Producing Natural Gas from Shale – Opportunities and Challenges of a Major New Energy Source
[Shale Gas 101]

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STANFORD UNIVERSITY

Air Pollution and Energy Source*

	CH_4	Oil	Coal
CO_2	117,000	164,000	208,000
CO	40	33	208
NO_x	92	448	457
SO_2	0.6	1,122	2,591
Particulates	7.0	84	2,744
Formaldehyde	0.75	0.22	0.221
Mercury	0	0.007	0.016

*Pounds/Billion BTU

EIA, 1998

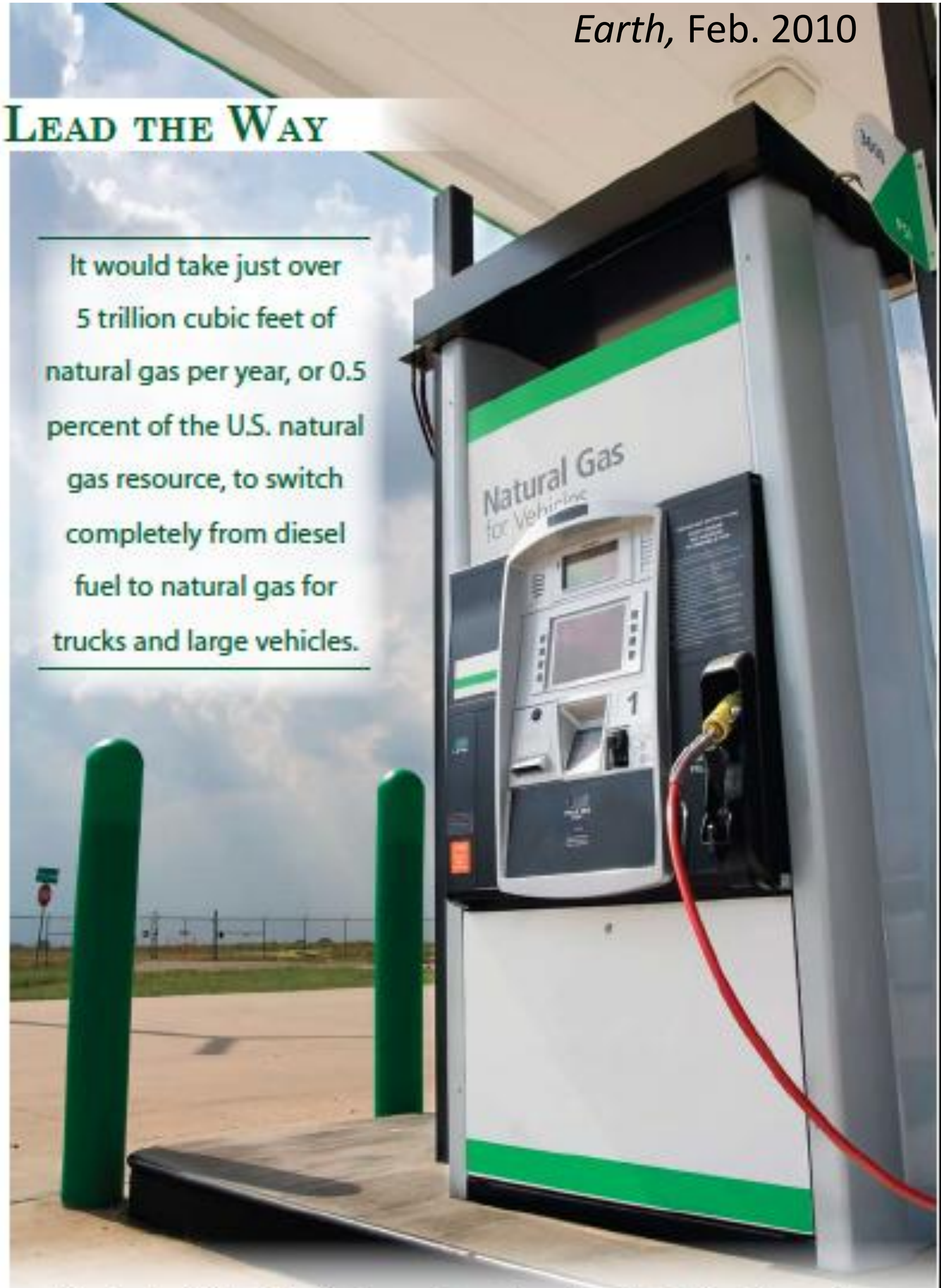
NATURAL GAS CAN LEAD THE WAY

Mark Zoback

Much of the debate concerning energy, climate and the economy involves how to manage the transition from fossil fuels to sustainable energy sources. In this context, it may seem ironic to promote one fossil fuel over another, but natural gas is an inexpensive, abundant and relatively clean fuel that can lead the transition away from coal and oil, while achieving significant reductions in greenhouse gas emissions and other pollutants over the next two decades. In short, increased use of domestic sources of natural gas needs to be an essential component of U.S. energy policy.

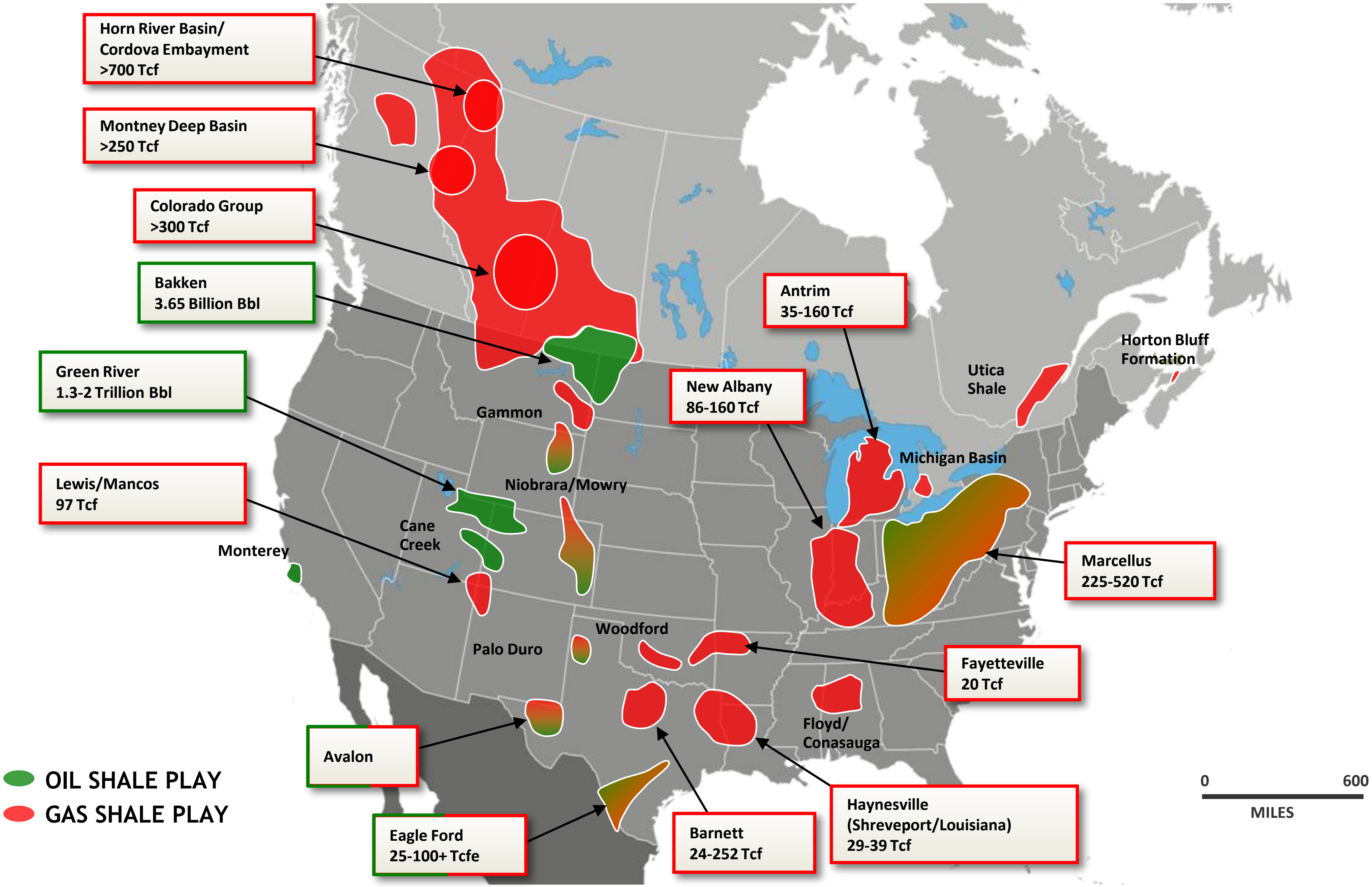
To accomplish this there are five key questions that need to be addressed: First, are domestic natural gas supplies adequate to offset the use of coal and oil to a significant degree? Second, can natural gas compete on an economic basis with coal for electricity generation? Third, is switching to natural gas necessary to achieve significant reductions of carbon dioxide emissions over the next 10 to 20 years? Fourth, is it reasonable to utilize natural gas to replace significant amounts of oil as a transportation fuel? And finally, can large-scale natural gas development proceed in an environmentally responsible manner?

With respect to supply, multiple independent assessments now put U.S. domestic natural gas resources at more



> It would take just over 5 trillion cubic feet of natural gas per year, or 0.5 percent of the U.S. natural gas resource, to switch completely from diesel fuel to natural gas for trucks and large vehicles.

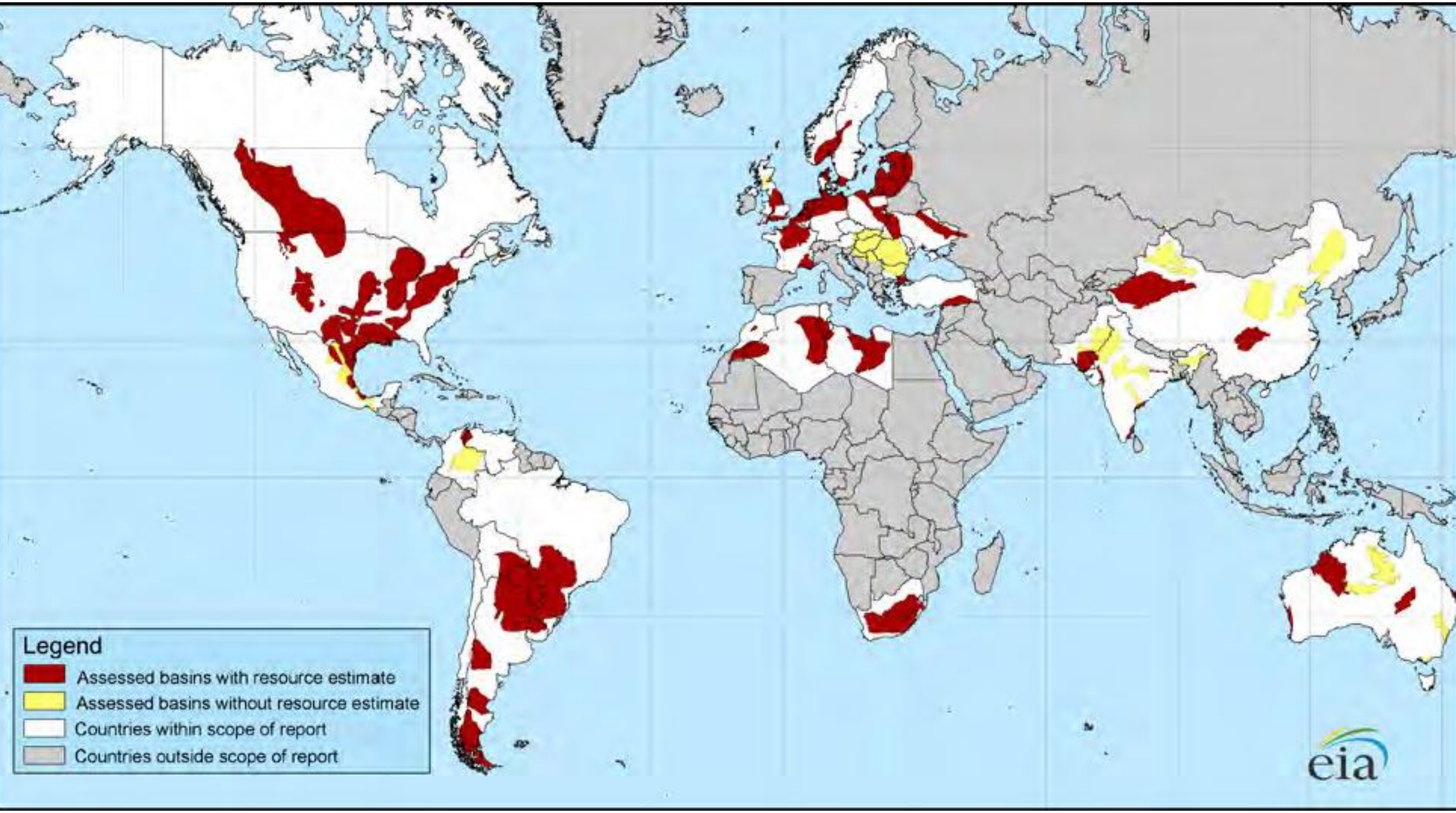
Opportunity: North American Shale Plays



~2300 TCF (85% Shale Gas)

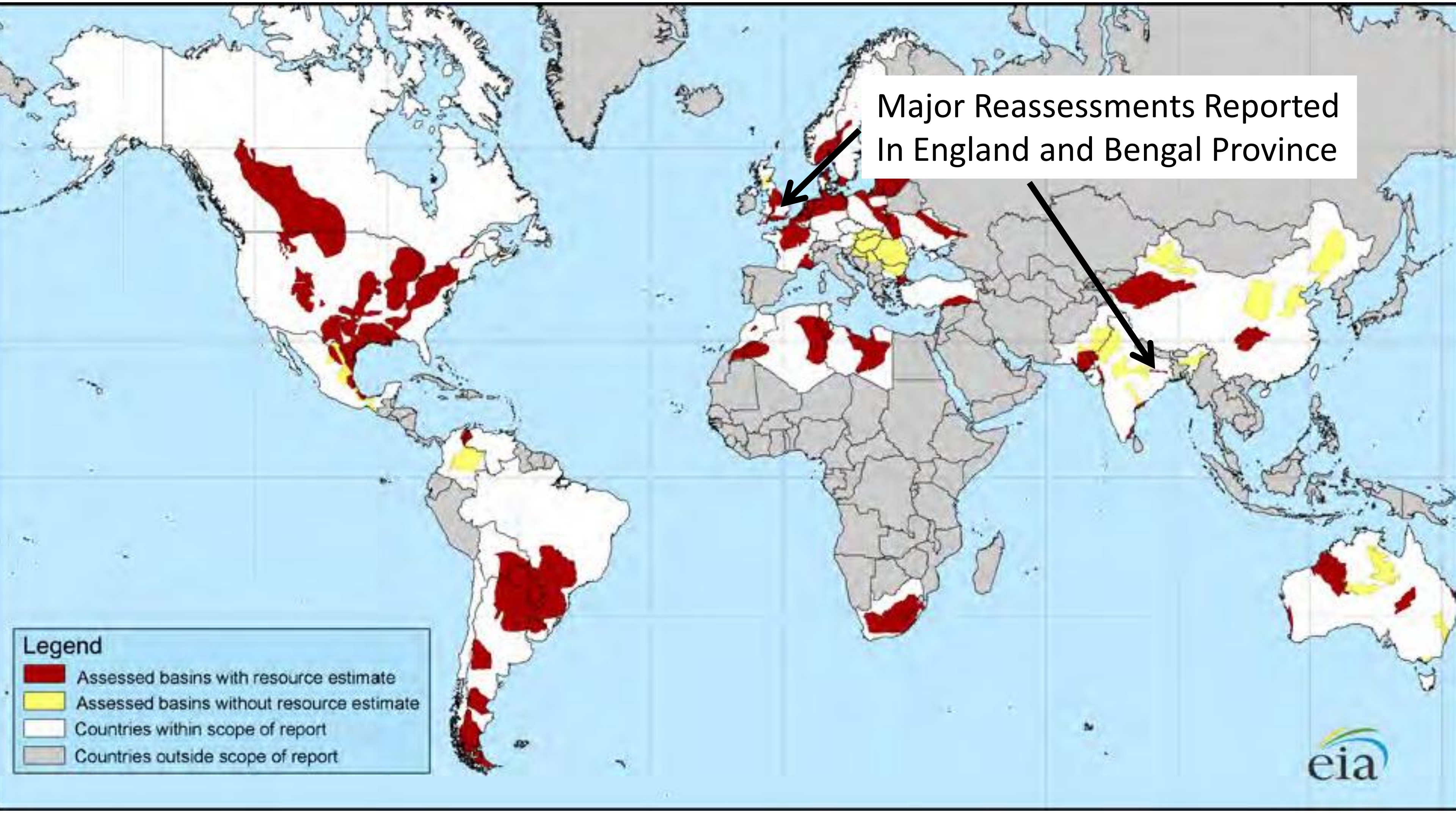
“100 years of Natural Gas” U.S. Consumption 23 TCF/y

Opportunity: Global Shale Plays



~22,600 TCF of Recoverable Reserves
6600 TCF from Shale (40%)
Current use ~160 TCF/year

Opportunity: Global Shale Plays



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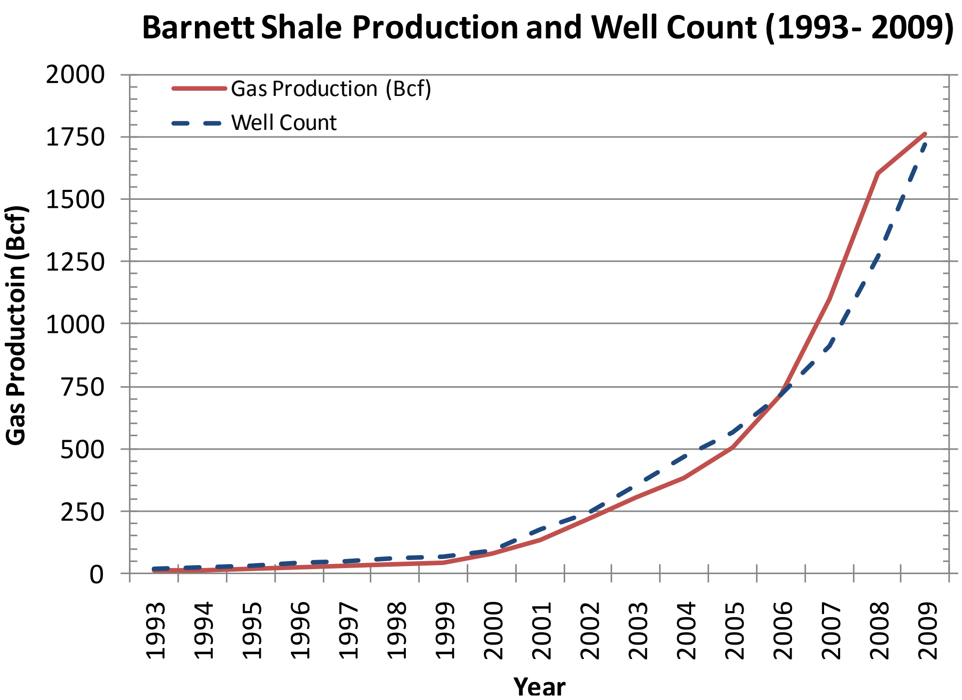
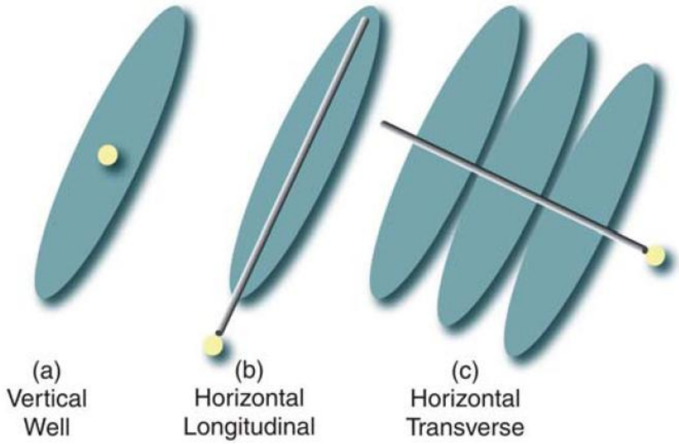
TIME
ENVIRONMENT SPECIAL
THIS ROCK COULD POWER THE WORLD
WHY SHALE CAN SOLVE THE ENERGY CRISIS
BY BRYAN WALSH
A century's worth is buried in our backyards ...
... but drilling for it threatens our land

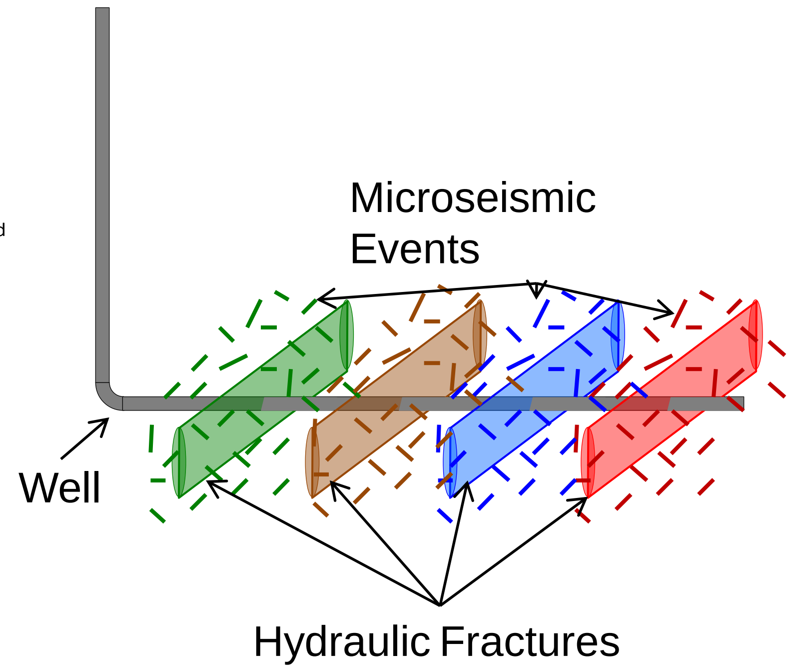
Drilling/Completion Technology
Key To Exploitation of Shale Gas



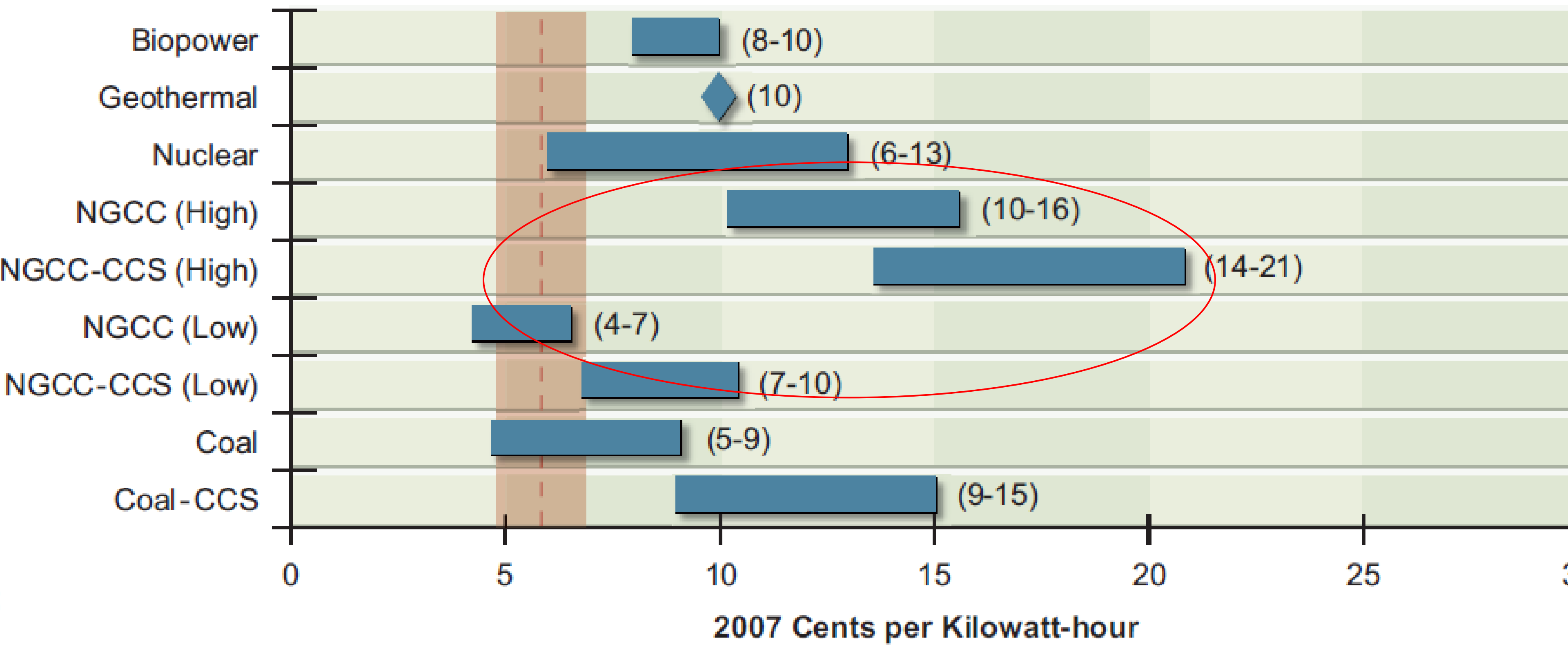
Source:
Texas Railroad
Commission



Horizontal Drilling and Multi-Stage
Slick-Water Hydraulic Fracturing
Induces Microearthquakes (M ~ -1 to M~ -3)
To Create a Permeable Fracture Network

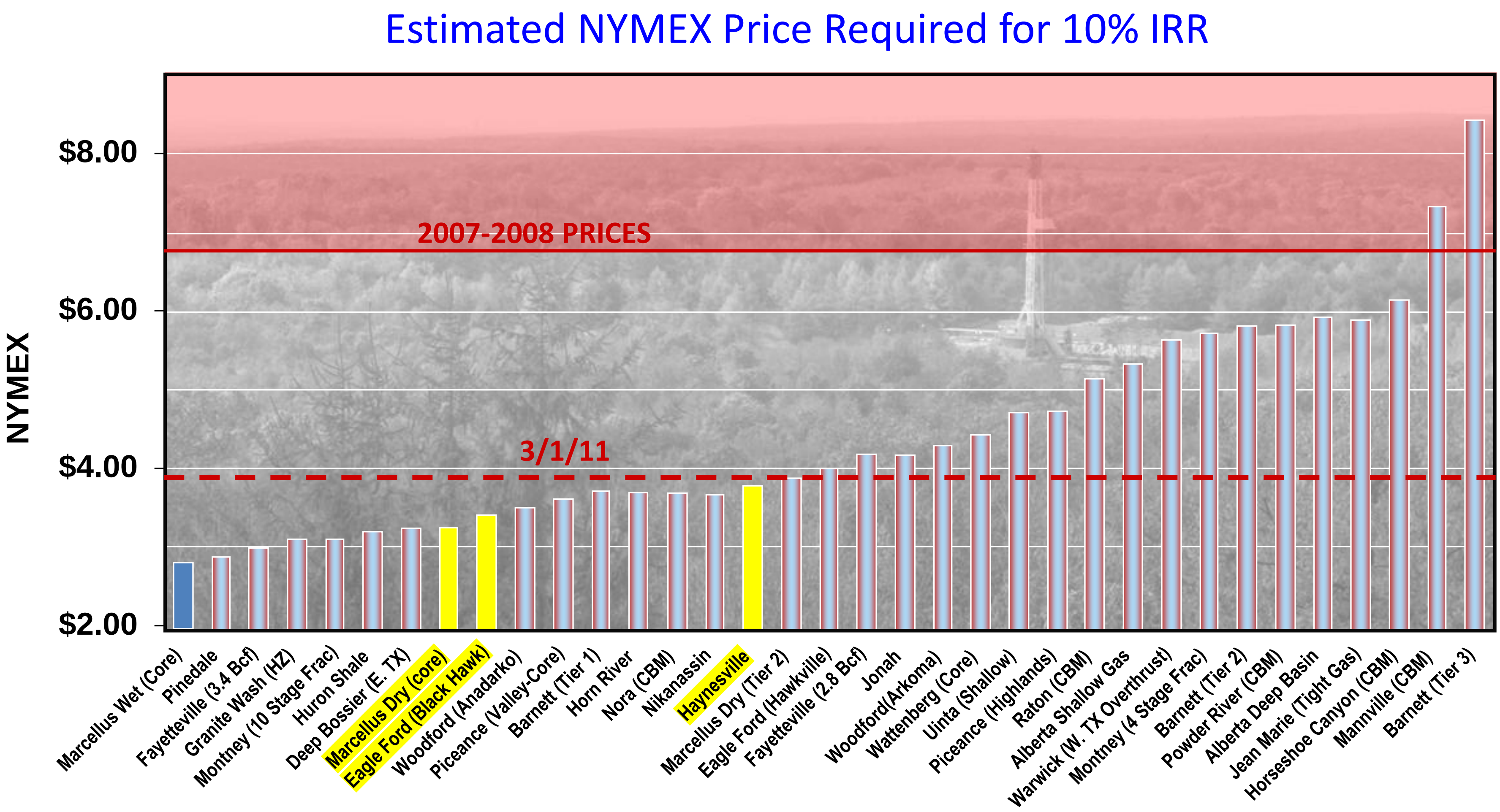


Gas And Coal Economics



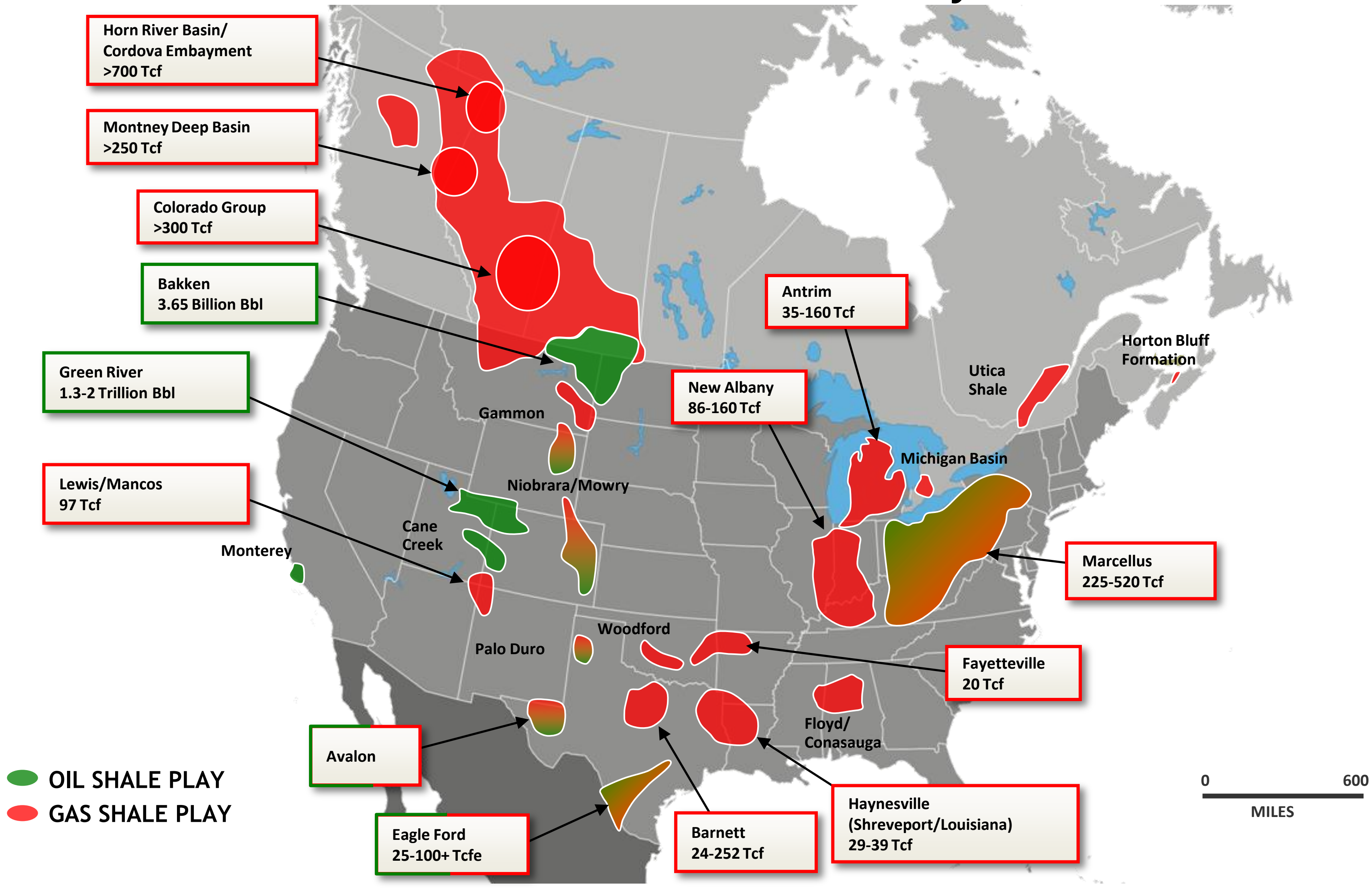
(from *America's Energy Future*) NAS - 2009

The Challenges of $4 Gas



Source: Morgan Stanley Research Report

The Next 5-10 Years
~100,000 Wells, 1-2 Million Hydrofracs



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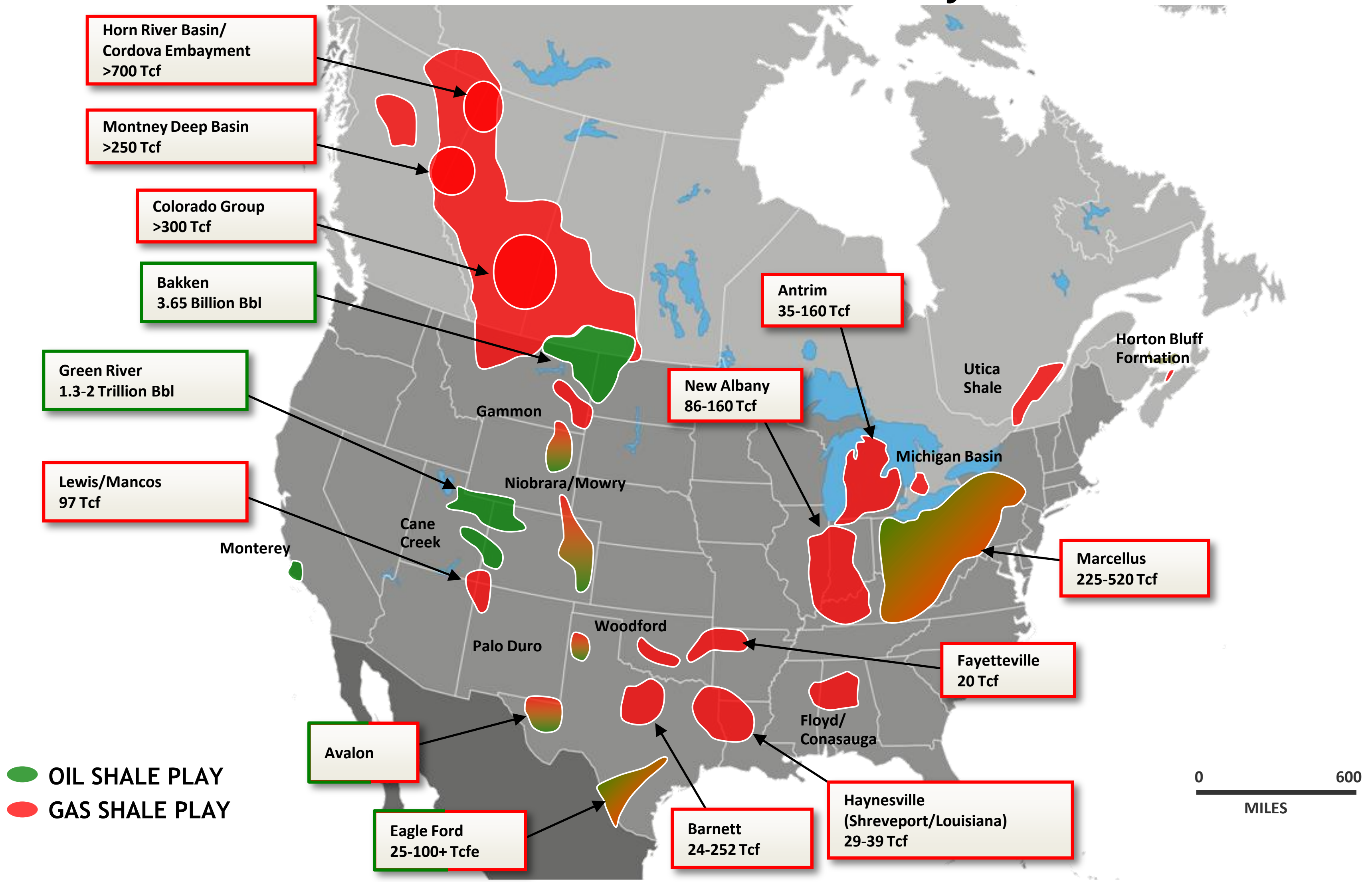

- How Do We Optimize Resource Development?

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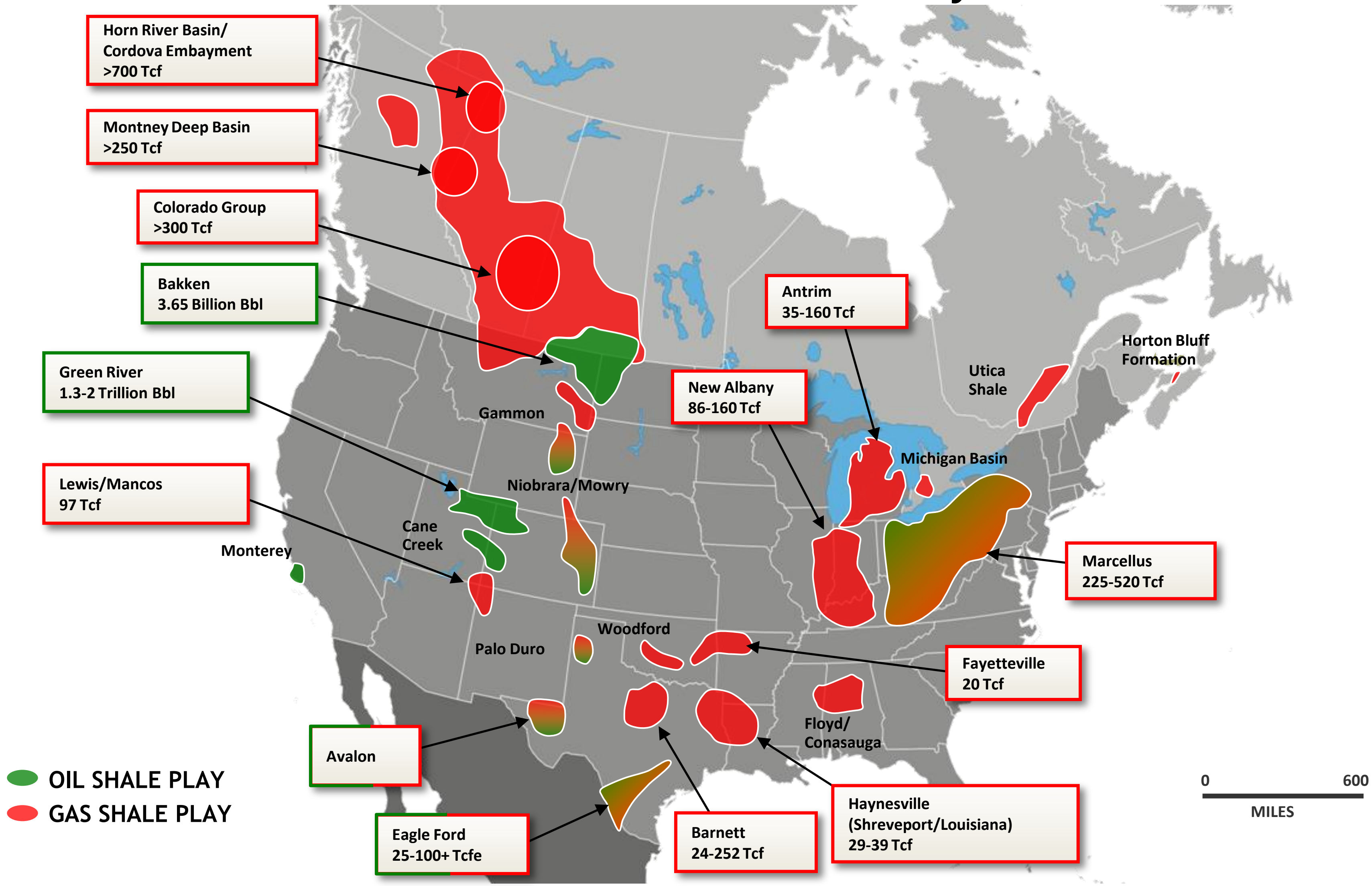
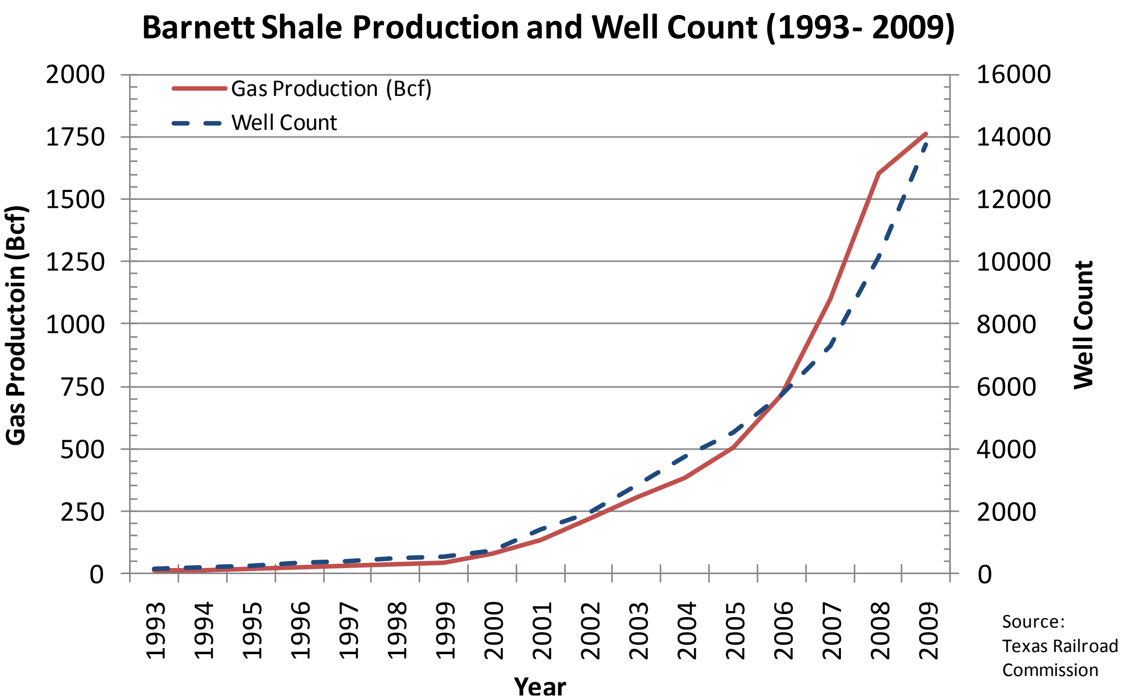
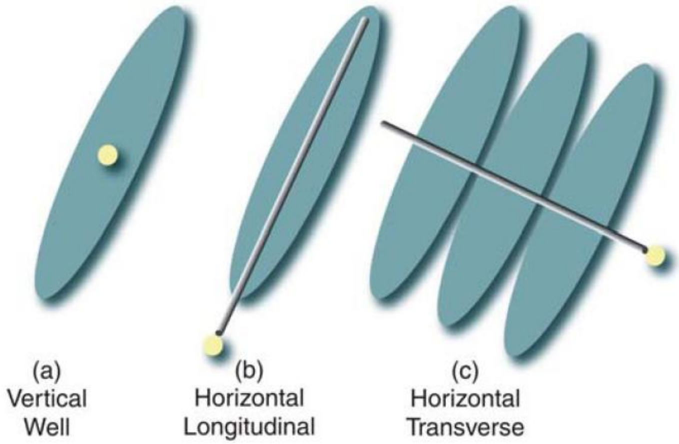


- How Do We Optimize Resource Development?
- How Do we Minimize the Environmental Impact?

Drilling/Completion Technology
Key To Exploitation of Shale Gas





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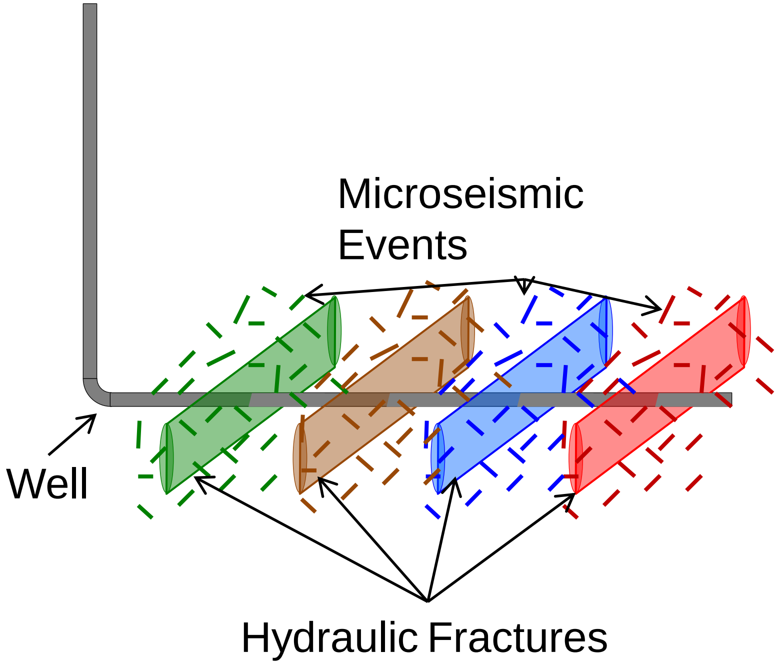
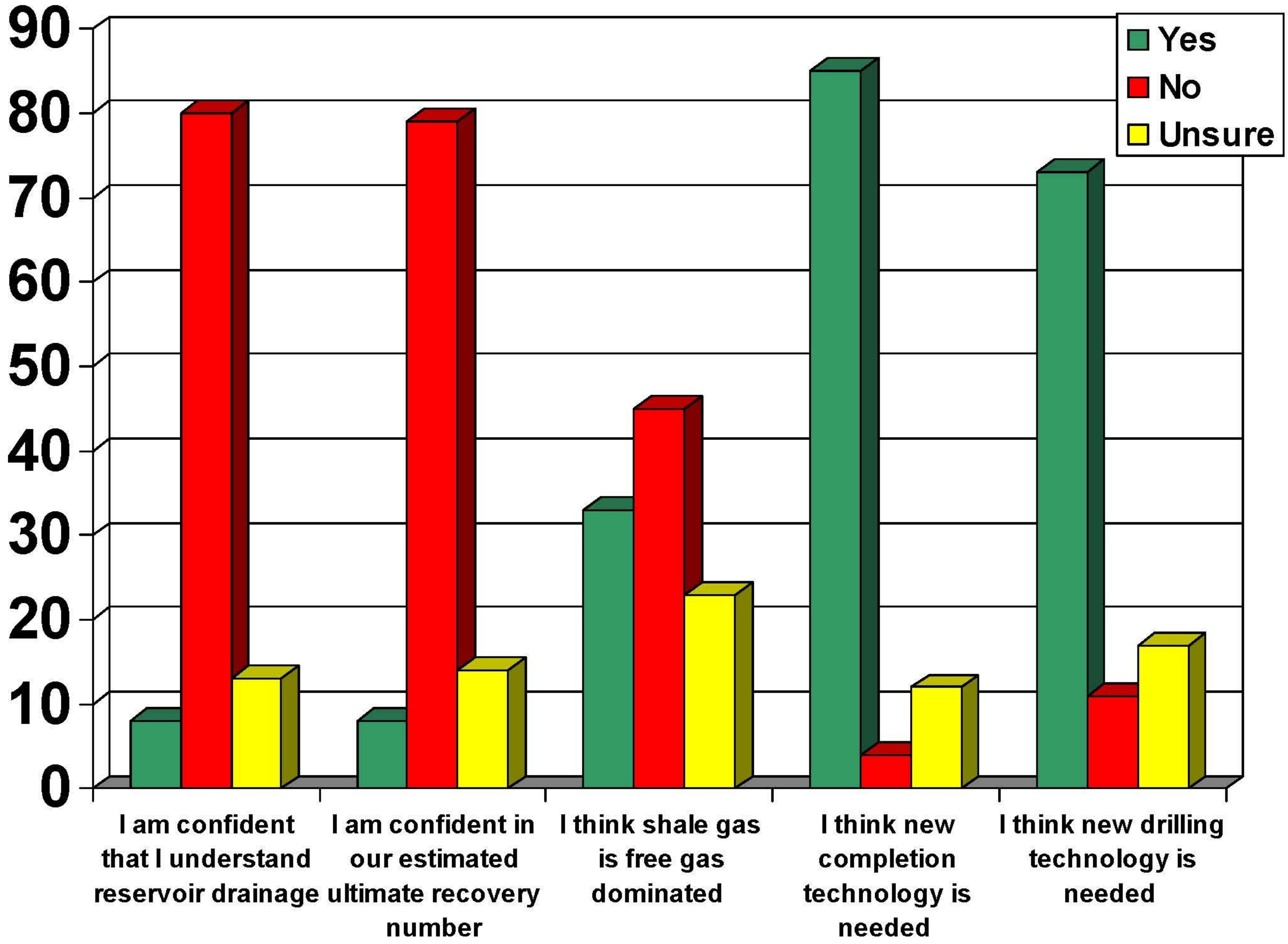


SPE Shale Gas Production Conference - Survey



Research Themes

- What factors control the success of slickwater frac'ing?
  - How do stress, fractures and rock properties affect the success of stimulation?
  - How do pressure and stress (and formation properties) evolve during stimulation?
  - What factors affect seismic and aseismic deformation mechanisms and how do these affect the reservoir?
  - Can we accurately model pore pressure and stress in the reservoir before, during, and after stimulation?
- How do we optimize slickwater frac'ing?

Multi-Disciplinary Studies of Shale Reservoirs

Current Research Collaborations

- ConocoPhillips – Barnett Microseismic and Frac Data, Shale Core, Fault Damage Zones
- Chevron – Geomechanics of Shale Gas and CO_2 Sequestration
- RPSEA - Montney Shale Gas (with LBNL, Texas A&M)
- Exxon – Heavy Oil, Adsorption and Swelling
- BP - Haynesville Core, Slickwater Frac'ing with CO_2, Geomechanics of Paleogene (GOM)
- DOE - CO_2 Sequestration in Shale Gas Reservoirs
- Hess – Bakken Shale, Frac'ing, Microseismic and Geomechanics
- Apache/Encana – Horn River Microseismic and Geomechancis Study

Outline of Presentation

1. Microseismicity and Reservoir Stimulation

2. Physical and Chemical Properties of Organic Rich Shales

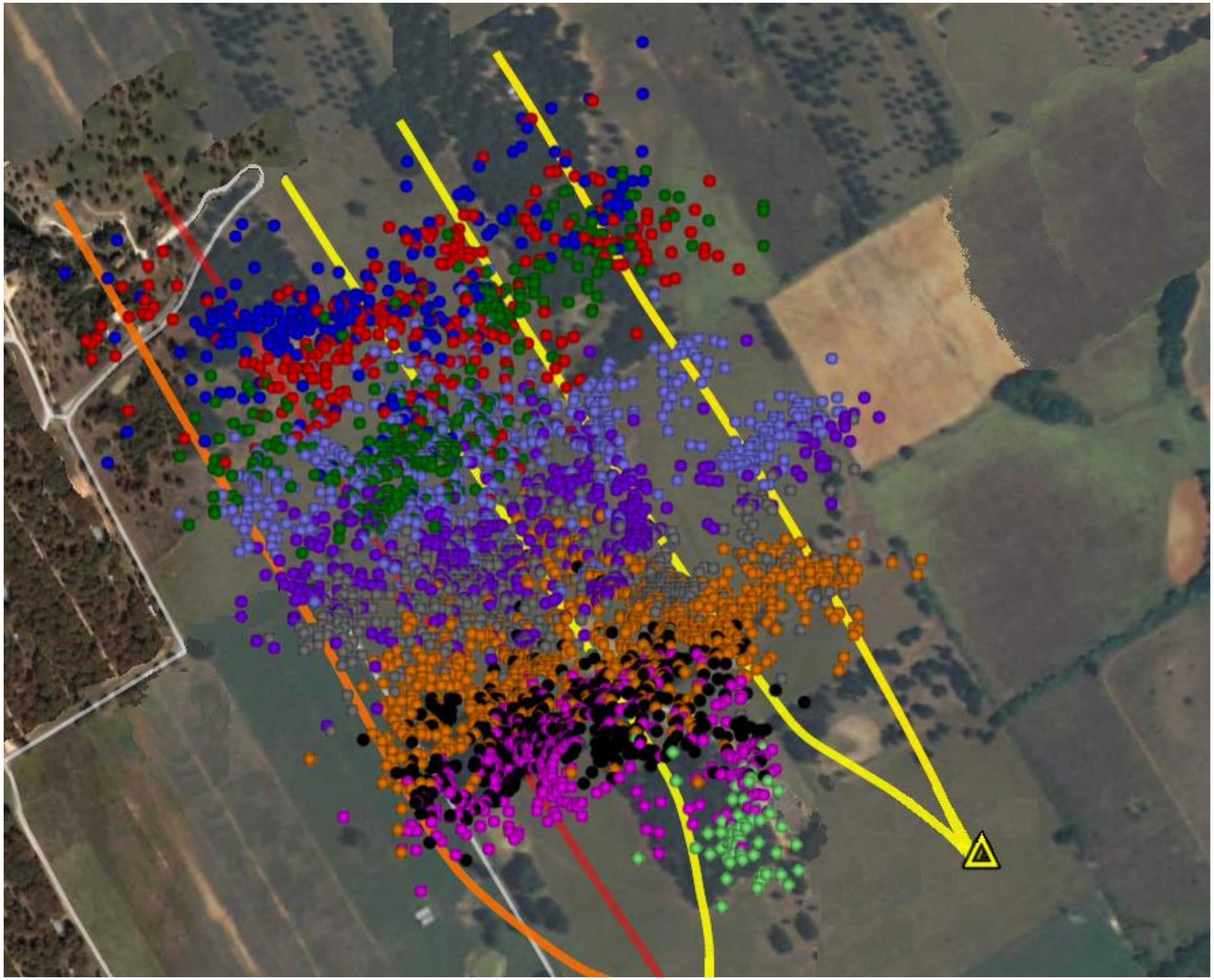
3. Reservoir Drainage and EUR

4. Aseismic Fault Slip During Reservoir Simulation

1. Managing Triggered Seismicity

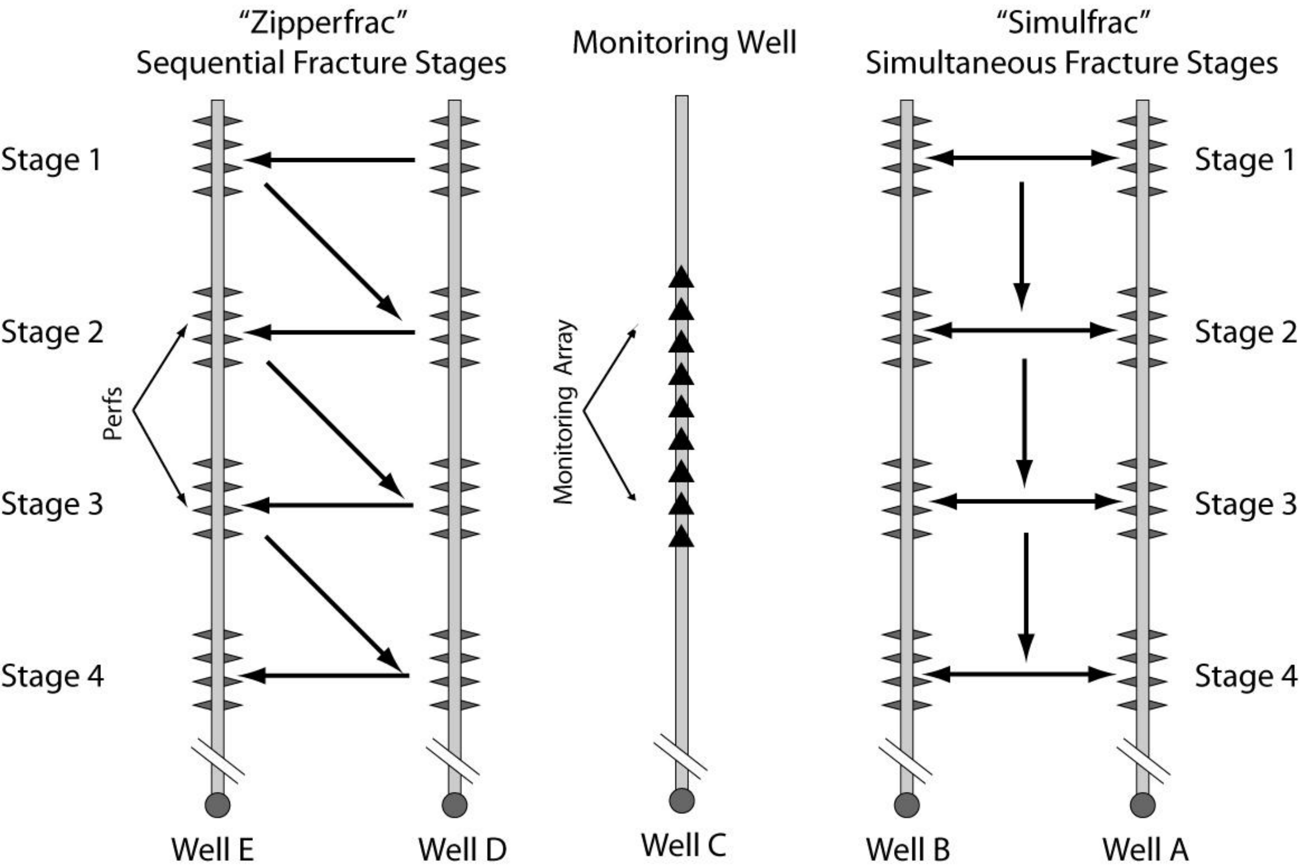
2. Minimizing the Environmental Impact Associated with Shale Gas Development

Wells - 50 Stages, ~ 100 Microearthquakes/Stage



Does the Cloud of Microearthquake Hypocenters Really Reflect the Stimulated Rock Volume?

Fracturing and Monitoring Program

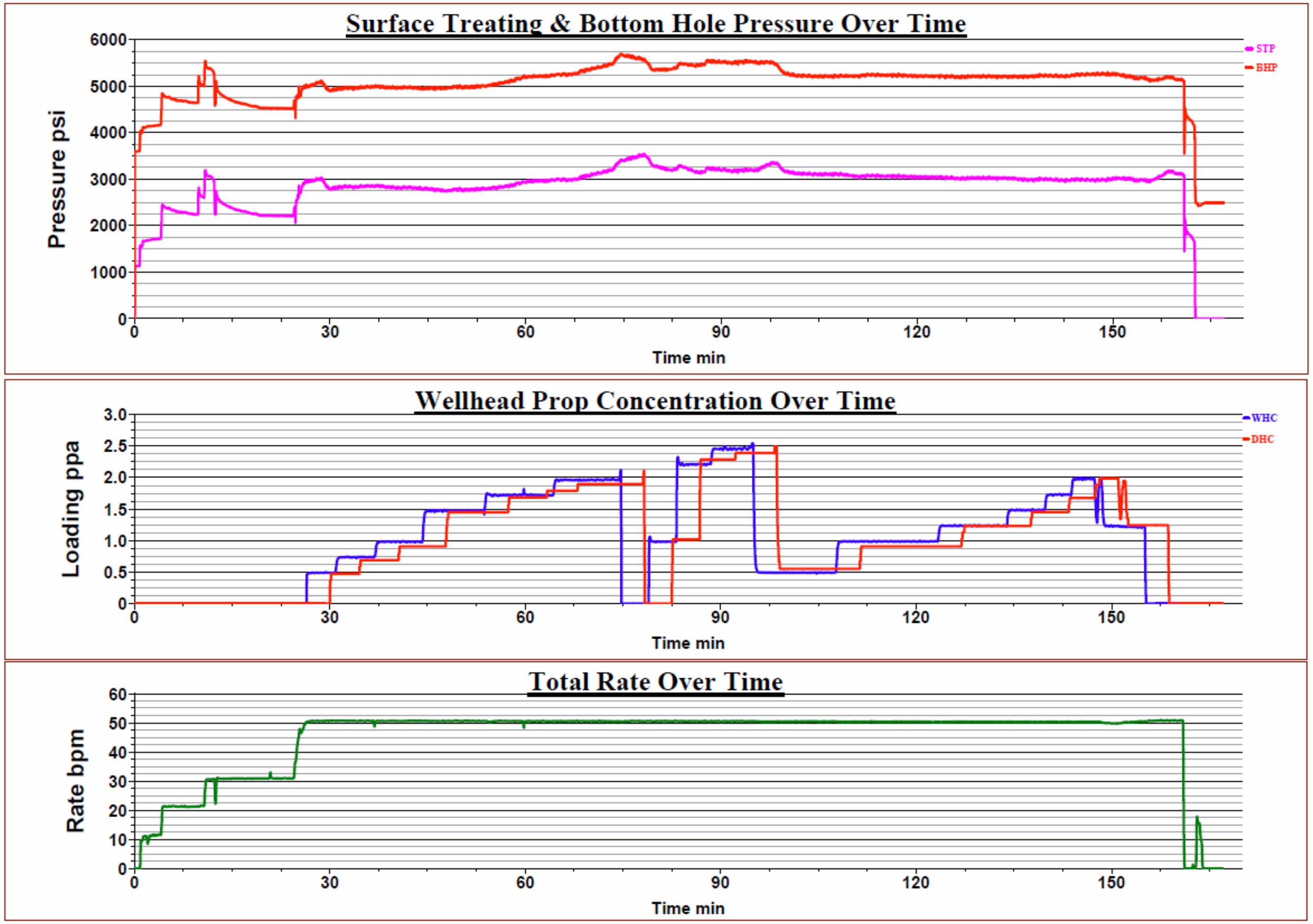


- Wells divided into 300 ft frac intervals
- 6 perf groups per interval, each 50 feet apart

- Stages in Well A and Well B are fractured at the same time, thus "simulfrac"
- Stage in Well D and Well E are alternately fractured, thus "zipperfrac"
- Well C is fractured conventionally
- Fracturing of Wells A, B, D, & E are monitored by an array in Well C
- Fracturing of Well C is monitored by an array in the vertical portion of Well B

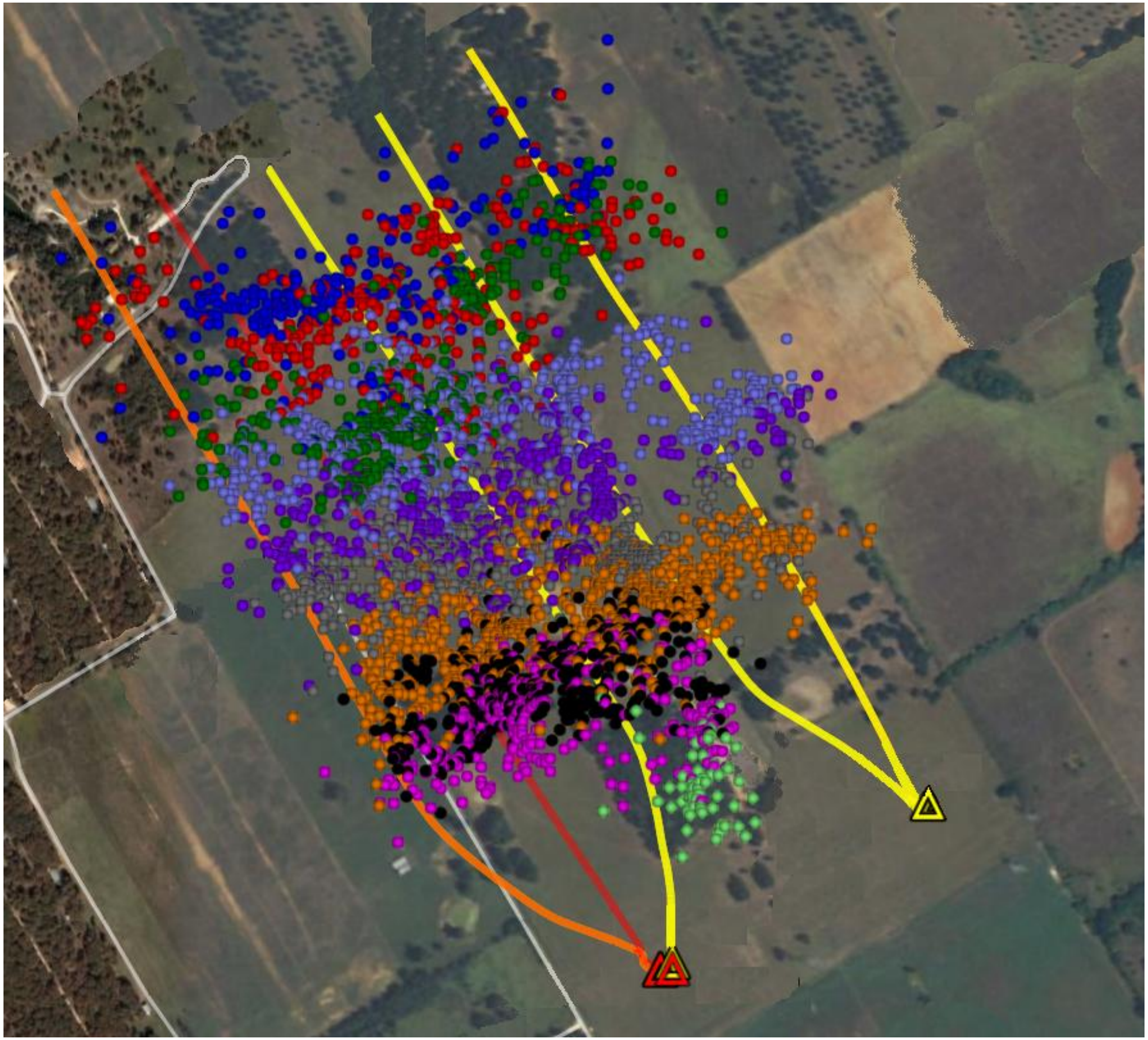
Nearly All Frac Stages Were Quite Similar

Water: ~325,000 gal, Sand: ~400,000 lbs, Pumping Time: ~150 mins, Max Slurry Rate: 50-60 bpm

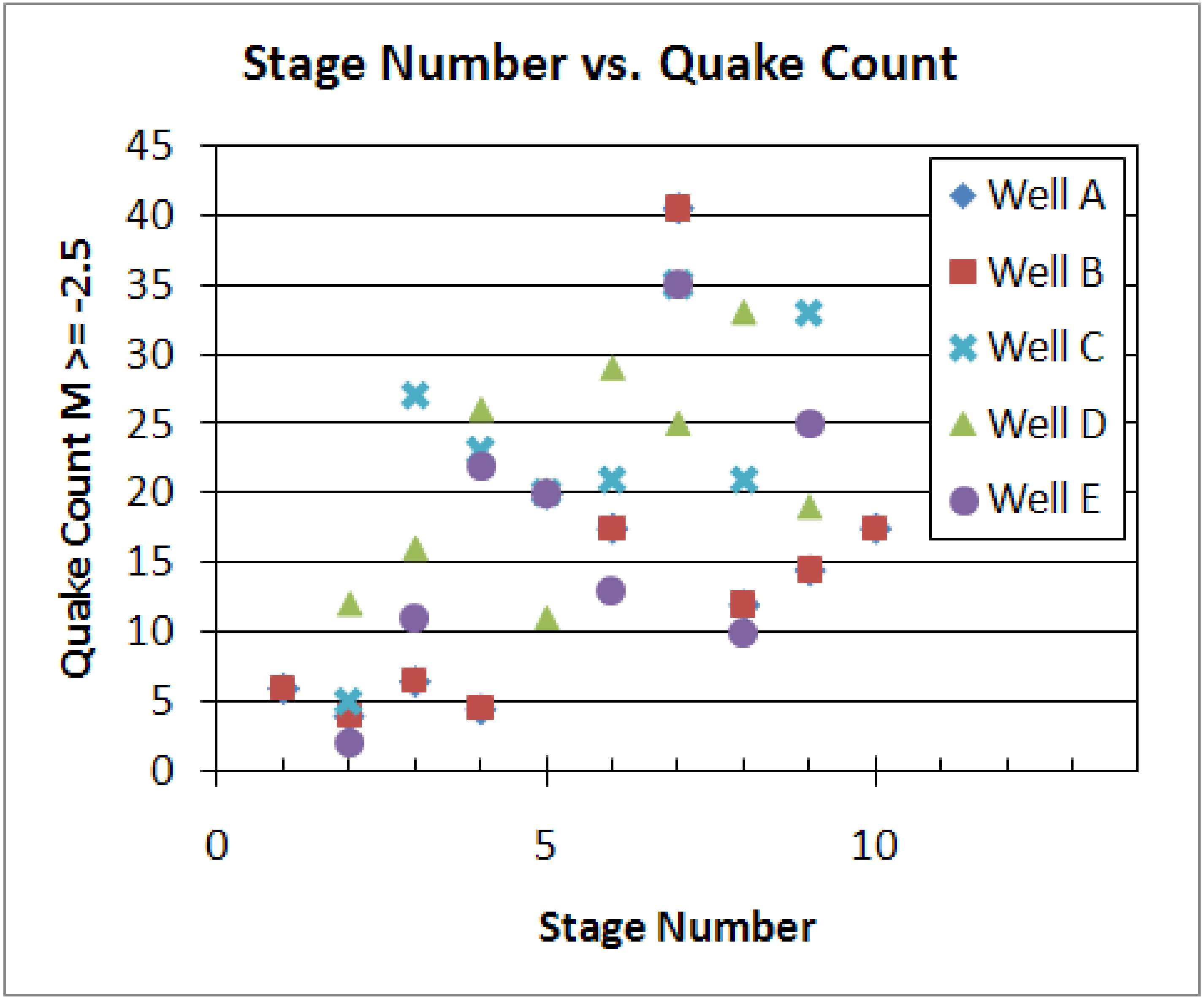


Well C
Stage 6

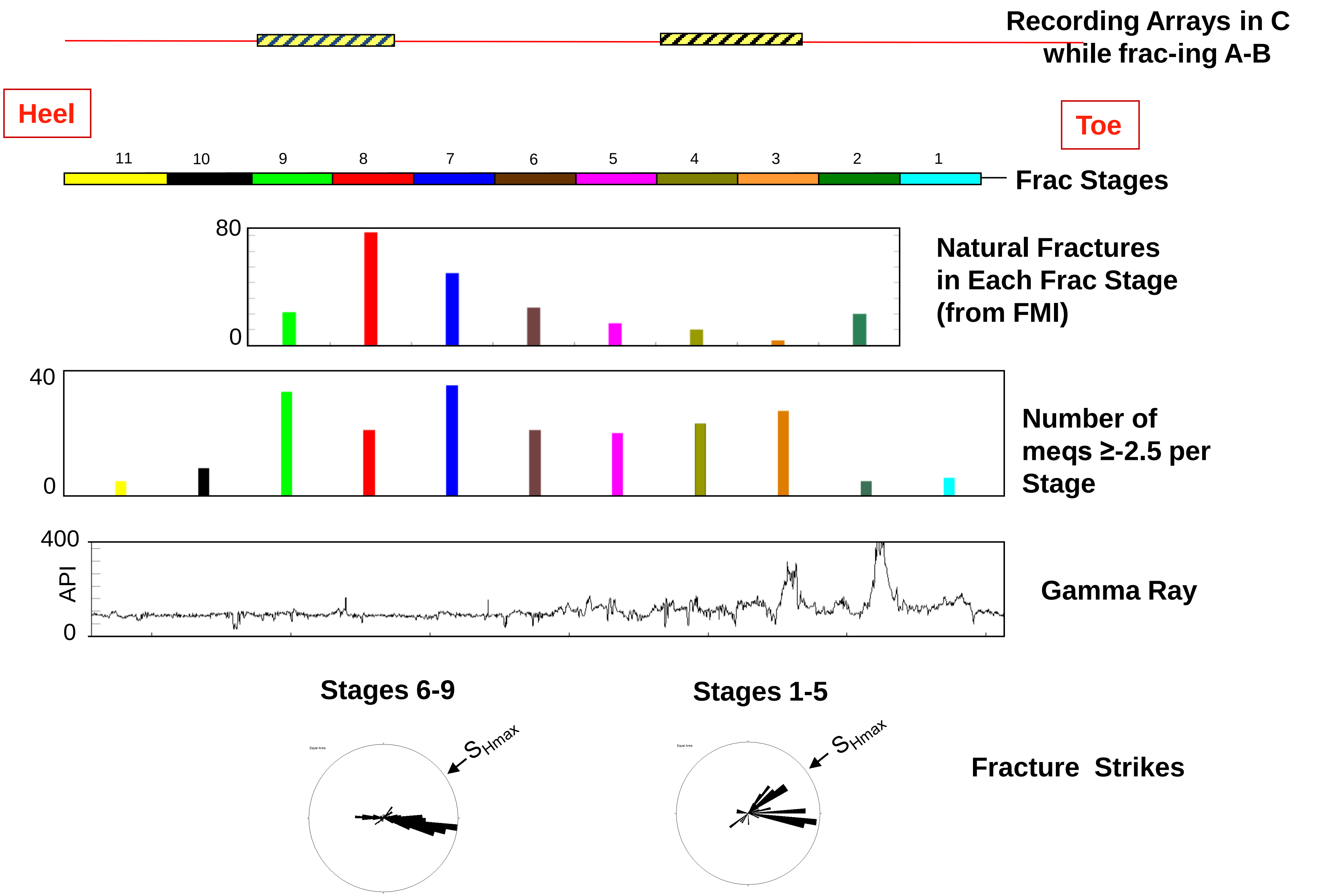
Number of Earthquakes Increase with Stage



Why More Microearthquakes in Later Stages?

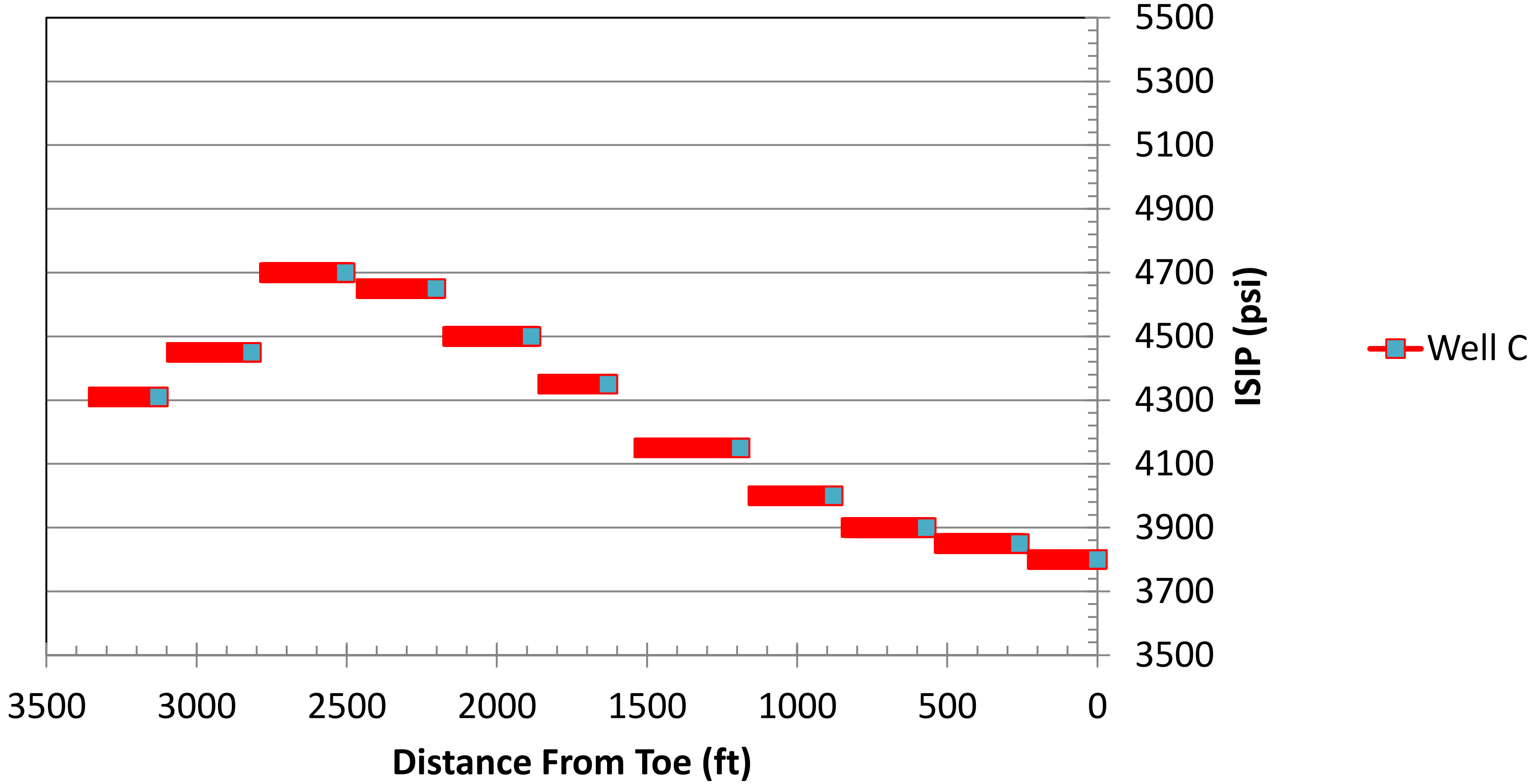


Well C



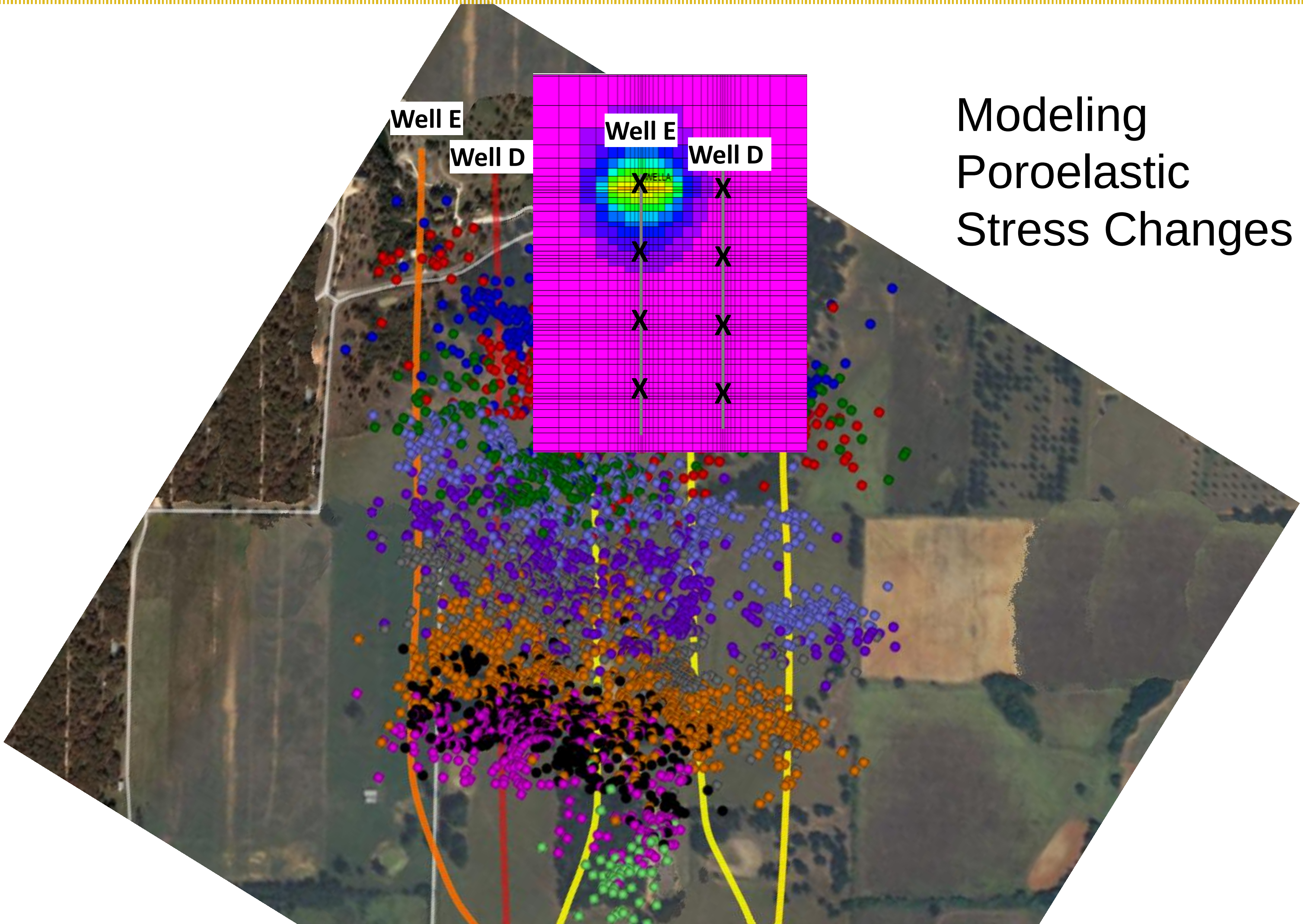
Recording Arrays in C
while frac-ing A-B
Heel
Toe
11
10
9
8
7
6
5
4
3
2
1
Frac Stages
80
0
Natural Fractures
in Each Frac Stage
(from FMI)
40
0
Number of
meqs ≥-2.5 per
Stage
400
API
0
Gamma Ray
Stages 6-9
Stages 1-5
SHmax
SHmax
Fracture Strikes

ISIP’s Escalate From Toe To Heel – Well C



- Cumulative increase in ISIPs from the toe to the heel of the well
- 900 psi difference between Stage 1 and peak at Stage 9
- Decline seen in last two stages

Is the Cumulative Effect of Frac'ing Changing Pore Pressure and Stress?



Modeling Poroelastic Stress Changes

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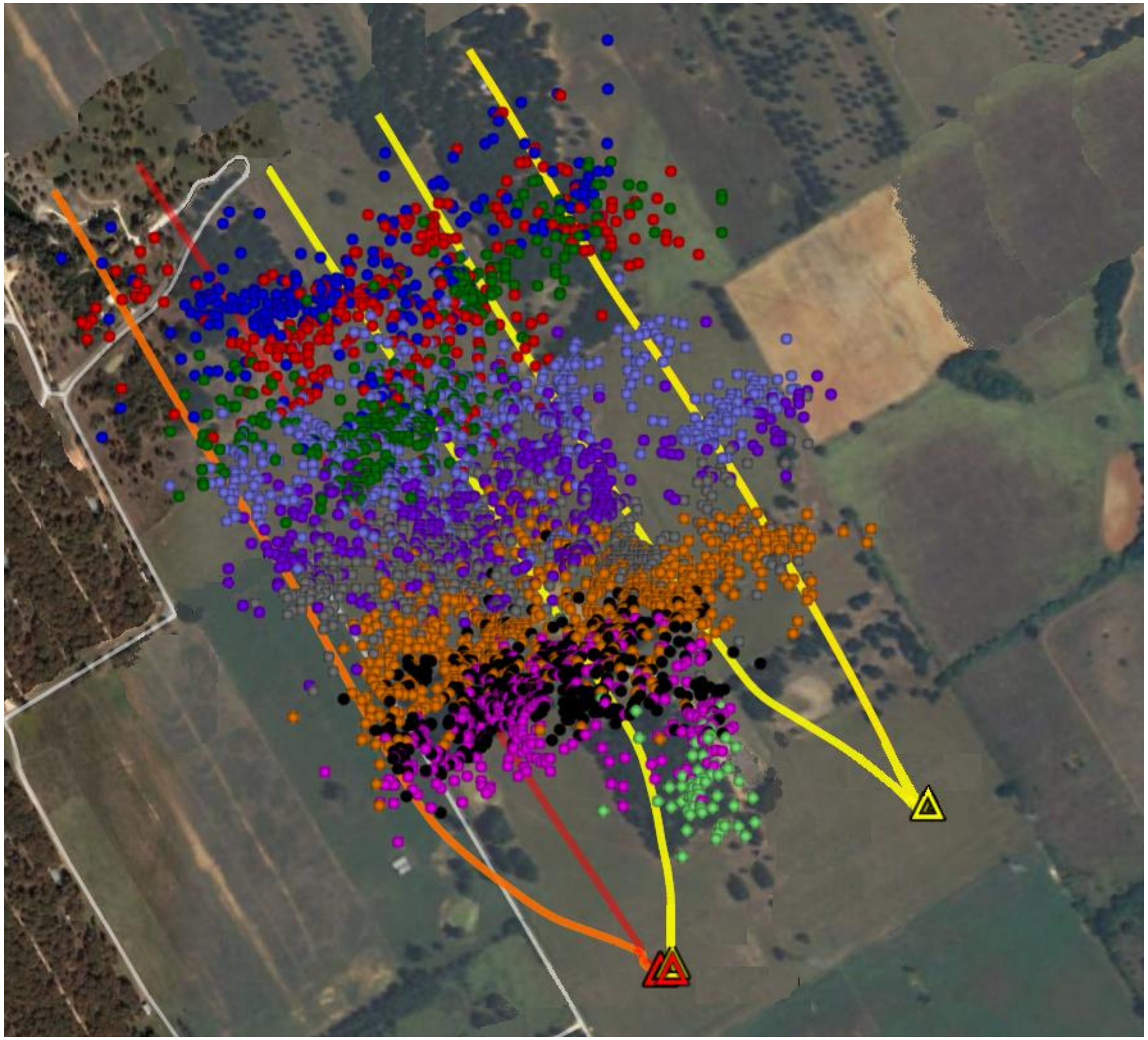
Physical and Chemical Properties of Organic Rich Shales

How Do the Properties of Shale Affect the Outcome of Hydraulic Fracturing Stimulation?



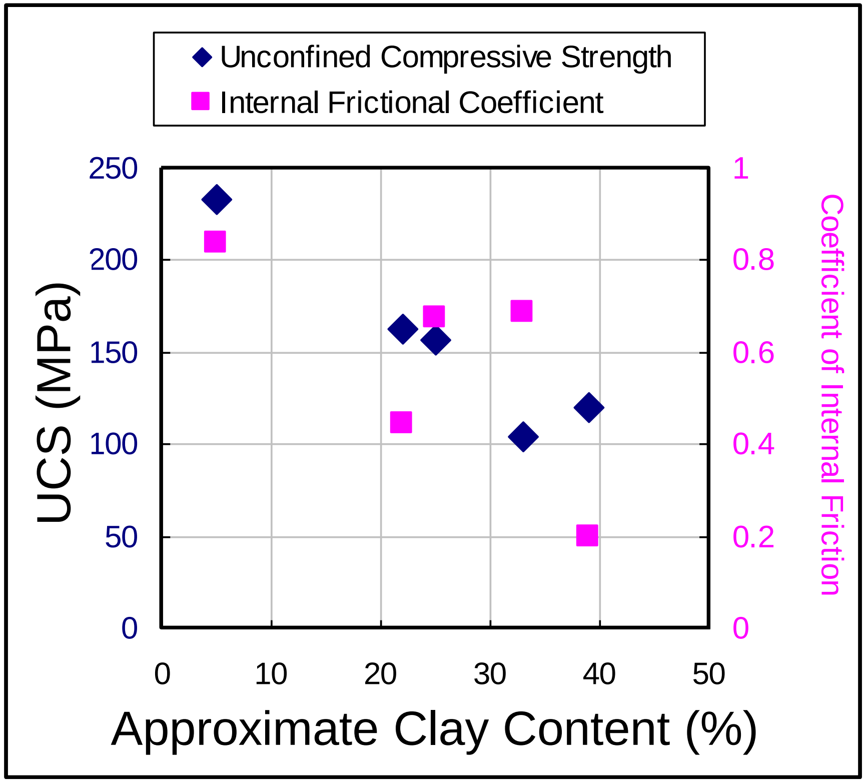
5 Wells, 40 Stages, 4050 Microseismic Events

Organic Rich Shales

Sample group	Clay	Carbonate	QFP	TOC
Barnett-dark	30-45	0-6	48-61	4.0-5.8
Barnett-light	2-7	39-81	16-53	0.4-1.3
Haynesville-dark	34-43	21-29	34-38	2.8-3.2
Haynesville-light	22-24	51-54	23-26	1.7-1.8
Fort St. John	34-42	3-6	54-60	1.6-2.2
Eagle Ford-1	n/a	n/a	n/a	n/a
Eagle Ford-2	n/a	n/a	n/a	n/a
Eagle Ford-3	n/a	n/a	n/a	n/a

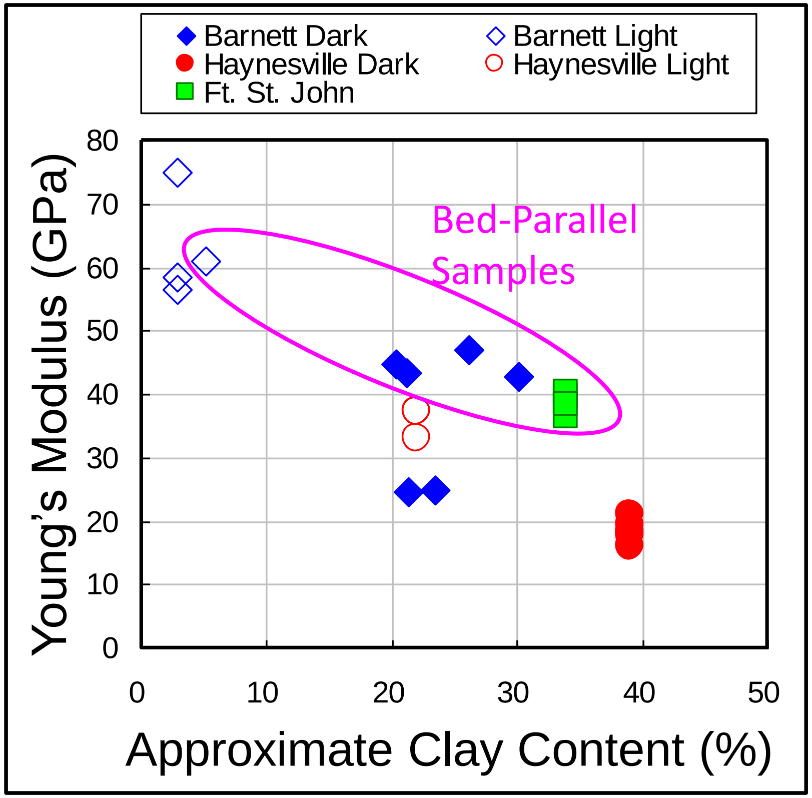
- Bedding plane and sample cylinder axis is either parallel (horizontal samples) or perpendicular (vertical samples)
- 3-10 % porosity
- All room dry, room temperature experiments

Strength



- Strength decreases with clay content
- Internal friction coefficient decreases from 0.9 to 0.2

Young's Modulus

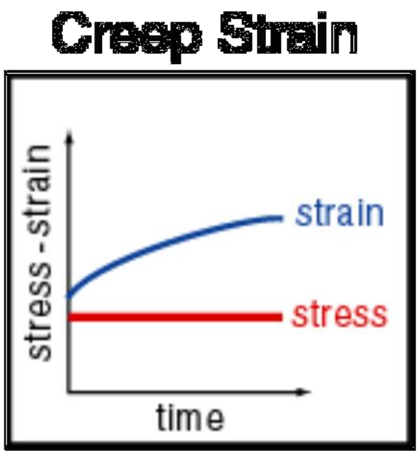


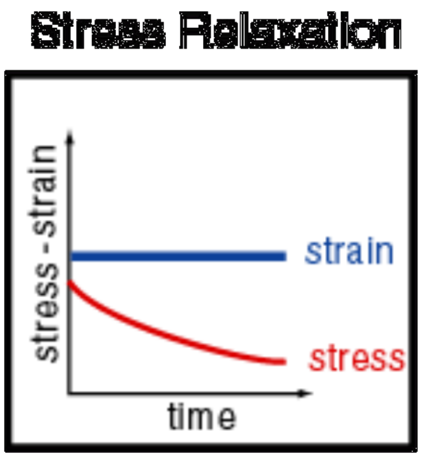
- Modulus correlate with clay content and porosity
- Bedding parallel samples are systematically stiffer

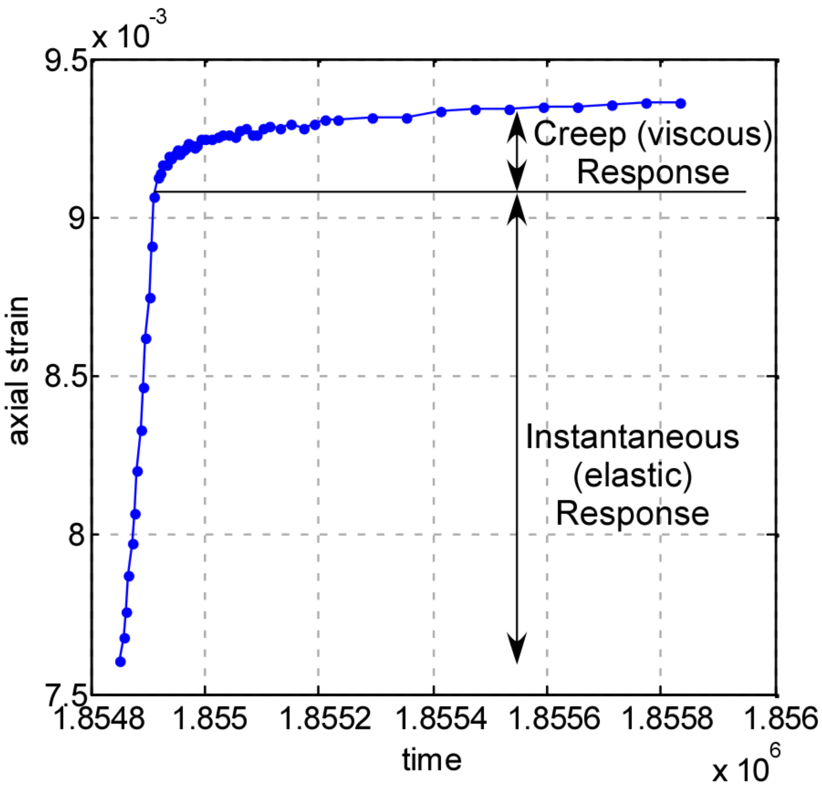
Shales Creep With Time (Viscoplastic)

Creep may prevent brittle fracturing (stimulation) and promote propant-embedment

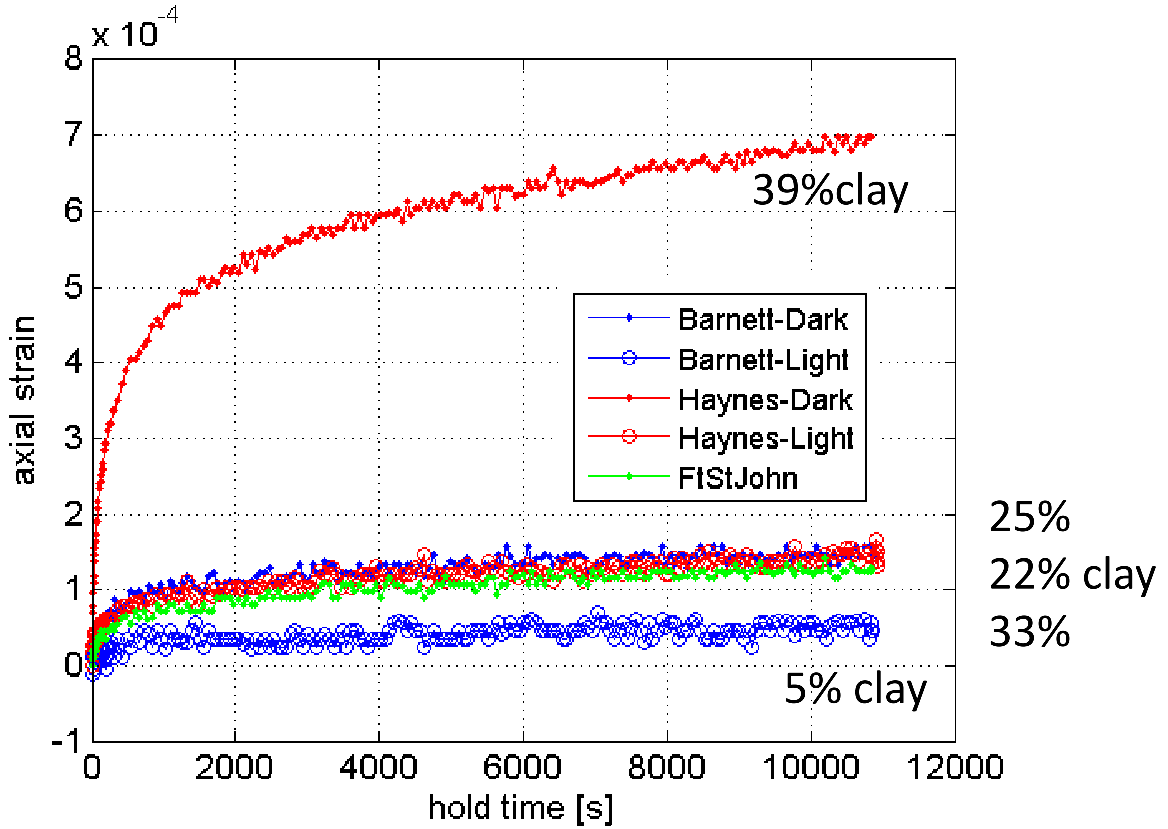
Creep relaxes stresses

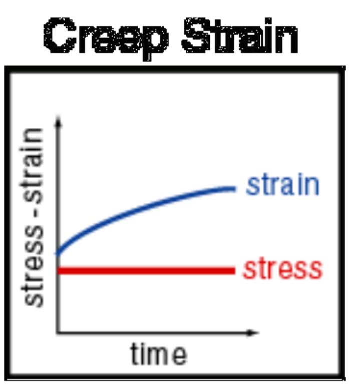


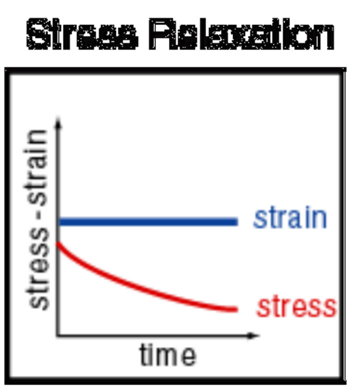




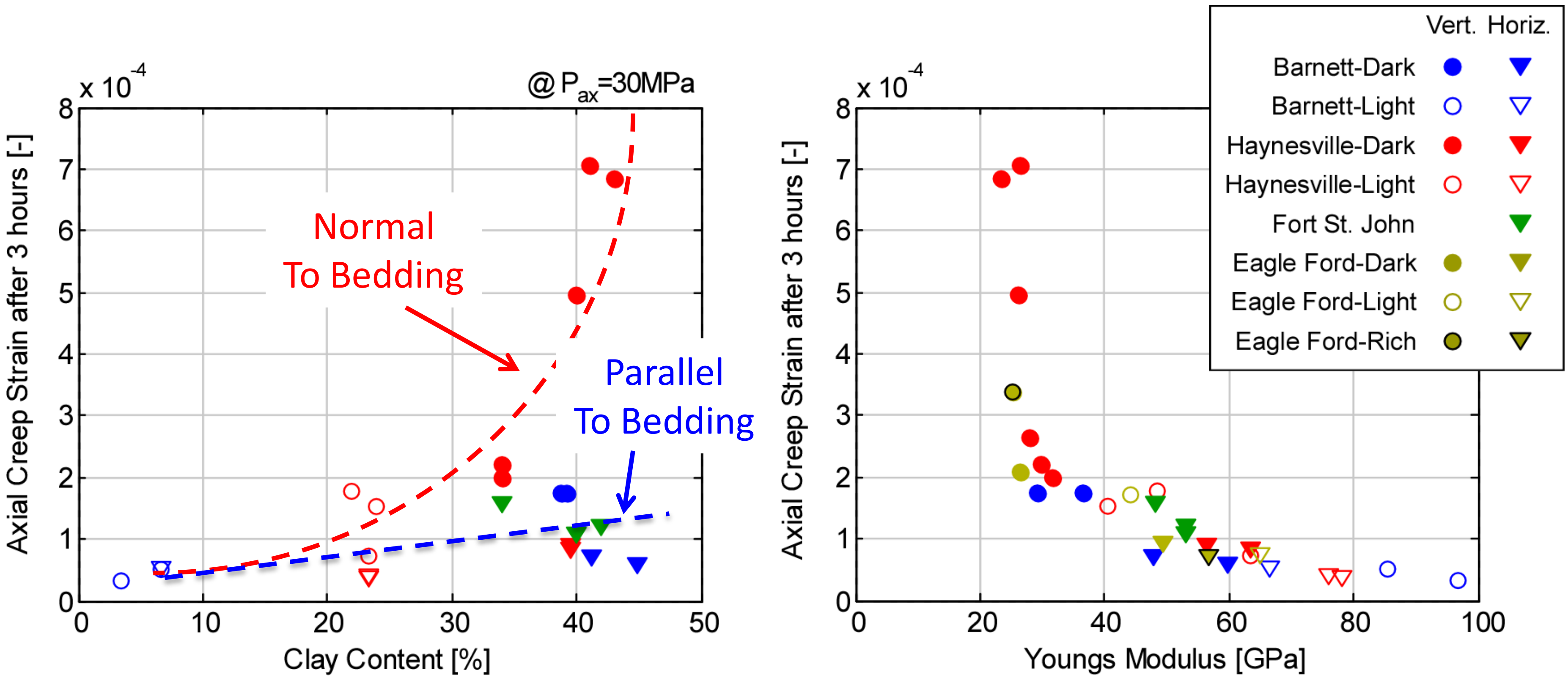
Creep Increases with Clay Content







Creep Strain vs. Clay and E

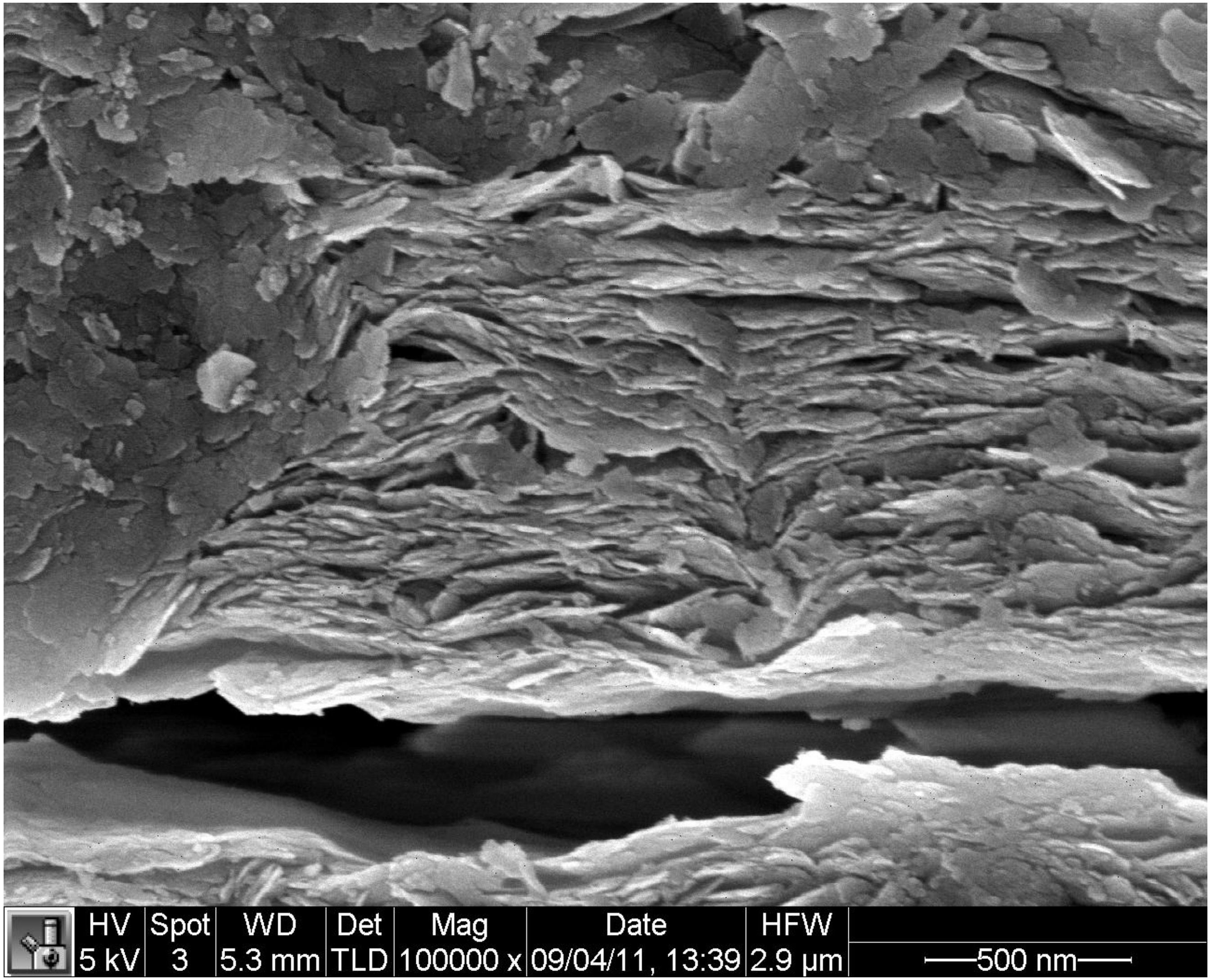


- Amount of creep (ductility) depends on clay content and orientation of loading with respect to bedding
- Young's modulus correlates with creep amount very well

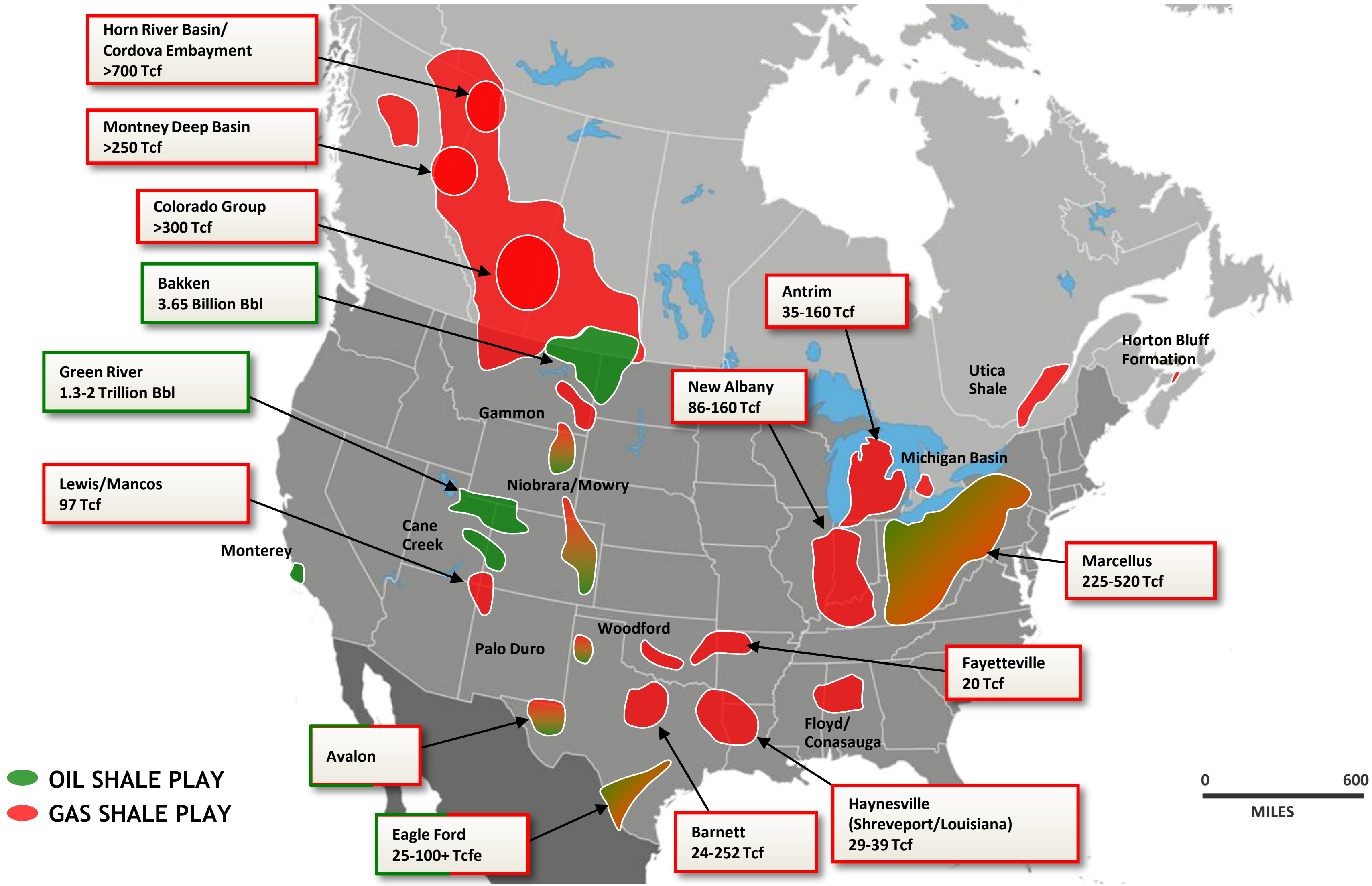
Eagleford Shale Pore Structure

2 cm

Eagleford Shale



Floyd Shale?


Horn River Basin/
Cordova Embayment
>700 Tcf
Montney Deep Basin
>250 Tcf
Colorado Group
>300 Tcf
Bakken
3.65 Billion Bbl
Green River
1.3-2 Trillion Bbl
Lewis/Mancos
97 Tcf
Monterey
Gammon
Niobrara/Mowry
Cane
Creek
Palo Duro
Woodford
Avalon
Eagle Ford
25-100+ Tcfe
Barnett
24-252 Tcf
Haynesville
(Shreveport/Louisiana)
29-39 Tcf
Fayetteville
20 Tcf
Floyd/
Conasauga
Marcellus
225-520 Tcf
New Albany
86-160 Tcf
Antrim
35-160 Tcf
Michigan Basin
Utica
Shale
Horton Bluff
Formation
0
600
MILES
OIL SHALE PLAY
GAS SHALE PLAY

Average Shale Properties

	BARNETT	MARCELLUS	EAGLE FORD	FLOYD
Depth (ft)	3 - 9,000	2 - 9,500	4 - 13,500	6 - 13,000
TOC (%)	1 - 10	1 - 15	2 - 7	1 - 7
RO (%)	0.7 - 2.3	0.5 - 4+	0.5 - 1.7	0.7 - 2+
Porosity (%)	2 - 14	2 - 15	6 - 14	1 - 12
Qtz + Calcite (%)	40 - 50	40 - 60	50 - 80	20 - 30
Clay (%)	20 - 40	30 - 50	15 - 35	45 - 65
Areal Extent (mi^2)	22,000	60,000	15,000	6,000
Resource Size (Tcf)	25 - 250	50 - 500	10 - 100	<<1

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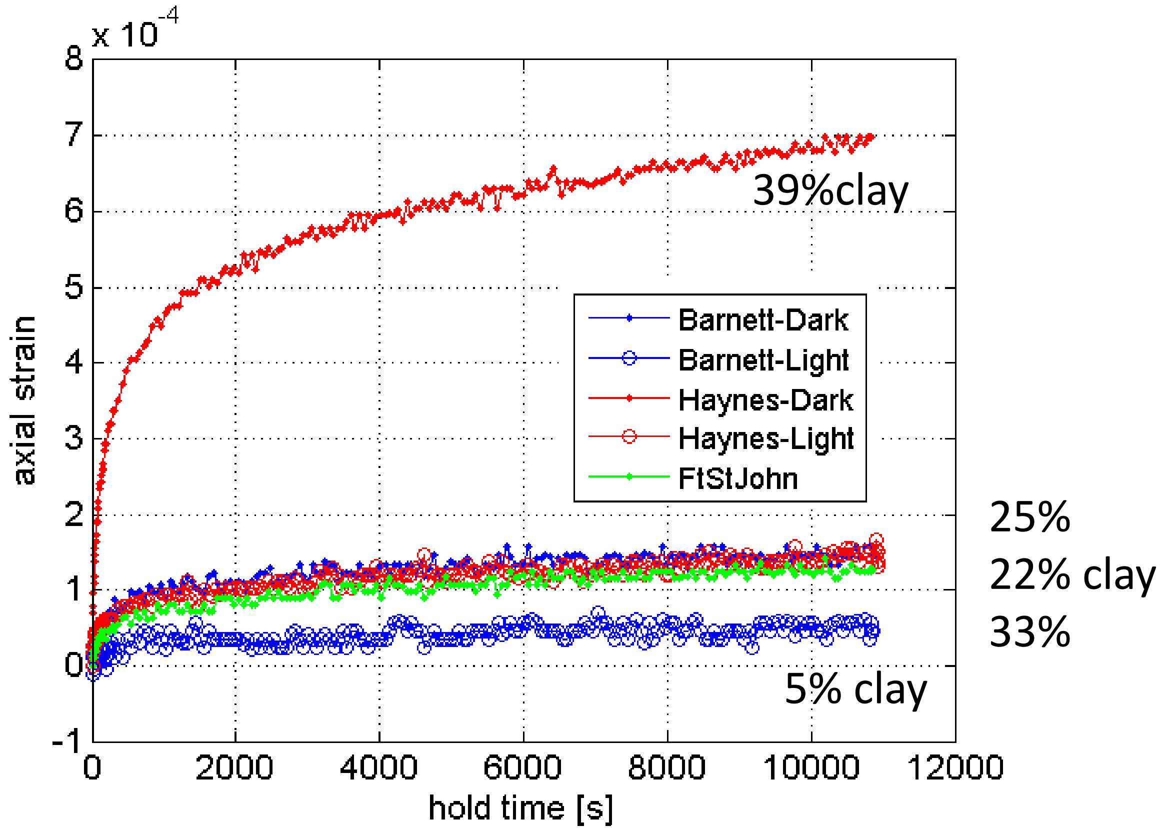
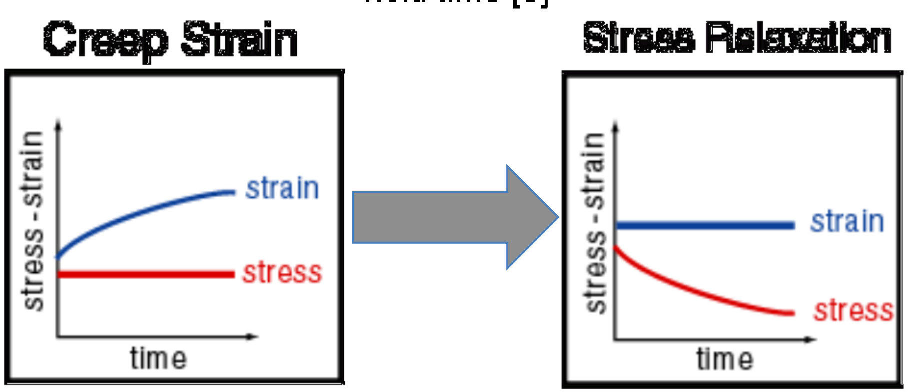
Is the Floyd Shale too Viscous to Stimulate?



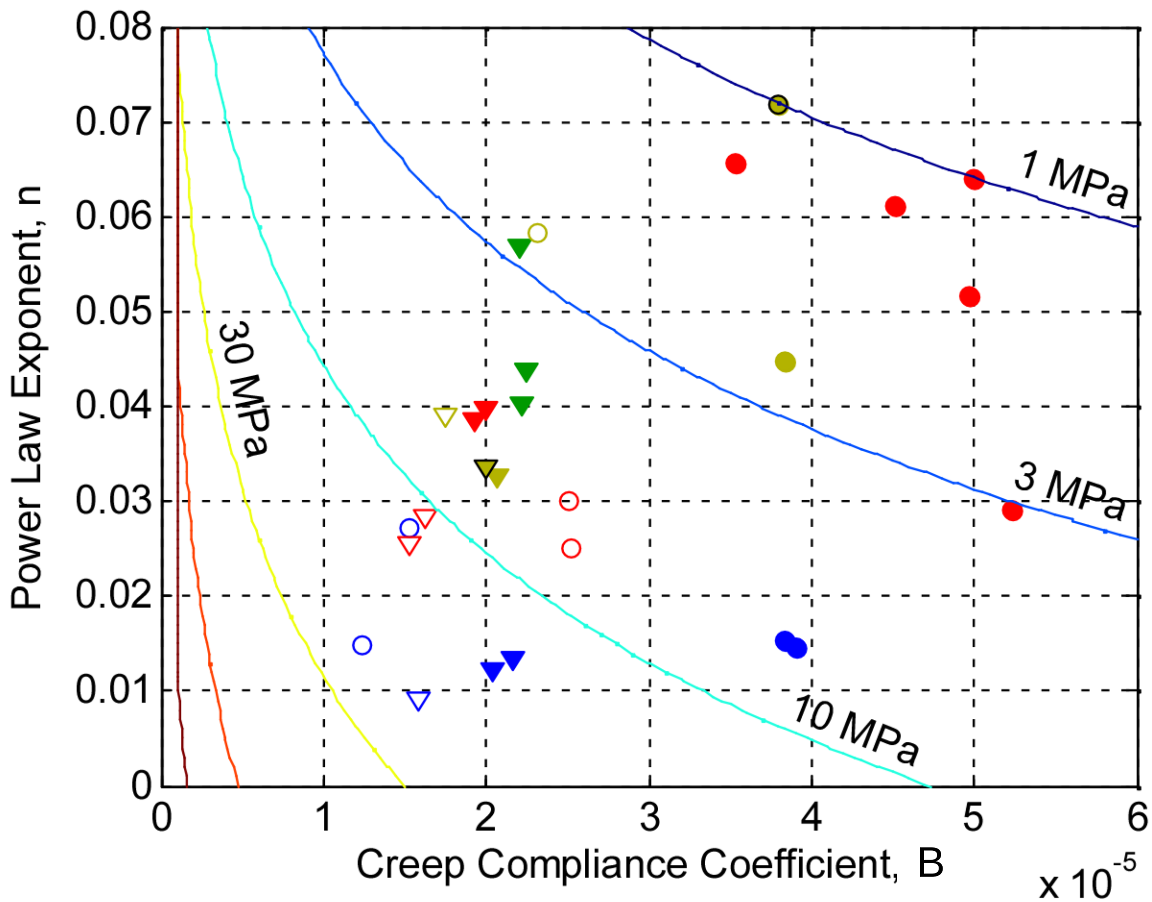


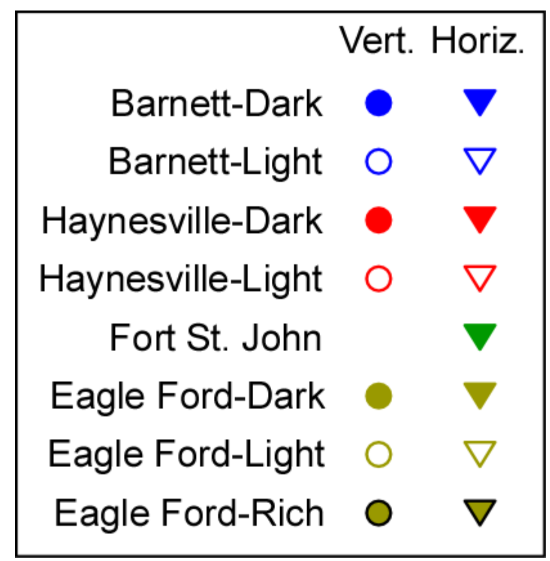
Accumulation of Differential Stress

$$\frac{d\sigma}{dt} = \dot{\varepsilon}\frac{1}{B}t^{-n} \quad \rightarrow \quad \sigma(t) = \frac{\dot{\varepsilon}}{(1-n)B}t^{1-n}$$

- Barnett Shale
  - 320 Ma
  - Stable intraplate

time = 150 Ma
strain rate = 10^{-19} s^{-1}





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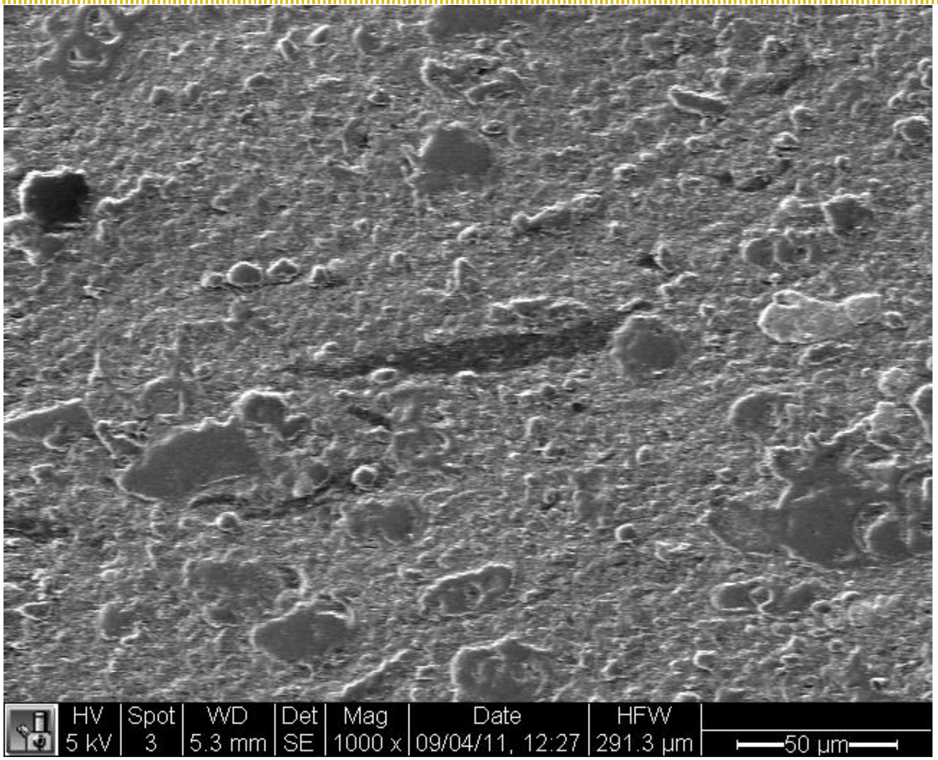

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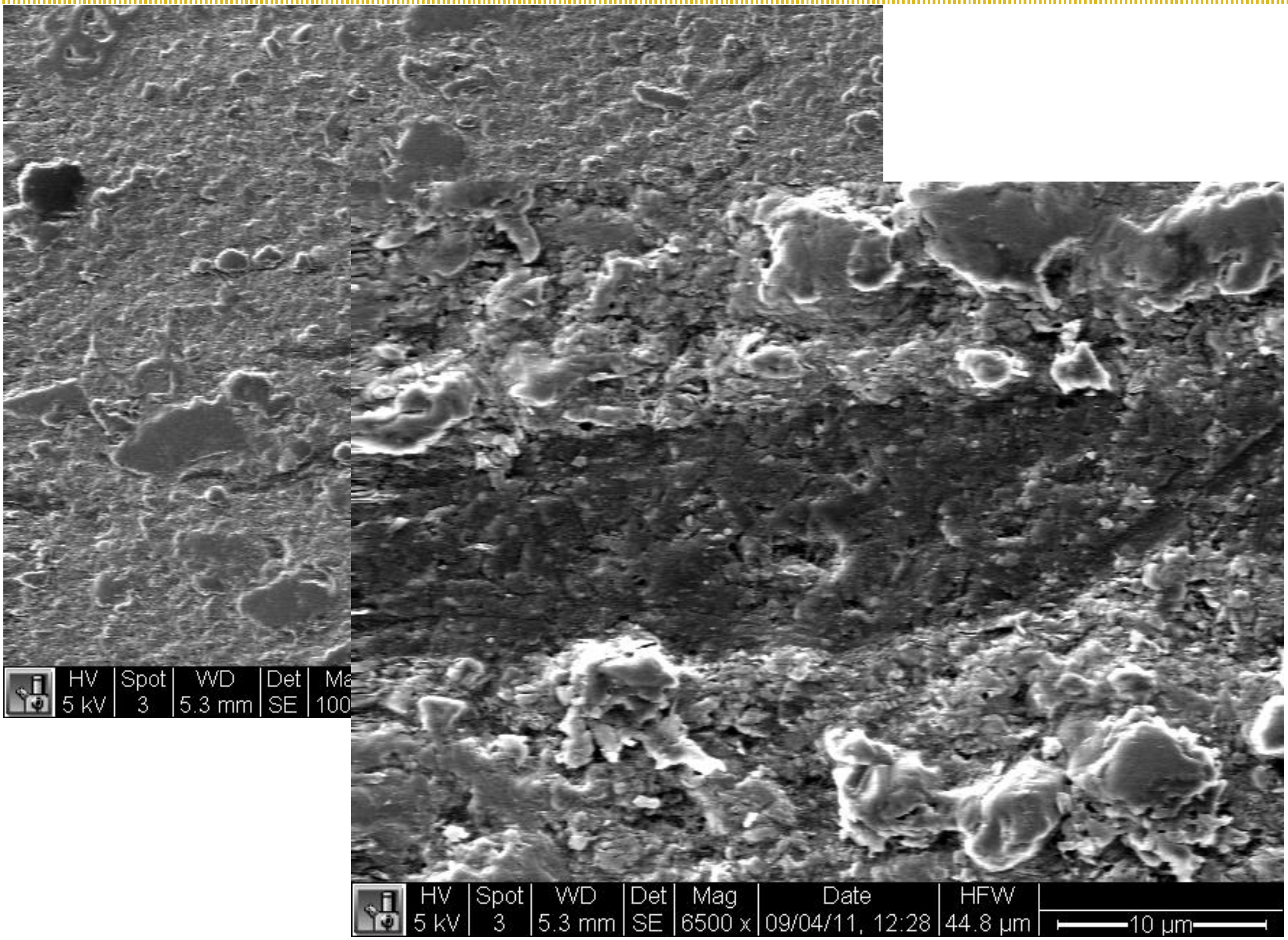

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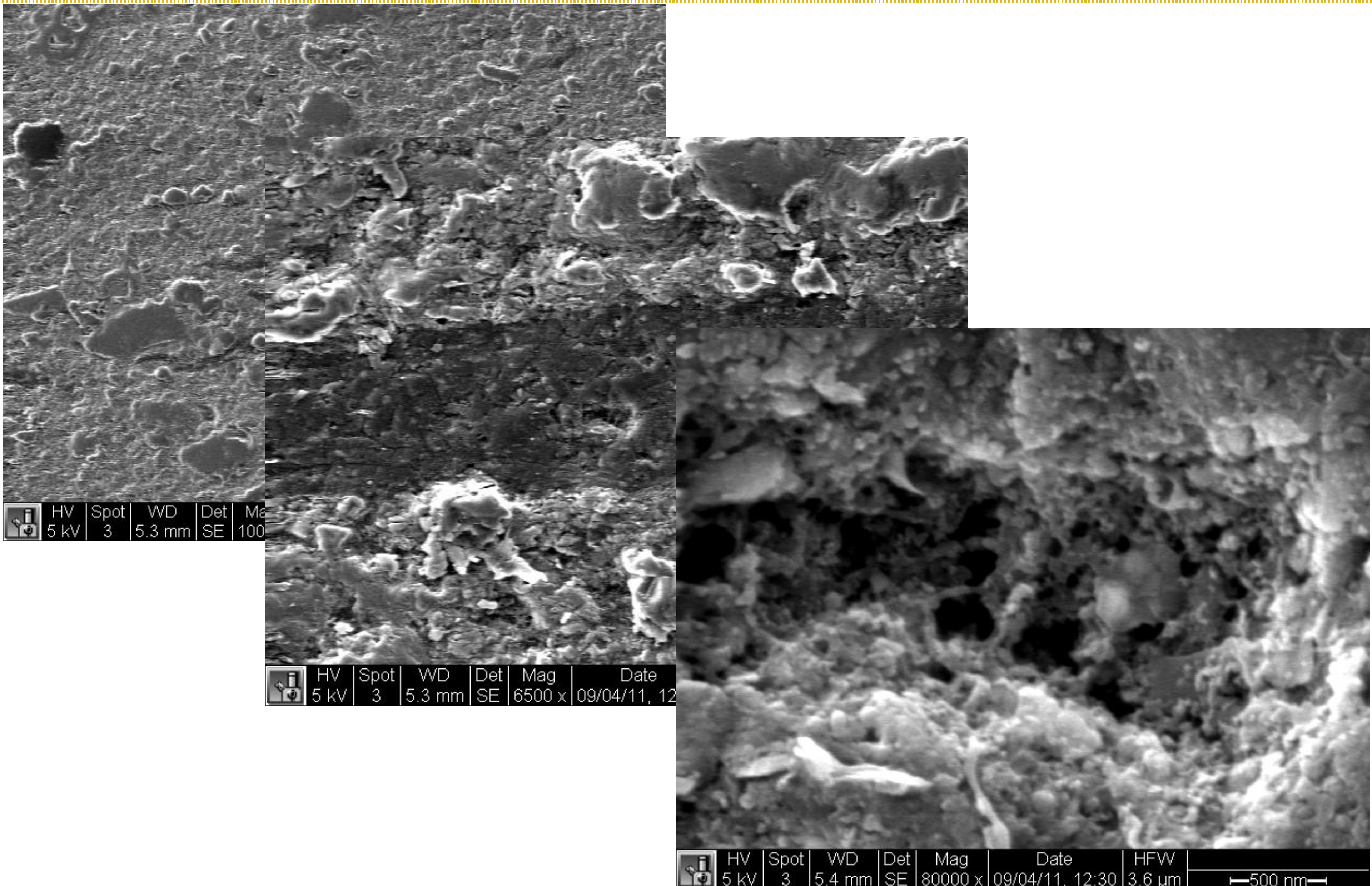

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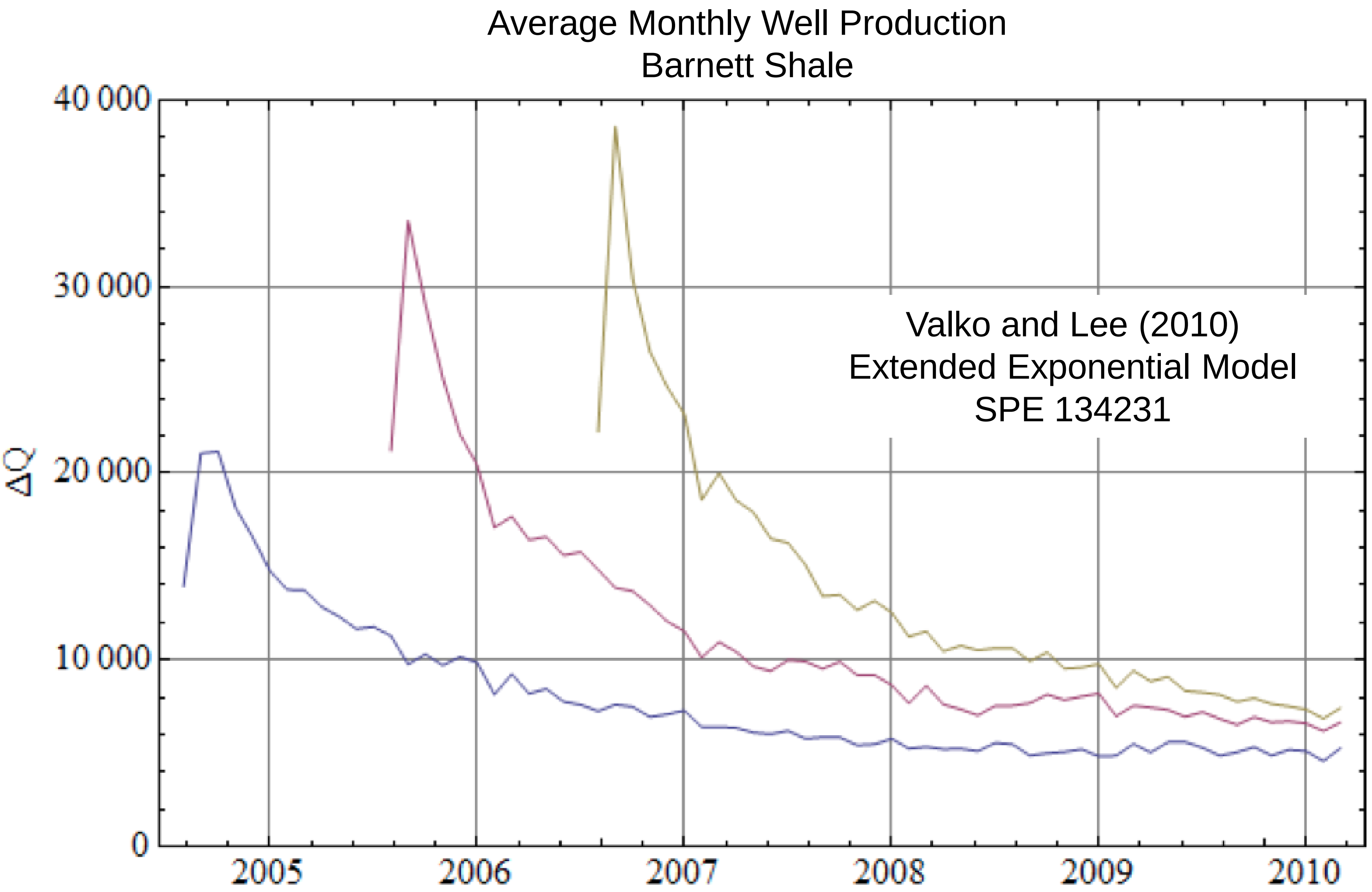
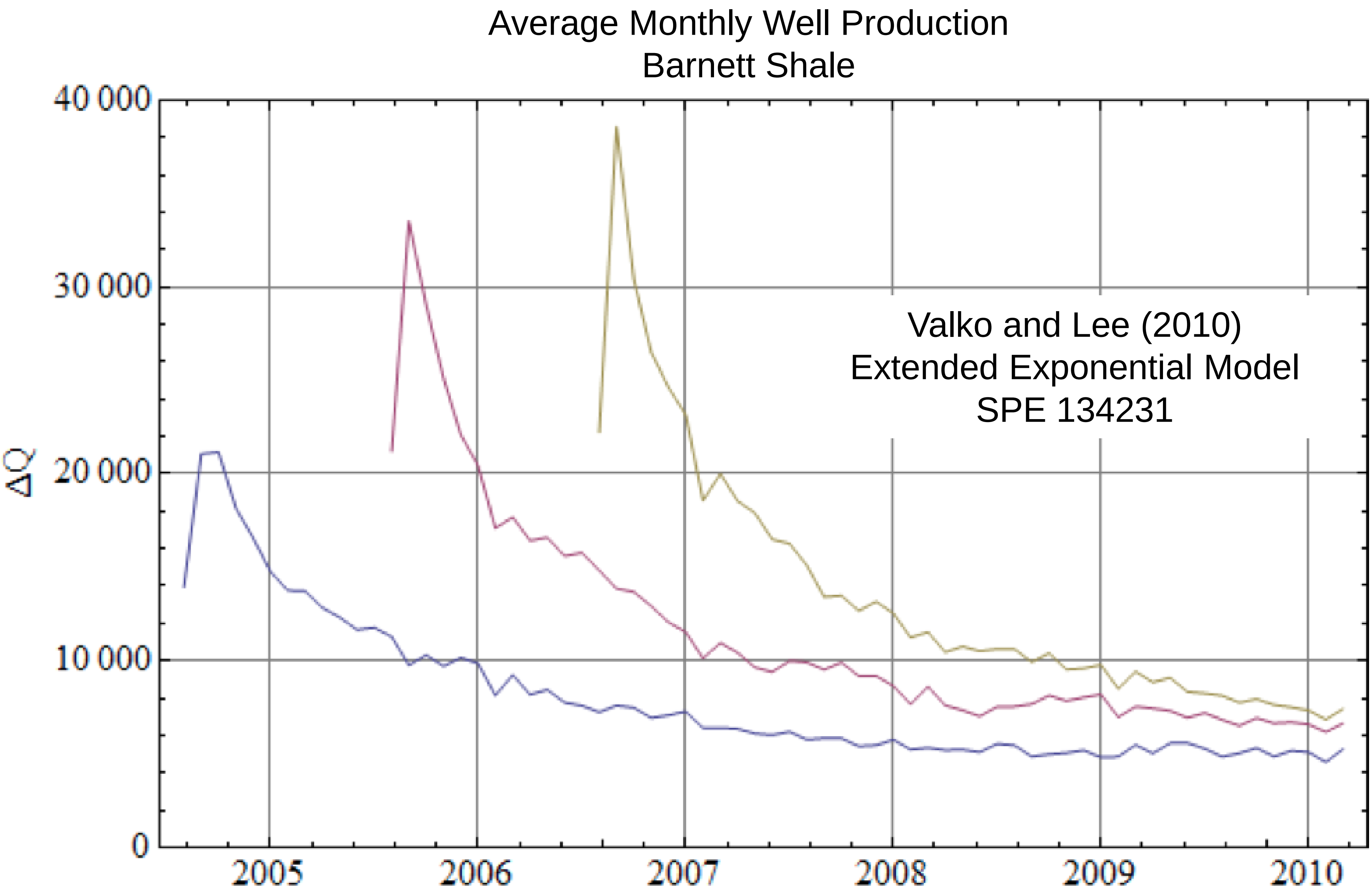
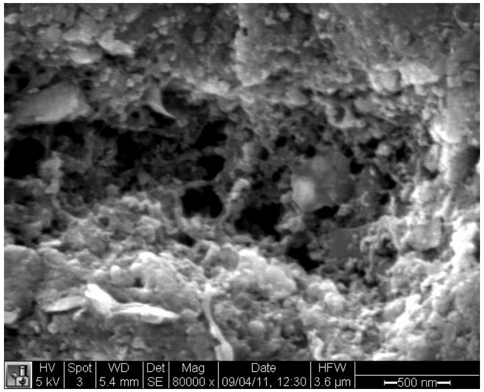
Reservoir Drainage and EUR

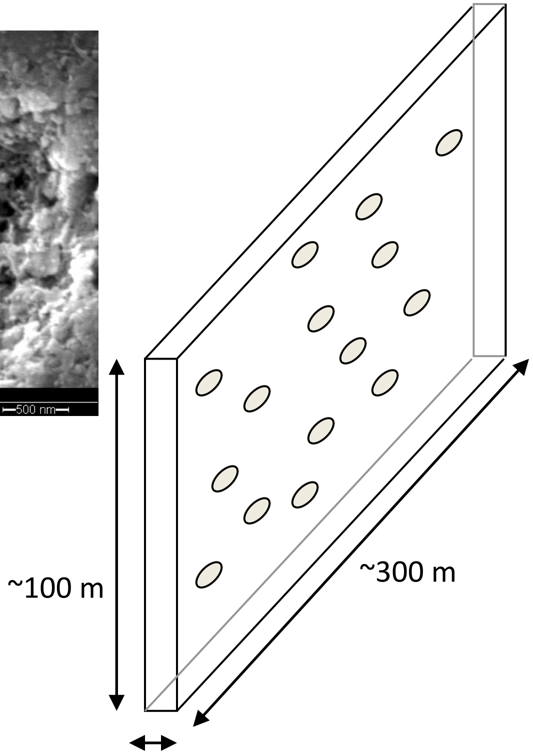


Why Is Production Persistent?



Reservoir Drainage and EUR



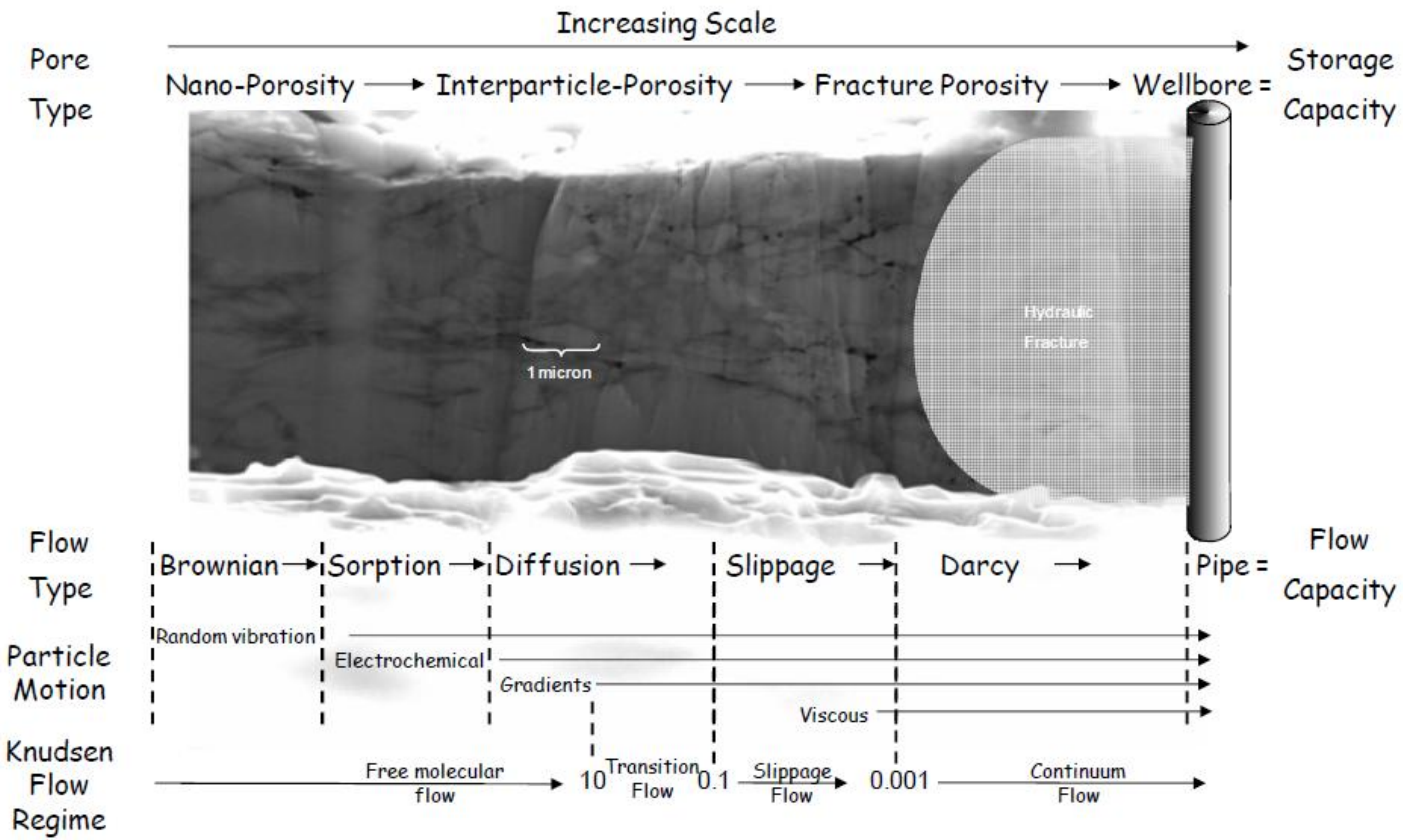


How does slip on ~100, ~ 1m fault patches change permeability and create an interconnected fracture network in the stimulated volume?

How is an interconnected pore and fracture network created from:

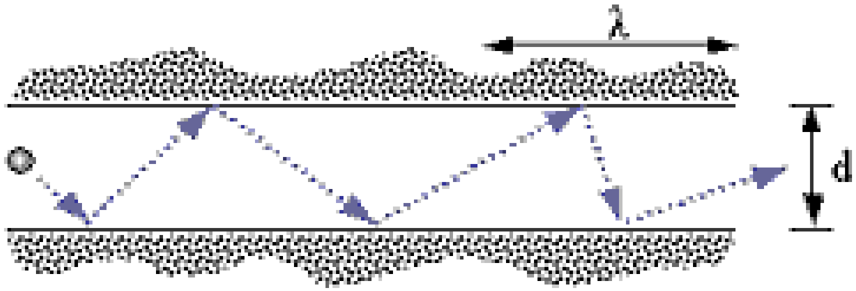
1. Nano-scale pore network?
2. Pre-existing micro-cracks?
3. Pre-existing macro-scale fractures?
4. Induced shear events?
5. Slick-water frac plane?

Scale Dependent Flow Mechanisms



Sondergeld et al., 2010

Knudsen Diffusion



• Knudsen diffusion will be the dominant mechanism whenever the mean free path is large compared with the pore diameter.

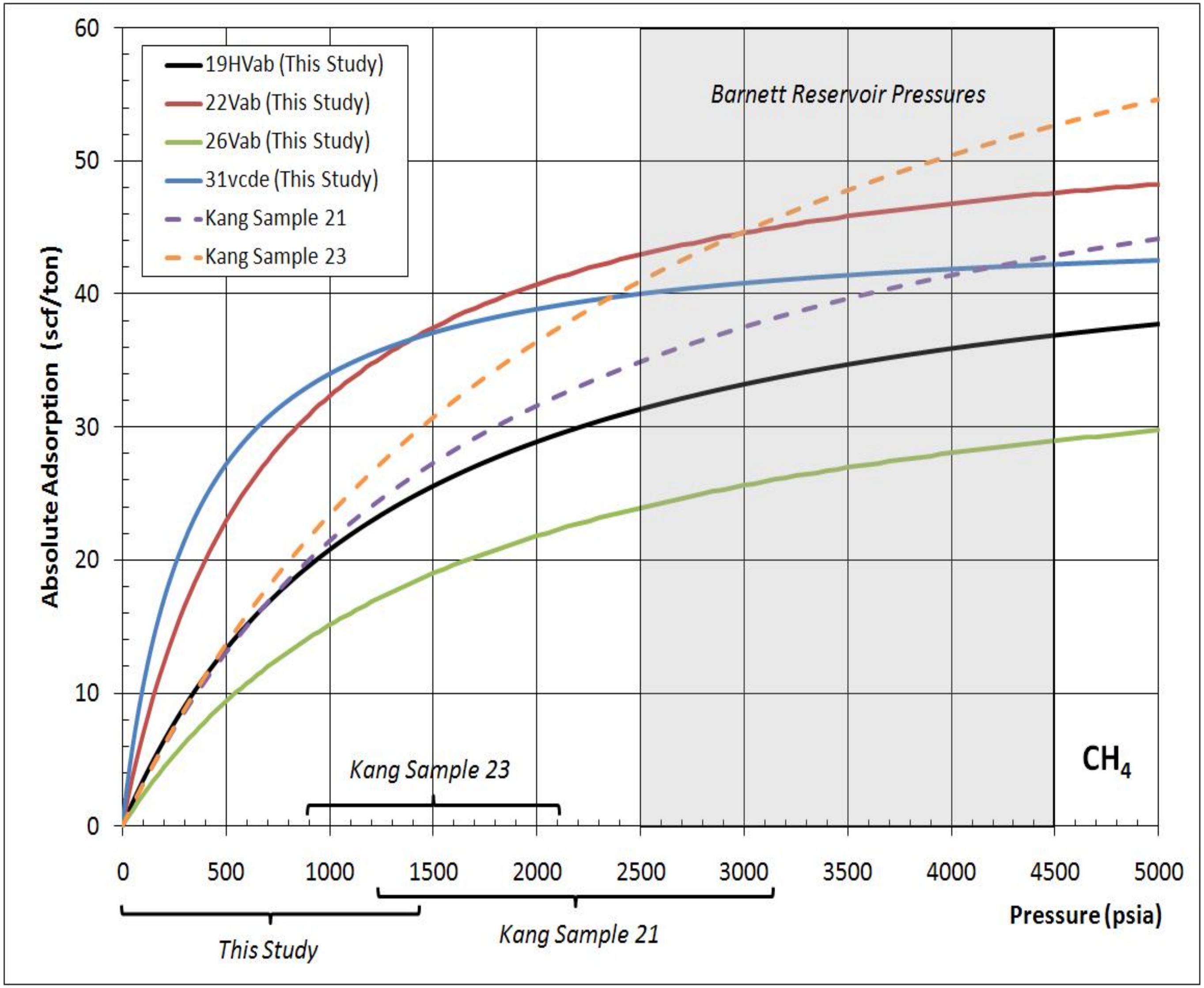
• Collisions with the pore walls will be more frequent than those between the molecules

Knudsen diffusion prevails:

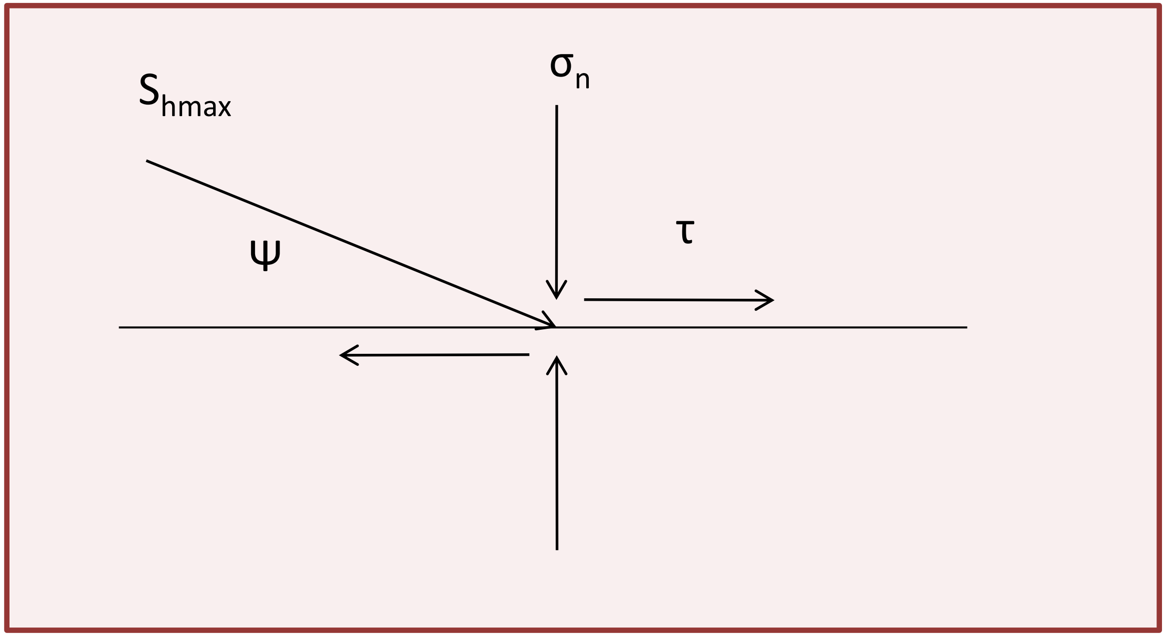
1) when gas density is low

2) when pore dimensions are very small

Is Desorption Important?

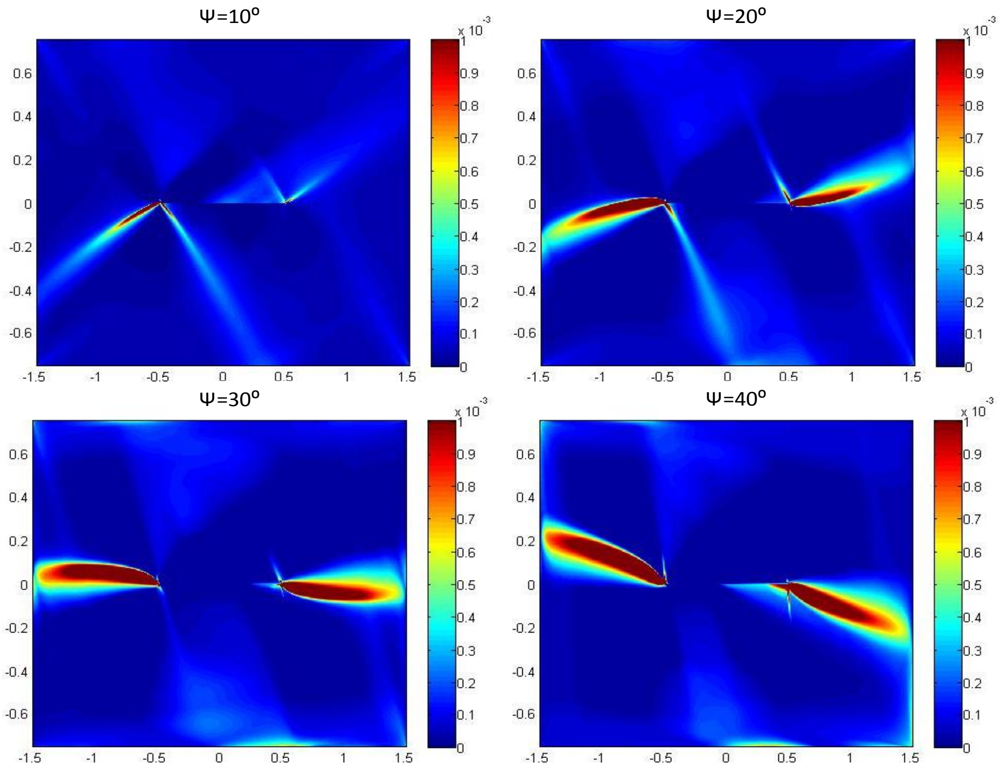


How Do Microearthquakes Affect Production?



Could the damage caused by ~5000 microearthquakes access
The gas in extremely small pores?

Off-Fault Damage – Zero Cohesion



Volume Affected by 4000 Microearthquakes Can Account for Less Than 1% of Gas Production in First 6 Months

Outline of Presentation

1. Microseismicity and Reservoir Stimulation

2. Physical and Chemical Properties of Organic Rich
   Shales

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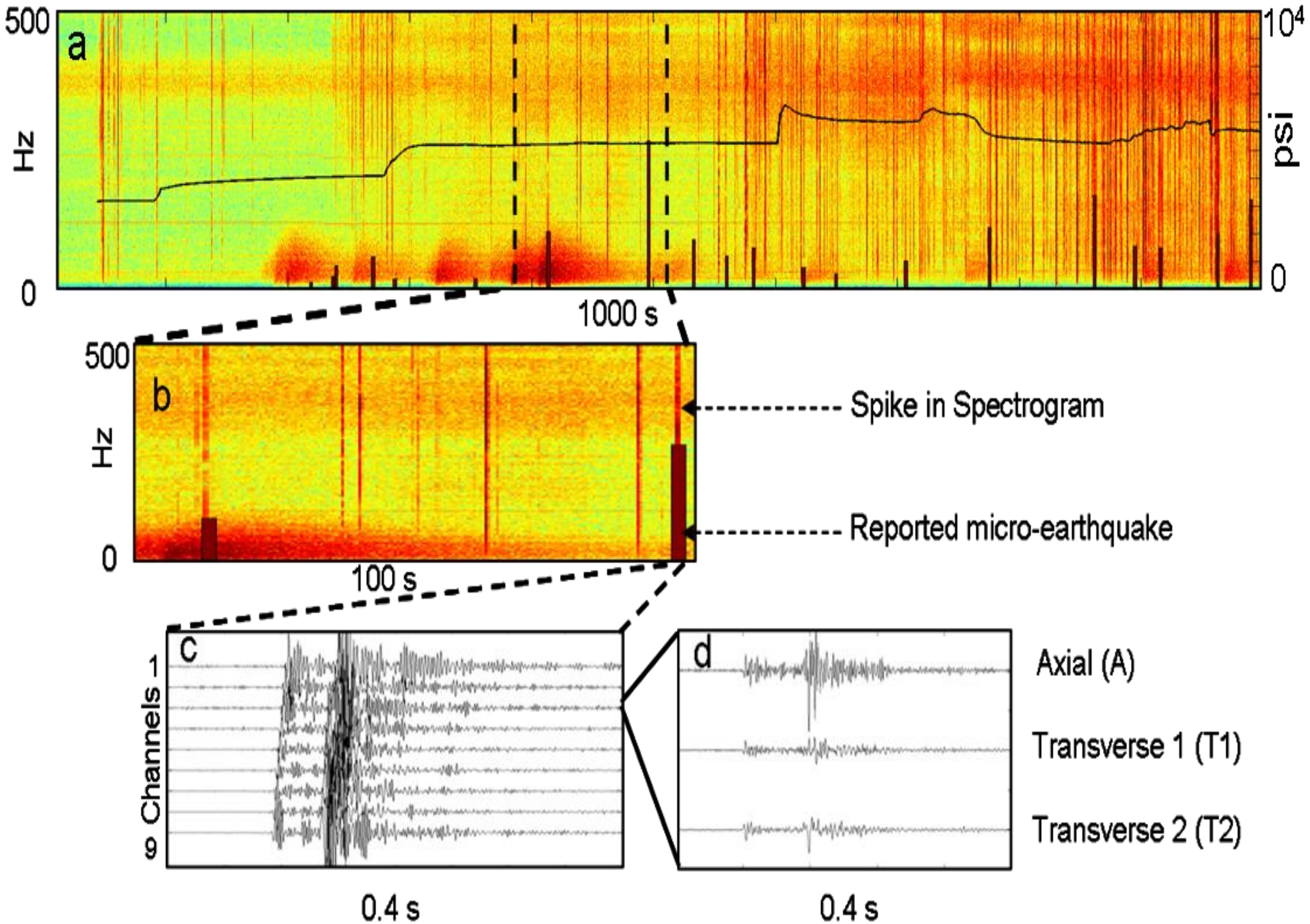
1. Managing Triggered Seismicity

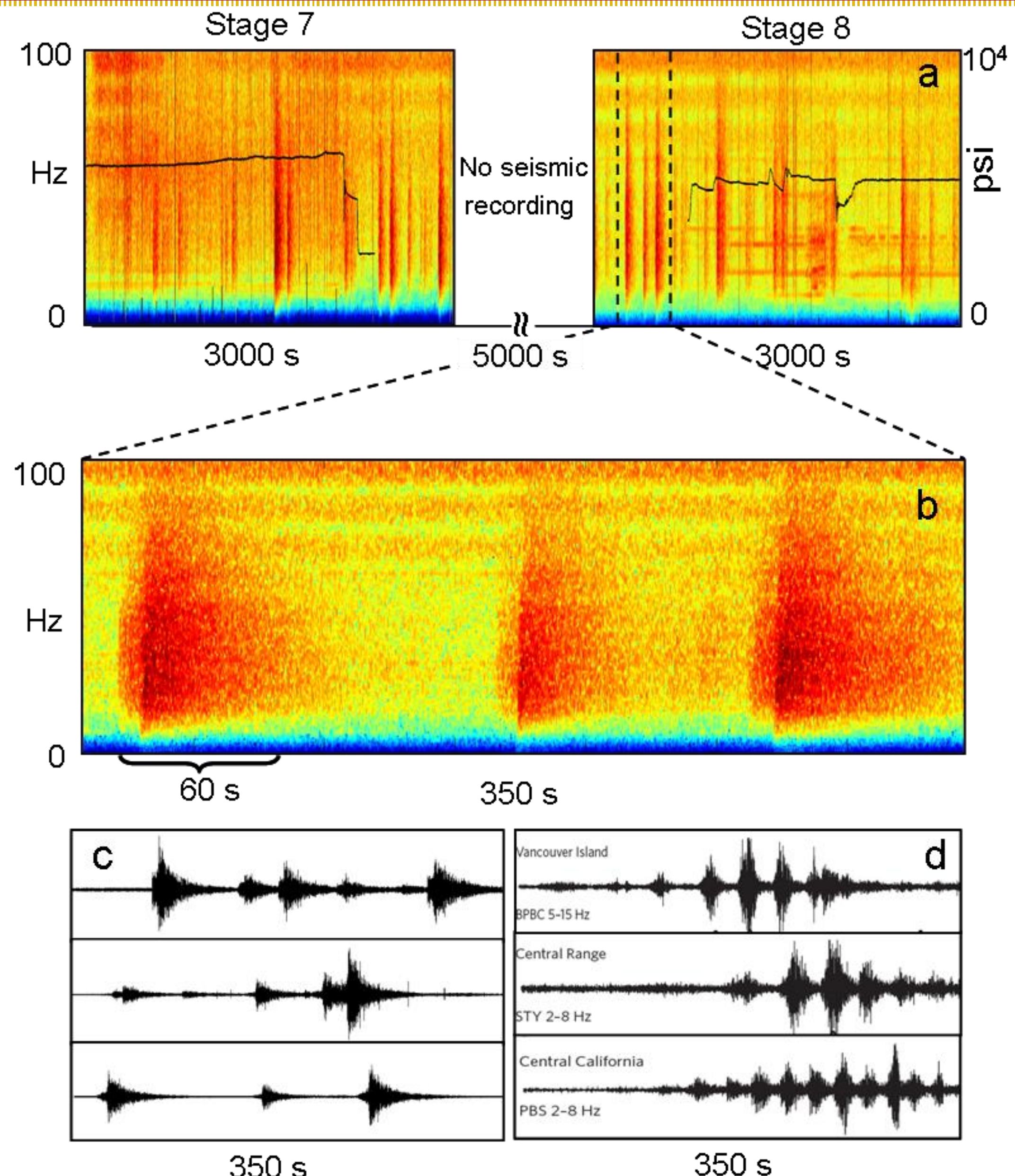
2. Minimizing the Environmental Impact Associated
   with Shale Gas Development

Typical Microearthquakes

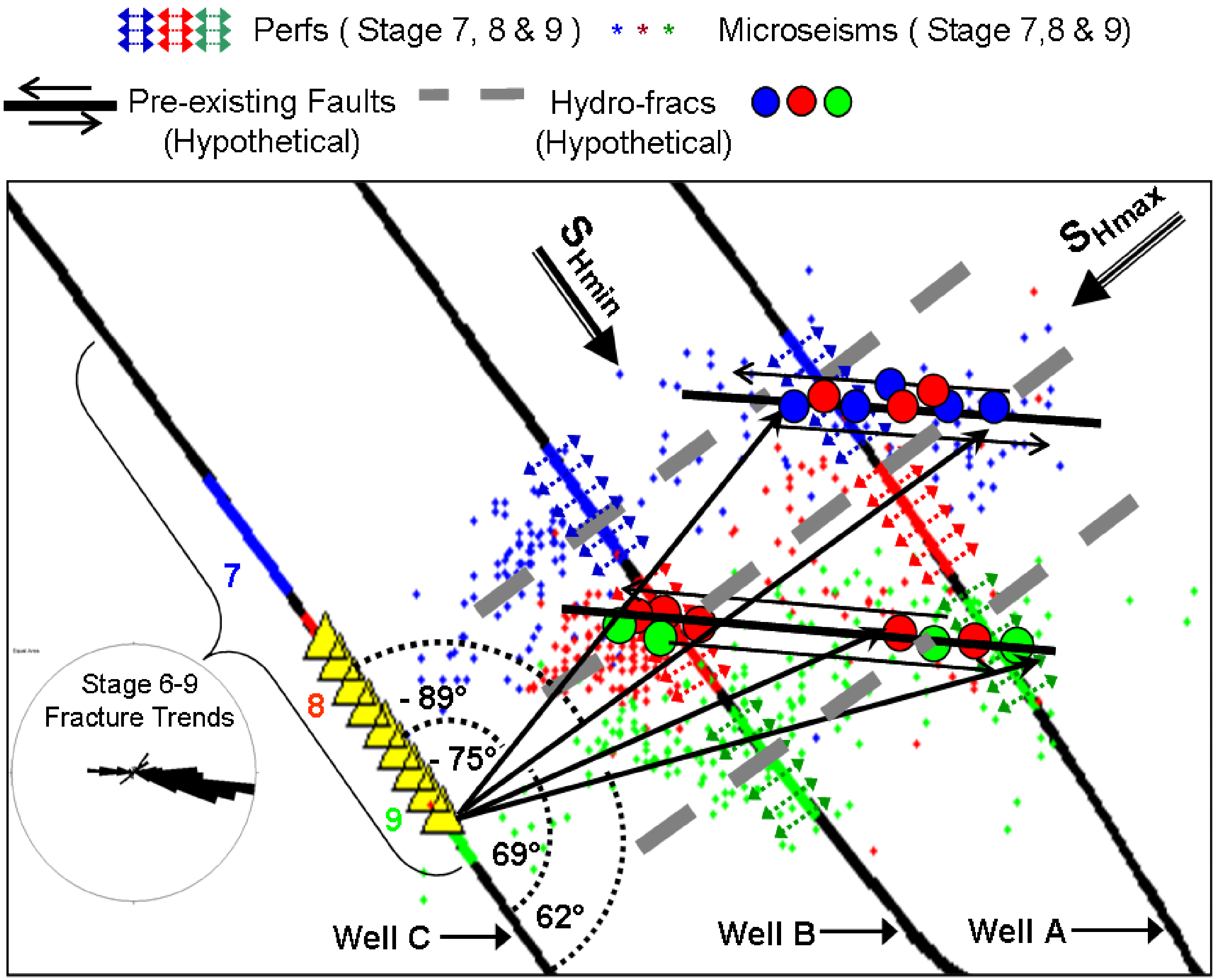


Das and Zoback, *The Leading Edge* (July 2011)

Long Period Long Duration Seismic Events

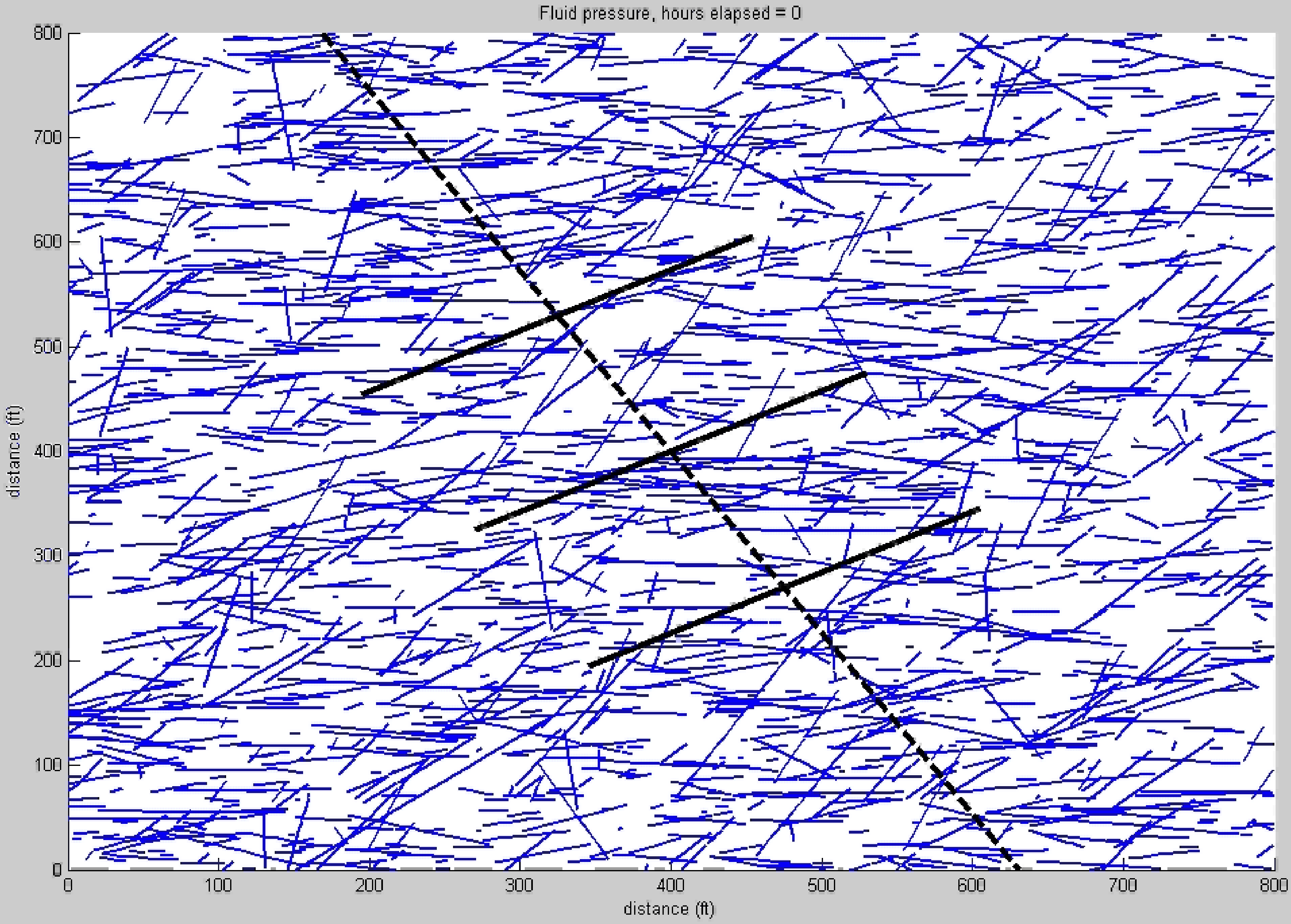


Slow Slip on Cross-Cutting Faults?

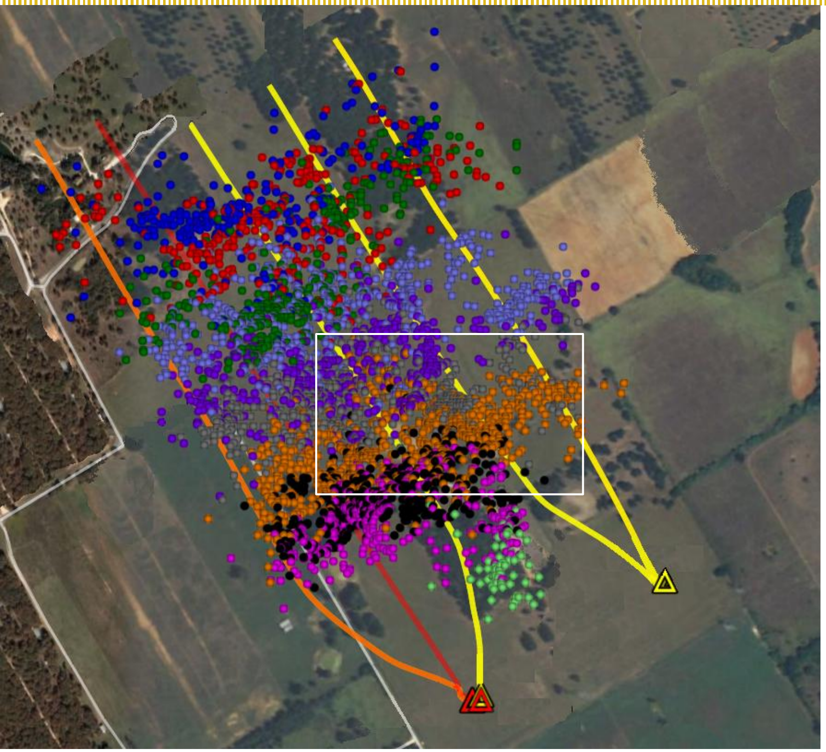


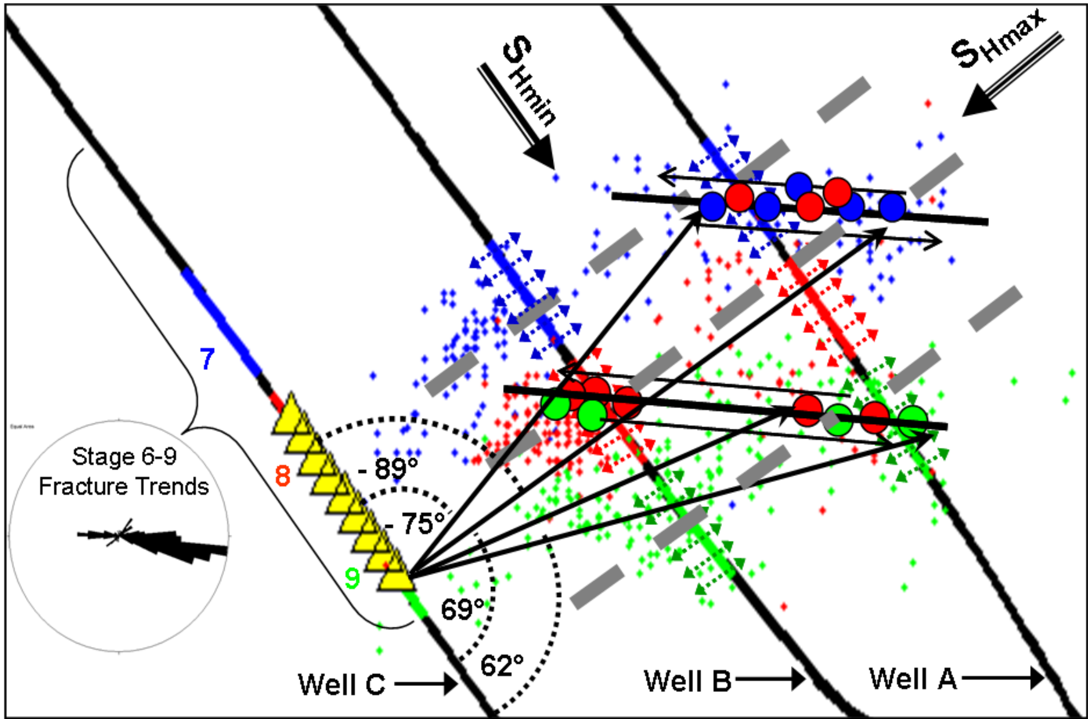
Das and Zoback, *The Leading Edge* (July 2011)

Evolution of Aseismic Slip in Reservoirs

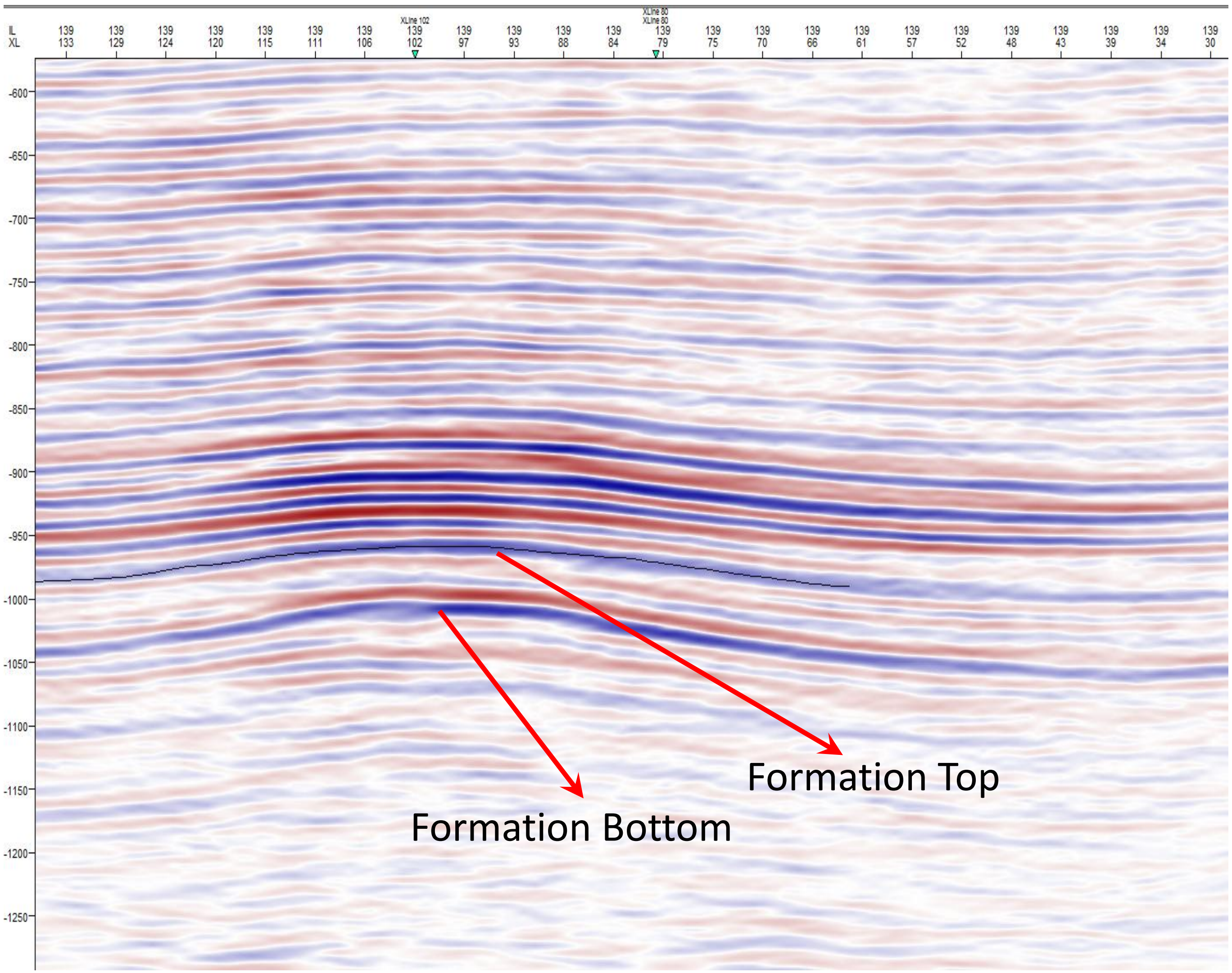


Can we Identify Optimal Areas For Reservoir Stimulation Before Drilling and Frac'ing?



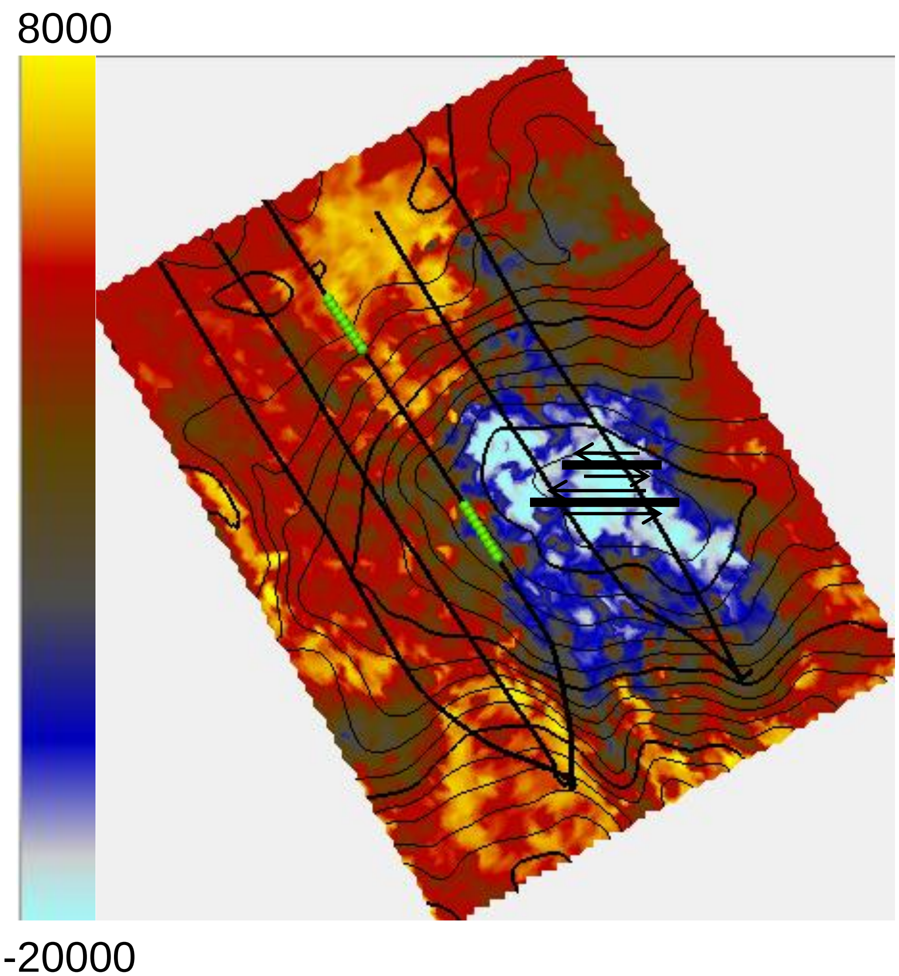


Relation of LPLD Events with Reservoir Properties

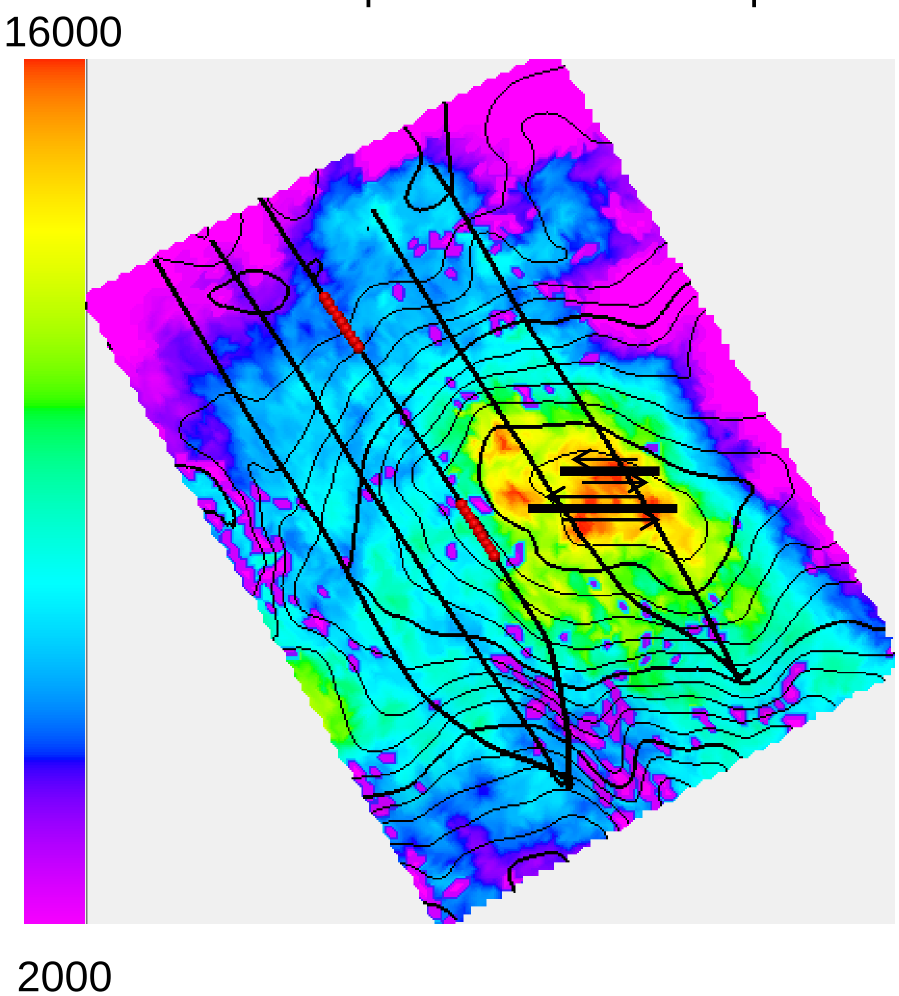


Attribute Analysis

Actual Amplitude Formation Top



RMS Amplitude Formation Top



Location of LPLD events are correlative with amplitude anomalies

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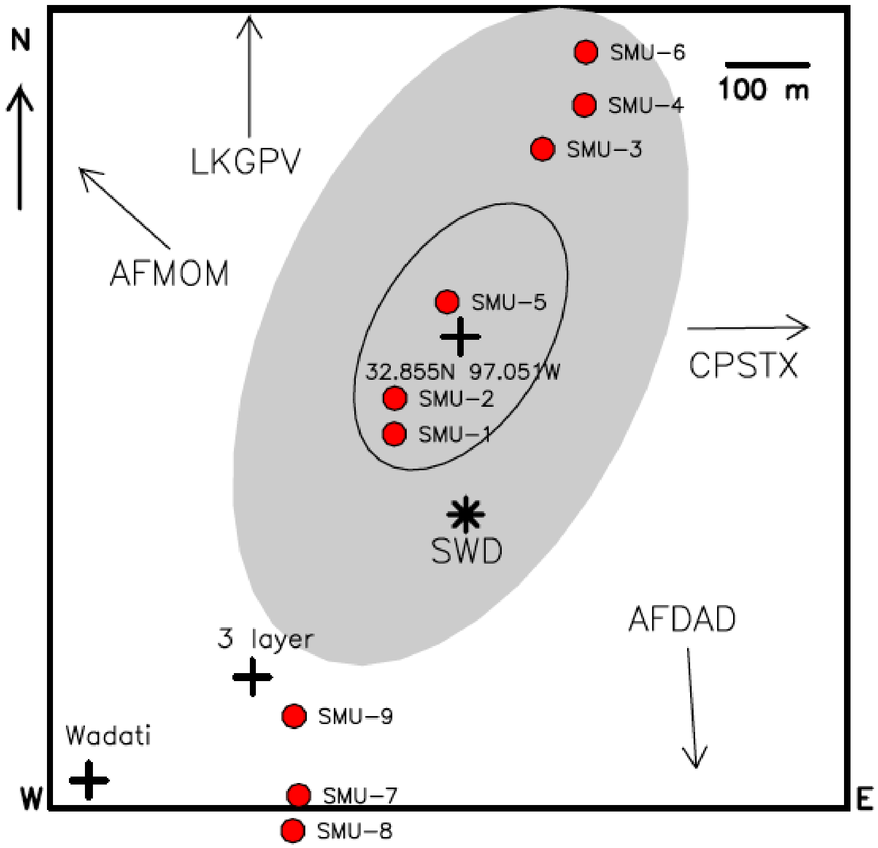
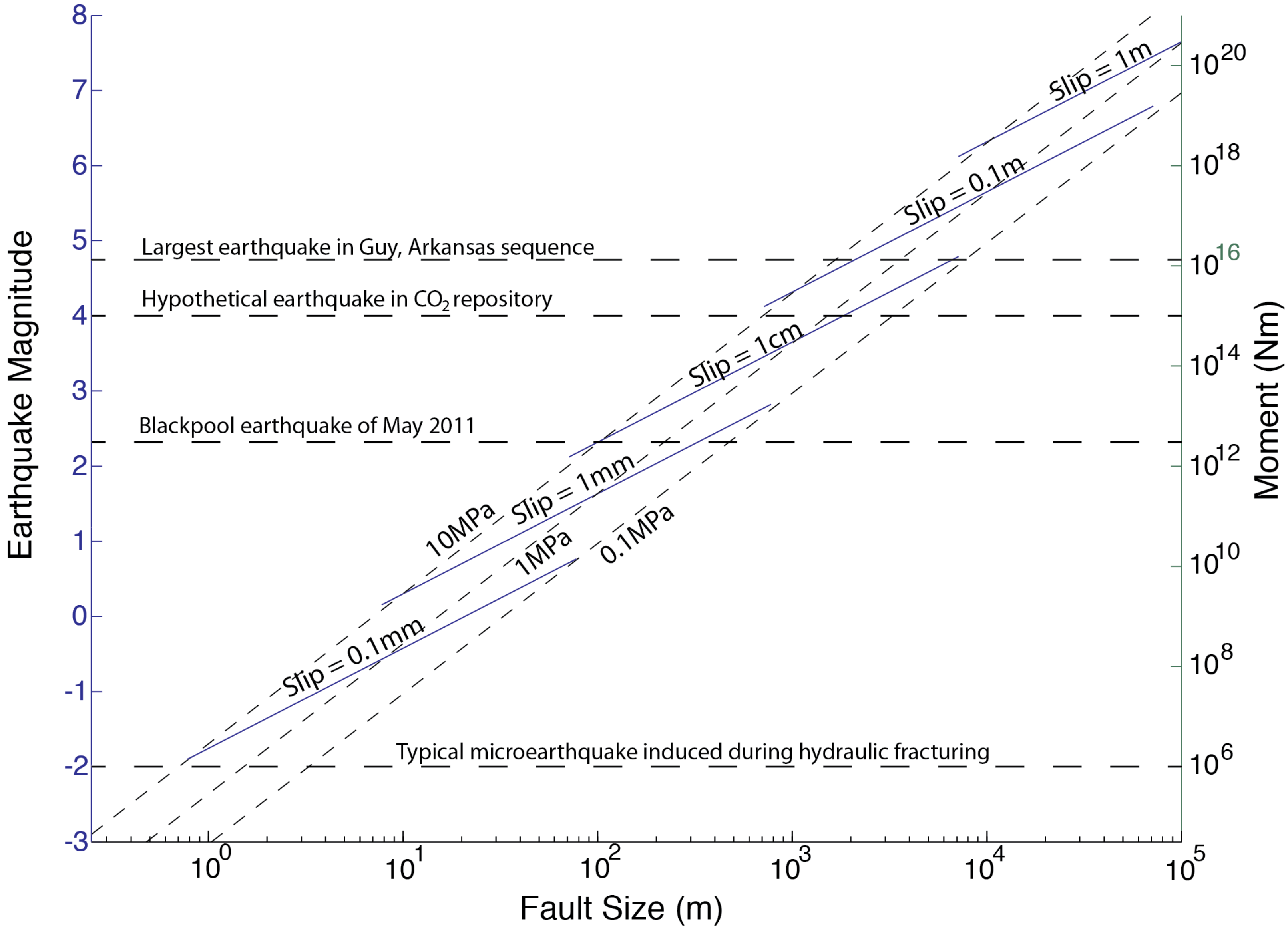
Earthquakes Triggered by Injection of Flow-Back Water After Hydraulic Fracturing

DFW – 2009   Magnitude 2.2-3.3



Frohlich et al. (2011)

Scaling Fault Slip in Earthquakes

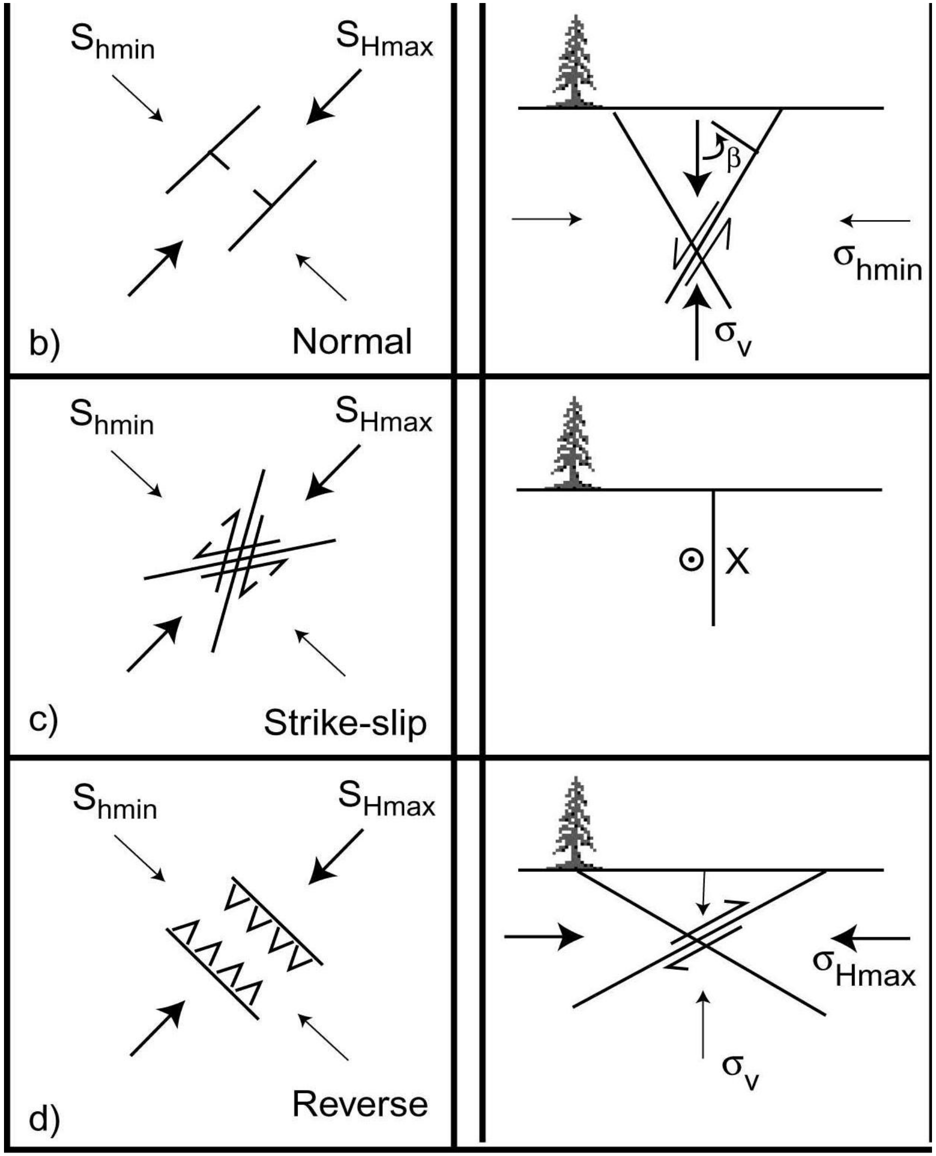


Relationship Between Stress State and Fault Slip

Normal

Strike-Slip

Reverse

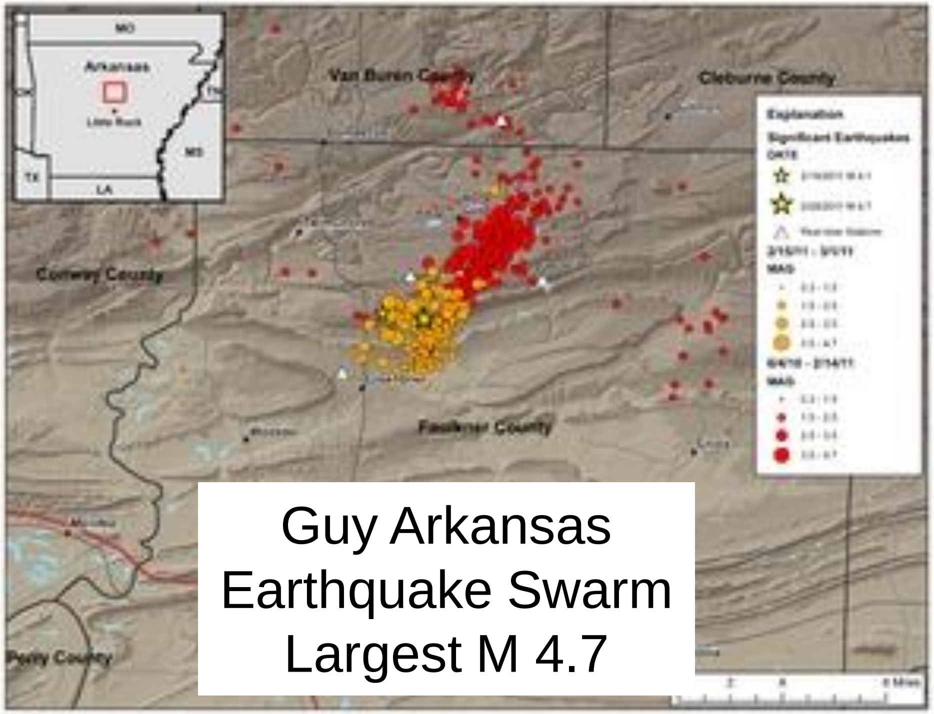


Map View Cross-section

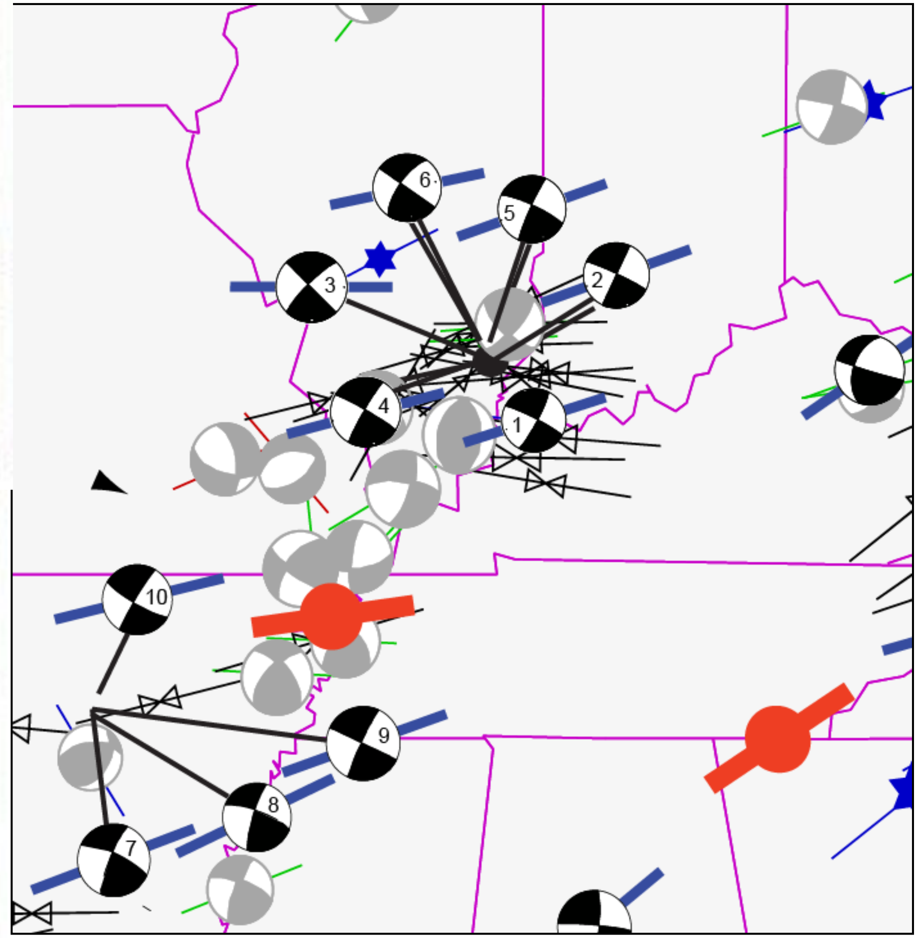
Normal faults trend parallel to S_{Hmax}

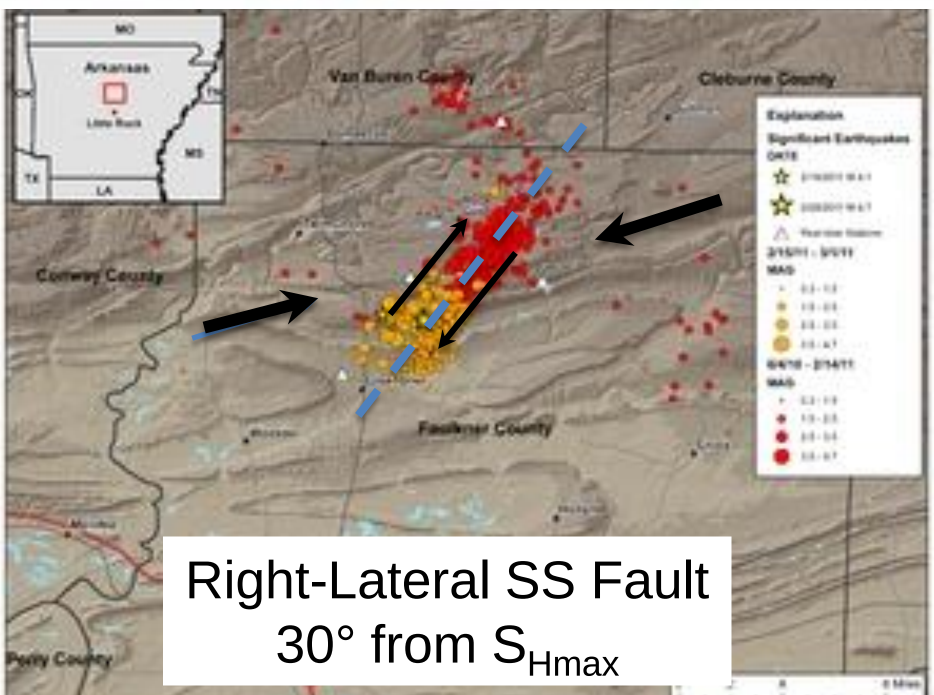
Strike-slip faults trend about ±30° from S_{Hmax}

Reverse faults trend perpendicular to S_{Hmax}



Stress Map
New Madrid Area

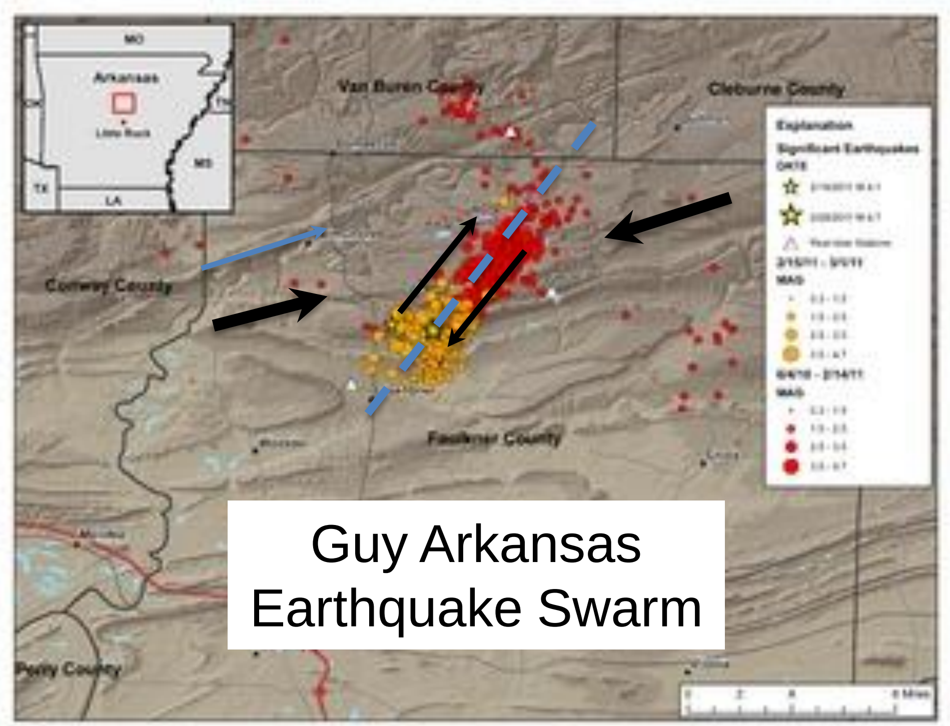




Hurd and Zoback (Submitted)

Managing the Risk Associated with Triggered Earthquakes Associated with Shale Gas Development

1. Monitor Microseismicity
2. Avoid Faults, Limit Pressure Increases
3. Be Prepared to Abandon Some Injection Wells*



or Injection Intervals*

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Secretary of Energy Advisory Board

Shale Gas Production Subcommittee 90-Day Report

August 18, 2011

U.S. DEPARTMENT OF ENERGY

http://www.shalegas.energy.gov/

SEAB Sub-Committee Charge

Secretary Chu Tasks Environmental, Industry and State Leaders to Recommend Best Practices for Safe, Responsible Development of America's Onshore Natural Gas Resources

President Obama directed Secretary Chu to convene this group as part of the President's "Blueprint for a Secure Energy Future"

"**Setting the Bar for Safety and Responsibility:** To provide recommendations from a range of independent experts, the Secretary of Energy, in consultation with the EPA Administrator and Secretary of Interior, should task the Secretary of Energy Advisory Board (SEAB) with establishing a subcommittee to examine fracking issues. The subcommittee will be supported by DOE, EPA and DOI, and its membership will extend beyond SEAB members to include leaders from industry, the environmental community, and states. The subcommittee will work to identify, within 90 days, any immediate steps that can be taken to improve the safety and environmental performance of fracking and to develop, within six months, consensus recommended advice to the agencies on practices for shale extraction to ensure the protection of public health and the environment."

DOE Shale Gas Subcommittee

- John Deutch – MIT
- Stephen Holditch – Texas A&M
- Fred Krupp – Environmental Defense Fund
- Katie McGinty – Pennsylvania DEP
- Sue Tierney – Massachusetts Energy
- Dan Yergin – Cambridge Energy Research
- Mark Zoback - Stanford

90 Day Report Summary

- Shale gas is extremely important to the energy security of the United States
- Shale gas currently accounts for 30% of the total US natural gas production
- Shale gas development has a large positive economic impact on local communities and states
- Shale gas development creates jobs
- Shale gas can be developed in an environmentally responsible manner.

90 Day Report Summary

- Improve public information about shale gas operations: Create a portal for access to a wide range of public information on shale gas development, to include current data available from state and federal regulatory agencies. The portal should be open to the public for use to study and analyze shale gas operations and results.

http://www.shalegas.energy.gov/

90 Day Report Summary

- Improve communication among state and federal regulators: Provide continuing annual support to STRONGER (the State Review of Oil and Natural Gas Environmental Regulation) and to the Ground Water Protection Council for expansion of the *Risk Based Data Management System* and similar projects that can be extended to all phases of shale gas development.

http://www.shalegas.energy.gov/

90 Day Report Summary

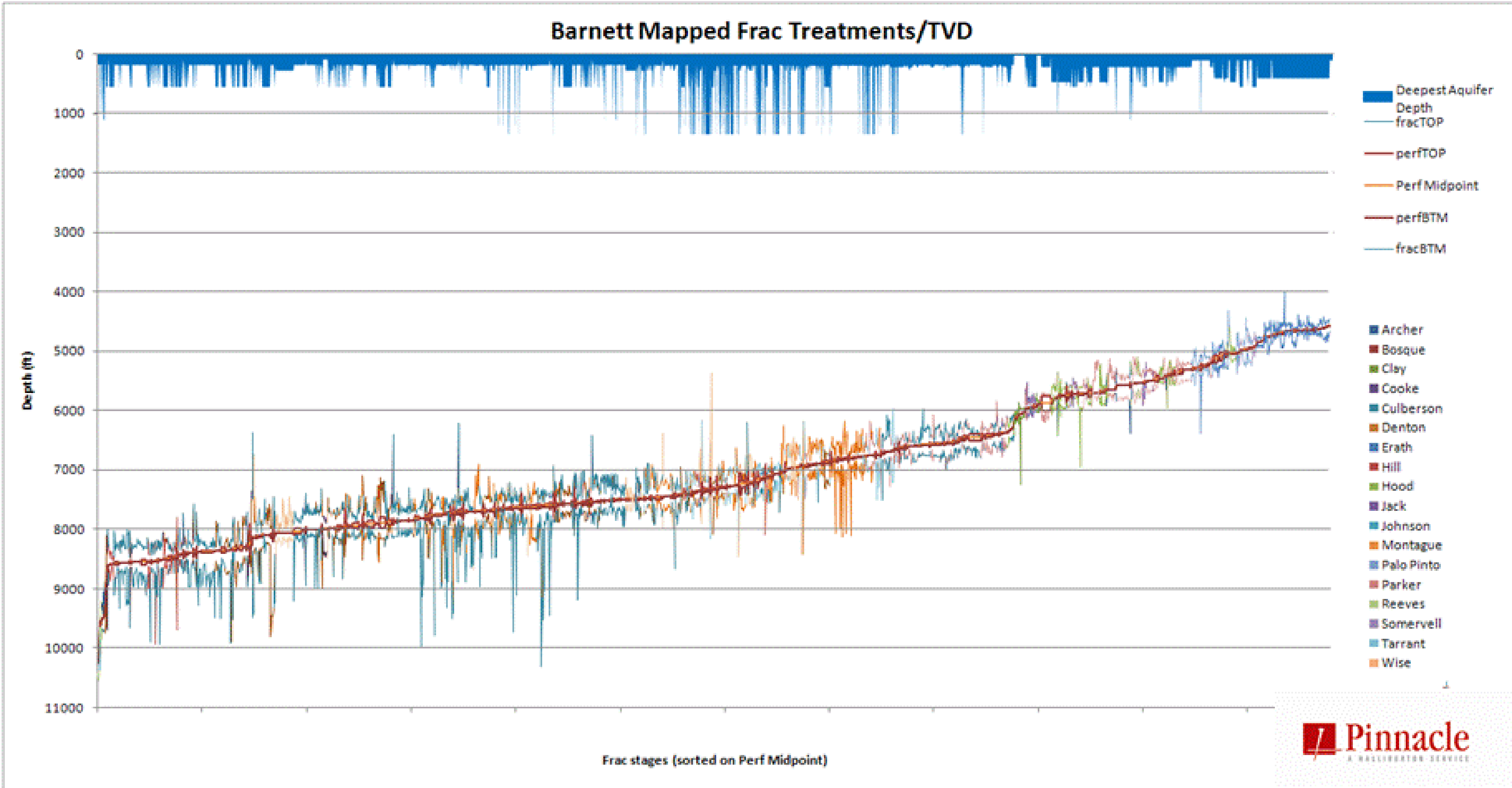
- Improve air quality: Measures should be taken to reduce emissions of air pollutants, ozone precursors, and methane as quickly as practicable. The Subcommittee supports adoption of rigorous standards for new and existing sources of methane, air toxics, ozone precursors and other air pollutants from shale gas operations.

90 Day Report Summary

- Protection of water quality: The Subcommittee urges adoption of a systems disclosure of the flow and composition of water at every stage of the shale gas production process.

Will Vertical Hydrofrac Growth Affect Water Supplies?

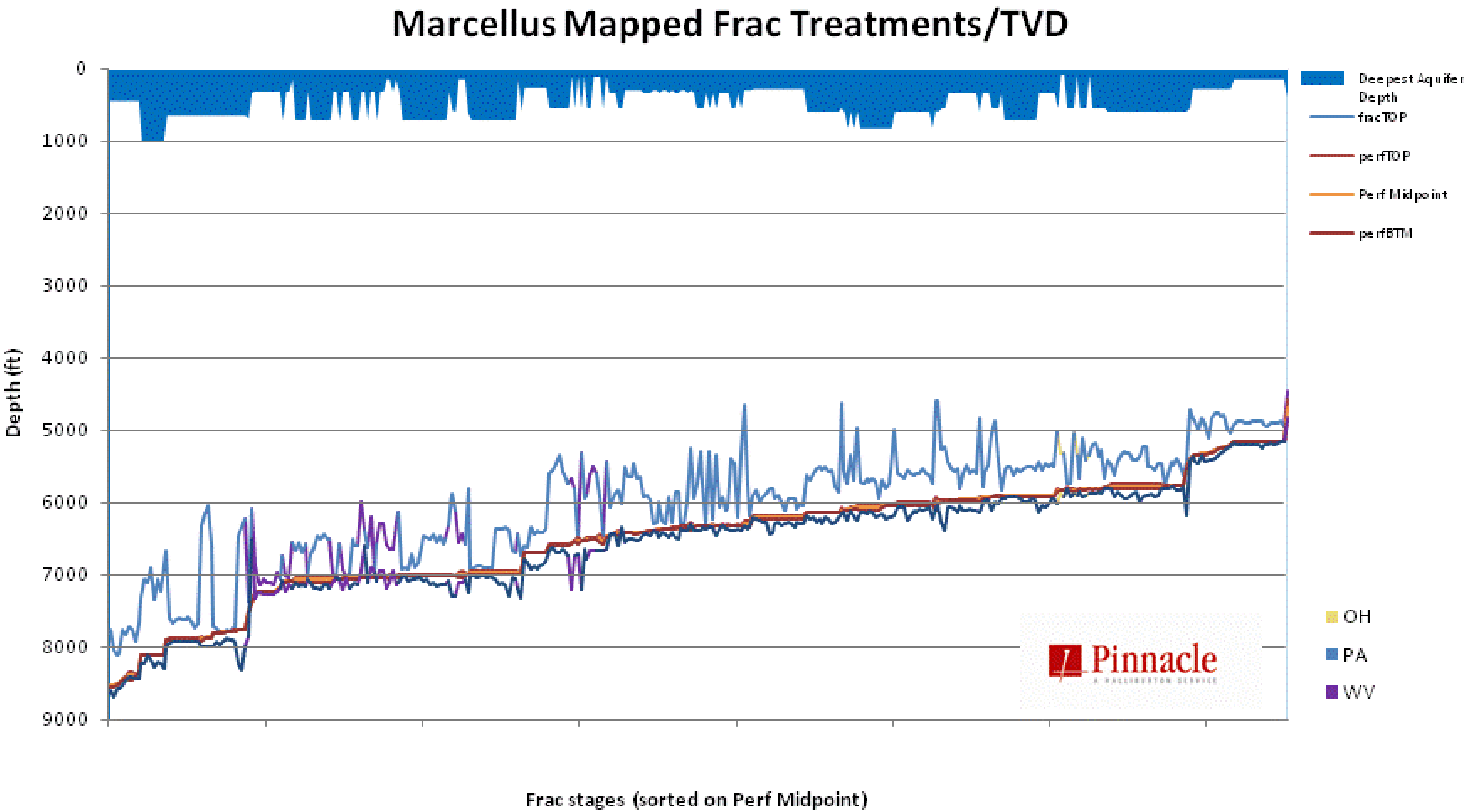
Depth of Affected Region Affected by Hydraulic Fracturing



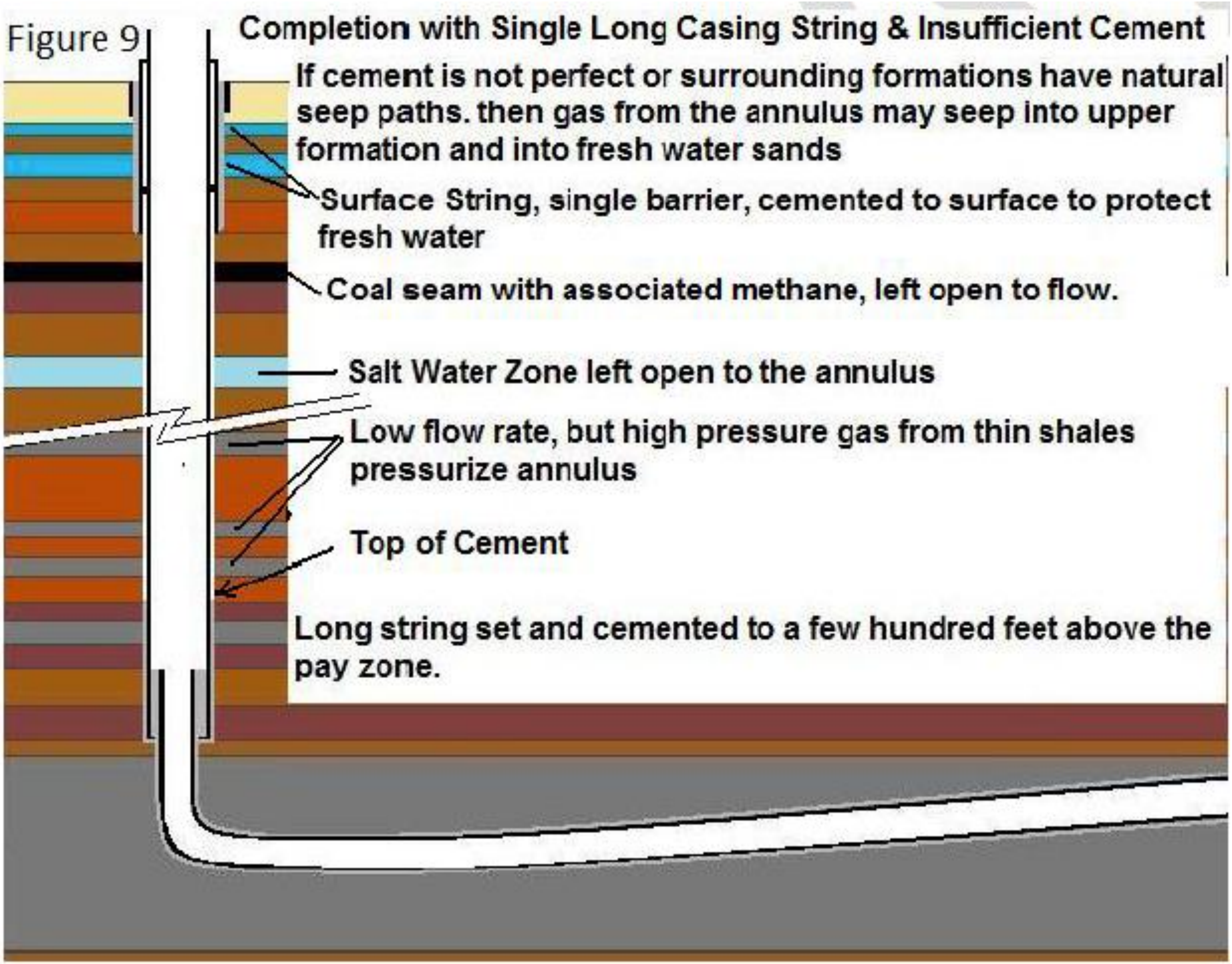
Fisher (2010)

http://nwis.waterdata.usgs.gov/nwis/inventory

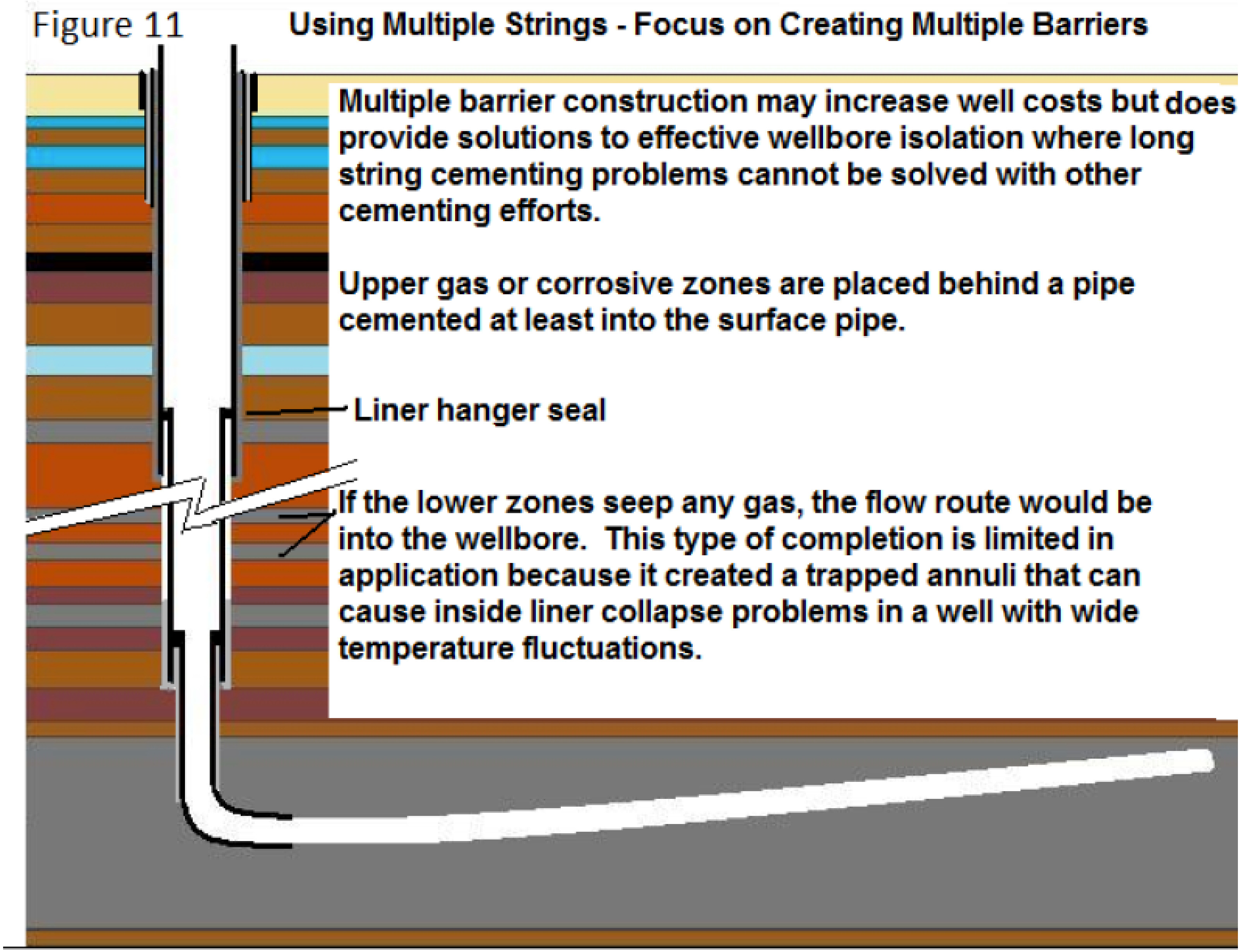
Depth of Affected Region Affected by Hydraulic Fracturing



Fisher (2010) http://nwis.waterdata.usgs.gov/nwis/inventory



Courtesy George King, Apache Corp.



Courtesy George King, Apache Corp.

90 Day Report Summary

- Disclosure of fracturing fluid composition: The Subcommittee shares the prevailing view that the risk of fracturing fluid leakage into drinking water sources through fractures made in deep shale reservoirs is remote. Nevertheless the Subcommittee believes there is no economic or technical reason to prevent public disclosure of all chemicals in fracturing fluids...

http://www.shalegas.energy.gov/

Water Issues Changing Rapidly

Water Issues Changing Rapidly

Figure 13. The Apache 34 pad in the Horn River Development of Northern British Colombia is a total of 6.3 acres where twelve multiple fractured horizontal wells recover gas from approximately 5000 acres.

Courtesy George King, Apache Corp.

90 Day Report Summary

- Reduction in the use of diesel fuel: The Subcommittee believes there is no technical or economic reason to use diesel in shale gas production and recommends reducing the use of diesel engines for surface power in favor of natural gas engines or electricity where available.

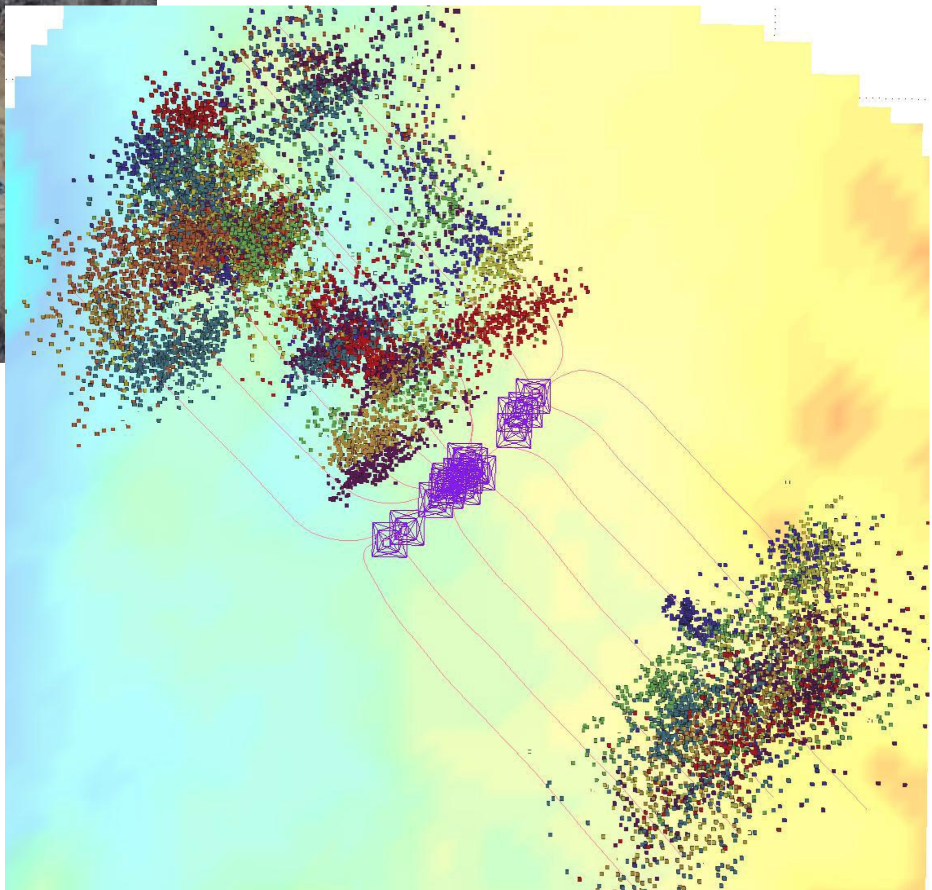
http://www.shalegas.energy.gov/

90 Day Report Summary

- Managing short-term and cumulative impacts on communities, land use, wildlife, and ecologies. Each relevant jurisdiction should pay greater attention to the combination of impacts from multiple drilling, production and delivery activities (e.g., impacts on air quality, traffic on roads, noise, visual pollution), and make efforts to plan for shale development impacts on a regional scale. Possible mechanisms include:

http://www.shalegas.energy.gov/

Pad Drilling is a Major Advance



Pad Drilling is a Major Advance

90 Day Report Summary

- Organizing for best practice: The Subcommittee believes the creation of a shale gas industry production organization dedicated to continuous improvement of best practice, defined as improvements in techniques and methods that rely on measurement and field experience, is needed to improve operational and environmental outcomes. The Subcommittee favors a national approach including regional mechanisms that recognize differences in geology, land use, water resources, and regulation.

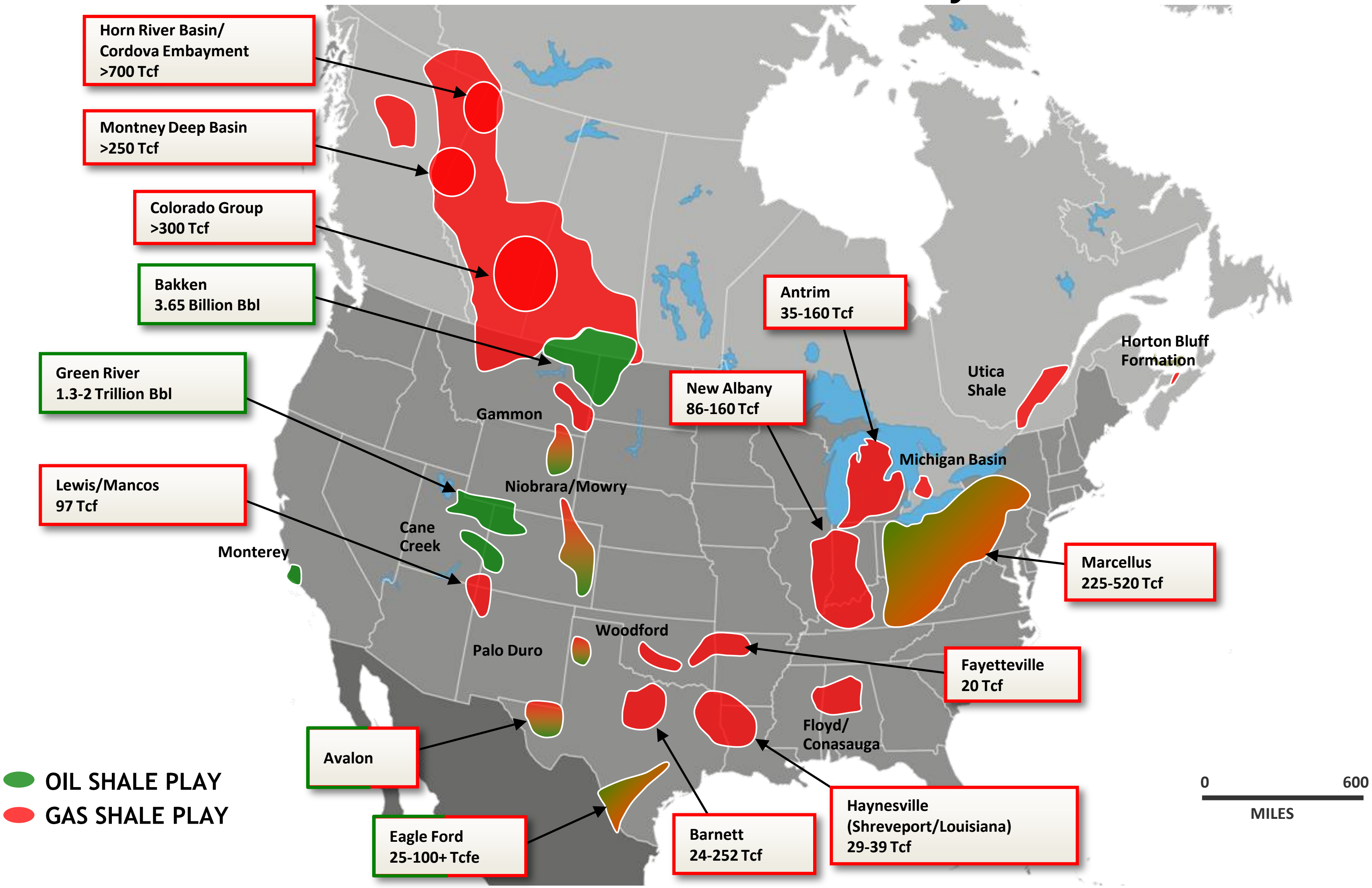
http://www.shalegas.energy.gov/

90 Day Report Summary

- Research and Development needs. The public should expect significant technical advances associated with shale gas production that will significantly improve the efficiency of shale gas production and that will reduce environmental impact.

http://www.shalegas.energy.gov/

The Next 5-10 Years
~100,000 Wells, 1-2 Million Hydrofracs



- Will We Optimize Resource Development?
- Will We Minimize the Environmental Impact?


TIME
ENVIRONMENT SPECIAL
THIS ROCK COULD POWER THE WORLD
WHY SHALE CAN SOLVE THE ENERGY CRISIS
BY BRYAN WALSH
A century's worth is buried in our backyards …
… but drilling for it threatens our land

But we still have a lot of work to do!