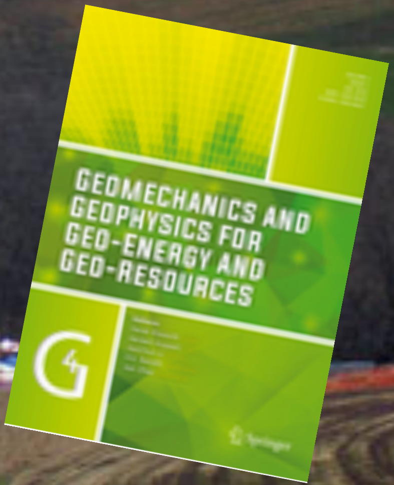
# Gas-Fracturing in Unconventional Reservoirs

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# Prospects for Gas-Fracturing in Unconventional Reservoirs

- Principal Issues in Shale Gas Production - Motivation
  - Energy Outlook: Security, Independence and Environment
  - Water-related issues
  - Waterless fracturing and gas displacement (ESGR)
- Gas-fracturing Observations
  - Breakdown Pressures
    - PMMA/Granite/Bluestone and Structure
      - Key Observations
      - Hypotheses
  - Fracture Complexity
      - Key Observations
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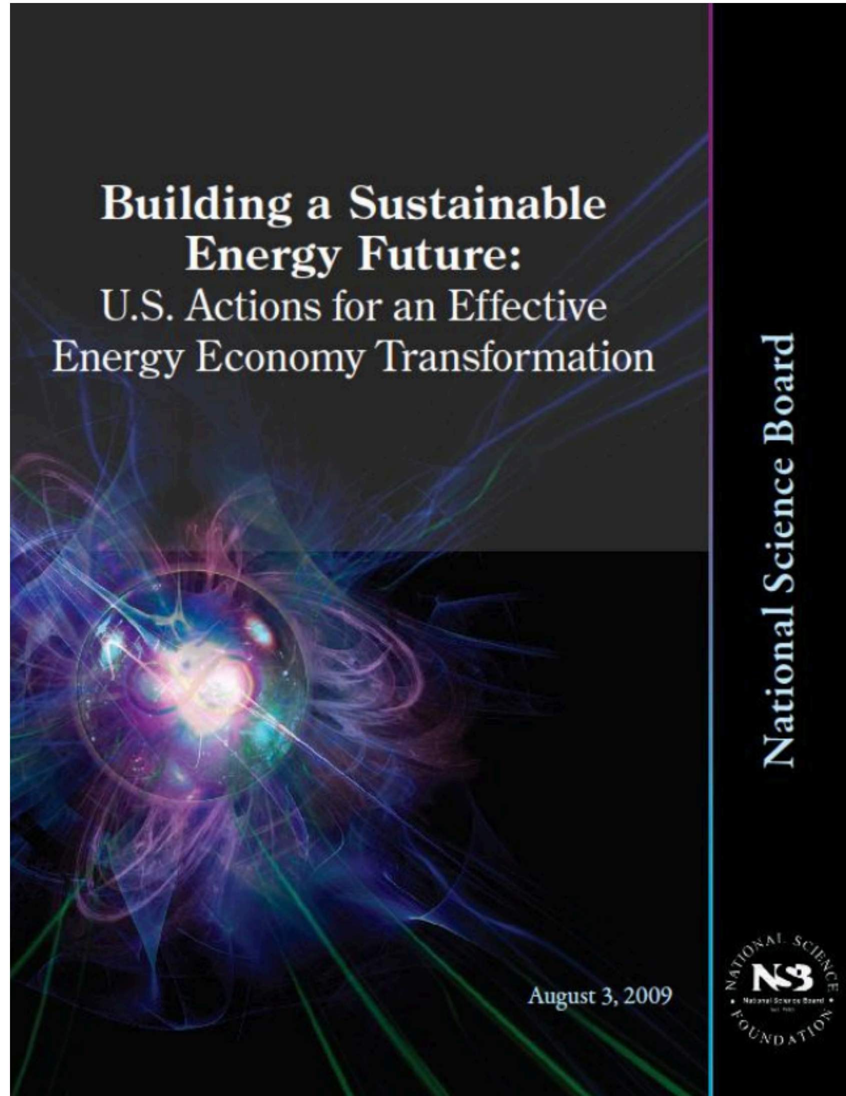
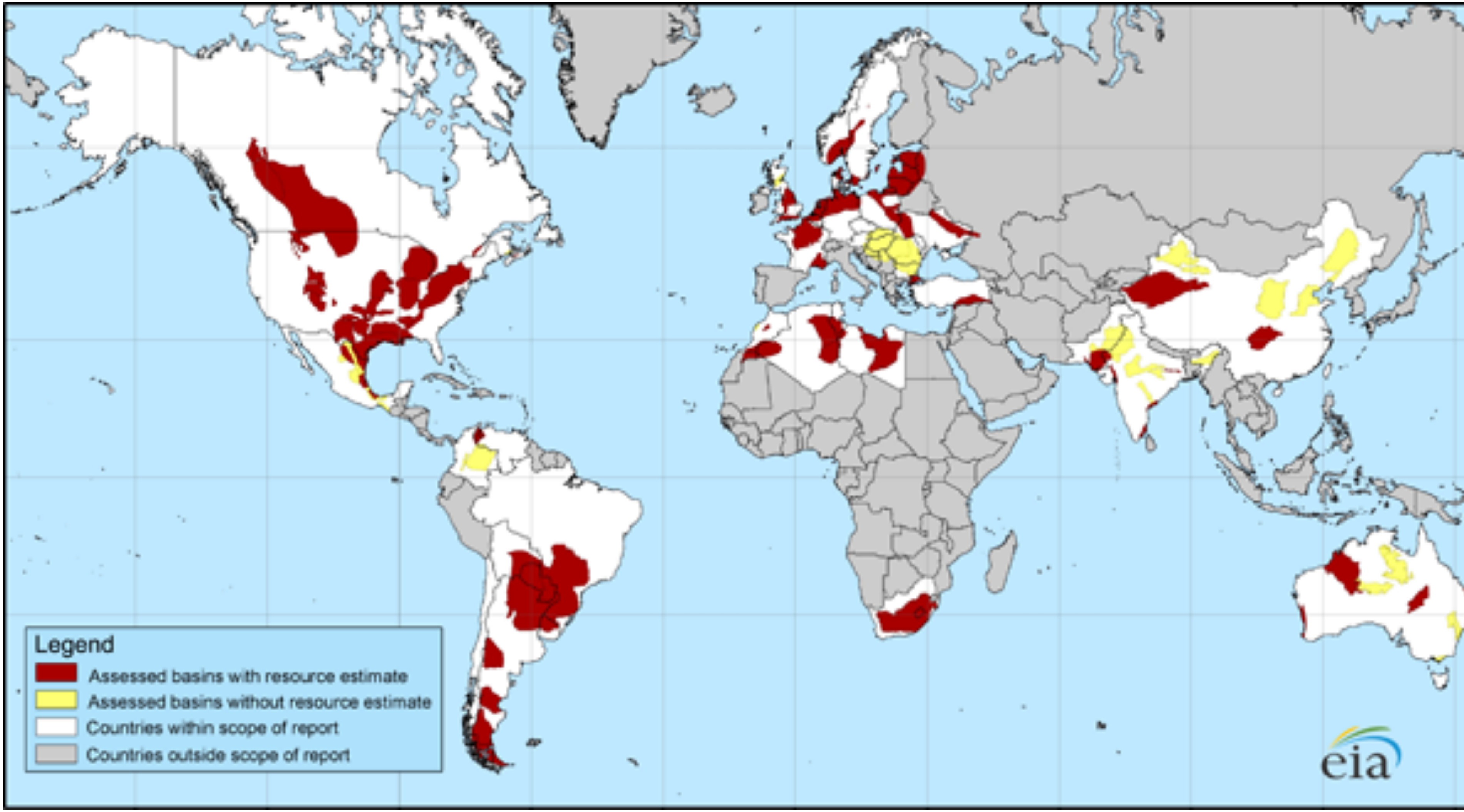
- Methods of Analysis
  - Mechanisms for Gas/Rock Interaction
  - Damage Mechanics
- Summary

# Implications for Energy Independence, Energy Security and for Climate Change?


Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011

# World Shale Plays and Reserves



# World Shale Plays and Reserves

[http://www.eia.gov/analysis/studies/worldshalegas/]

**Table 1. Estimated shale gas technically recoverable resources for select basins in 32 countries, compared to existing reported reserves, production and consumption during 2009**

| | 2009 Natural Gas Market[1] (trillion cubic feet, dry basis) | | | Proved Natural Gas Reserves[2] (trillion cubic feet) | Technically Recoverable Shale Gas Resources (trillion cubic feet) |
|---|---|---|---|---|---|
| | Production | Consump-tion | Imports (Exports) | | |
| **Europe** | | | | | |
| France | 0.03 | 1.73 | 98% | 0.2 | 180 |
| Germany | 0.51 | 3.27 | 84% | 6.2 | 8 |
| Netherlands | 2.79 | 1.72 | (62%) | 49.0 | 17 |
| Norway | 3.65 | 0.16 | (2,156%) | 72.0 | 83 |
| U.K. | 2.09 | 3.11 | 33% | 9.0 | 20 |
| Denmark | 0.30 | 0.16 | (91%) | 2.1 | 23 |
| Sweden | - | 0.04 | 100% | | 41 |
| Poland | 0.21 | 0.58 | 64% | 5.8 | 187 |
| Turkey | 0.03 | 1.24 | 98% | 0.2 | 15 |
| Ukraine | 0.72 | 1.56 | 54% | 39.0 | 42 |
| Lithuania | - | 0.10 | 100% | | 4 |
| Others[3] | 0.48 | 0.95 | 50% | 2.71 | 19 |
| **North America** | | | | | |
| United States[4] | 20.6 | 22.8 | 10% | 272.5 | 862 |
| Canada | 5.63 | 3.01 | (87%) | 62.0 | 388 |
| Mexico | 1.77 | 2.15 | 18% | 12.0 | 681 |
| **Asia** | | | | | |
| China | 2.93 | 3.08 | 5% | 107.0 | 1,275 |
| India | 1.43 | 1.87 | 24% | 37.9 | 63 |
| Pakistan | 1.36 | 1.36 | - | 29.7 | 51 |
| **Australia** | 1.67 | 1.09 | (52%) | 110.0 | 396 |
| **Africa** | | | | | |
| South Africa | 0.07 | 0.19 | 63% | - | 485 |
| Libya | 0.56 | 0.21 | (165%) | 54.7 | 290 |
| Tunisia | 0.13 | 0.17 | 26% | 2.3 | 18 |
| Algeria | 2.88 | 1.02 | (183%) | 159.0 | 231 |
| Morocco | 0.00 | 0.02 | 90% | 0.1 | 11 |
| Western Sahara | - | - | | - | 7 |
| Mauritania | - | - | | 1.0 | 0 |
| **South America** | | | | | |
| Venezuela | 0.65 | 0.71 | 9% | 178.9 | 11 |
| Colombia | 0.37 | 0.31 | (21%) | 4.0 | 19 |
| Argentina | 1.46 | 1.52 | 4% | 13.4 | 774 |
| Brazil | 0.36 | 0.66 | 45% | 12.9 | 226 |
| Chile | 0.05 | 0.10 | 52% | 3.5 | 64 |
| Uruguay | - | 0.00 | 100% | | 21 |
| Paraguay | - | - | | | 62 |
| Bolivia | 0.45 | 0.10 | (346%) | 26.5 | 48 |
| **Total of above areas** | **53.1** | **55.0** | **(3%)** | **1,274** | **6,622** |
| **Total world** | **106.5** | **106.7** | **0%** | **6,609** | |

Sources:
[1]Dry production and consumption: EIA, International Energy Statistics, as of March 8, 2011.
[2] Proved gas reserves: *Oil and Gas Journal*, Dec., 6, 2010, P. 46-49.
[3]Romania, Hungary, Bulgaria.
[4] U.S. data are from various EIA sources. The proved natural gas reserves number in this table is from the U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2009 report, whereas the 245 trillion cubic feet estimate used in the Annual Energy Outlook 2011 report and cited on the previous page is from the previous year estimate.

# Consumption -versus- Reserve/Res[obscured]rce

## Natural Gas and Other Fossil

| | United States | | | | |
|---|---|---|---|---|---|
| Source | Consumption | Reserv | | | |
| Coalbed | ~2 | | | | |
| Gas Shale | | | | | |
| | | | | | Tcf |
| | | | | | Tcf equiv. |
| | | | ~70 | | Tcf equiv. |
| **T** | | | **~350** | | Tcf equiv. |

Global Energy Capacity ~15 TW ($10^{12}$W=Trillion W)

Annual Energy Consumption ~ 500 EJ/y ($10^{18}$J/y)

1 EJ ~ 1 Quadrillion Btu ~ 1 Tcf gas

Global Energy Consumption: ~ 500 EJ/y

~500 Quads /y

Equivalent to: ~ 500 Tcf gas/y

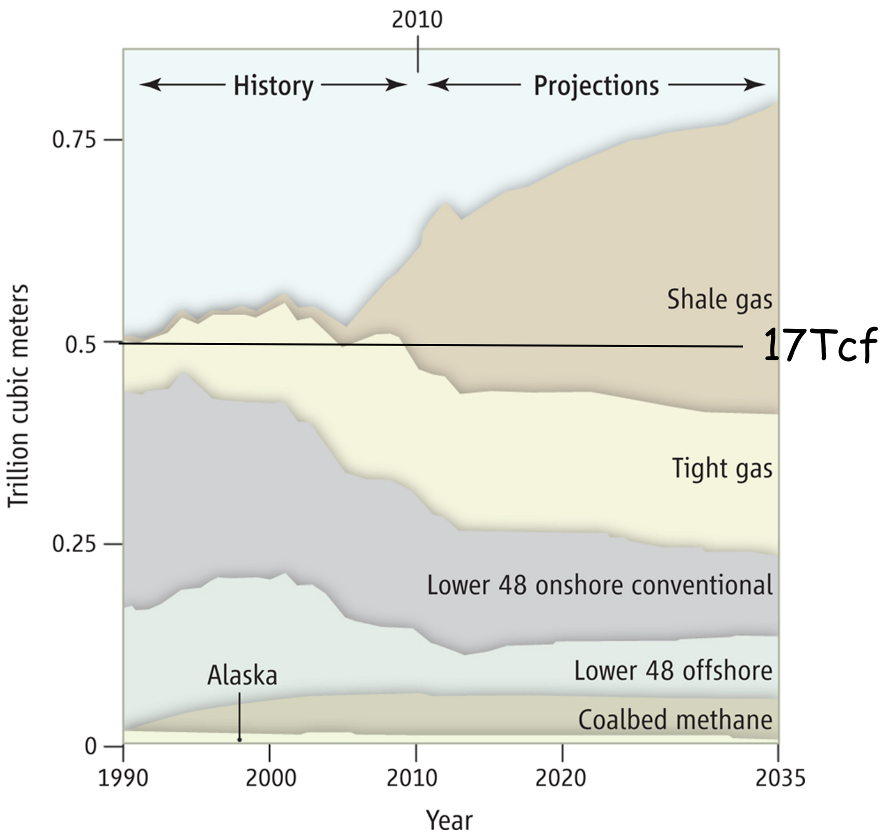
G… energy capacity ~15TW x $10^5$s x 365 d = $500\times10^{18}$J/y = 500 EJ/y

1 Tcf ~ 1 EJ ~ 1 Quad

[International Energy Outlook 2010, US EIA, 2010]

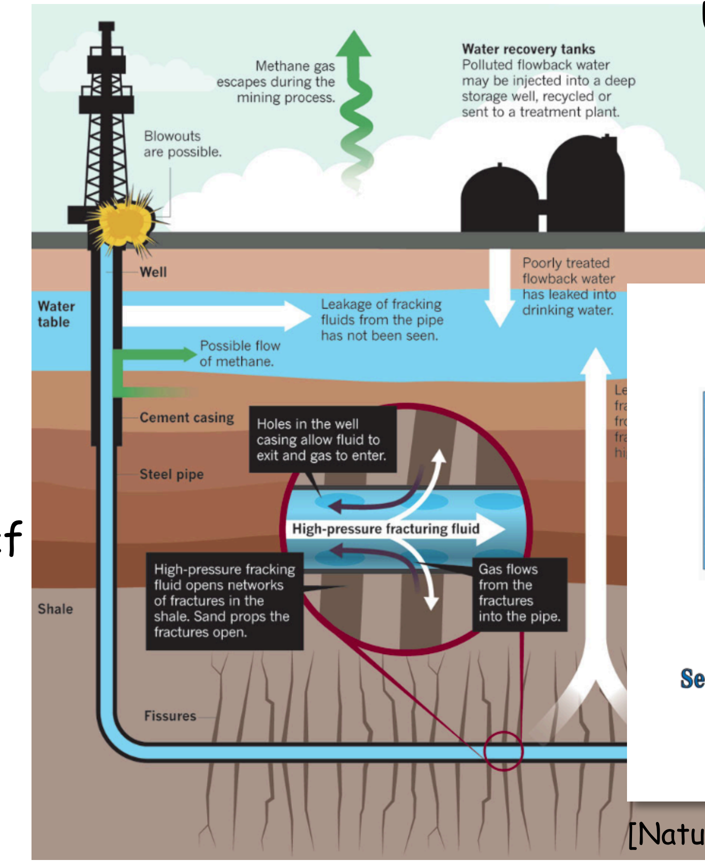
# Projected Growth and Opportunities

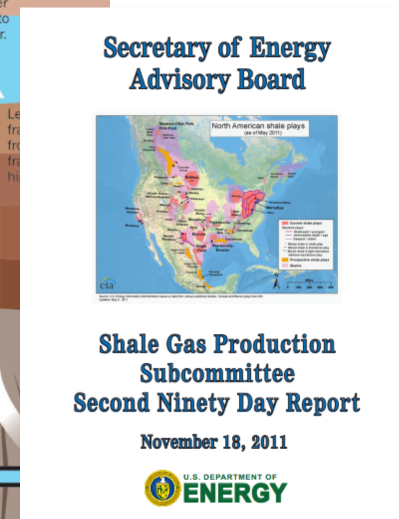
Natural Gas Utilization




[Science, Oct 18, 2012]

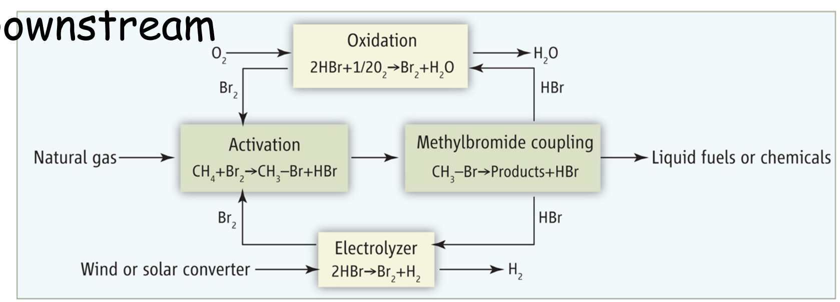
Upstream




[Nature, 2011]

Downstream





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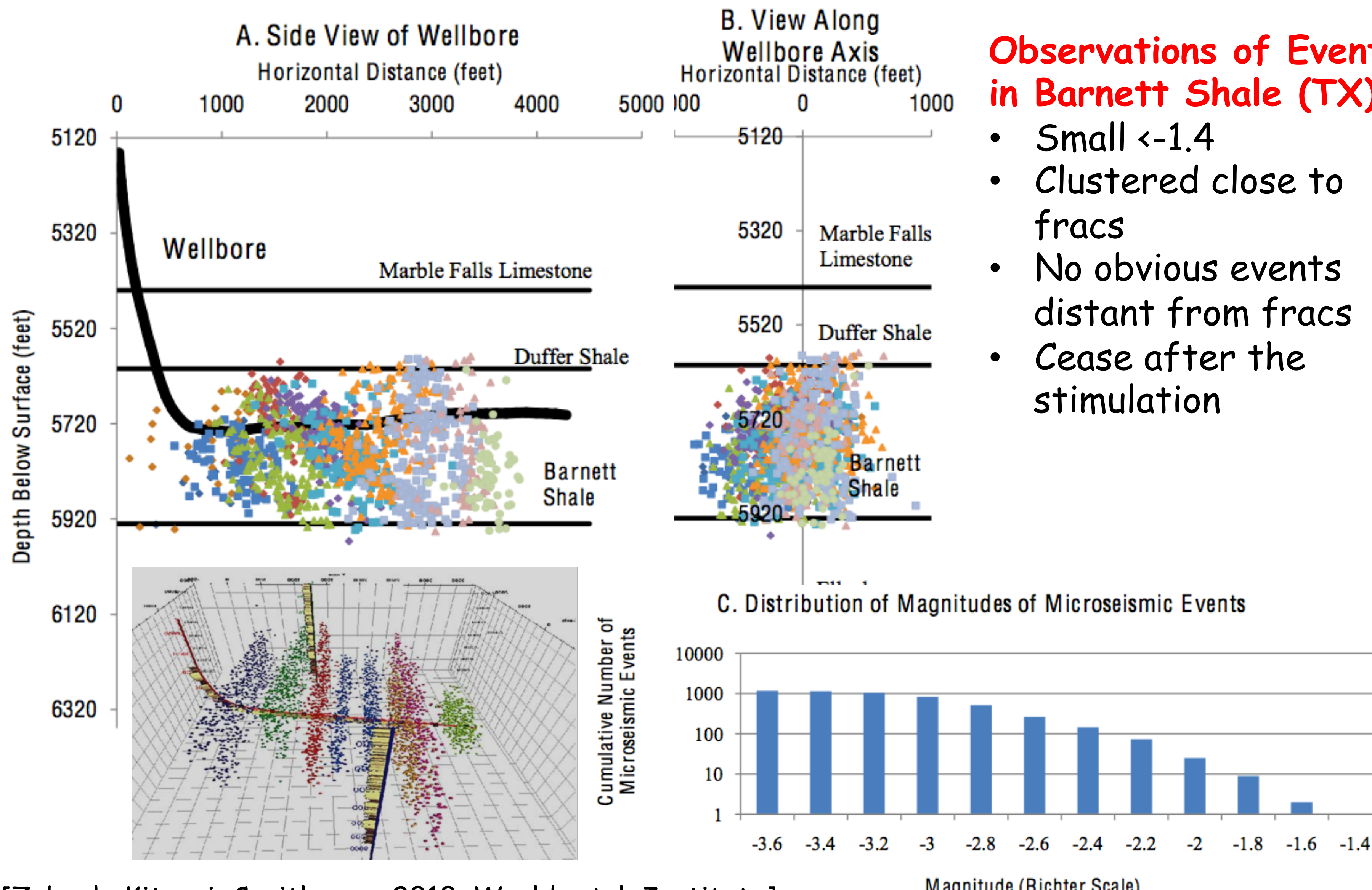
# Issues – Rural Industrialization

# Induced Seismicity




## Observations of Events in Barnett Shale (TX)

- Small <-1.4
- Clustered close to fracs
- No obvious events distant from fracs
- Cease after the stimulation

[Zoback, Kitasei, Copithorne, 2010, Worldwatch Institute]

# Induced Seismicity

NEWSFOCUS

**Ohio rumblings.** Wastewater injected at this site in Youngstown triggered jolting earthquakes that prompted injection-well shutdowns and strong new regulations.

SEISMOLOGY

## Learning How to NOT Make Your Own Earthquakes

**As fluid injections into Earth's crust trigger quakes across the United States, researchers are scrambling to learn how to avoid making more**

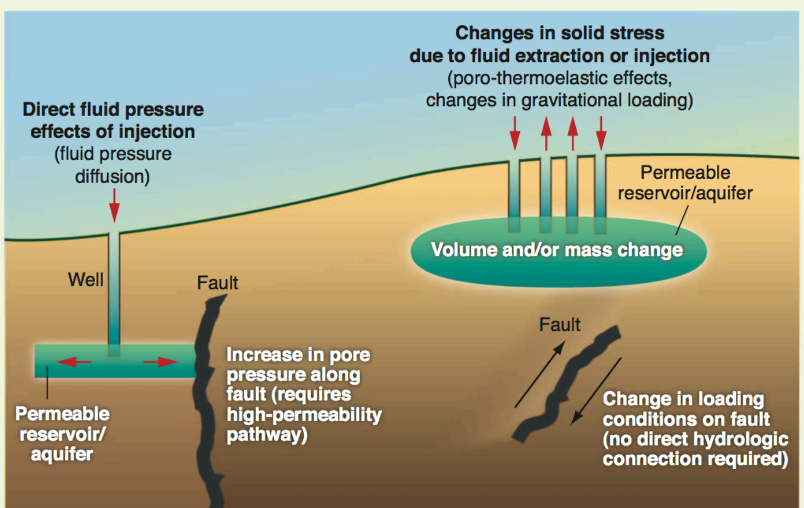
First off, fracking for shale gas is not touching off the earthquakes that have been shaking previously calm regions from New Mexico to Texas, Ohio, and Arkansas. But all manner of other energy-related fluid injection—including deep disposal of fracking's wastewater, seismicity, they are beginning to see a way ahead: learn as you go. Thorough preinjection studies followed by close monitoring of cautiously increasing injection offer to lower, although never eliminate, the risk of triggering intolerable earthquakes.

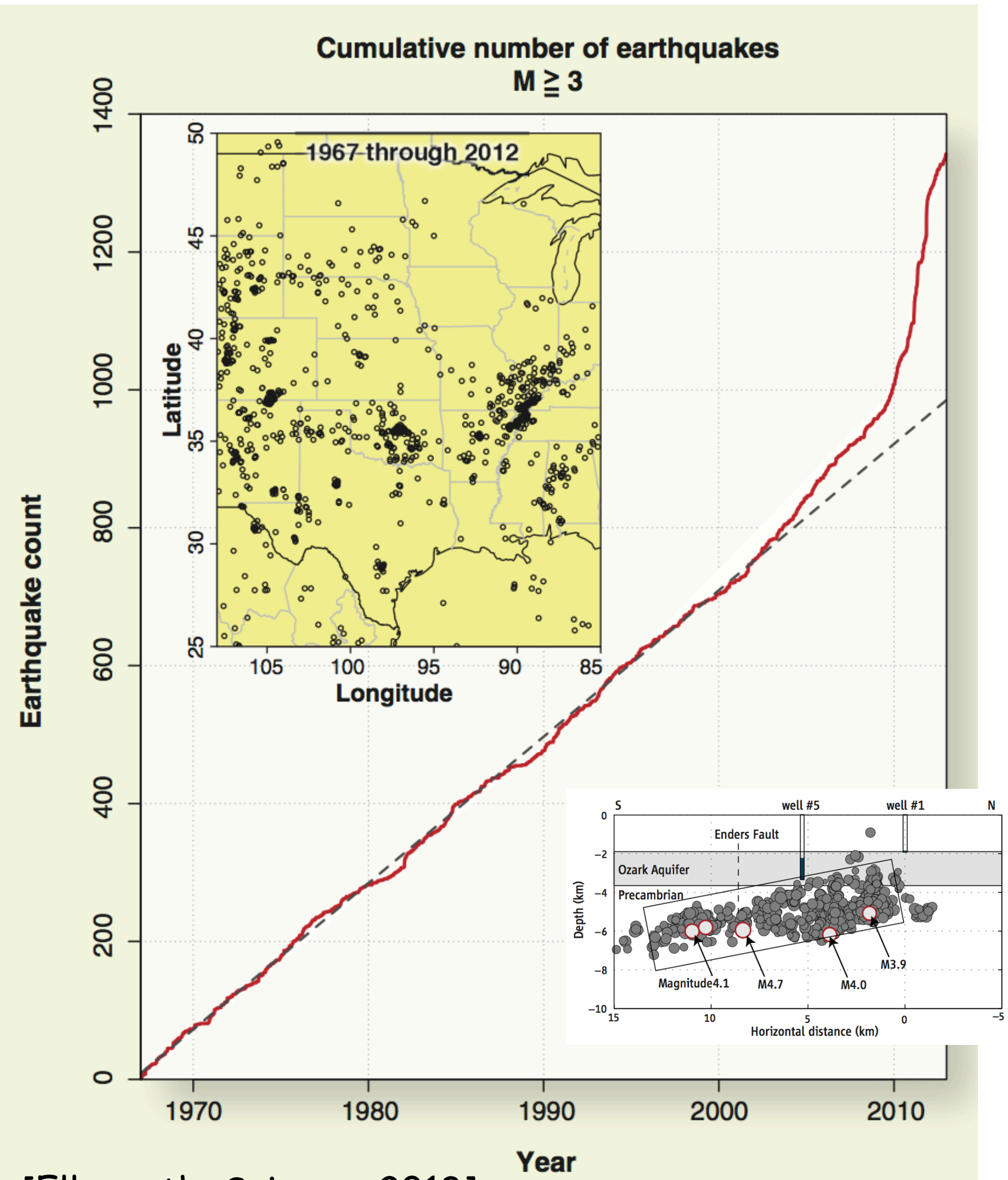
Arkansas. In the current March/April issue of *Seismological Research Letters*, the University of Memphis seismologist recounts his learn-as-you-go experience with injection-triggered quakes strong enough to seriously shake up the locals.

Fracking for natural gas, formally known as hydraulic fracturing, had come to Arkansas around 2009. Not that a seismologist in Memphis would have noticed. Injecting water into gas-bearing shale at high pressures does break the rock to free the gas—that's the point, after all. But the resulting tiny quakes rarely get above magnitude 0 (the logarithmic scale includes negative numbers), never mind to the magnitude-3 quakes that people might feel.

But shale gas drillers need to dispose of the millions of liters of water laden with natural brines and added chemicals that flow back up after a shale gas well has been fracked (*Science*, 25 June 2010, p. 1624). Injecting fracking wastewater into deep rock is a common solution, so starting in April 2009, 1- to 3-kilometer-deep disposal wells were sunk in the vicinity of Guy (population 706) and Greenbrier (population 4706), Arkansas.

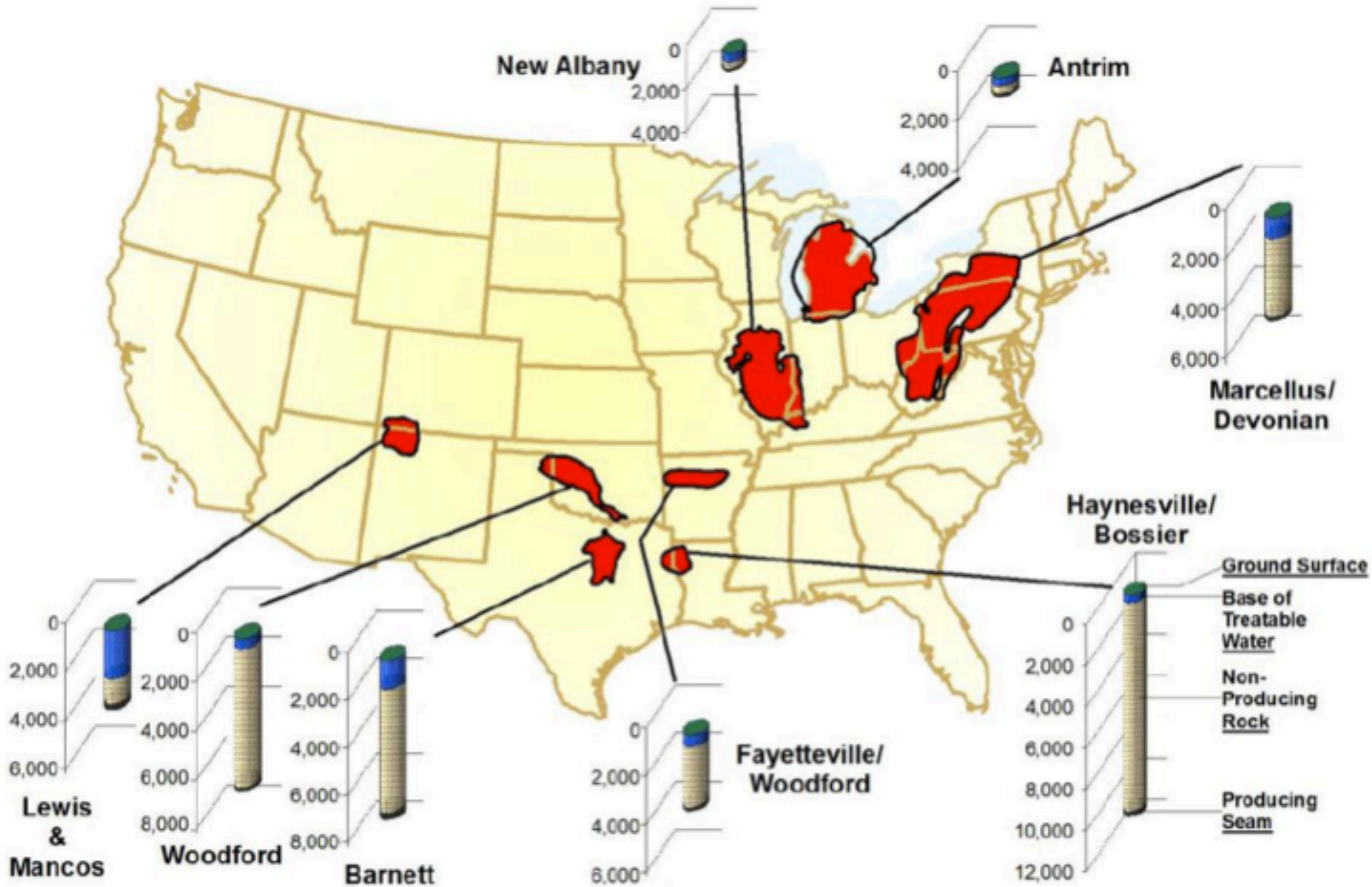
That's when Horton and Scott Ausbrooks of the Arkansas Geological Survey took note of a curious cluster of earthquakes near Greenbrier. The Guy-Greenbrier area had had only one quake of magnitude 2.5 or greater in 2007 and two in 2008. But there were



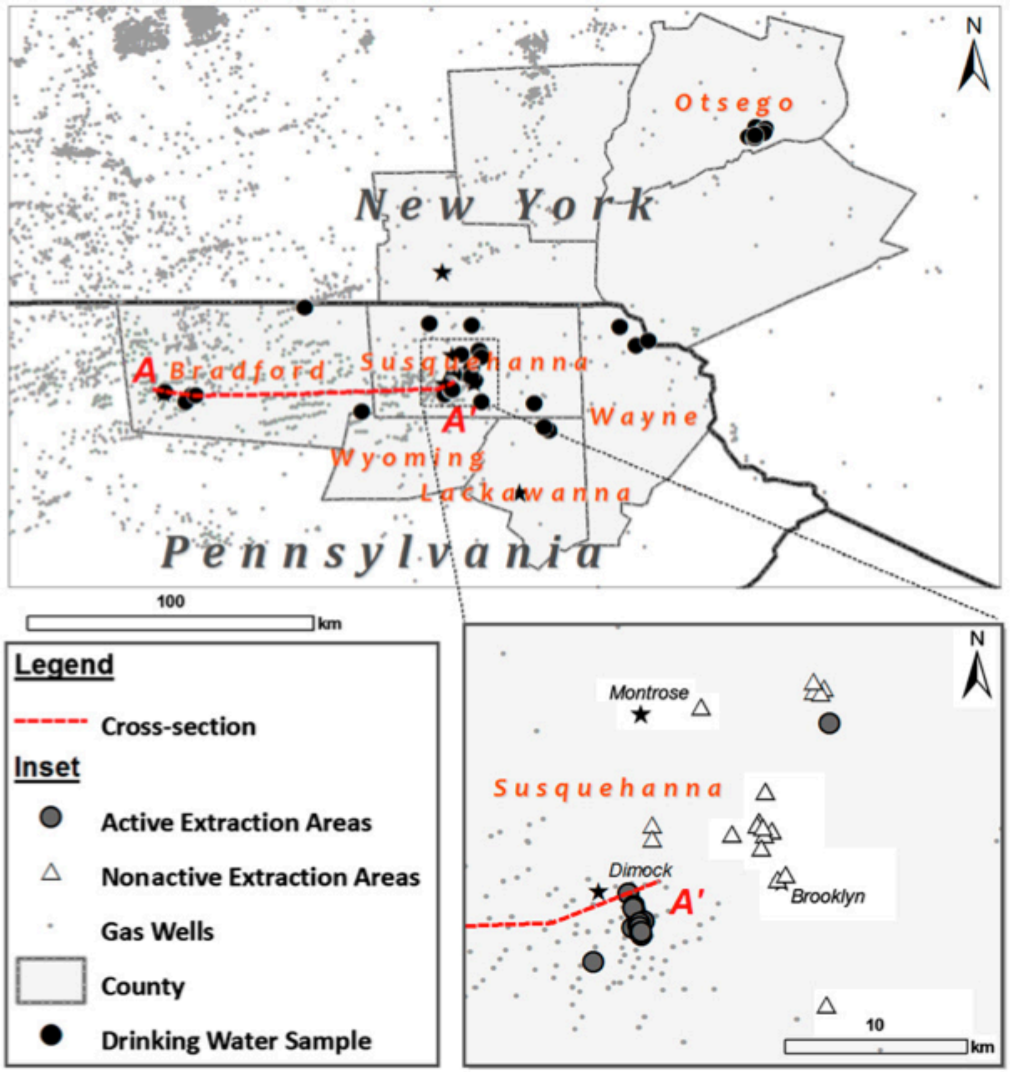

[Ellsworth, Science, 2013]

# Groundwater

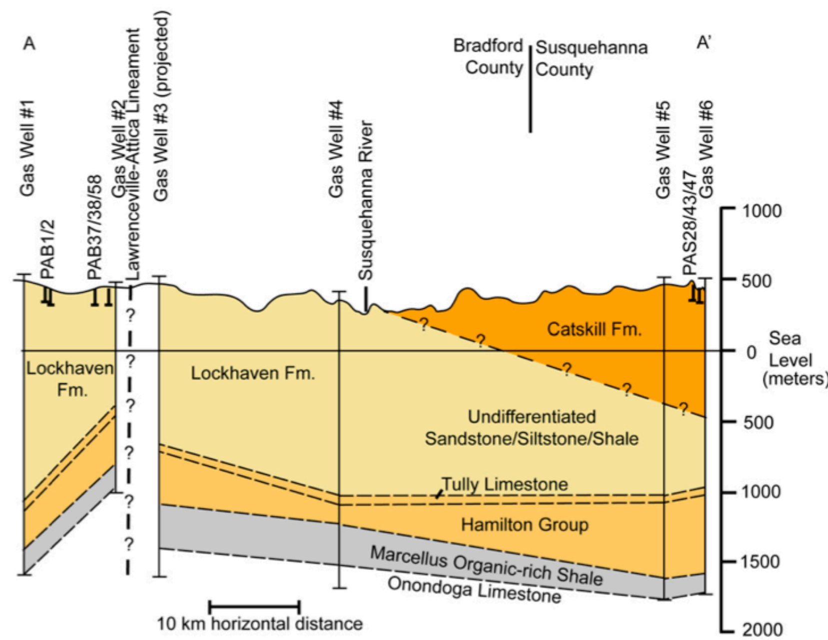



[Zoback, Kitasei, Copithorne, 2010, Worldwatch Institute]

# Groundwater Near-Wellbore

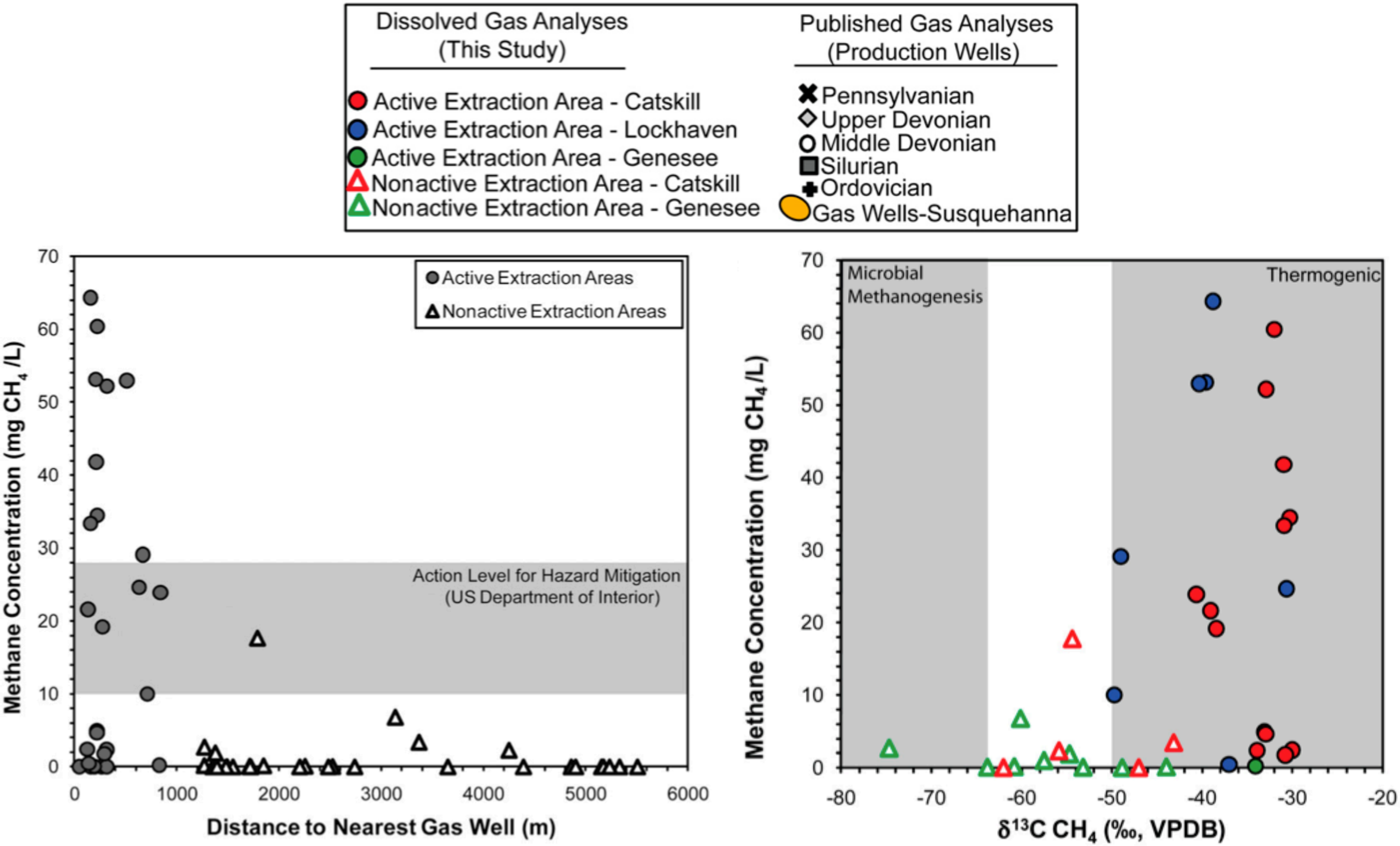






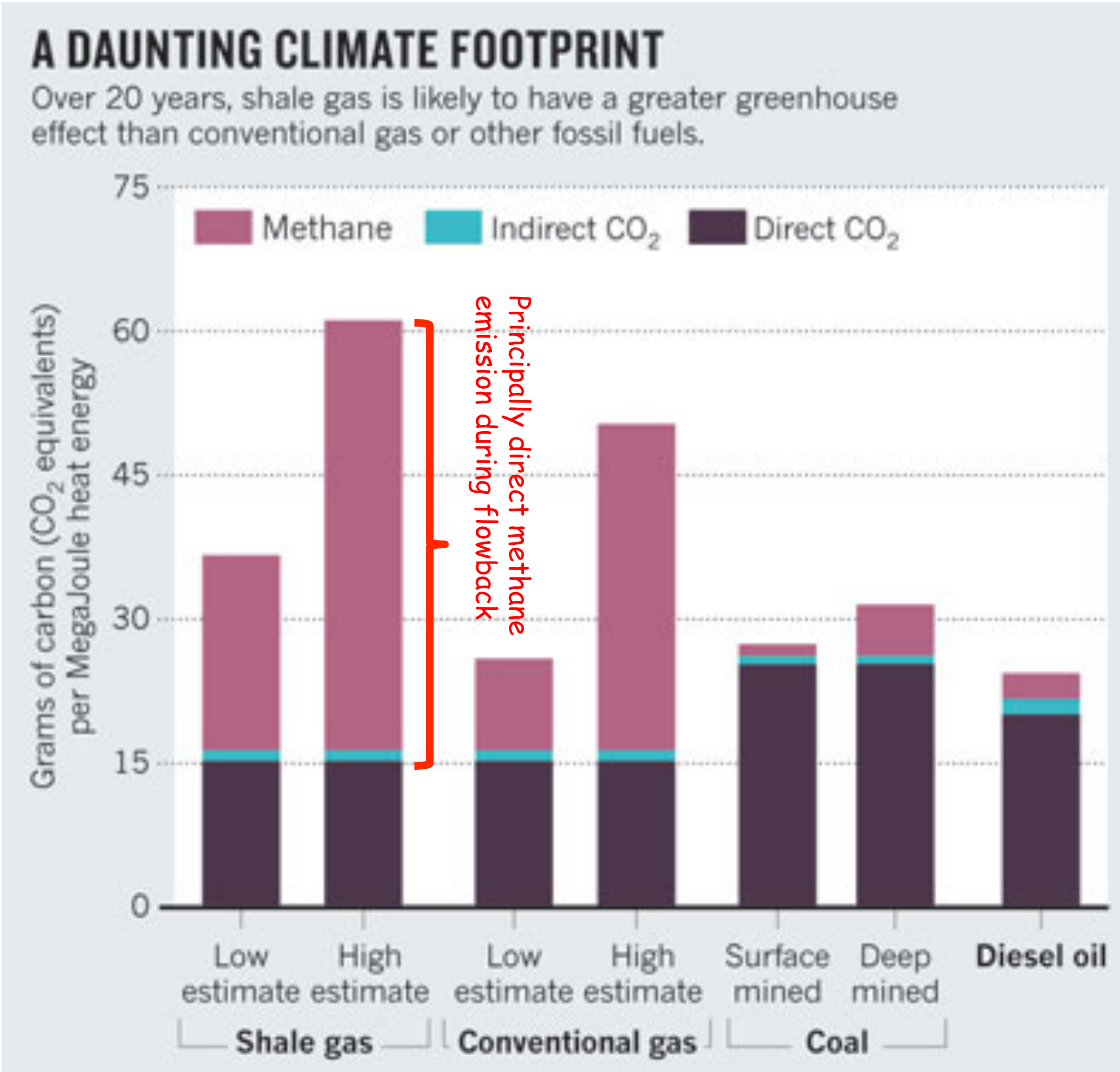

[Osborne, Vengosh, Warner, Jackson, 2011, PNAS]

# Groundwater Near-Wellbore



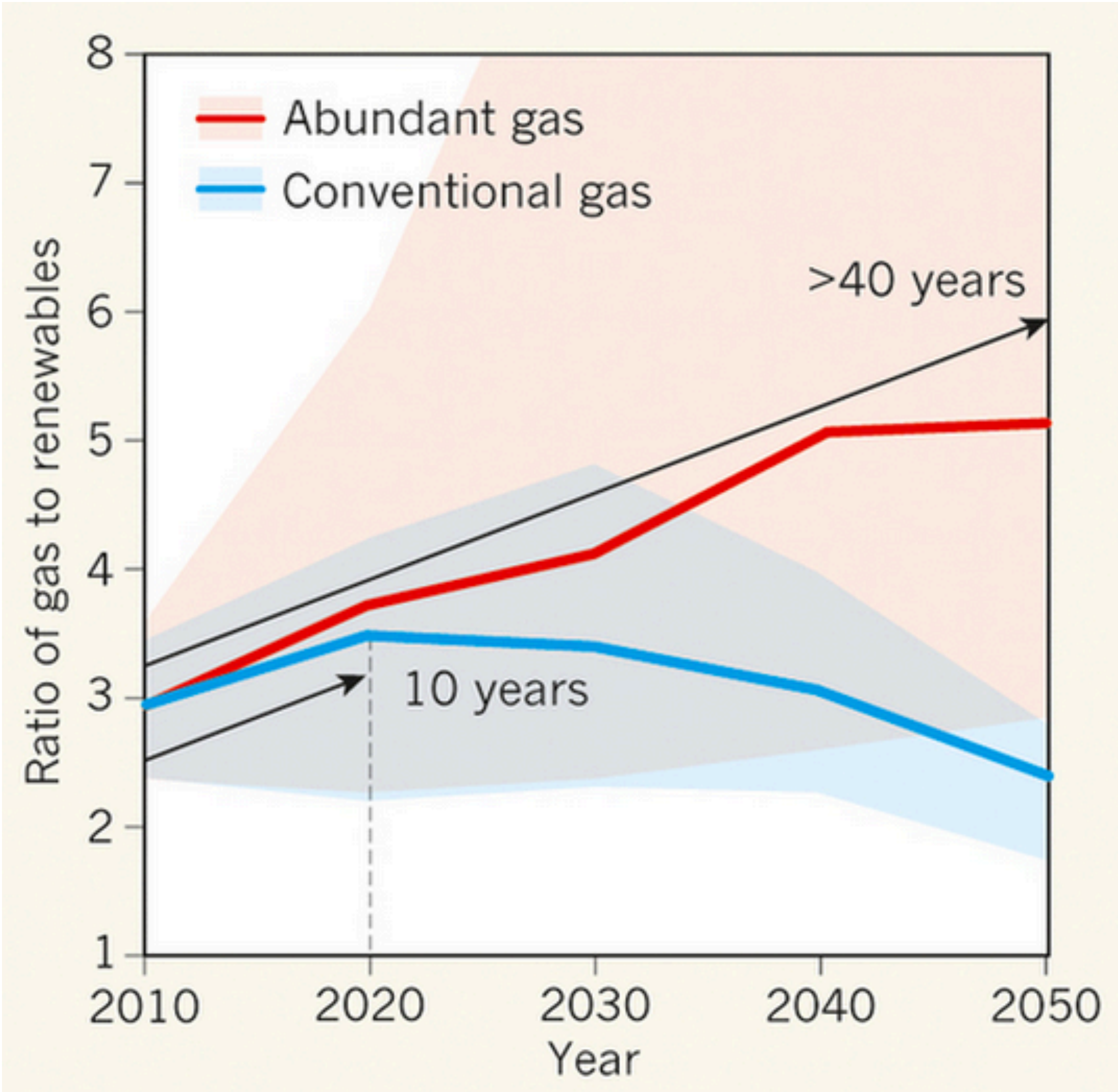

[Osborne, Vengosh, Warner, Jackson, 2011, PNAS]

# Life-Cycle Loadings




[Howarth, Santoro, Ingraffea, 2011, Climatic Change]

# Impacts of Abundant Gas Supply

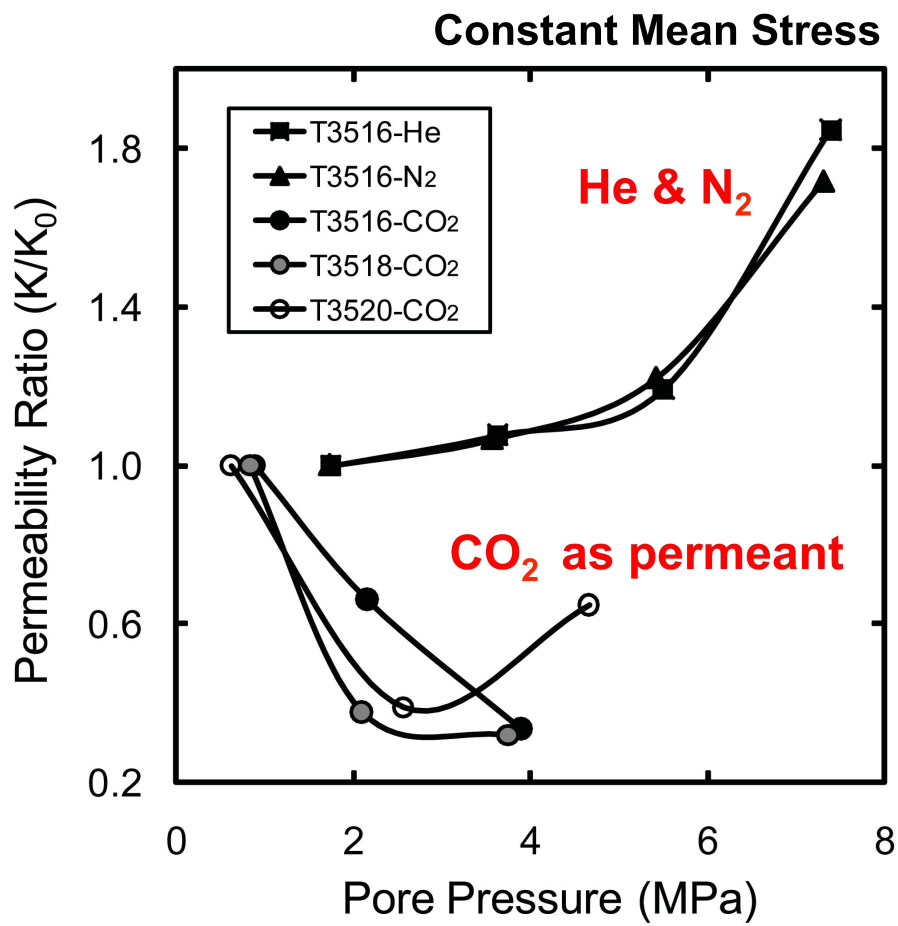



Role of abundant natural gas supply… impact on reducing use of coal …….but also of decreasing the penetration of renewables

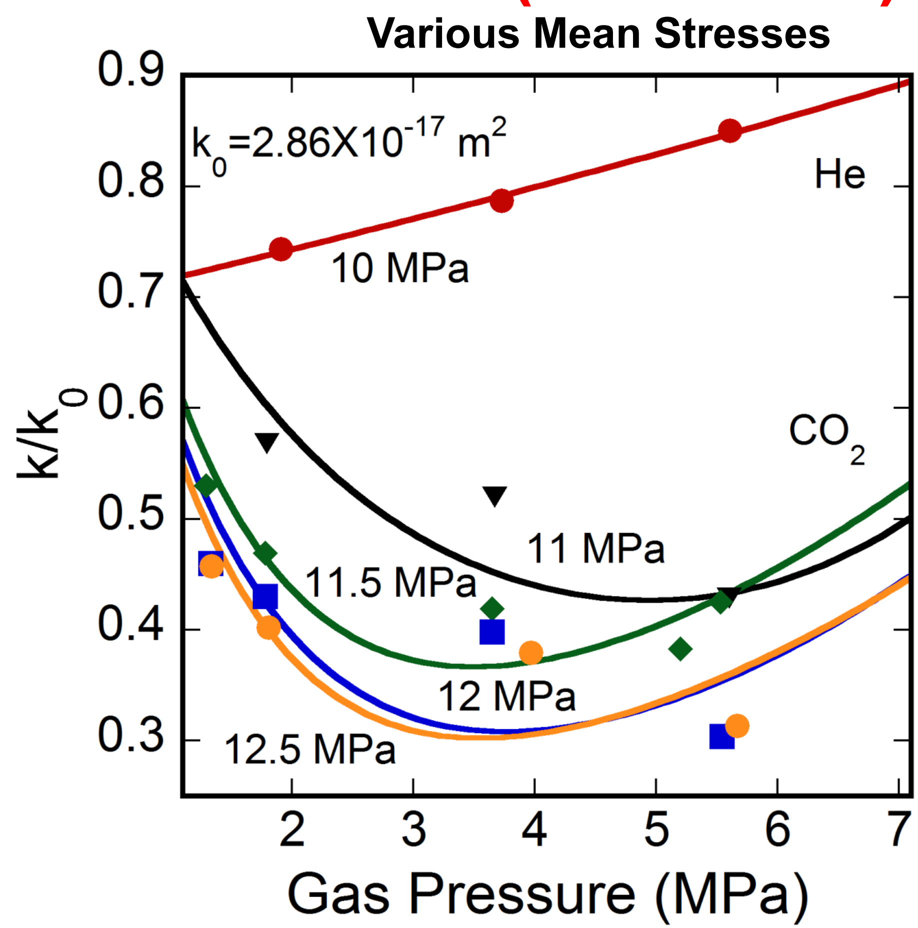
[McJeon et al., Nature, 2015]

# Permeability Evolution – Implications for Gas Recovery?

## Coal



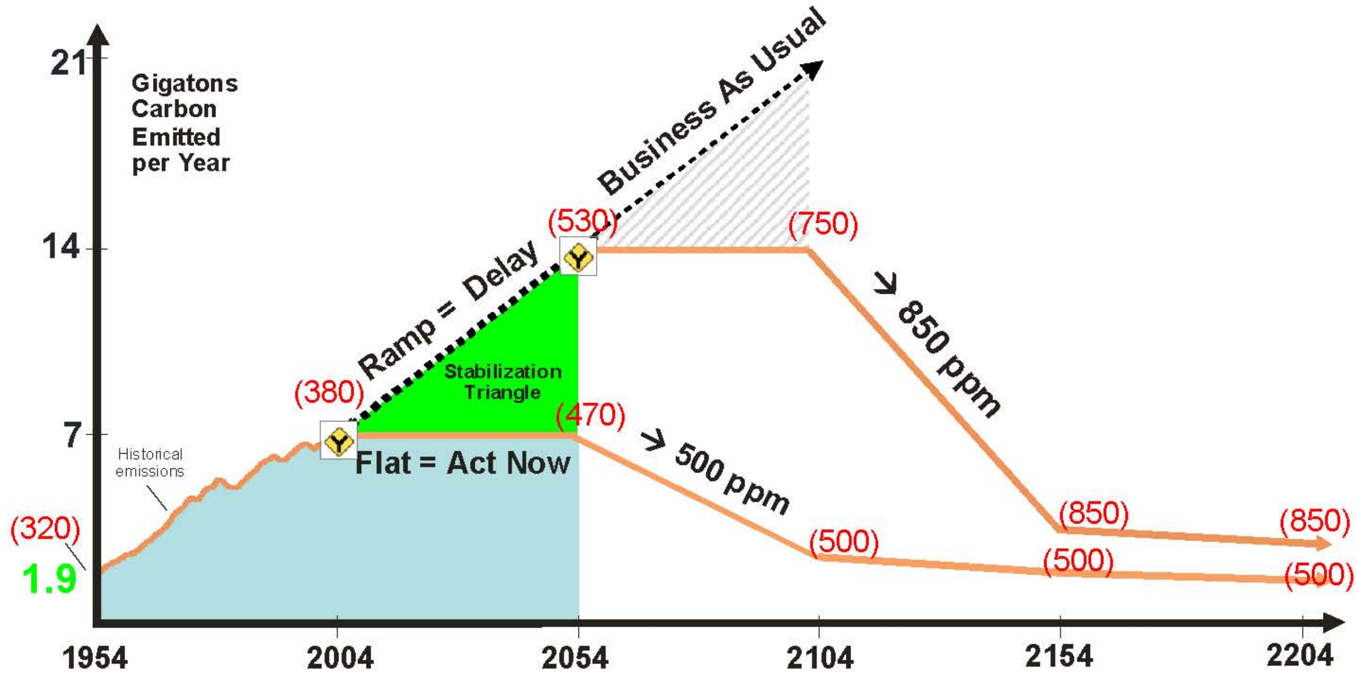

## Gas Shale (Marcellus)




## $CO_2$ as permeant - Analogous to $CH_4$

# Capacity Needs – Socolow Wedges

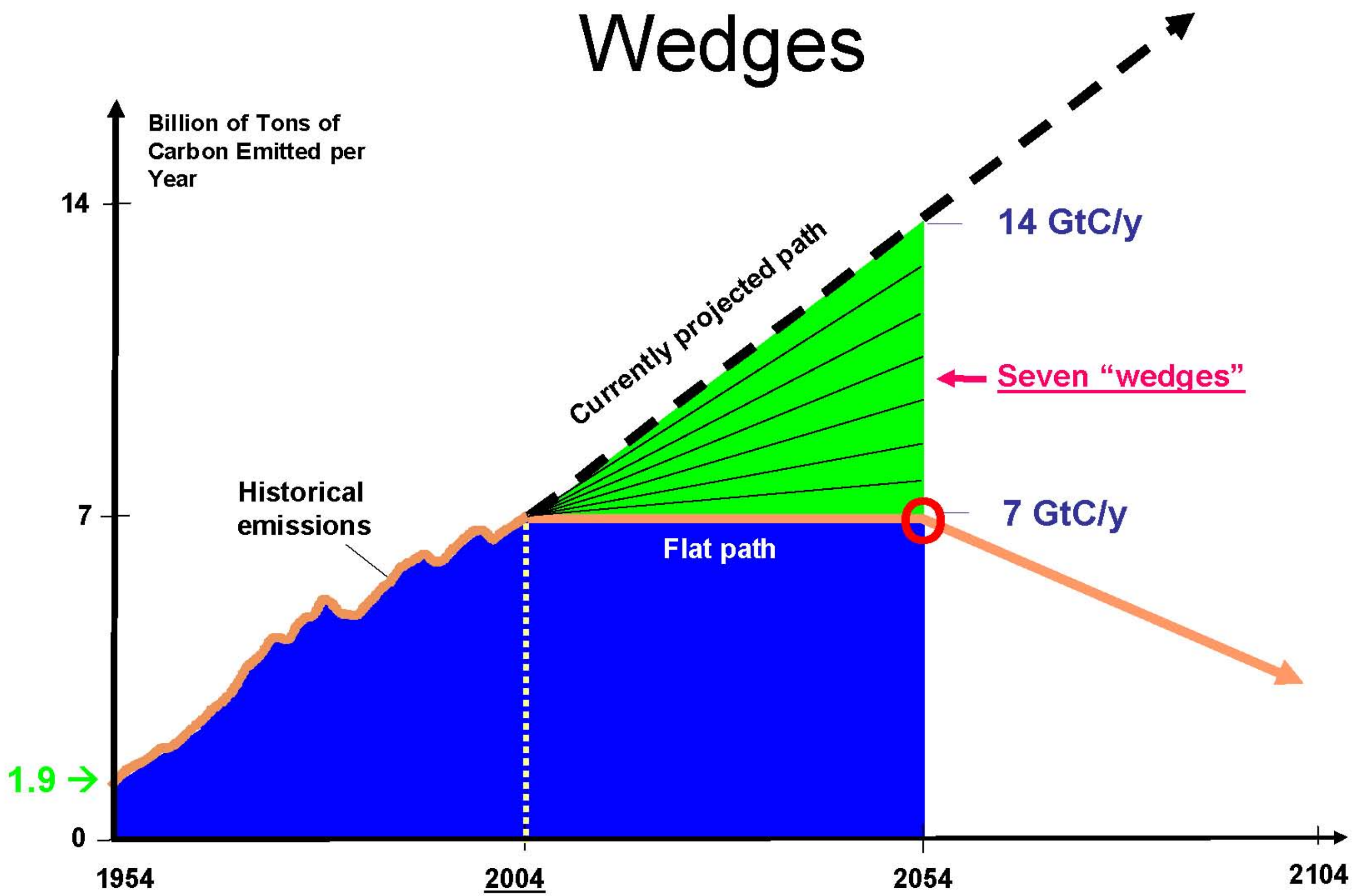
## The Stabilization Triangle: Beat doubling or accept tripling




Values in parentheses are ppm. Note the identity (a fact about the size of the Earth's atmosphere): 1 ppm = 2.1 GtC.

[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

# Capacity Needs – Socolow Wedges

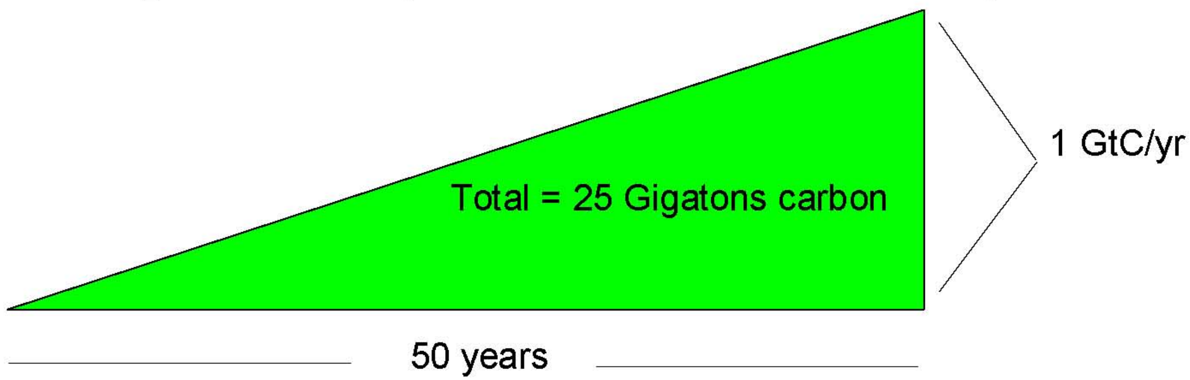



[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

# Capacity Needs – Socolow Wedges

## What is a “Wedge”?

A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr.



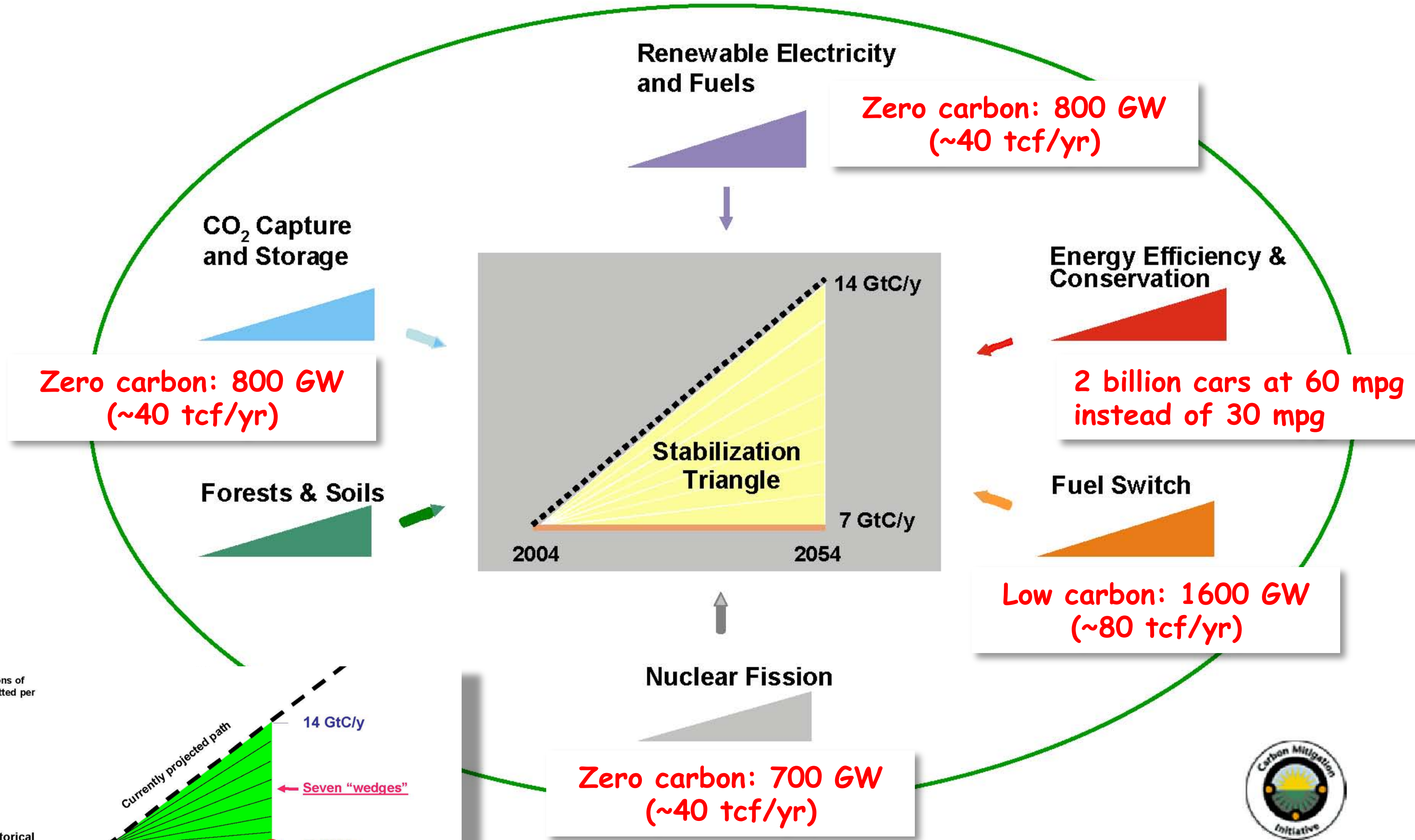

Cumulatively, a wedge redirects the flow of 25 Gt(C) in its first 50 years. This is 2.5 trillion dollars at $100/t(C).

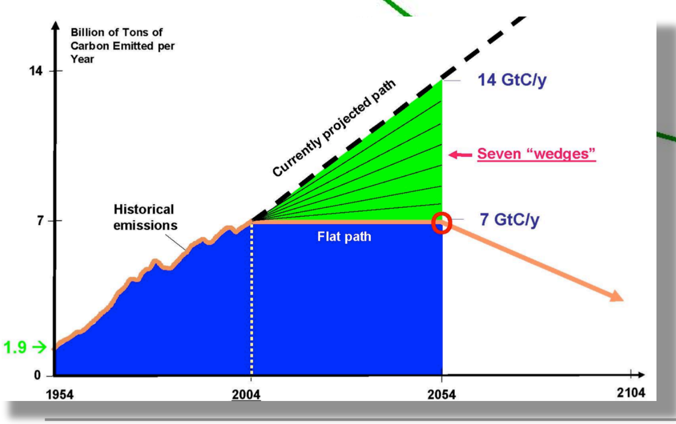
A “solution” to the Greenhouse problem should have the potential to provide at least one wedge.

[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

# Capacity Needs – Socolow Wedges

## Fill the Stabilization Triangle with Seven Wedges

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# Motivation

**Gas Recovery (Improved production)**

- Energetic fracturing – reducing diffusion lengths

**Incidental Benefits (Improved environmental protection)**

- Decrease water usage
  - Resource usage
  - Induced seismicity
  - Reduce surface transportation/disruption
- Minimize effect on sensitive reservoir rocks
  - Avoid pore occlusion with fluids
  - Avoid swelling of clays
  - Avoid recovery of NORMS
- Reduce life-cycle equivalent $CO_2$ costs

# Key Coupled Processes Related to Gas-Fracturing in Unconventional Reservoirs

- Principal Issues in Shale Gas Production
  - Energy Outlook: Security, Independence and Environment
  - Water-related issues
  - **Waterless fracturing and gas displacement (ESGR)**
- Observations
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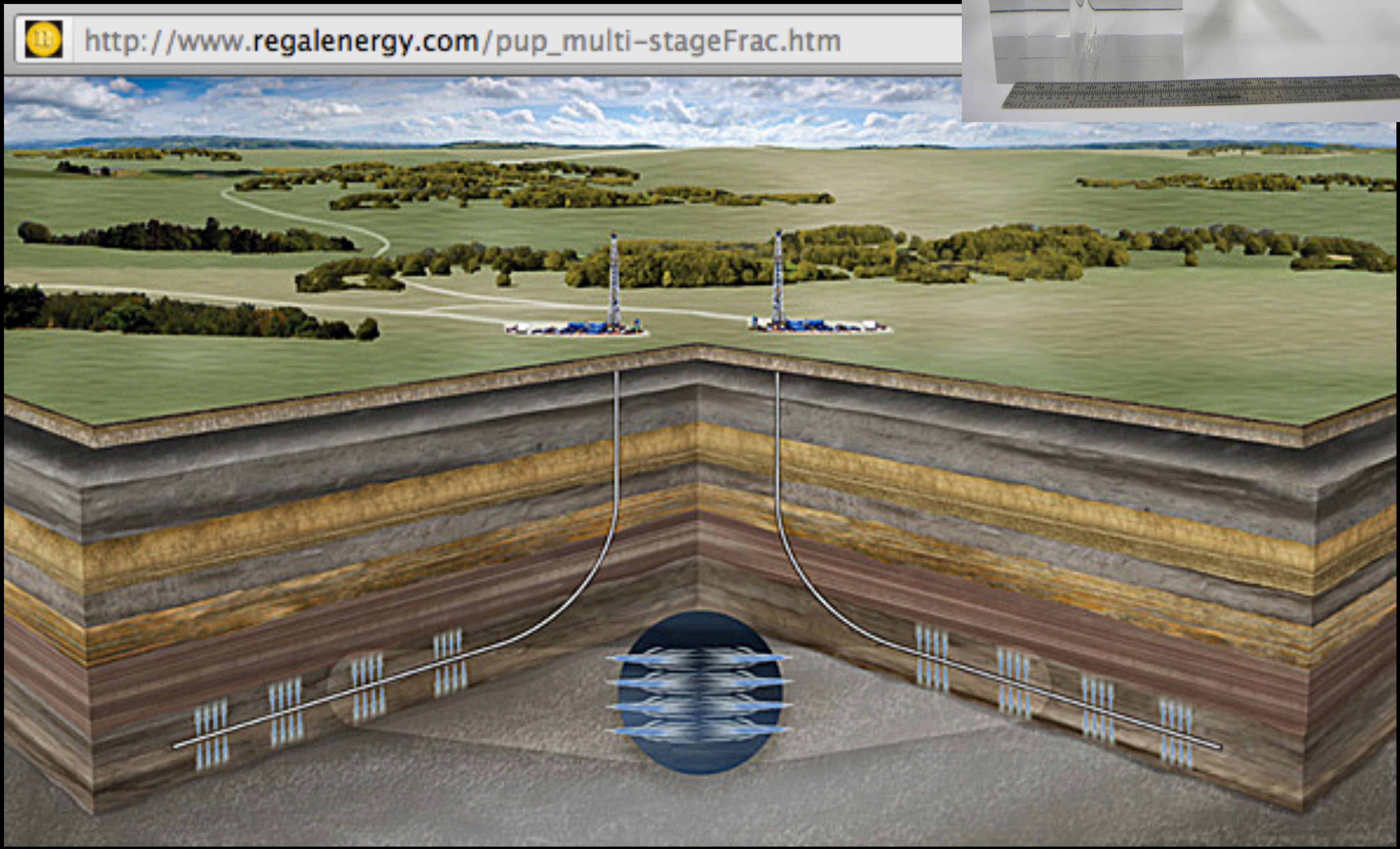
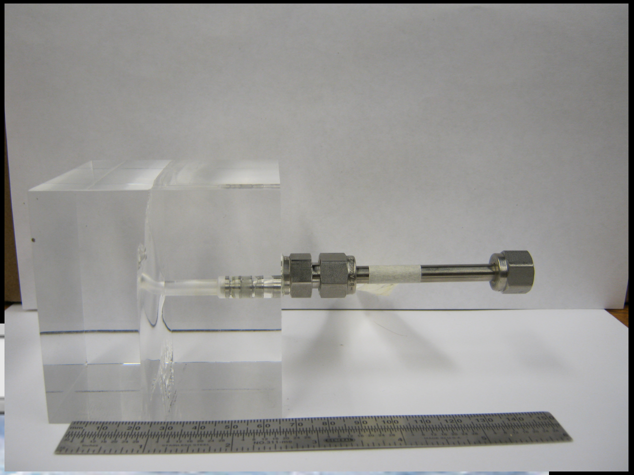
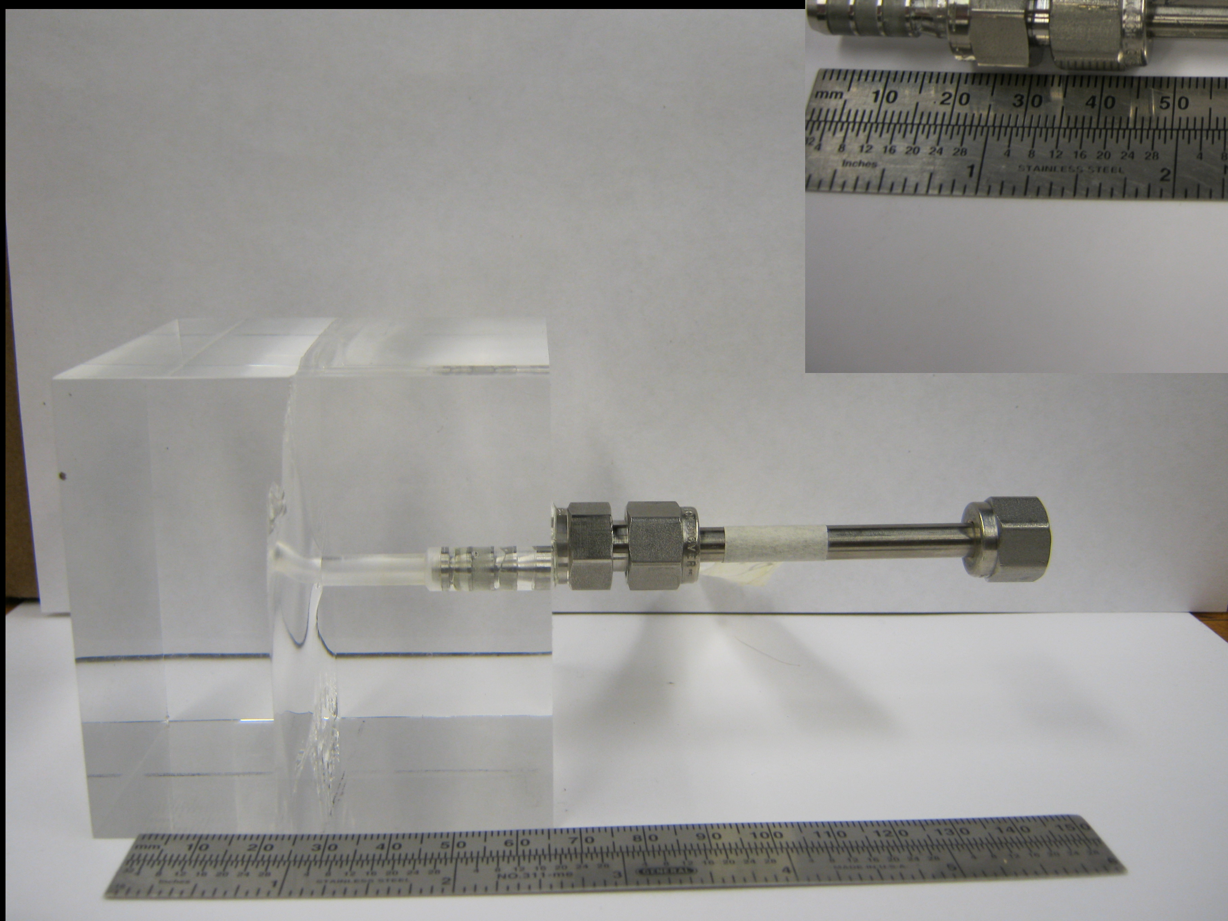
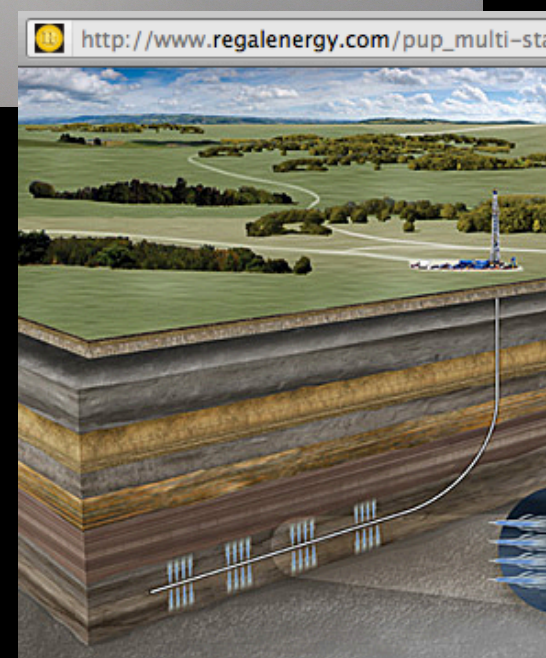
# Fluid Delivery



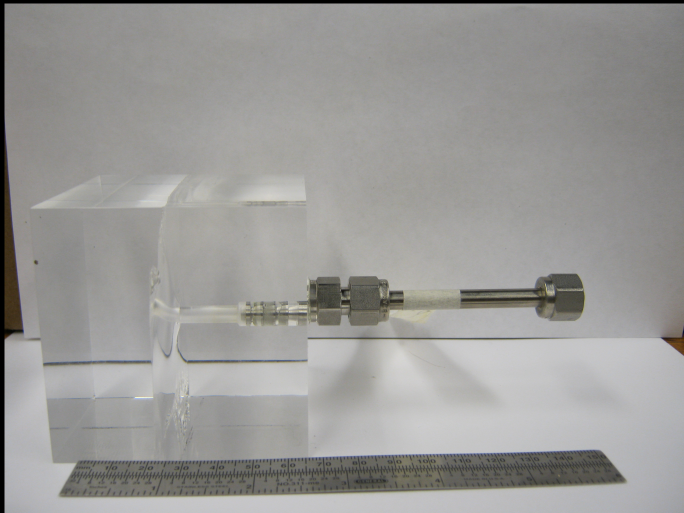



# Borehole Fracture in PMMA (Polymethyl methacrylate aka: Lucite, Plexiglas, Perspex, Acrylic)

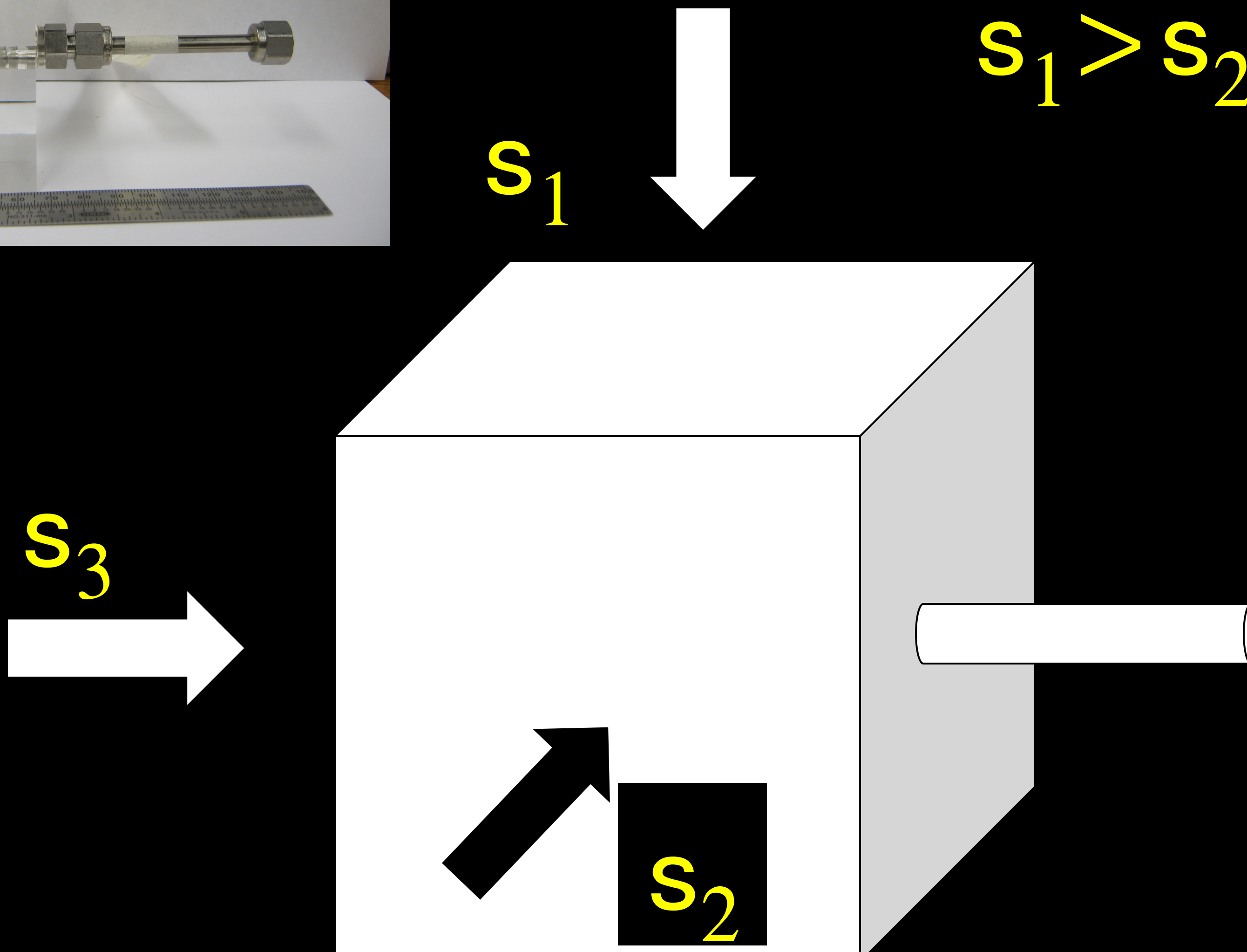


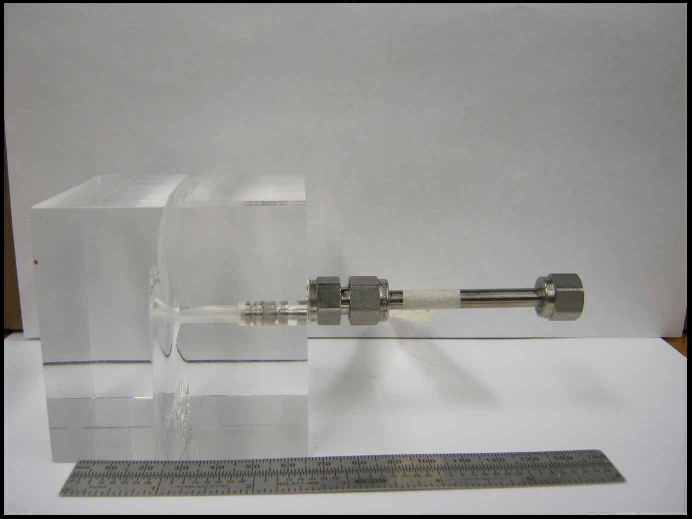


# Stress State



$s_1 > s_2 > s_3$





Hydrofracture, view below is in the $s_3$ direction

$s_1 = s_2$ = 10 MPa ( ≈1500 psi)
Pp fail = 43.3 MPa (≈ 6200 psi)

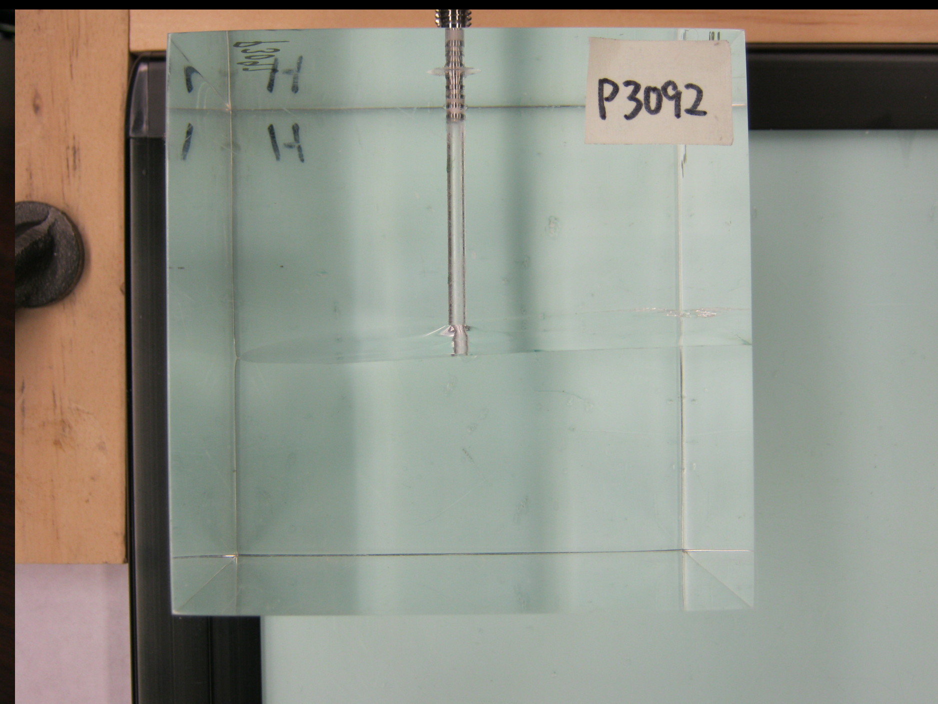
p3006; water

# PMMA: $N_2$ hydrofrac

# PMMA:

$N_2$ hydrofrac

$H_2O$ hydrofrac



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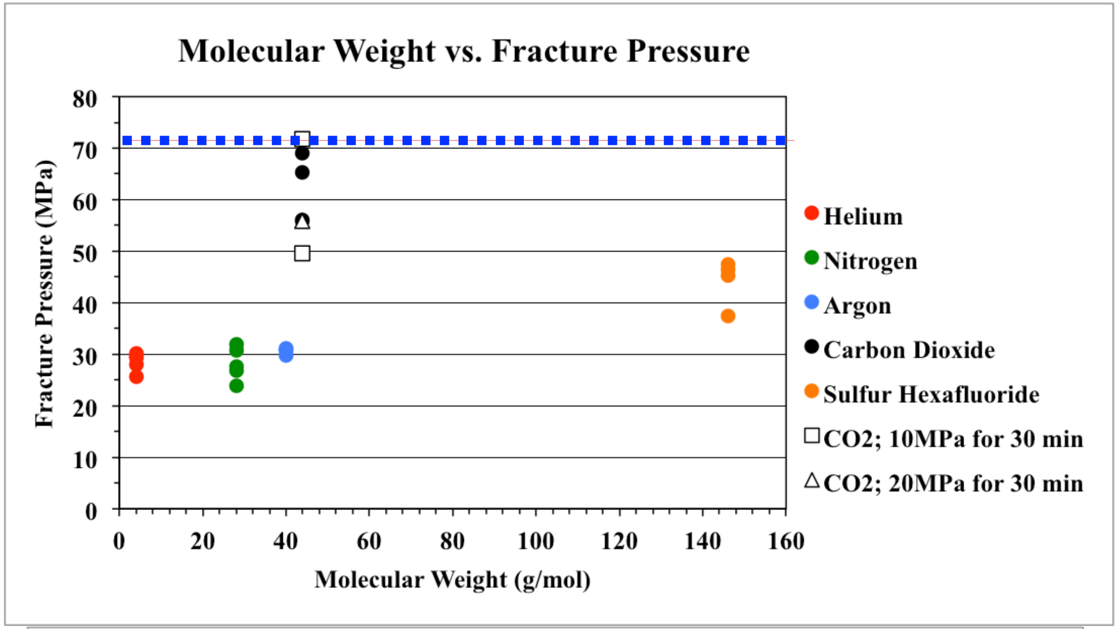
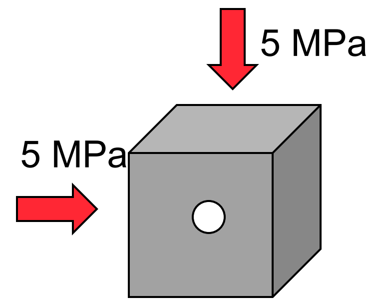
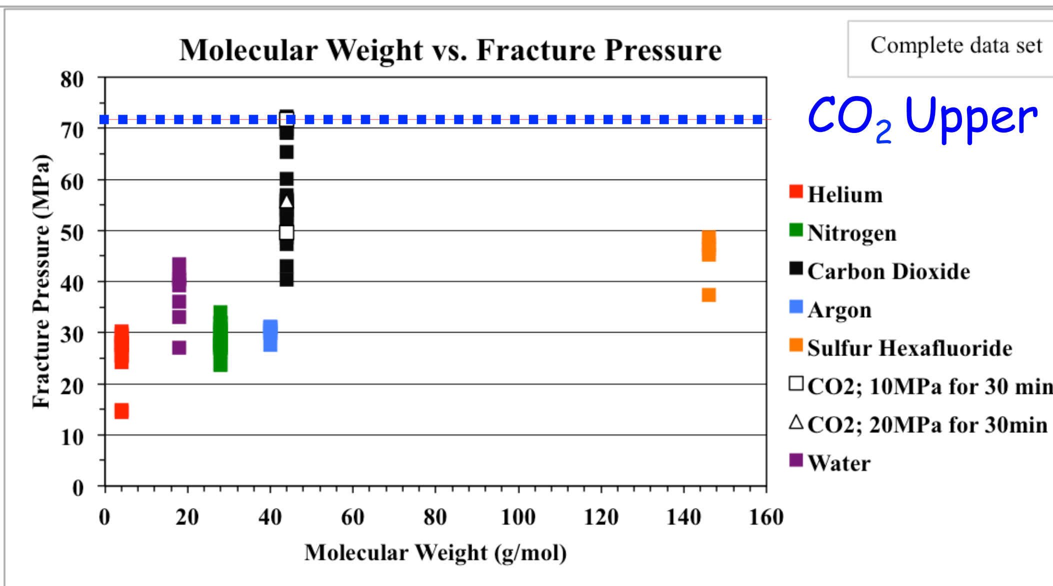
# $P_b$ is fluid/fluid-state dependent




$S_h=S_v=5$ MPa



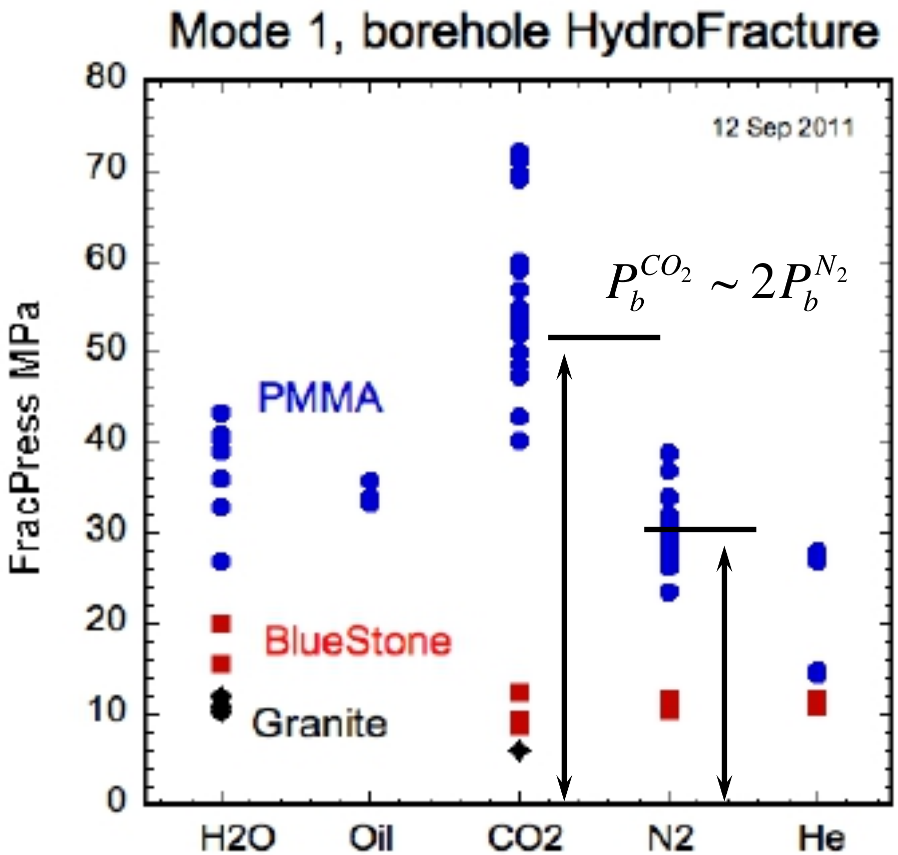




$CO_2$ Upper Bound - Tensile Strength ~ 70 MPa

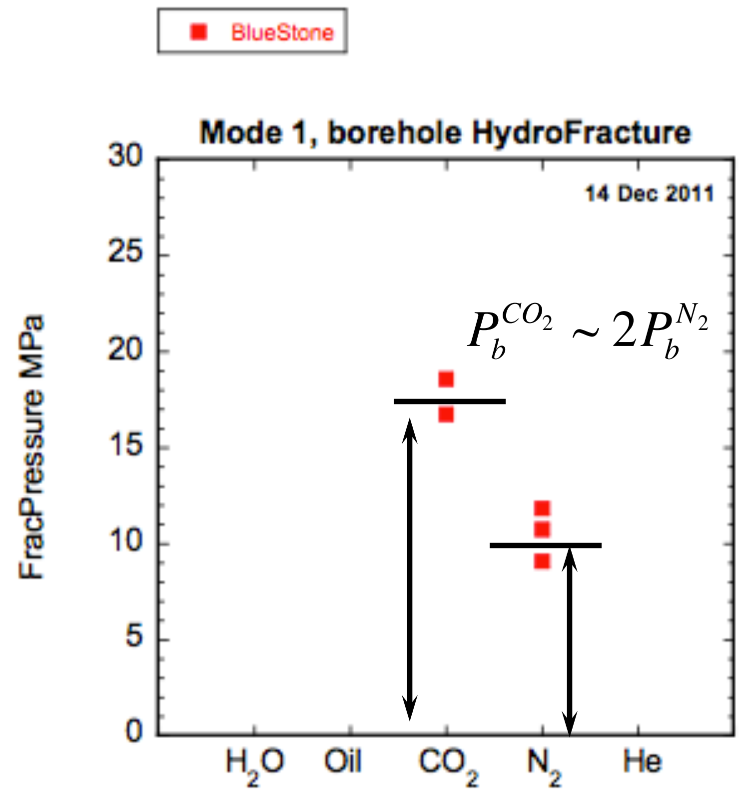
All Data

# $P_b$ for $CO_2$:$N_2$ are ~2:1 for PMMA/Bluestone

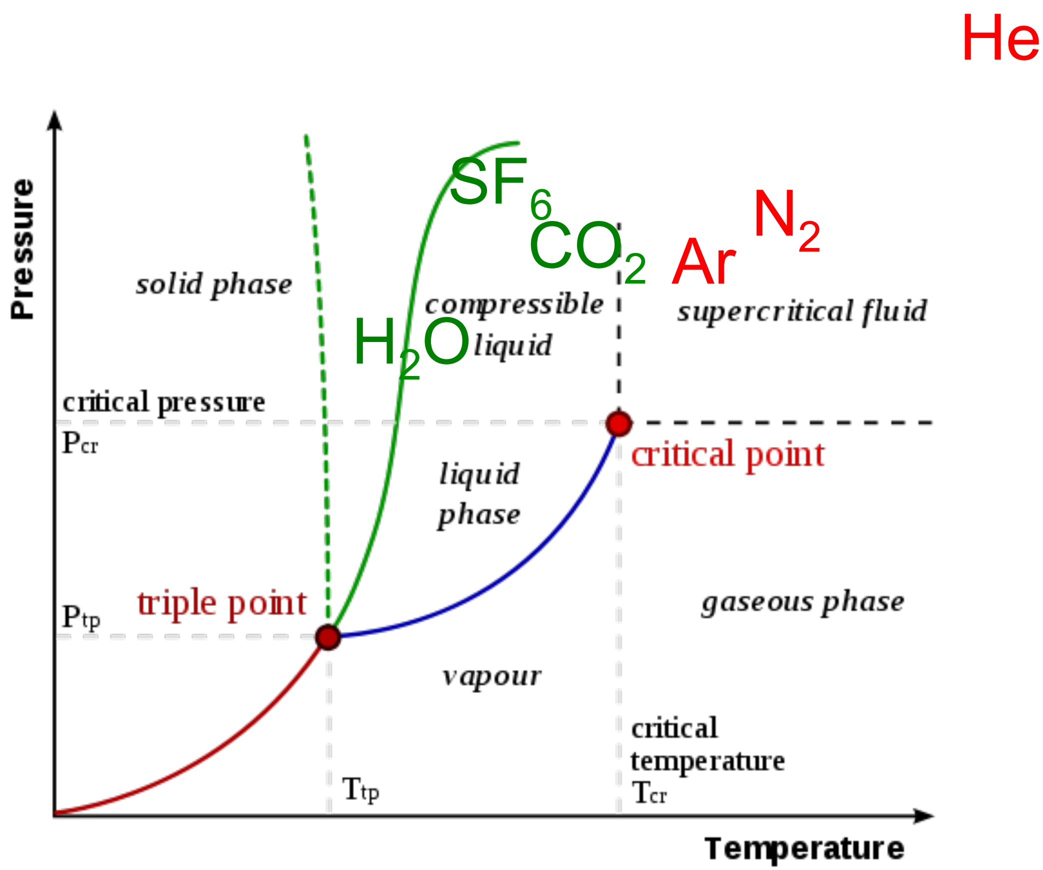
PMMA




Rock



# Fracturing Fluid Properties




1. Ar, $N_2$ and He are supercritical (no interfacial tension)
2. Water, $CO_2$ and $SF_6$ are liquids (interfacial tension)

| Substance[3][4] | Critical temperature | Critical pressure (absolute) |
|---|---|---|
| Helium | −267.96 °C (5.19 K) | 2.24 atm (227 kPa) |
| Hydrogen | −239.95 °C (33.20 K) | 12.8 atm (1,300 kPa) |
| Neon | −228.75 °C (44.40 K) | 27.2 atm (2,760 kPa) |
| $CH_4$ (Methane) | −82.3 °C (190.9 K) | 45.79 atm (4,640 kPa) |
| Nitrogen | −146.9 °C (126.3 K) | 33.5 atm (3,390 kPa) |
| Fluorine | −128.85 °C (144.30 K) | 51.5 atm (5,220 kPa) |
| Argon | −122.4 °C (150.8 K) | 48.1 atm (4,870 kPa) |
| Oxygen | −118.6 °C (154.6 K) | 49.8 atm (5,050 kPa) |
| Krypton | −63.8 °C (209.4 K) | 54.3 atm (5,500 kPa) |
| Xenon | 16.6 °C (289.8 K) | 57.6 atm (5,840 kPa) |
| $CO_2$ | 31.04 °C (304.19 K) | 72.8 atm (7,380 kPa) |
| $N_2O$ | 36.4 °C (309.6 K) | 71.5 atm (7,240 kPa) |
| Ammonia[5] | 132.4 °C (405.6 K) | 111.3 atm (11,280 kPa) |
| Chlorine | 143.8 °C (417.0 K) | 76.0 atm (7,700 kPa) |
| Bromine | 310.8 °C (584.0 K) | 102 atm (10,300 kPa) |
| Water[6][7] | 373.946 °C (647.096 K) | 217.7 atm (22,060 kPa) |
| $H_2SO_4$ | 654 °C (927 K) | 45.4 atm (4,600 kPa) |
| Sulfur | 1,040.85 °C (1,314.00 K) | 207 atm (21,000 kPa) |
| Mercury | 1,476.9 °C (1,750.1 K) | 1,720 atm (174,000 kPa) |
| Caesium | 1,664.85 °C (1,938.00 K) | 94 atm (9,500 kPa) |
| Ethanol | 241 °C (514 K) | 62.18 atm (63 bar, 6,300 kPa) |
| Lithium | 2,950 °C (3,220 K) | 652 atm (66,100 kPa) |
| Gold | 6,977 °C (7,250 K) | 5,000 atm (510,000 kPa) |
| Aluminium | 7,577 °C (7,850 K) | |
| Iron | 8,227 °C (8,500 K) | |

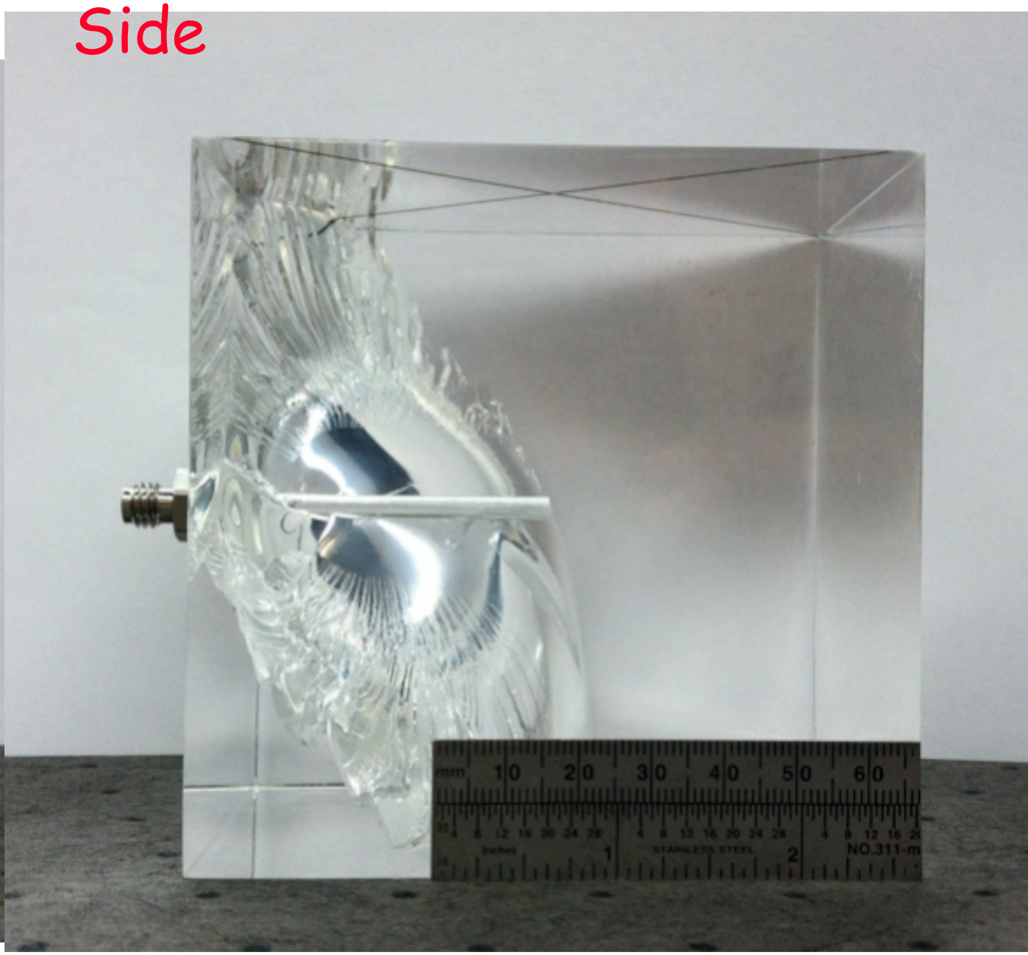
$SF_6$ [ 46C; 3.6MPa]

[Source: http://en.wikipedia.org/wiki/Critical_point_(thermodynamics)]

# Complexity - $N_2$

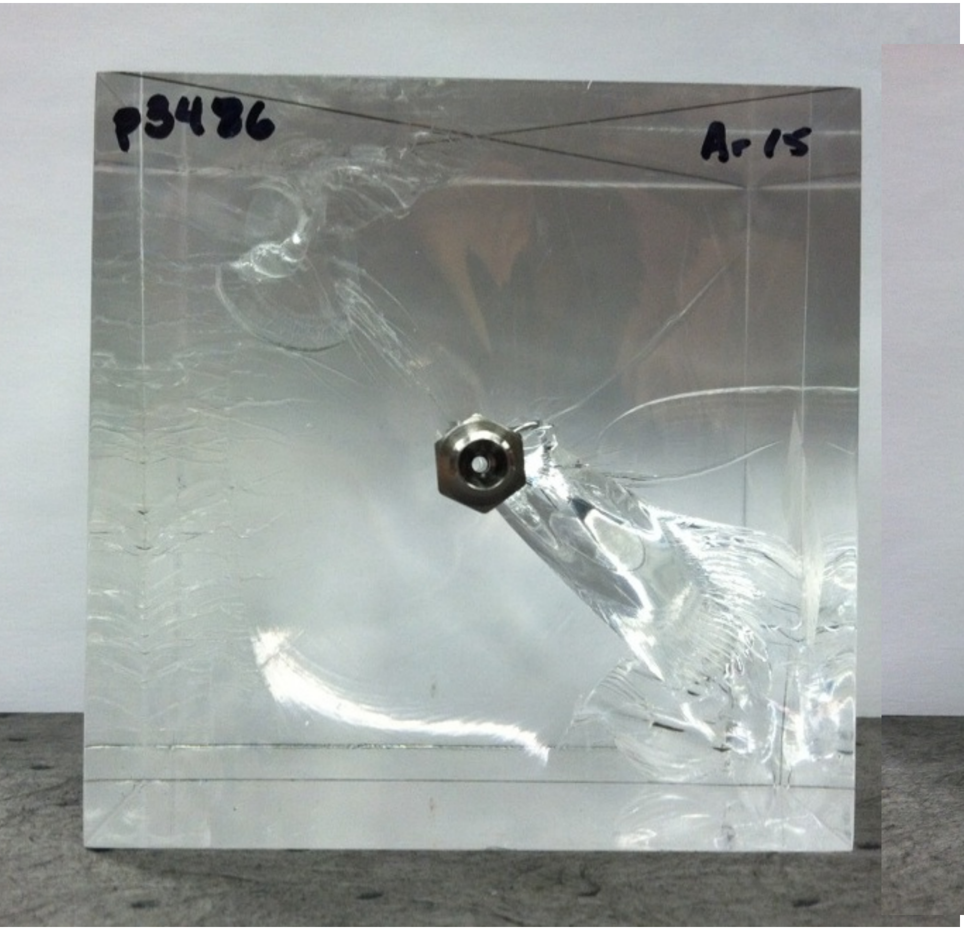
Front


Side



# Complexity - Ar

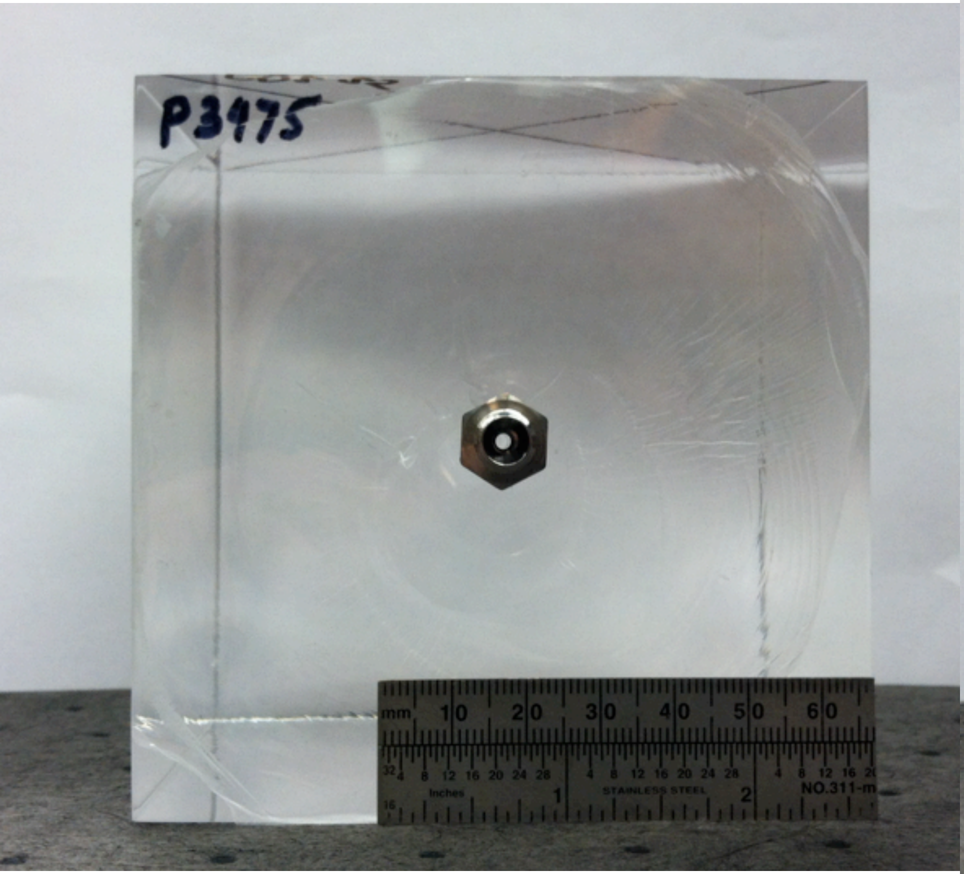
Front



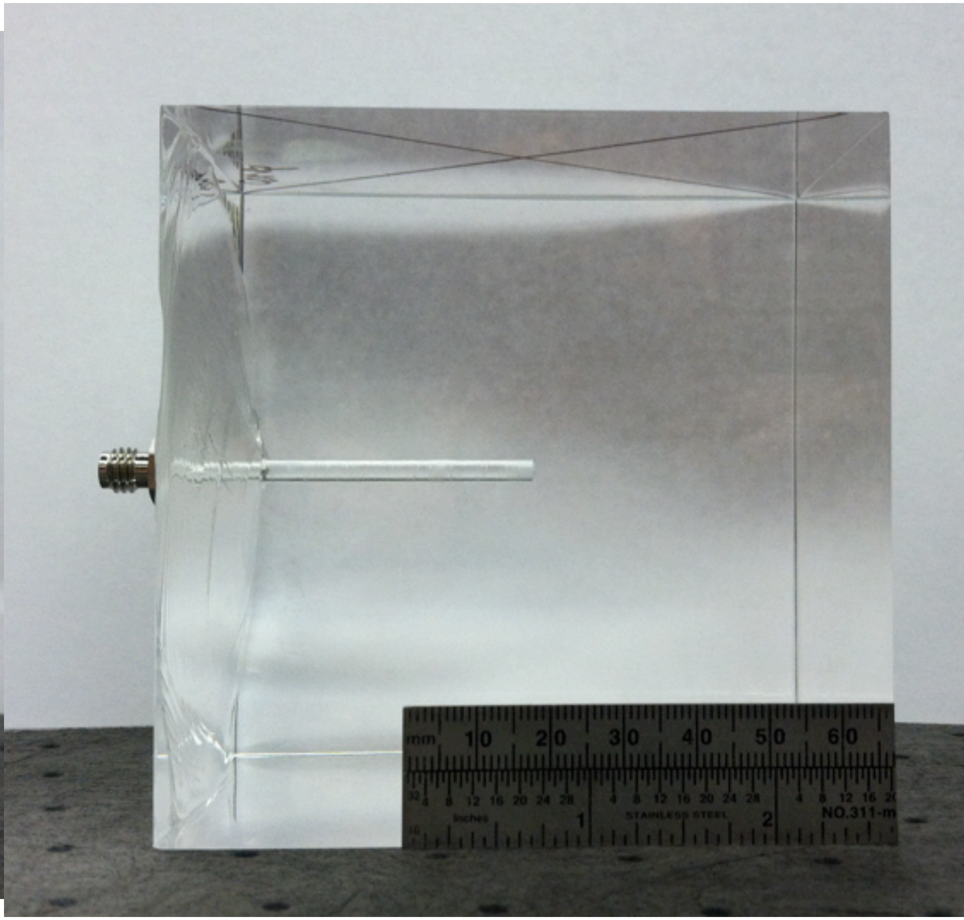

Side

# Complexity – $CO_2$

Front

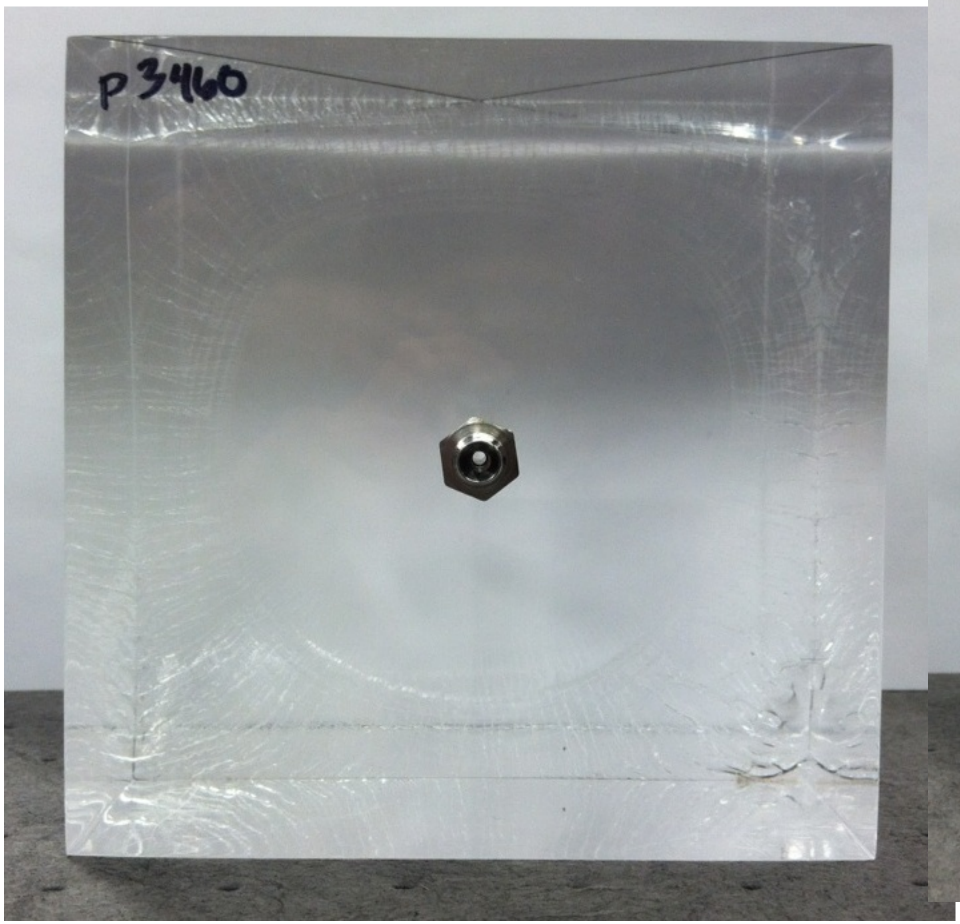



Side



# Complexity - He

Front

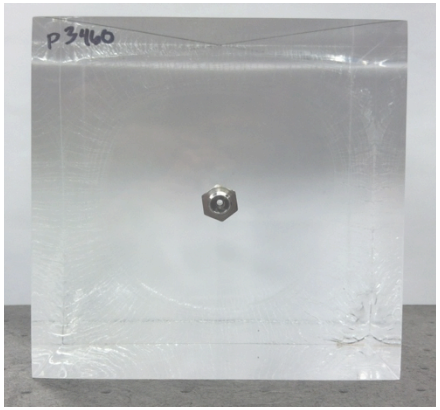



Side

# Fracture Complexity

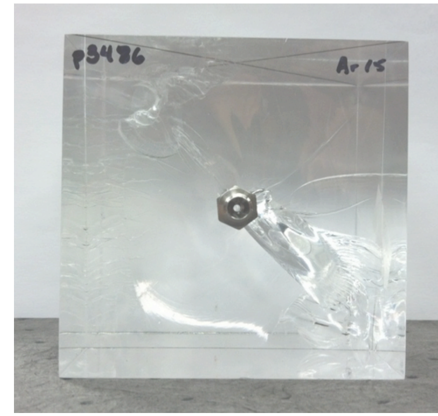
## Super-critical Fluids

Helium, He



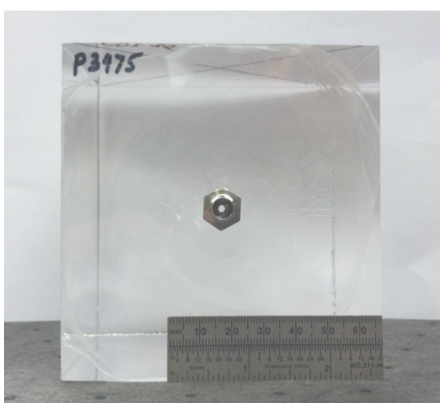

Nitrogen, $N_2$

Argon, Ar



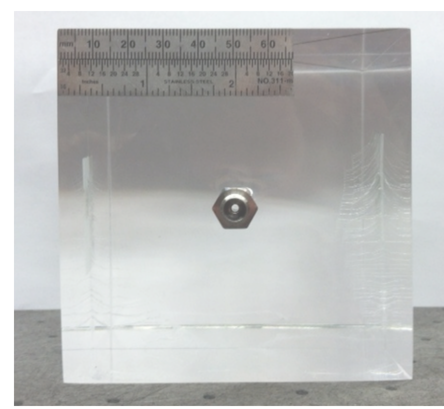

## Sub-critical Fluids

Carbon Dioxide, $CO_2$

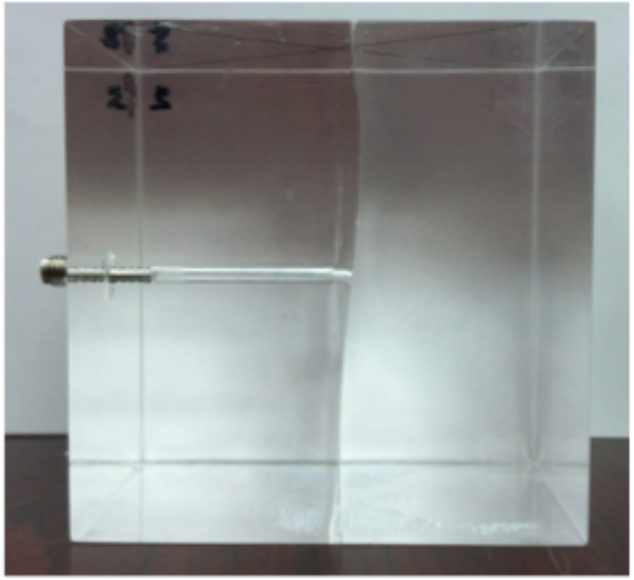


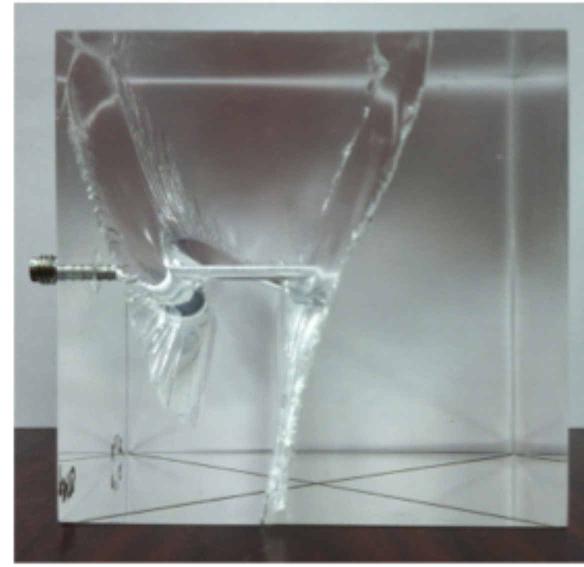

Water, $H_2O$


Sulfur Hexafluoride, $SF_6$

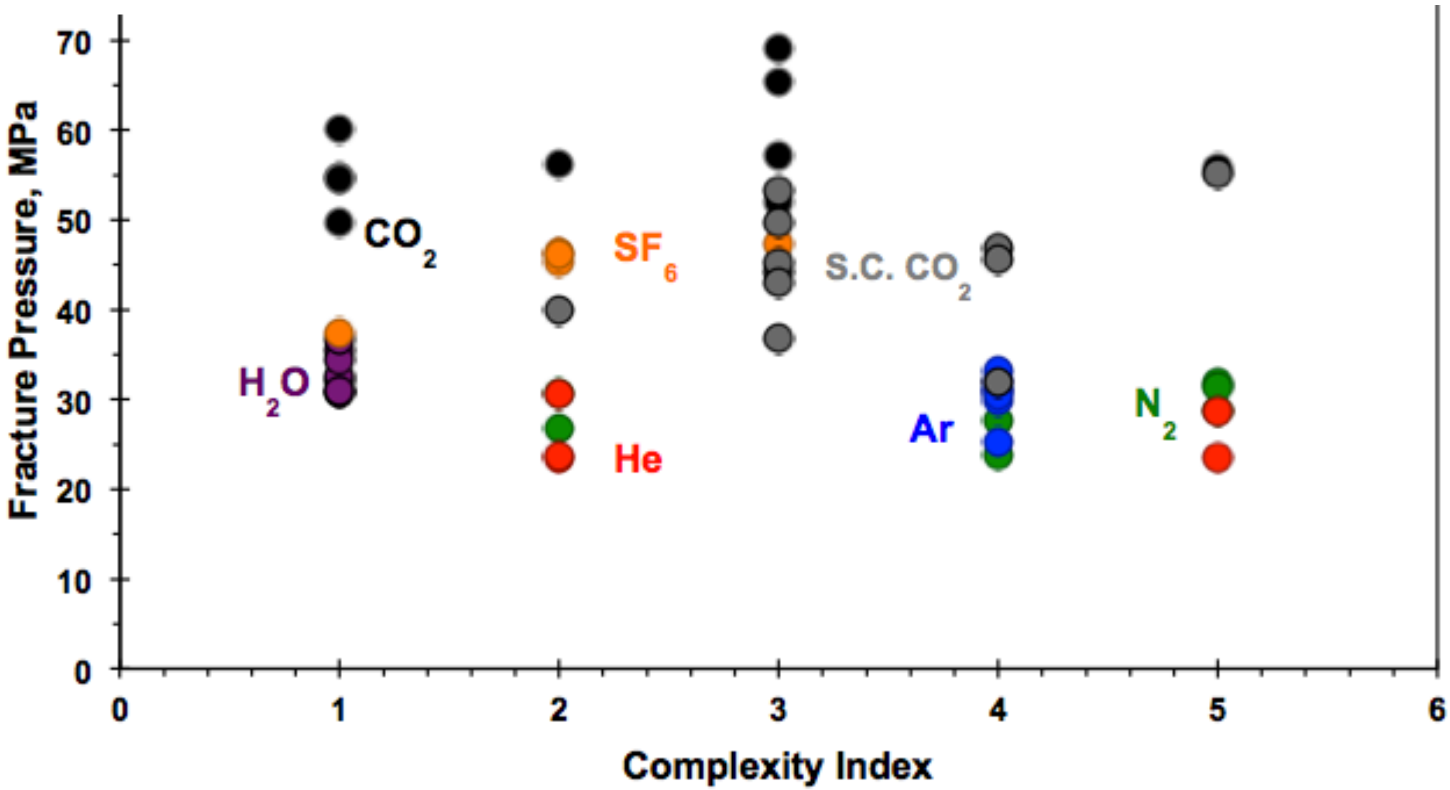


# Fracture / Complexity





Fracture Complexity



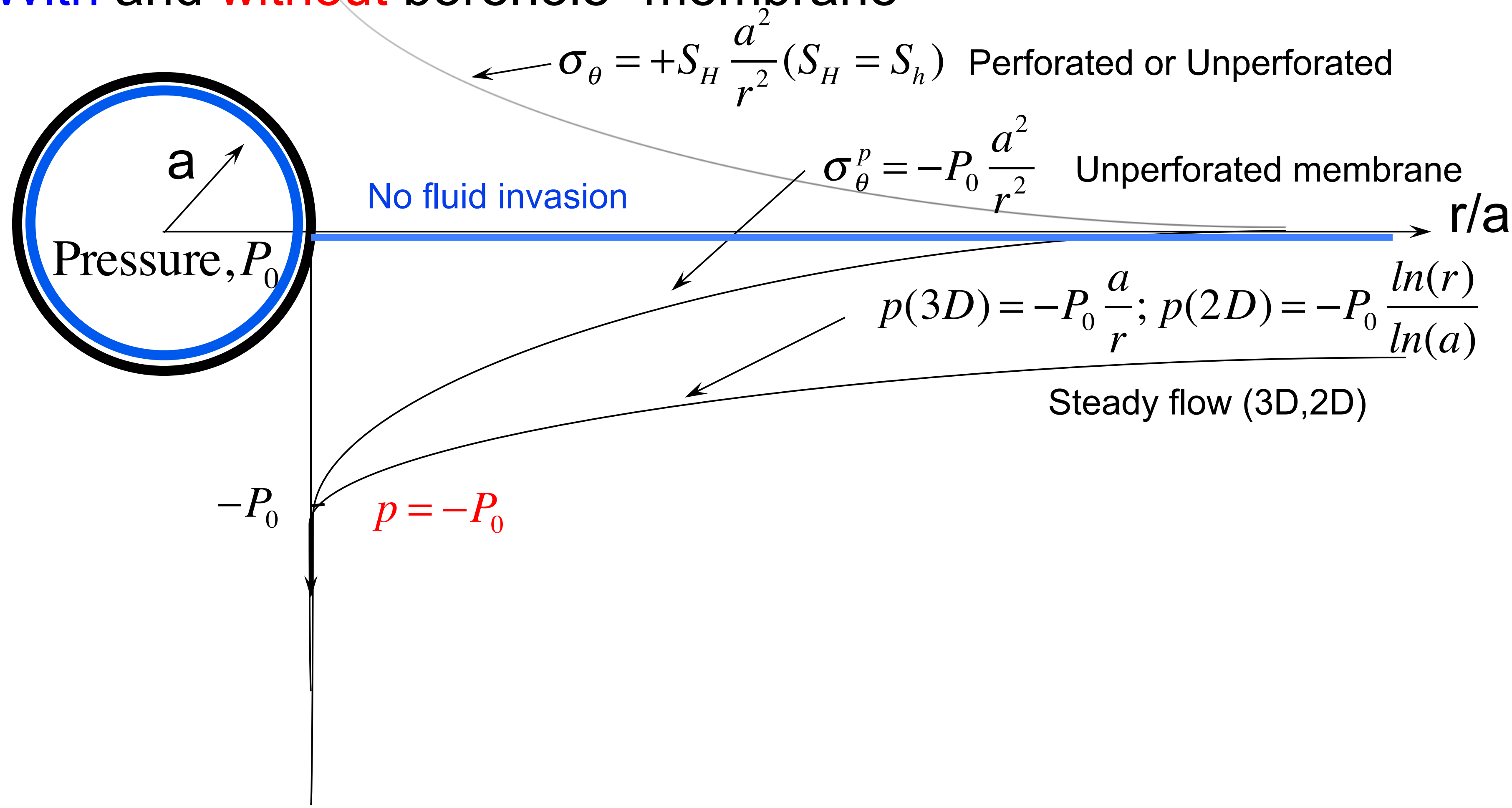

PMMA

# Prospects for Gas-Fracturing in Unconventional Reservoirs

- Principal Issues in Shale Gas Production
  - Energy Outlook: Security, Independence and Environment
  - Water-related issues
  - Waterless fracturing and gas displacement (ESGR)
- Observations
  - Breakdown Pressures
    - PMMA/Granite/Bluestone and Structure
      - Key Observations
      - Hypotheses
  - Fracture Complexity
    - PMMA
      - Key Observations
      - Hypotheses
  - Fracture Propagation Velocities
- **Methods of Analysis**
  - **Mechanisms for Gas/Rock Interaction**
  - **Damage Mechanics**
- **Summary**

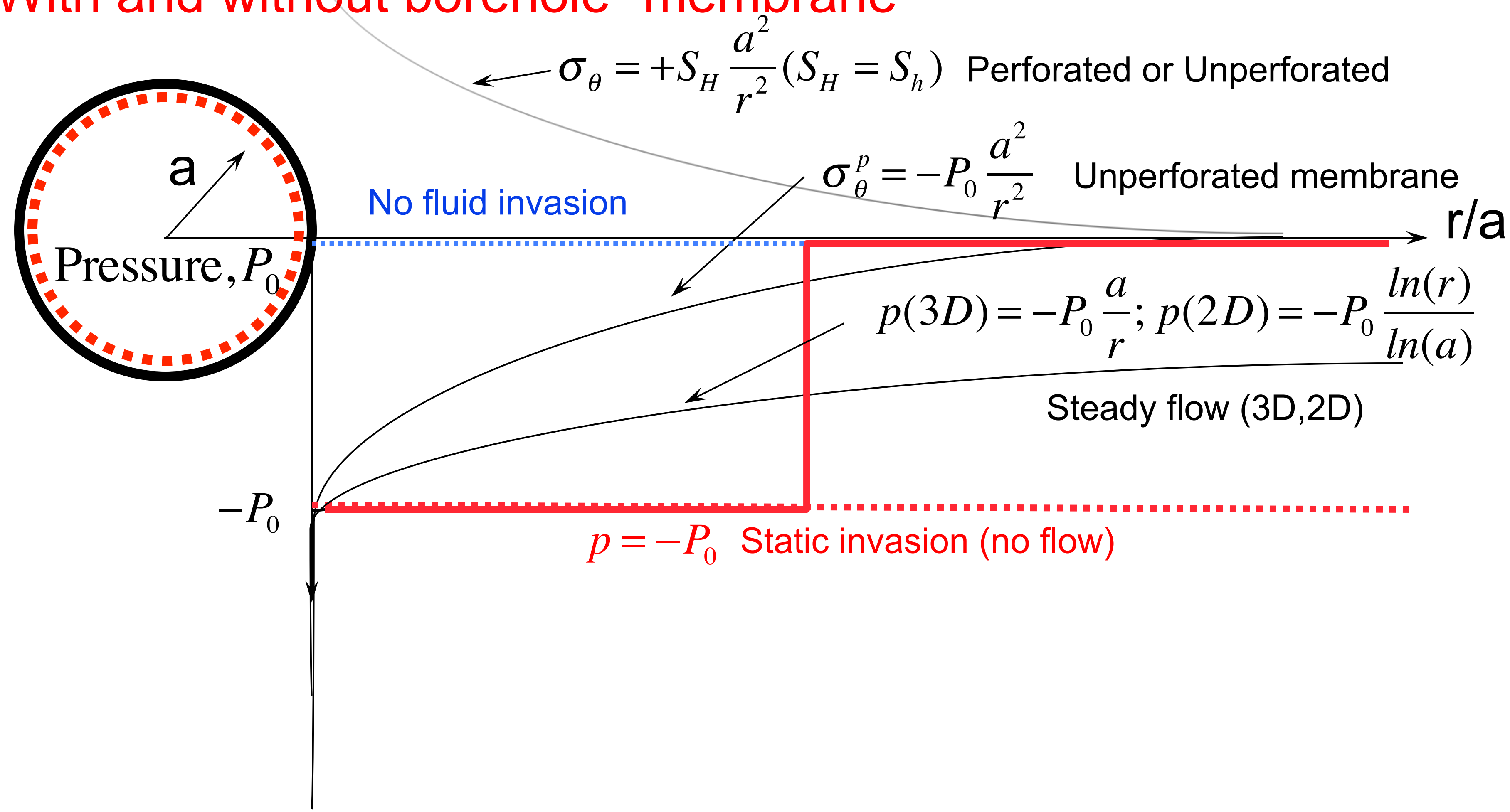
# Fluid Pressures Around Borehole

With and without borehole “membrane”



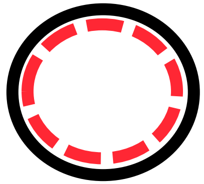
# Fluid Pressures Around Borehole

With and without borehole "membrane"



# Longitudinal Hydraulic Fracture

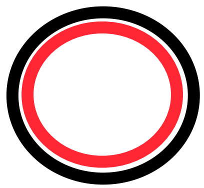
## Fracture Breakdown Pressure for fracture along borehole (plane strain)



"Permeable:" $\sigma_T = \sigma_{\theta\theta} = 3S_h - S_H - P_0 + (1+\eta)P_w$

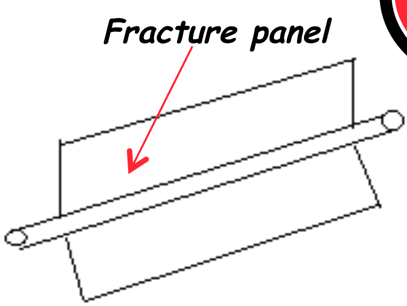
$$P_w = \frac{\sigma_T - 3S_h + S_H + P_0}{(1+\eta)}$$

$$\eta = \frac{\nu}{1-\nu}\alpha \; therefore \; \eta[0 \rightarrow \alpha]$$

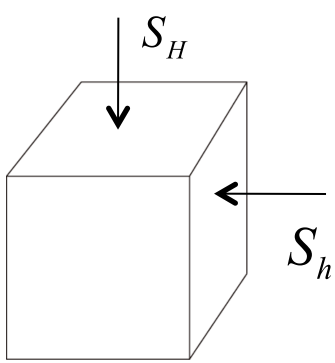


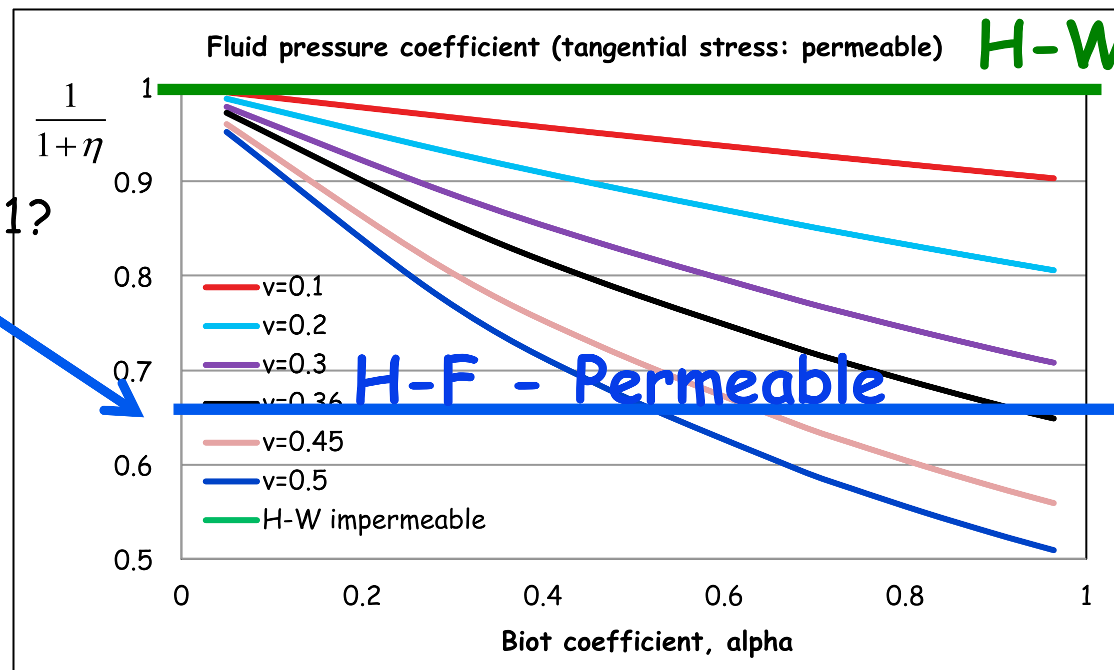
"Impermeable:" $\sigma_T = \sigma_{\theta\theta} = 3S_h - S_H - P_0 + P_w$

$$P_w = \sigma_T - 3S_h + S_H + P_0$$

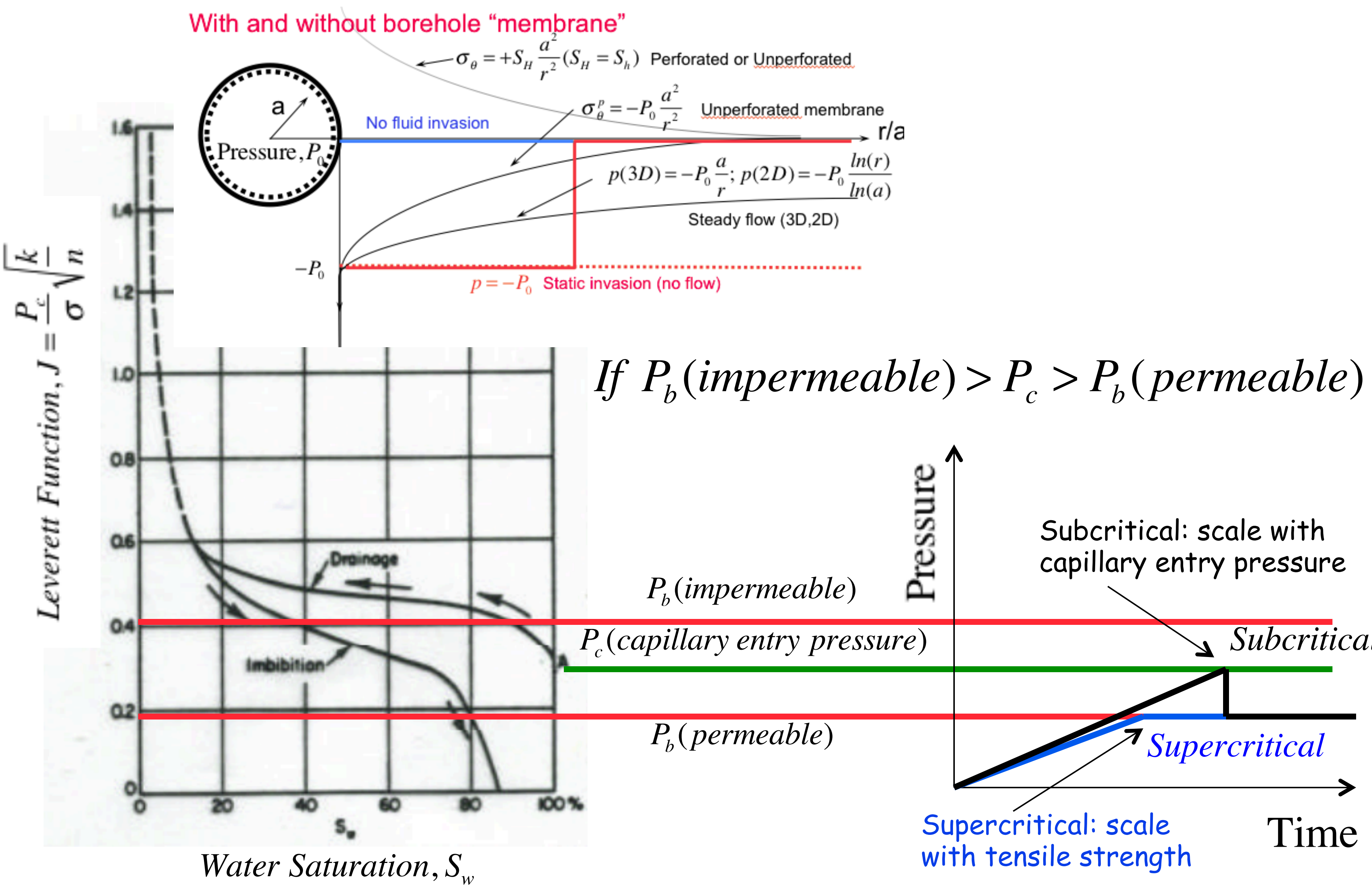



$PMMA : \nu = 0.36; \alpha = 1?$



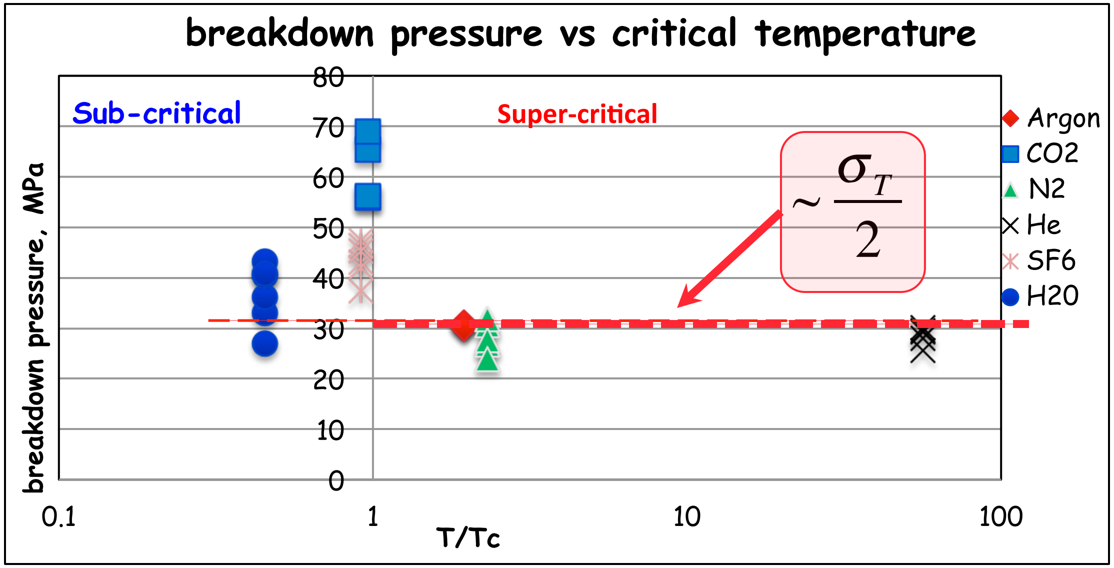



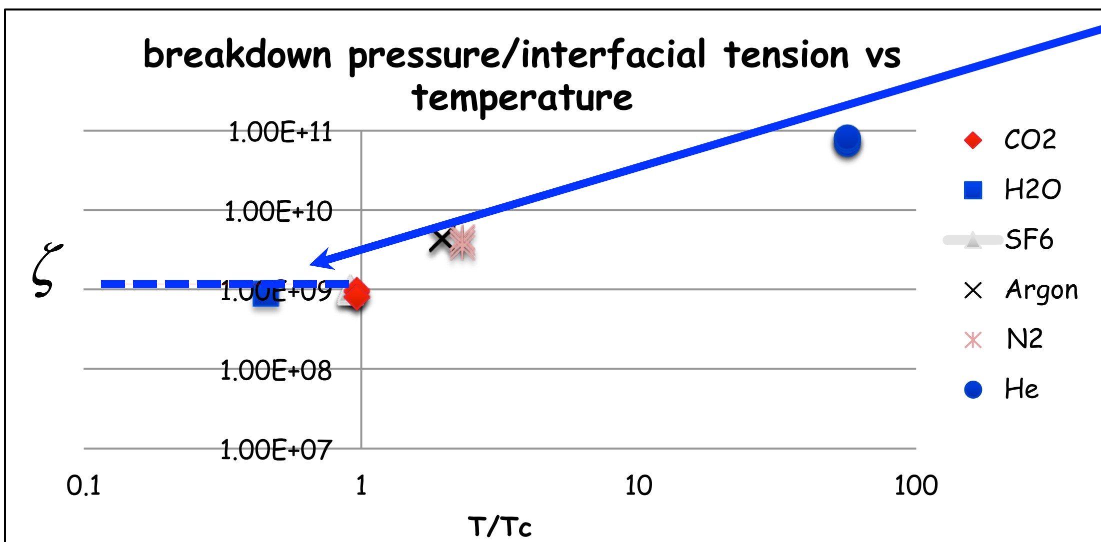
# Entry Pressures into Borehole Wall



# Fluid Invasion – SubCrit/SuperCrit

**Quantify breakdown pressure relationship with interfacial tension**




**Super-critical (invasion):**

1. Pb dependent on tensile strength
2. Pb independent of interfacial tension

**Sub-critical (no-invasion):**

*Invasion pressure scales with, J :*

$$J = \frac{P_c}{\sigma}\sqrt{\frac{k}{n}}$$

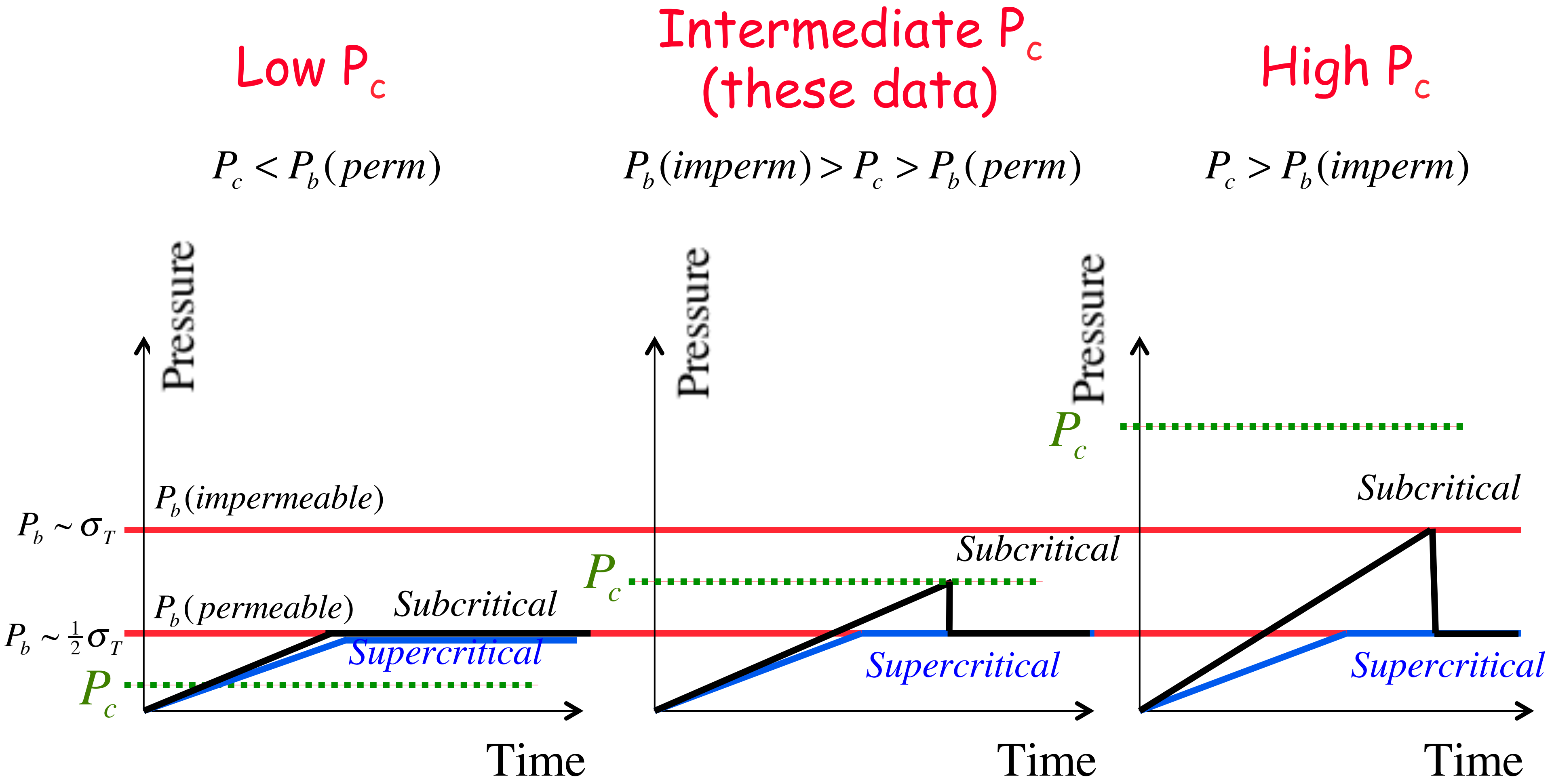
$$\varsigma = \frac{P_b}{\sigma} = \frac{MPa}{mN/m} = \frac{10^6 N/m^2}{10^{-3} N/m} = \frac{10^9}{m}$$

**Therfore:**

1. Pb independent of tensile strength
2. Pb dependent on interfacial tension

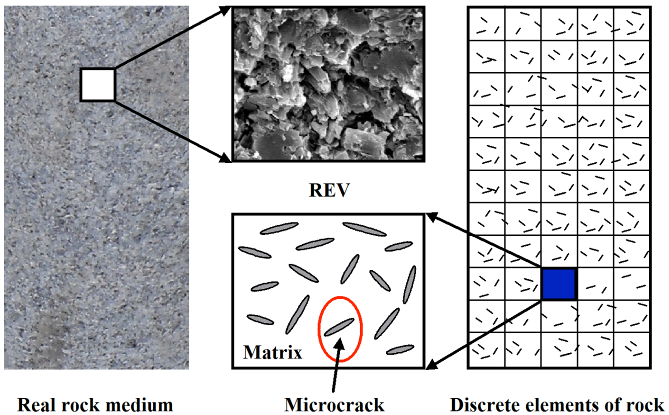
# Schematic Response

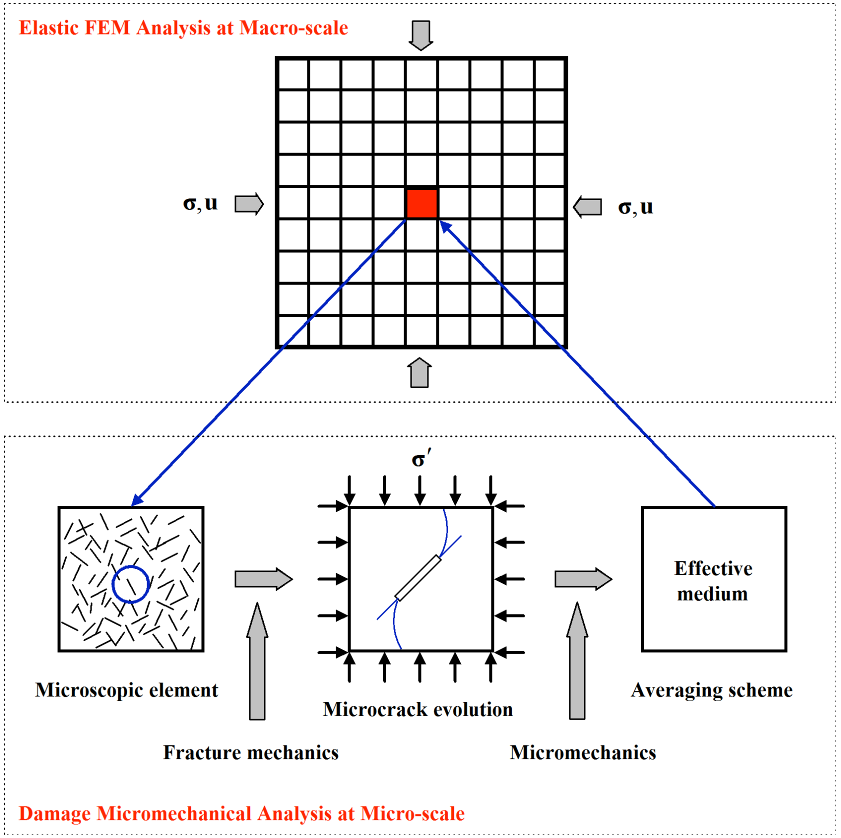
Response for various capillary pressure magnitudes relative to tensile strength of the borehole wall – low stress regime.



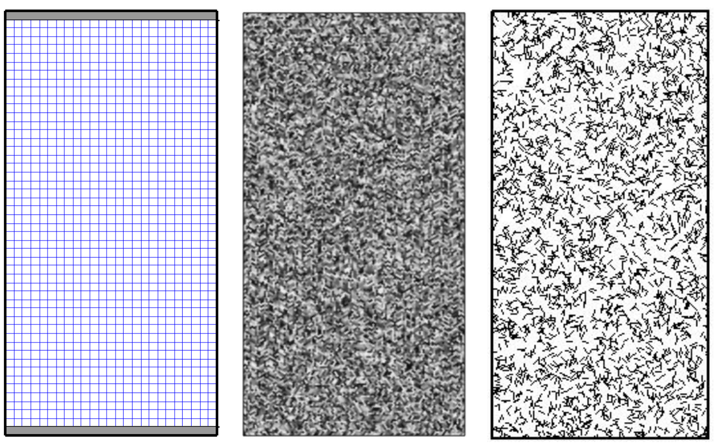
# Modeling – Damage Mechanics

## Microscopic-macroscopic model



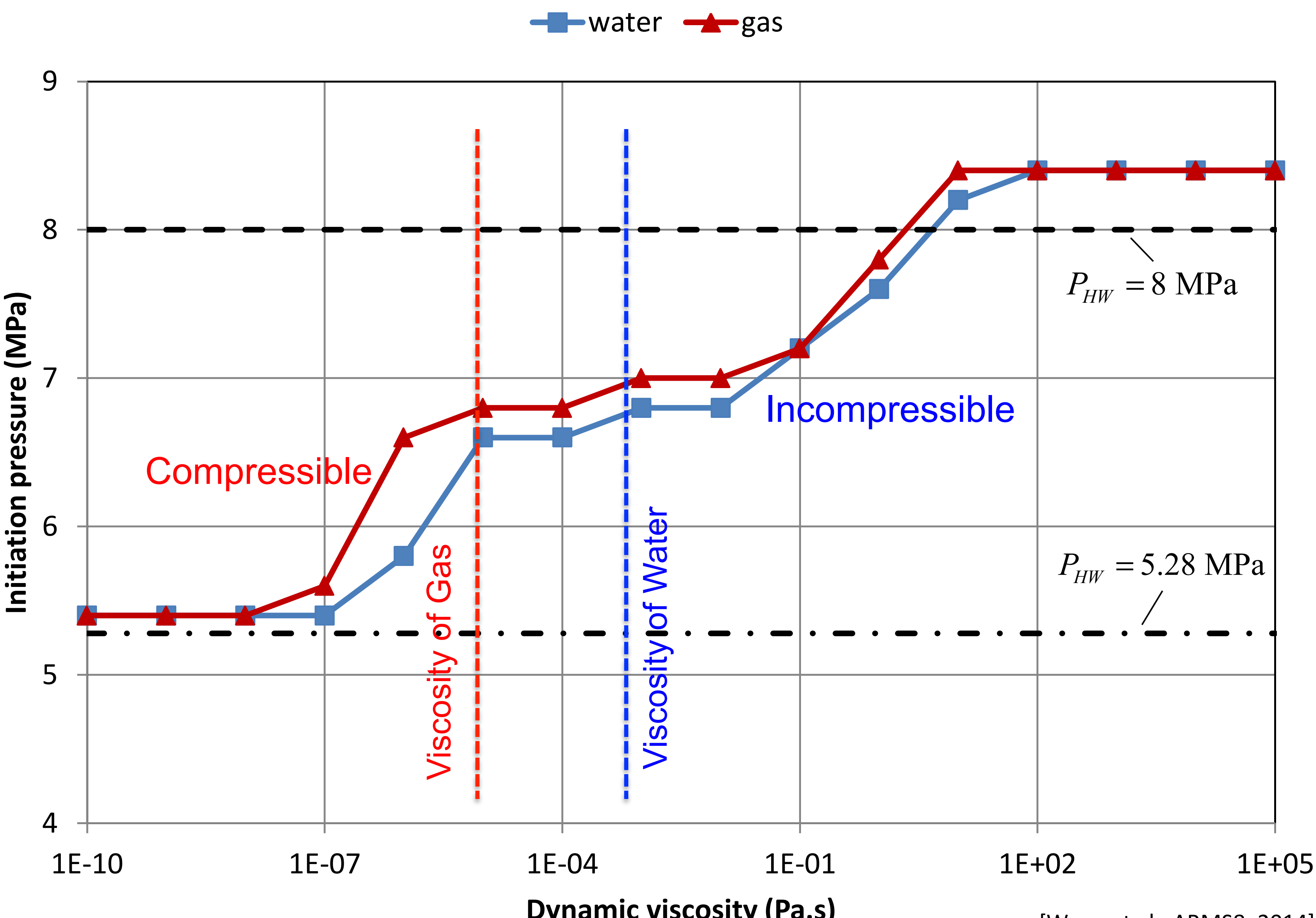




## Specimen geometry



[Lu et al., Computers and Geotechnics, 2013]

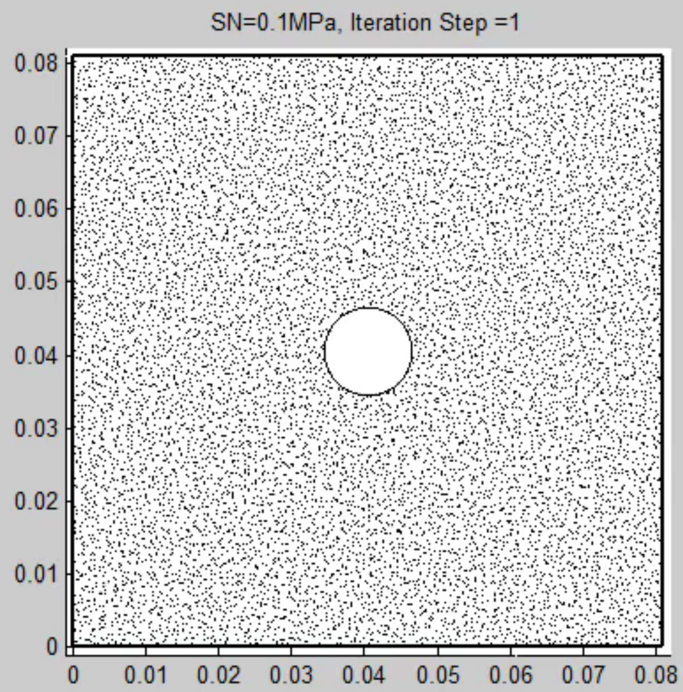
# Water fracturing vs. gas fracturing



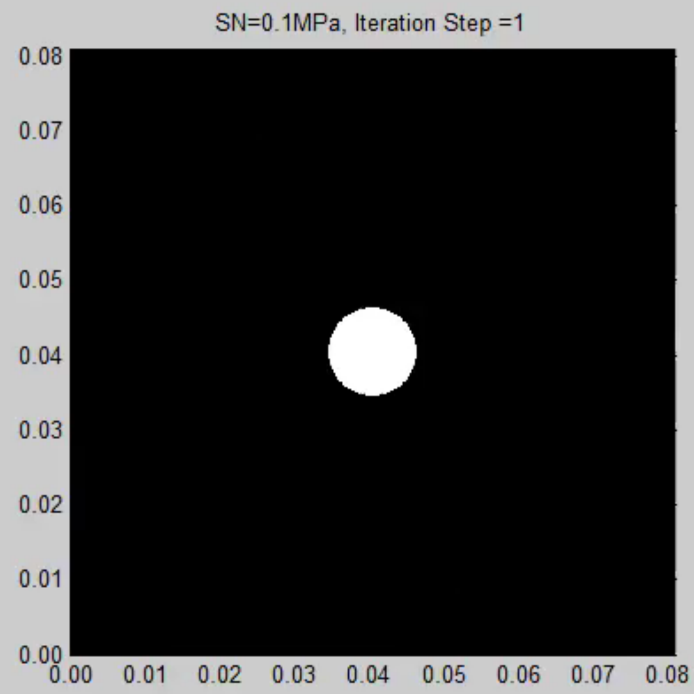

[Wang et al., ARMS8, 2014]

# Modeling – Fracture Propagation

## Driven by fluid pressure




Microcrack growth




Macrocrack growth

# Modeling - Hydraulic fracturing with ideal gas


**Gas fracturing (Compressible)**

with the same material parameters of rock and pressurization rate

**Water fracturing (Incompressible)**

# Summary

Shale gas is a significant resource and offers:

- Energy: Security, Independence and Environment
- Has a variety of water-related issues
- Waterless fracturing offers some advantages if understood

Advantages of gas fracturing

- Reduced water use
- Potential sequestration if GHG
- Generation of complex fracture networks
- Enhanced Shale Gas Recovery if $CO_2$

Experiments indicate some promise with behavior related to:

- Breakdown pressures related to gas state/type
- Fracture complexity related to gas state/type
  - Supercritical $N_2$ more complex, He less complex… why?

Improved mechanistic understanding needed to fully utilize the promise of these observations

- Integrated program across scales – Observation – Expt. - Analysis
- Determine benefits:
  - Feasibility/productivity/longevity
  - Environment: Water consumption/protection and induced seismicity….