Diffusion-Limited Fracture-Matrix Interaction and Gas Recovery in Barnett Shale

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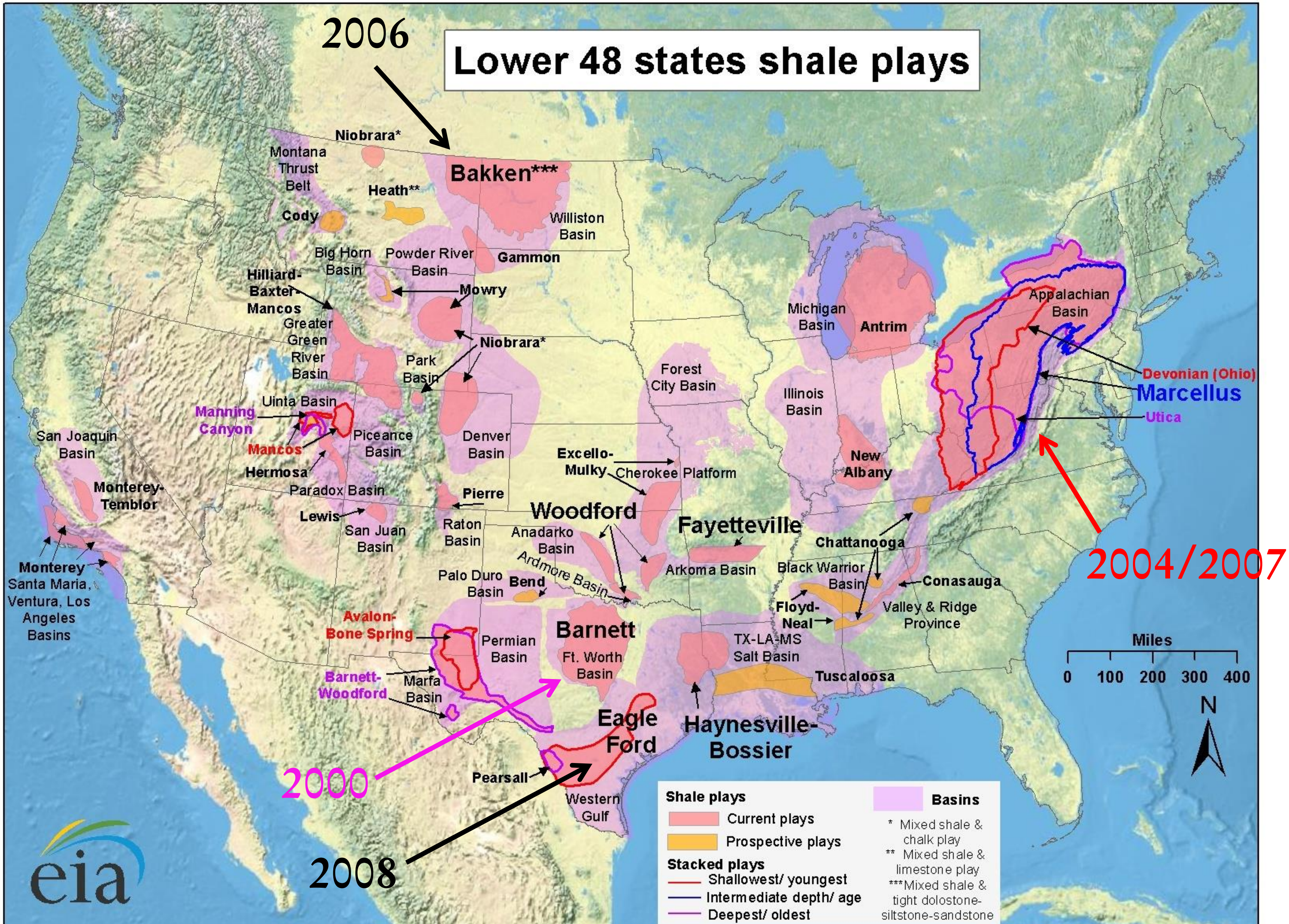
Presentation at Session "A Comprehensive Look at Hydraulic Fracturing for Hydrocarbon Recovery and Other Purposes"

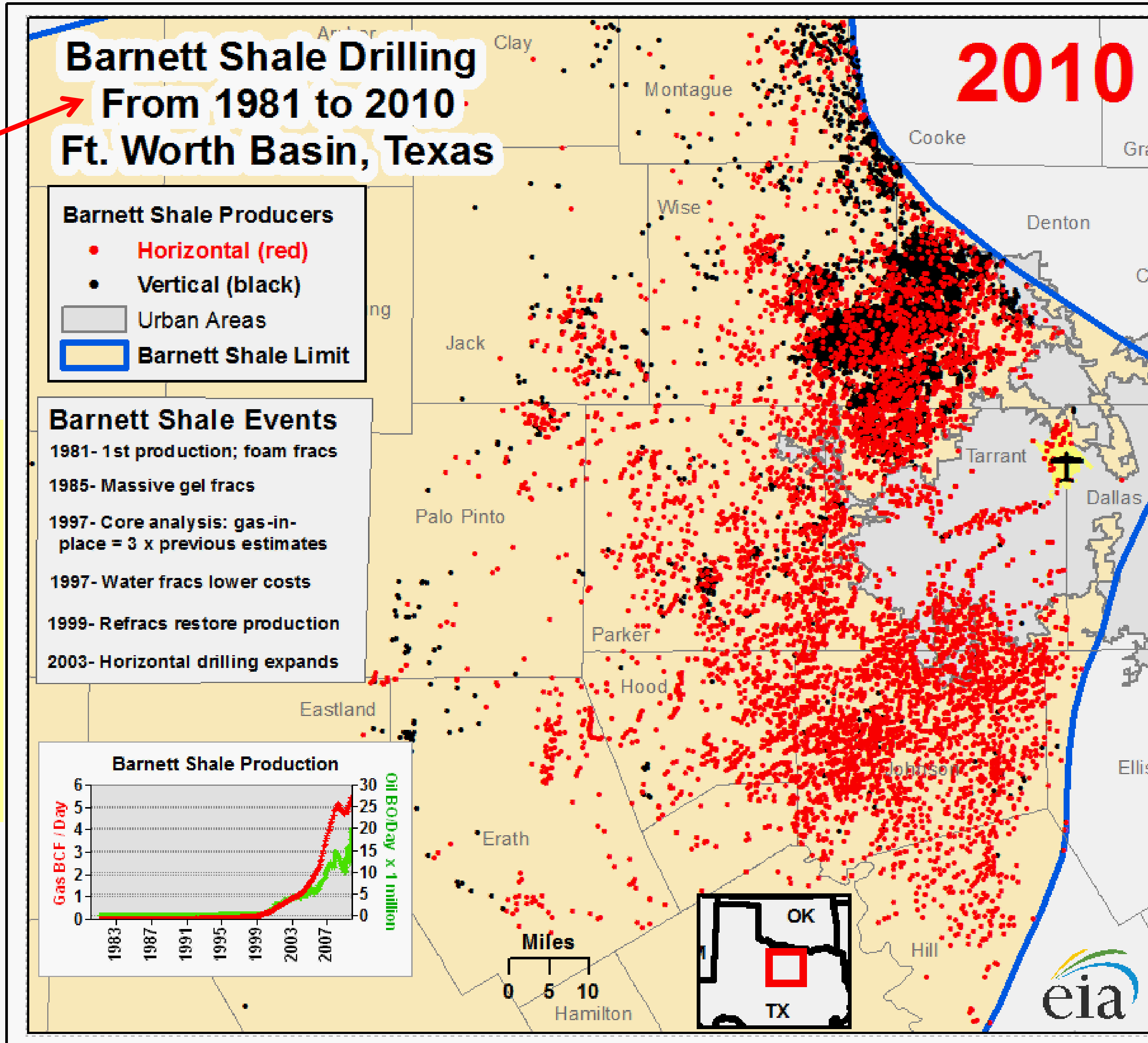
2013 GSA Annual Meeting and Exposition

Denver, Colorado, October 28, 2013



Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm



http://www.eia.gov/todayinenergy/detail.cfm?id=2170

Updated June 1, 2011

What is horizontal drilling and hydraulic fracturing?

http://www.hydraulicfracturing.com/Process/Pages/information.aspx

~$5K/ft for drilling and completion

Pressures at 480 to 850 bars to open existing fractures or initiate new fractures

Carrizo Oil and Gas Company

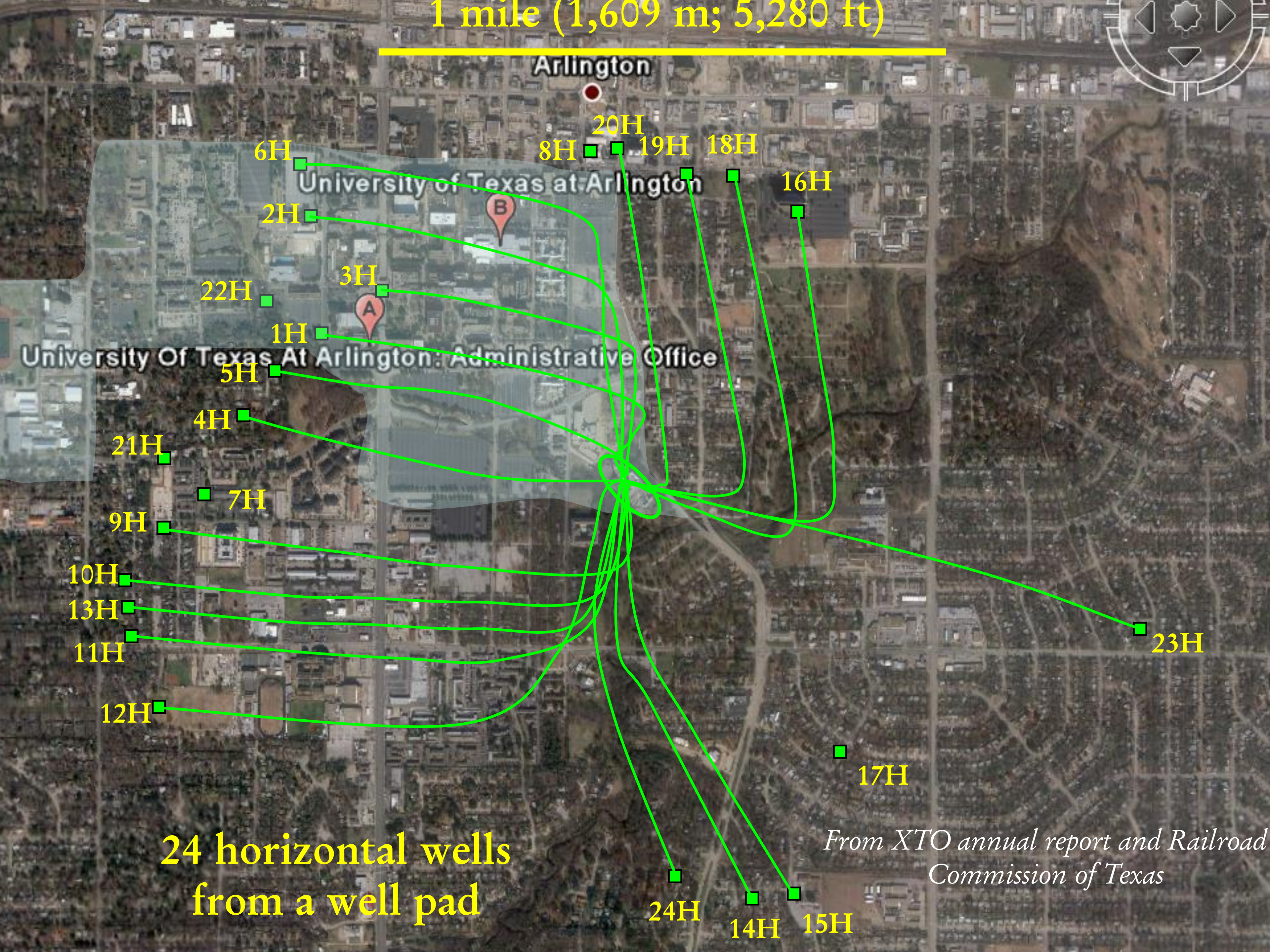
$400,000 one-time donation

$391,000 ($1,000 per acre) for the righ

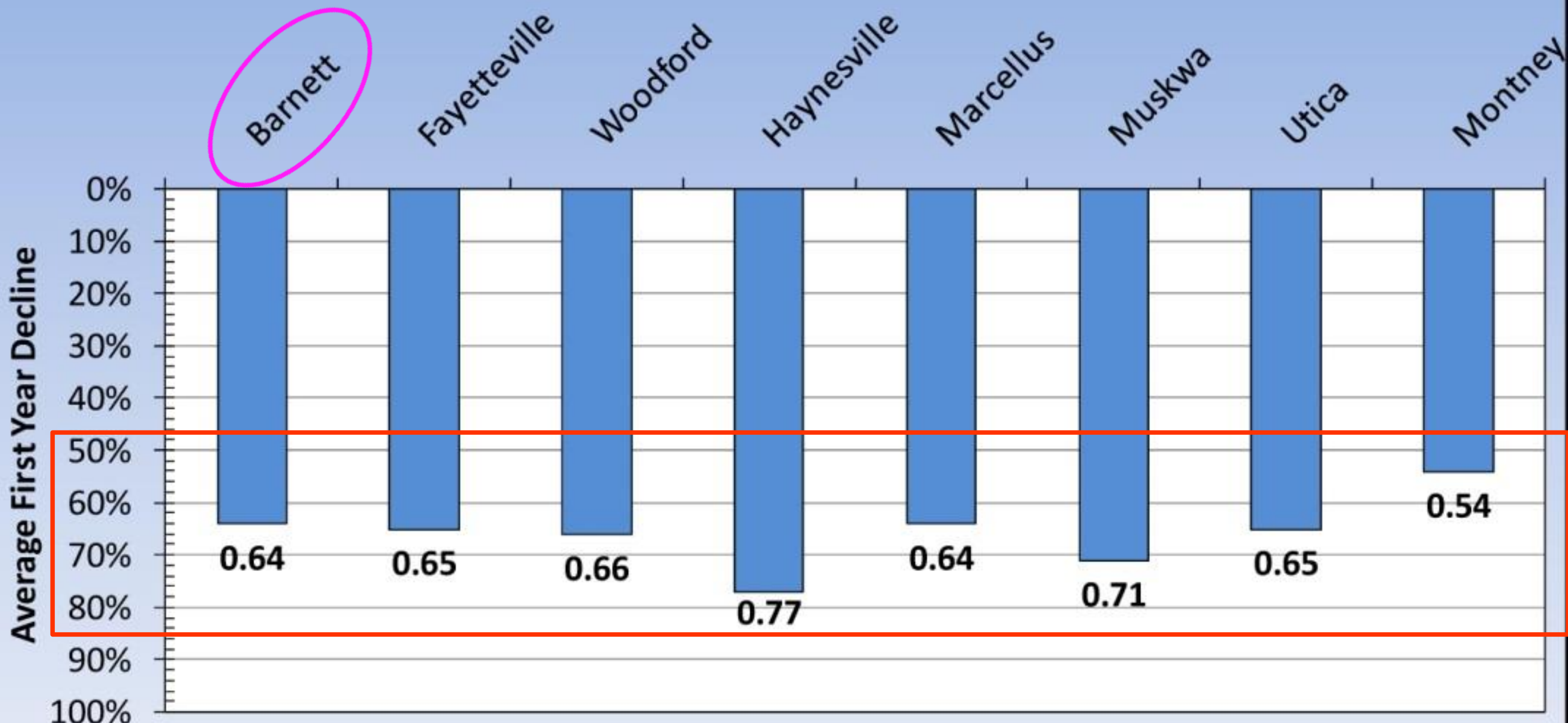
27% royalty

Barnett drilling location at 2008
University of Texas at Arlington

http://www.star-telegram.com/2010/09/30/2510136/u
arlington-pad-site-exemplifies.html

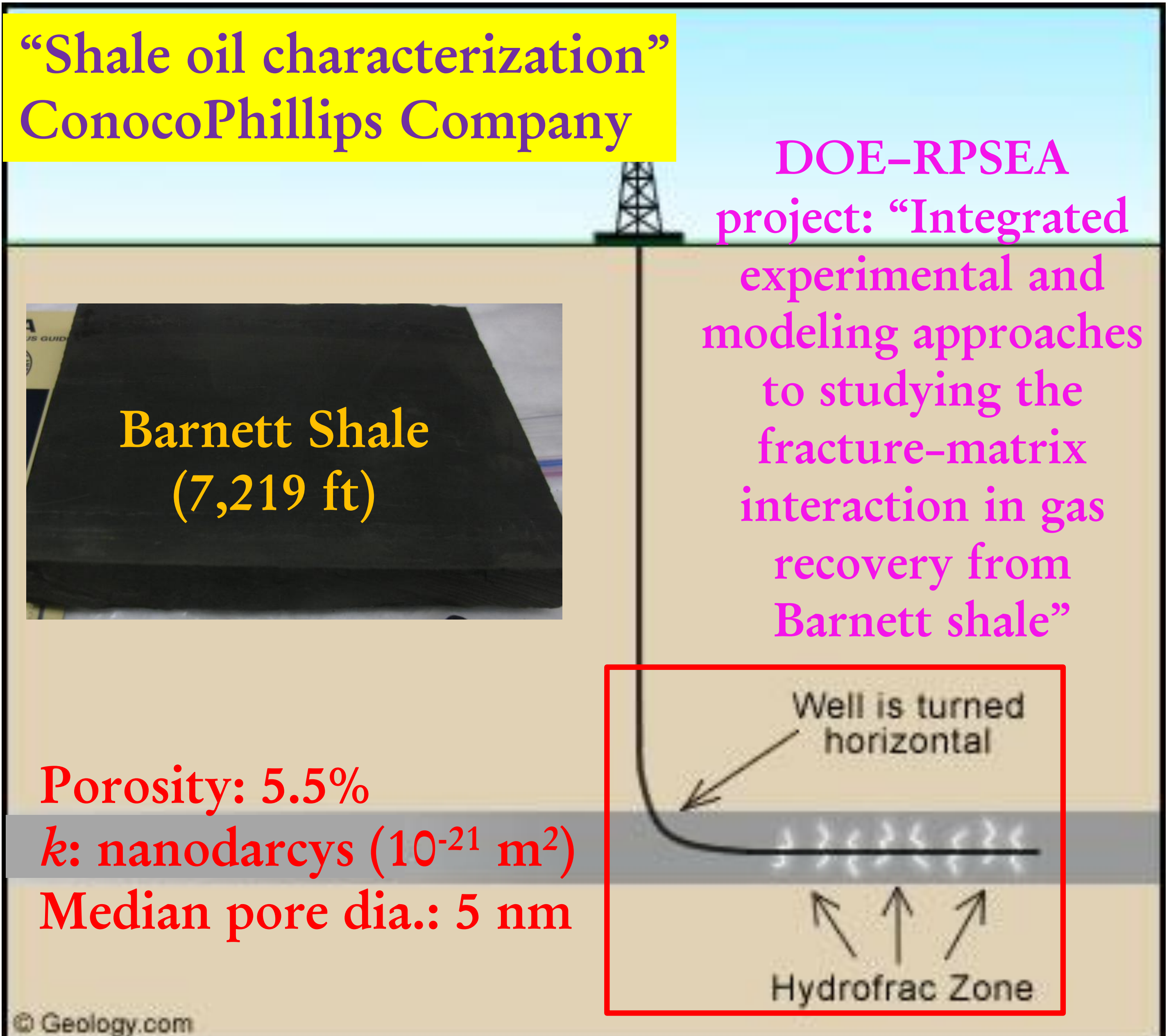

1 mile (1,609 m; 5,280 ft)
Arlington
University of Texas at Arlington
University Of Texas At Arlington: Administrative Office
6H
2H
3H
22H
1H
5H
4H
21H
7H
9H
10H
13H
11H
12H
20H
8H
19H
18H
16H
23H
17H
24H
14H
15H
24 horizontal wells from a well pad
From XTO annual report and Railroad Commission of Texas

Average First Year Decline



Low gas recovery factor 12–30% for Barnett Shale (King, 2012)

Pore Structure and Hydrocarbon Production

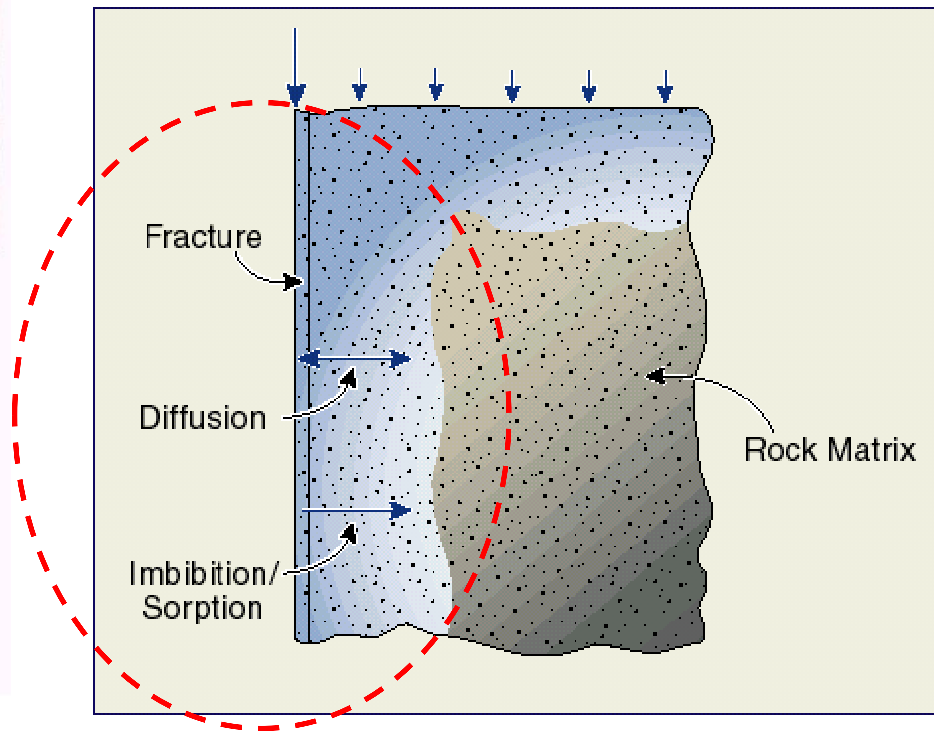


Pore structure

- Amount of gas in place
- Free vs. adsorbed gas
- Tortuous transport pathways
- Gas deliverability from nanopores to well bore

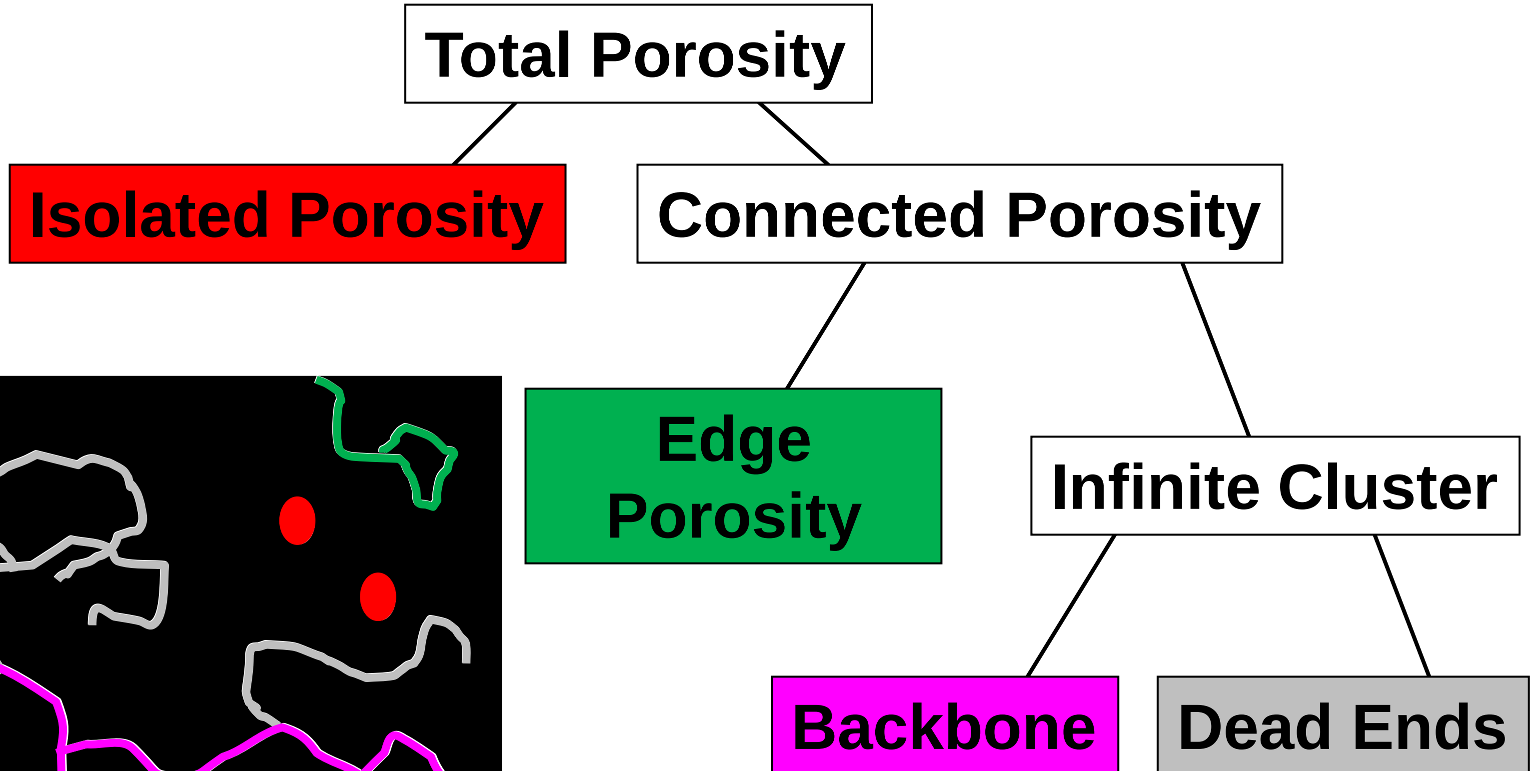
Fracture–Matrix Interaction

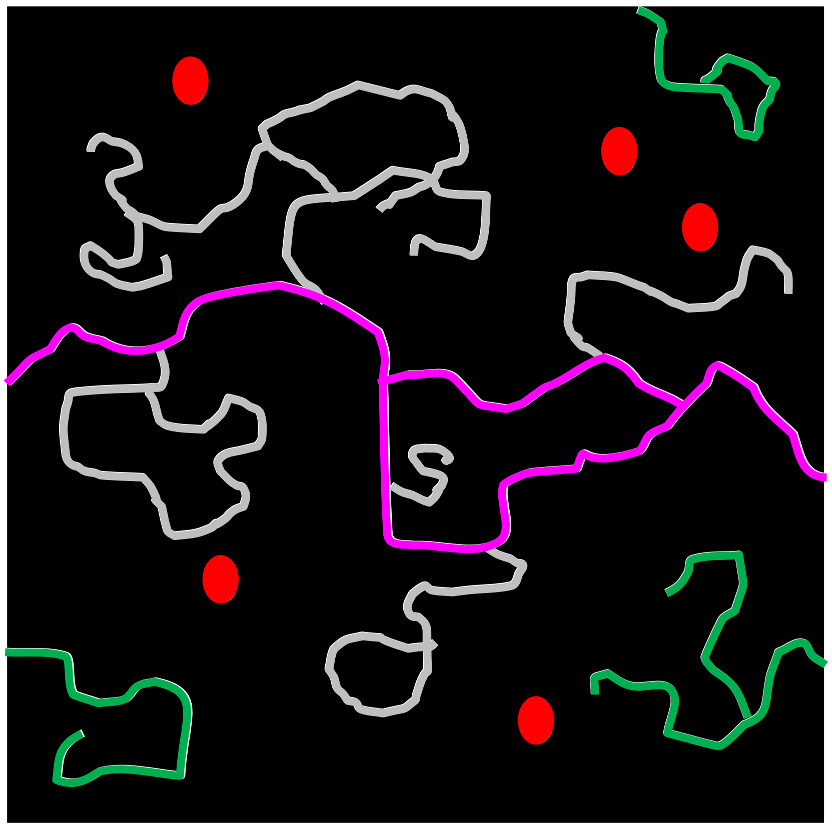
Field observation (preferential flow in a fracture network) of dye distribution in unsaturated fractured tuff at Yucca Mt.



My work on fracture transport starts with this rock

Pore Geometry and Topology



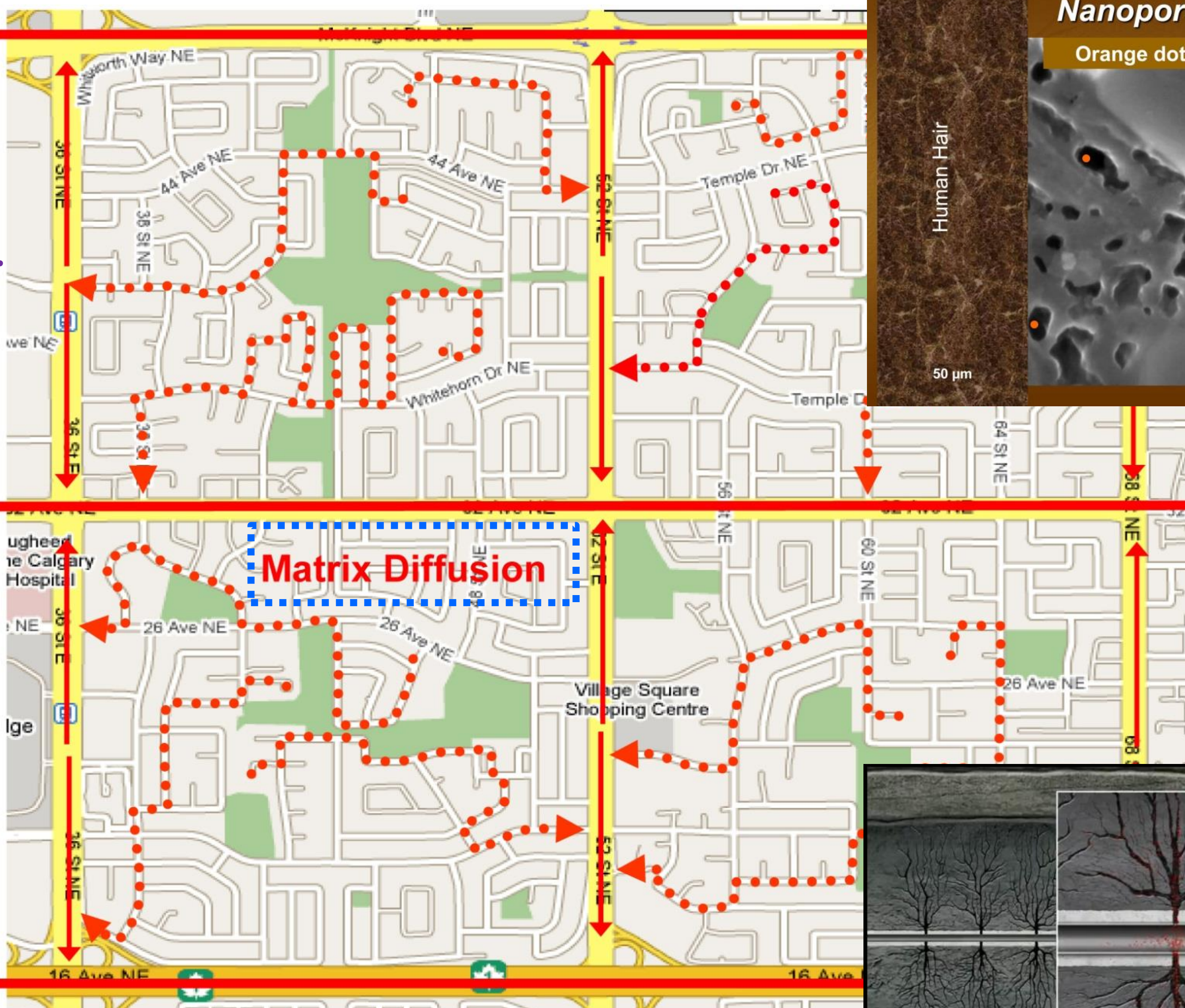


Pore structure: shape, volume, size, size–distribution, connectivity, and surface area

Shale Gas Flow: Matrix "diffusion" vs. "Darcy" flow

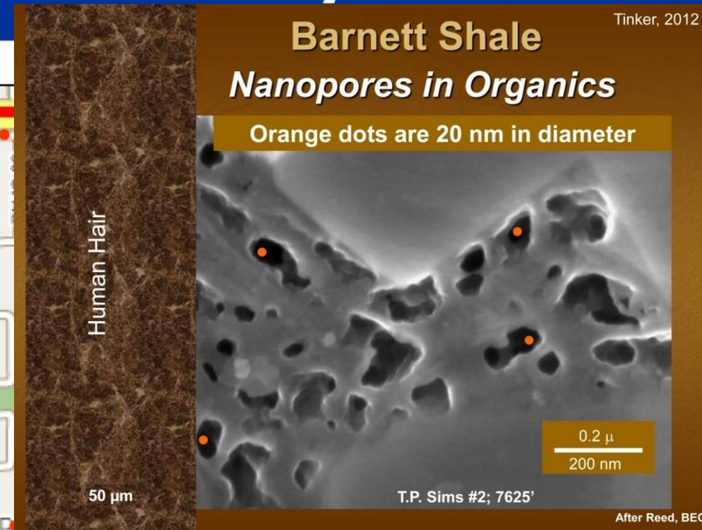
drive your car out of neighborhood blind-folded

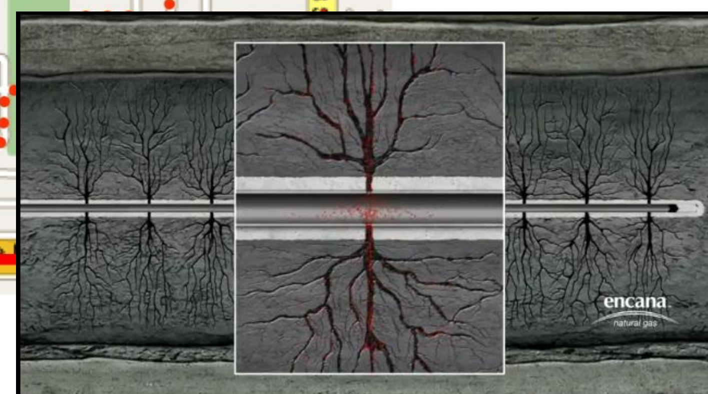
random walk



Darcy Flow

to well bore





http://www.transcanada.com/customerexpress/docs/presentations_general/2009_North_American_Shale_Gas_Overview_NECA.pdf

Three Data Points ← anecdotal

- Gas molecule movement in shale on the order of 10 feet in the lifetime of a well - Dr. Mohan Kelcar, University of Tulsa.
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→ ~1 m/yr movement (advection vs. diffusion ?)

LaFollette, R. 2010. Key Considerations for Hydraulic Fracturing of Gas Shales. Manager, Shale Gas Technology, BJ Services Company, September 9, 2010. www.pttc.org/aapg/lafollette.pdf

Pore Connectivity and Diffusion

- Same mathematics for diffusion and imbibition:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D_s(\theta)\frac{\partial c}{\partial x} \right] \qquad \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x} \right]$$

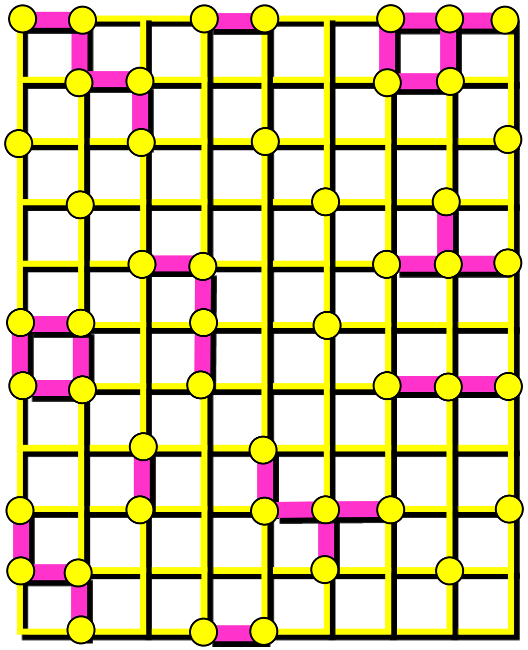
- Affected the same way by pore connectivity:

Pore connectivity:	High Classical	Low Anomalous
Time–dependence:		
Distance to front	$t^{0.5}$	$t^{0.263}$
Diffusion coefficient	constant	$t^{-0.48}$
Distance–dependence:		
Diffusion coefficient	constant	$t^{-1.83}$

Ewing and Horton (2002)

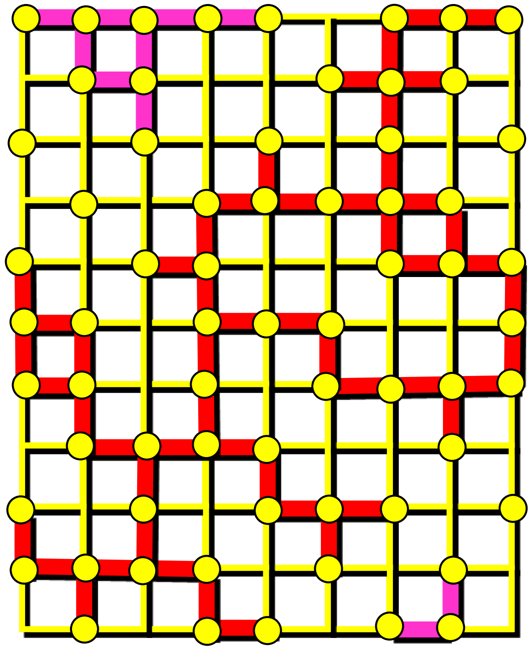
Percolation Theory

The mathematics of how macroscopic properties result from local (microscopic) connections



***p* is the local connection probability**

percolation threshold
$0.5 < p_c < 0.66$
(for 2D square lattice)



***p* = 0.5**

***p* = 0.66**

"Ant in a labyrinth"

↕

Solute in a pore system

Multiple Approaches to Studying Pore Structure

- Imbibition with samples of different shapes (UTA)
- Edge-accessible porosity (UTA)
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- N_2 adsorption isotherm (Saitama Univ.; Quantachrome)
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- Imaging after Wood's metal impregnation (Univ. Hannover; Swiss EPMA)
- Microtomography (high-resolution, synchrotron) (PNNL-EMSL; Swiss Light Source; Univ. Hannover; Saitama Univ.)
- Focused Ion Beam/SEM imaging (PNNL-EMSL)
- *Small-Angle Neutron Scattering (SANS)*
- Pore-scale network modeling (ISU)

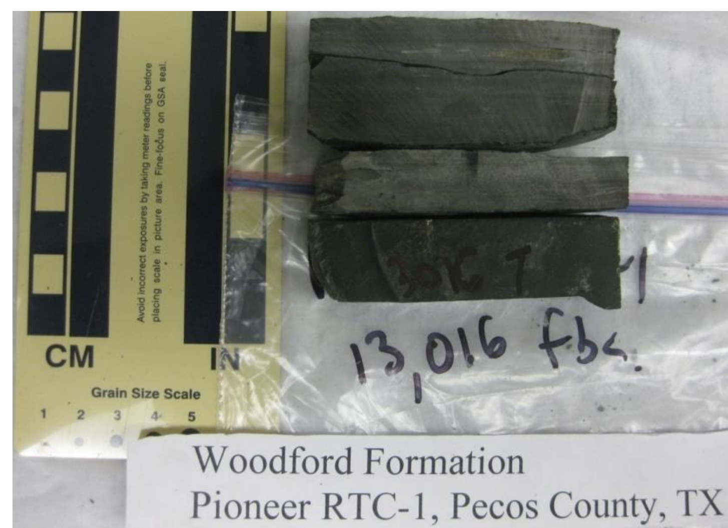
http://www.beg.utexas.edu/abs/abstract.php?d=2012-09-14


Core Research Center of the
Bureau of Economic
Geology (BEG) in Texas

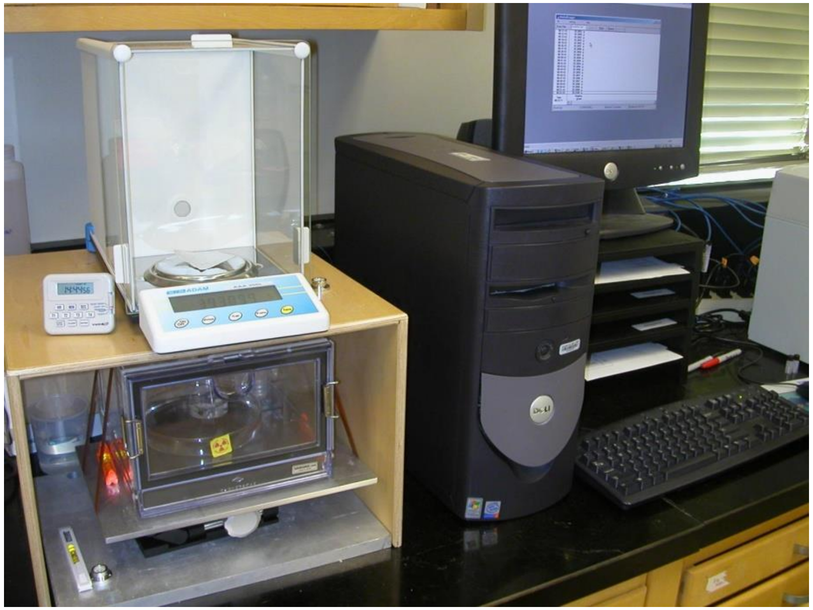

Barnett shale

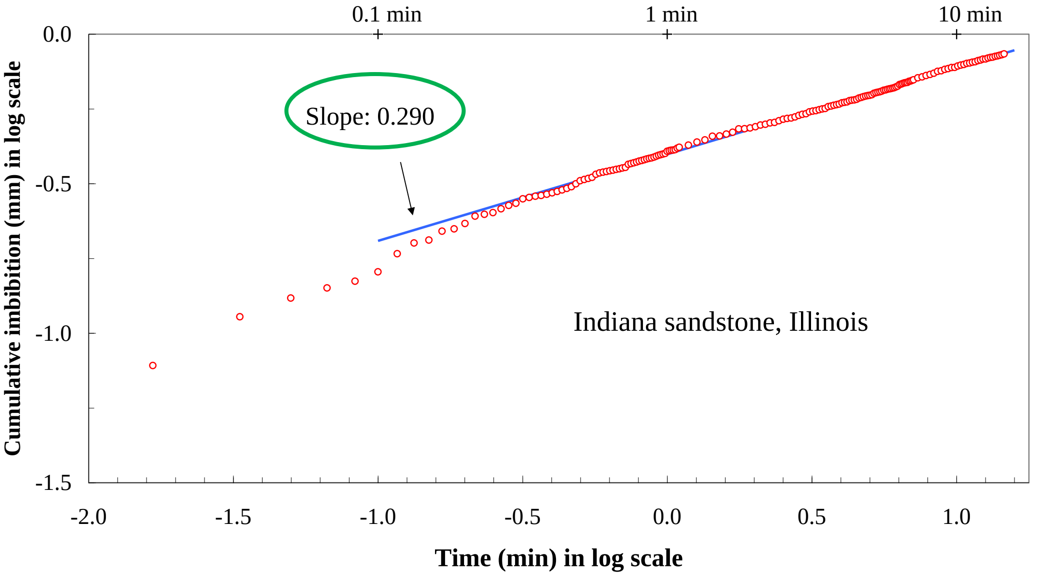

11178 fbs
Haynesville Formation
NRF Energy Huffmann #1, Harrison County, TX

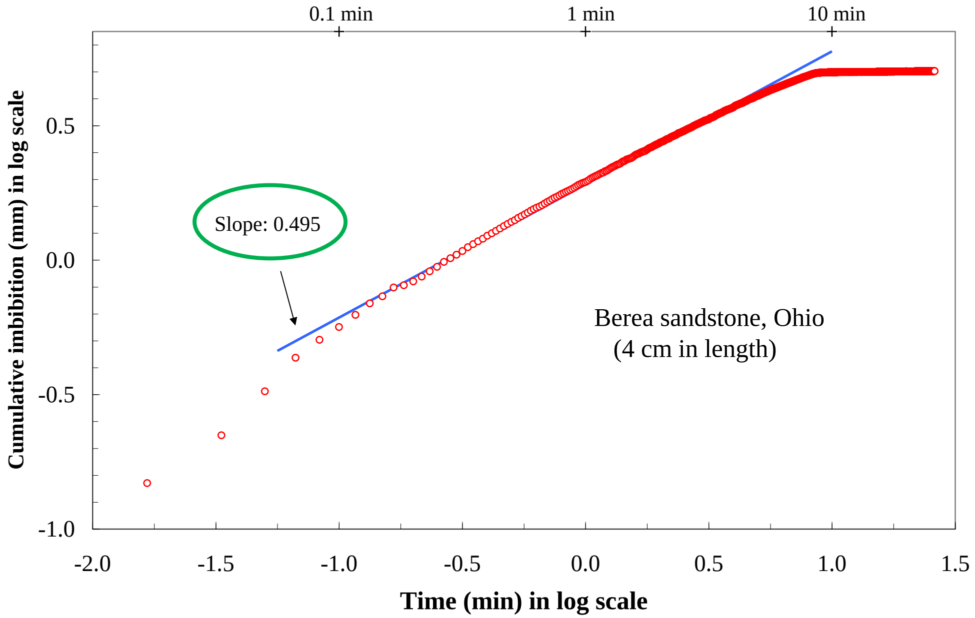

GSA
PHOTO SCALE/FOCUS GUIDE
CM
11,842 fbs
Pearsall Formation
Tidewater Wilson, La Salle County, TX


CM
IN
Grain Size Scale
13,016 fbs
Woodford Formation
Pioneer RTC-1, Pecos County, TX

(Spontaneous) Imbibition Test

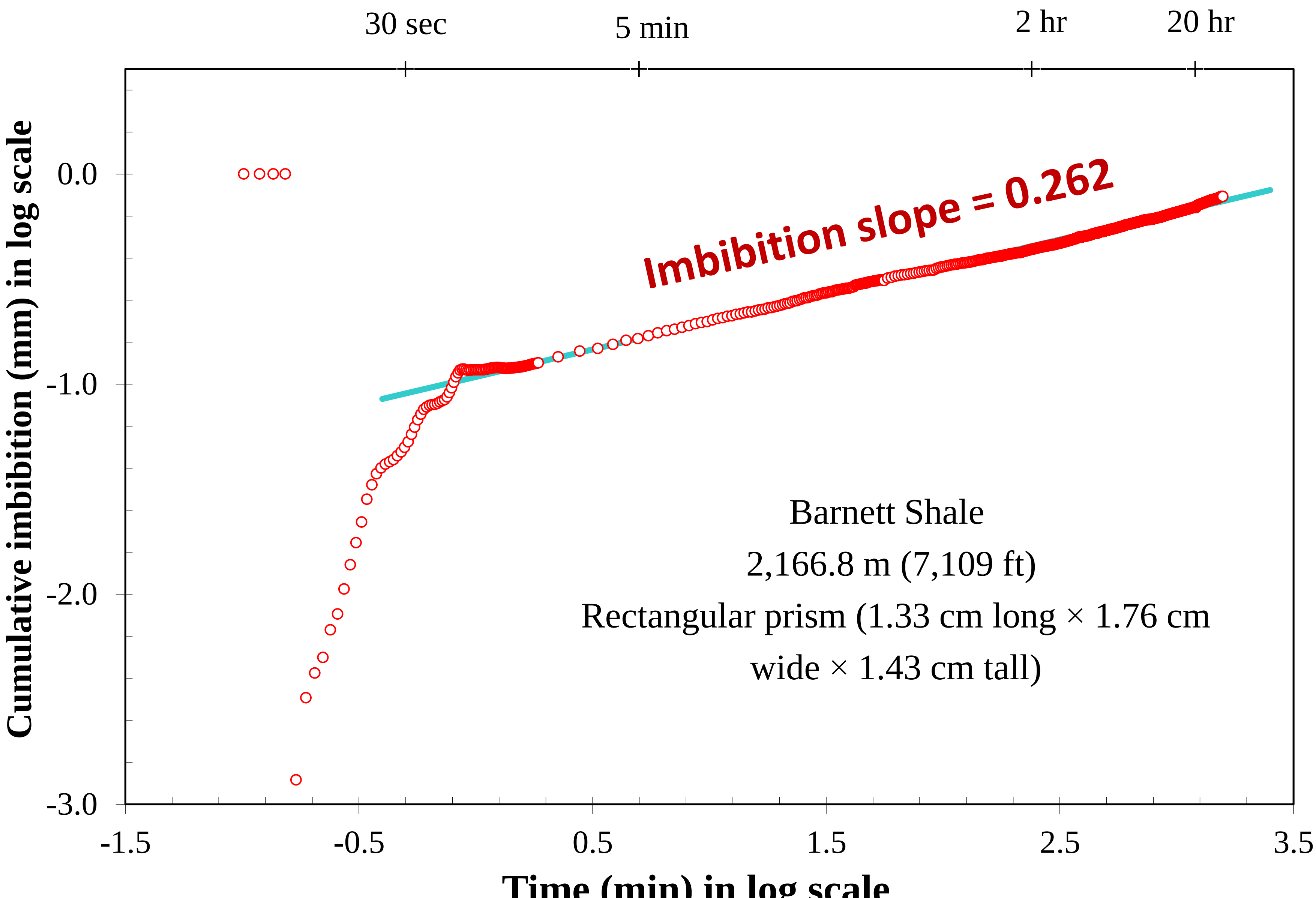






- Rock sample epoxy-coated along length → 1D flow
- Imbibition rate monitored continuously over time

Low Pore-Connectivity of Shale Samples



Imbibition Results for Barnett Shale Samples

Depth	Sample dimension	Height/width	Imbibition slope
7,109 ft (2,167 m)	1.33 cm L×1.76 cm W ×1.43 cm H (Vertical)	0.93	0.214 ±0.059 (N=3)
	1.76 cm L×1.72 cm W ×1.32 cm H (Horizontal)	0.76	0.291 ±0.027 (N=3)
7,136 ft (2,175 m)	1.38 cm L×1.71 cm W ×1.72 cm H (Vertical)	1.12	0.269 ±0.0045 (N=3)
	1.73 cm L×1.73 cm W ×1.21 cm H (Horizontal)	0.70	0.216 ±0.040 (N=3)
7,169 ft (2,185 m)	1.35 cm L×1.79 cm W ×1.81 cm H (Vertical)	1.16	0.273 ±0.050 (N=3)
	1.24 cm L×1.78 cm W ×1.32 cm H (Horizontal)	0.87	0.357 ±0.006 (N=3)
7,199 ft (2,194 m)	1.24 cm L×1.74 cm W ×1.67 cm H (Vertical)	1.12	0.284 ±0.062 (N=3)
	1.74 cm L×1.72 cm W × 1.26 cm H (Horizontal)	0.67	0.282 ±0.047 (N=3)
7,219 ft (2,200 m)	1.37 cm L×1.74 cm W × 1.95 cm H (Vertical)	1.25	0.306 ±0.019 (N=3)
	1.69 cm L×1.71 cm W ×1.36 cm H (Horizontal)	0.80	0.264 ±0.046 (N=3)

Imbibition Results: Shape Effect

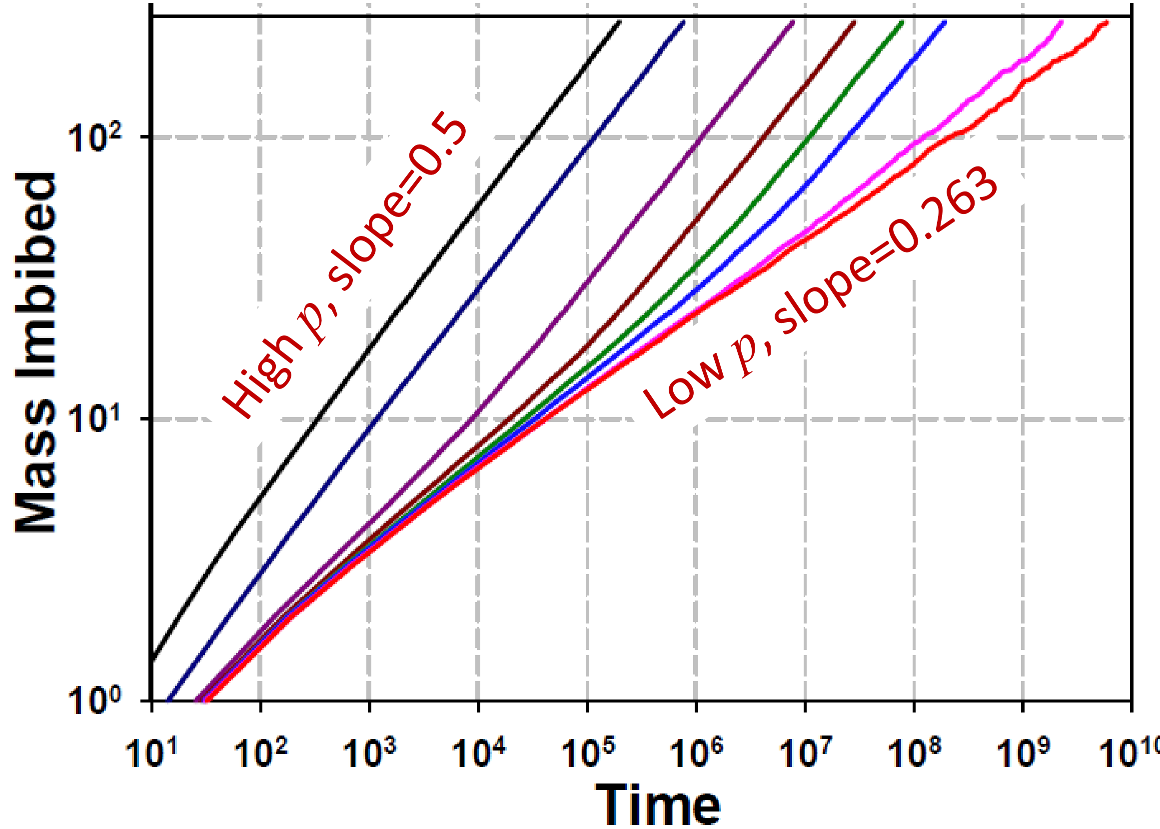
Rock	Core height/width	Imbibition slope
Berea Sandstone	1.18	0.649 ± 0.022
	2.35	0.488 ± 0.006
	4.71	0.494 ± 0.008
Welded tuff	0.40	0.513 ± 0.014
	1.00	0.371 ± 0.024
Dolomite	0.40	0.487 ± 0.035
	1.00	0.344 ± 0.004 → 0.556 ± 0.048
	1.16	0.300 ± 0.036
Indiana Sandstone	0.40	0.272 ± 0.047
	1.16	0.253 ± 0.006
	2.33	0.291 ± 0.008

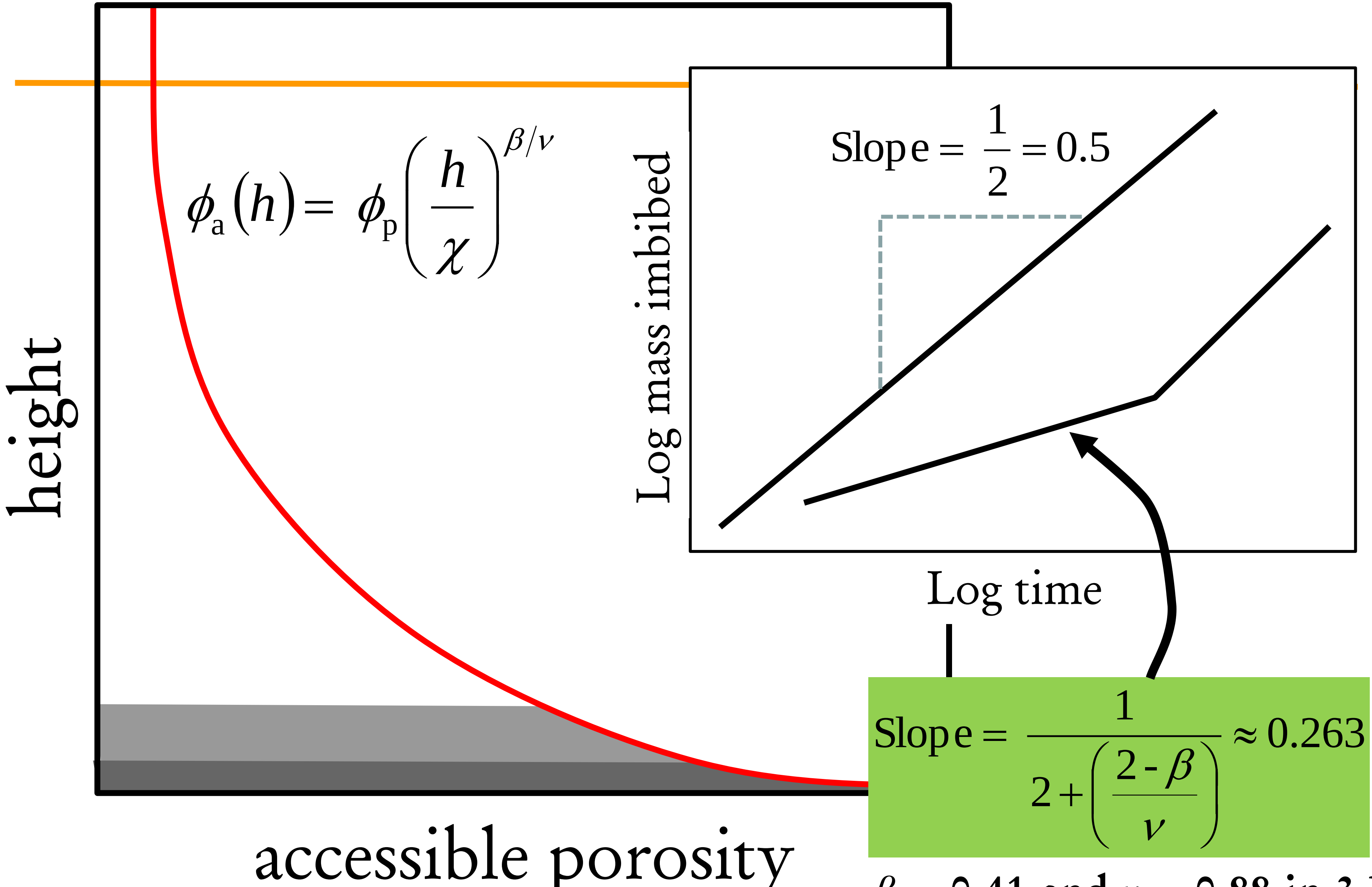
Pore-Scale Network: Imbibition Simulation

- p is pore connectivity probability;

  p_c is the percolation threshold

- **Slope = 0.5 at high p**
- **Slope = 0.26 at $p=p_c$**
- At intermediate p values, at some time or distance to the wetting front, the slope transitions from 0.26 to 0.50



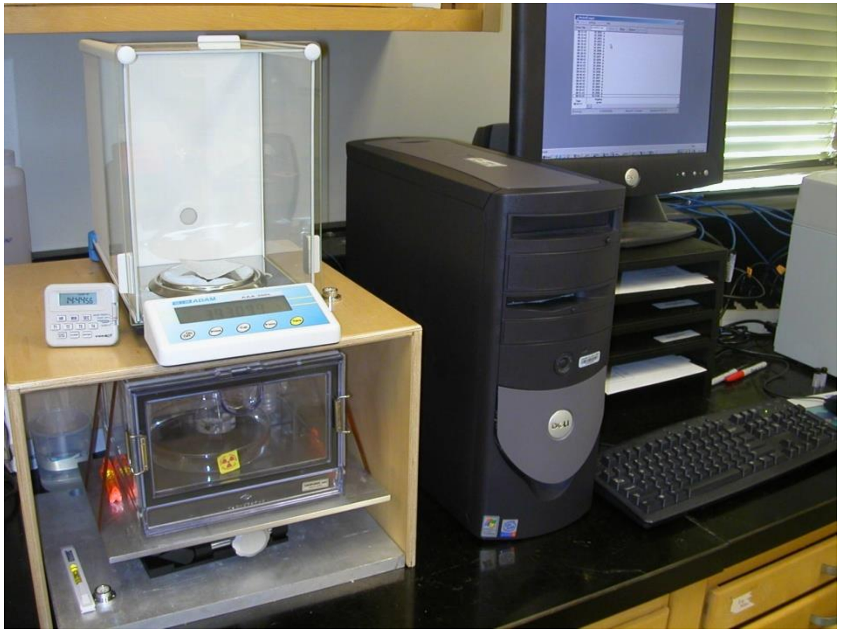


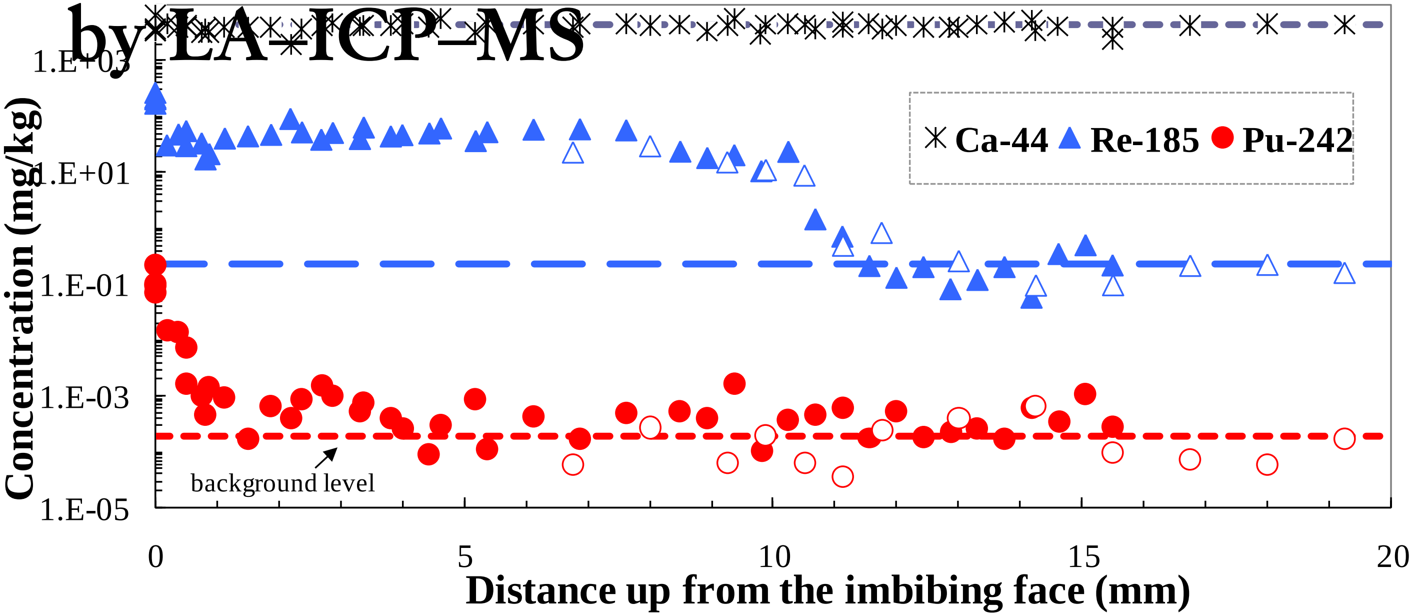
$\beta \approx 0.41$ and $\nu \approx 0.88$ in 3-D

Stauffer, D., Aharony, A., 1994. *Introduction to Percolation Theory* (2nd Ed.). Taylor and Francis, London.

Imbibition: Work Plan

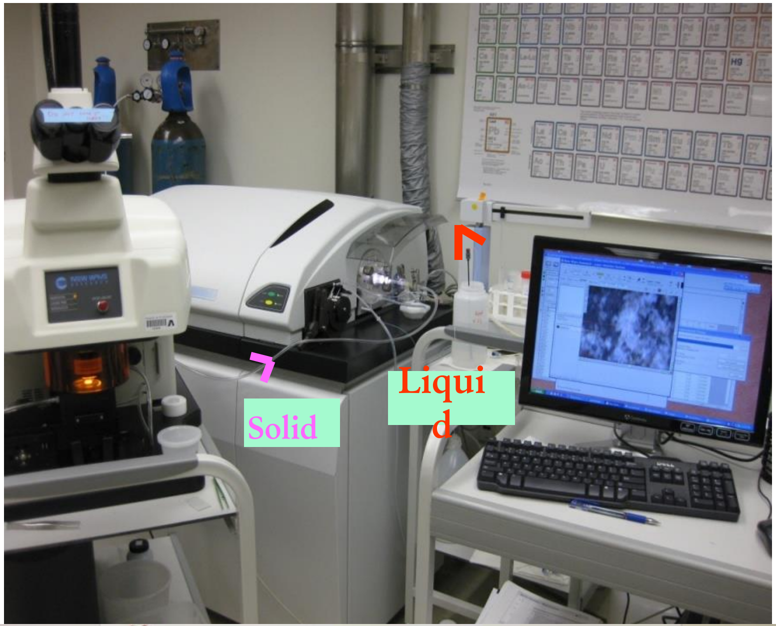
- More fluids: API brine (8 wt% NaCl+2 wt% $CaCl_2$); *n*-decane ($C_{10}H_{22}$); fracturing fluid
- Suitable organic-element tracers in *n*-decane, and imbibition distance mapped by LA-ICP-MS

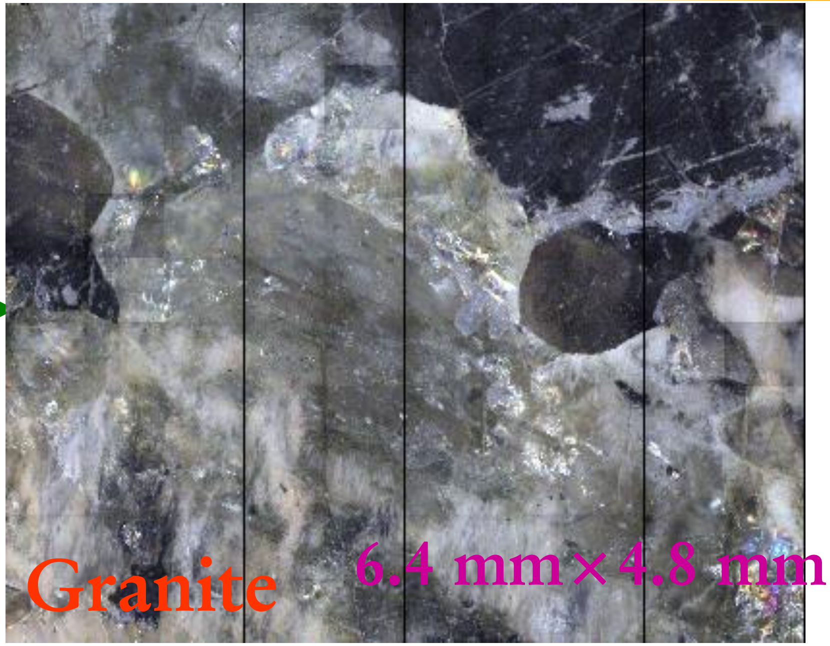


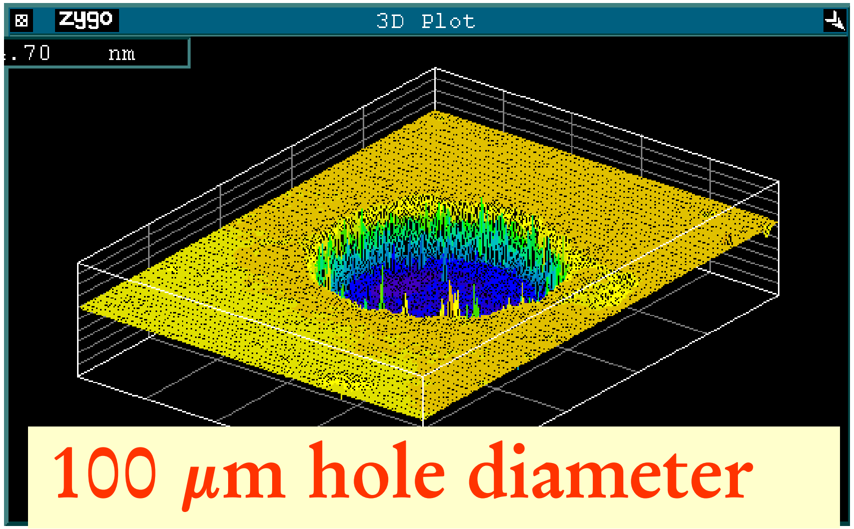


- Initially dry
- Strong capillarity
- Sharp front
- Advection dominant

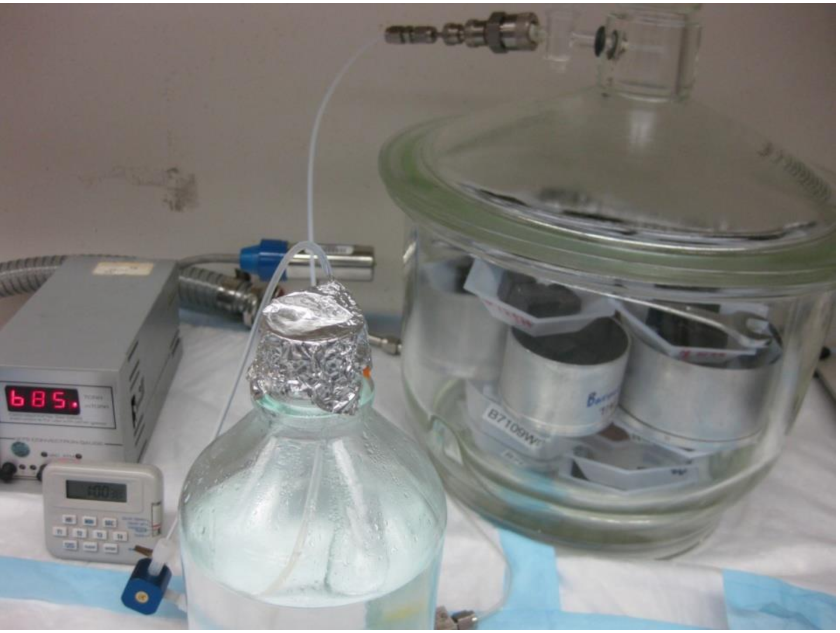
Laser Ablation-ICP-MS for Micro-Scale Profiling

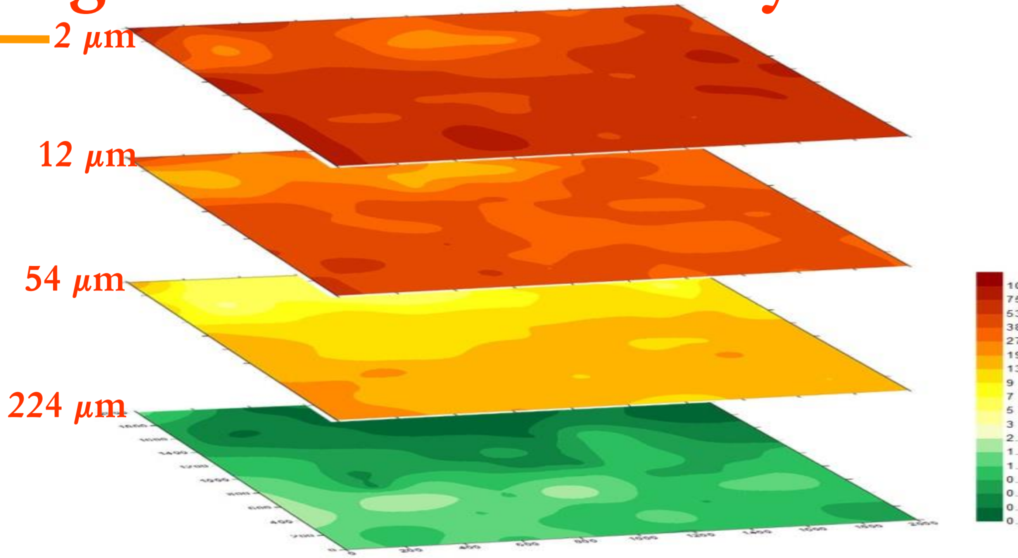






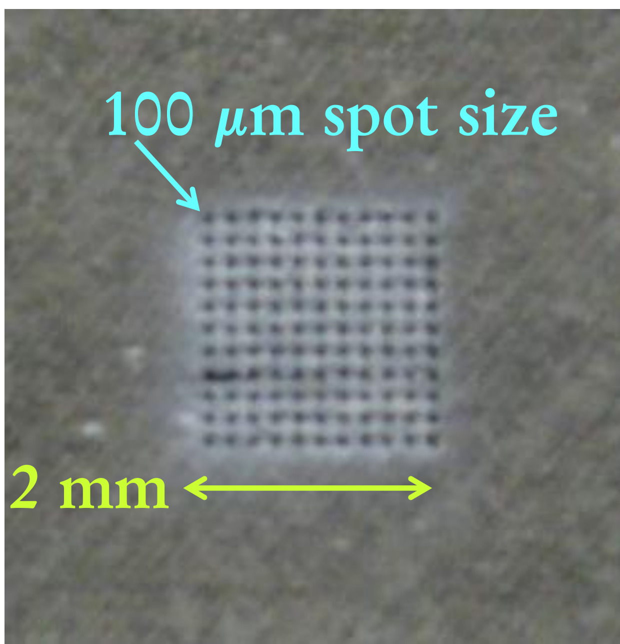
3D Elemental Mapping: Edge-Accessible Porosity

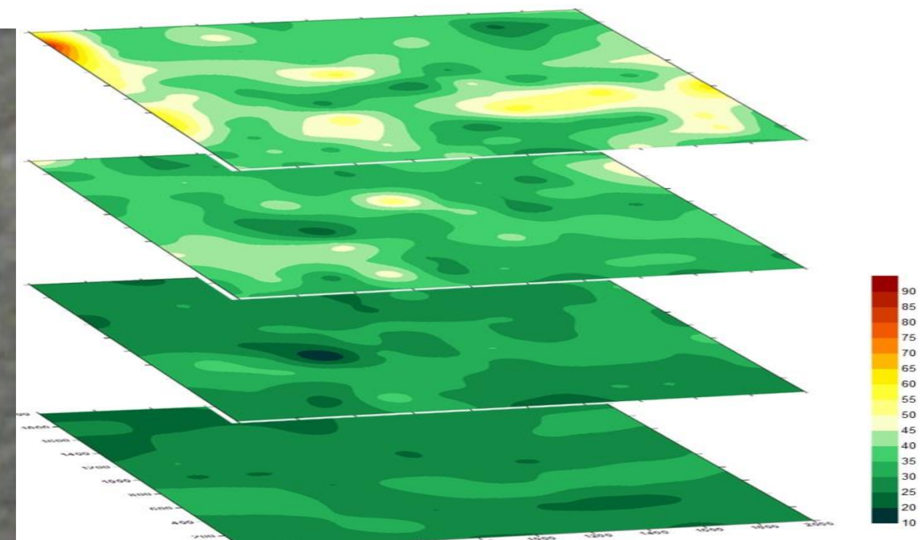




ReO_4^- (non-sorbing)

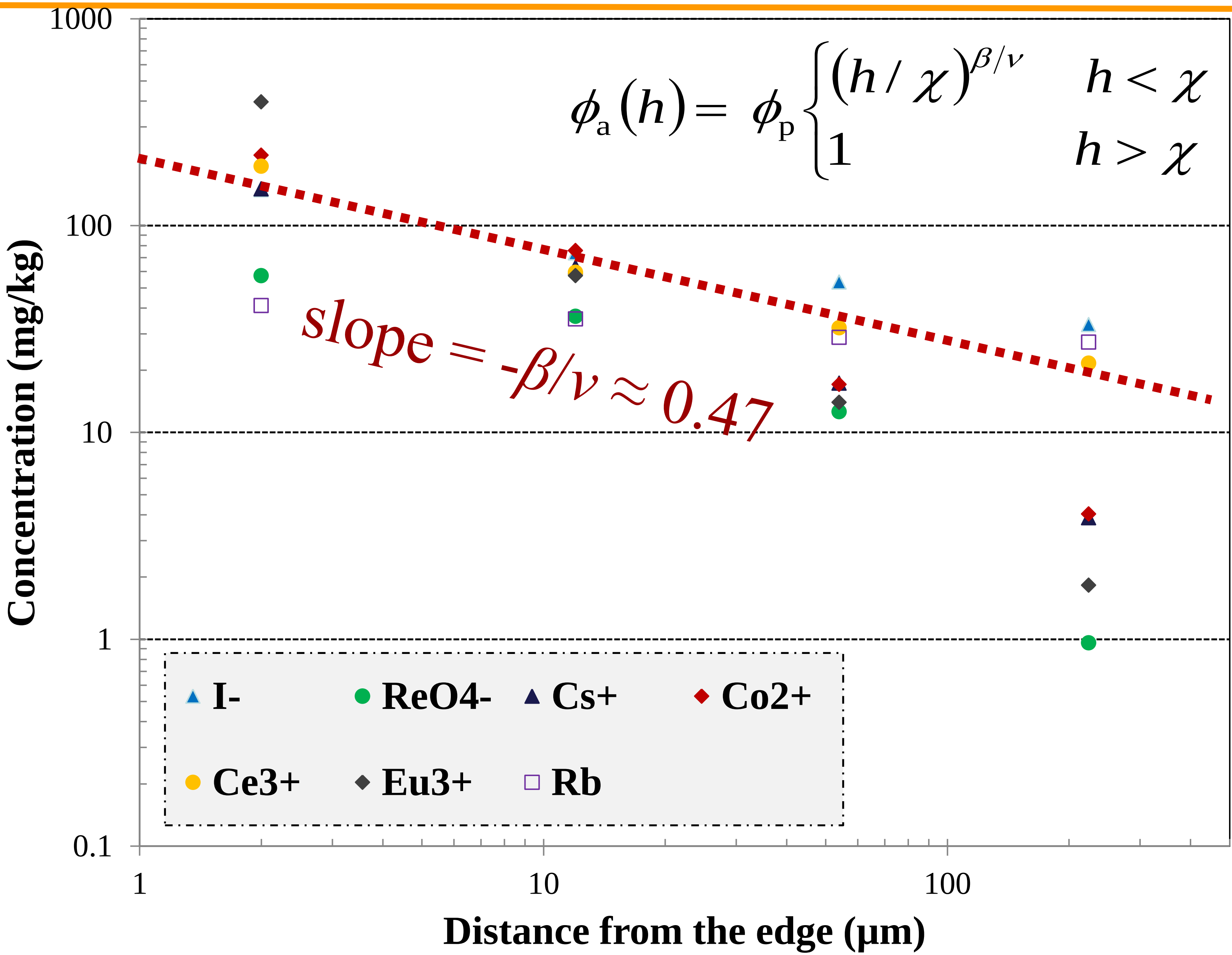
After 1 hr, vacuum in connected space = 1 – 0.68 torr / 740 torr = 99.91%



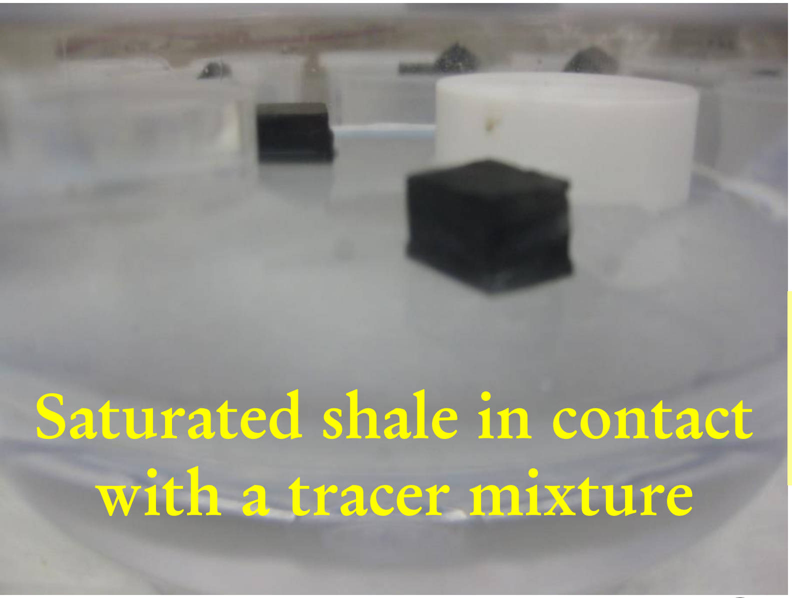


Rb (intrinsic)

Averaged Concentration (N=121) vs. Depth



Liquid Tracer Diffusion in Saturated Samples

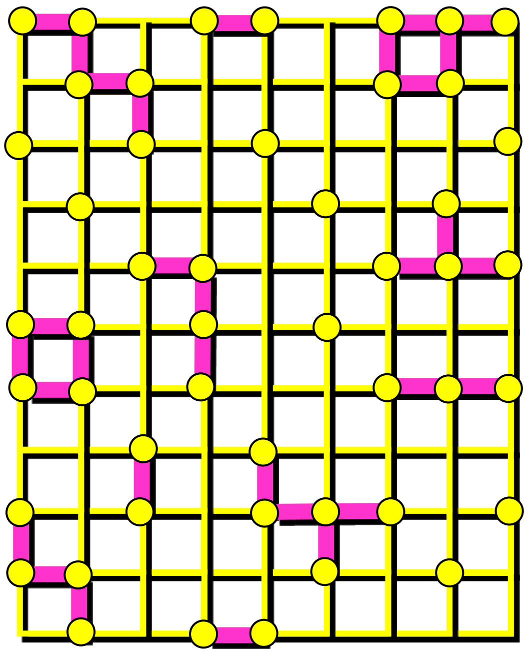


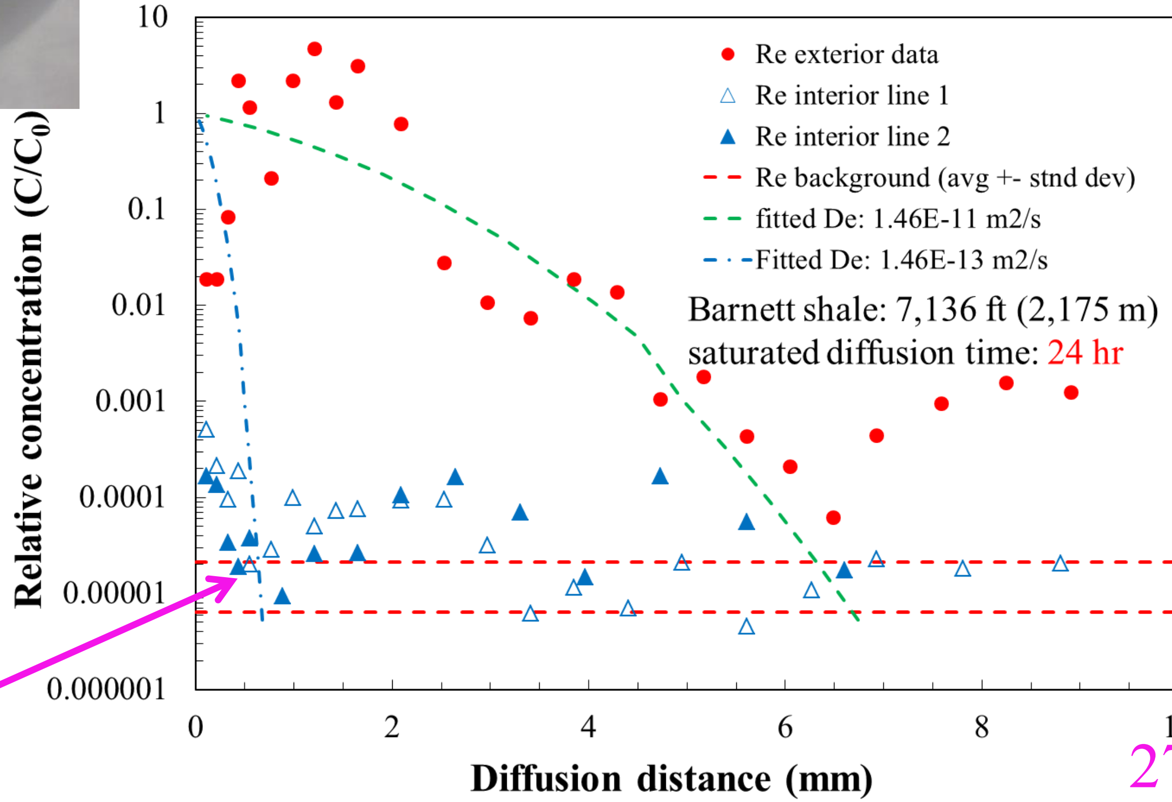
$$\frac{C}{C_0} = \frac{1}{2} erfc \frac{x}{2\sqrt{D_e t}}$$

$$\tau = \frac{D_0}{De}$$

Fitted tortuosity τ

✓ 100 (exterior); 10,000 (interior)





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$$\frac{C(x,t)}{C_0} = erfc\left(\frac{x}{2(D_e t)^{0.5}}\right)$$

$$D_e = \frac{\delta D_0}{\tau}$$

For $C/C_0 = 0.5$ @ 1 m/y, $\tau = 613$

For $C/C_0 = 0.01$ @ 1 m/y, $\tau = 9{,}800$

LaFollette, R. 2010. Key Considerations for Hydraulic Fracturing of Gas Shales. Manager, Shale Gas Technology, BJ Services Company, September 9, 2010. www.pttc.org/aapg/lafollette.pdf

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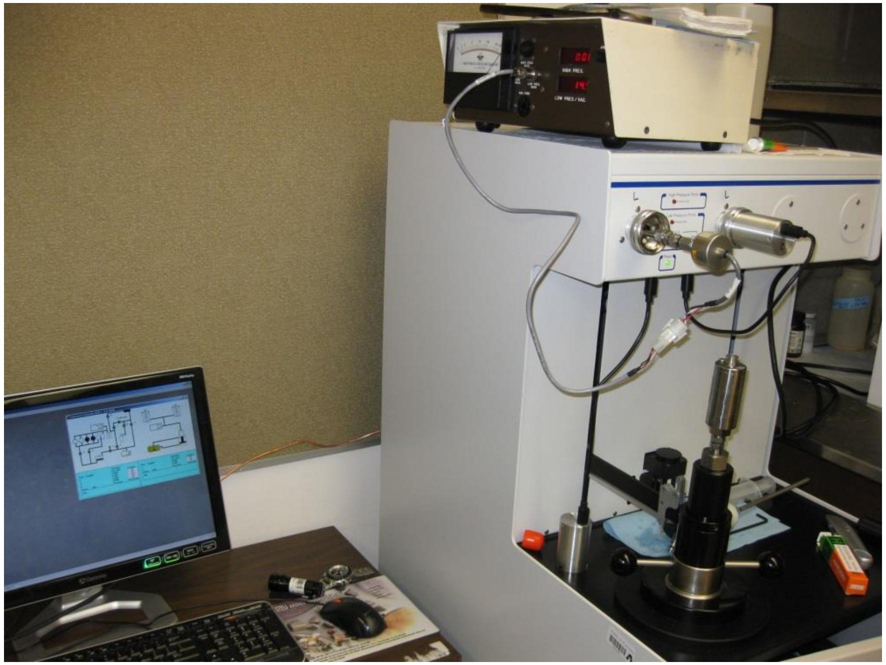
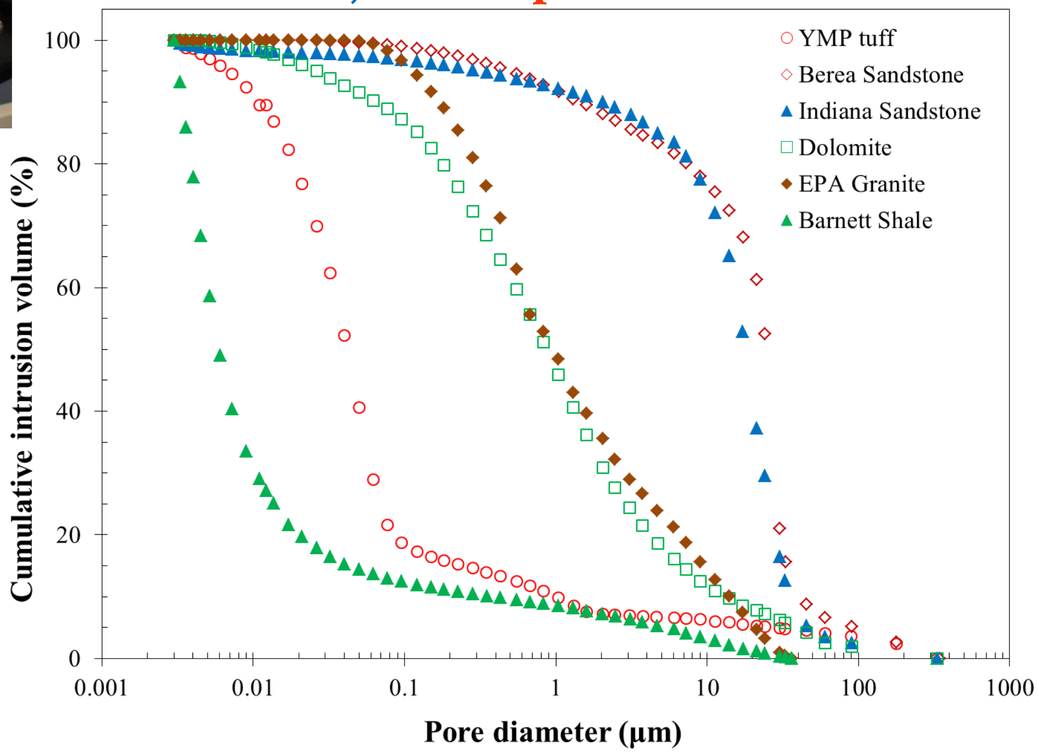
http://www.beg.utexas.edu/abs/abstract.php?d=2012-09-14

MIP Intrusion Results: Pore-Throat Size Distribution



Barnett Shale sample (~15 mm cube) in the penetrometer



- Mercury Injection Porosimetry (MIP)
- Measurable pore diameter range: 3 nm to 360 μm

MIP Results: 6 Representative Rocks

Depth	Porosity (%)	Median pore-throat diameter (nm)	Permeability (μdarcy)	Tortuosity
Berea Sandstone	22.9 ± 1.72	$23{,}776 \pm 876$	$(595 \pm 21.2) \times 10^3$	3.31 ± 0.33
Indiana Sandstone	16.4 ± 0.4	$19{,}963 \pm 2{,}932$	$(221 \pm 40.8) \times 10^3$	4.68 ± 1.68
Welded Tuff	10.0 ± 0.5	47 ± 7.1	0.83 ± 0.14	$1{,}745 \pm 66$
Dolomite	9.15	873	409	38.3
Barnett Shale (7,199')	5.97 ± 1.43	6.1 ± 0.3	$(4.96 \pm 1.42) \times 10^{-3}$	$12{,}867 \pm 16{,}224$
NC Granite	1.05	970	12.4	38.2

Permeability: Katz and Thompson (1986; 1987)
Tortuosity: Hager (1998)

Summary

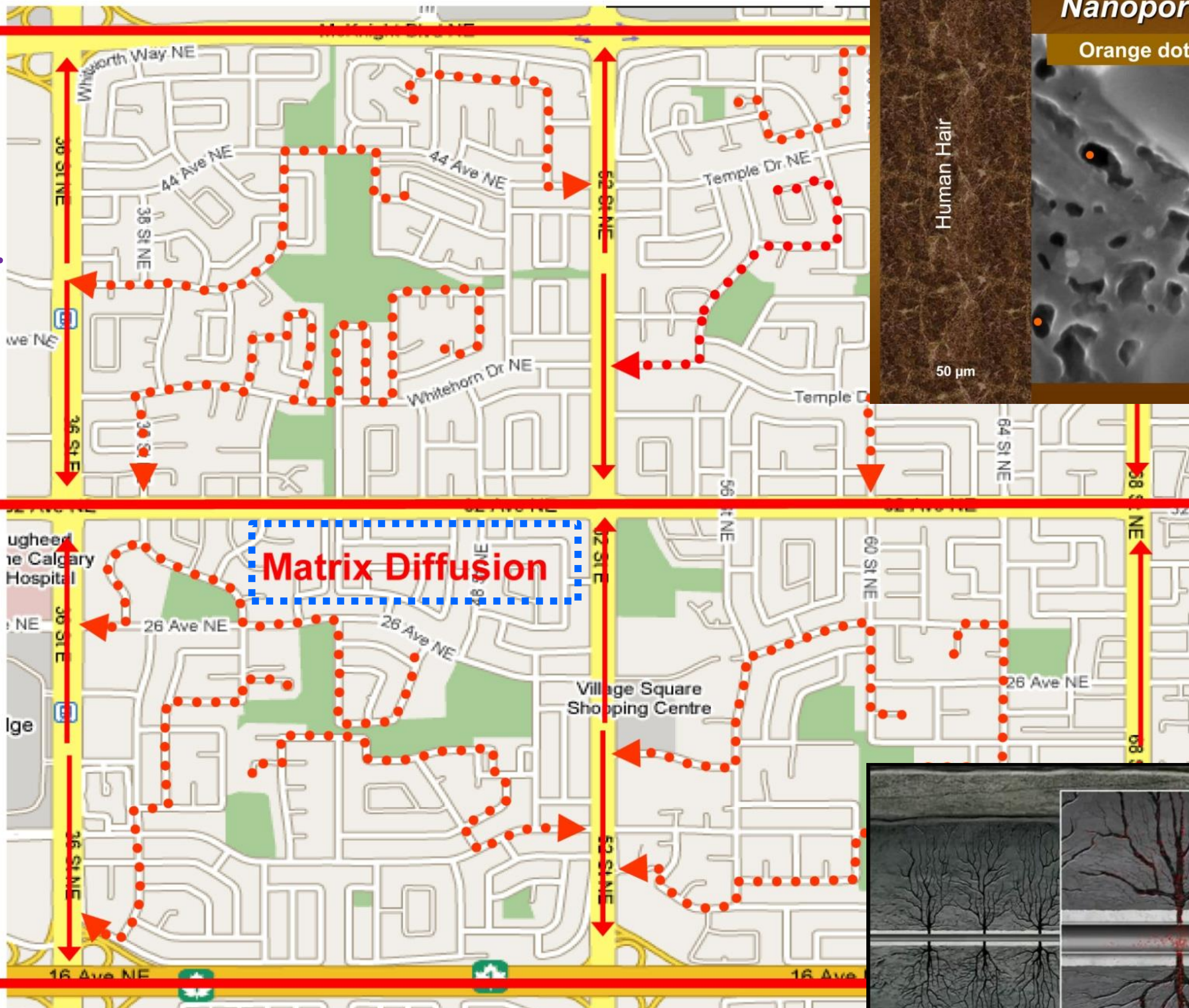
- Steep 1st year decline and low overall hydrocarbon production observed in stimulated shales
- Shales show low pore connectivity, which reduces gas diffusion from matrix to stimulated fractured network
- Several complementary approaches are used to investigate pore structure in natural rock
  - ✓ Imbibition and diffusion: macroscopic method
  - ✓ Porosimetry and vapor condensation: indirect method
  - ✓ Imaging (Wood's metal, FIB/SEM, SANS): nano-scale tool

Hu lab's group members with Dan Steward (10/4/2013)

Shale Gas Flow: Matrix "diffusion" vs. "Darcy" flow

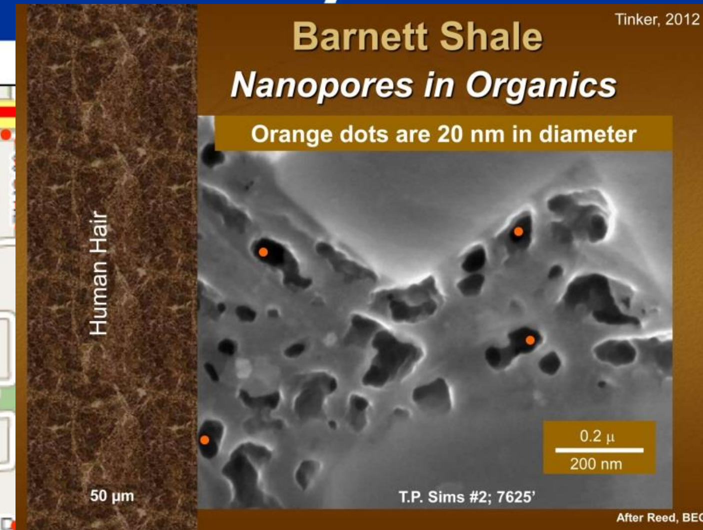
drive your car out of neighborhood blind-folded

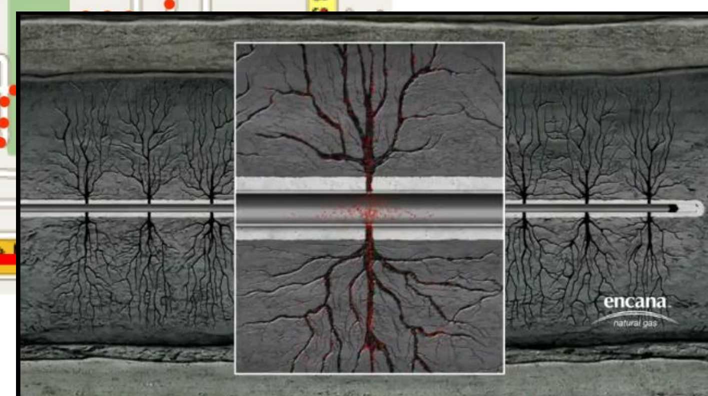
random walk



Darcy Flow

to well bore





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