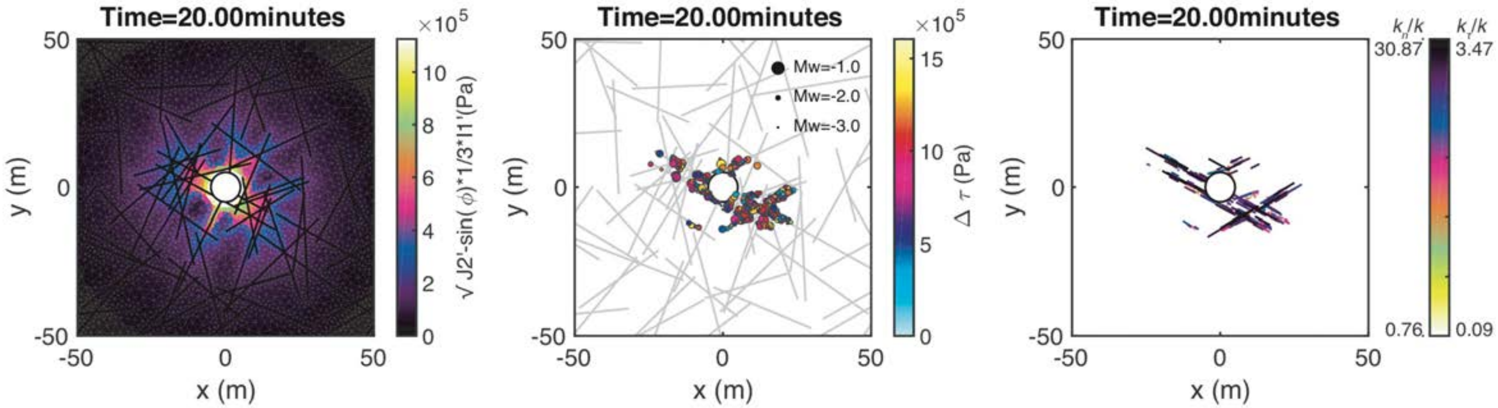
Why?:
Location accuracy (volume scales with distance^3

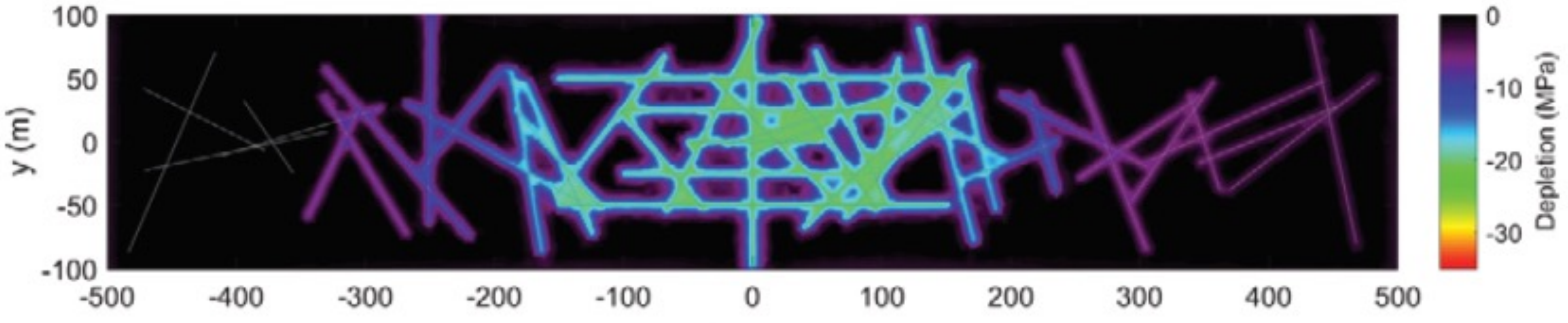
The SRV model implicitly envisions flow from throughout the matrix within the SRV

What's Wrong with the Idea of the Stimulated Rock Volume?



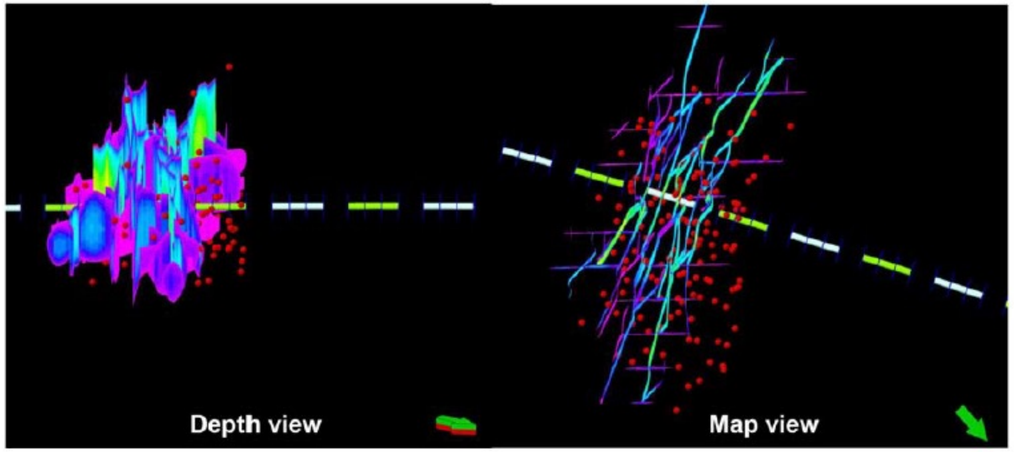




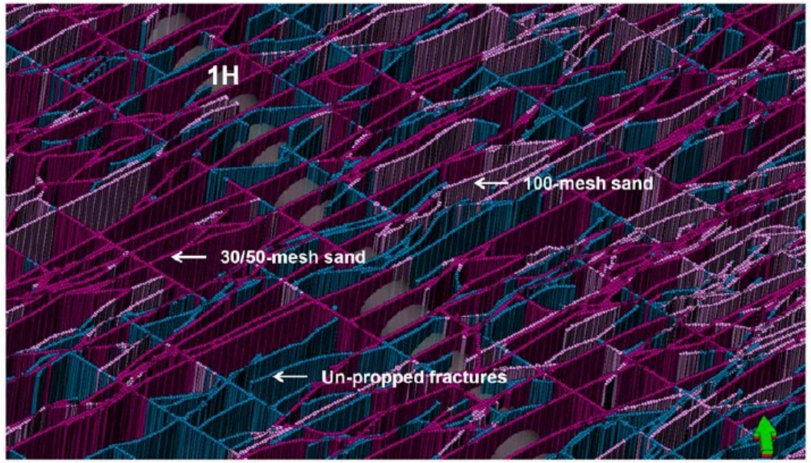


Production Doesn't Come from the Volume Defined by an Envelope Surrounding the Microseismic Cloud, it Comes from the Formation Adjacent to the Permeable Fractures

“Complex” Models of Hydraulic Fractures and Shear Fractures



Cippolla et al. (2018)



netics

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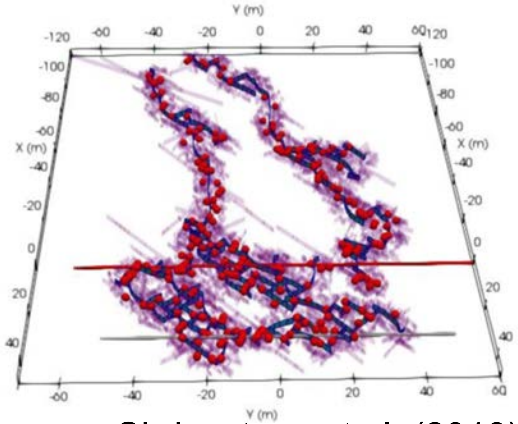
where $\alpha = A\left(\frac{P_r^2 - P_{bhf}^2}{P_s}\right)\sqrt{\frac{c_g \phi_m k_m}{\pi\eta}}$



Shrivastava et al. (2018)

*When history matching production data, one cannot distinguish between various models of “complexity” as long as they have the same surface area

Inducing Shear Slip on Poorly-Oriented Planes

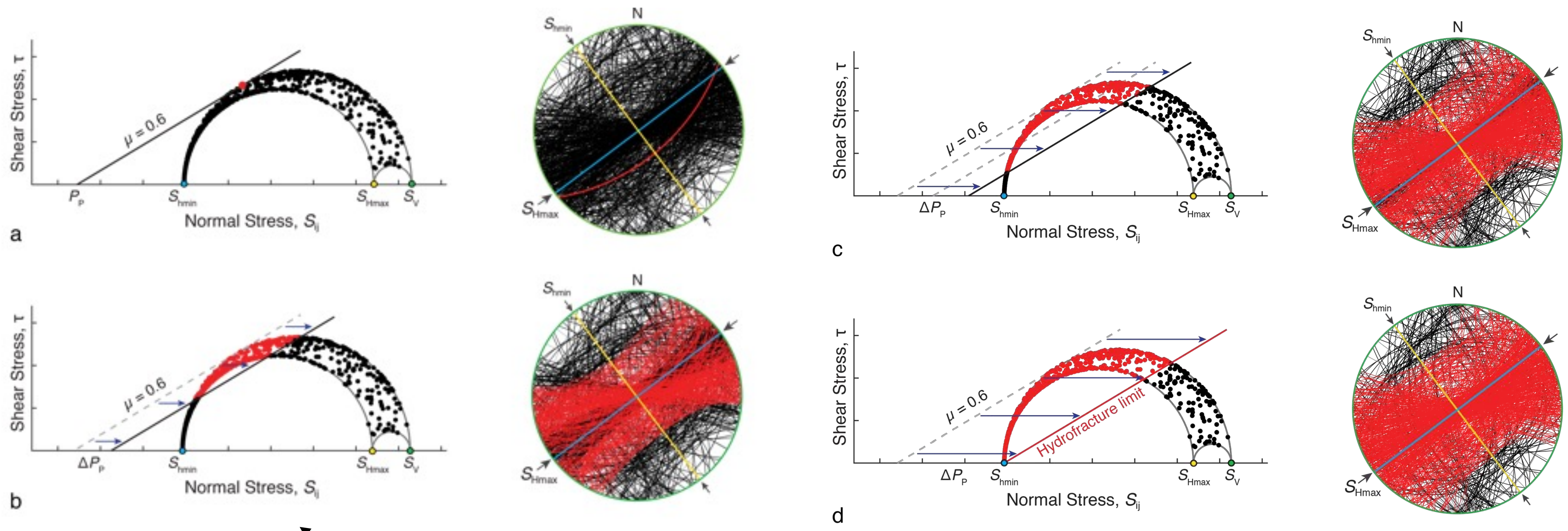
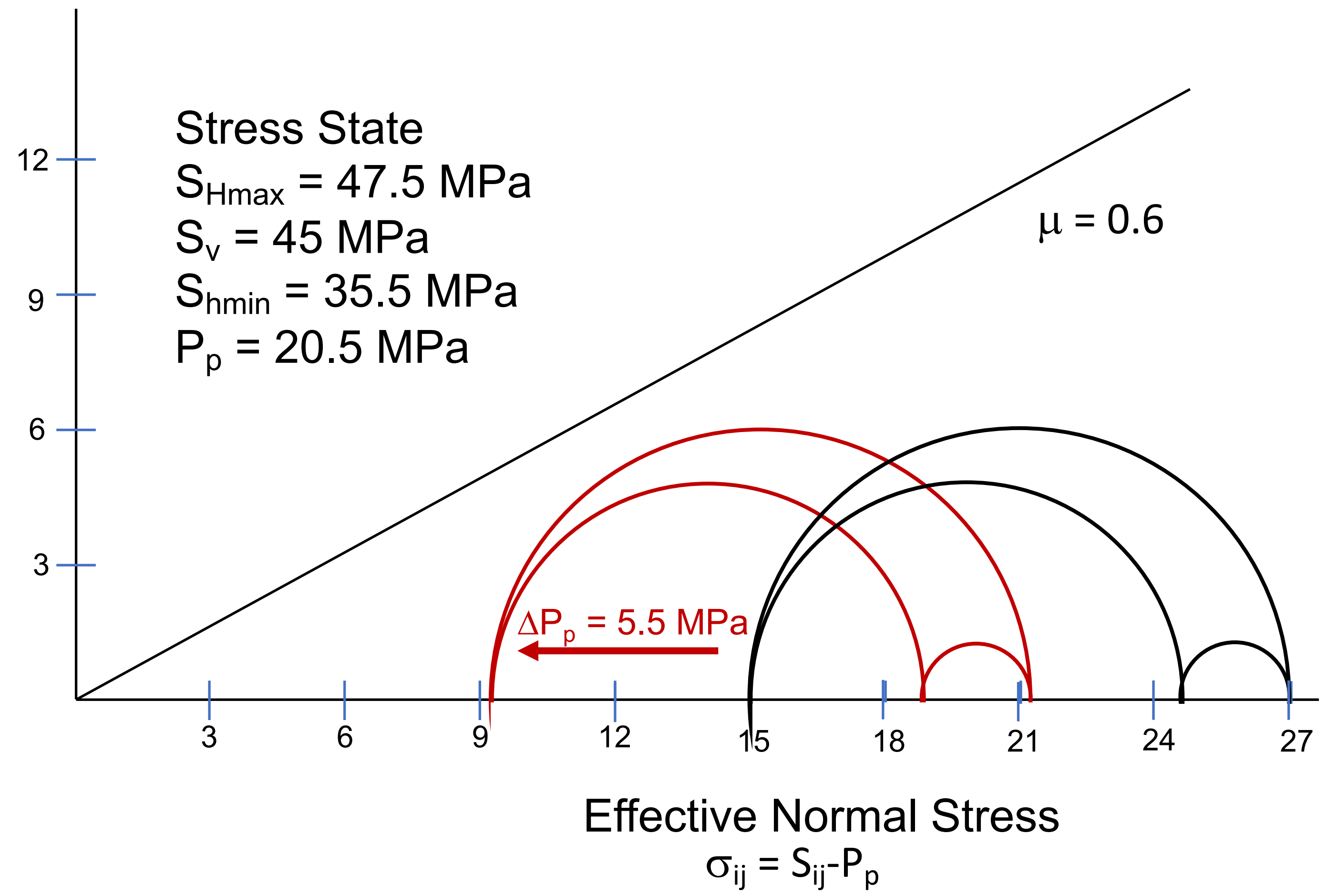


Fig. 10.4

Total stress, NOT effective stress

Typical Representation Using Mohr Circles to Indicate the Likelihood of Slip Resulting from an Increase in Pore Pressure



Why do I Prefer to Represent This Process with Total Stress on the Horizontal Axis and Not Effective Stress?

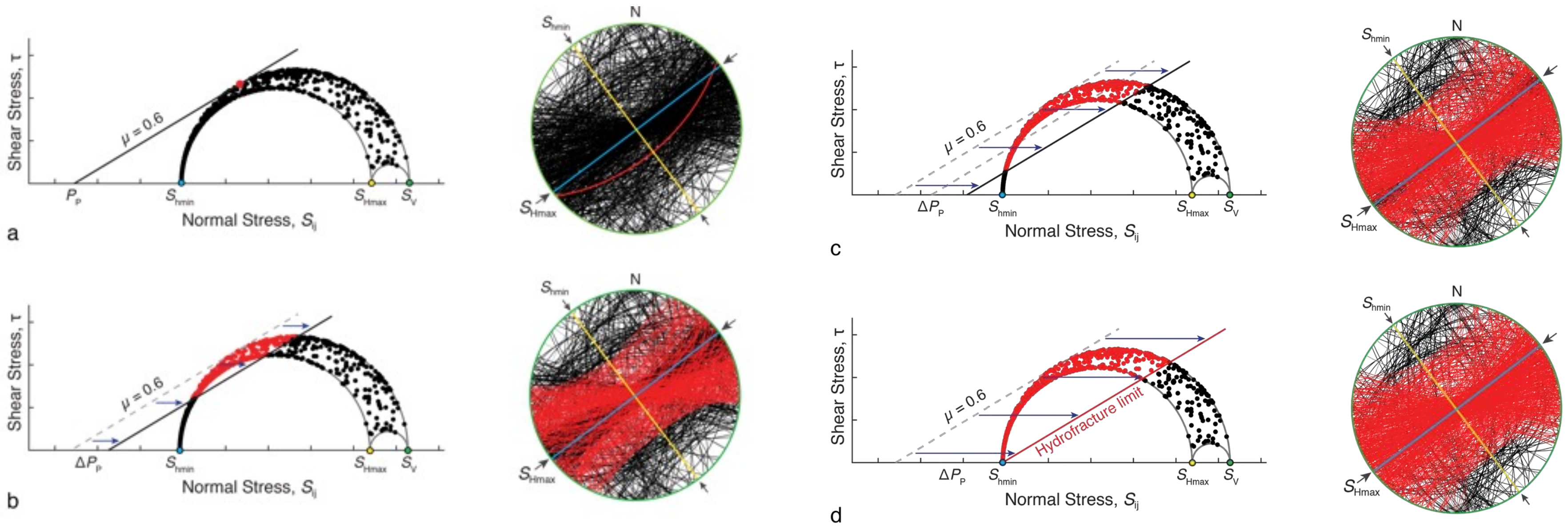


Fig. 10.4

Because the traditional model assumes all three principal stresses change the same amount in response to uniform depletion

Inducing Shear Slip on Poorly-Oriented Planes

Comparison of Planes from Image Log and Faults Implied by Focal Plane Mechanisms

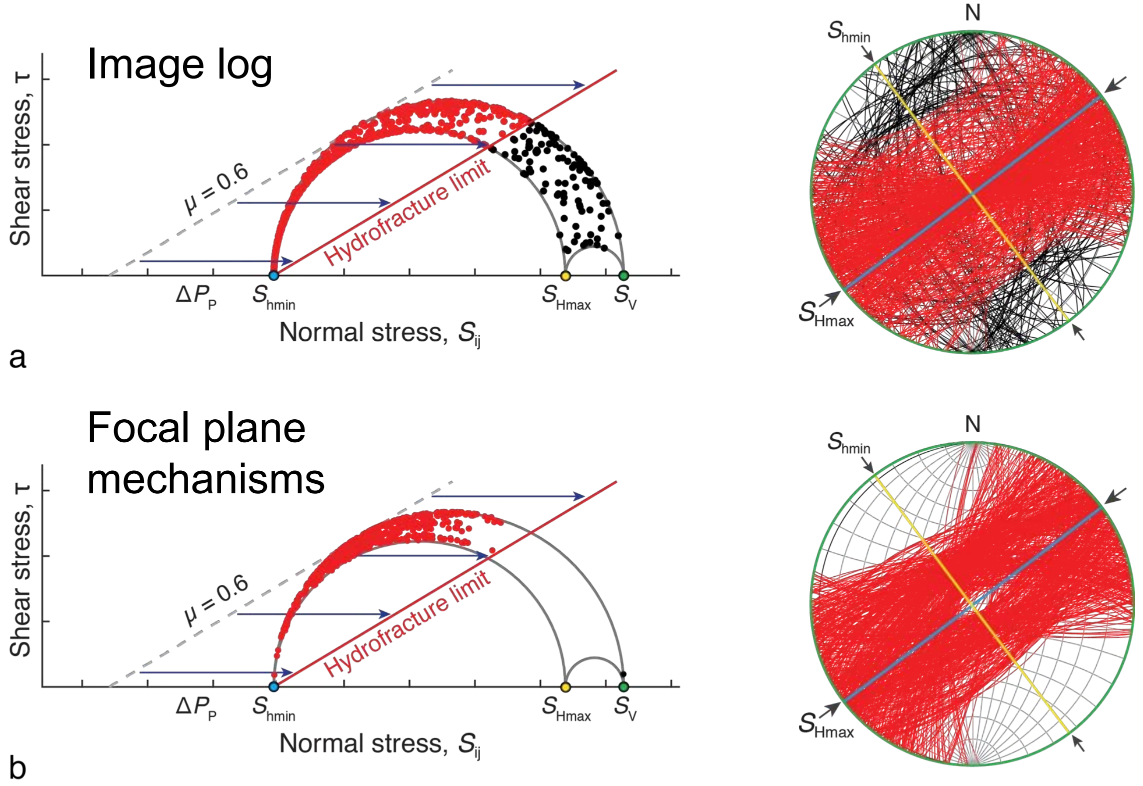
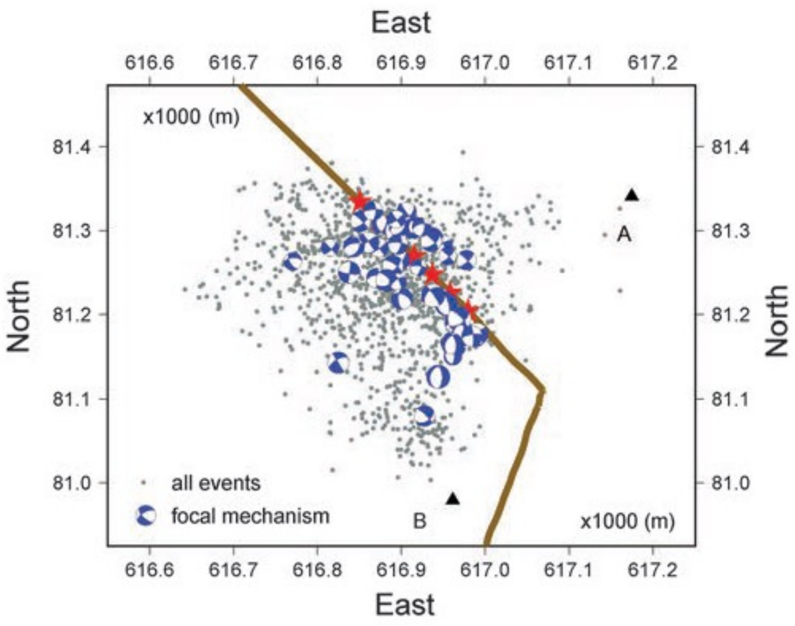
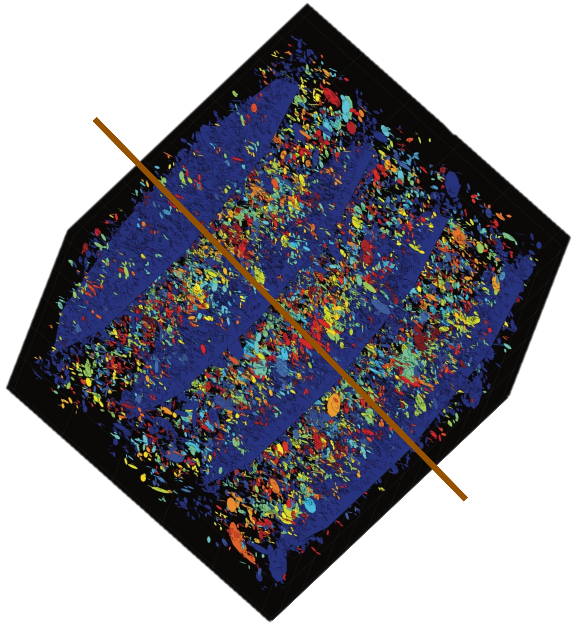


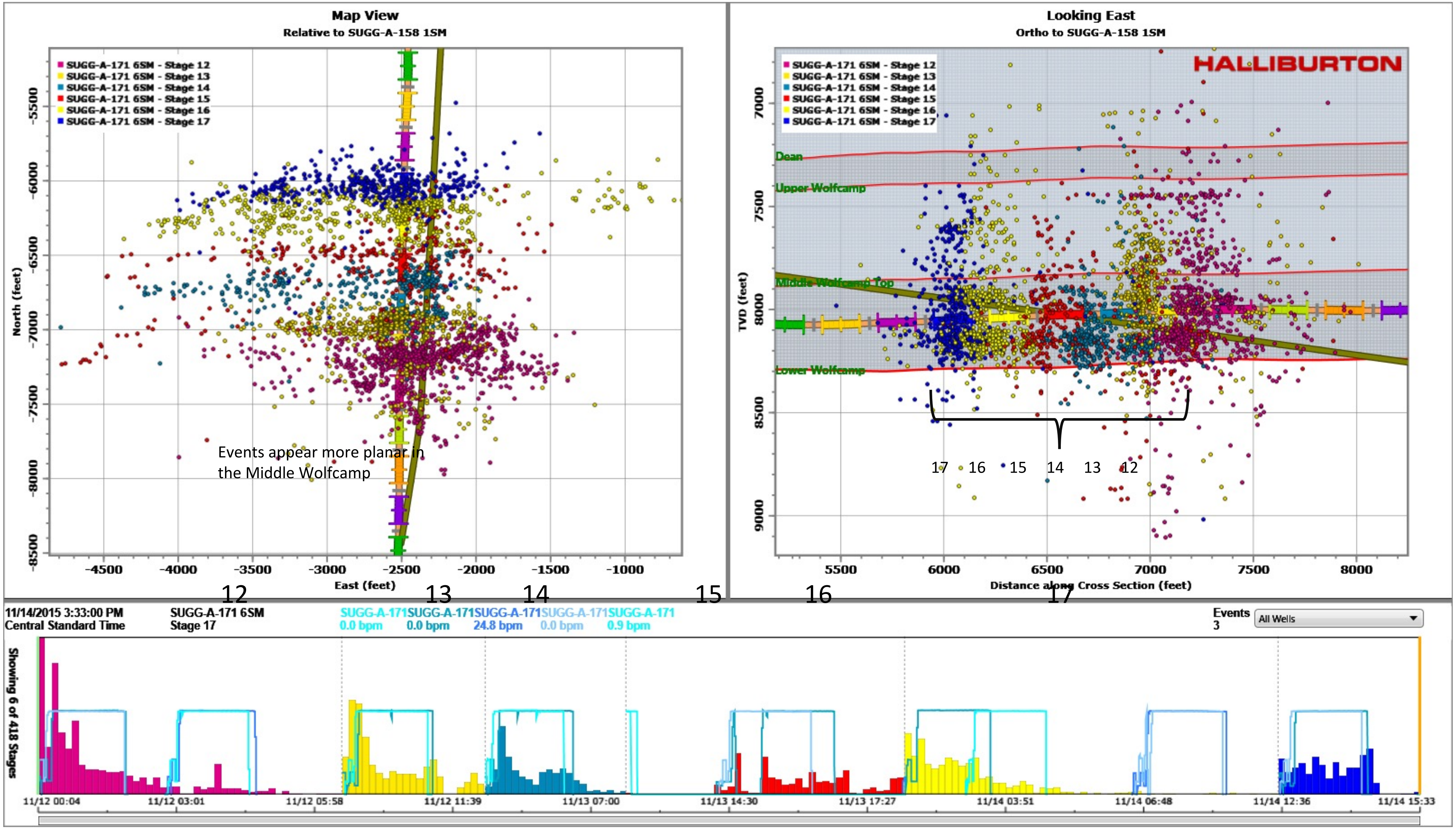
Fig. 10.8



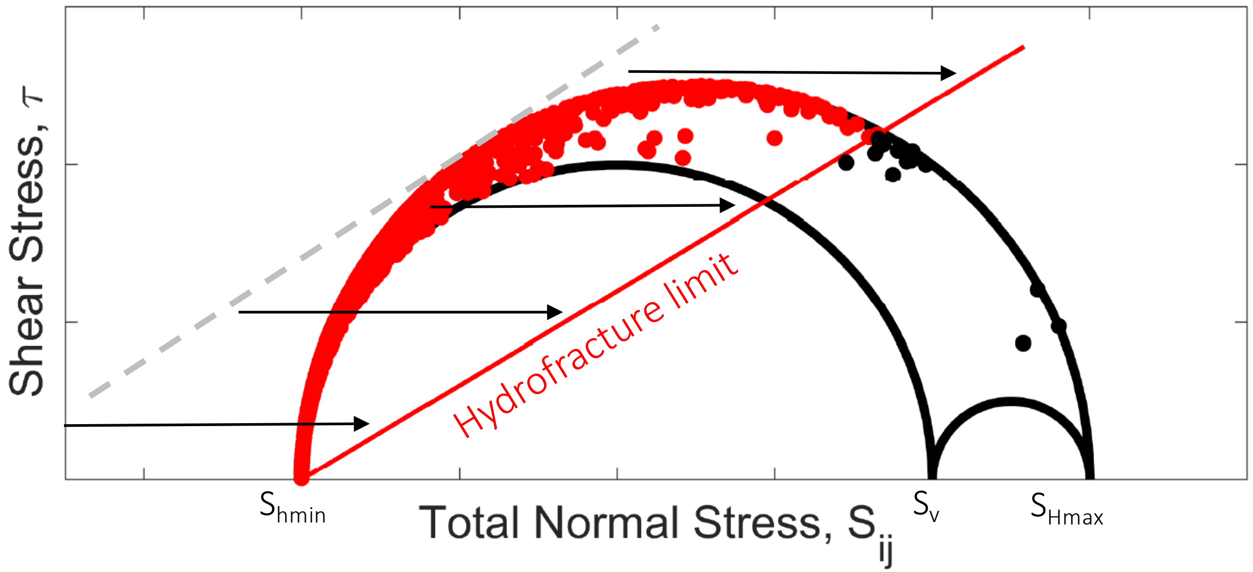


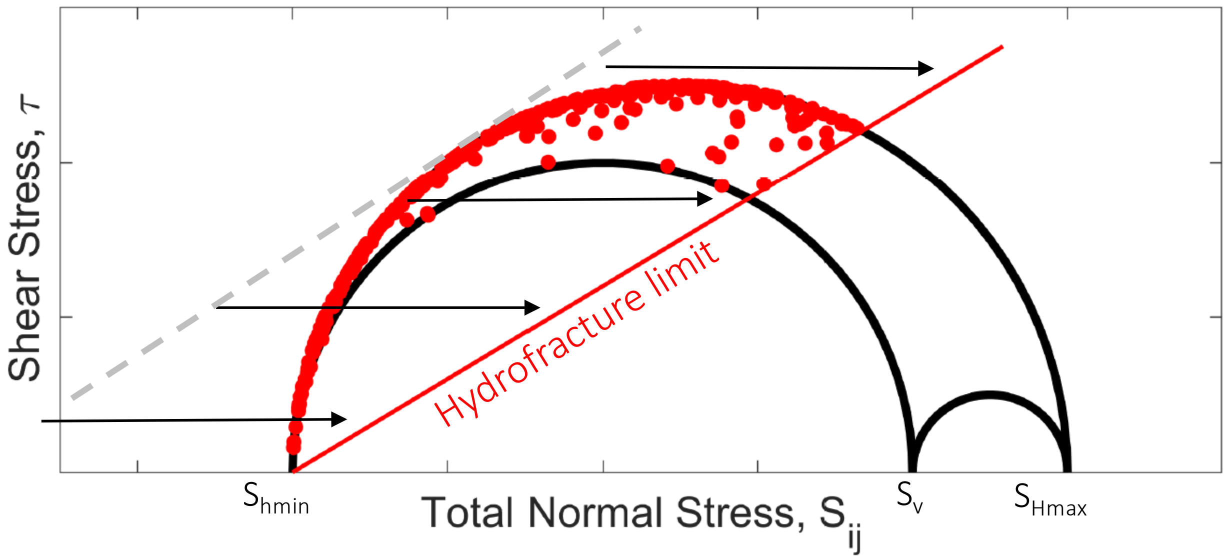
Comparing Computed Slipping Planes from Image Logs With Observed Slipping Planes from Focal Plane Mechanisms

HFTS-I Microseismic Data

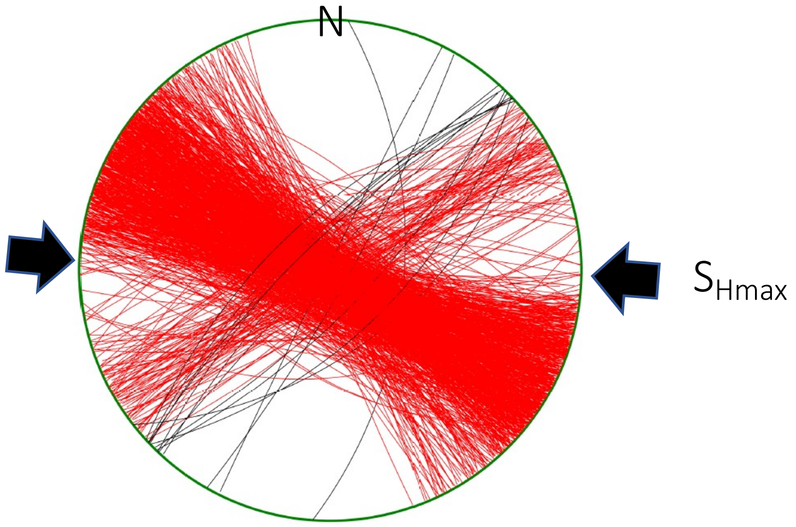


Preliminary Comparison with FMI Log

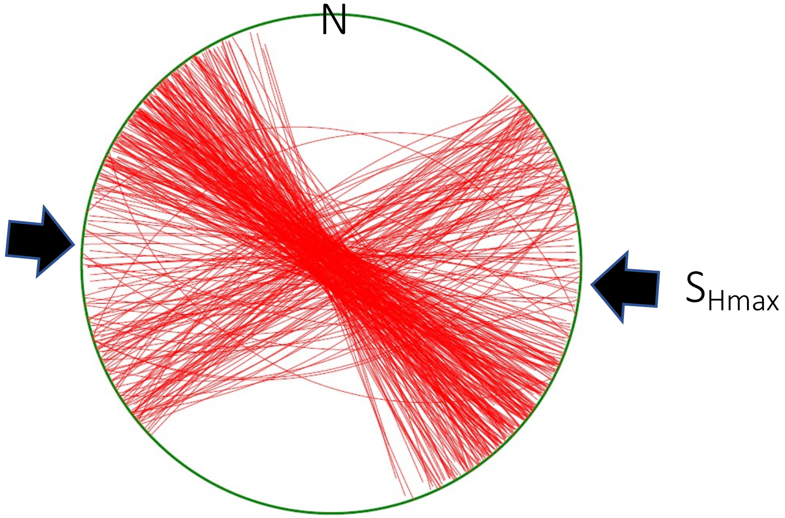




Faults from FMI log



Slipping Faults from FM's



Does Slip (and/or Opening) Occur on Horizontal Bedding Planes?

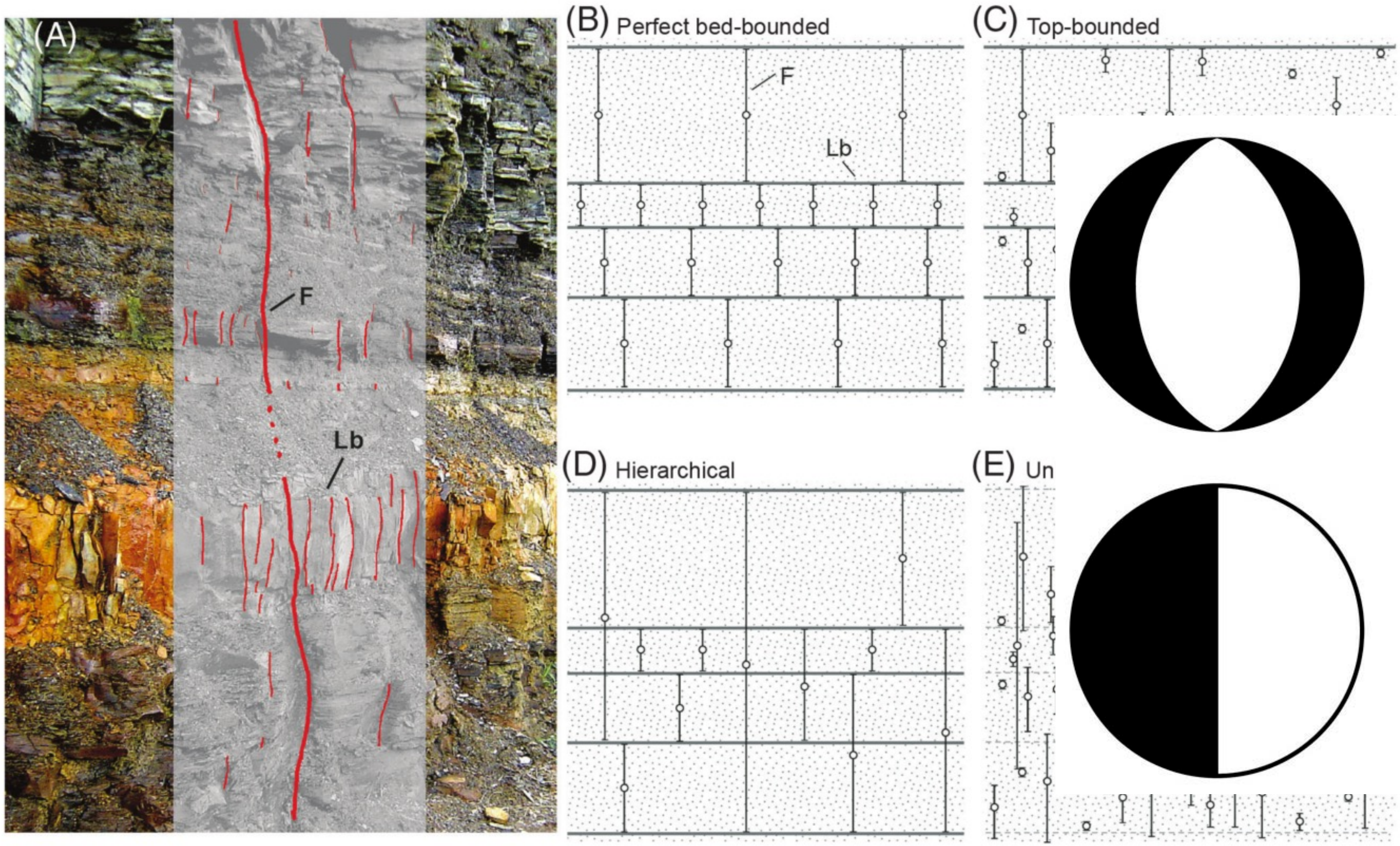


Fig. 7.21

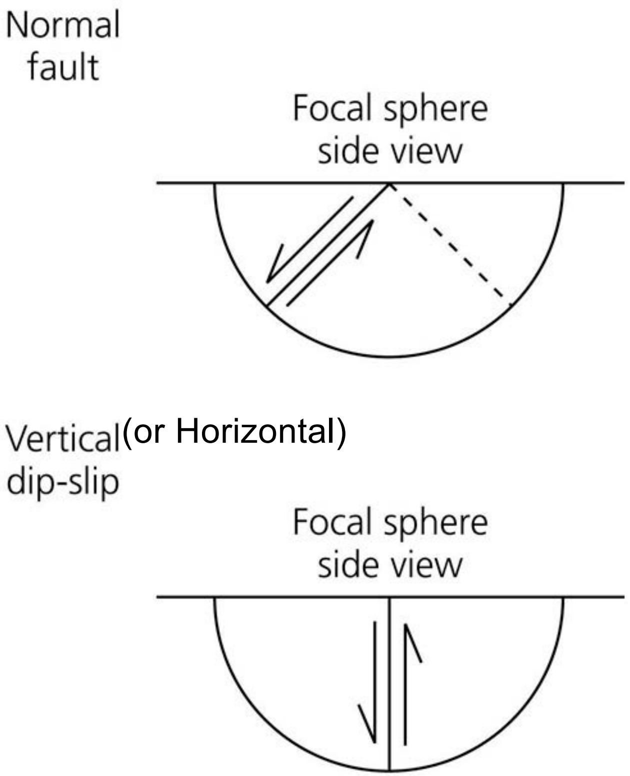


Fig. 9.10

Slip (and/or Opening) on Horizontal Planes (or Vertical Planes Planes Parallel or Perpendicular to S_{Hmax})

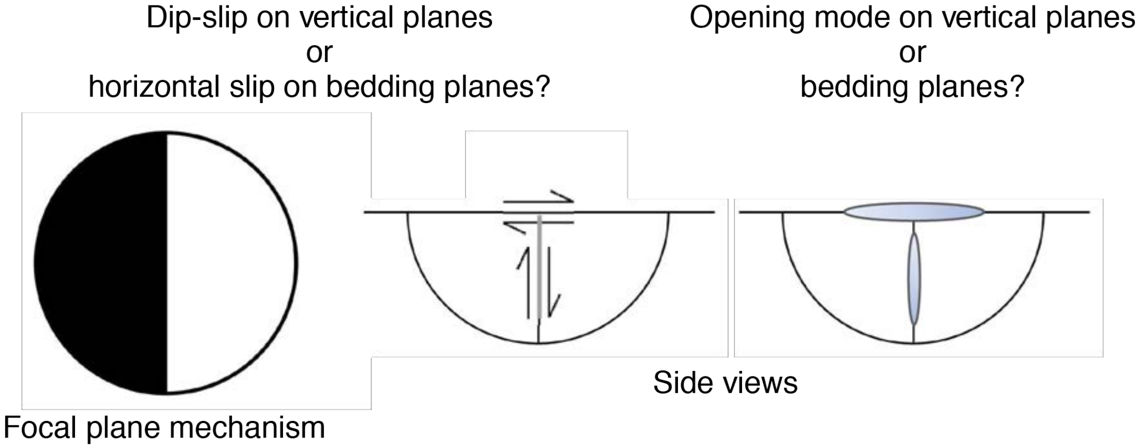


Fig. 10.7

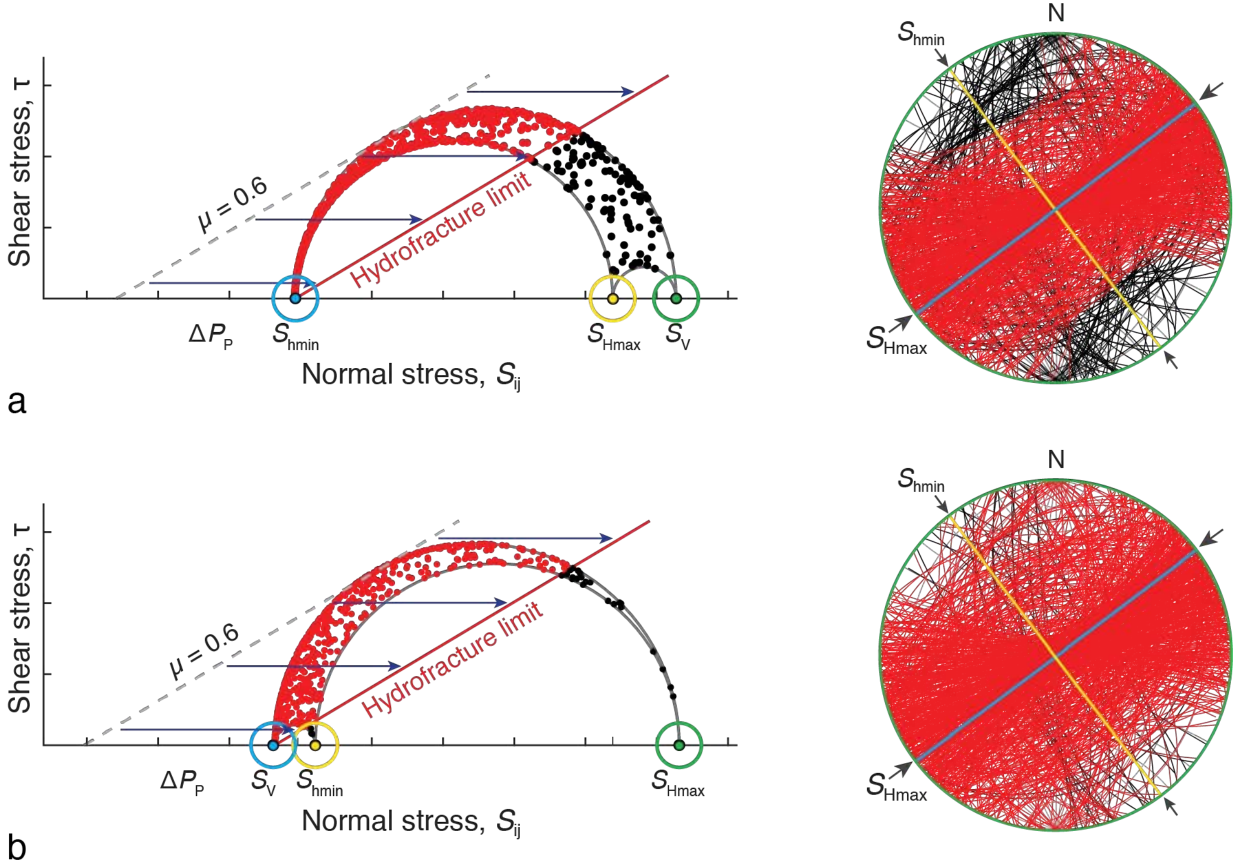
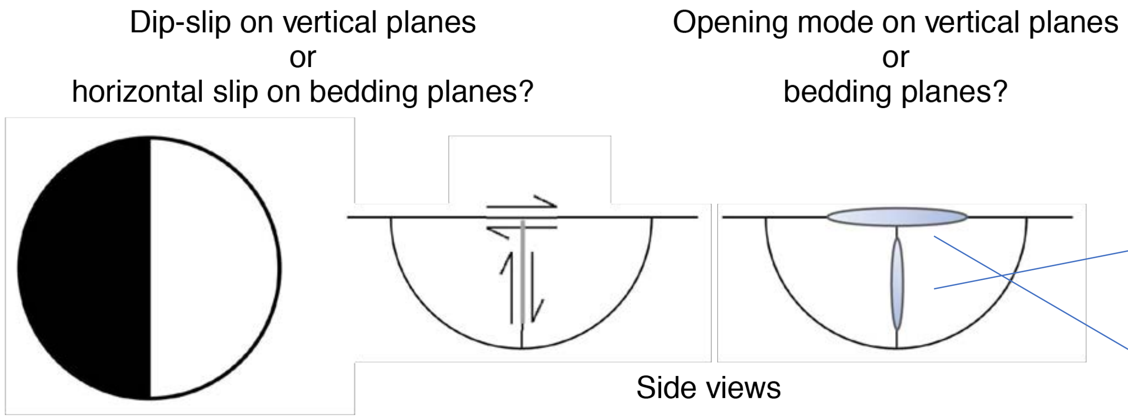
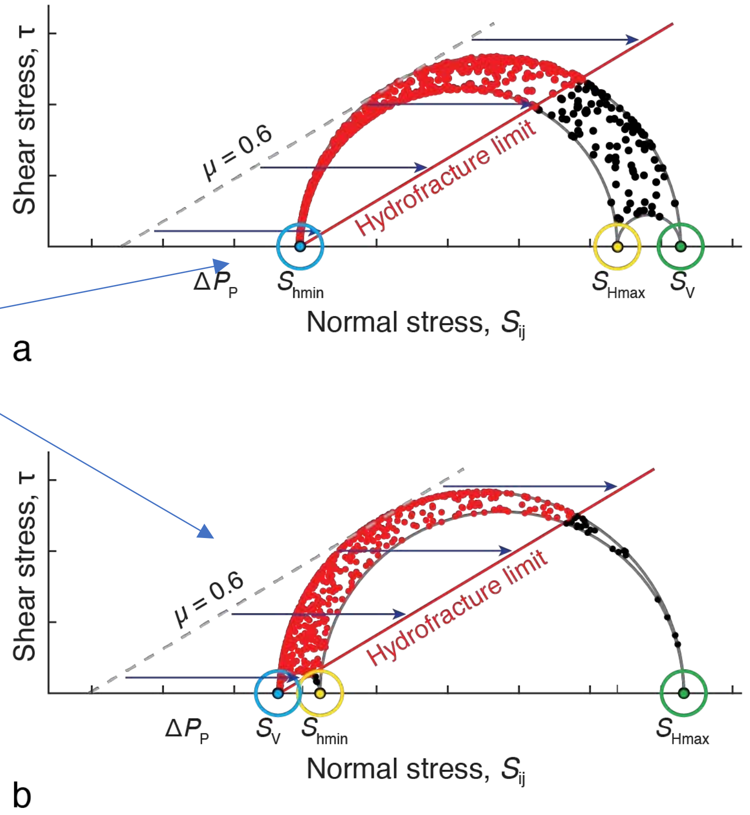
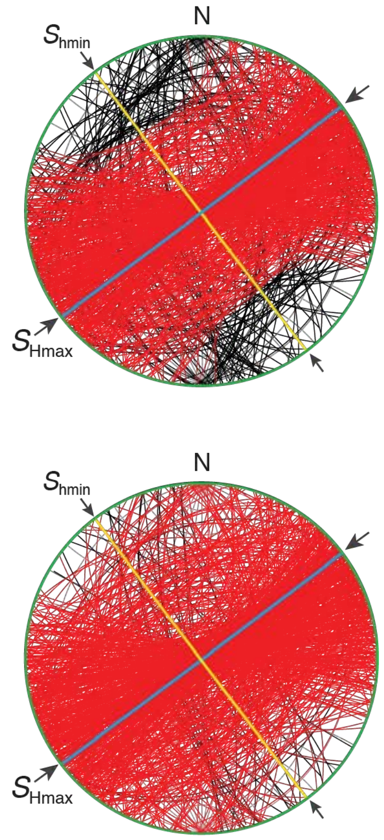


Fig. 10.8

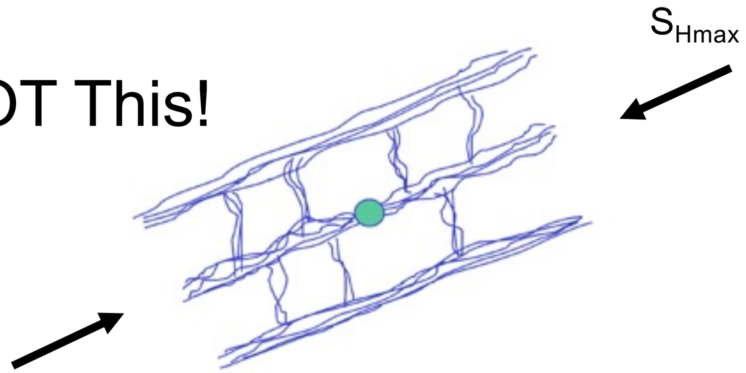
Slip (and/or Opening) on Horizontal Planes (or Vertical Planes Planes Parallel or Perpendicular to S_{Hmax})







But NOT This!



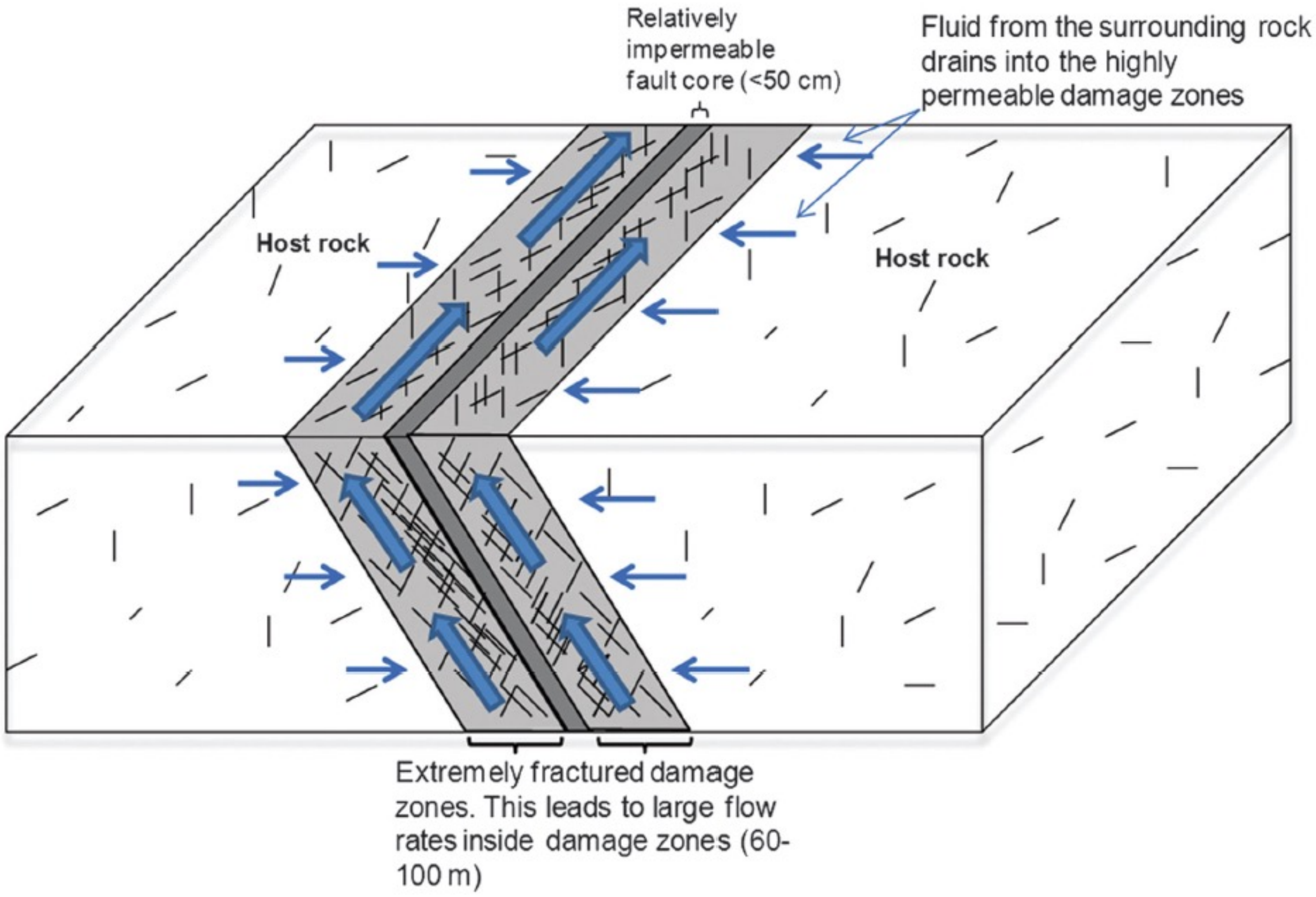
Three Topics

- Get the Stress Right (You Can't do Geomechanics Right With the Wrong Stress State).
    - Lessons from North America
    - Drilling Horizontal Wells in the Correct Direction (Bakken Example)

- Optimizing Well Placement When Exploiting Stacked Pay
    - Lithologically-Controlled Variations of the Least Principal Stress with Depth and its Impact on Multi-Stage Hydraulic Fracturing
    - Modeling Hydraulic Fracture Growth (ResFrac)
    - Optimizing Drainage Area (Petro.ai)

- Shear Faulting and Its Affect on Production Stimulation
    - Importance of Microseismic Events
    - Pad-scale Faulting Which Can *Hijack* Hydraulic Fracture Stages

Fault Zone Architecture
(Fault Cores Can be Impermeable)



Johri et al. (2014a)

Microseismic Propagation Along Damage Zones

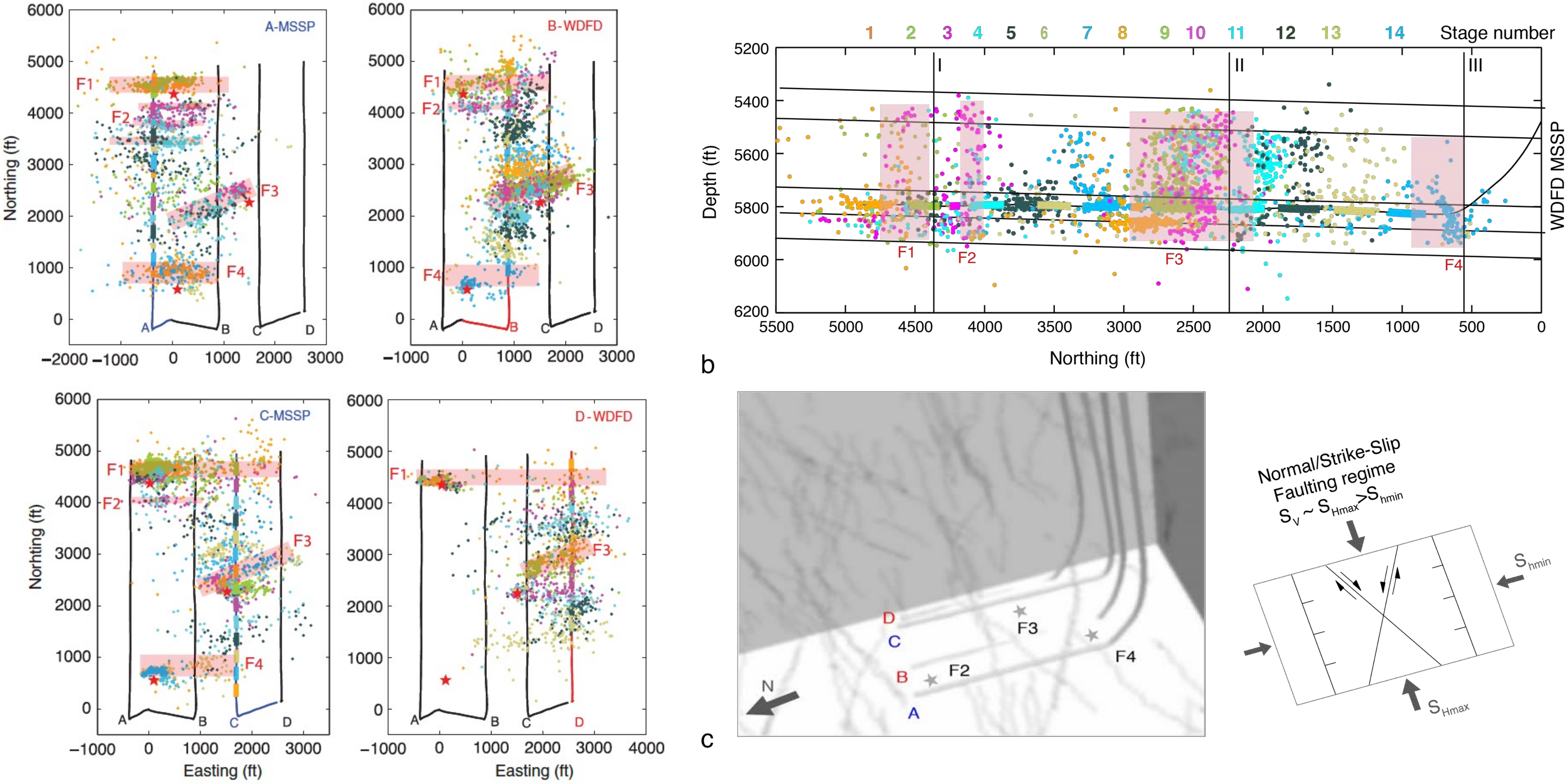


Fig. 7.25

Dense Fracture Cluster In Wellbore Correspond to Fault Damage Zone
Barnett Shale

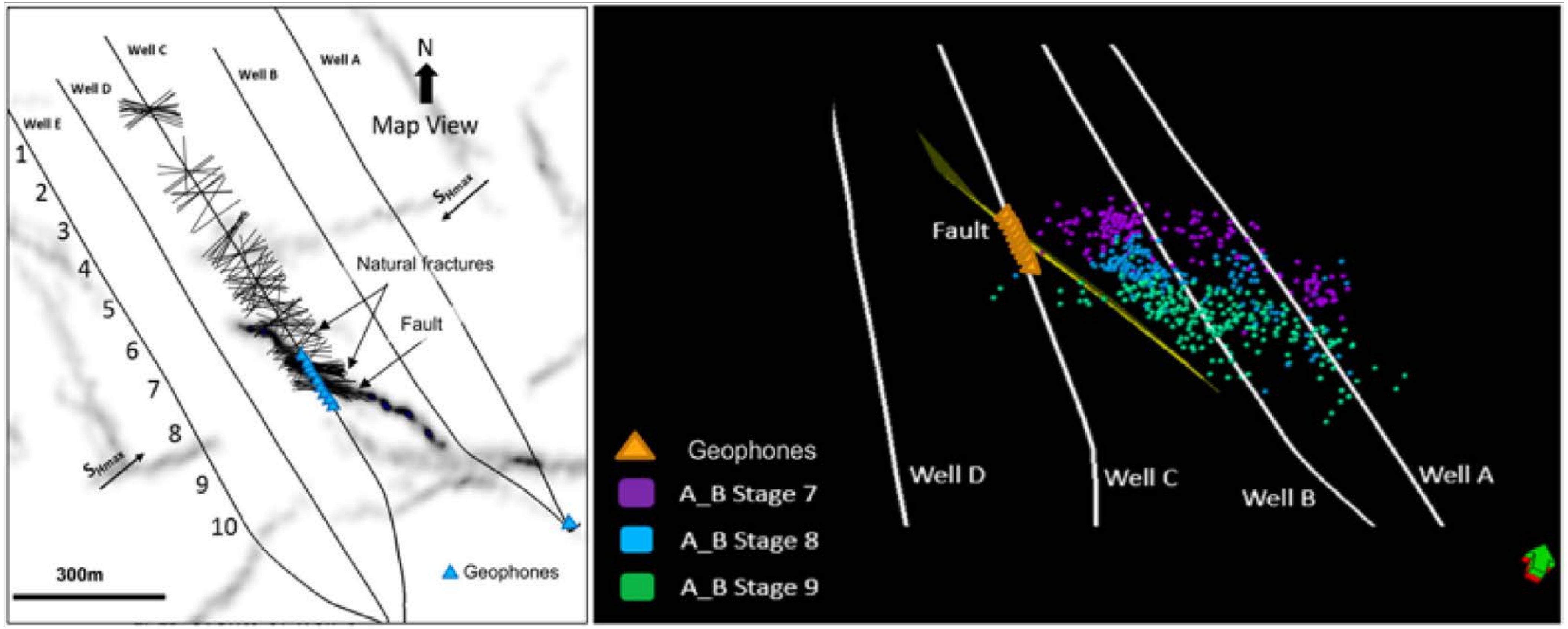
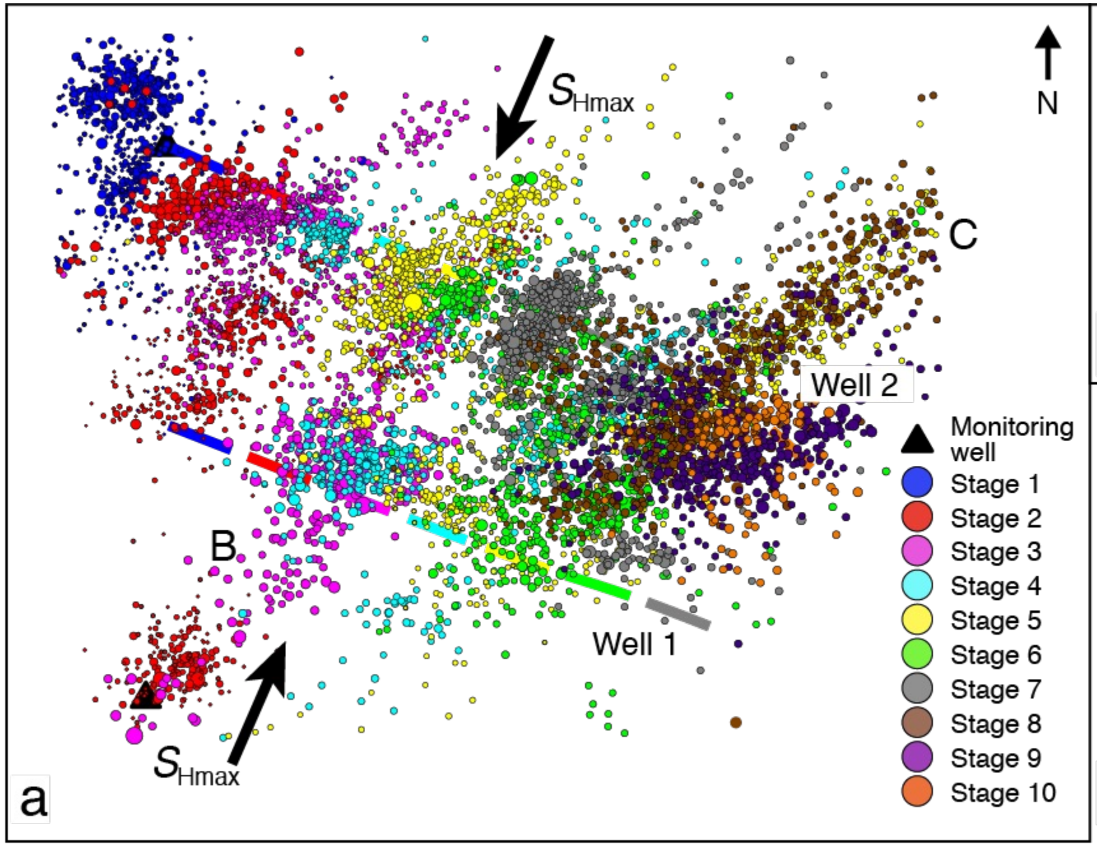


Fig. 7.28 Ant Tracking

Modified from Farghal and Zoback (2015)

Ant Tracking Reveals Fault Damage Zones

Barnett Shale Data Set 2



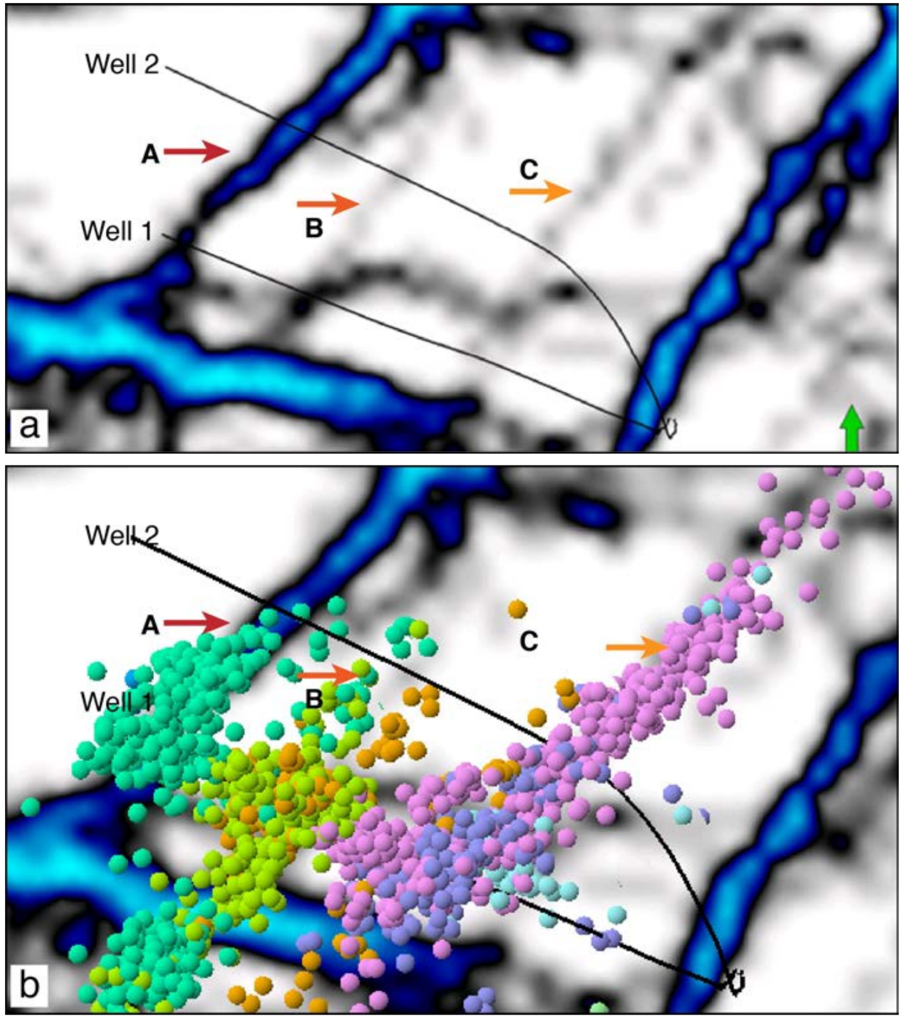
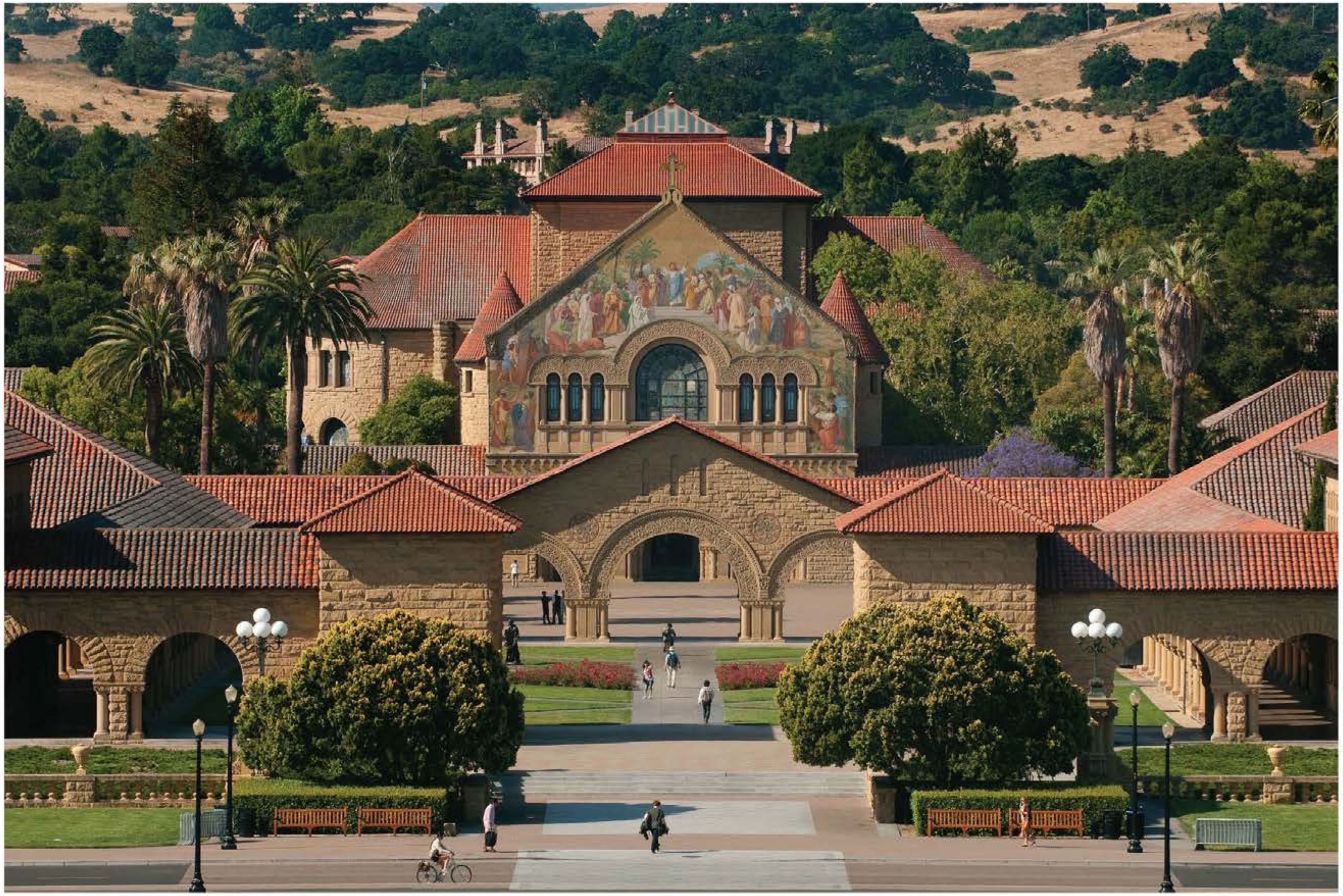


Fig. 7.29

Modified from Farghal and Zoback (2015)



Thank you