Particle laden flows INTO Nature:

Sediment transport in unconventional reservoir stimulation

Brendon Hall, ION Geophysical

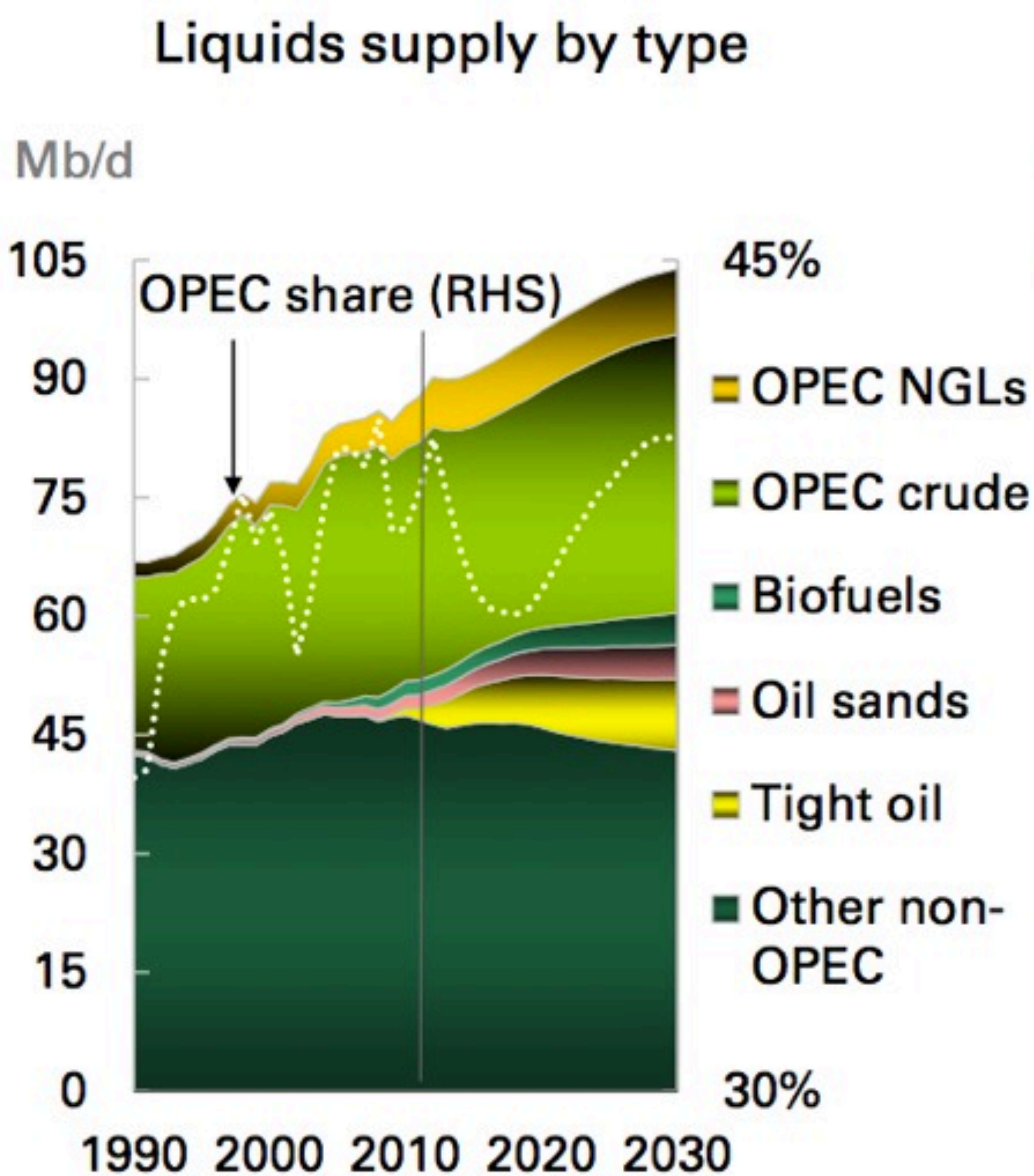
Wednesday, December 18, 2013

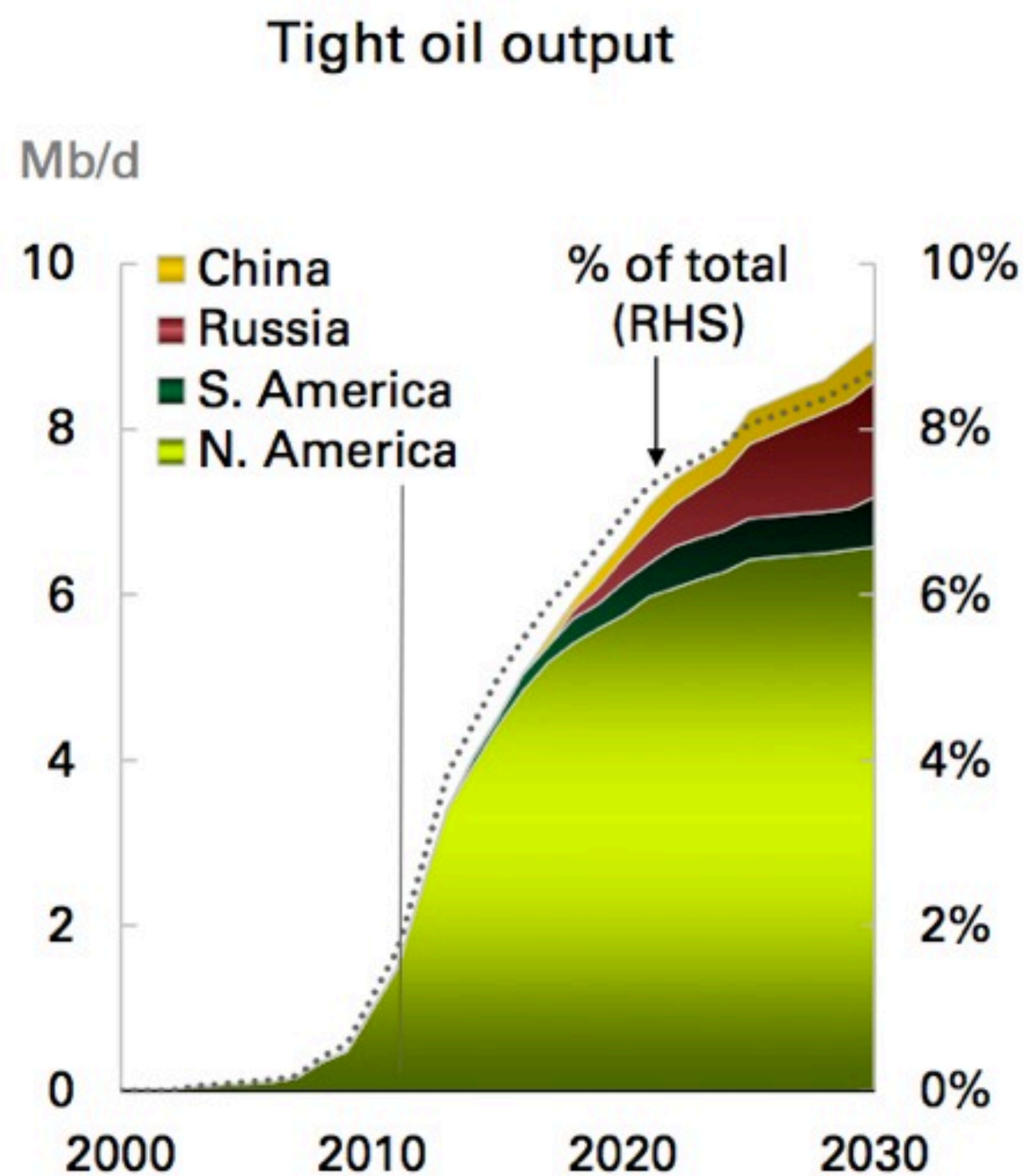
Outline

- Background - the shale boom
- Technology overview - hydraulic fracturing
- Modeling - fracturing and proppant transport

November 12, 2013...

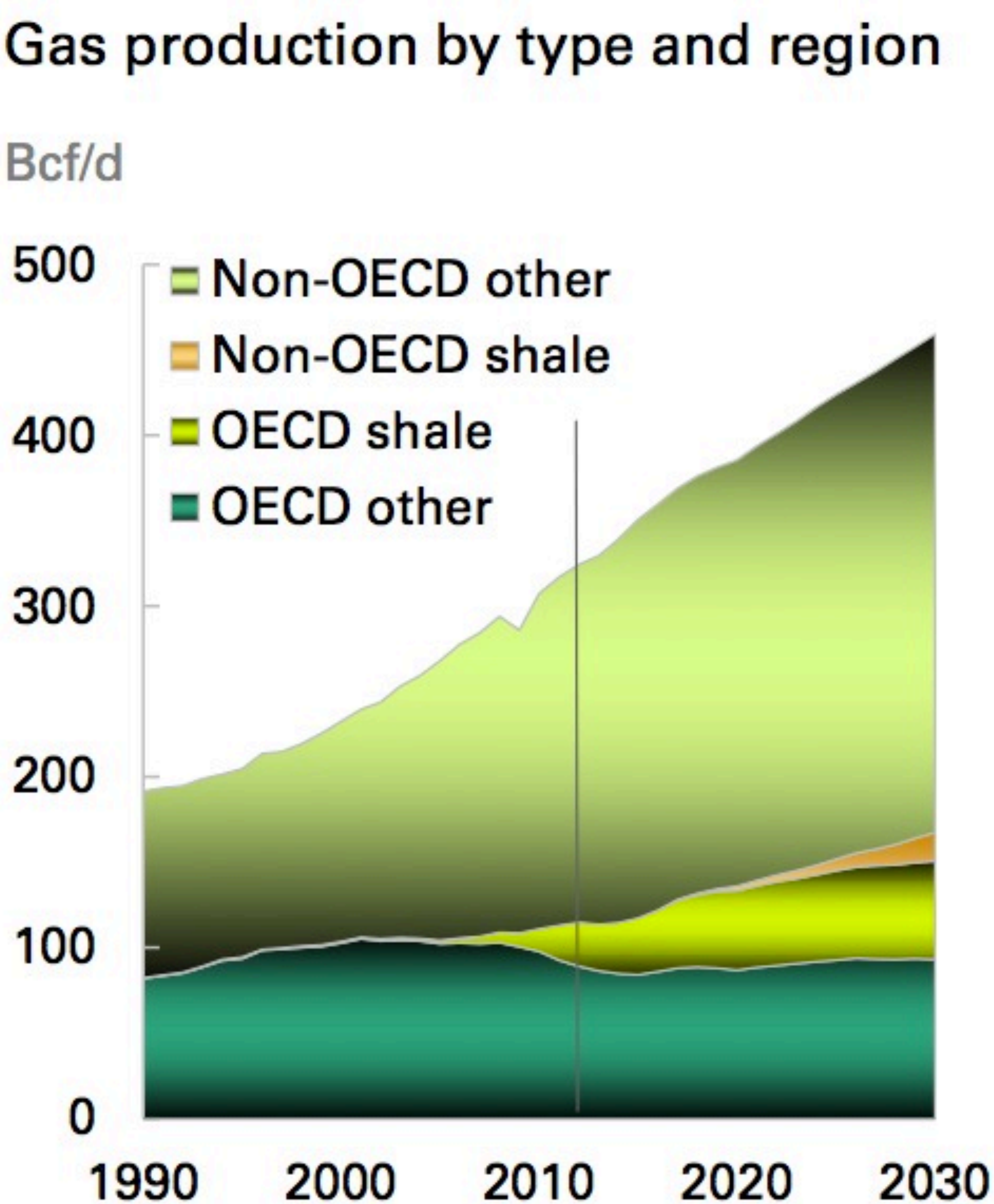
Tight oil will drive liquid supply growth...

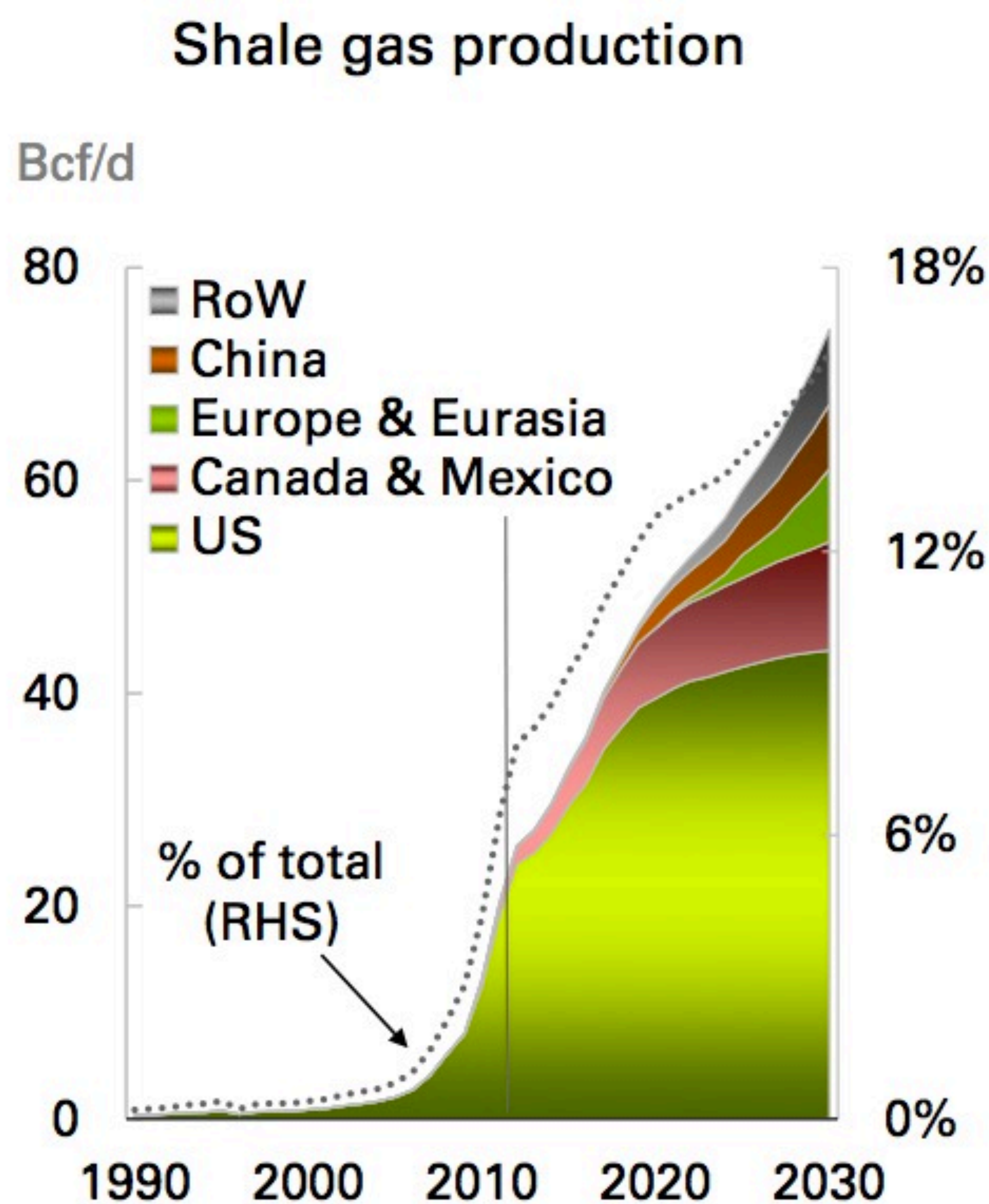




BP Energy Outlook 2013

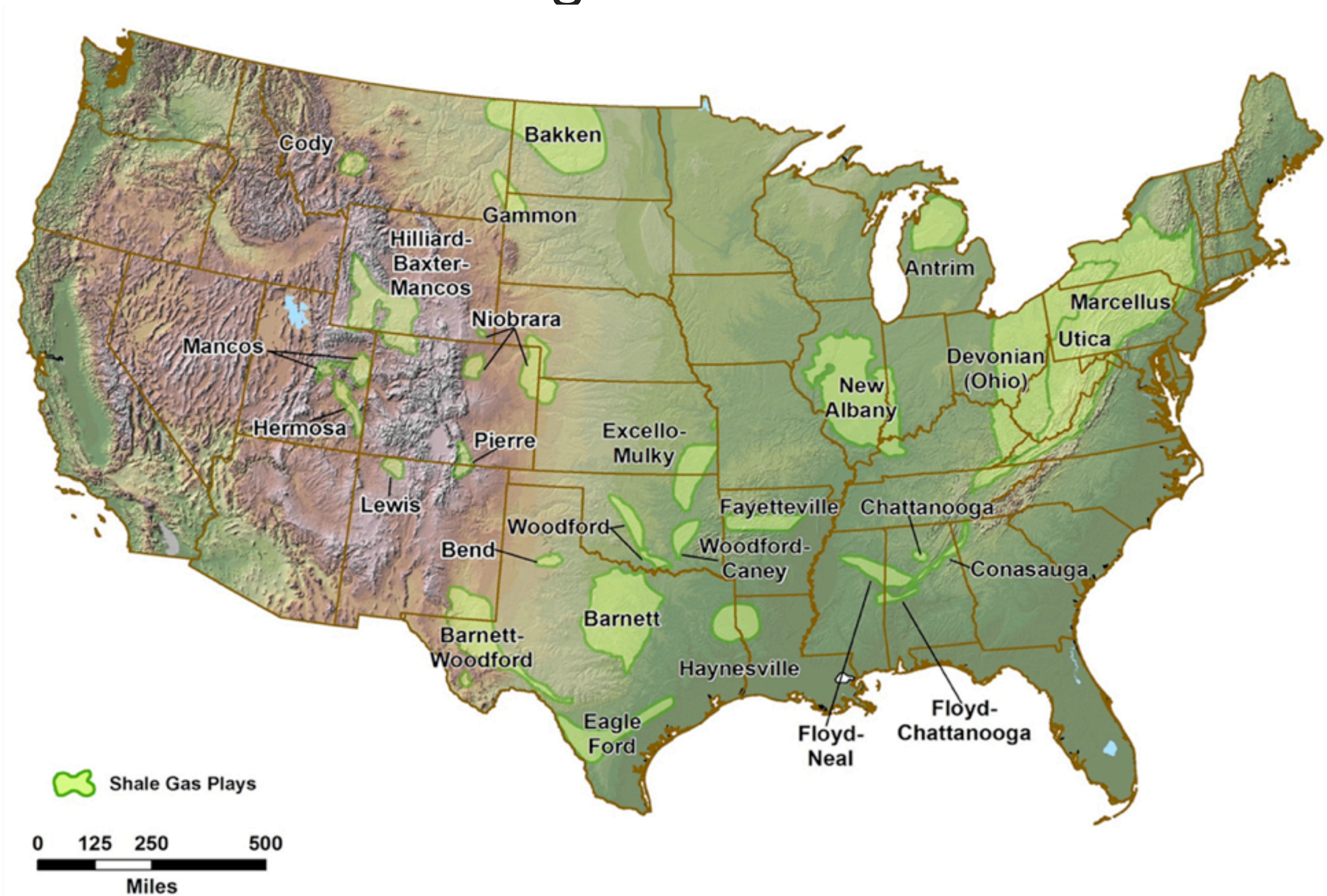
Growth of gas supply driven by US shale...



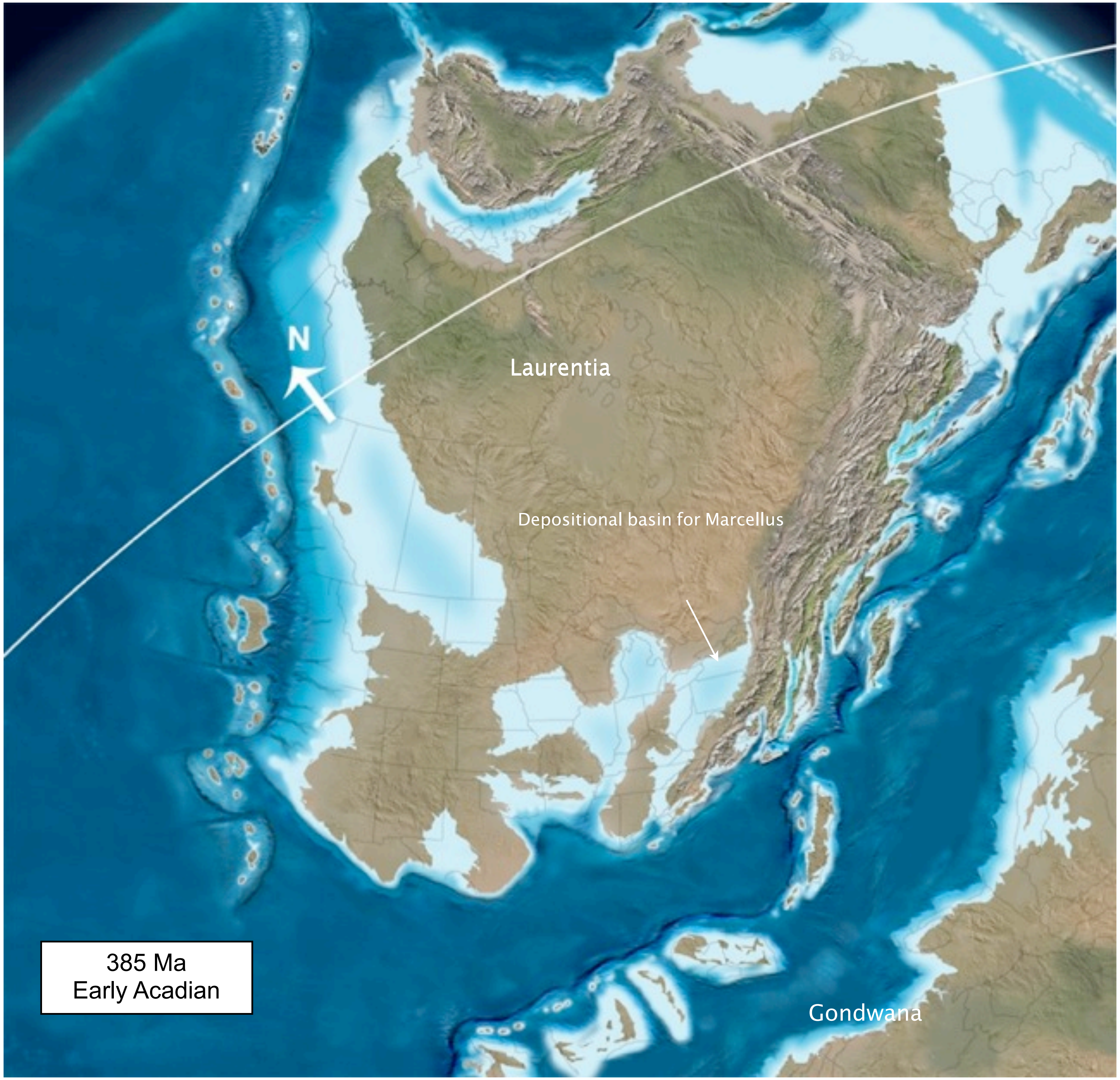


BP Energy Outlook 2013

Where does shale gas/oil come from?

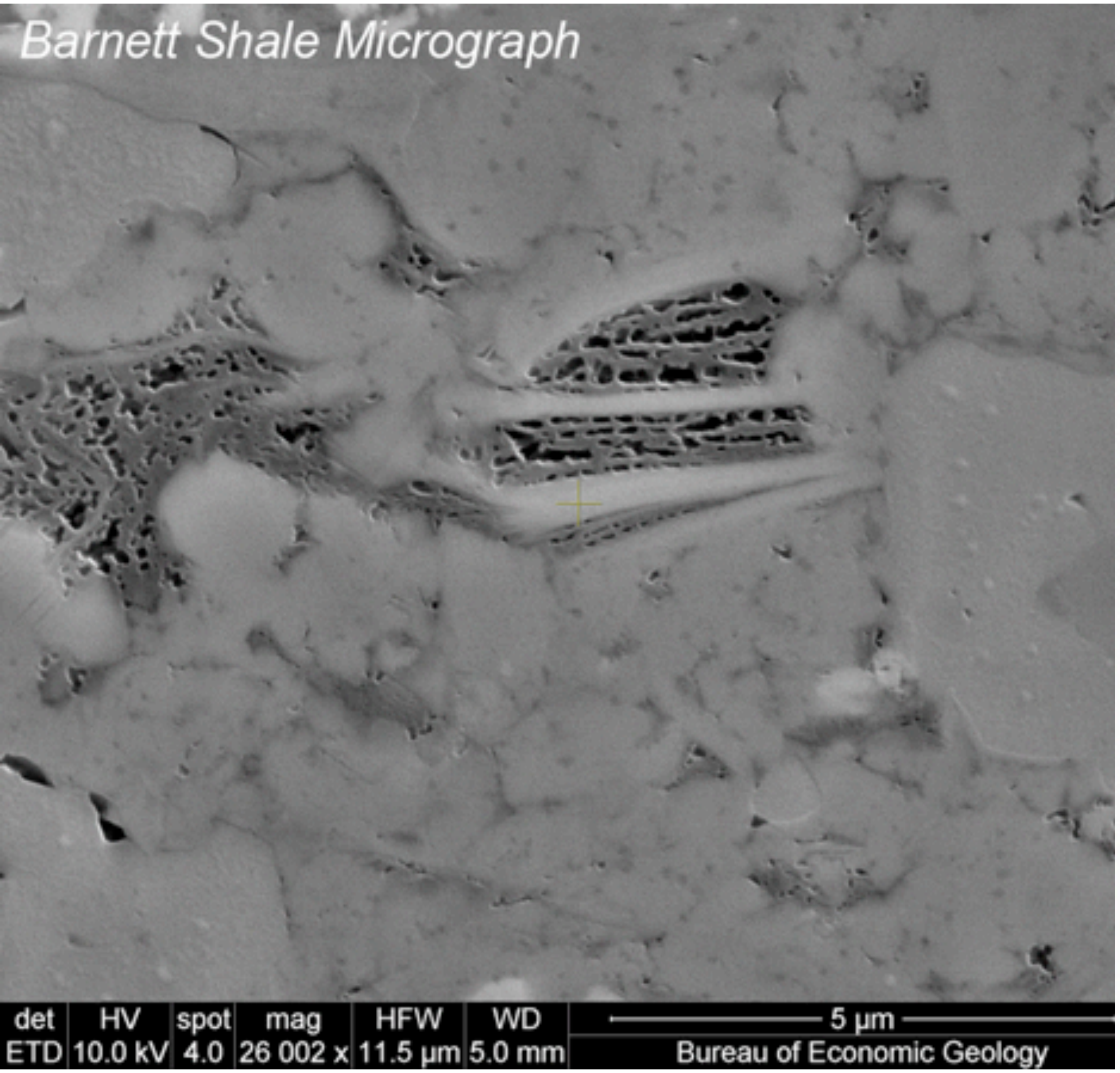


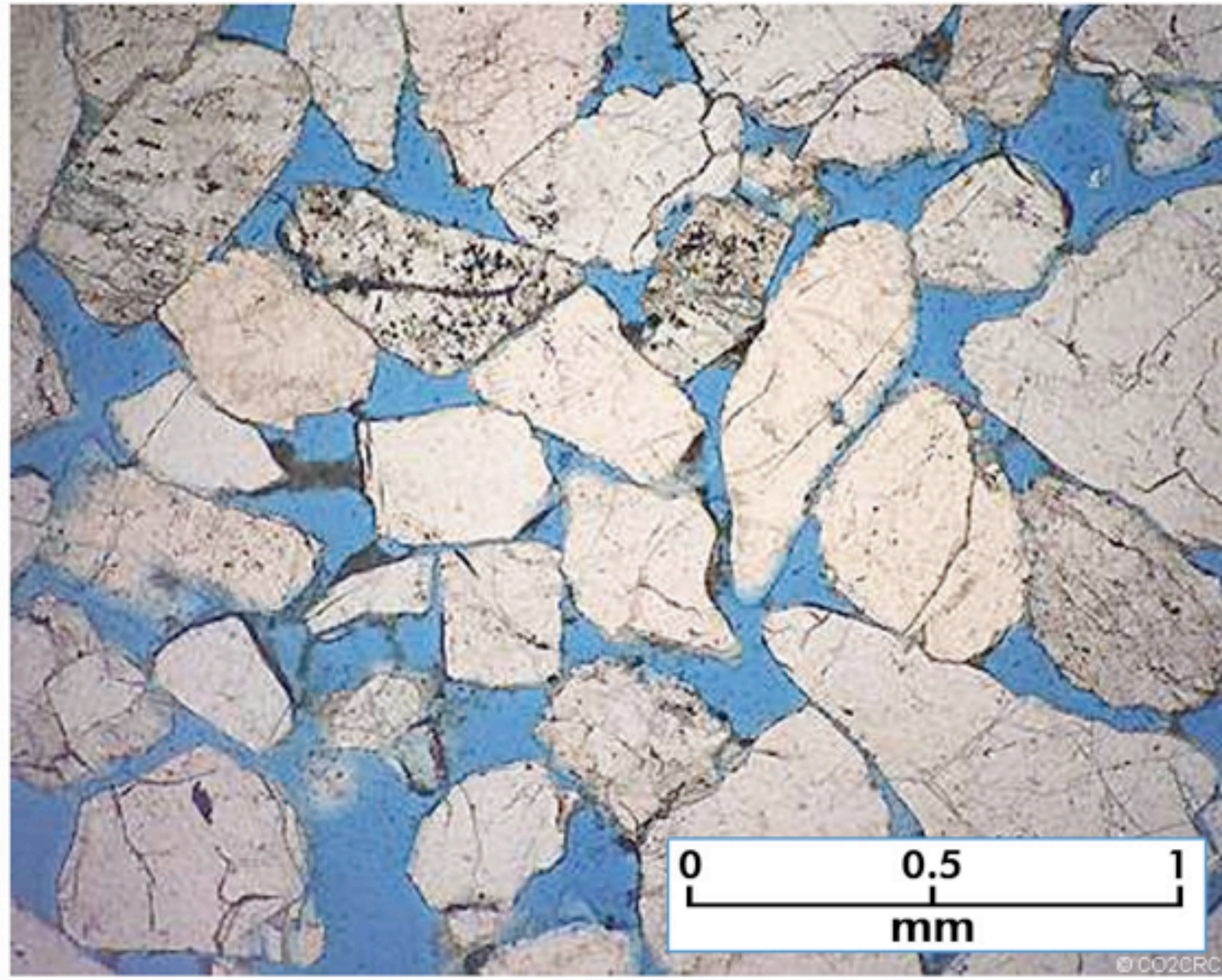
Marcellus deposition

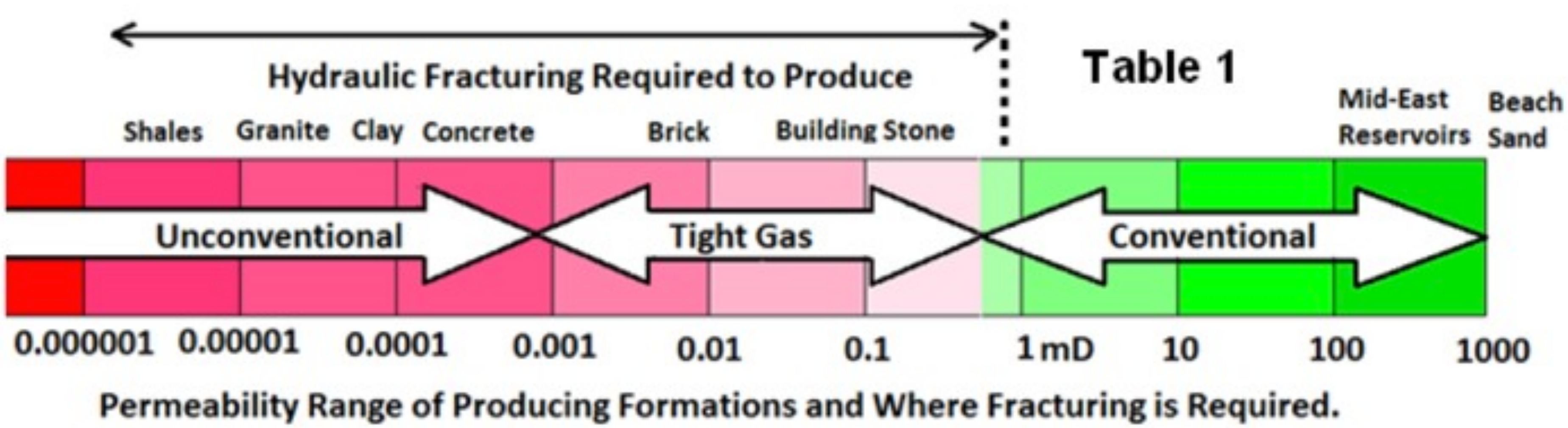


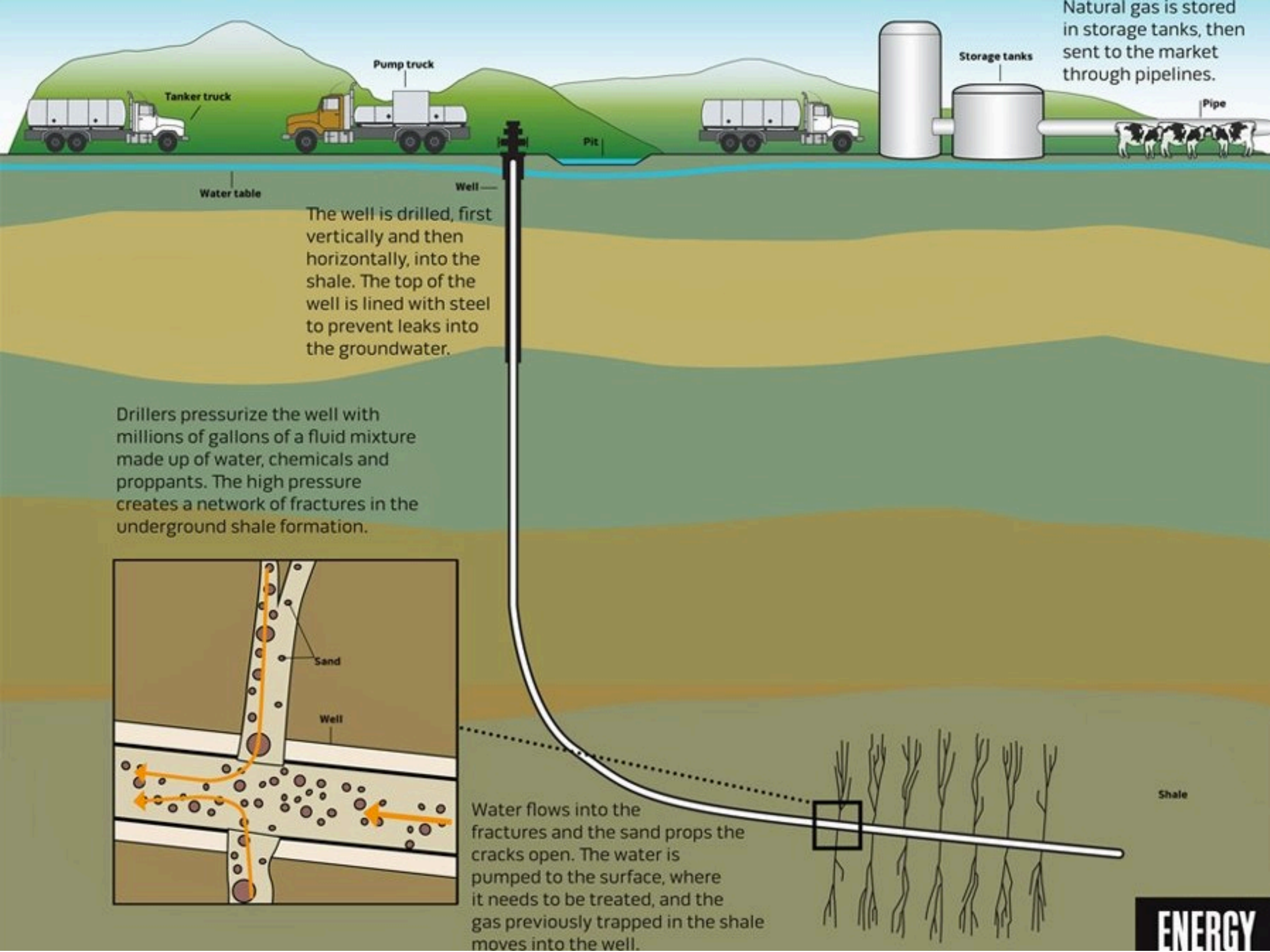
R. C. Blakey (http://www2.nau.edu/rcb7/nam.html)

What makes it unconventional?









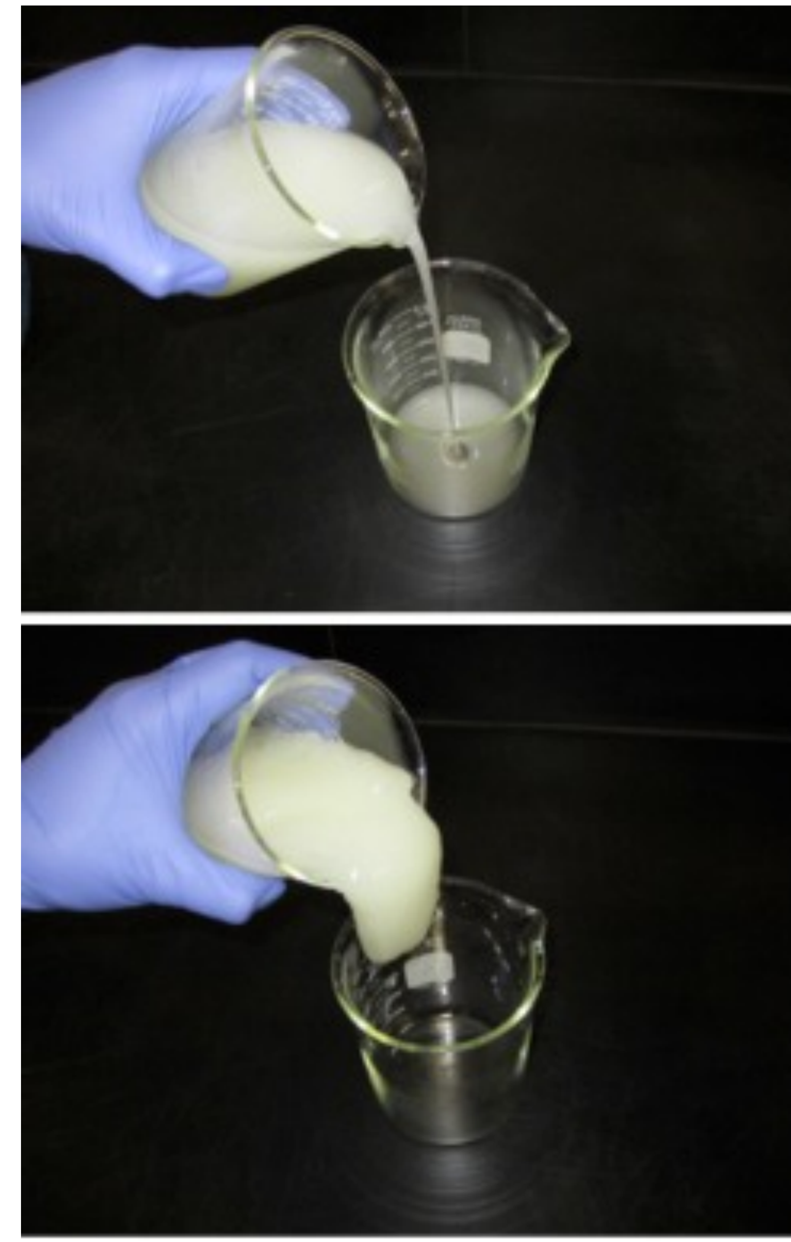
Natural gas is stored in storage tanks, then sent to the market through pipelines.
Pump truck
Tanker truck
Storage tanks
Pipe
Pit
Water table
Well
The well is drilled, first vertically and then horizontally, into the shale. The top of the well is lined with steel to prevent leaks into the groundwater.
Drillers pressurize the well with millions of gallons of a fluid mixture made up of water, chemicals and proppants. The high pressure creates a network of fractures in the underground shale formation.
Sand
Well
Shale
Water flows into the fractures and the sand props the cracks open. The water is pumped to the surface, where it needs to be treated, and the gas previously trapped in the shale moves into the well.
ENERGY


HALLIBURTON

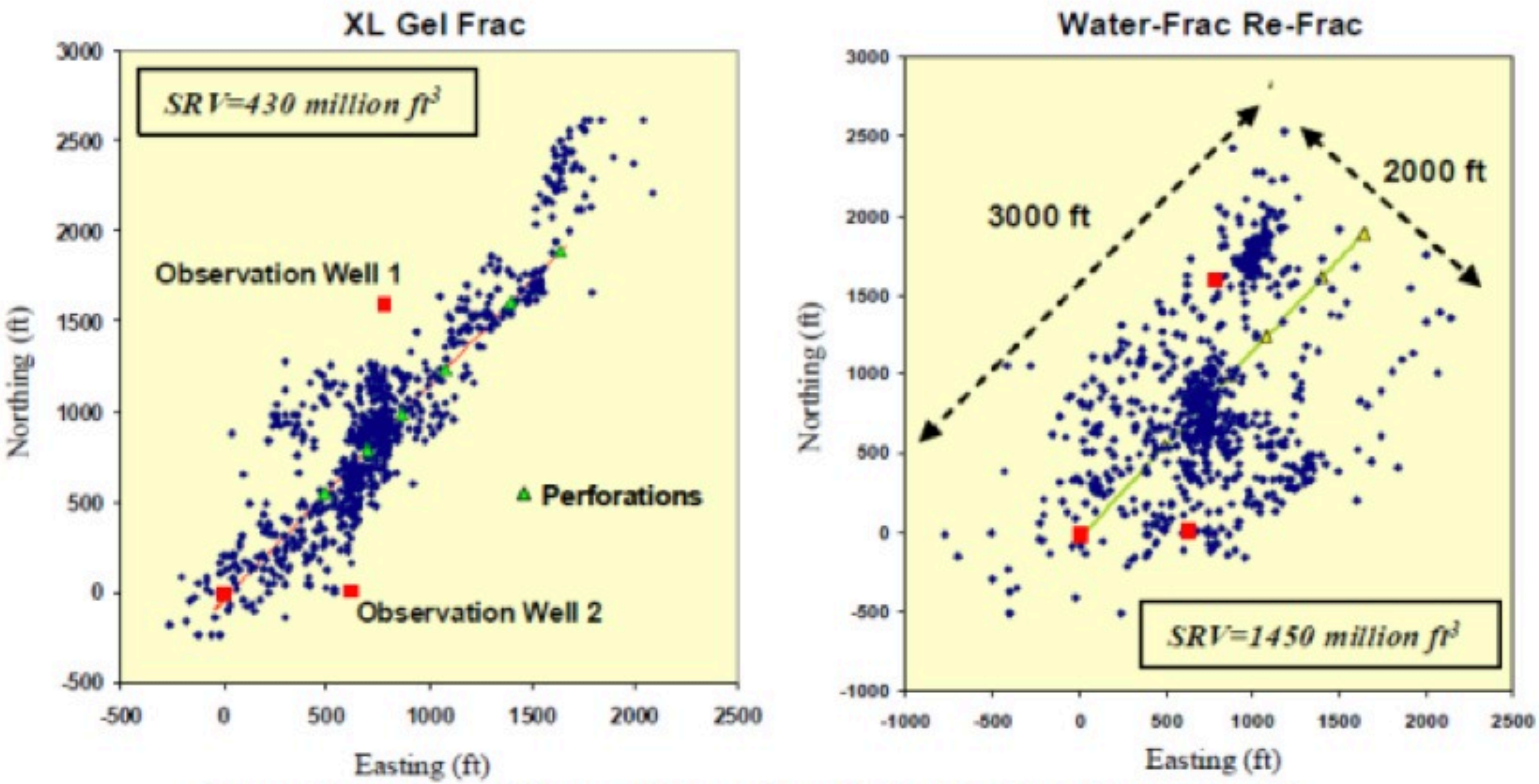
Fracturing fluids

Fluid	Viscosity	Proppant Size
Water @ 20C	1cP	
Slickwater	2-3 cP	40/70 mesh 212 - 420 µm
Linear gel	10-30 cP	30/50 mesh 300 - 600 µm
Crosslinked gel	100-1000 cP	20/40 and 16/30 420 - 1180 µm

http://momentivefracline.com/fracturing-fluids-101



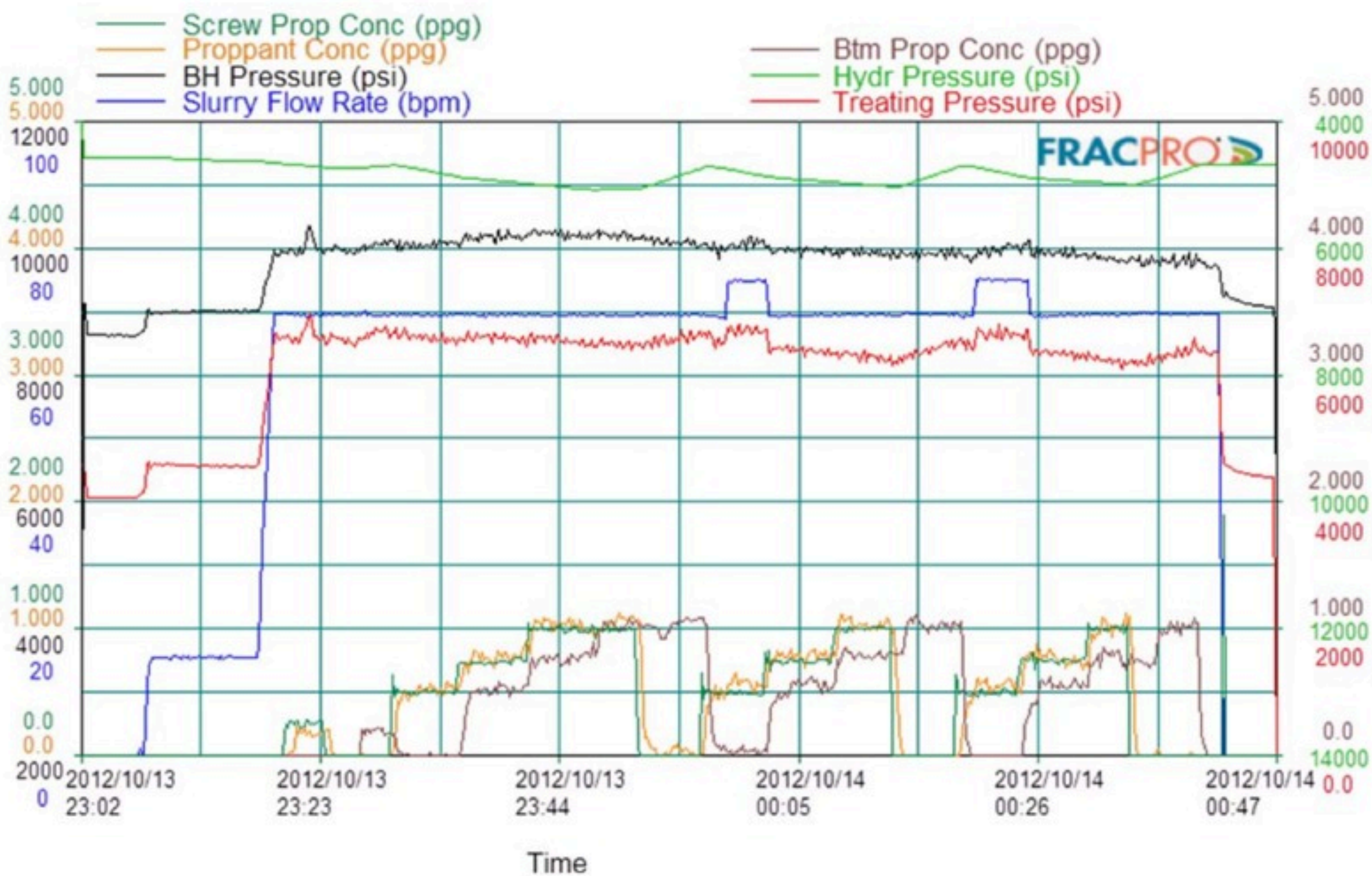
Gel vs. slickwater fractures



Comparison of XL Gel frac and Water-Frac Re-frac, horizontal Barnett well

Source: Cipolla, et. al., SPE 124843 modified from Warpinski, et. al., SPE 95568.

A typical treatment schedule



Example Middle Bakken slickwater fracture treatment plot. Pearson (2013)

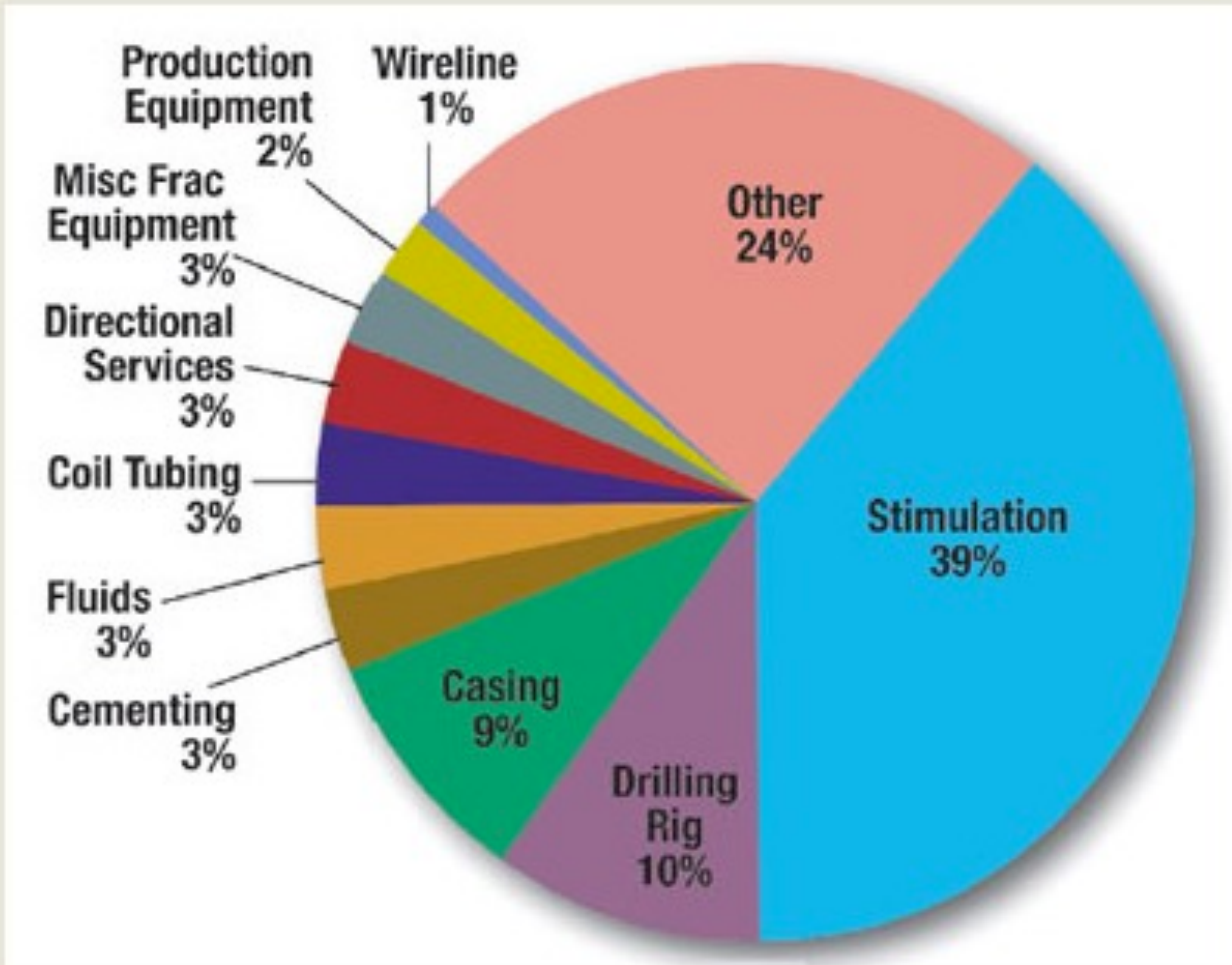
Environmental concerns

By the numbers

(based on the Bakken)

- length of laterals: 10, 000 ft (3 km)
- depth of wells: 10, 000 ft
- # of stages: 30
- length of fractures: up to 1000 ft
- amount of water/well: 250,000 bbls (40 Mliters)
- amount of proppant/well: 3,000,000 lbs
- average well cost: $8 million

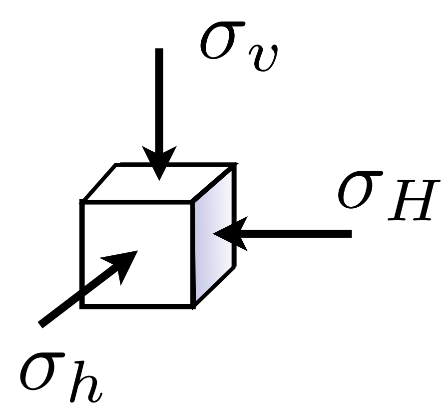
The need for modeling



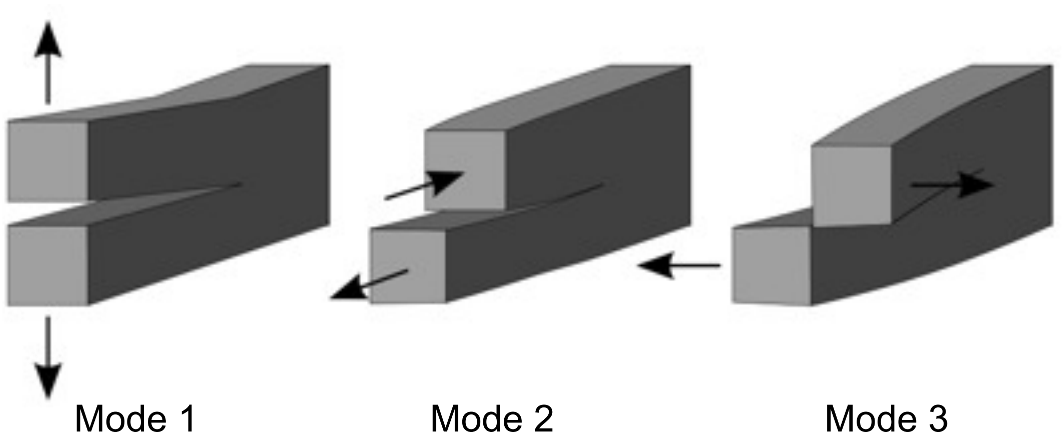
Stimulation dominates spending in plays such as the Eagle Ford. (Images courtesy of Bernstein Research)

Solid mechanics...

State of Stress in the Earth

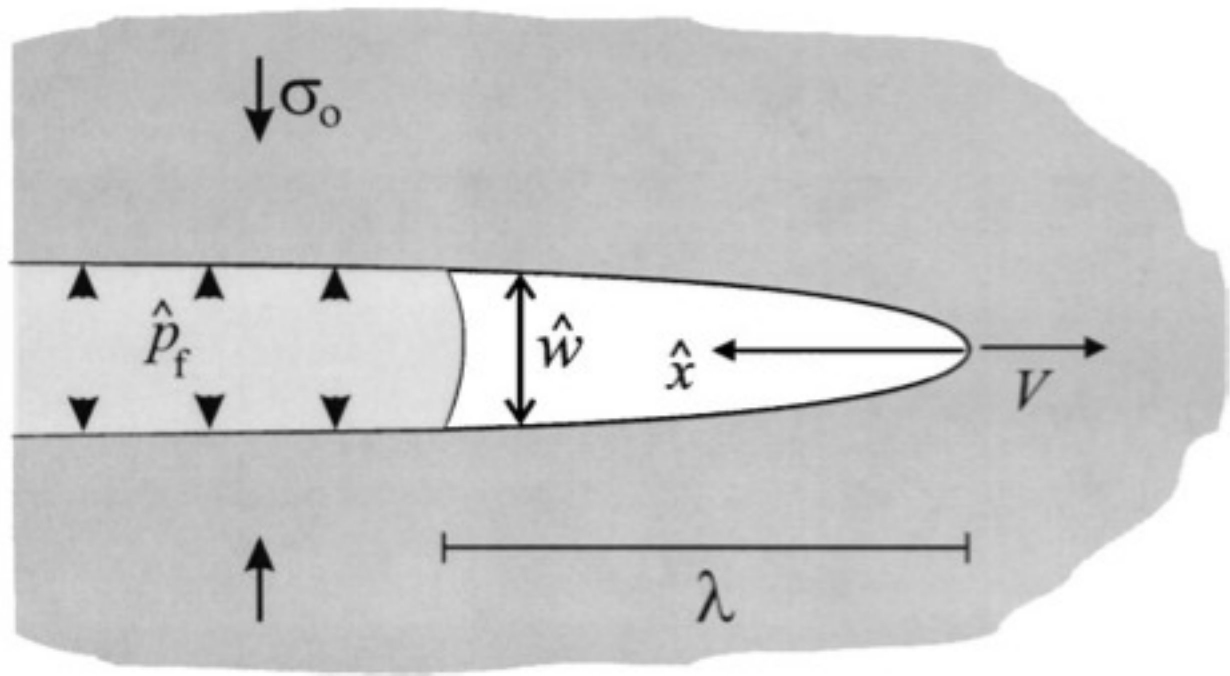


Crack propagation modes



Typical shale strength:
60-125 MPa (compression)
9-13 MPa (tension)

...and fluid mechanics

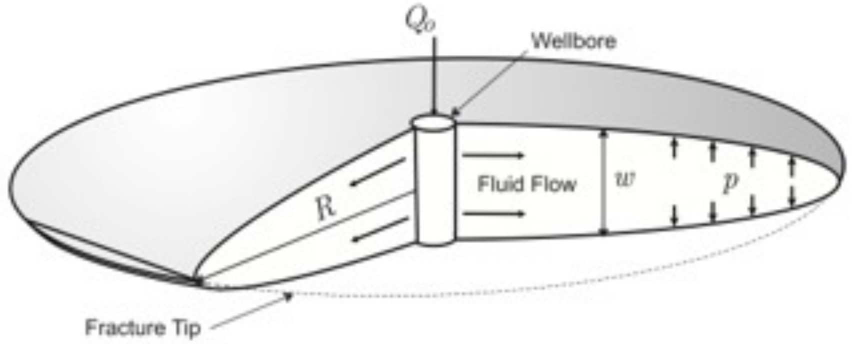


Semi-infinite fluid driven crack with lag zone adjacent to the tip.
Detournay (2004)

Detournay and Garagash 2003, The near-tip region of a fluid-drive fracture propagating in a permeable elastic solid. *J. Fluid Mech*, **vol. 494, pp. 1-32.**

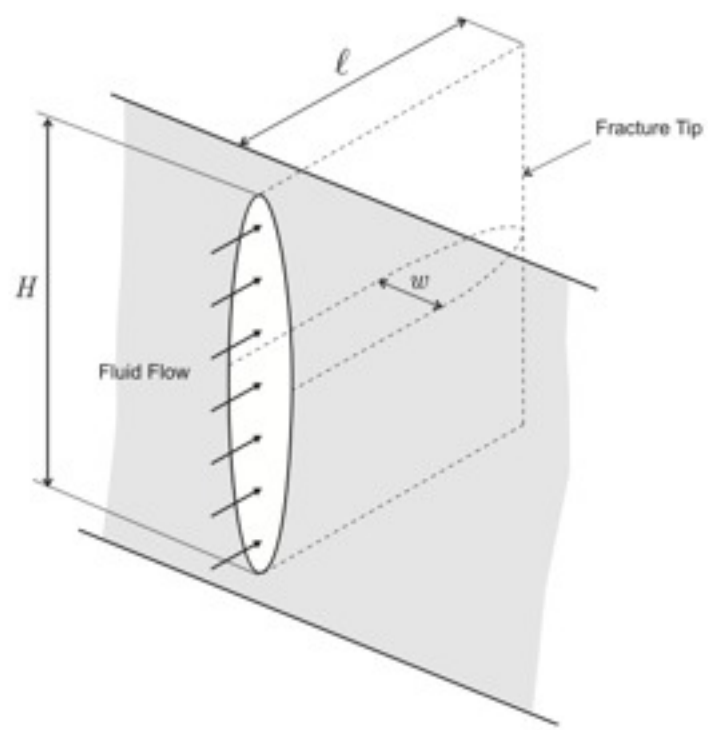
Analytic fracture models

Radial model



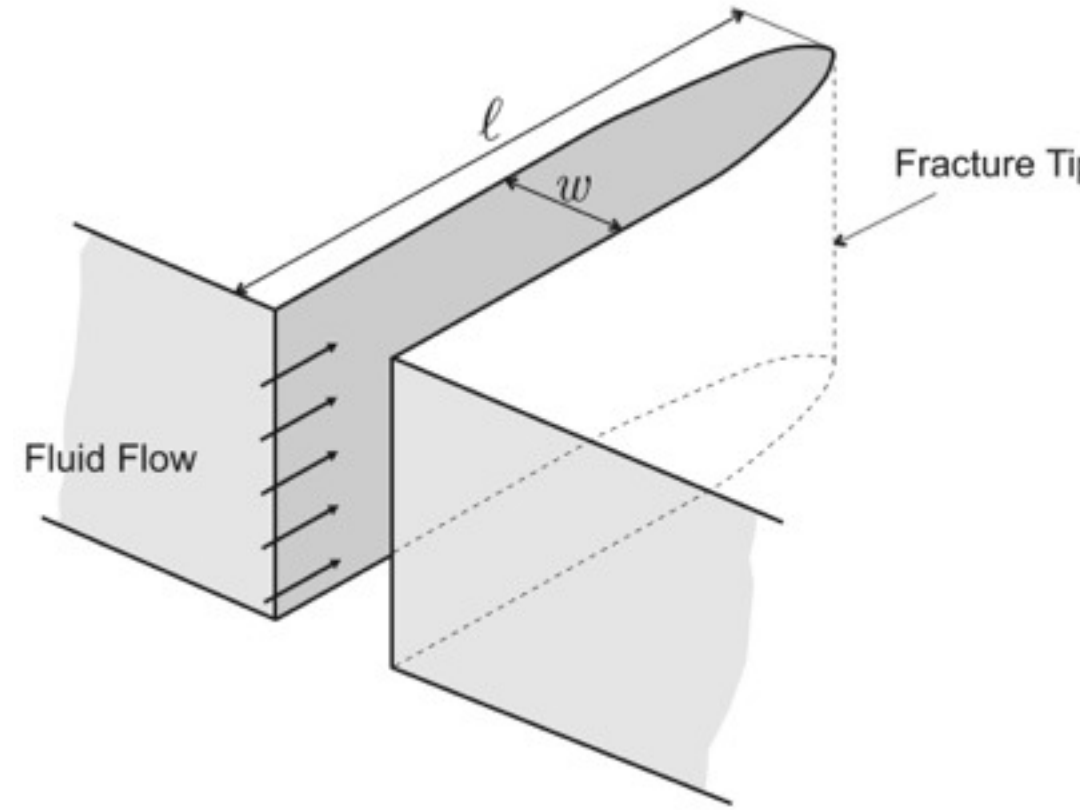
Sneddon (1946)

PKN model



Perkins & Kern (1961)
Nordren (1969)

KGD model

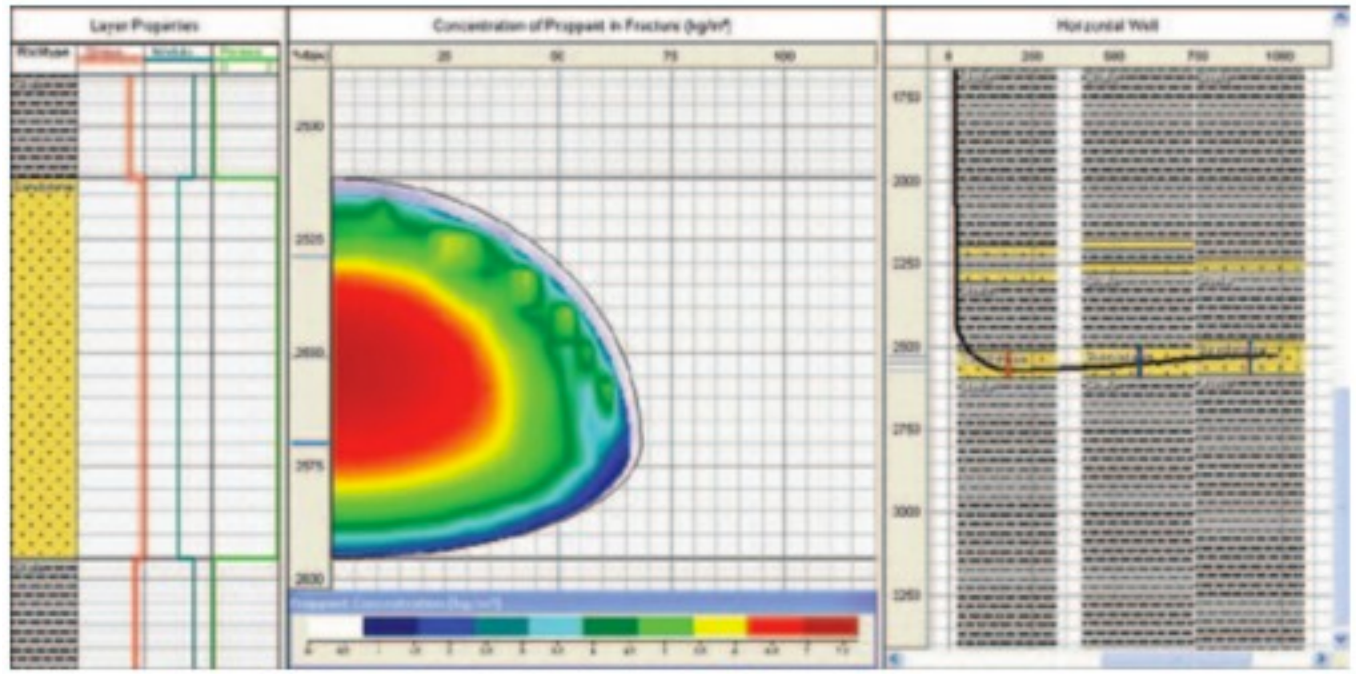


$$L_{frac}(t) = 1.078 \left(\frac{E' q_0^3}{\mu_f} \right)^{1/6} t^{2/3}$$

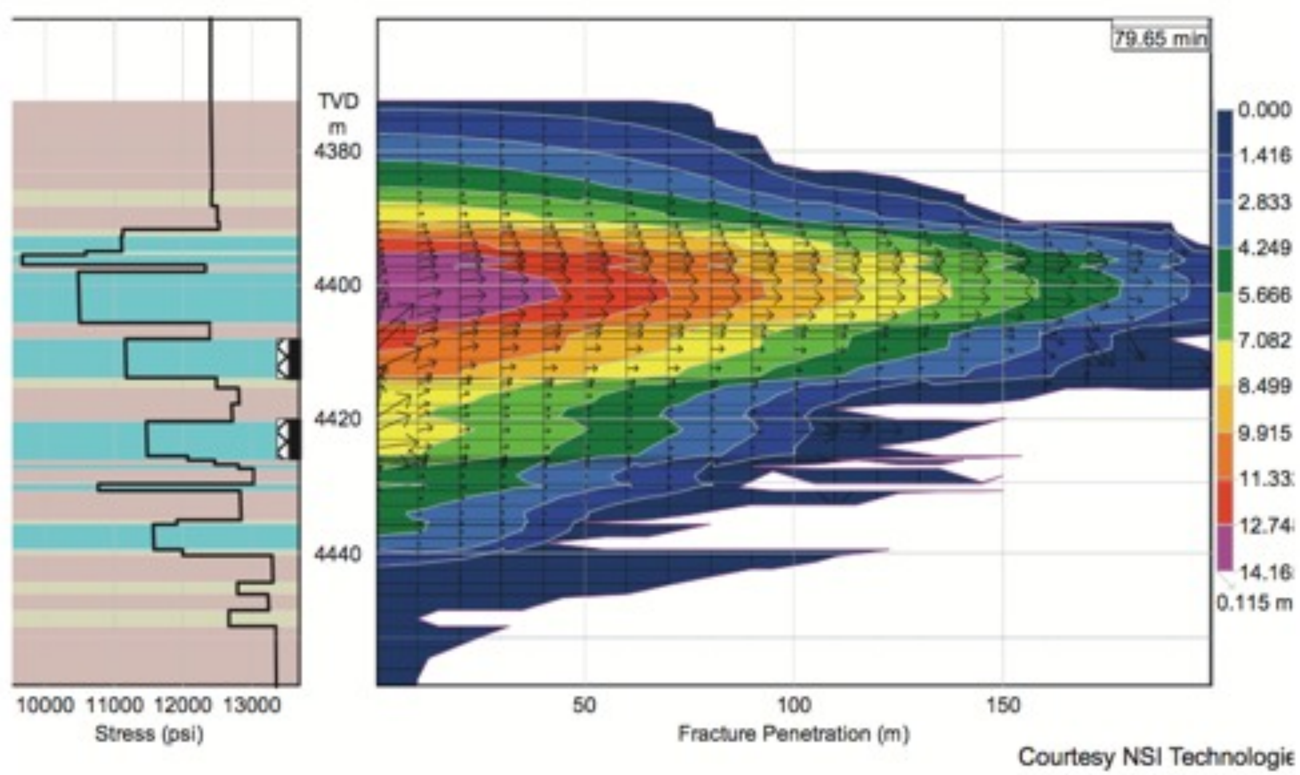
$$w_o^h(t) = 2.36 \left(\frac{\mu_f q_0^3}{E'} \right) t^{1/3}$$

Khristianovich & Zheltov (1955)
Geertsma & de Klerk (1969)

Fracture modeling software



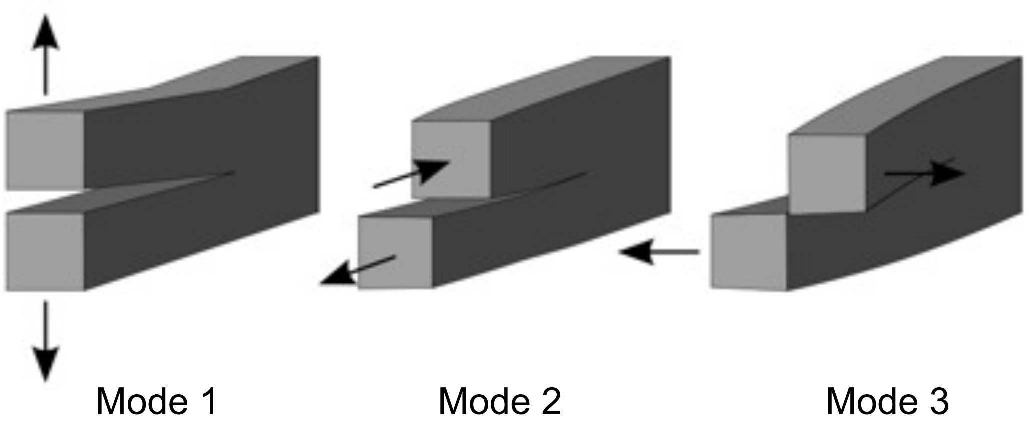
StrataGen FracPro software



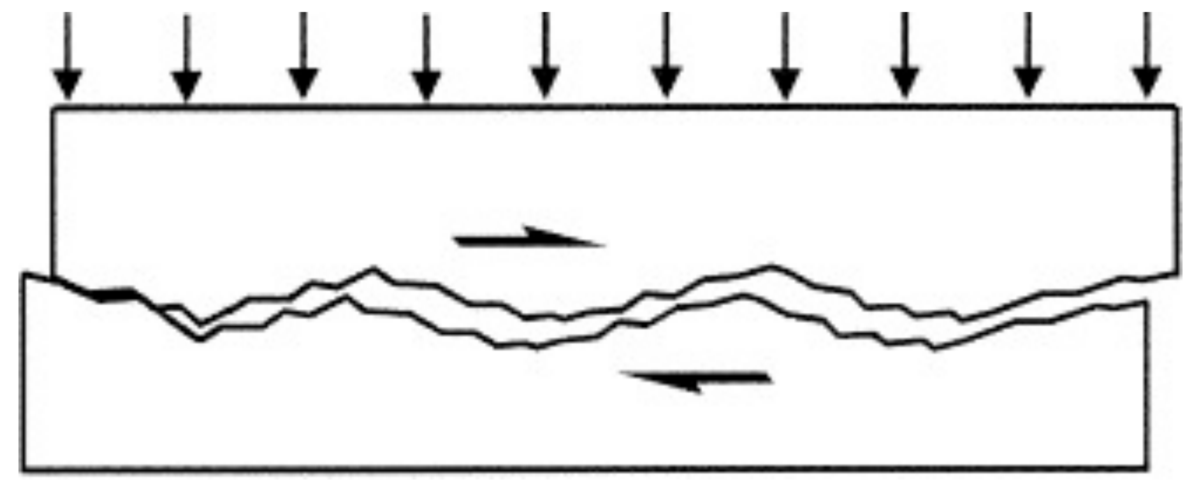
NSI Technologies StimPlan software

But there is more going on...

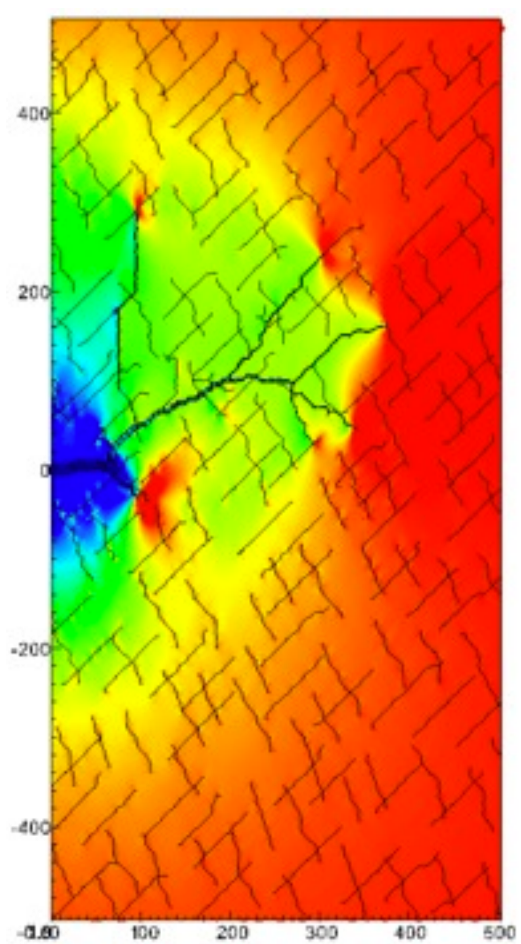
Crack Propagation



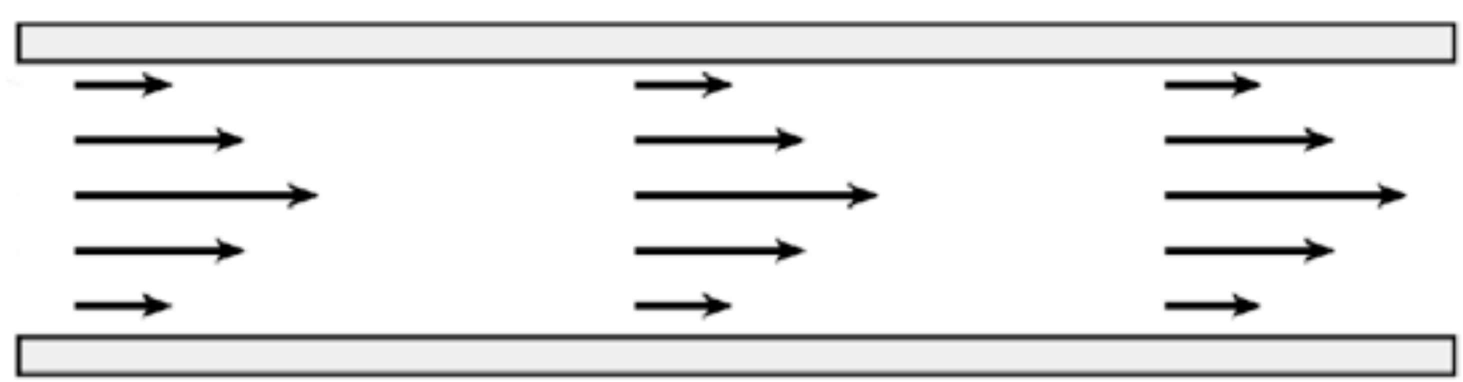
Joint Model



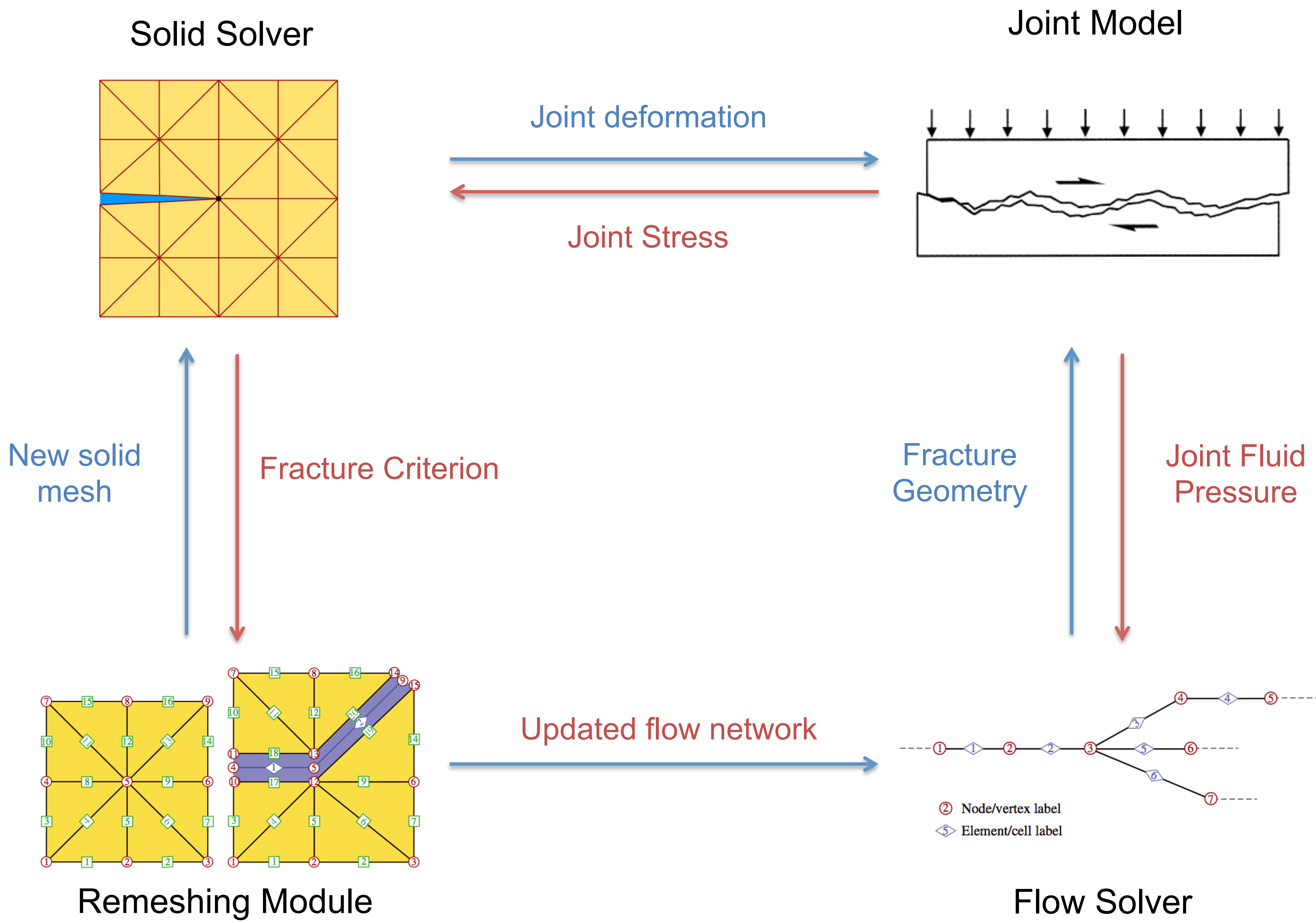
Dynamic Stress



Viscous Fluid Flow in Fracture



LLNL GEOS

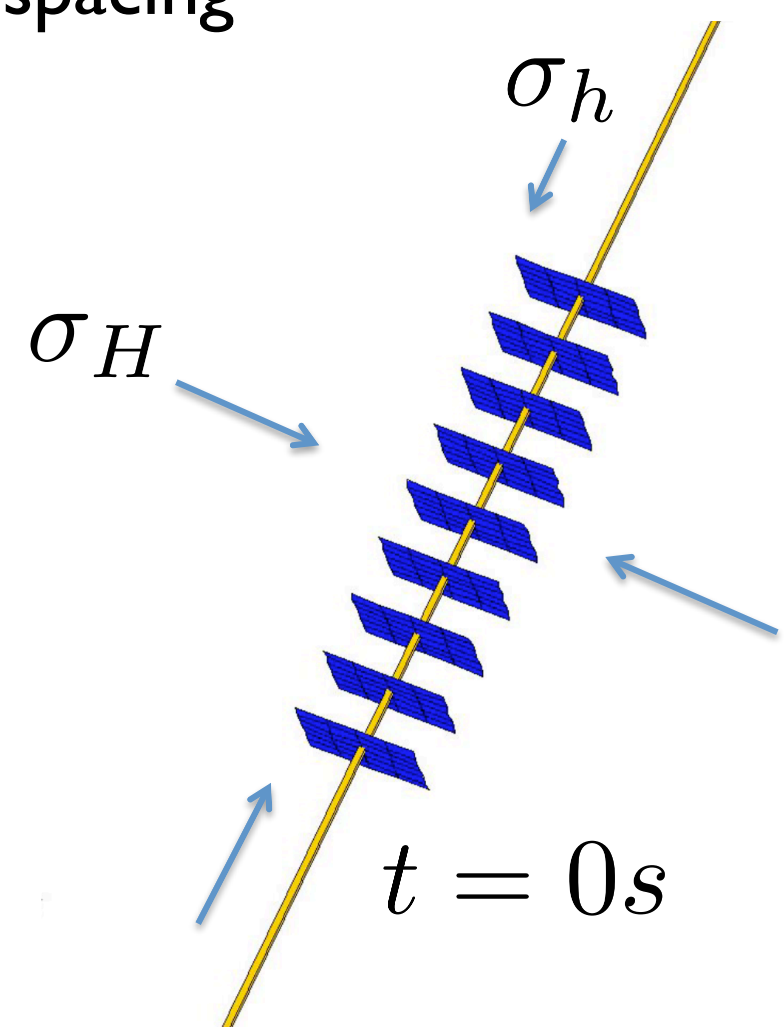


Fu et al. 2012

LLNL GEOS

Recent work has focused on 3D simulations. The simulation results shown are based on the following initial and boundary conditions:

- 100 m formation thickness
- Single stage with 9 perforations with 20 m spacing
- Fluid injection rate of 75 bbl/min (water)
- Stress ratio of $\sigma_h/\sigma_H = 0.85$



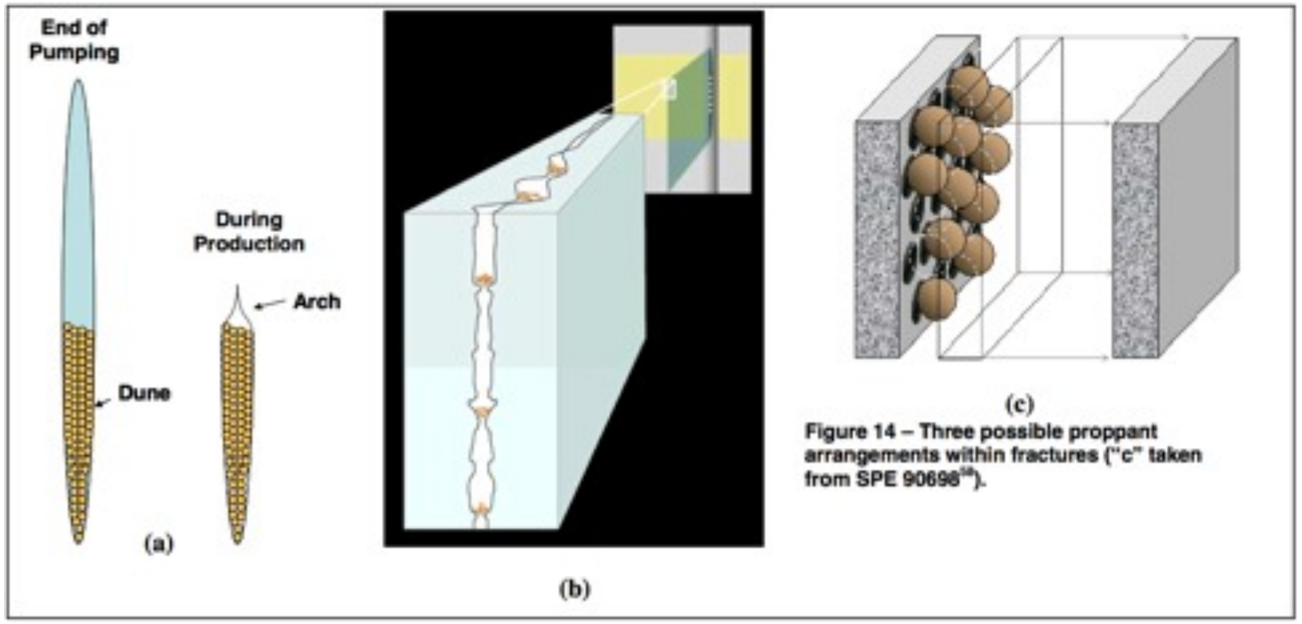
THE WALL STREET JOURNAL. | BUSINESS

BUSINESS

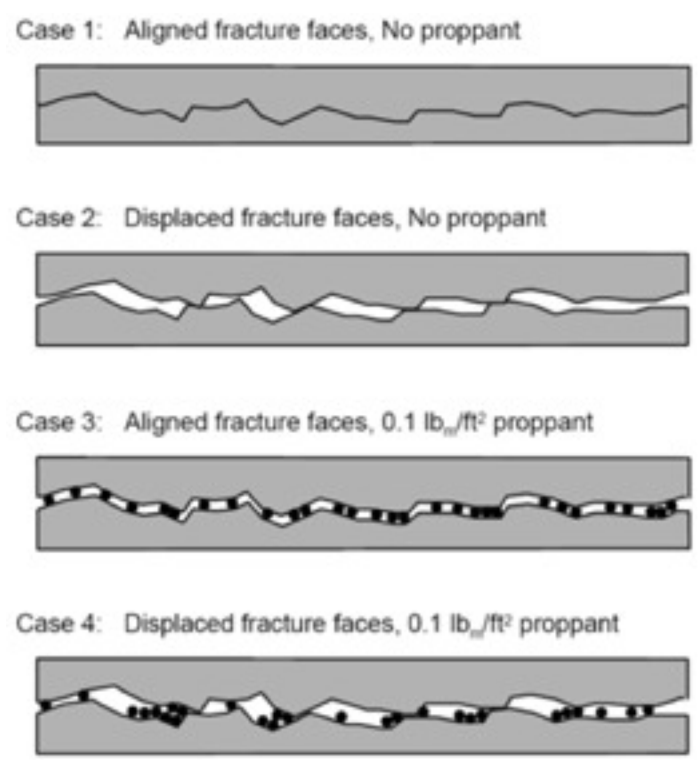
In Fracking, Sand Is the New Gold

Energy Boom Fuels Demand for Key Ingredient Used in Drilling Wells; 100 Sand Mines in Wisconsin

Why proppant?



Proppant bed arrangements, from Palisch (2008)



Fracture faces as described during lab testing by Fredd et al (2008)

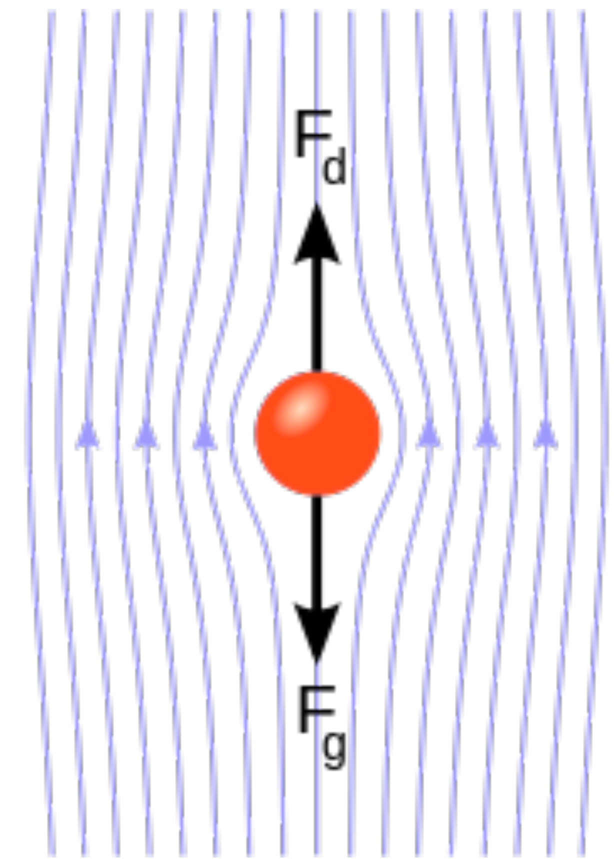
Proppant transport

- What is the effective (propped) fracture length?
- What type (size, density, strength) of proppant should be used?
- What quantity, concentration of proppant should be used?
- What fluid viscosity & injection rate should be used?

Proppant settling speed

Stoke's Law

$$V_s = \frac{(\rho_p - \rho_f)\, g d_p^2}{18\mu}$$



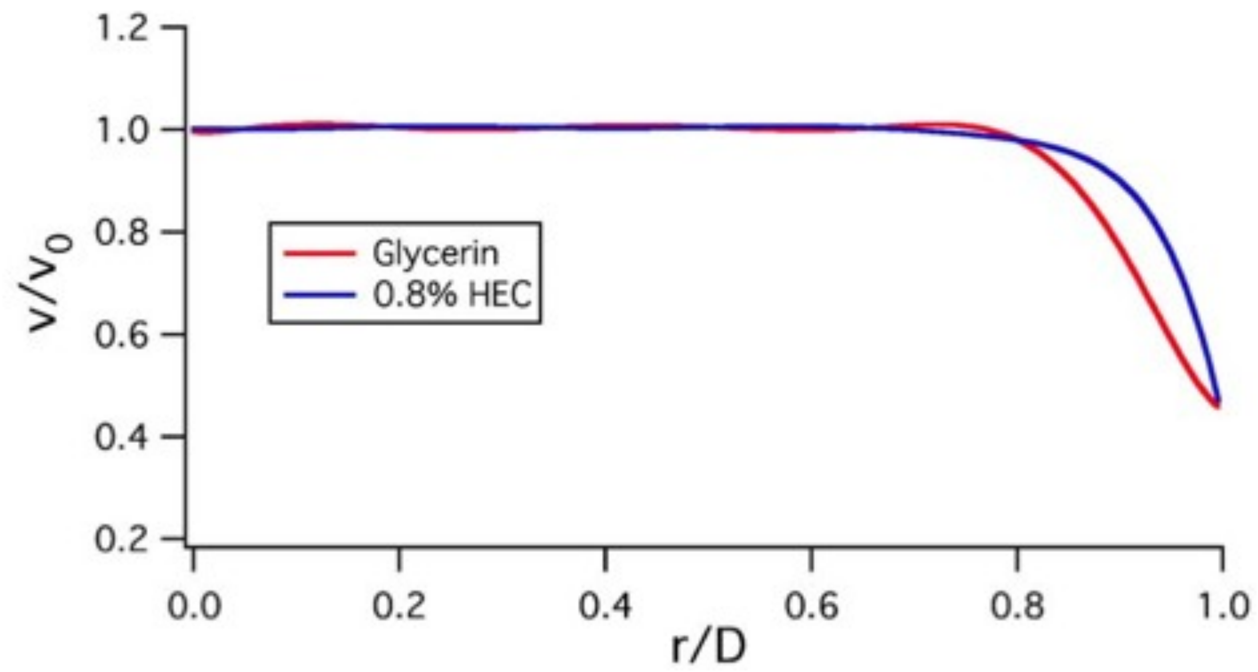
Assumptions

- unbounded, laminar flow
- smooth, spherical particles
- no particle/particle interactions

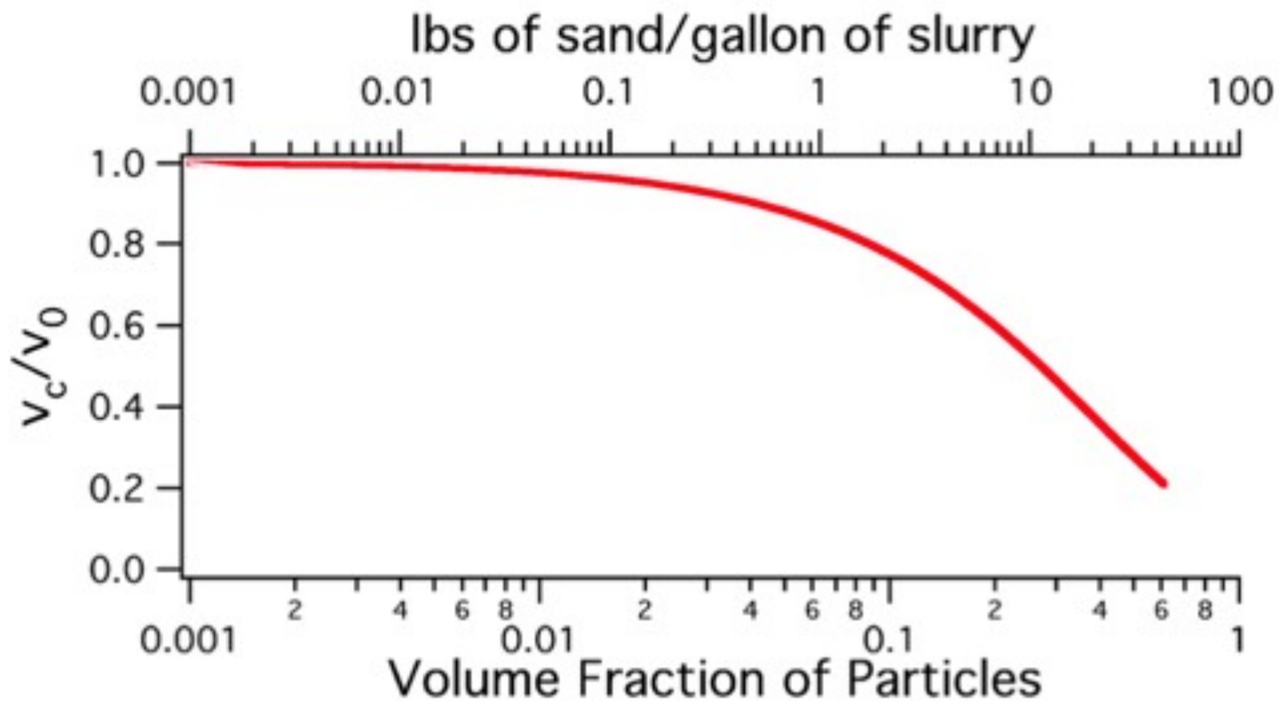
Proppant settling speed

Novotny, 1977

Influence of walls
Zhu (1999)

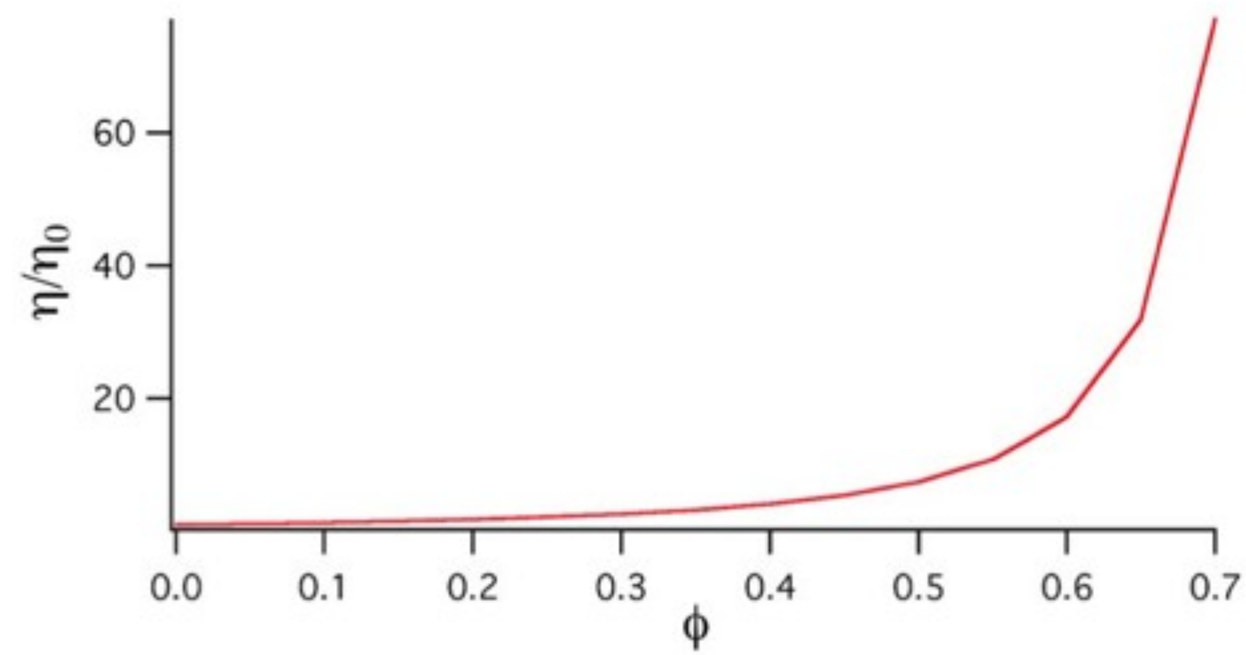


Hindered settling
Zhu (1999)

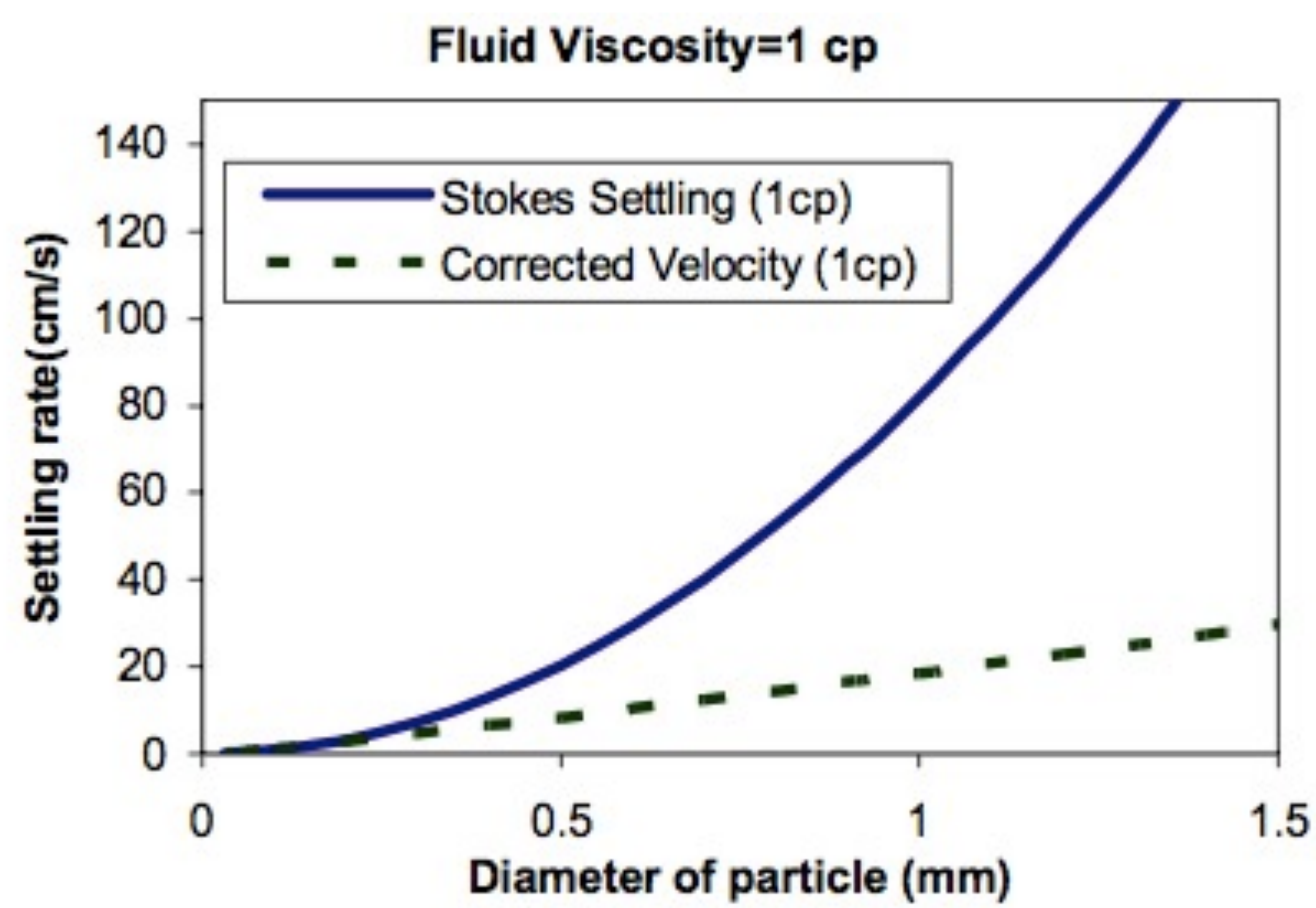


Proppant settling speed

Effective viscosity
Zhu (1999)



Inertial effects
Gadde (2004)



Modeling settling

Gadde (2004)

Mass conservation (slurry)

$$\frac{\partial\left(\rho w\right)}{\partial t}+\nabla\cdot\left(\rho\vec{q}\right)=-\rho_f q_l$$

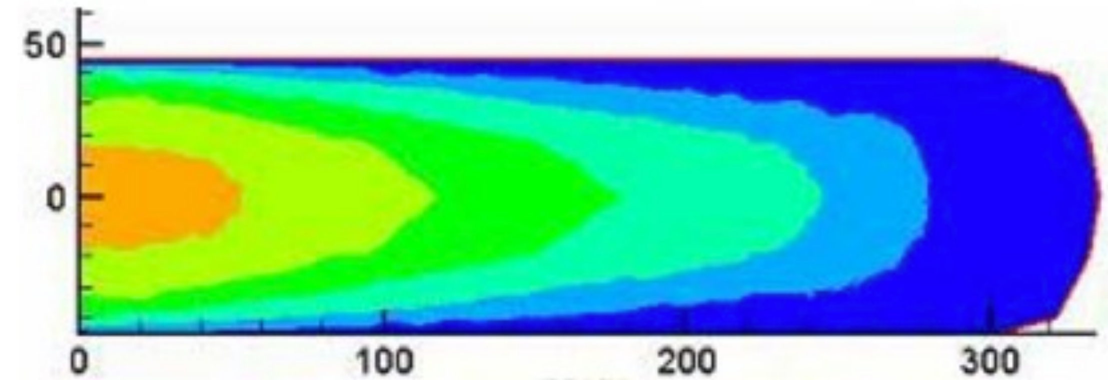
Mass conservation (particles)

$$\frac{\partial\left(c\rho_p w\right)}{\partial t}+\nabla\cdot\left(c\rho_p\vec{q_p}\right)=0$$

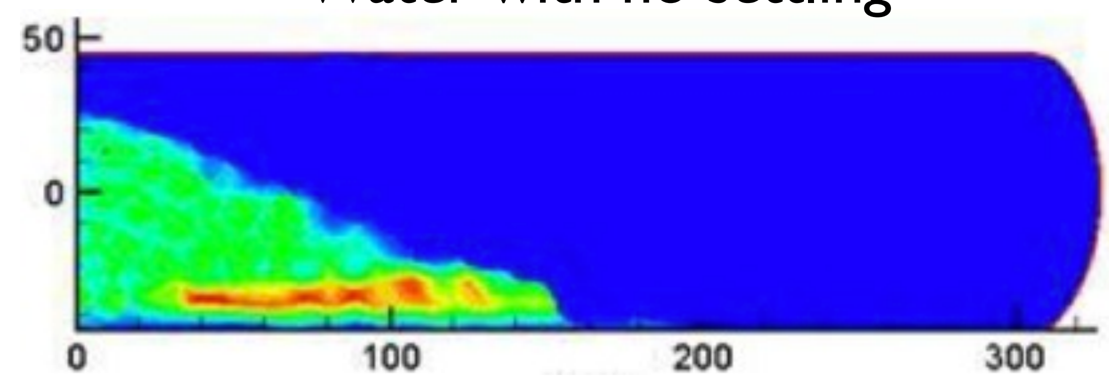
Particle velocity

$$\vec{q}_p=\vec{q}+\hat{k}V_s$$

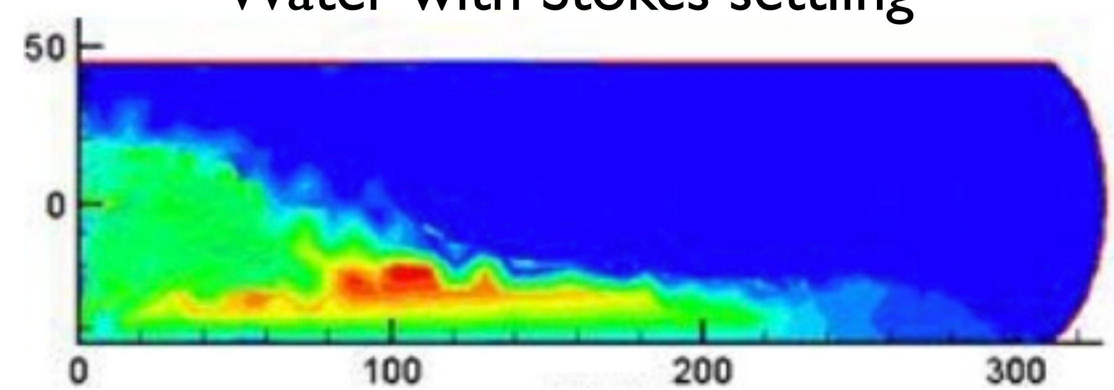
FEM solver for $w(x,y,t)$



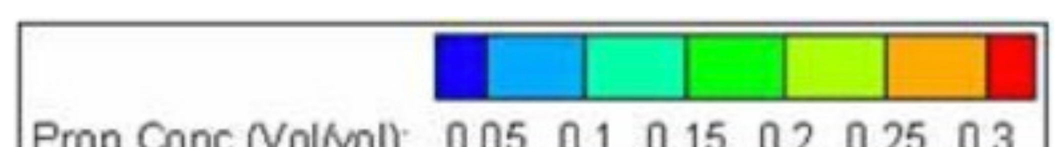
Water with no settling



Water with Stokes settling

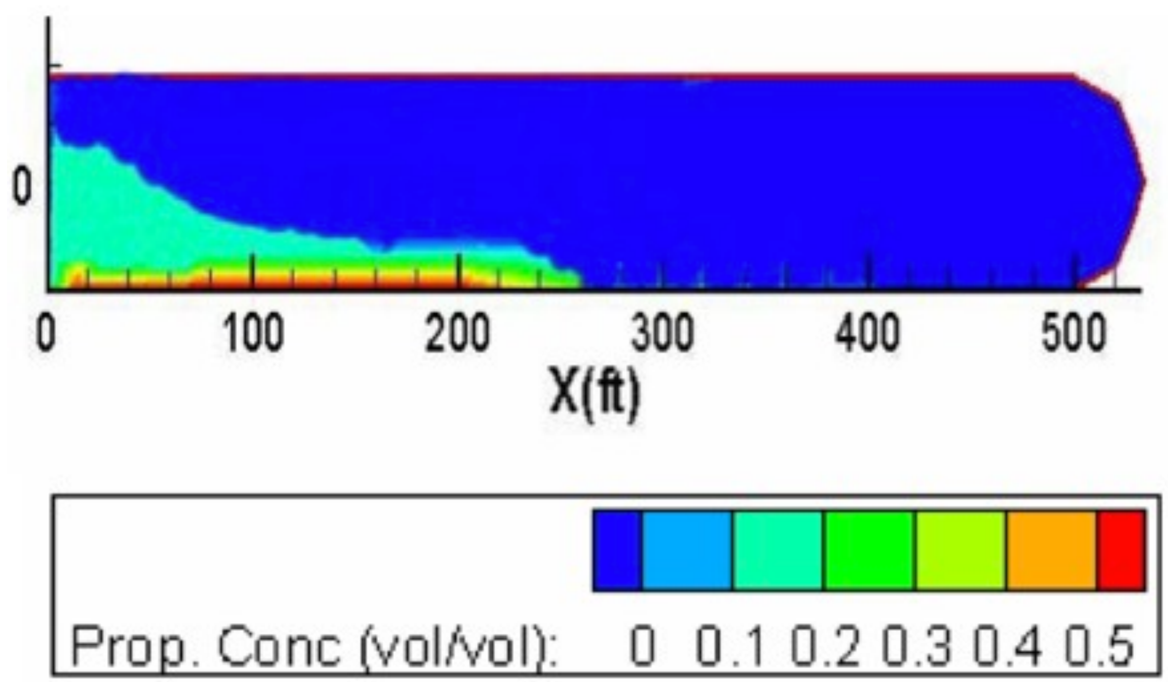


Water with corrected settling

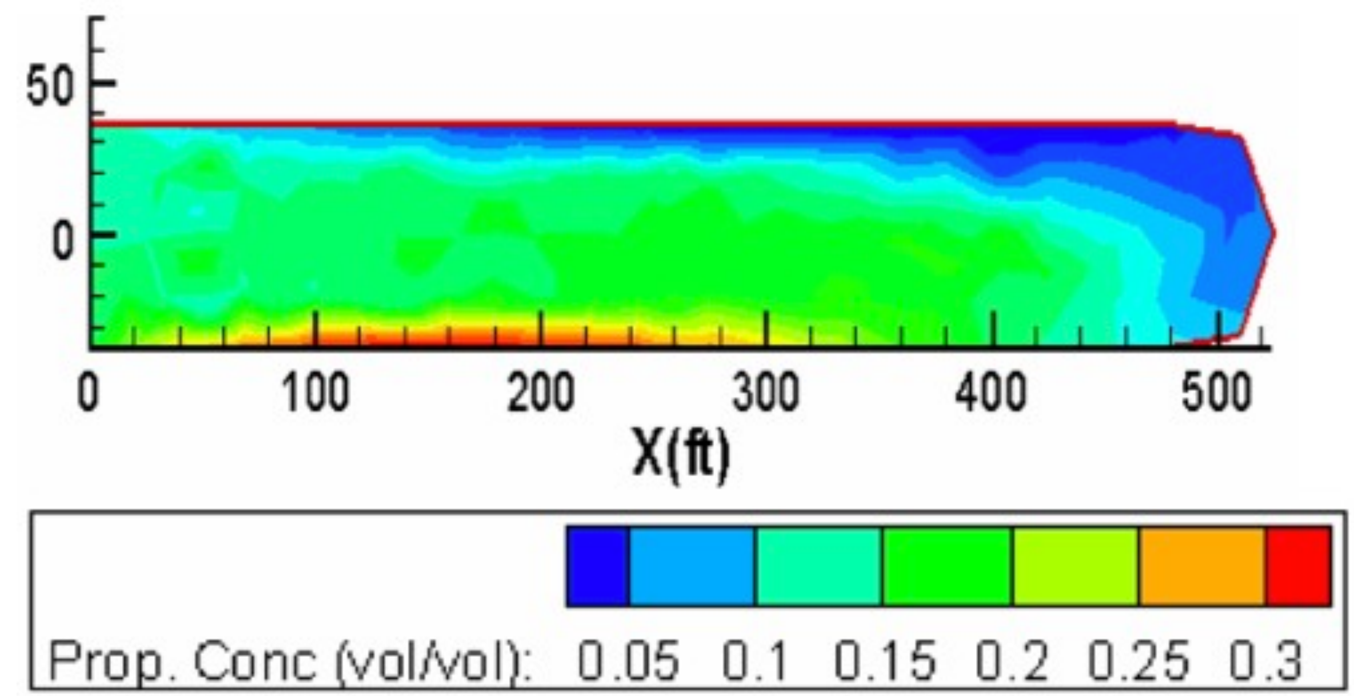


Modeling settling

Gadde (2004)



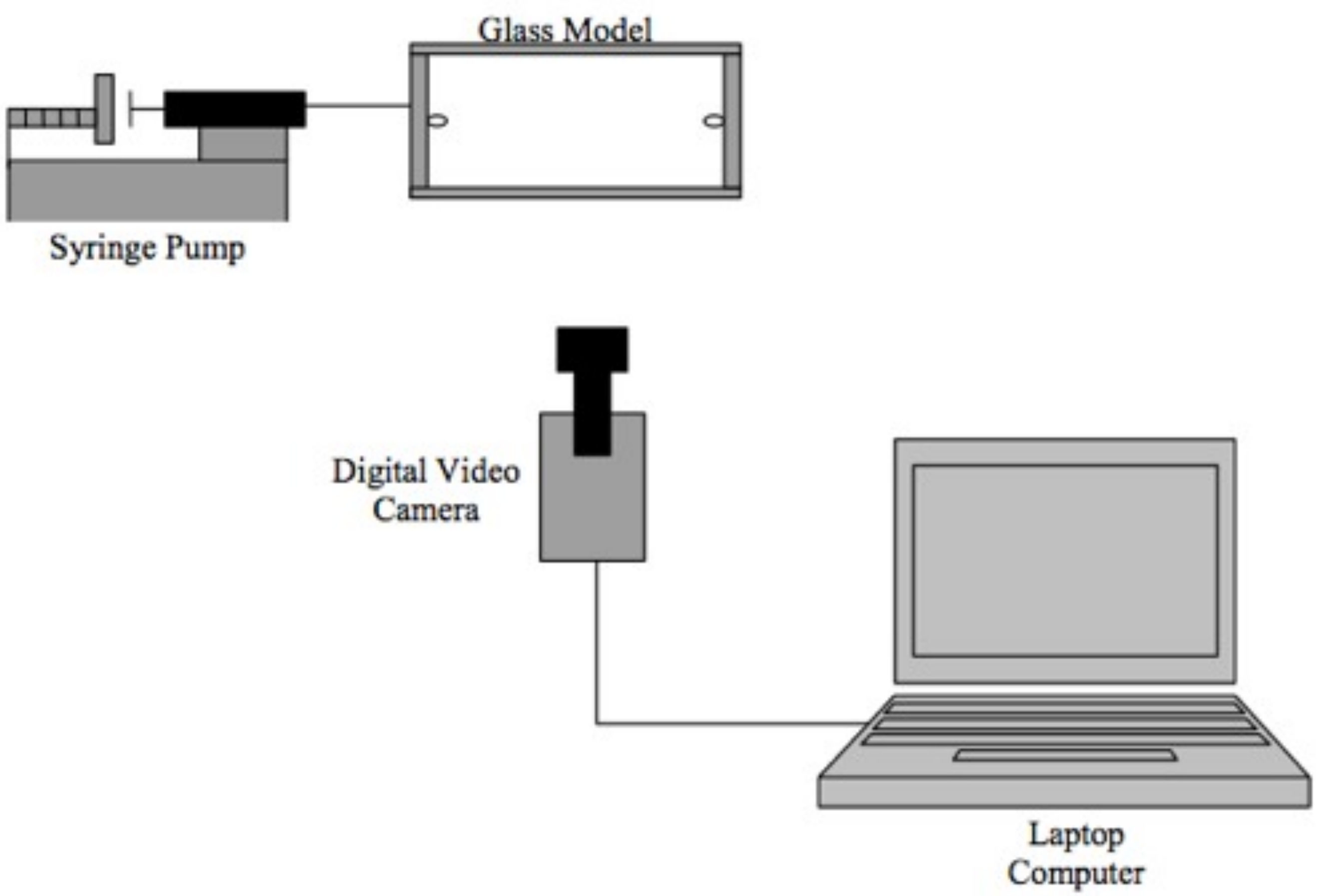
Proppant concentration for 1 cp fluid with corrected settling

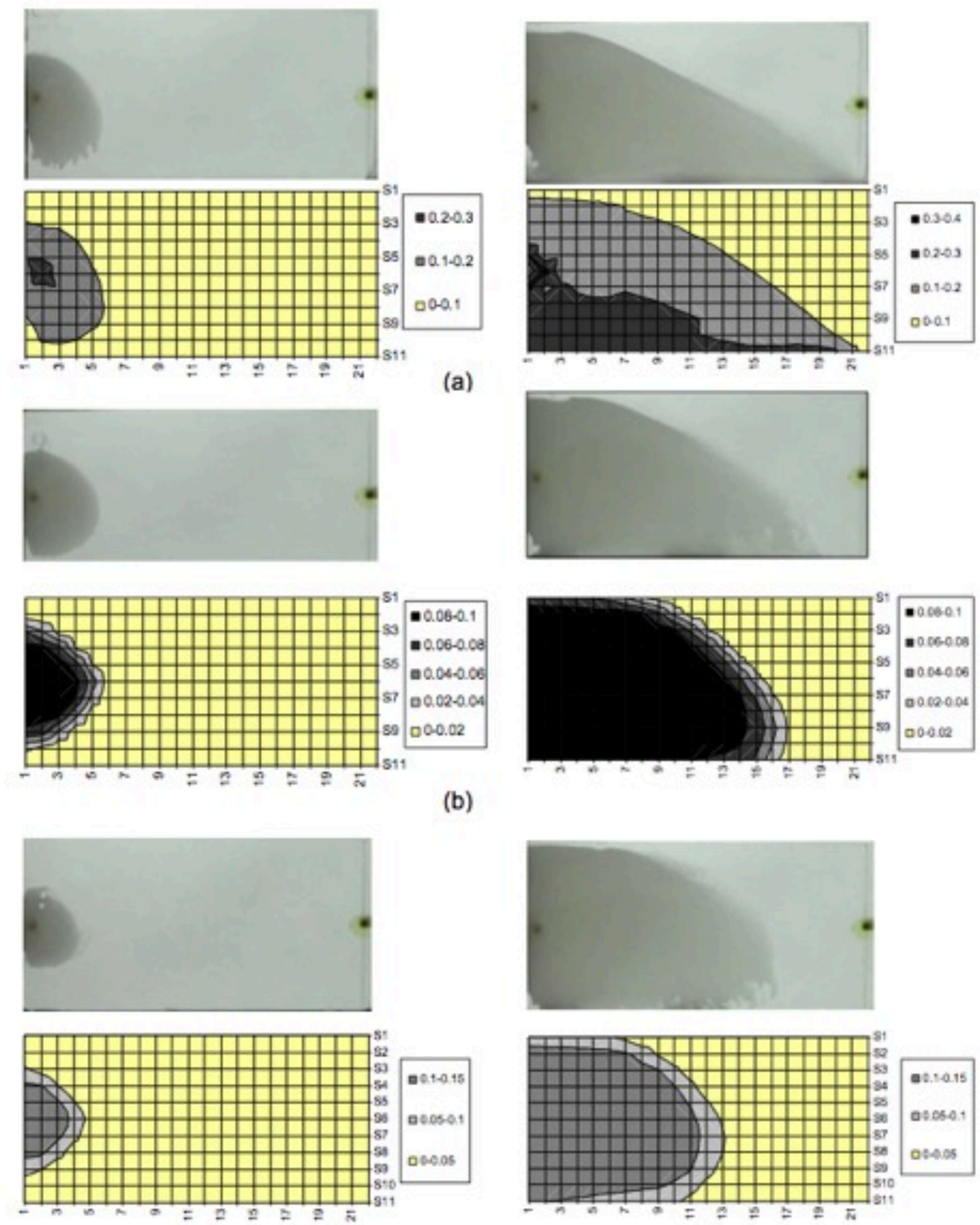


Proppant concentration for 100 cp fluid with corrected settling

Proppant settling experiments

Shokir & Al-Quraishi (2007)





Proppant transport

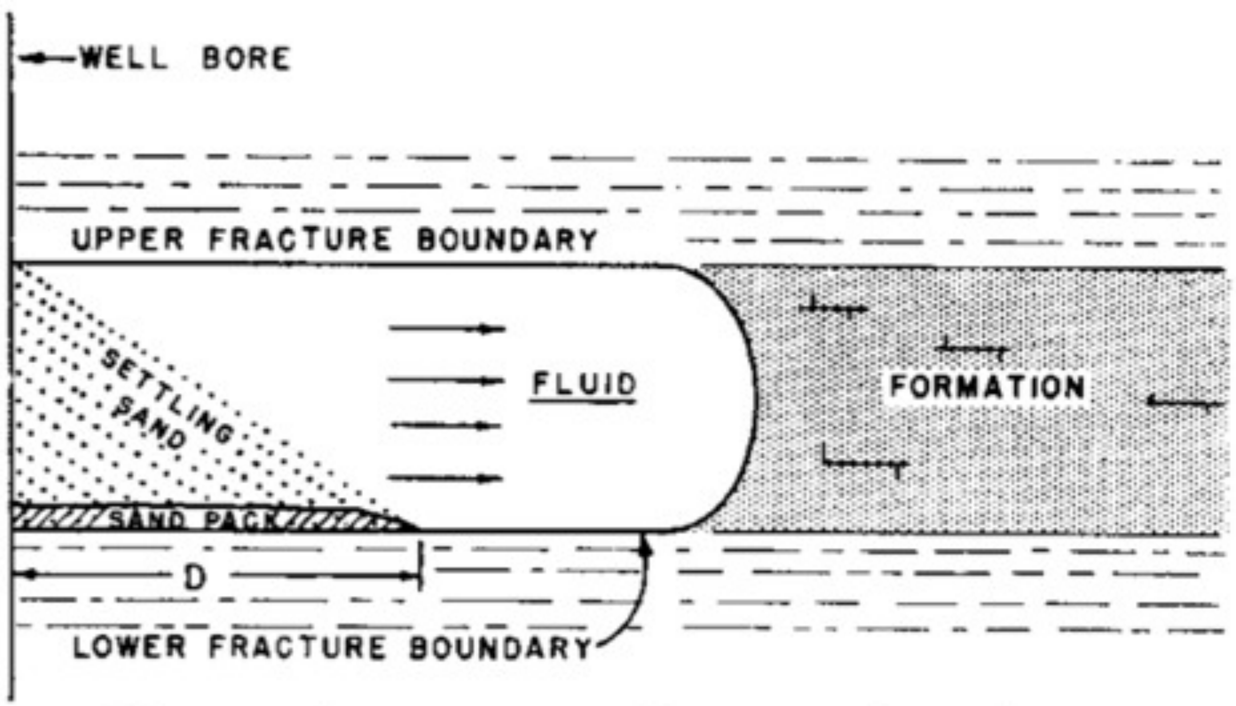


FIG. 3—BUILD-UP OF SETTLED SAND BED.

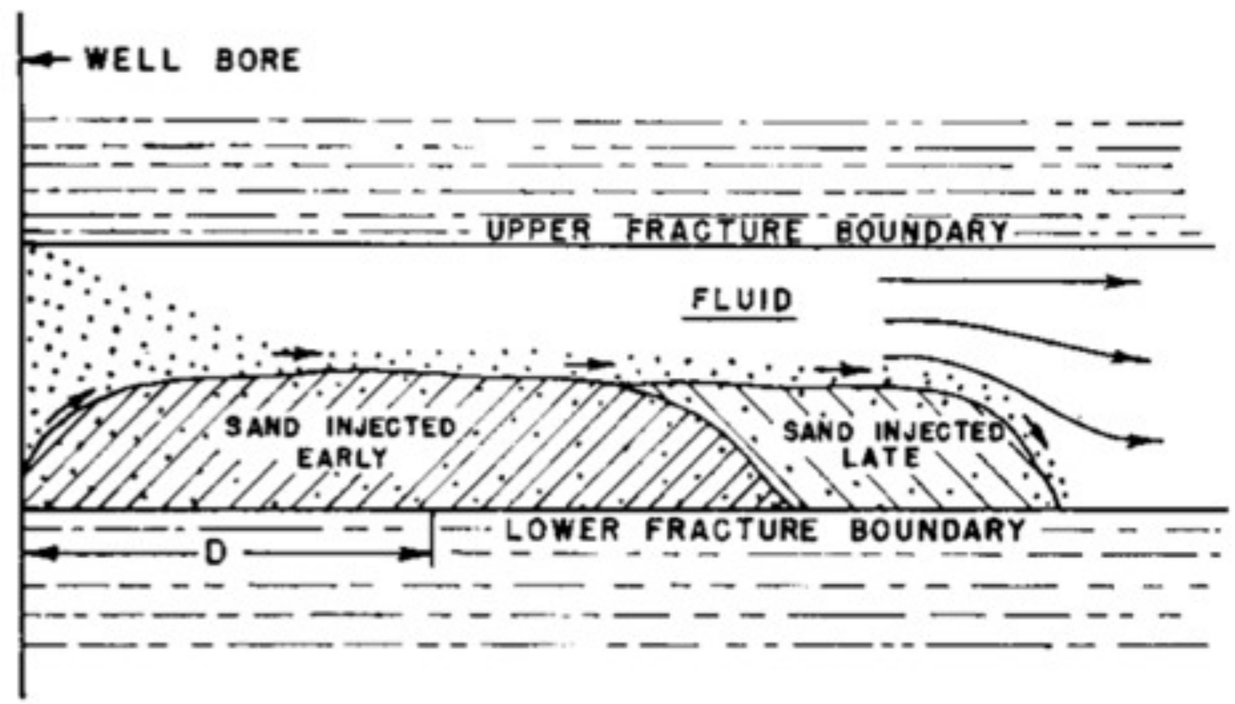


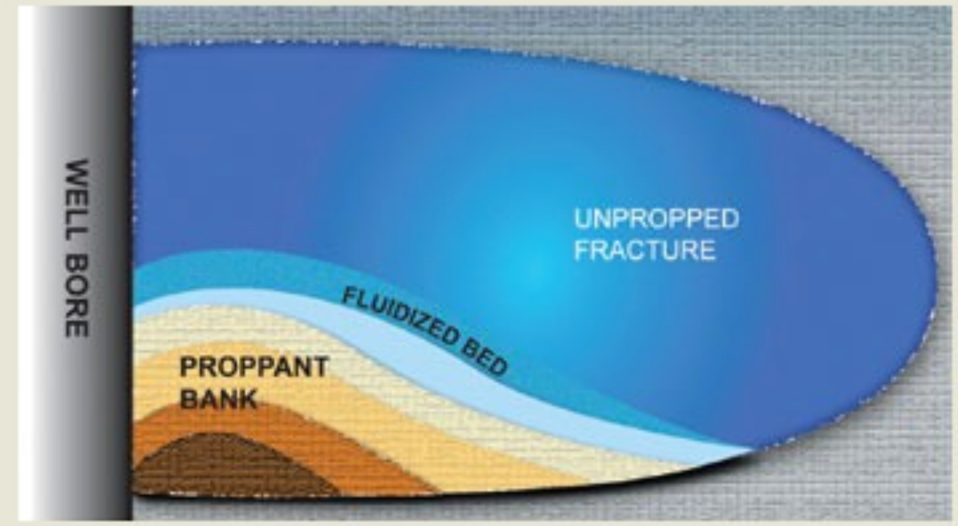
FIG. 5—FINAL POSITION OF SAND INJECTED LATE IN TREATMENT.

The formation of proppant beds. Kern et al. (1957)

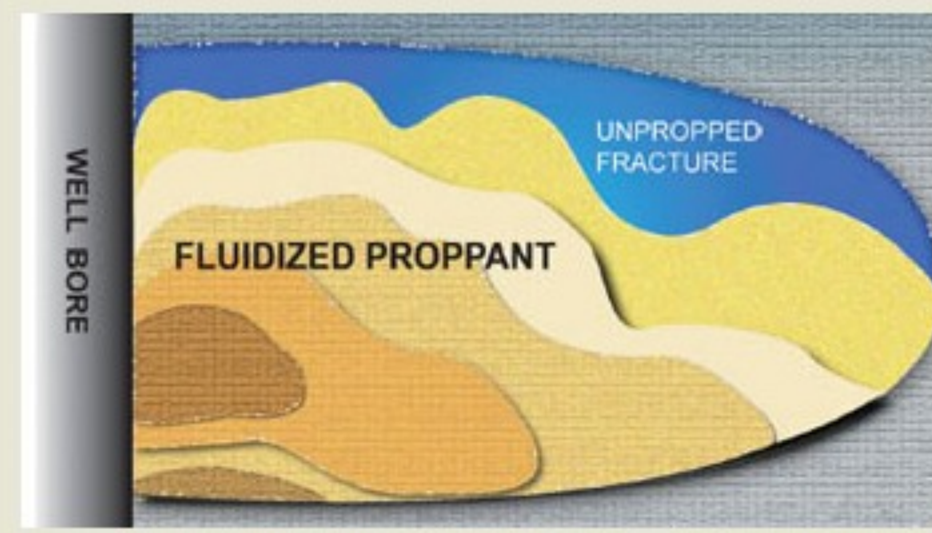
Engineering the perfect proppant...

Nanotechnology Research Contributes to Fracking Proppant Development

by Karen Boman | Rigzone Staff | Friday, July 29, 2011



Conventional slickwater bed load proppant transport

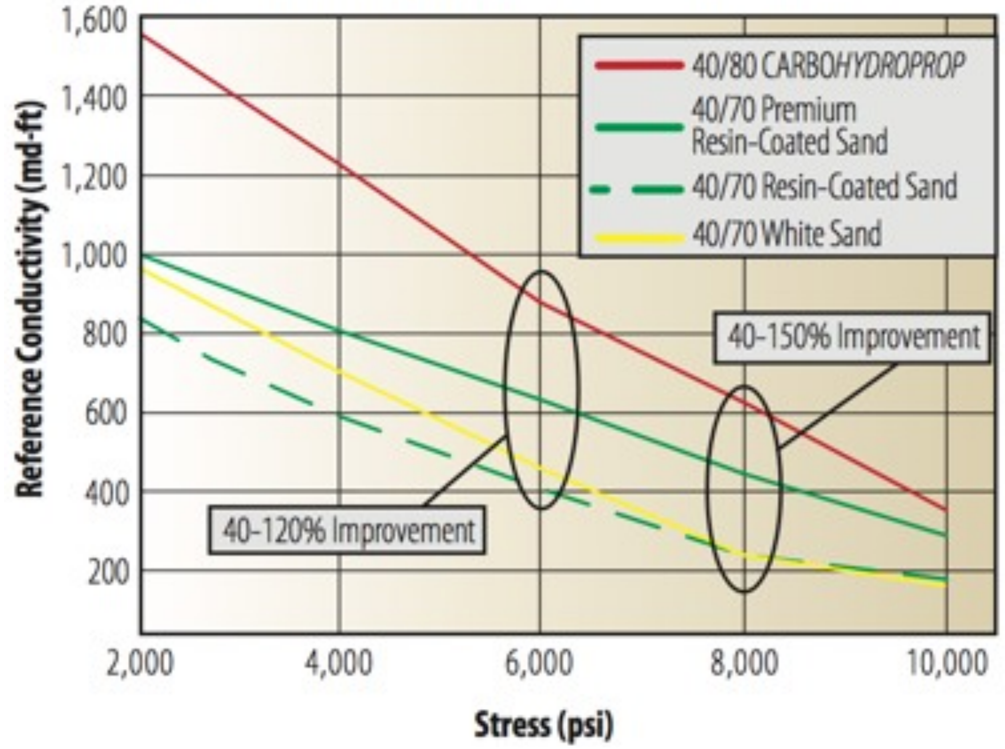


Trican's FlowRider solution causes microscopic air bubbles to adhere to sand, making it as transportable as ultra-lightweight proppant. Slickwater with proppant transportation modifier

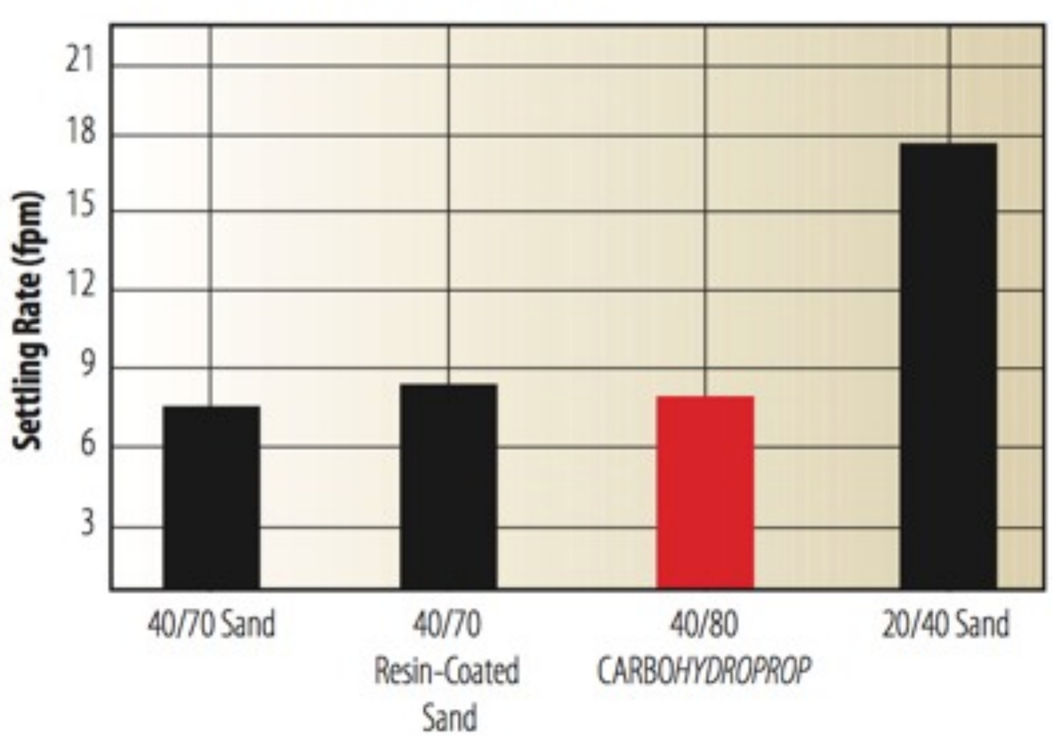
CARBO*HYDROPROP*®

Lightweight ceramic proppant for slickwater fracturing

Reference conductivity comparison between 40/80 CARBO*HYDROPROP* and other products



Settling Rate in 2% KCl Fluid



CARBO*HYDROPROP* 40/80

Physical and Chemical Properties

Typical Sieve Analysis [weight % retained]

U.S. Mesh [mesh]	Microns	40/80
+40 mesh	+425	2
-40+50 mesh	-425+300	68
-50+80 mesh	-300+180	30
Median Particle Diameter [microns]		325
API Crush Test		
% by weight fines generated	@5000psi	0.5%
	@7500 psi	2.0%

Sizing Requirements: *A minimum of 90% of the tested sample should fall between the designated sieve sizes. These specifications meet the recommended practices as detailed in ISO 13503-2.*

Typical Additional Properties

Apparent Specific Gravity	2.55
Roundness	0.8
Sphericity	0.9
Bulk Density [lb/ft³]	87
[g/cm³]	1.40
Absolute Volume [gal/lb]	0.047
Solubility in 12/3 HCl/HF Acid [% weight loss]	4.8

Summary

- There is a real need for improved proppant transport models and experiments
- Transport models need to account for all sediment transport modes
- Transport models need to be coupled with hydraulic fracture models
- For a collection of references, email me at

brendon.hall@gmail.com