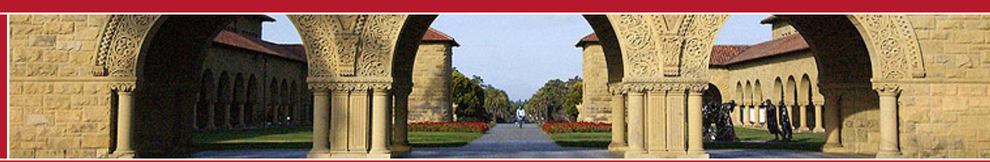
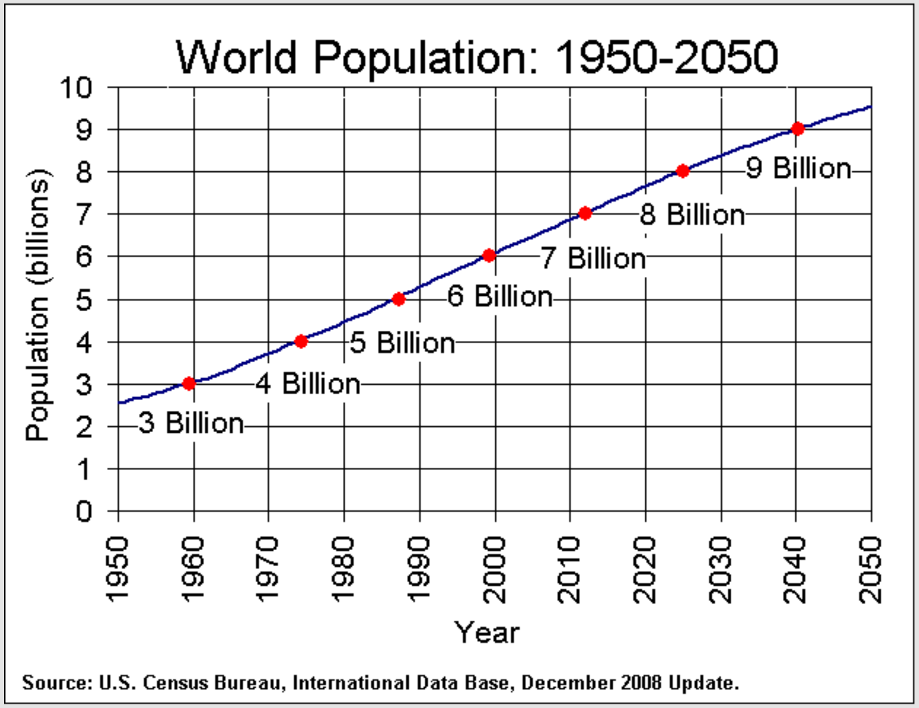
Producing Natural Gas from Shale – Opportunities and Challenges of a Major New Energy Source

Mark D. Zoback
Professor of Geophysics
Stanford University



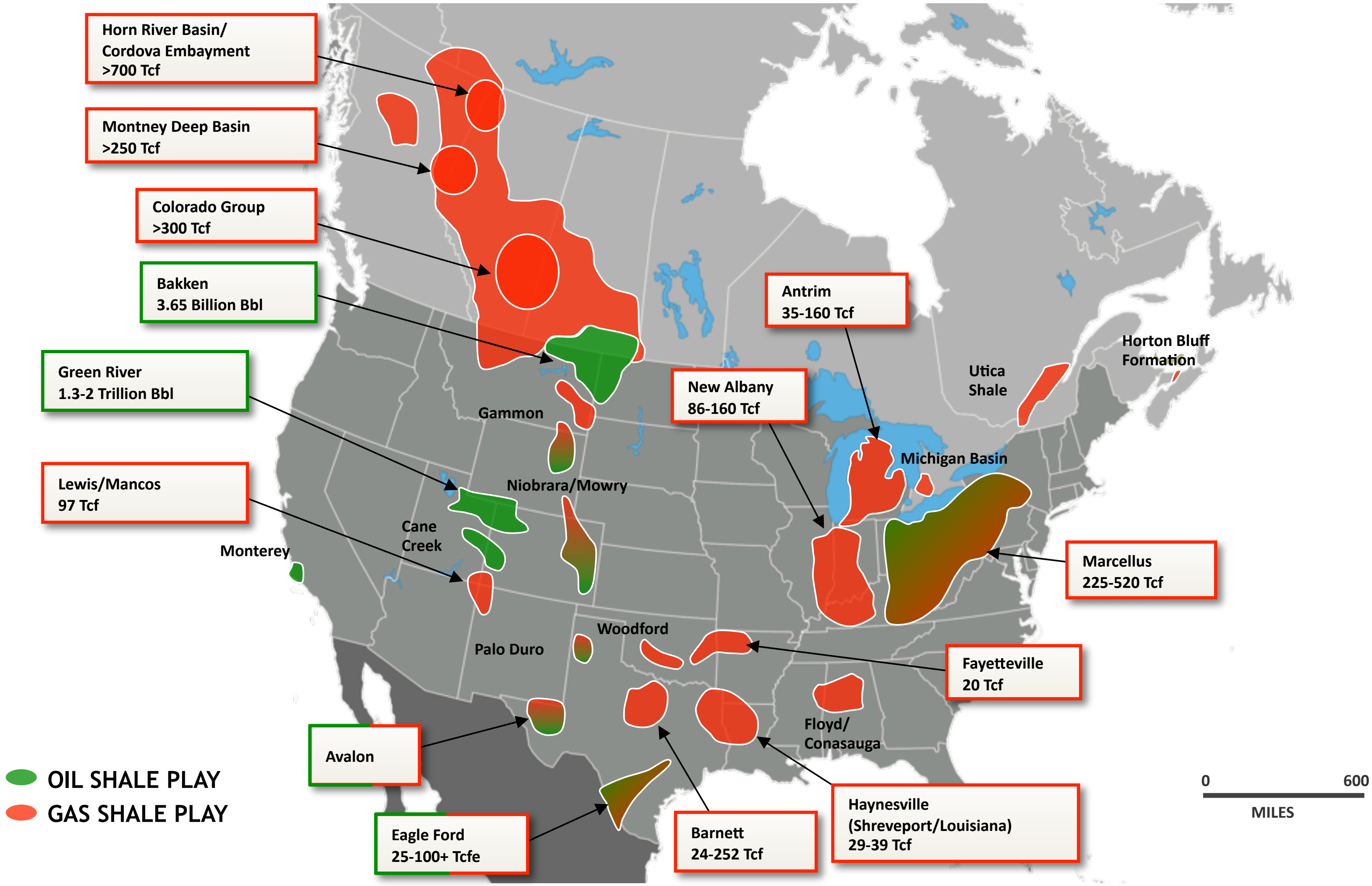
STANFORD UNIVERSITY

Global Energy and Environment Challenge



How Do We Provide Accessible, Affordable, and Secure Energy While Protecting the Planet (2x by 2050, 3-4x by 2100)?

Opportunity: North American Shale Plays



~2300 TCF (85% Shale Gas)

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

Air Pollution and Energy Source*

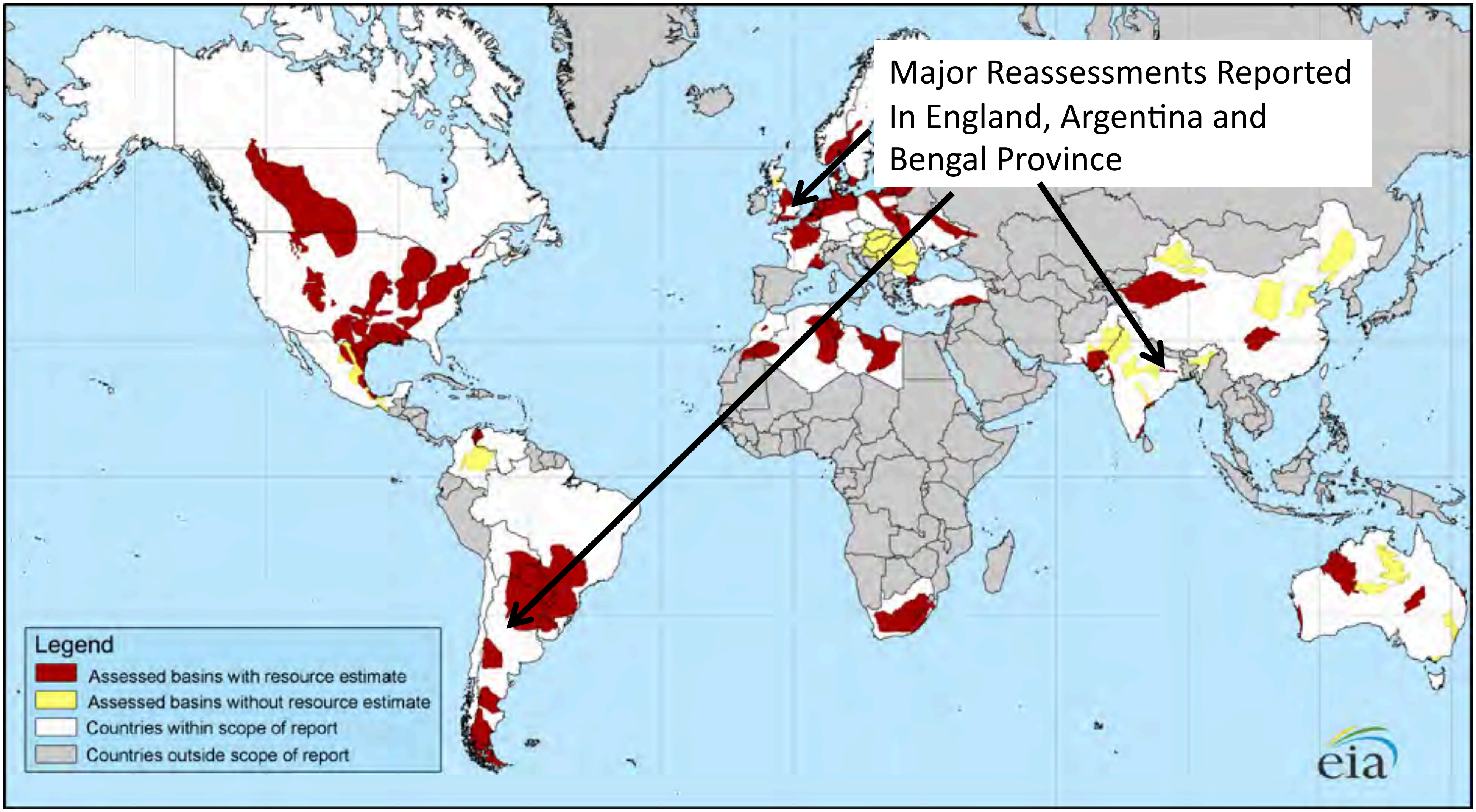
	CH_4	Oil	Coal
CO_2	117,000	164,000	208,000
CO	40	33	208
NO_x	92	448	457
SO_2	0.6	1,122	2,591
Particulates	7.0	84	2,744
Formaldehyde	0.75	0.22	0.221
Mercury	0	0.007	0.016

*Pounds/Billion BTU

EIA, 1998

GCEP Global Climate & Energy Project

Opportunity: Global Shale Plays



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

Earth, Feb. 2010

A COMMENT

NATURAL GAS CAN LEAD THE WAY

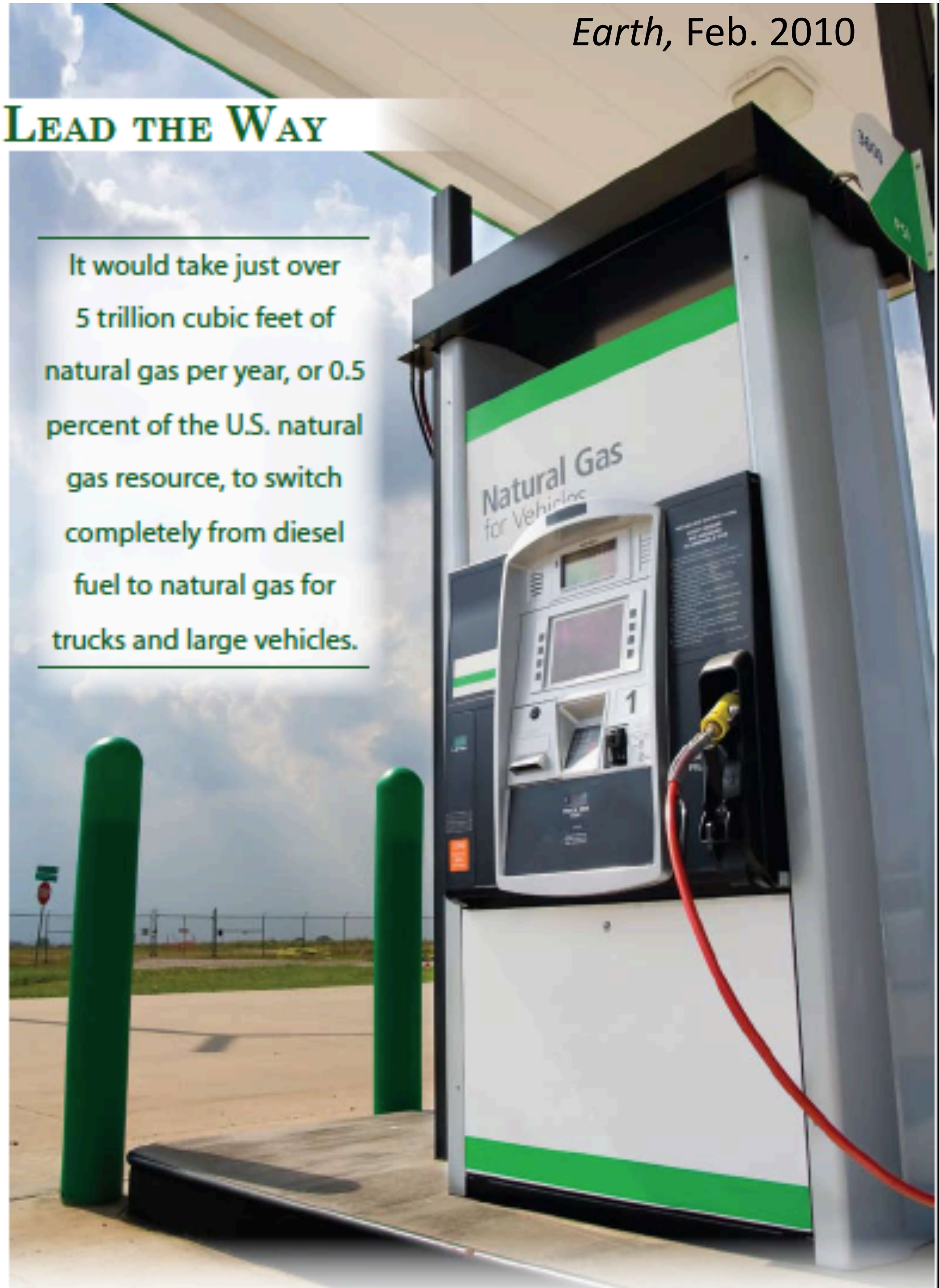
Mark Zoback

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 than 2,000 trillion cubic feet (TCF), largely

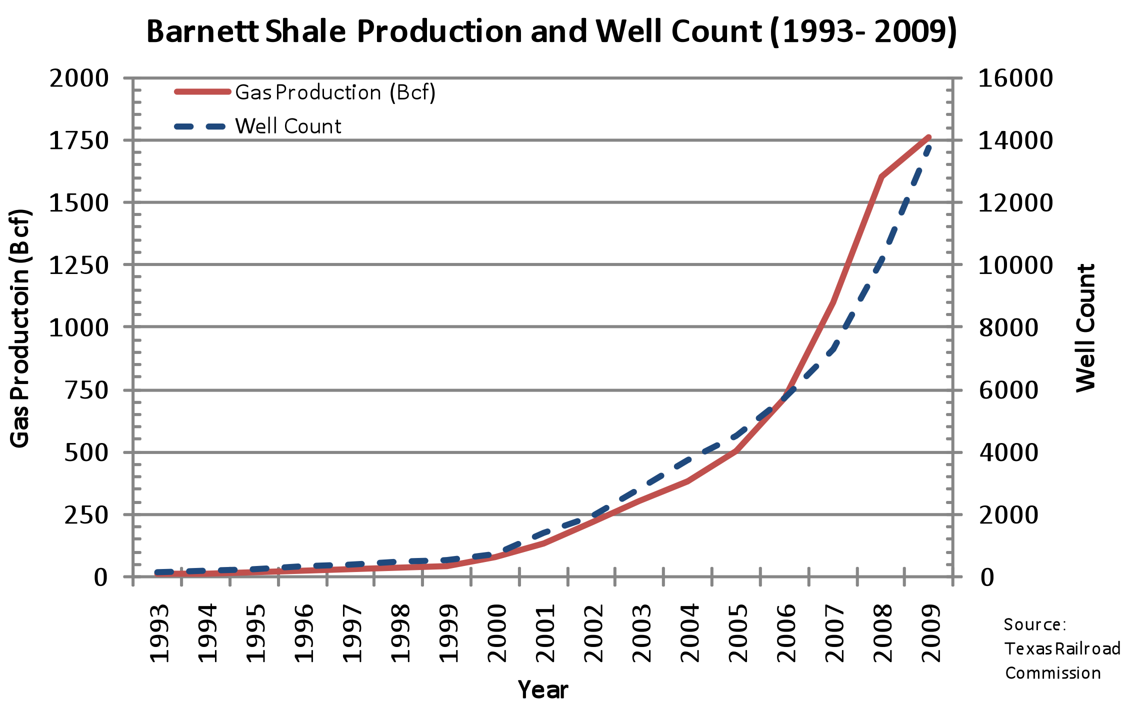
> It would take just over 5 trillion cubic feet of natural gas per year, or 0.5 percent of the U.S. natural gas resource, to switch completely from diesel fuel to natural gas for trucks and large vehicles.



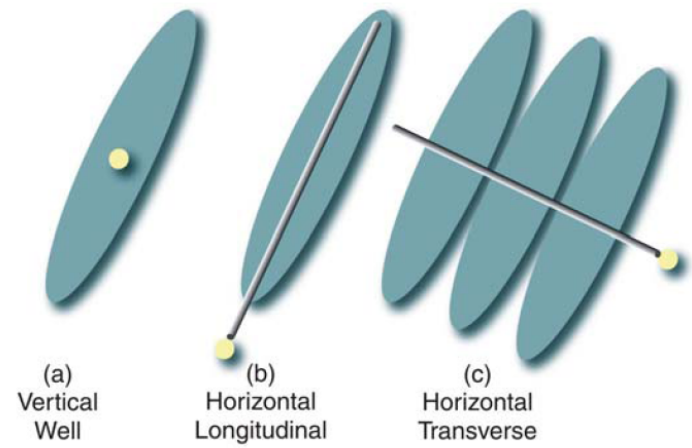
negating the two historical advantages

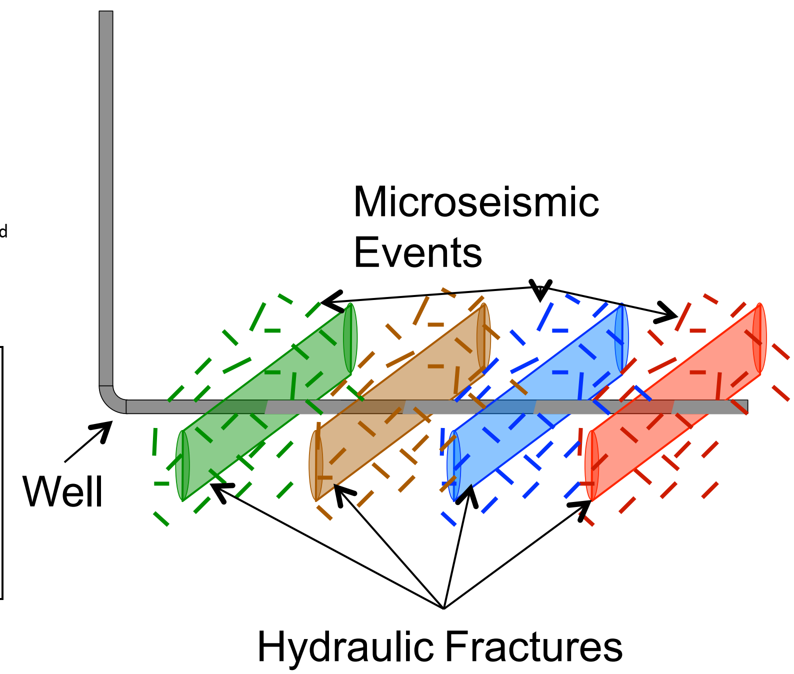
to gas to achieve the desired degree of

Drilling/Completion Technology
Key To Exploitation of Shale Gas



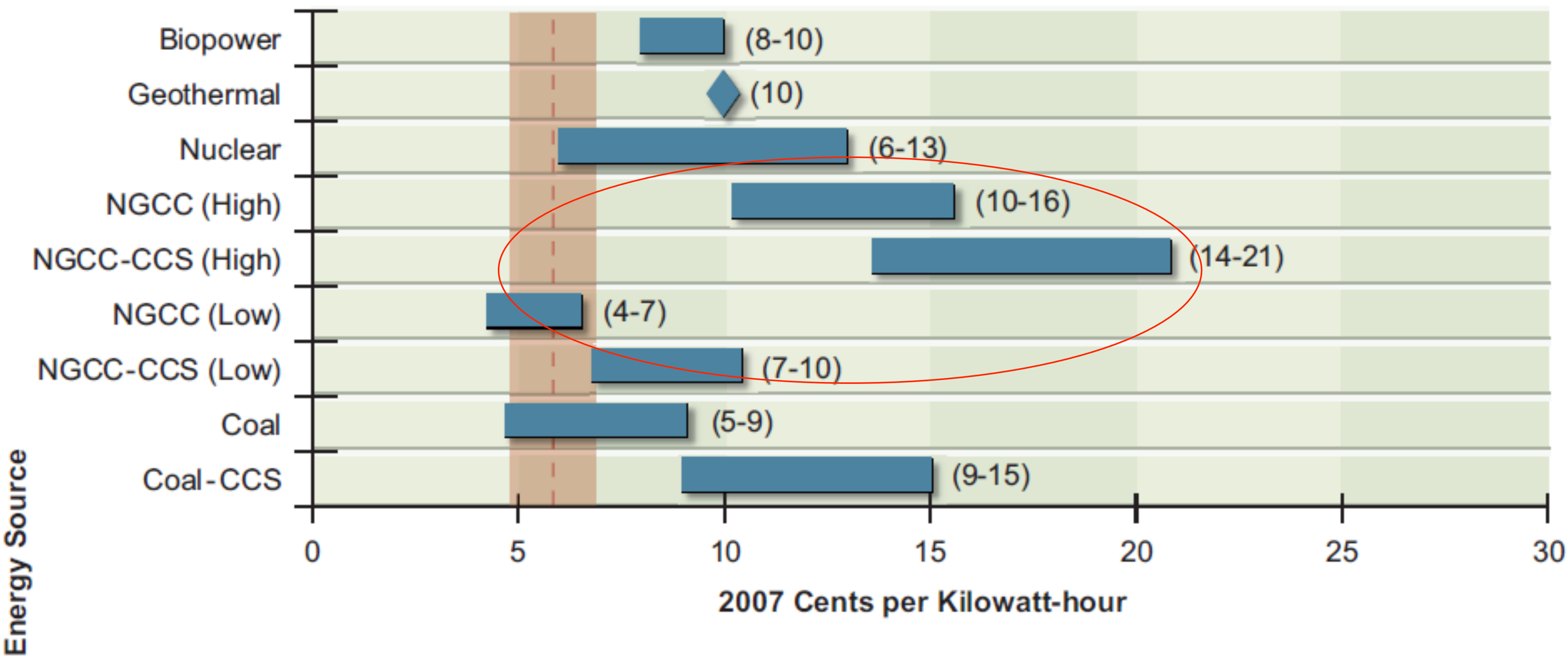
Source: Texas Railroad Commission





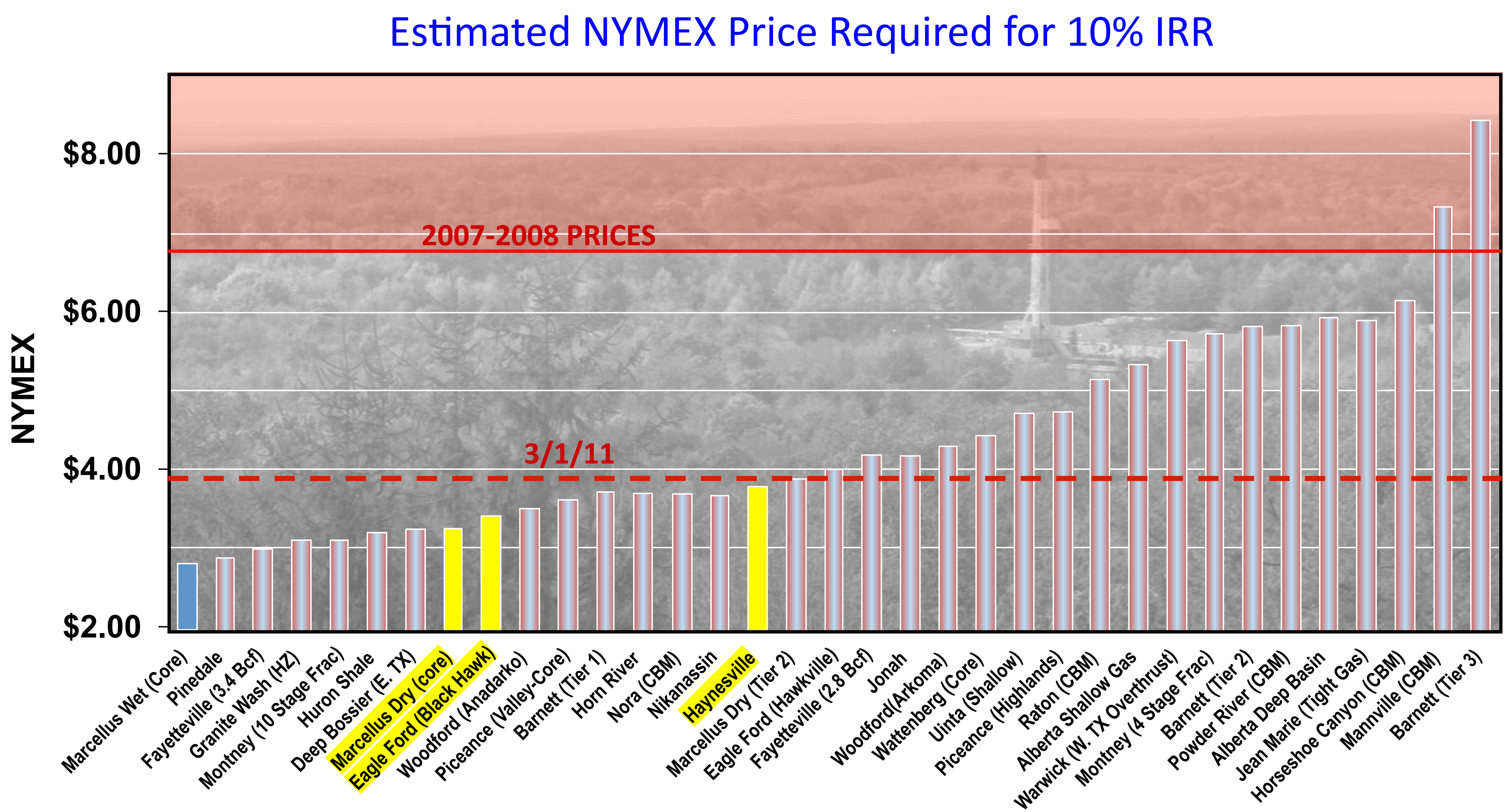
Horizontal Drilling and Multi-Stage
Slick-Water Hydraulic Fracturing
Induces Microearthquakes (M ~ -1 to M~ -3)
To Create a Permeable Fracture Network

Gas And Coal Economics



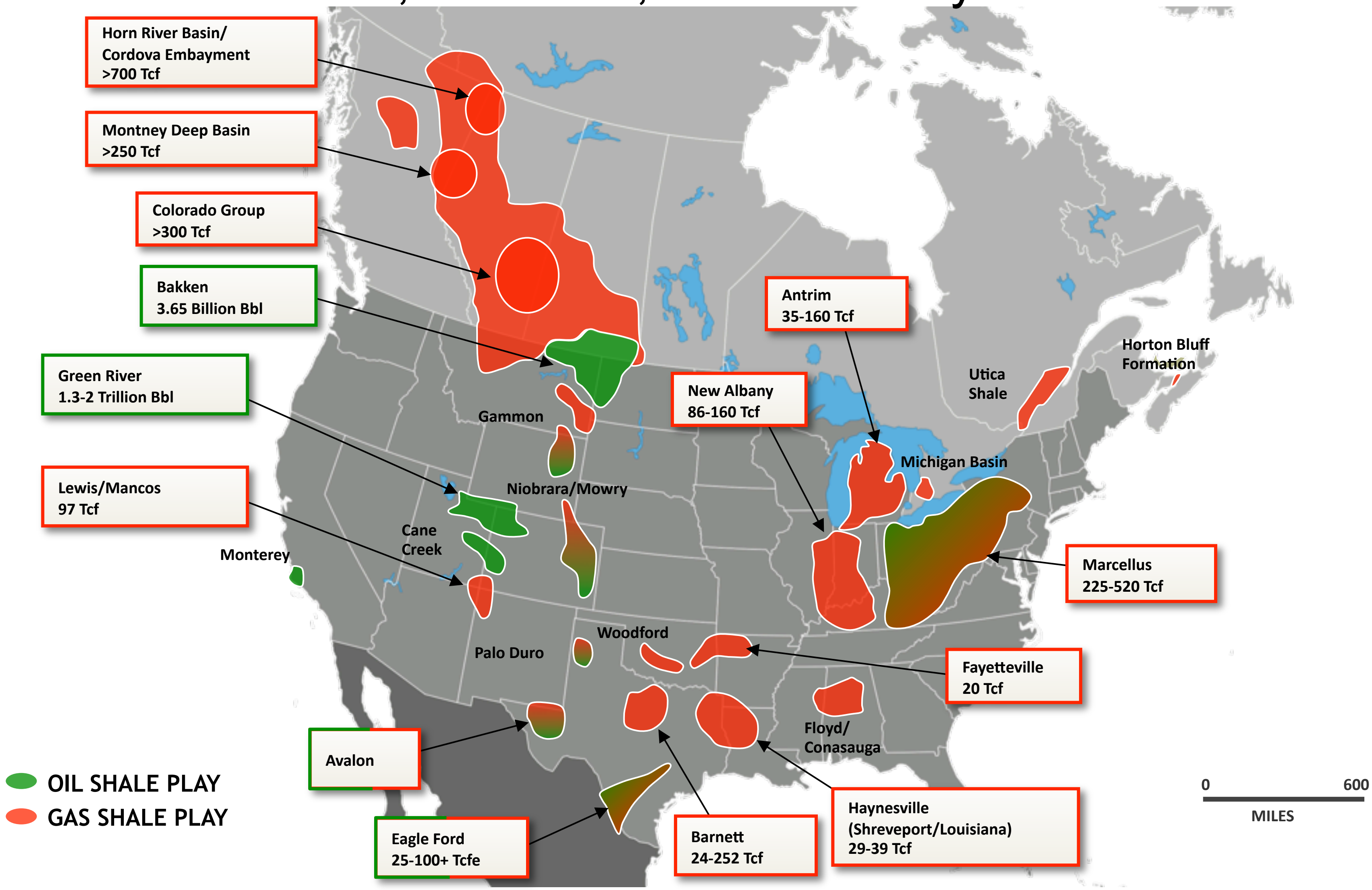
(from *America's Energy Future*) NAS - 2009

The Challenges of $4 Gas



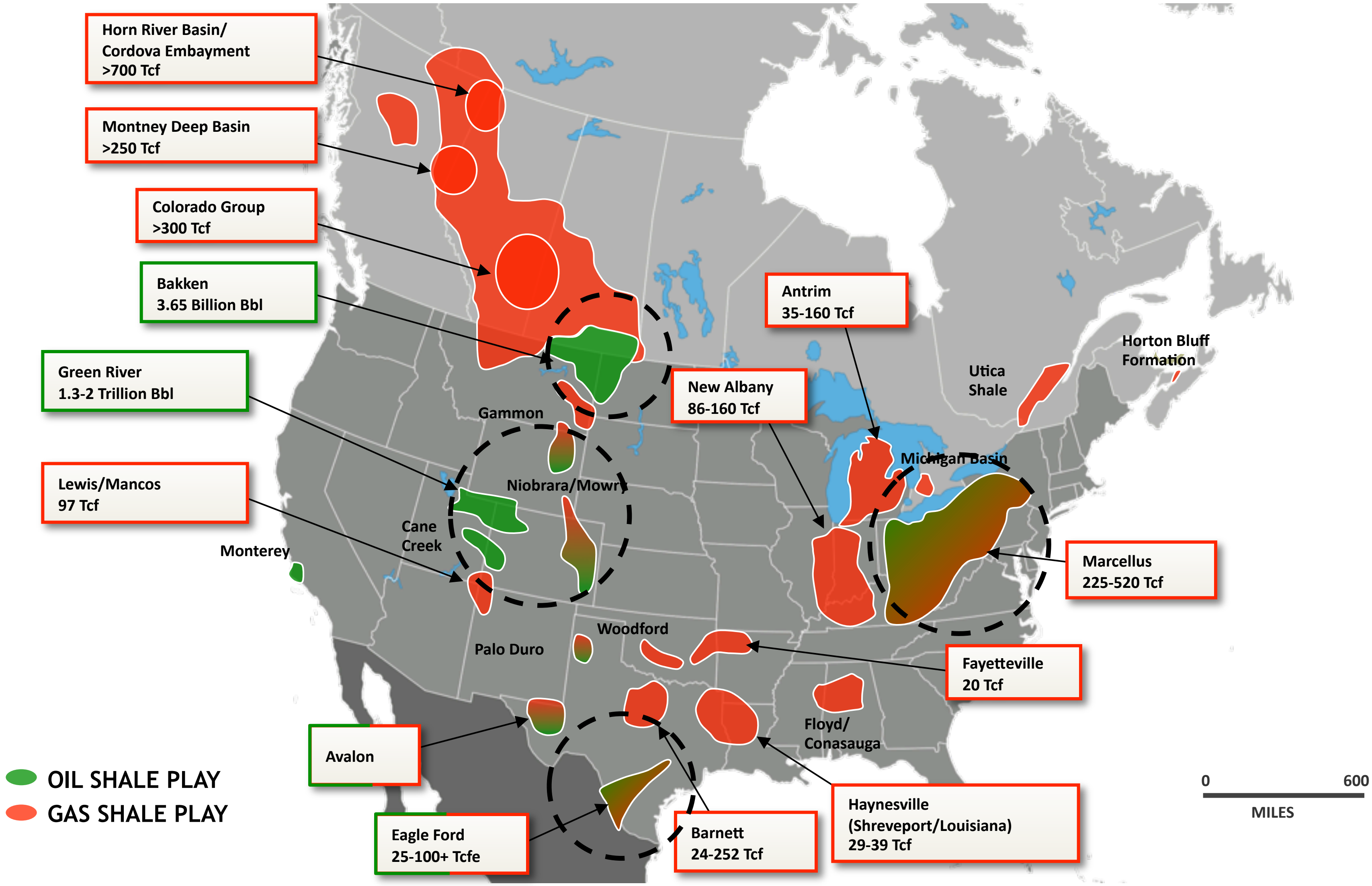
Source: Morgan Stanley Research Report

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



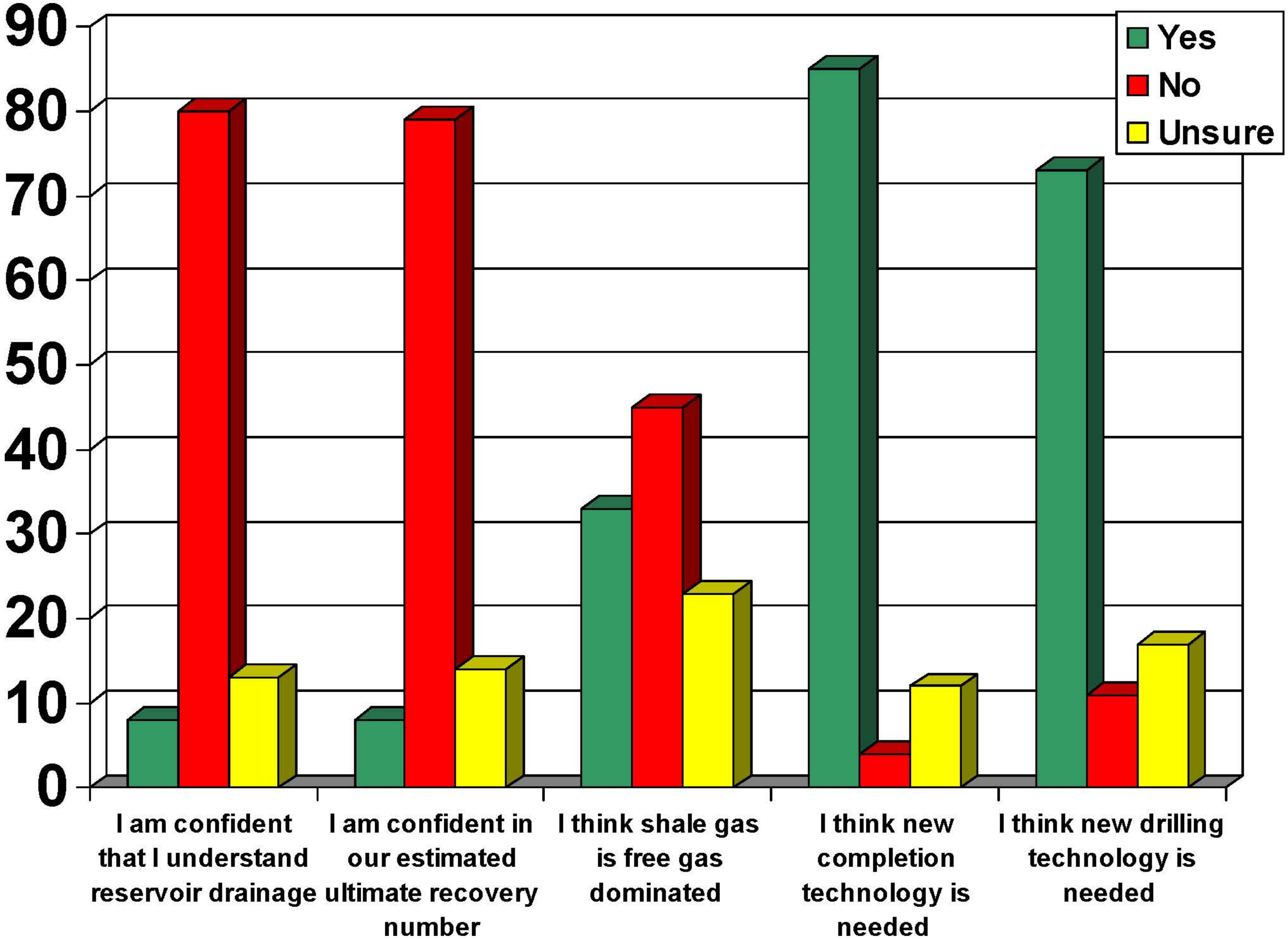
- How Do We Optimize Resource Development?
- How Do we Minimize the Environmental Impact?

Opportunity: North American Shale Oil Plays



Recoverable Oil Reserves?????

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?

Outline of Presentation

1. Microseismicity and Reservoir Stimulation

2. Physical and Chemical Properties of Organic Rich Shales

3. Reservoir Drainage and EUR

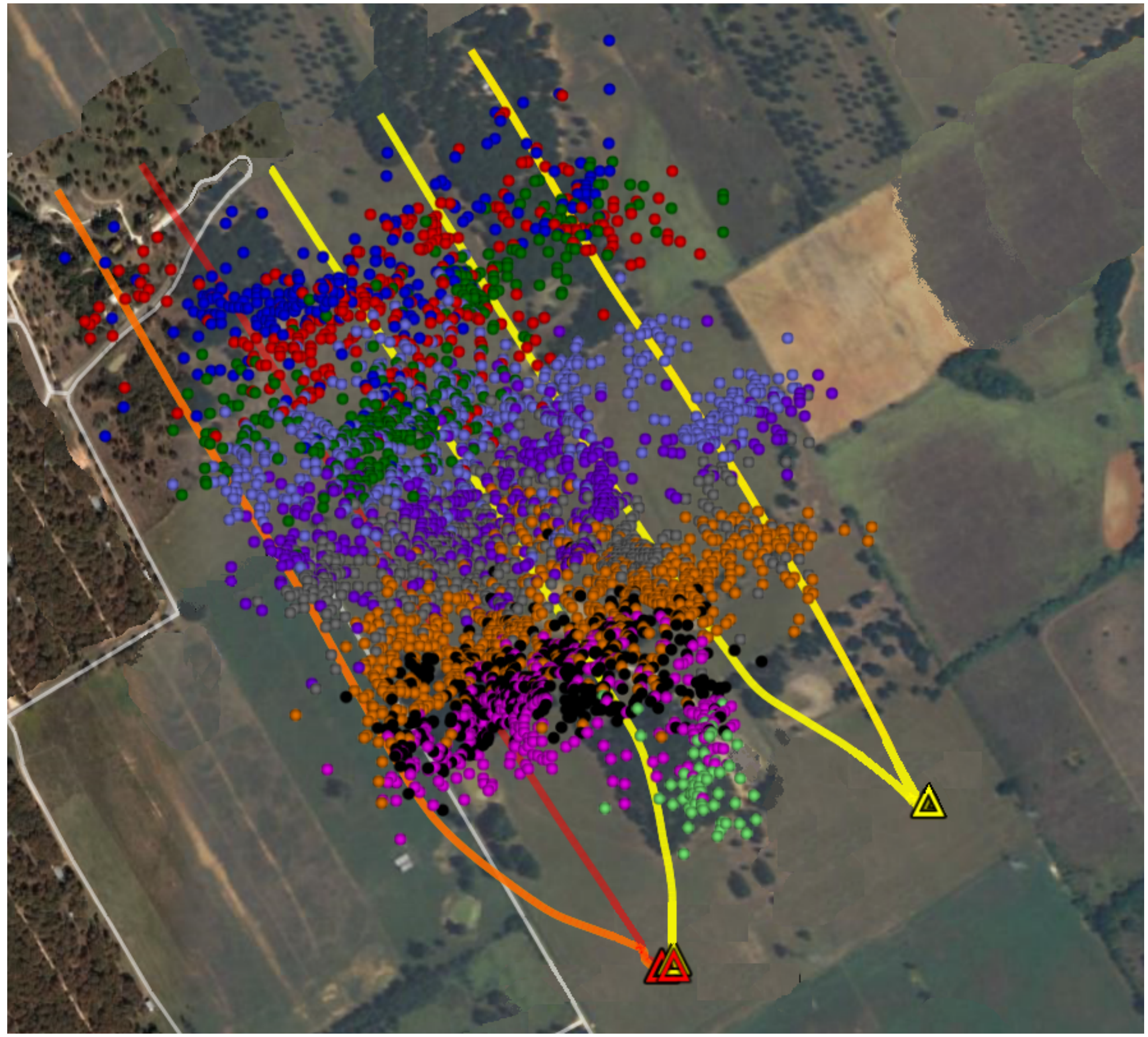
4. Aseismic Fault Slip During Reservoir Simulation

5. Managing Triggered Seismicity

6. Minimizing the Environmental Impact Associated with Shale Gas Development

Physical and Chemical Properties of Organic Rich Shales

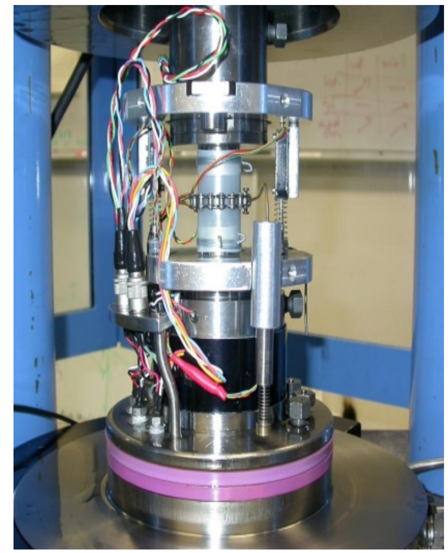
How Do the Properties of Shale Affect the Outcome of Hydraulic Fracturing Stimulation?



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

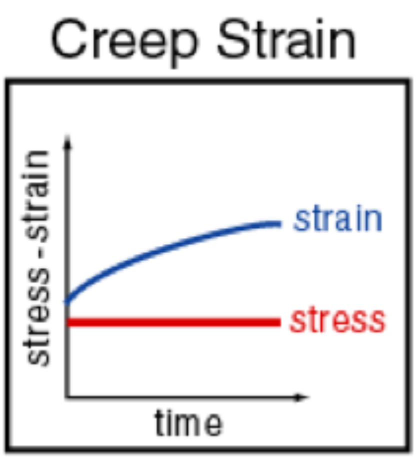


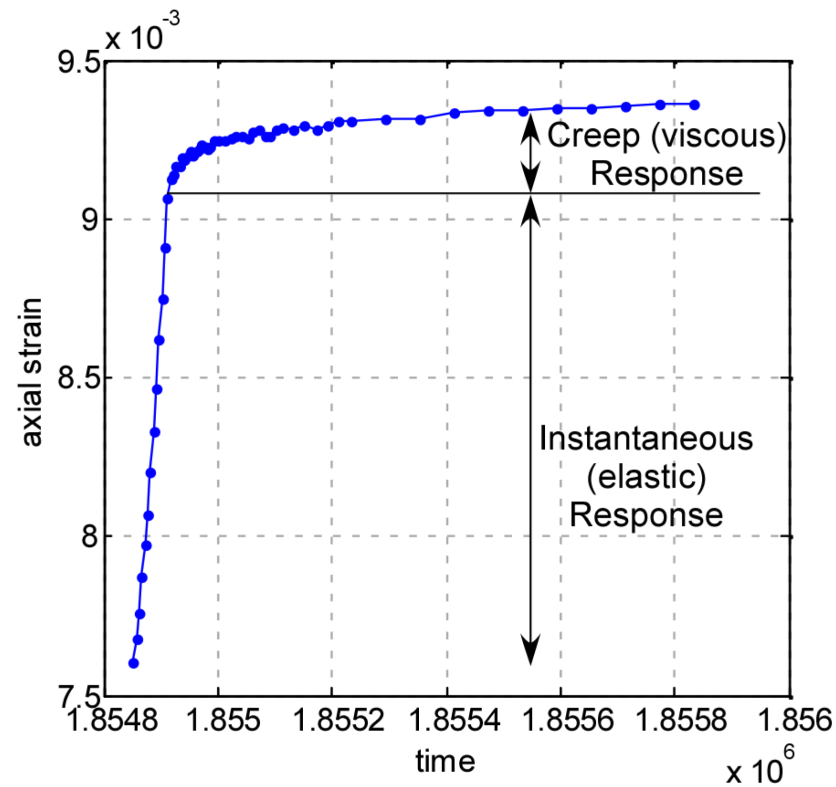
- Bedding plane and sample cylinder axis is either parallel (horizontal samples) or perpendicular (vertical samples)
- 3-10 % porosity
- All room dry, room temperature experiments

Shales Creep With Time (Viscoplastic)

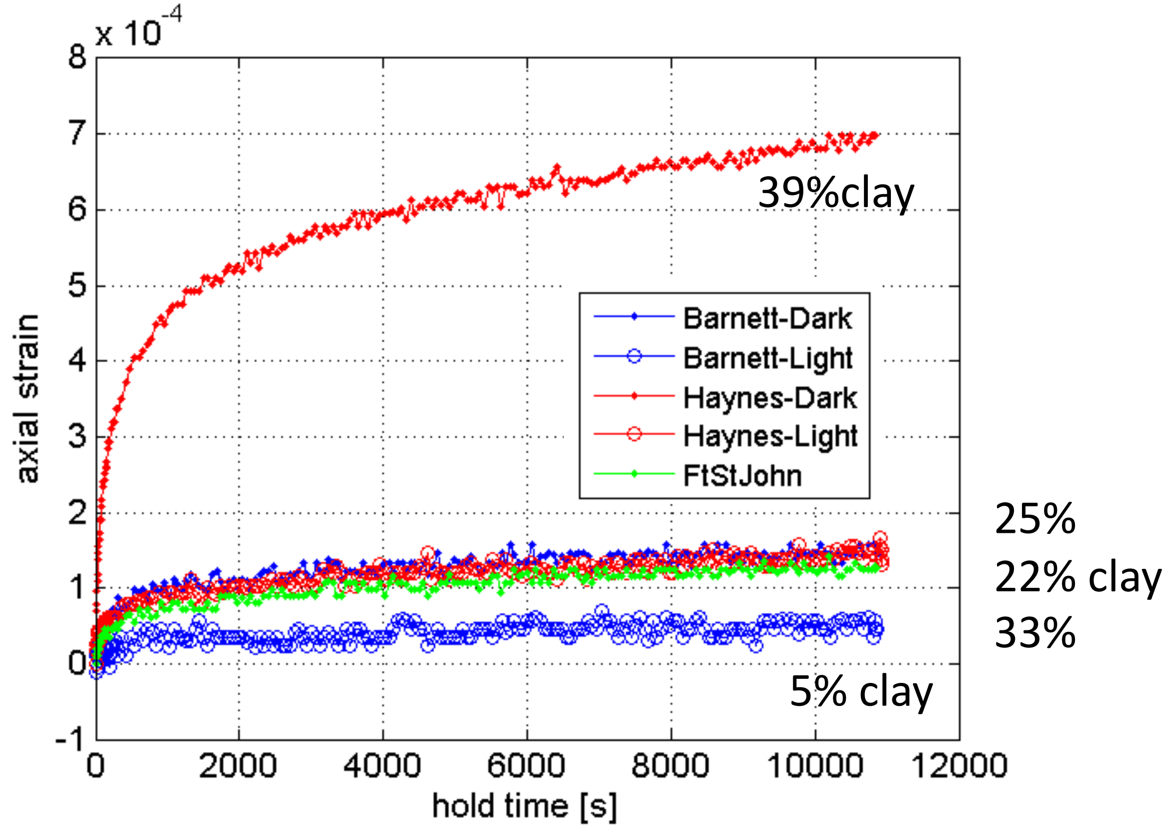
Creep may prevent brittle fracturing (stimulation) and promote propant-embedment

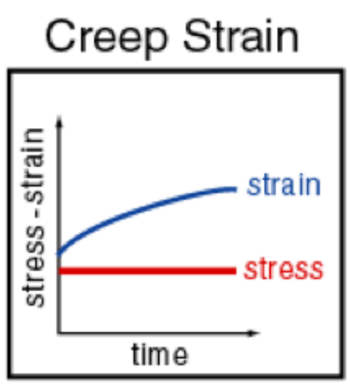
Creep relaxes stresses



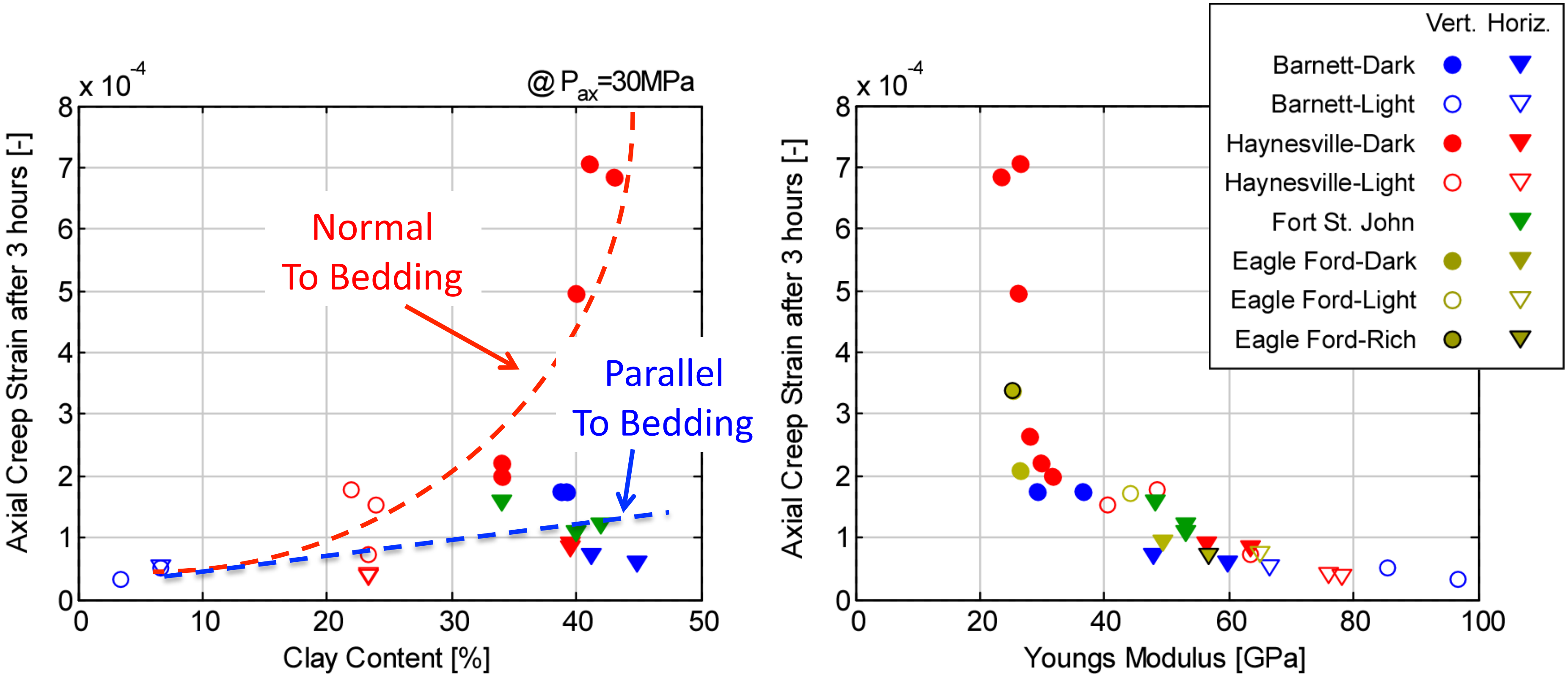


Creep Increases with Clay Content



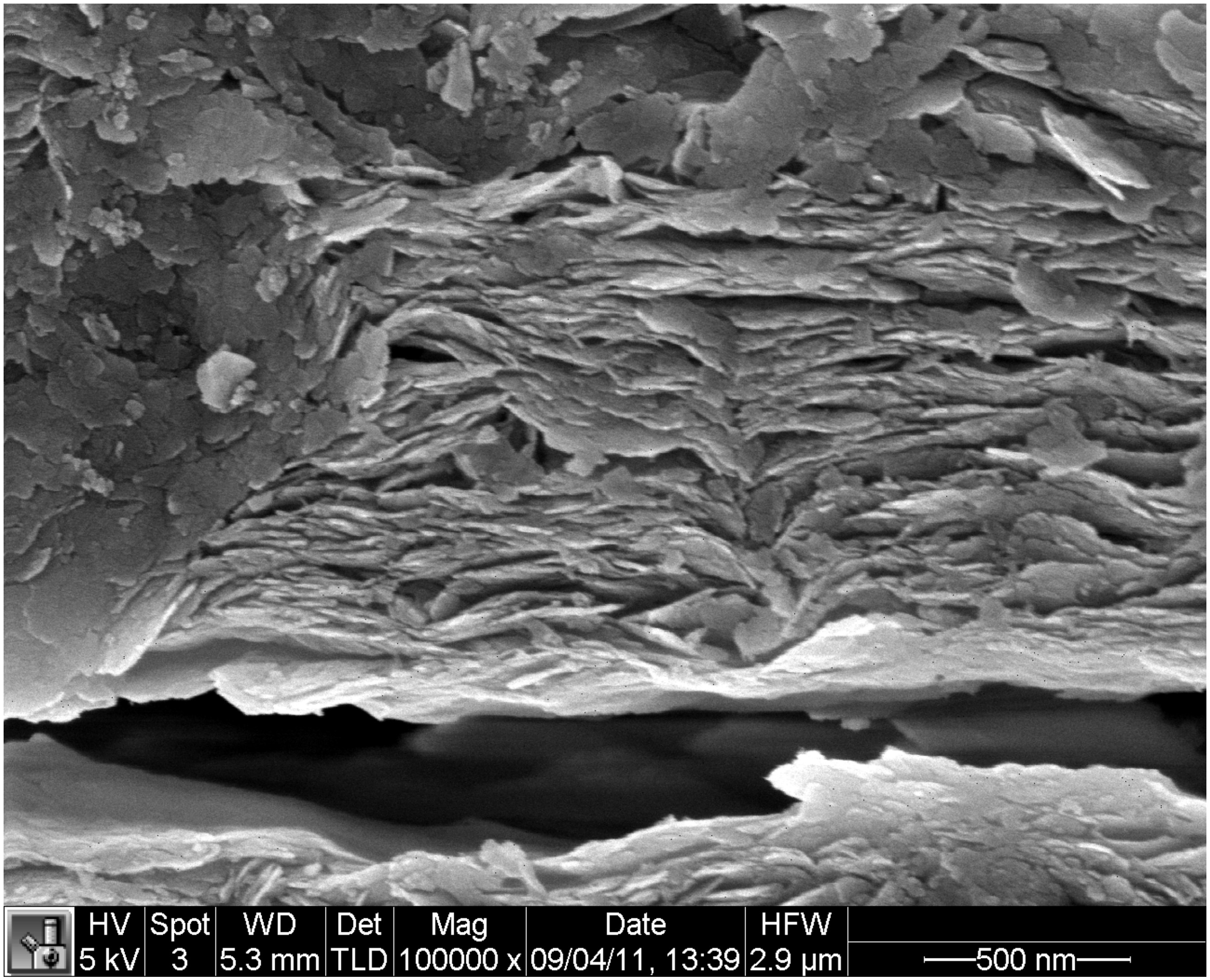


Creep Strain vs. Clay and E

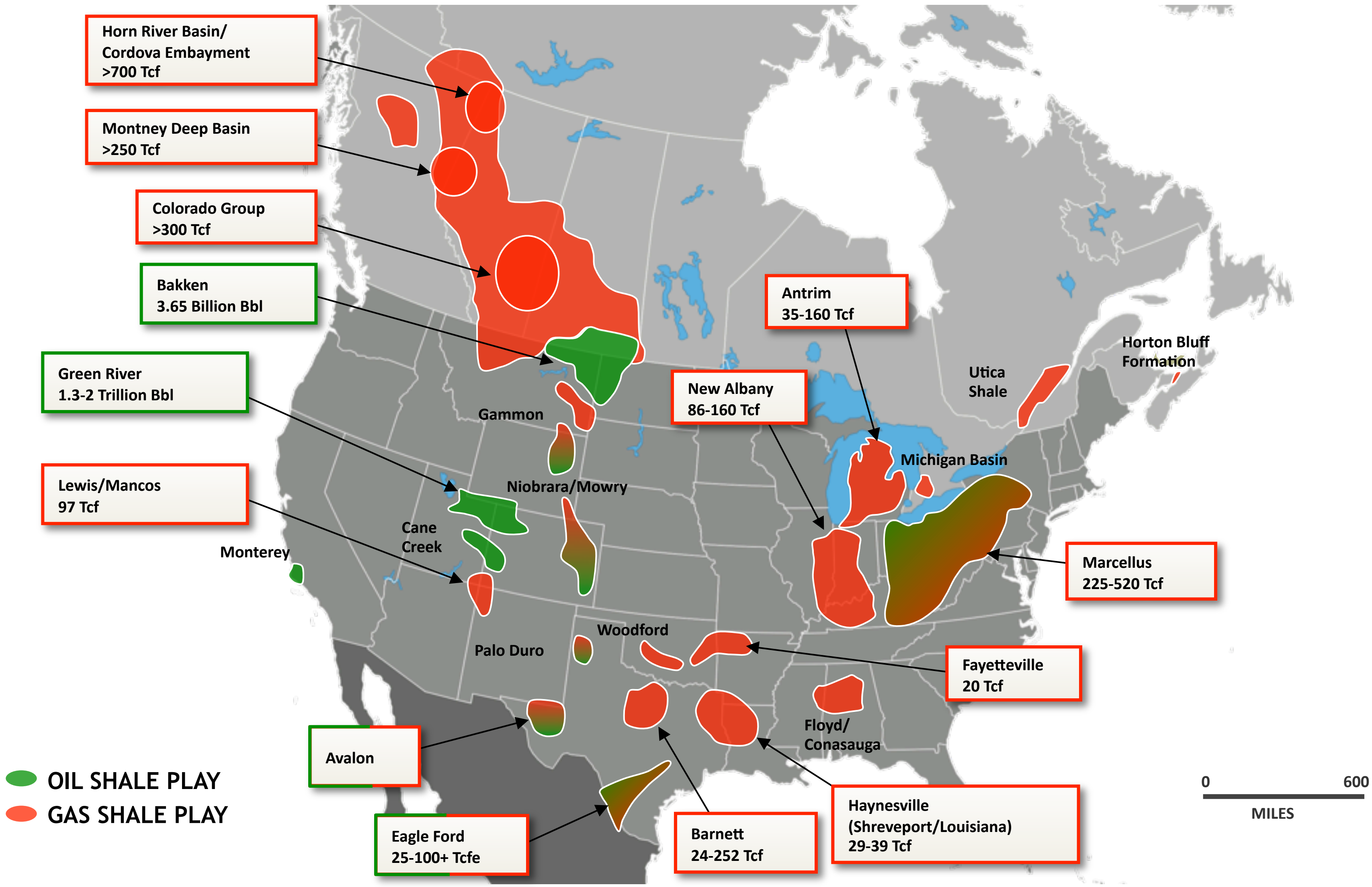


- Amount of creep (ductility) depends on clay content and orientation of loading with respect to bedding
- Young's modulus correlates with creep amount very well

Eagleford Shale



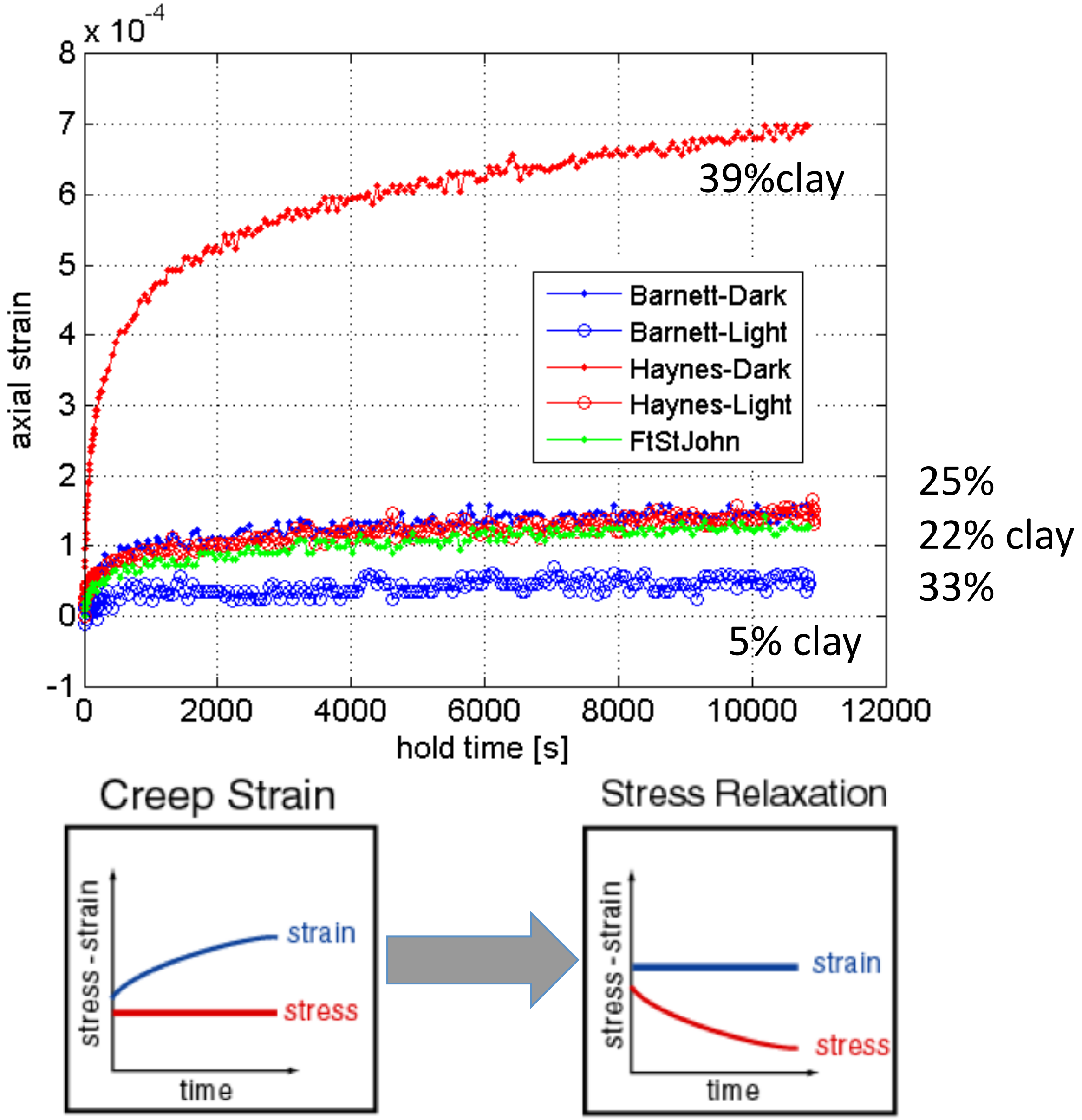
Floyd Shale?


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
Antrim 35-160 Tcf
New Albany 86-160 Tcf
Utica Shale
Horton Bluff Formation
Michigan Basin
Marcellus 225-520 Tcf
Fayetteville 20 Tcf
Floyd/ Conasauga
Avalon
Eagle Ford 25-100+ Tcfe
Barnett 24-252 Tcf
Haynesville (Shreveport/Louisiana) 29-39 Tcf
OIL SHALE PLAY
GAS SHALE PLAY
0
600
MILES

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

Is the Floyd Shale too Viscous to Stimulate?

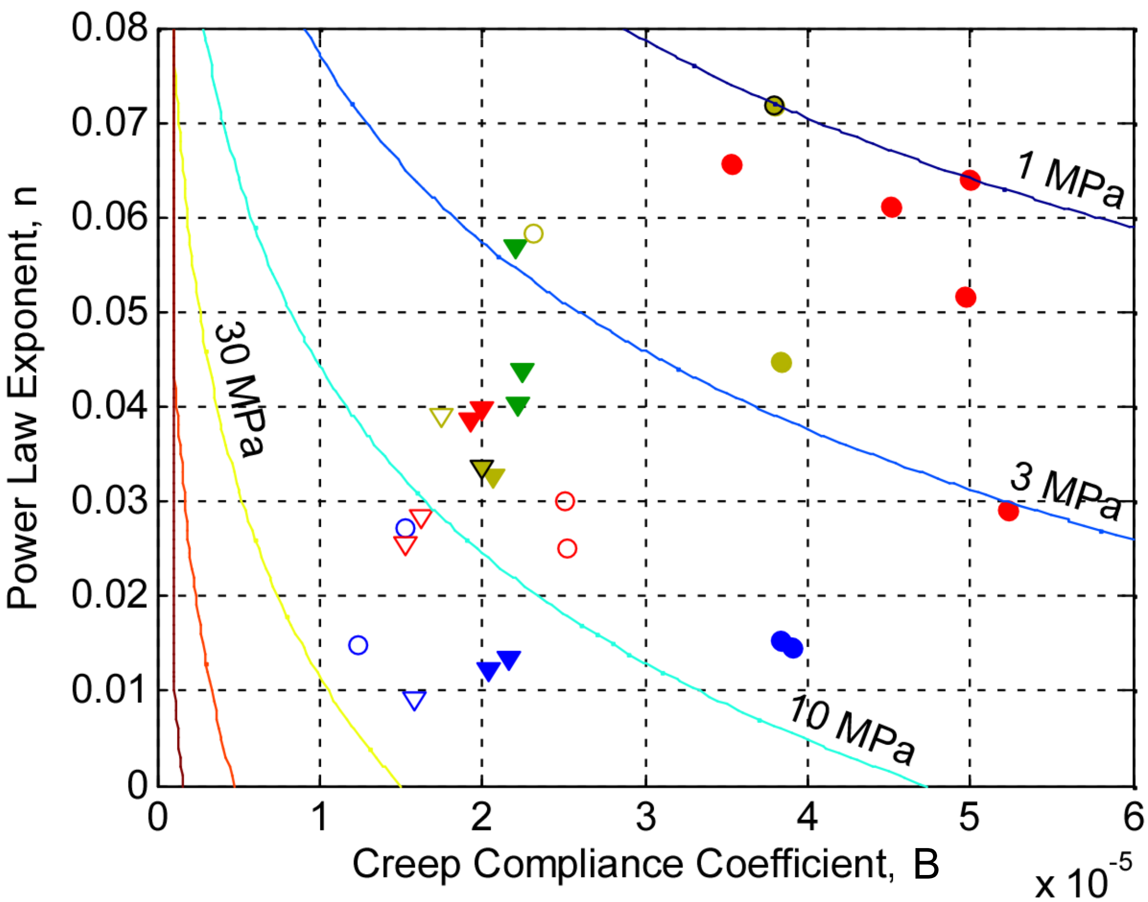


Accumulation of Differential Stress

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

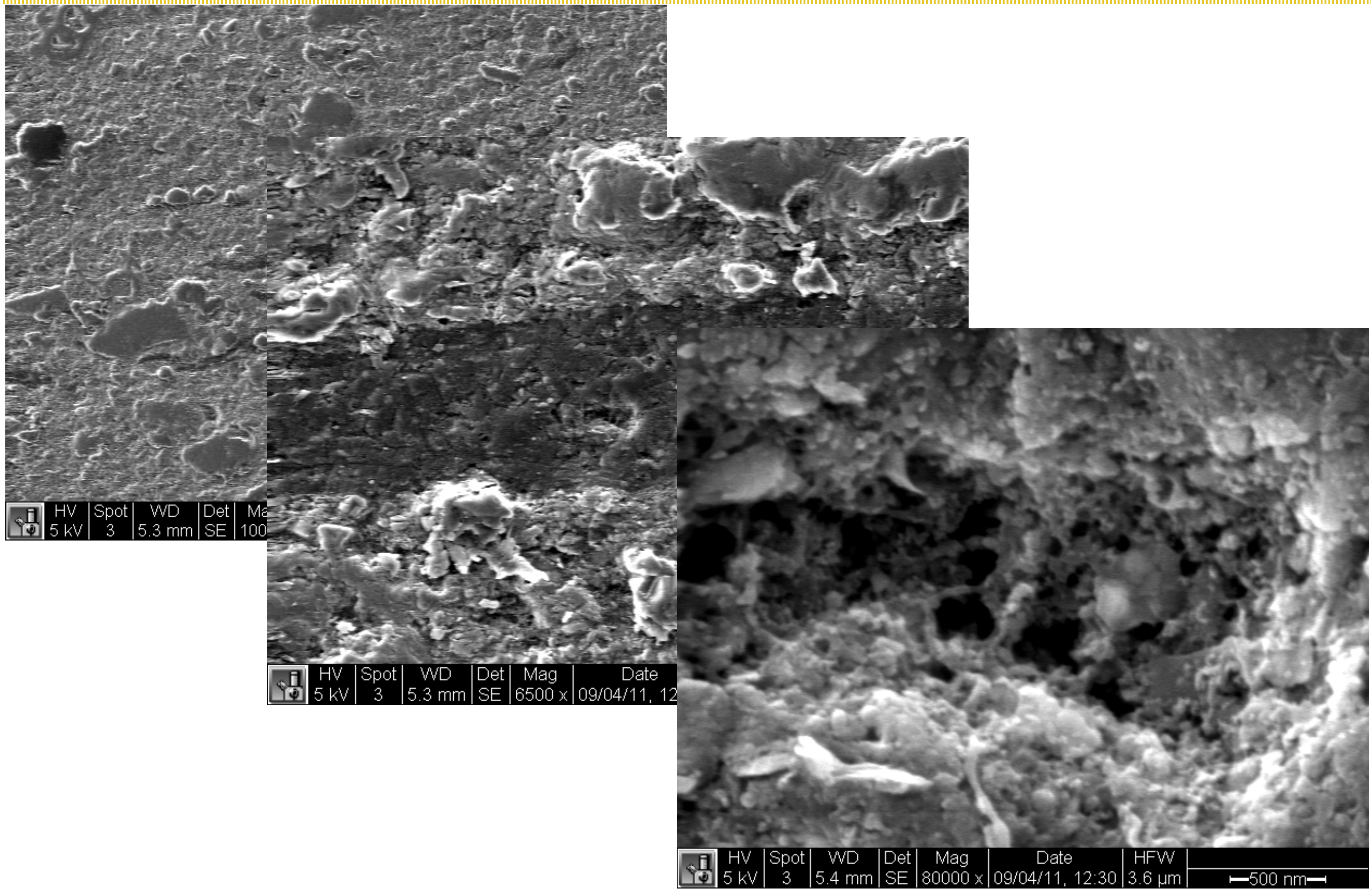
- Barnett Shale
  - 320 Ma
  - Stable intraplate

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



	Vert.	Horiz.
Barnett-Dark	●	▼
Barnett-Light	○	▽
Haynesville-Dark	●	▼
Haynesville-Light	○	▽
Fort St. John		▼
Eagle Ford-Dark	●	▼
Eagle Ford-Light	○	▽
Eagle Ford-Rich	●	▼

Eagleford Shale Pore Structure



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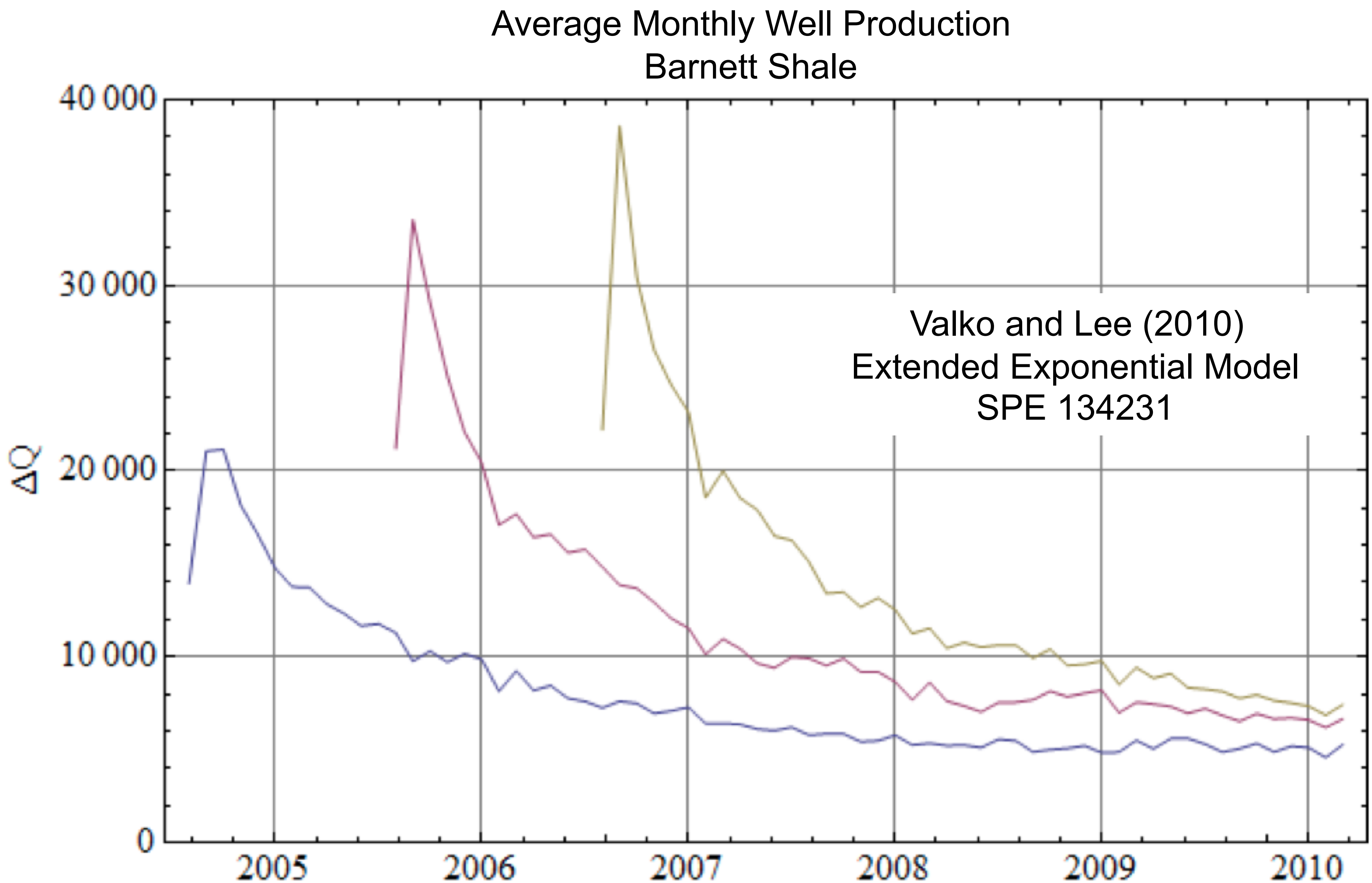
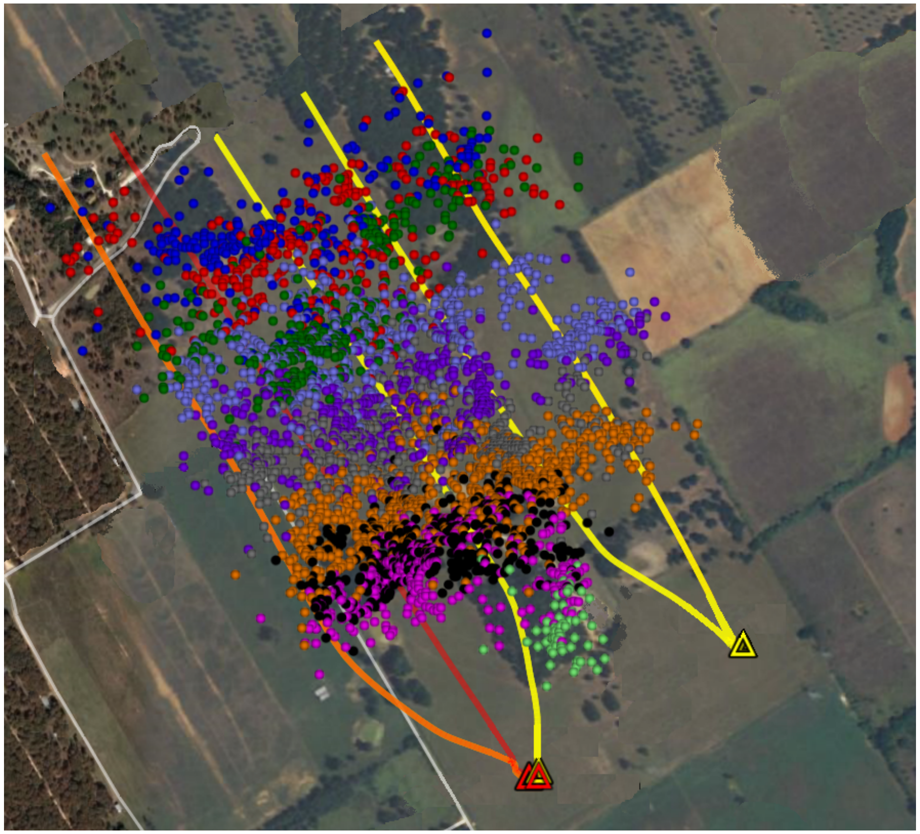
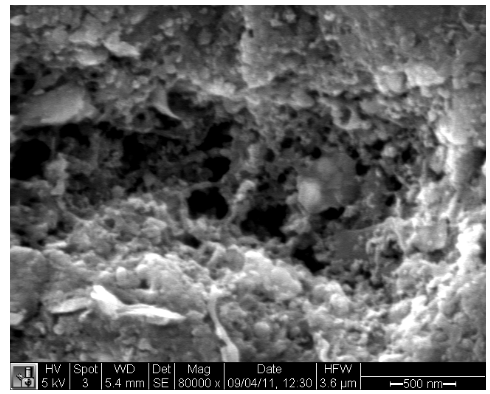
Why Is Production Persistent?

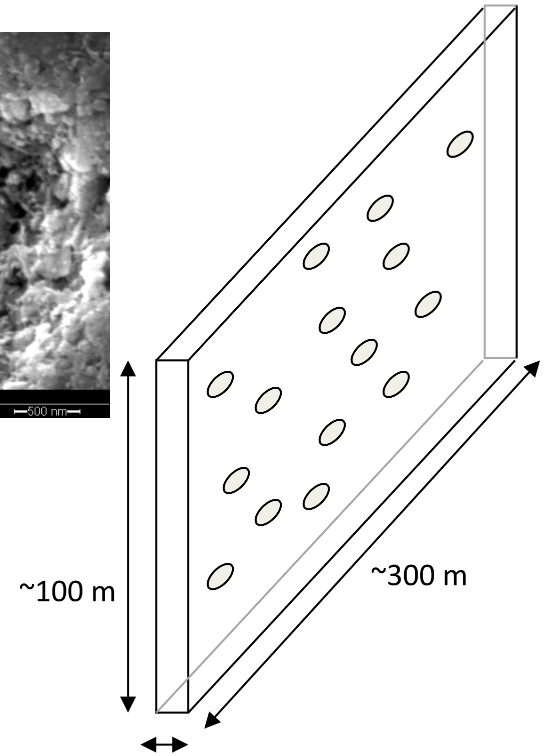


Reservoir Drainage and EUR



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:

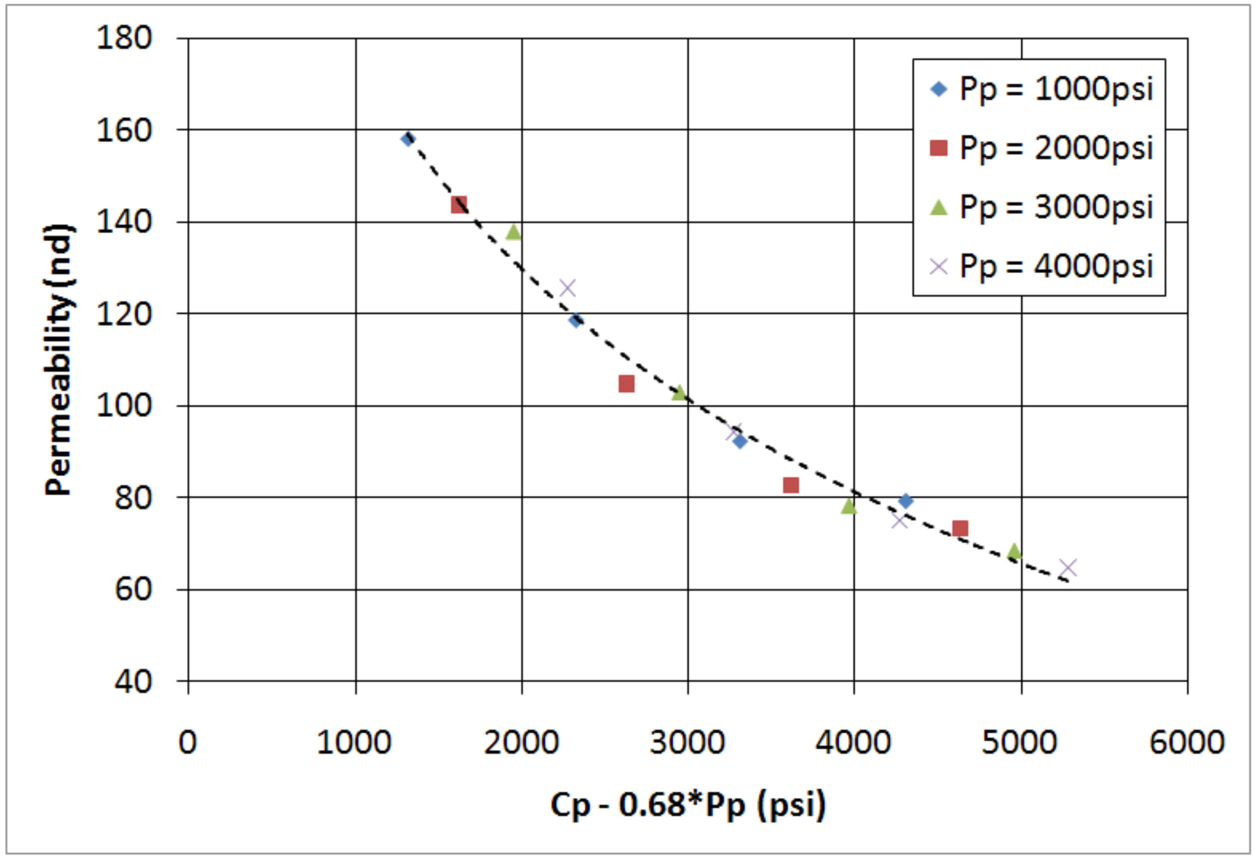
1. Nano-scale pore network?
2. Pre-existing micro-cracks?
3. Pre-existing macro-scale fractures?
4. Induced shear events?
5. Slick-water frac plane?

Permeability of Barnett Shale

Barnett Shale 31Ha

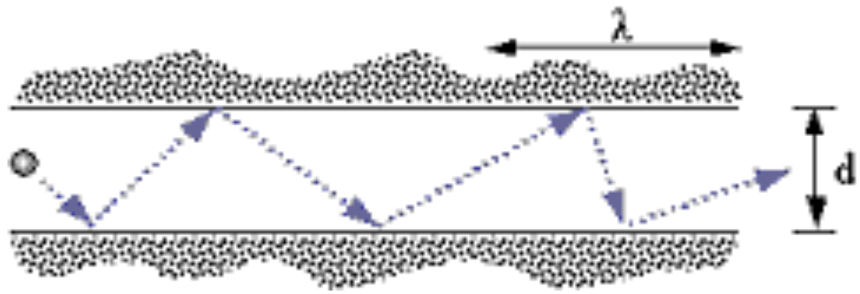
- Typical dark, organic-rich sample
- 51.3% qtz, 0.4% carbonate, 37.4% clay, 5.3% TOC
- Density porosity: 10.7%

Effective Stress Coefficient: χ = 0.68



Permeability Dominated by Flow Through Microcracks

Knudsen Diffusion



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

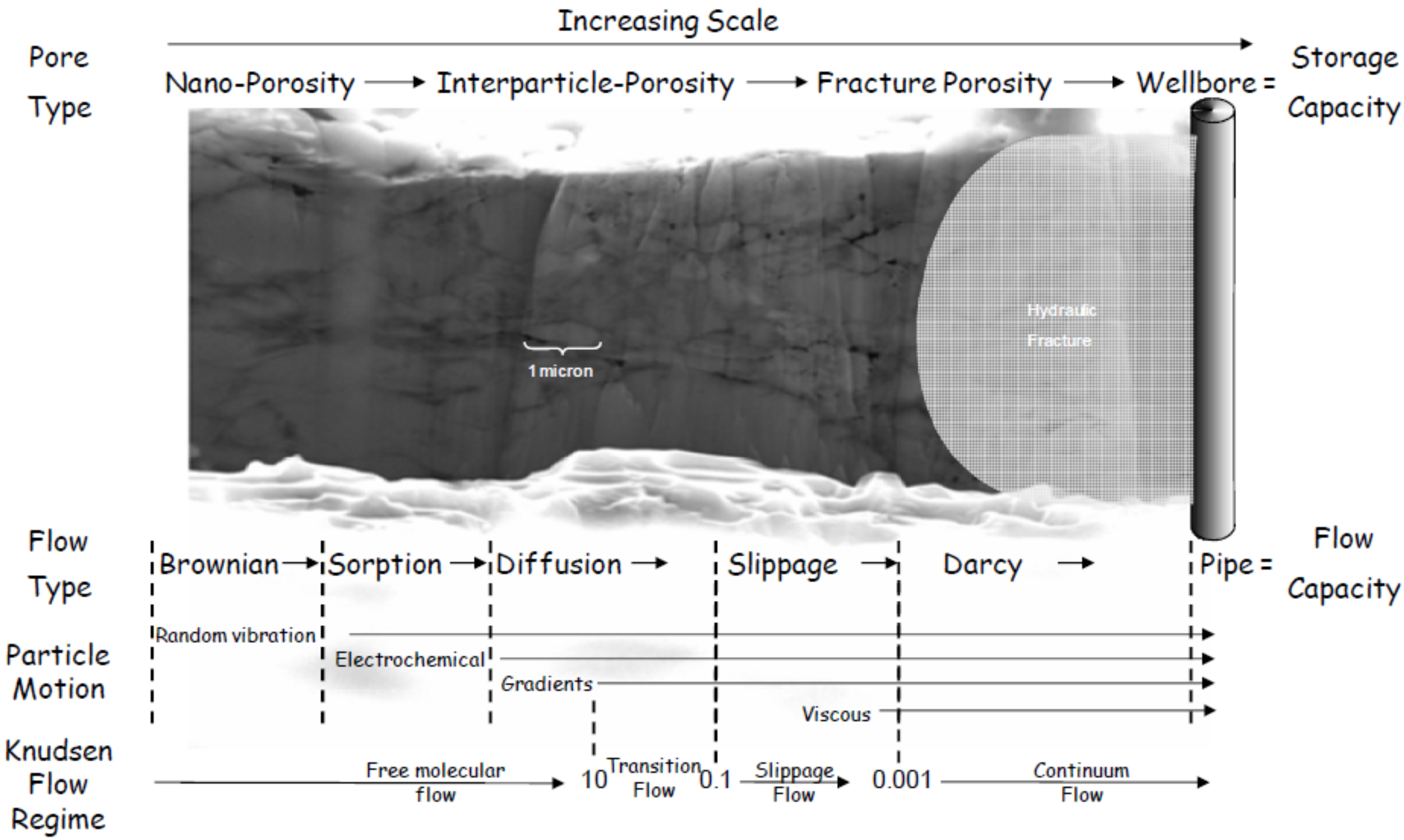
• Collisions with the pore walls will be more frequent than those between the molecules

Knudsen diffusion prevails:

1) when gas density is low

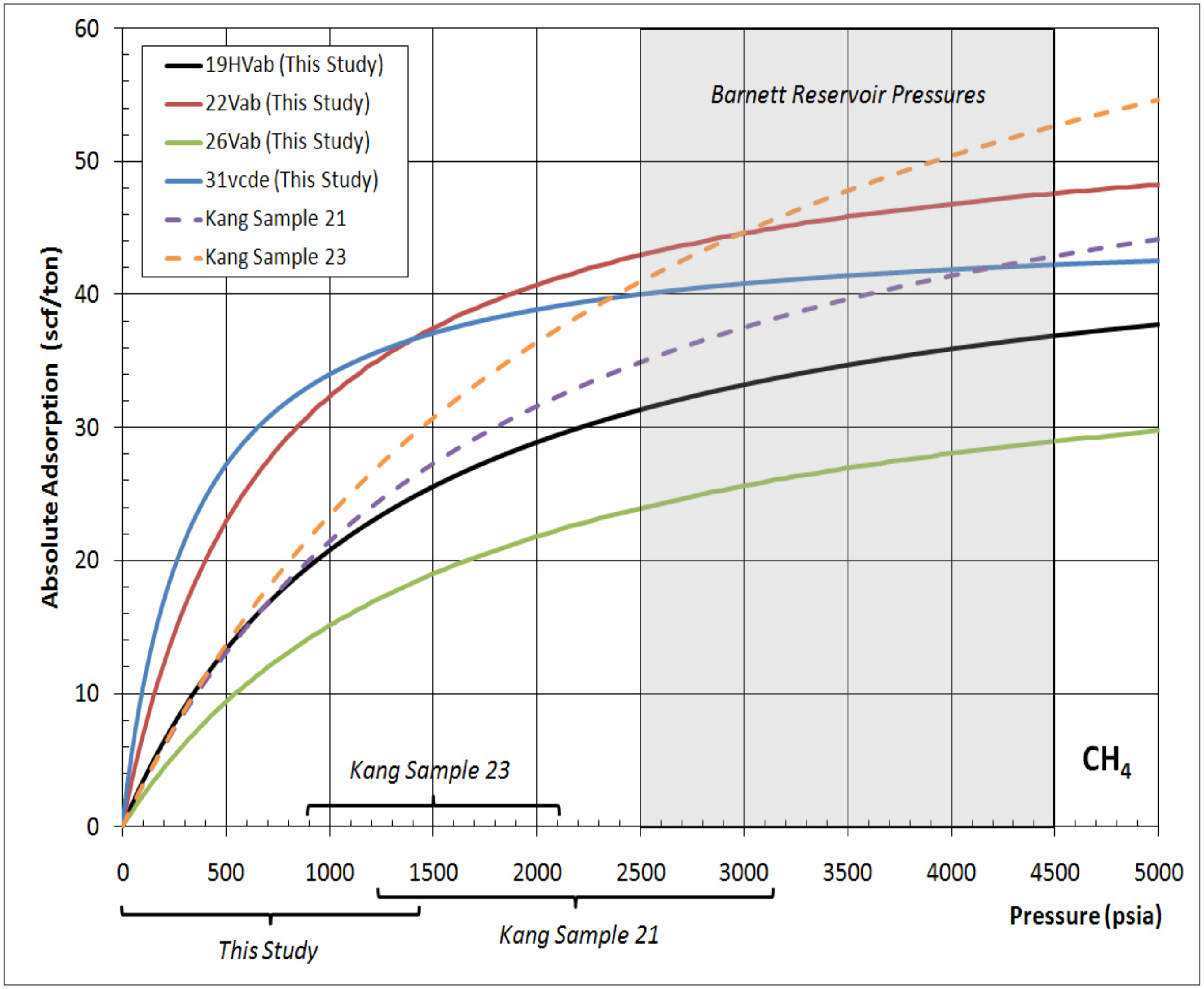
2) when pore dimensions are very small

Scale Dependent Flow Mechanisms



Sondergeld et al., 2010

Is Desorption Important?



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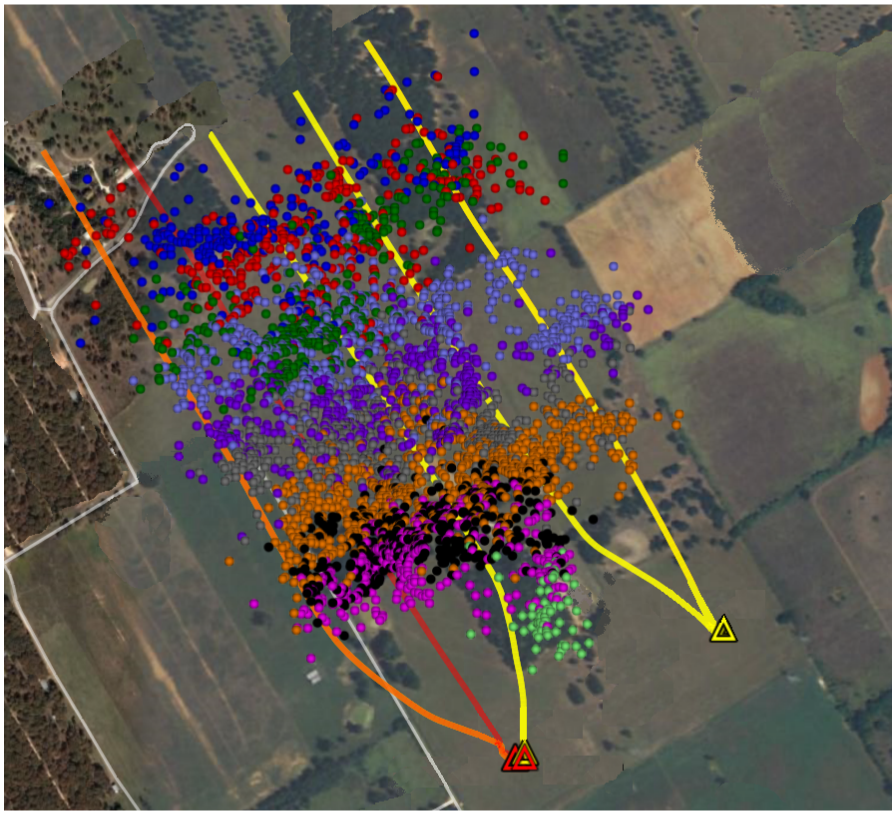
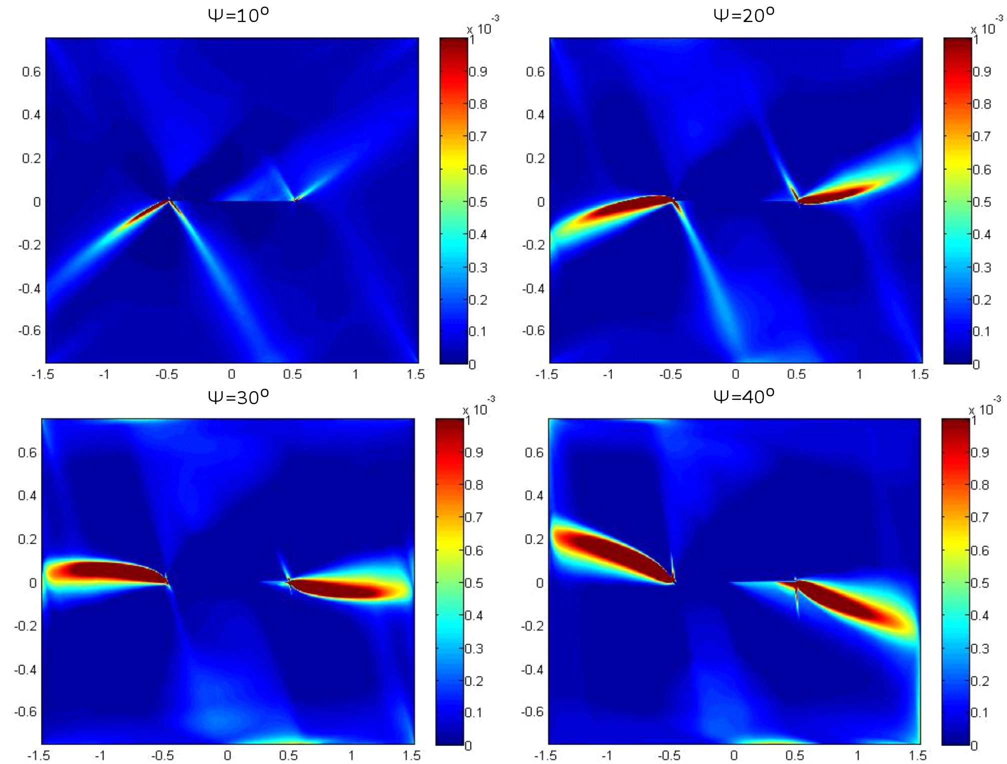
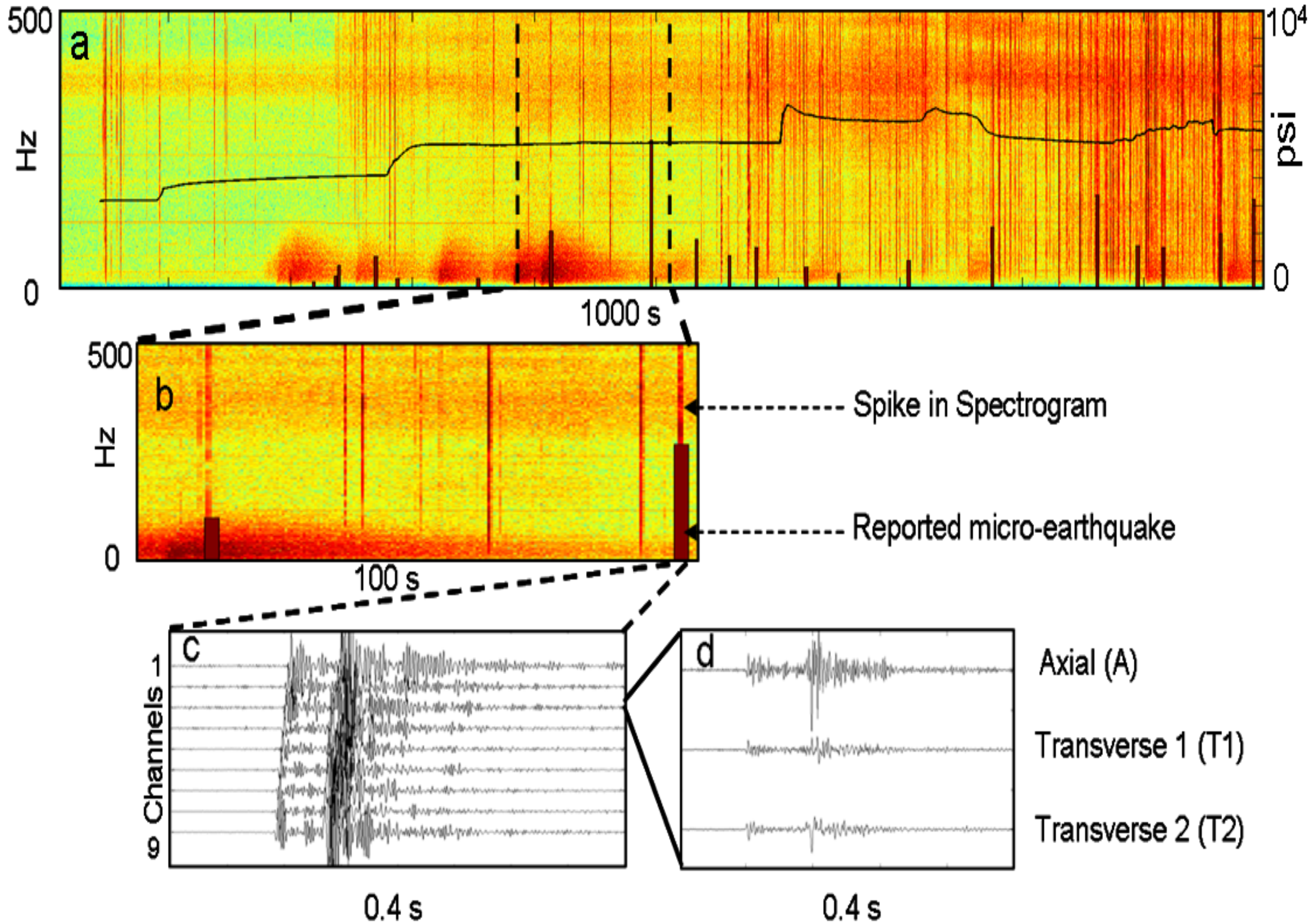
Off-Fault Damage – Zero Cohesion





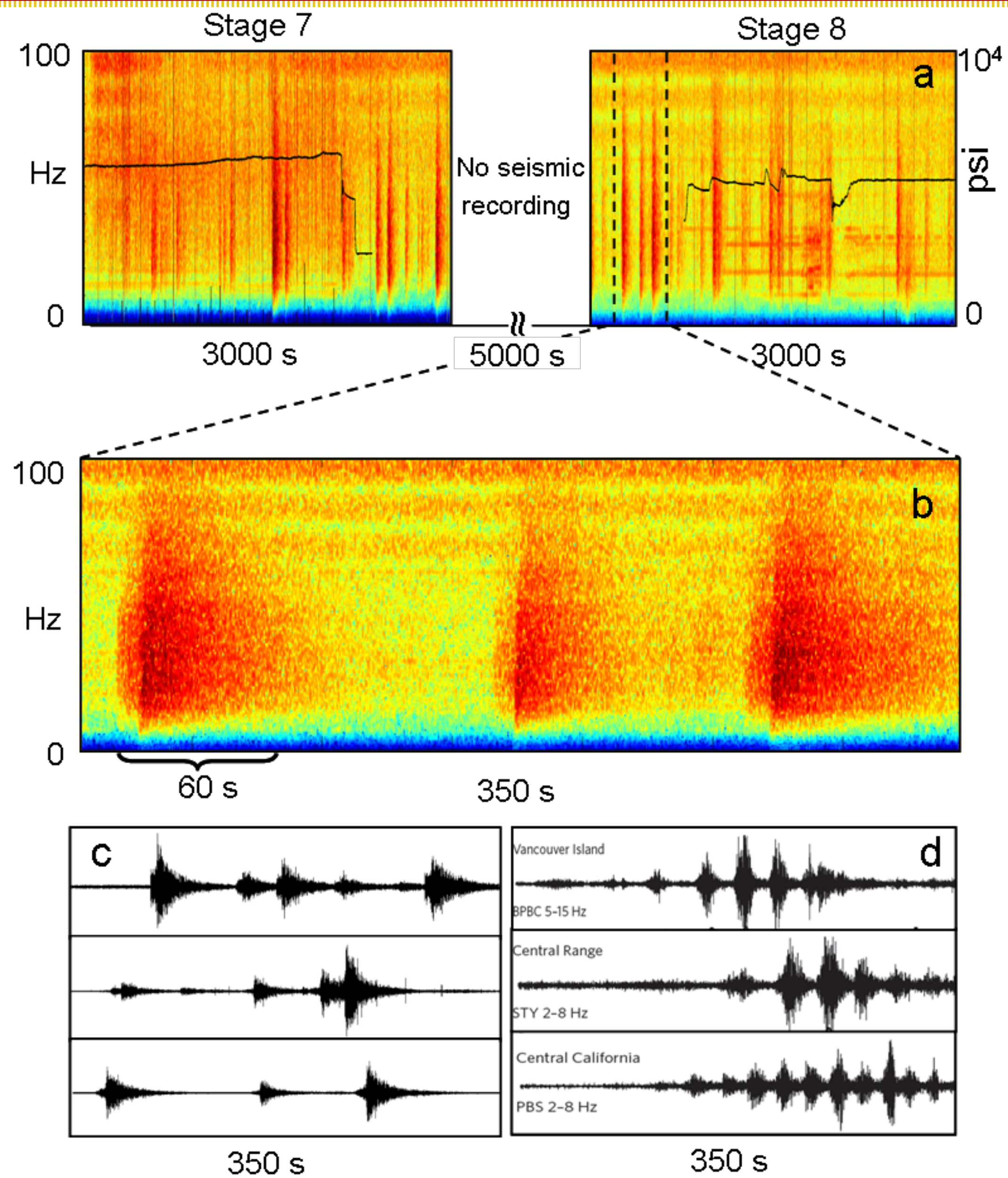
Volume Affected by 4000 Microearthquakes Can
Account for Less Than 1% of Gas Production in First 6 Months

Typical Microearthquakes

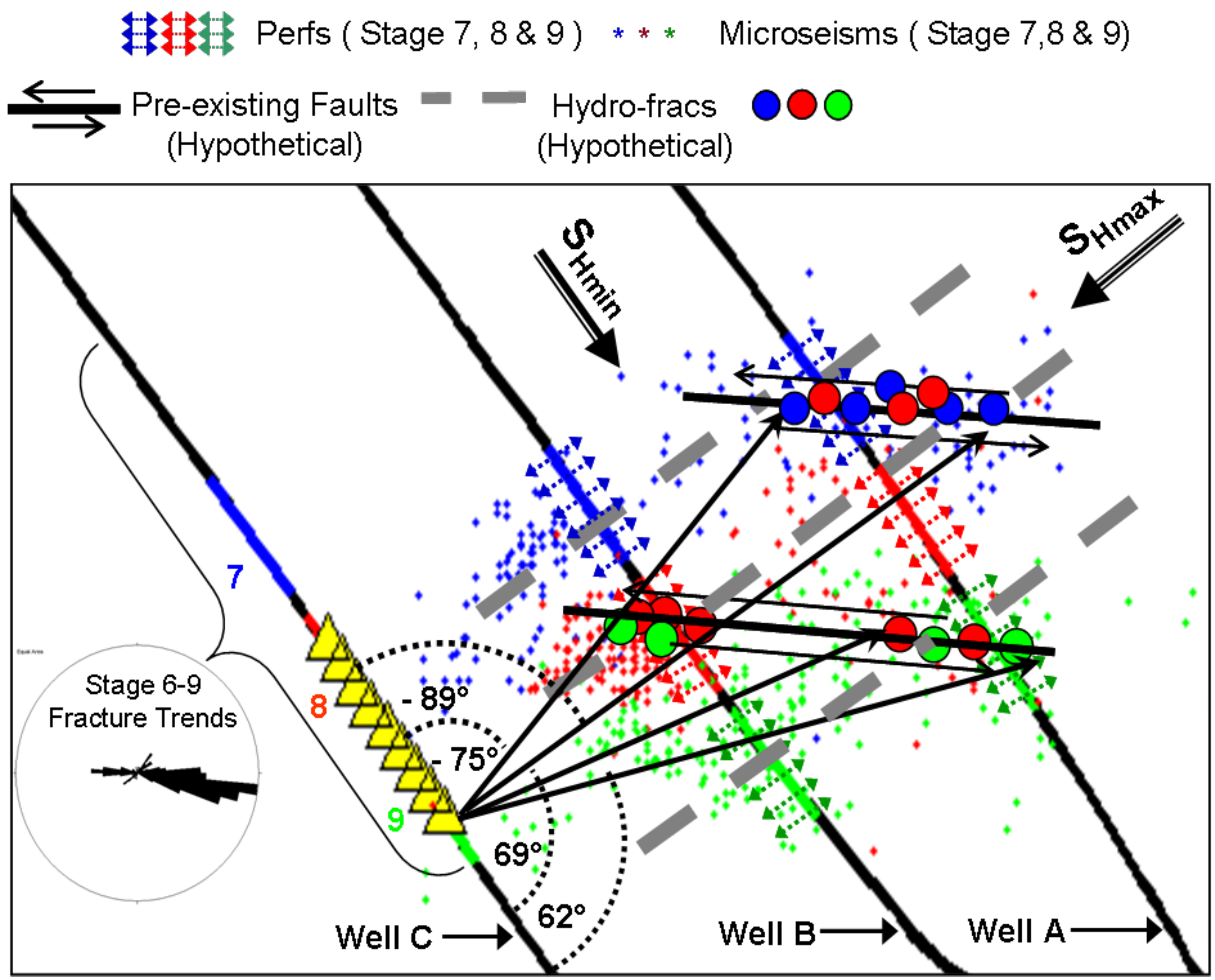


Das and Zoback, *The Leading Edge* (July 2011)

Long Period Long Duration Seismic Events

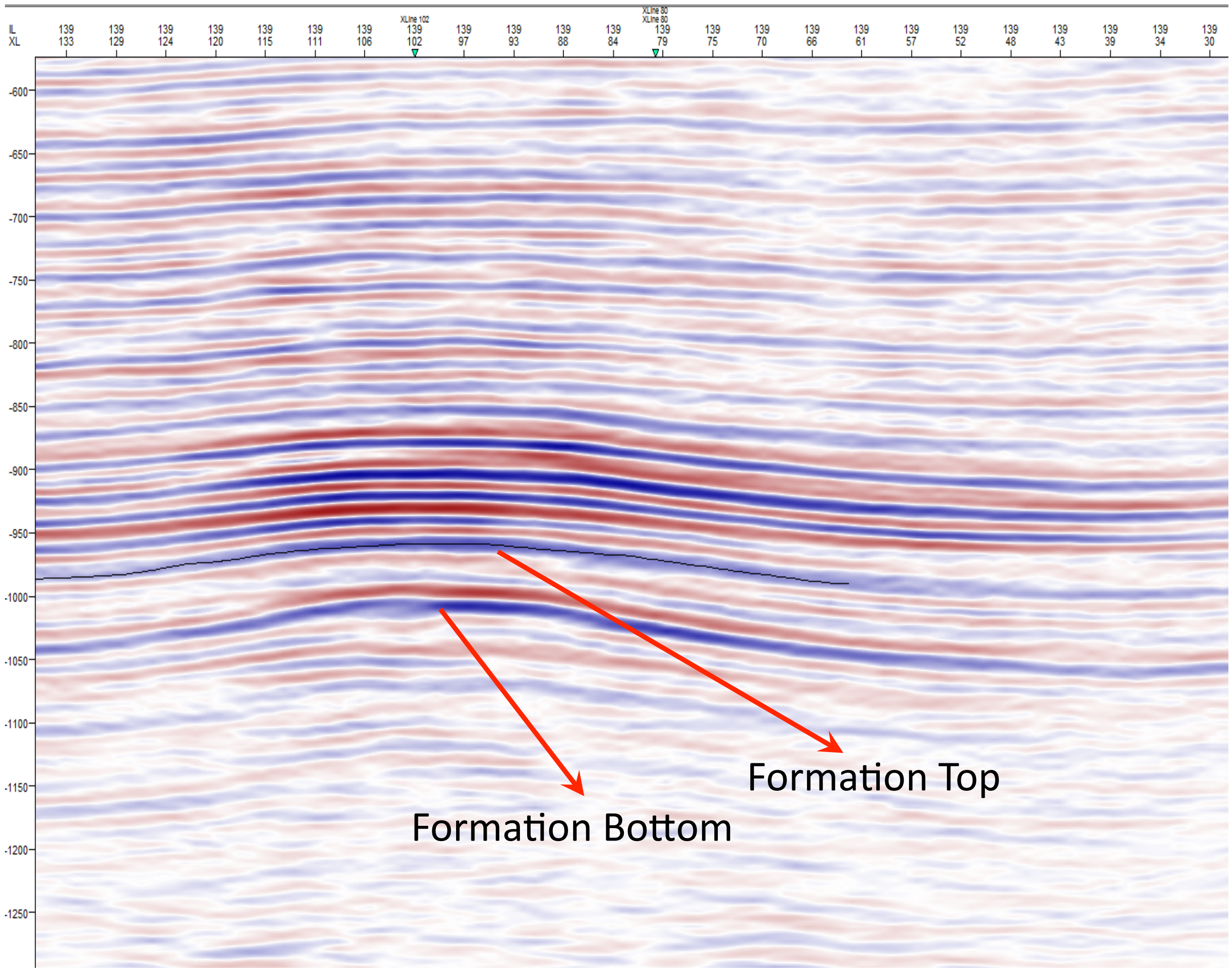


Slow Slip on Cross-Cutting Faults?



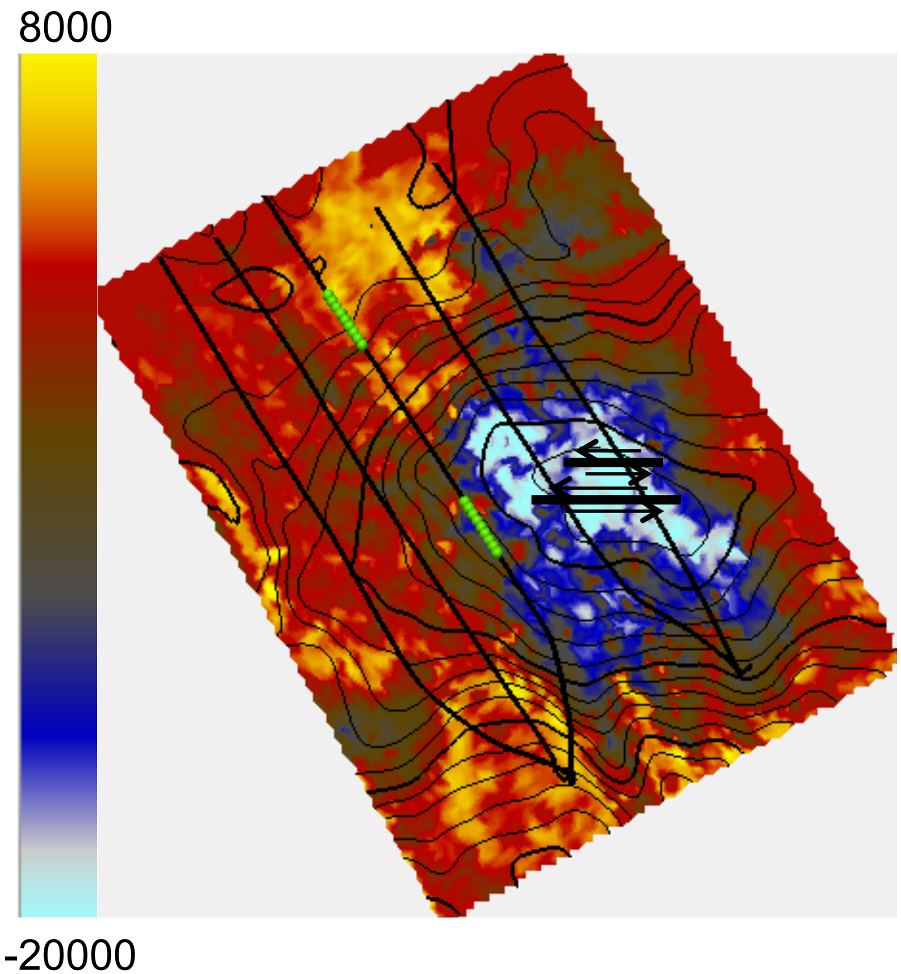
Das and Zoback, *The Leading Edge* (July 2011)

Relation of LPLD Events with Reservoir Properties

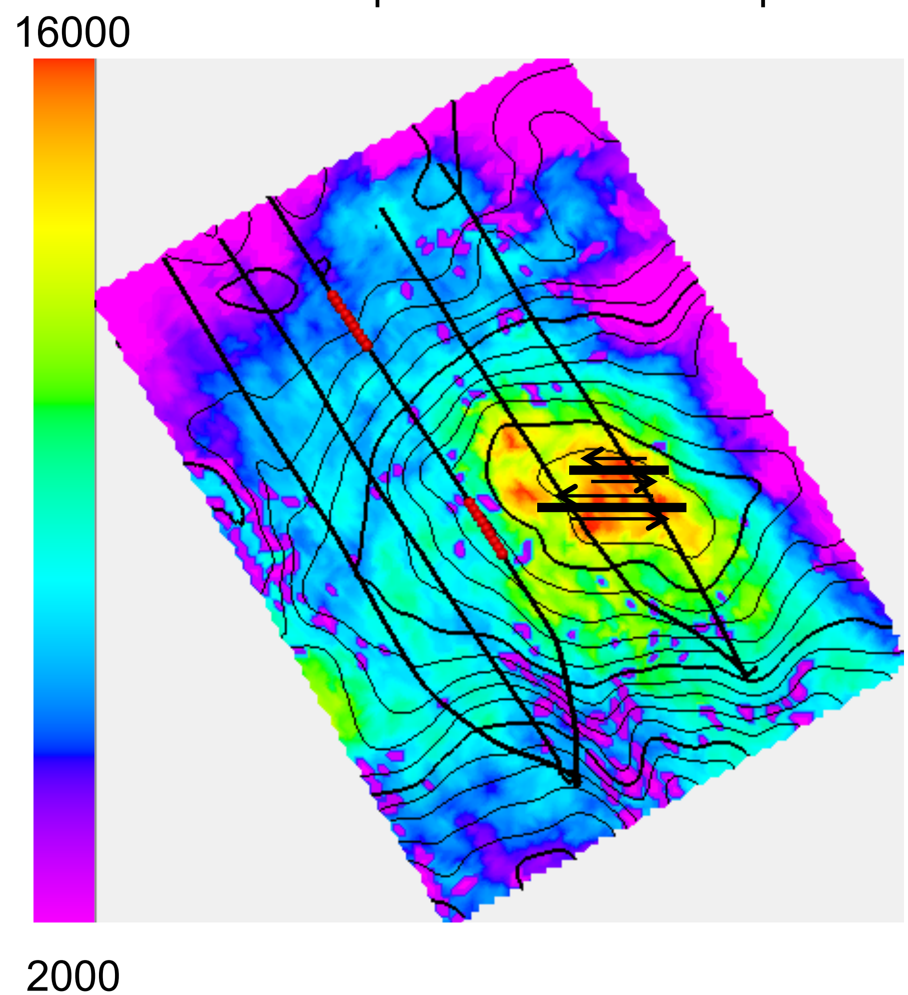


Attribute Analysis

Actual Amplitude Formation Top

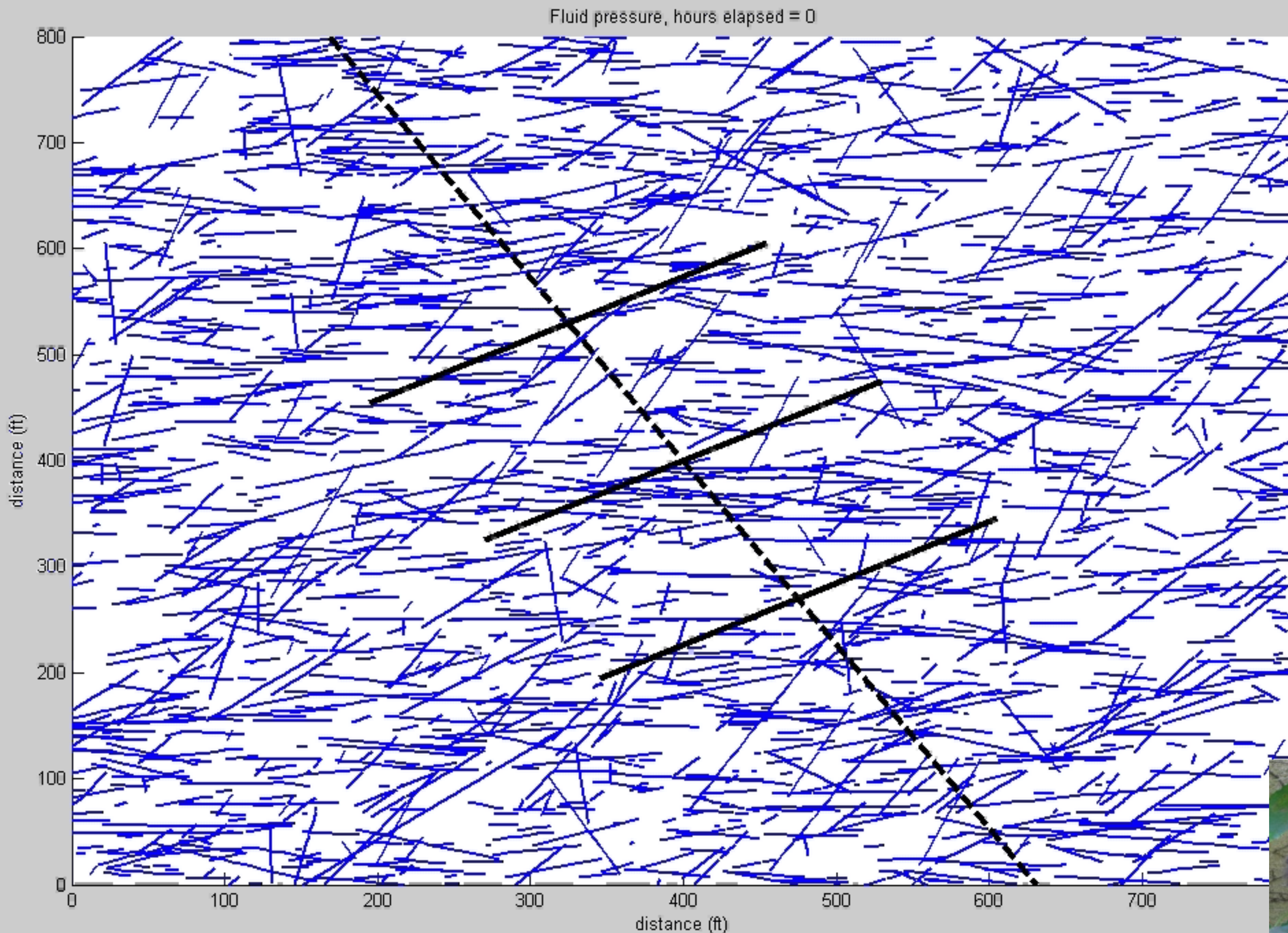


RMS Amplitude Formation Top



Location of LPLD events are correlative with amplitude anomalies

Evolution of Aseismic Slip in Reservoirs



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

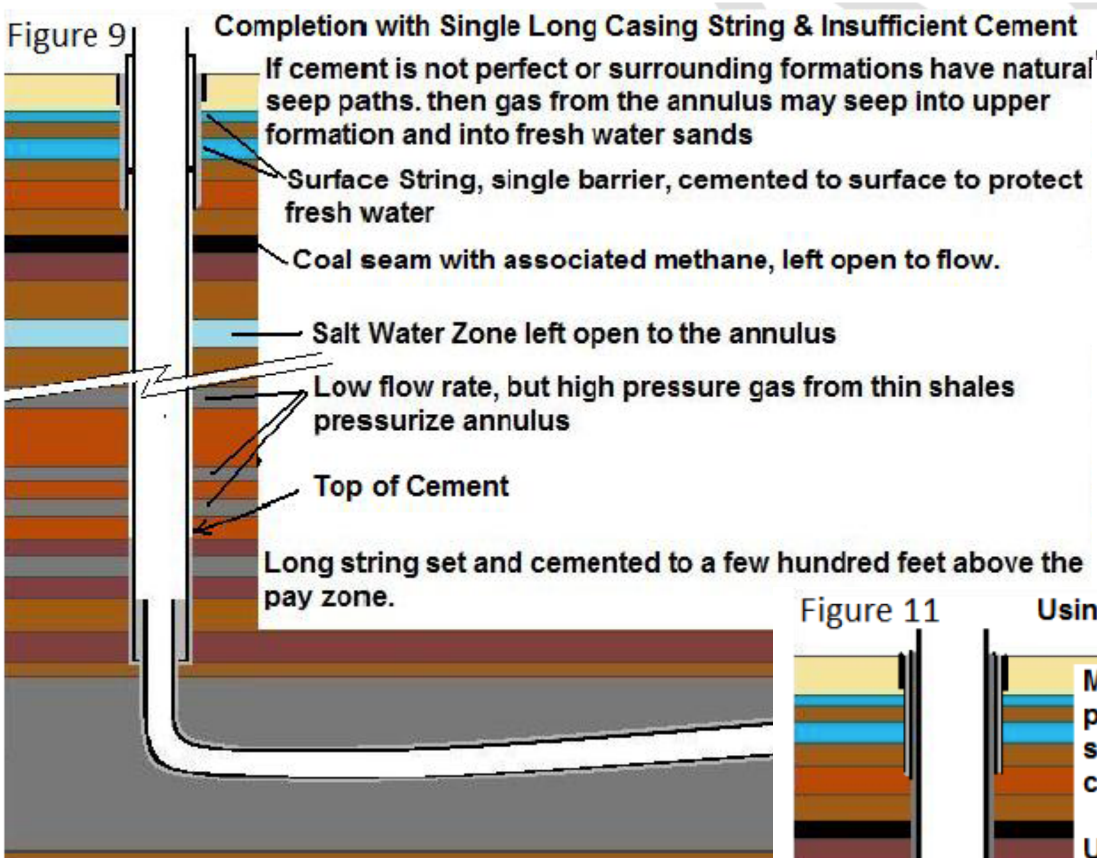
- John Deutch – MIT
- Stephen Holditch – Texas A&M
- Fred Krupp – Environmental Defense Fund
- Katie McGinty – Pennsylvania DEP
- Sue Tierney – Massachusetts Energy
- Dan Yergin – Cambridge Energy Research
- Mark Zoback - Stanford

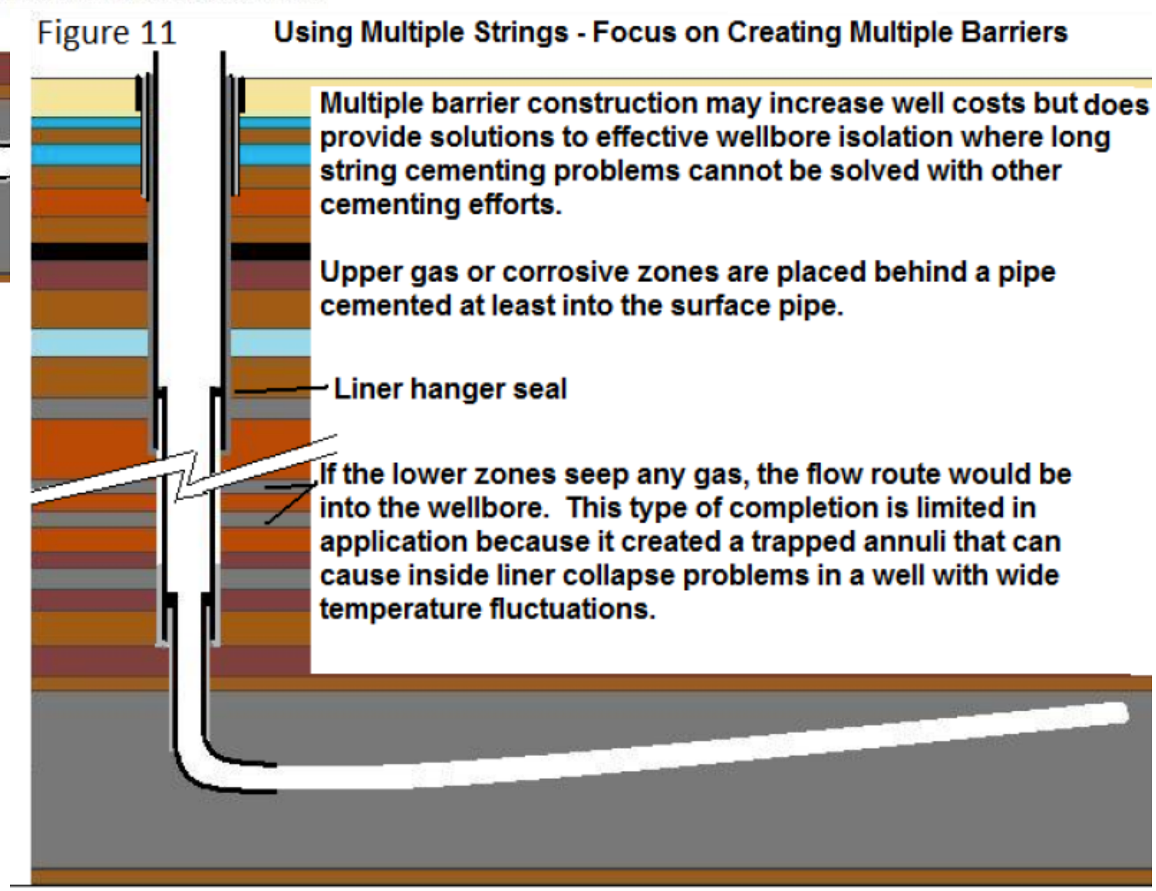
90 Day Report Summary

- 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

- 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.

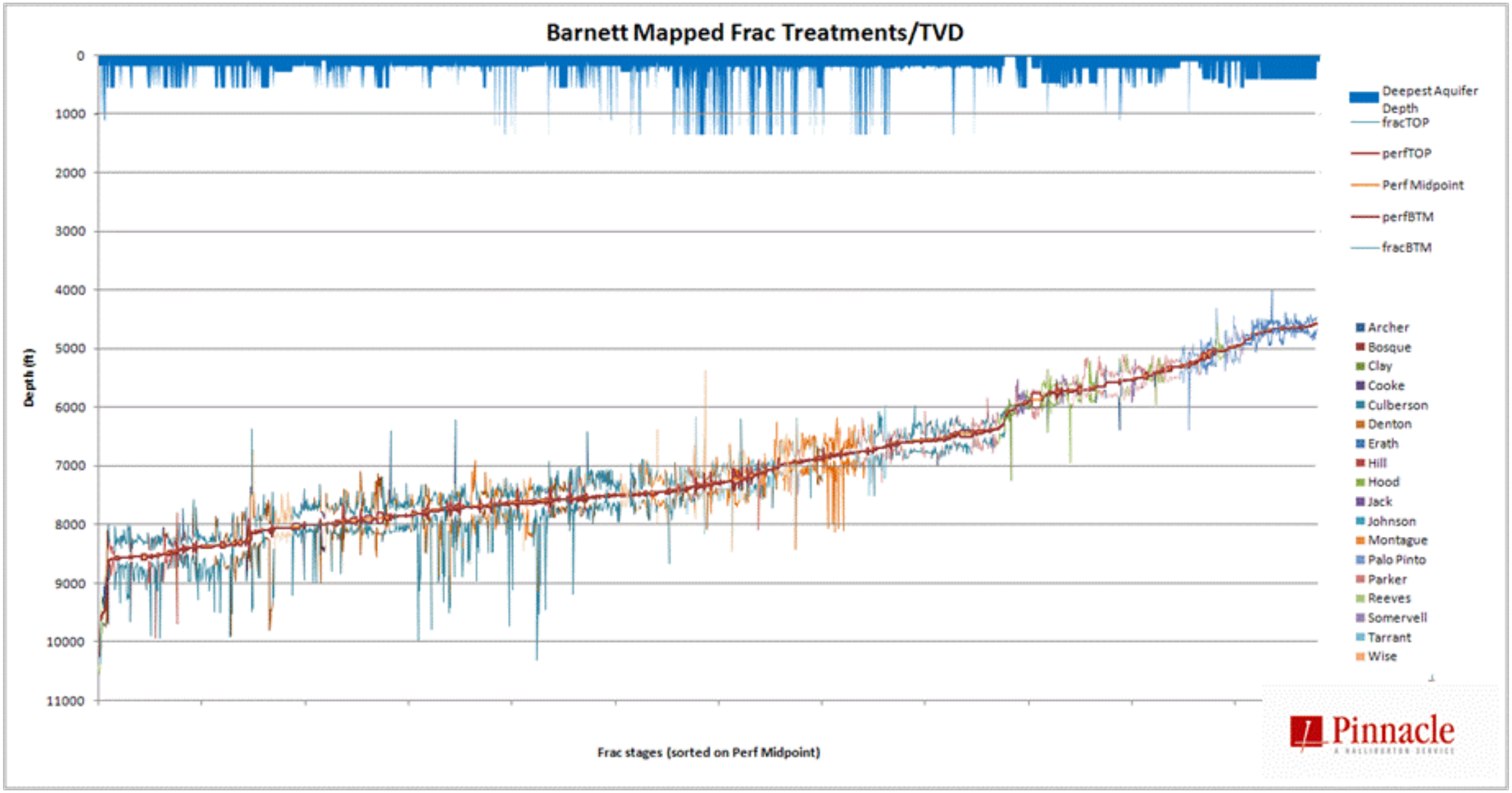




Courtesy George King, Apache Corp.

Will Vertical Hydrofrac Growth Affect Water Supplies?

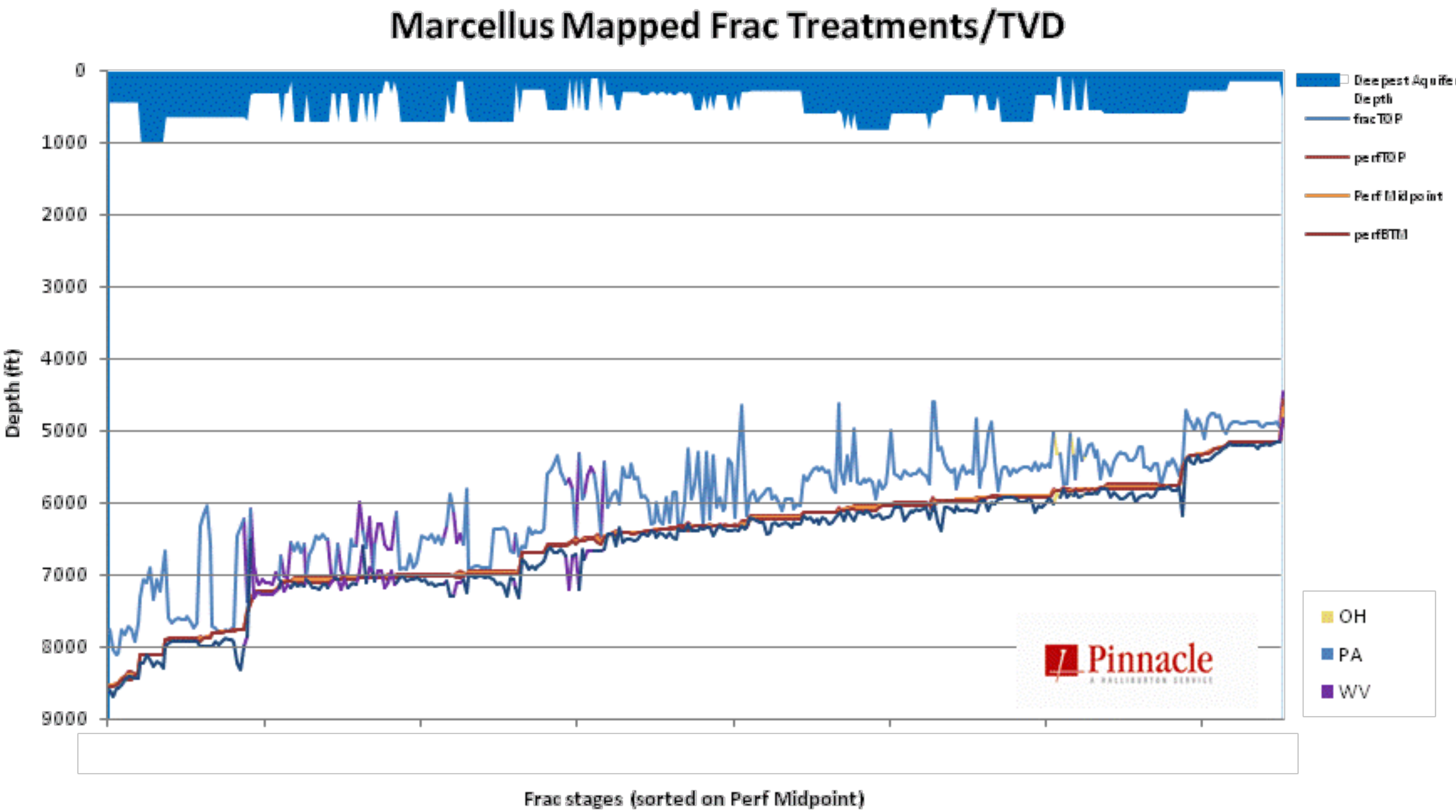
Depth of Affected Region Affected by Hydraulic Fracturing



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

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/

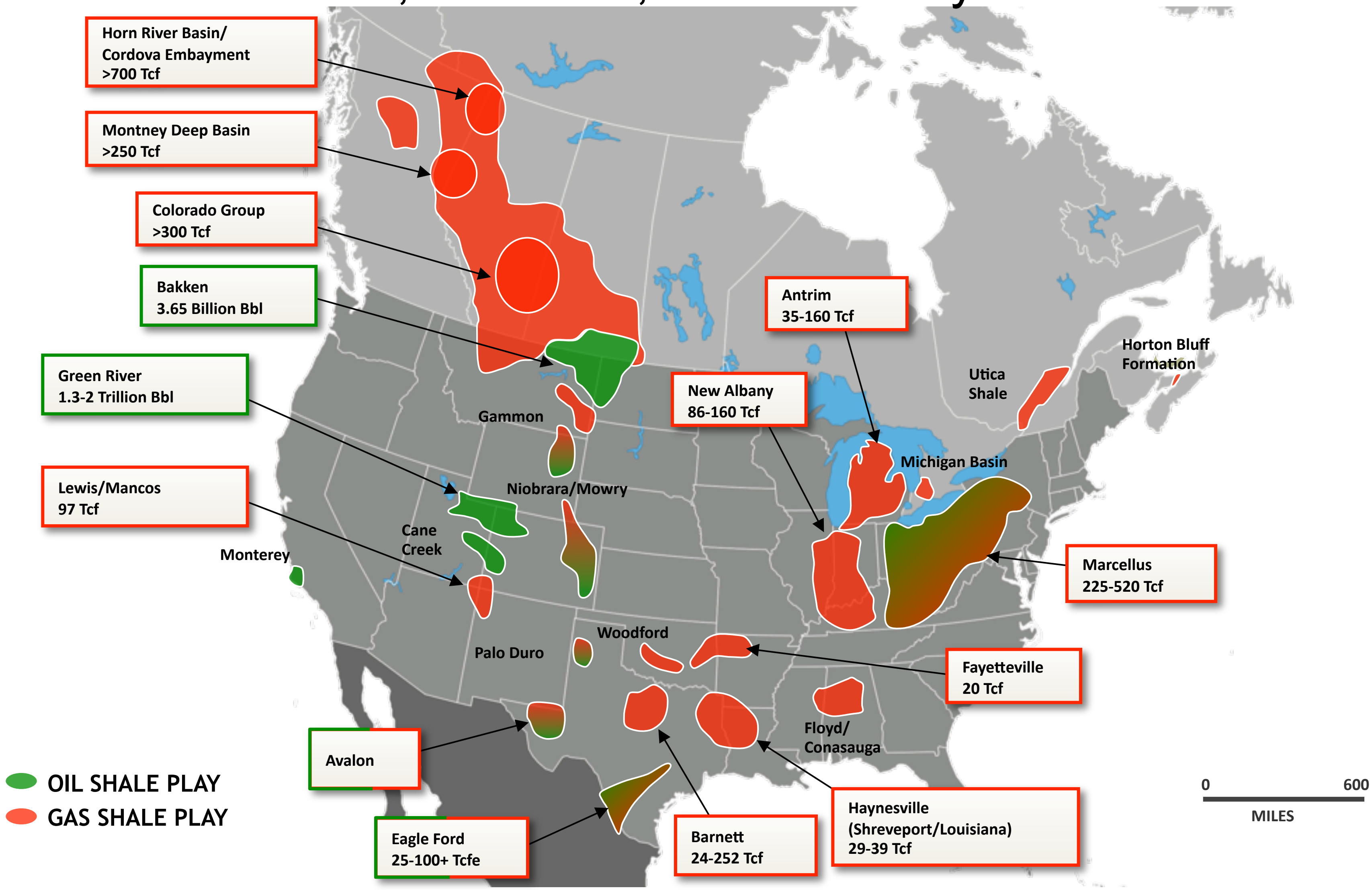
Water Issues Changing Rapidly

Pad Drilling Using Saline Water Wells

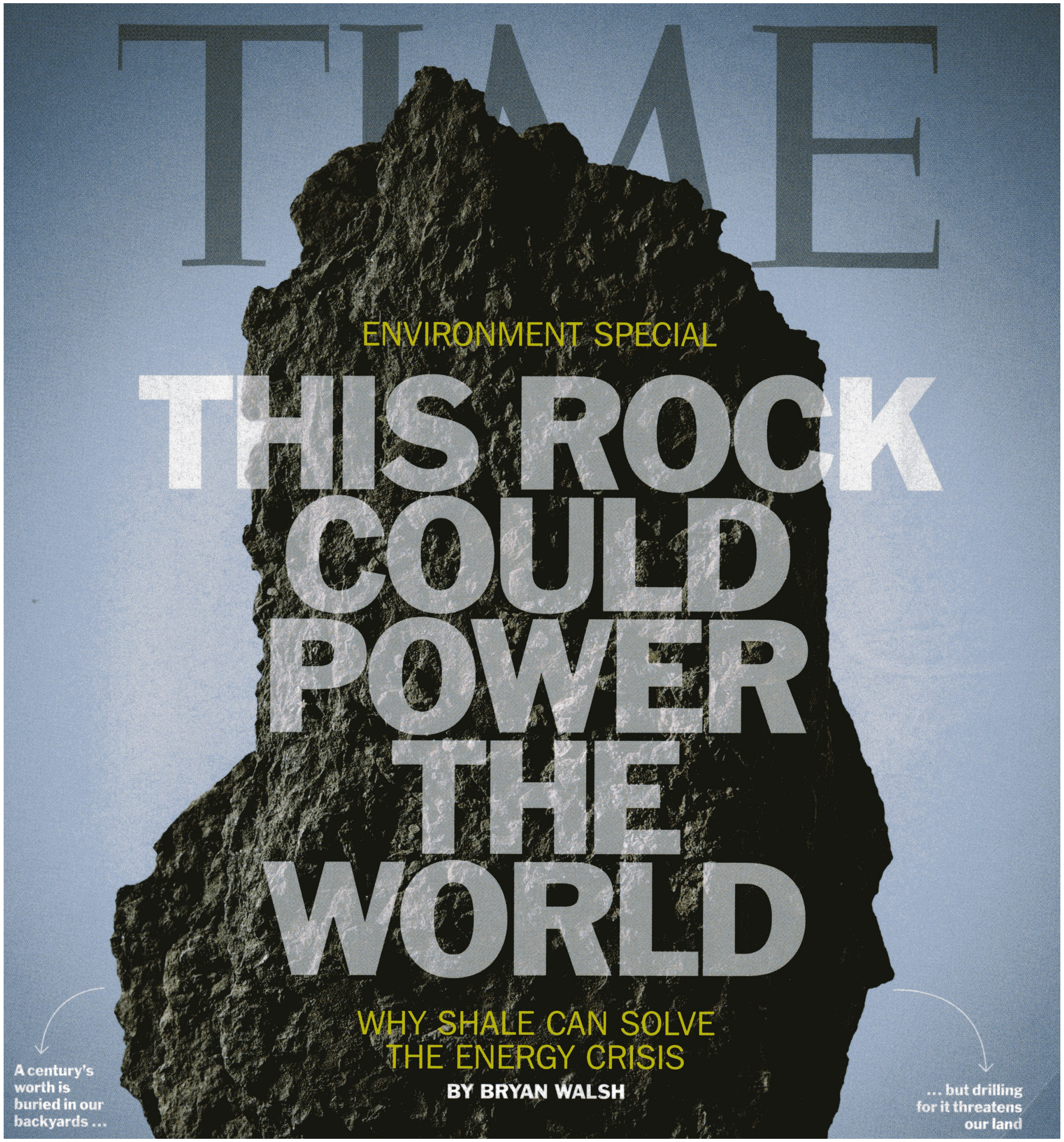
Figure 13. The Apache 34 pad in the Horn River Development of Northern British Colombia is a total of 6.3 acres where twelve multiple fractured horizontal wells recover gas from approximately 5000 acres.

Courtesy George King, Apache Corp.

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!