FRACKING TECHNOLOGY, SHALE FRAGMENTATION AND SOME IDEAS TO IMPROVE EFFICIENCY AND MITIGATE ENVIRONMENTAL FOOTPRINT

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Motivation

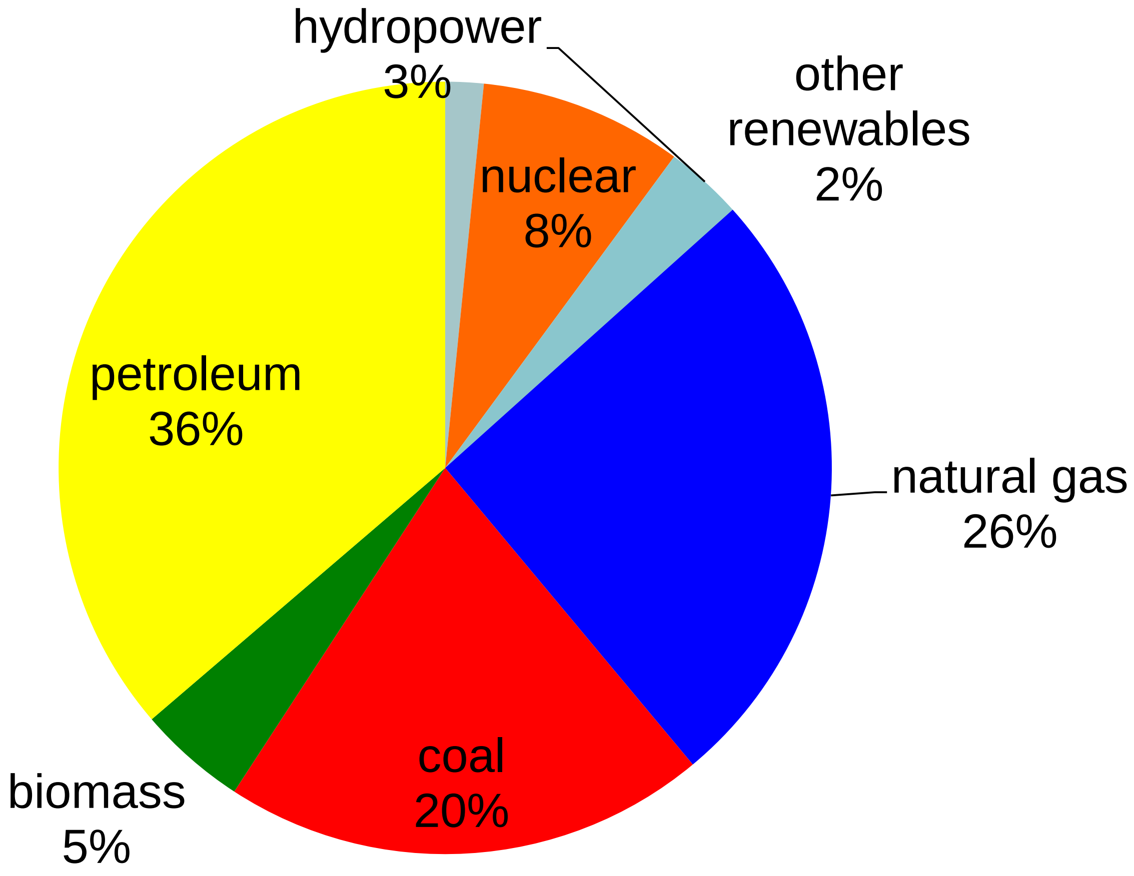
Although impressive advances in hydraulic fracturing have taken place and most aspects are well understood, one vital information is lacking:

- **The geometry of the crack system hydraulically produced in the shale, its evolution, crack spacing and crack width, are not known, and expert opinions differ widely.**

- **Progress in this regard would likely allow improvements, optimization of effectiveness and reduction of environmental footprint.**

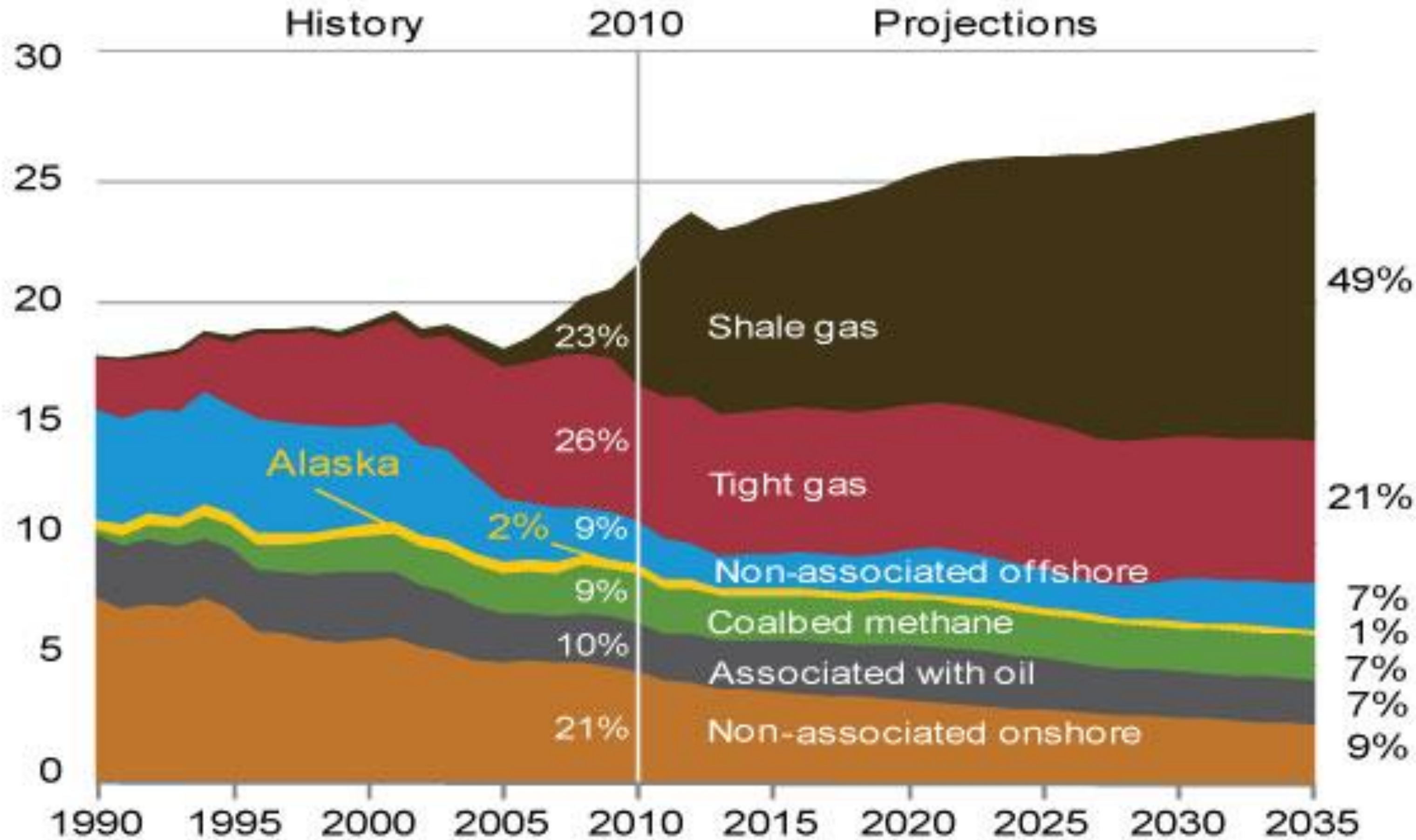
Overview of Hydraulic Fracturing Technology (aka "Fracking")

Where do we get our energy?



U.S. Natural Gas Production, 1990-2035

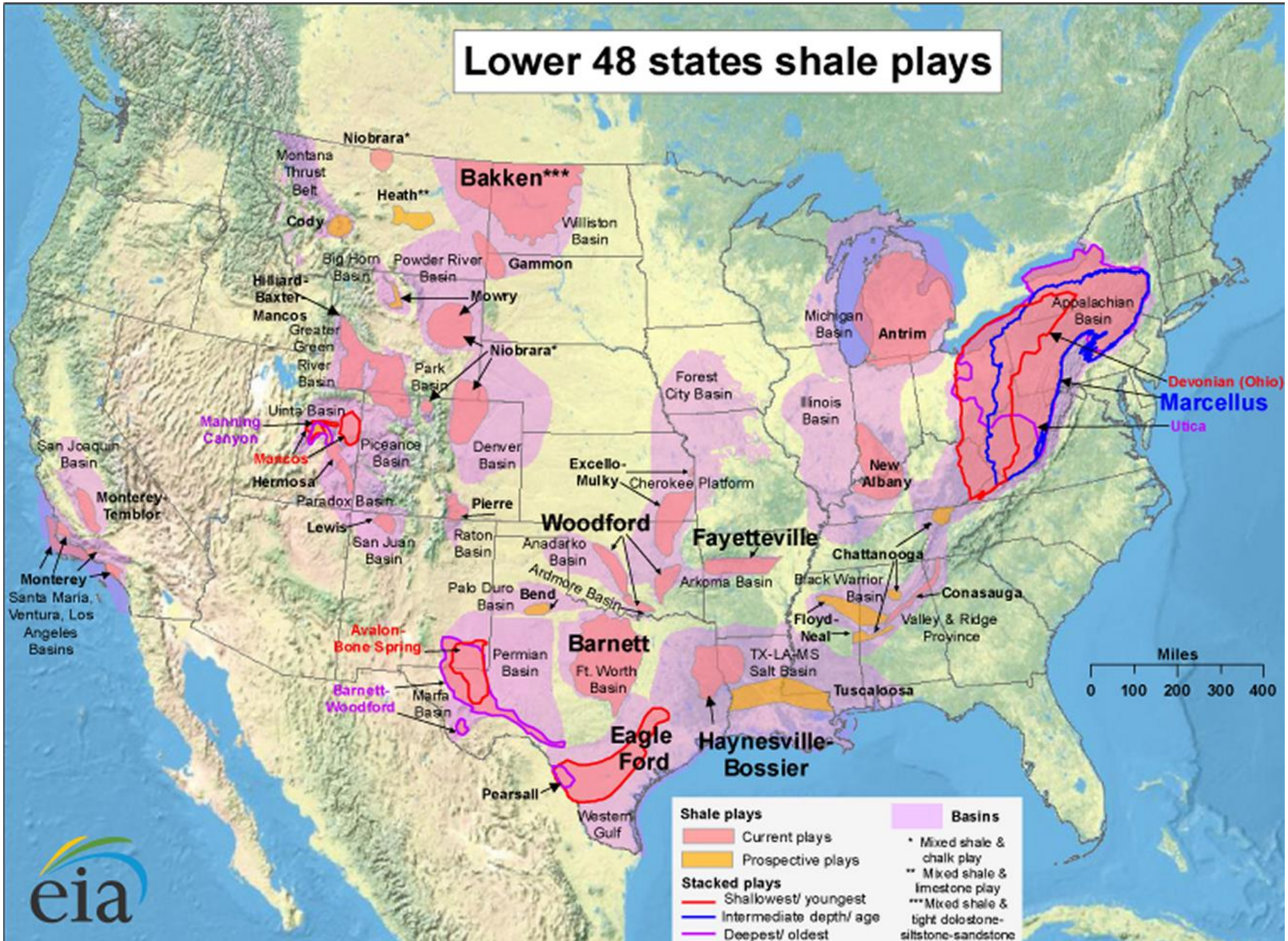
trillion cubic feet



Source: U.S. Energy Information Administration, AEO2012 Early Release Overview, January 23, 2012.

http://205.254.135.7/energy_in_brief/about_shale_gas.cfm

Gas Shale Distribution

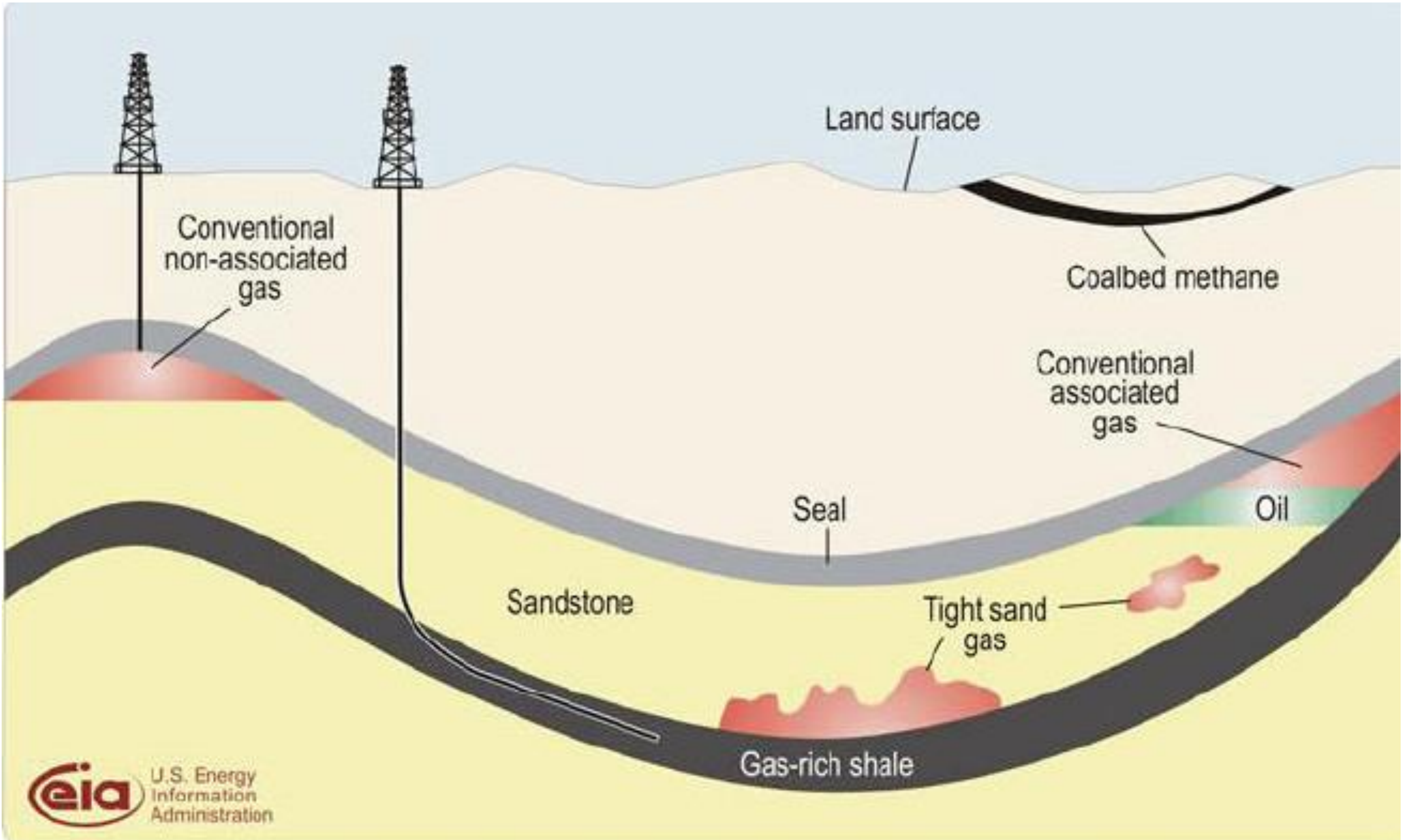


Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Provenance of Natural Gas

- Formed by organic matter (marine organisms, plants) trapped in sedimentary rocks
- “Conventional” natural gas is trapped in porous rock (sandstone domes)
- “Unconventional” natural gas is trapped in micropores of tighter rocks and in nanopores of shale

Schematic of Natural Gas Resources



Development and Features of Fracking

- Has been developed gradually since 1947, without government support (except recently, became obvious).
- Fracking involves:
  - Drilling a well, to reach shale layer typically 3 km down
  - Turning drill to horizontal, extending it for a few km
  - Injecting fluid under pressures up to about 25 MPa at pump—cca 2 mil. gal. (which equals 1.7 mm of rain over lease area, per stage). The fluid is 99% water plus chemicals and proppant (fine sand). Only about 15% returns to the surface.
  - Extracting the gas, reinjecting contaminated water

Typical Drill Pad and Extraction Site

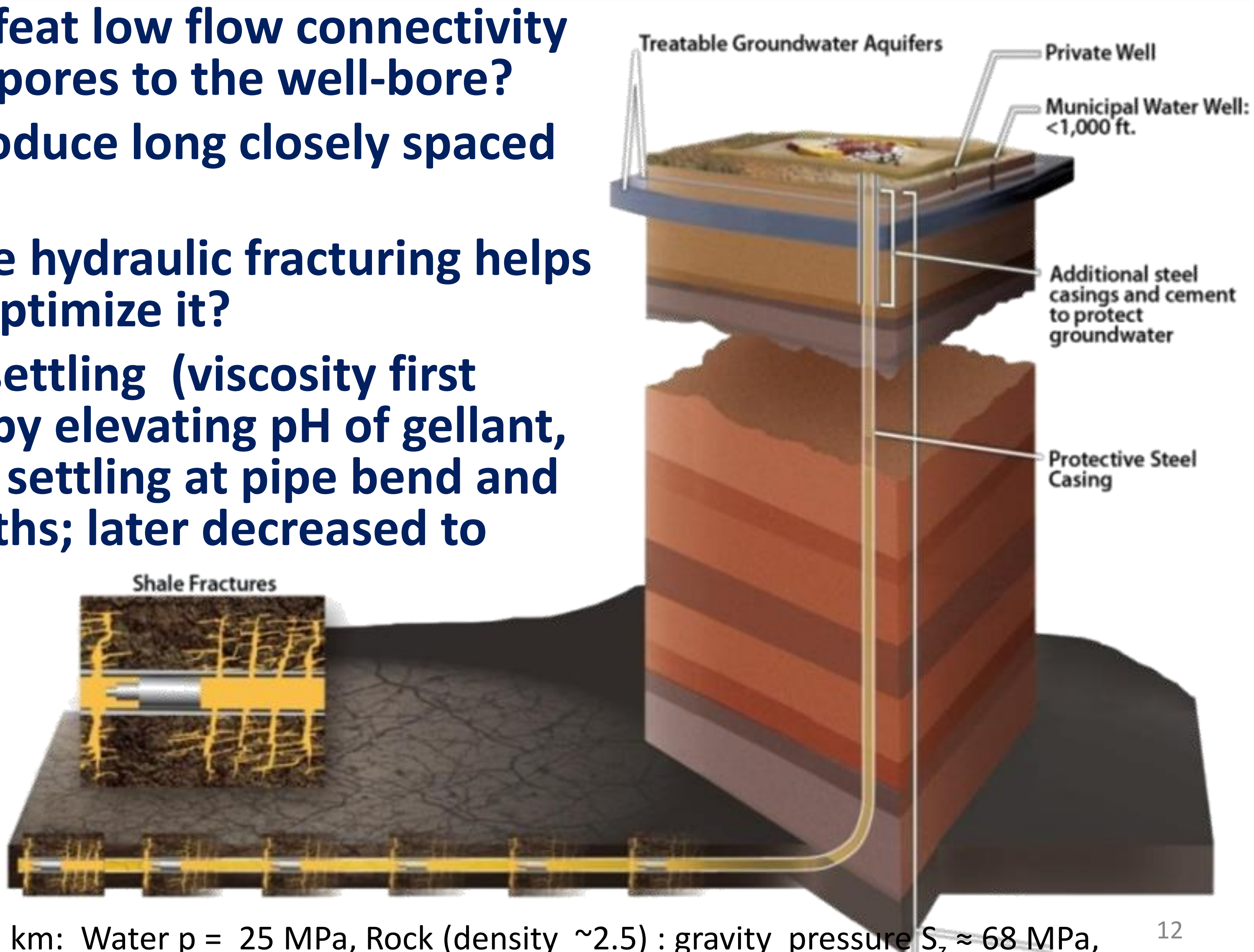
Fracking Fluid

Often a small amount of polymer is added as a friction reducer.

Sometimes a gellant (viscosifier) is added to limit proppant settling. It can be polymerized and its viscosity can be adjusted by changing the pH with borate or zirconium ions.

Drilling and Fracking Operation

- **How to defeat low flow connectivity from nanopores to the well-bore?**
- **How to produce long closely spaced cracks?**
- **Multi-stage hydraulic fracturing helps – how to optimize it?**
- **Proppant settling (viscosity first increased by elevating pH of gellant, to prevent settling at pipe bend and crack mouths; later decreased to penetrate deeper).**
- **etc.**



At depth 2.5 km: Water p = 25 MPa, Rock (density ~2.5) : gravity pressure $S_z \approx 68$ MPa, Tectonic pressures = 55 and 42 MPa, Pump: 25 MPa, Pump + water pressure = 25+25 MPa (more with drilling mud). Shale density = 2 to 2.7, typical 2.5. Granite 2.75

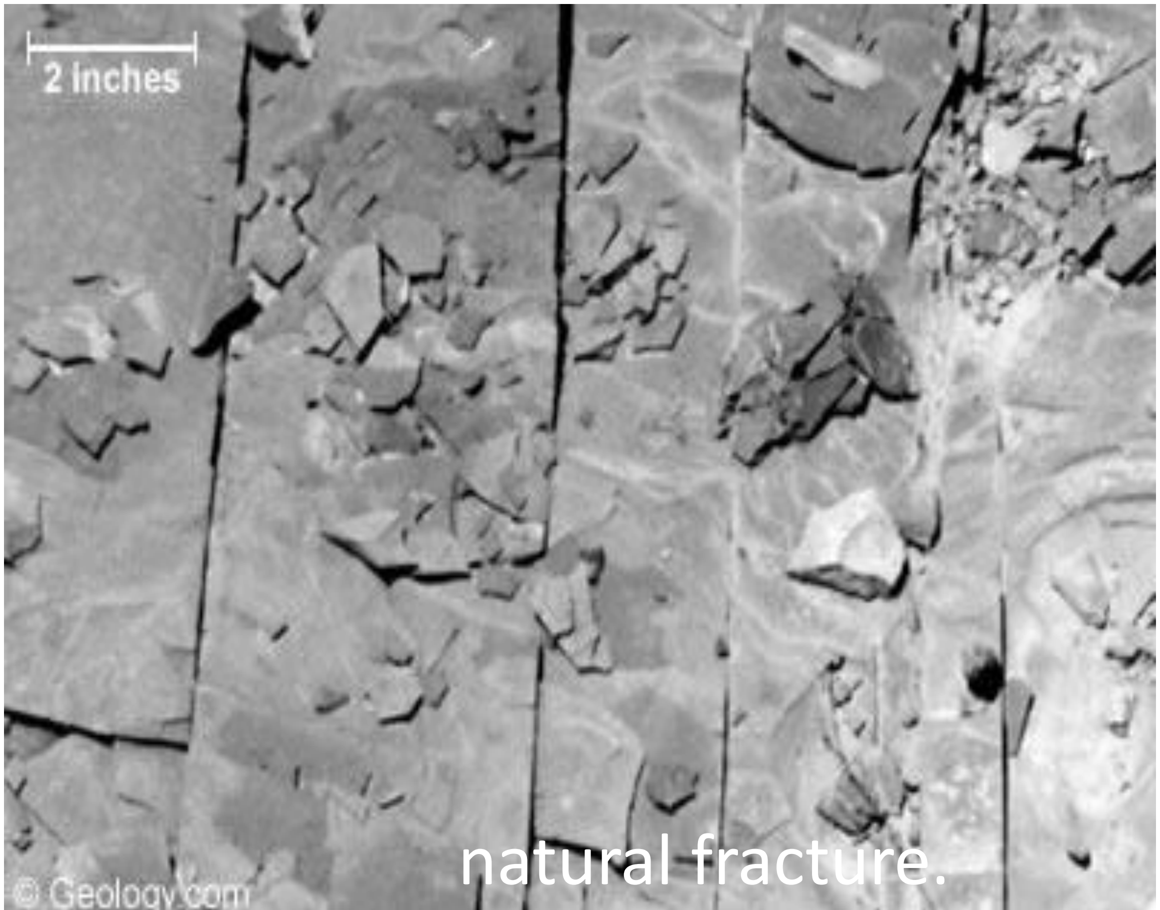
Horizontal Drilling

(Marcellus Shale)

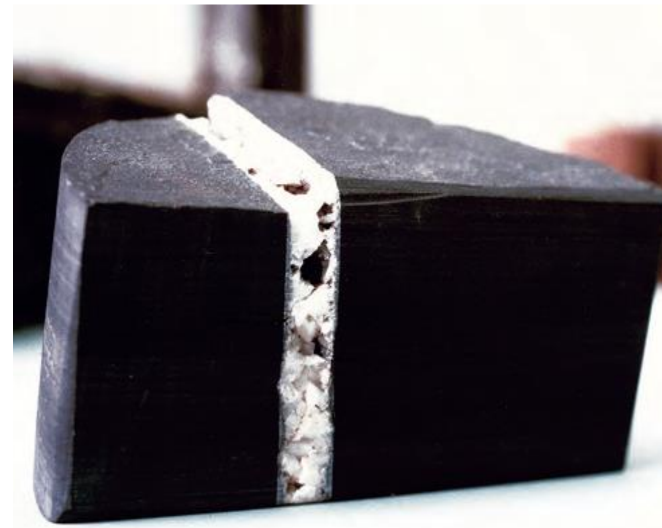
- vastly enlarges gas extraction zone
- vastly reduces devastation on earth surface
- The well bore is turned to horizontal with a **radius big enough** for the high-strength steel pipe to remain elastic (typical pipe dia. 3.5 in.).

Source: Geology.com

Vertical Joints in Devonian Shale (Marcellus)



Surface outcrop

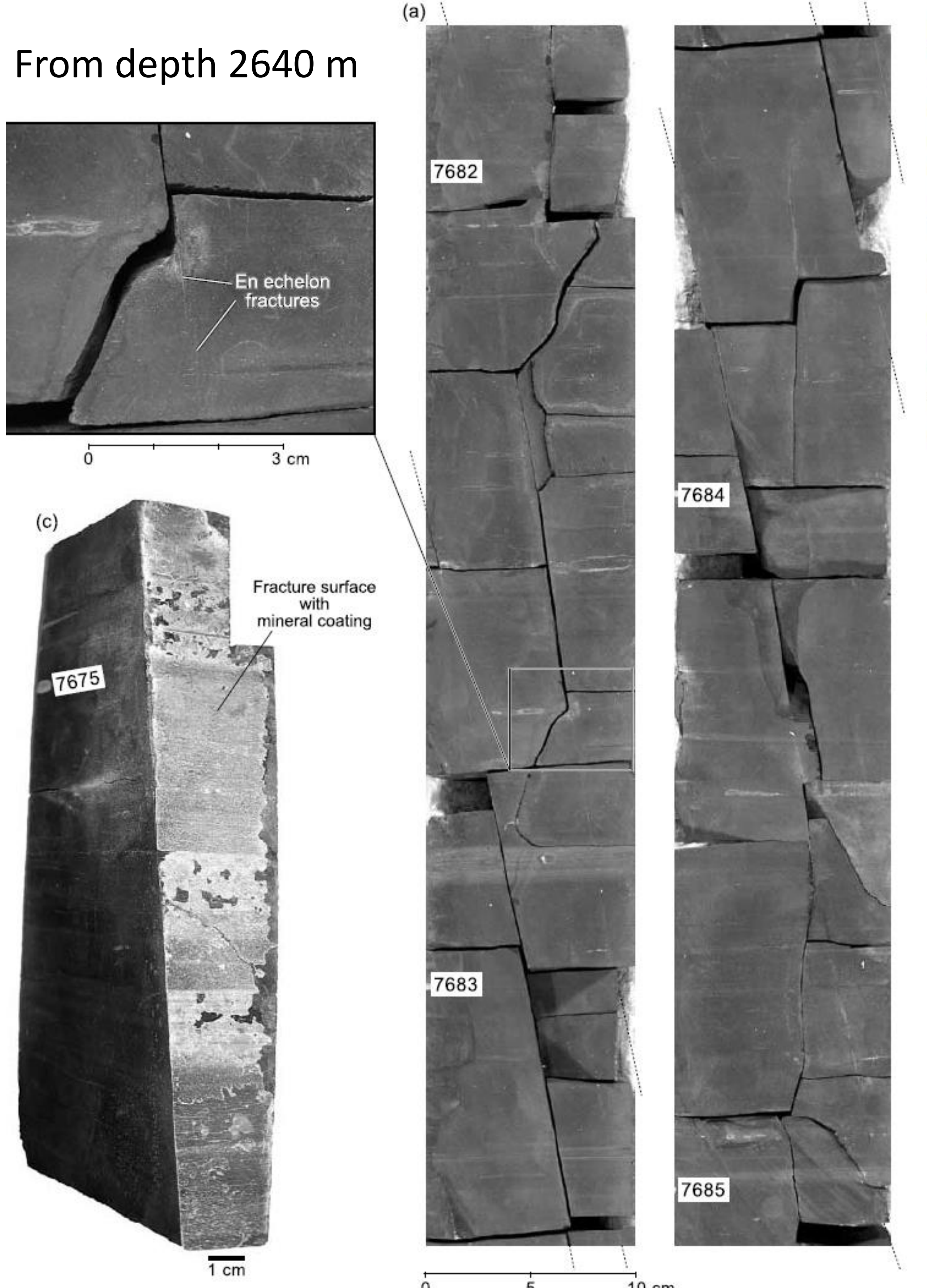


Drill core

(3.5 in. dia.) of Marcellus shale from West Virginia, with a joint filled by calcite

Natural Fractures in Shale Cores, Sealed with Calcite

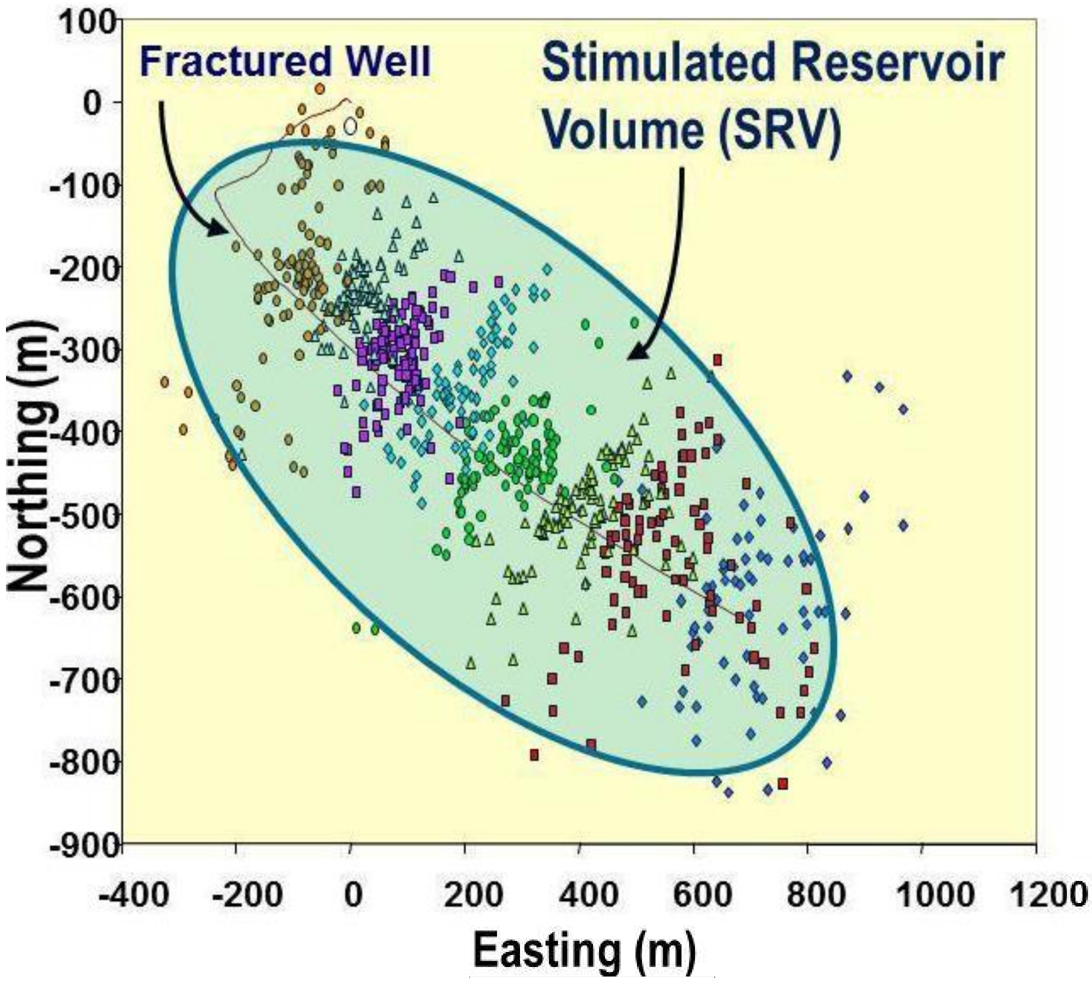
From depth 2640 m



Gale et al. (2007), Am. Assoc. of Petroleum Engrs. Bulletin

Microseismic sources in Marcellus shale reveal extent of fracturing

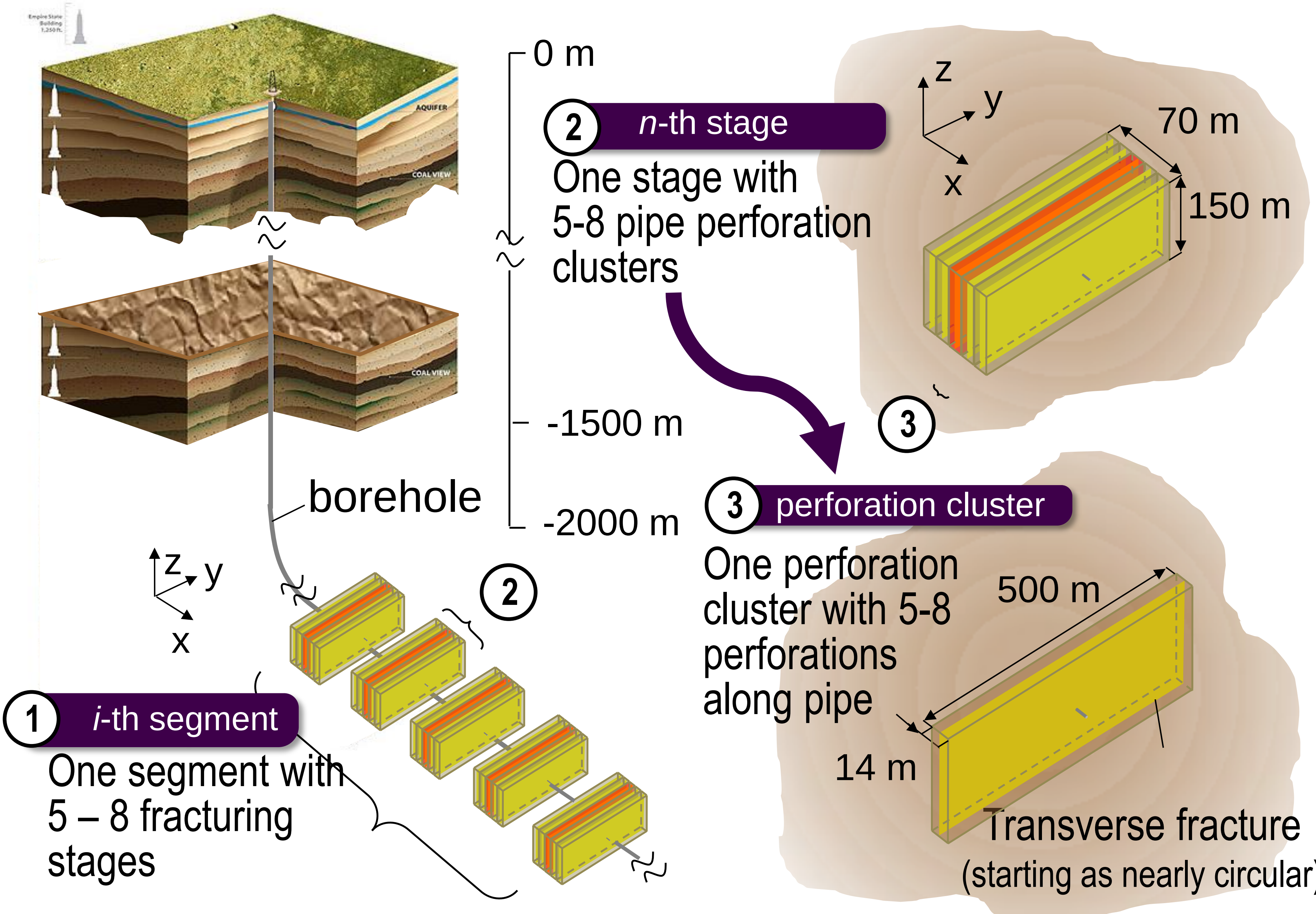
Plan view



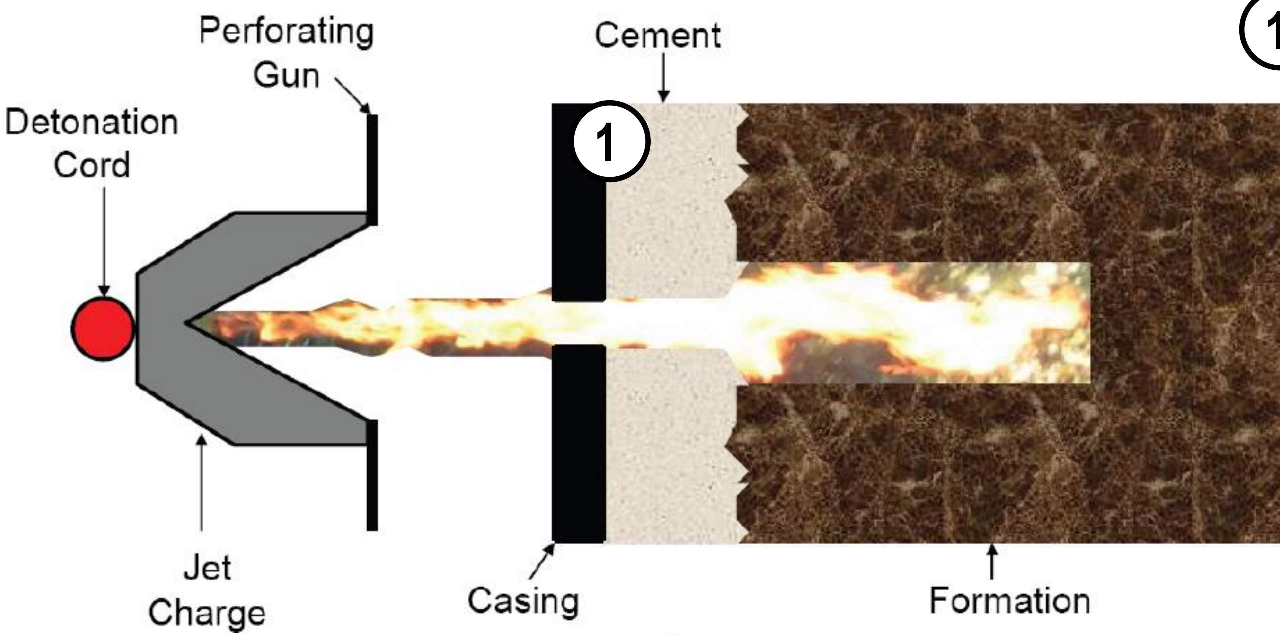
One segment with 12 stages (each in a different color), each stage having 5 to 8 clusters, each cluster having about 5 pipe perforations

Source: Rimrock Energy, SPE 119896

Main Features of the Well

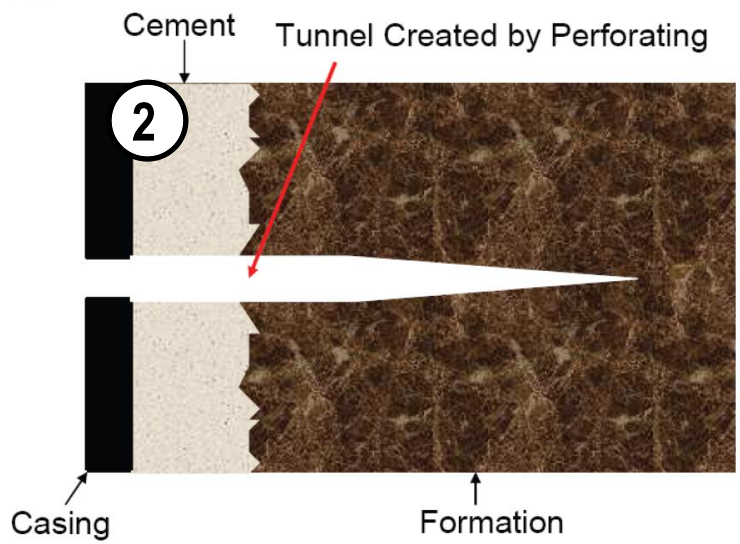


Perforation of High Strength Steel Pipe



(1) The shaped charge is detonated and a jet of very <u>hot, high-pressure gas vaporizes the steel</u> pipe, cement, and rock formation in its path

Common method: jet-perforating guns with shaped explosive charges.



(2)

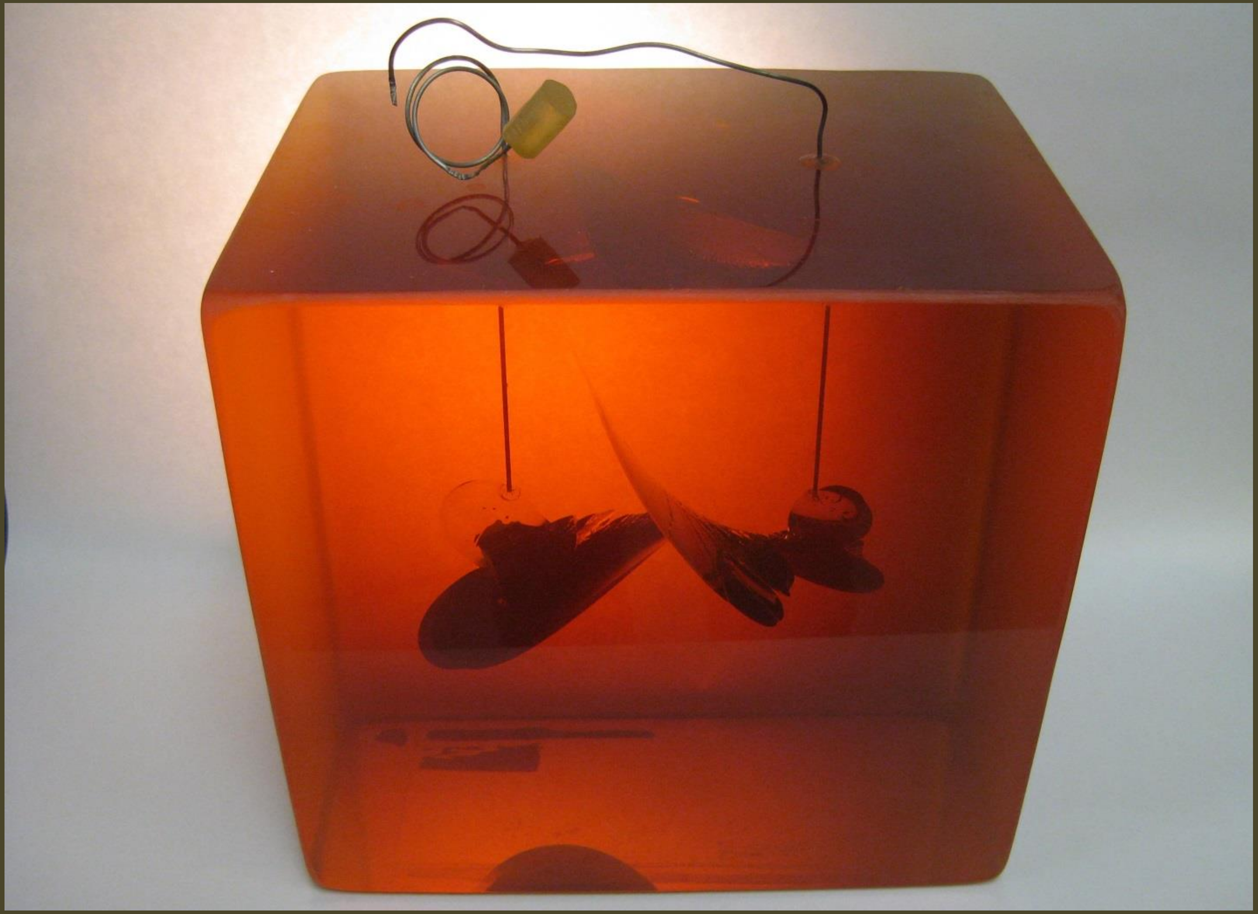
Result: A tunnel, isolated by cement mortar, from production casing (or pipe) to rock formation.

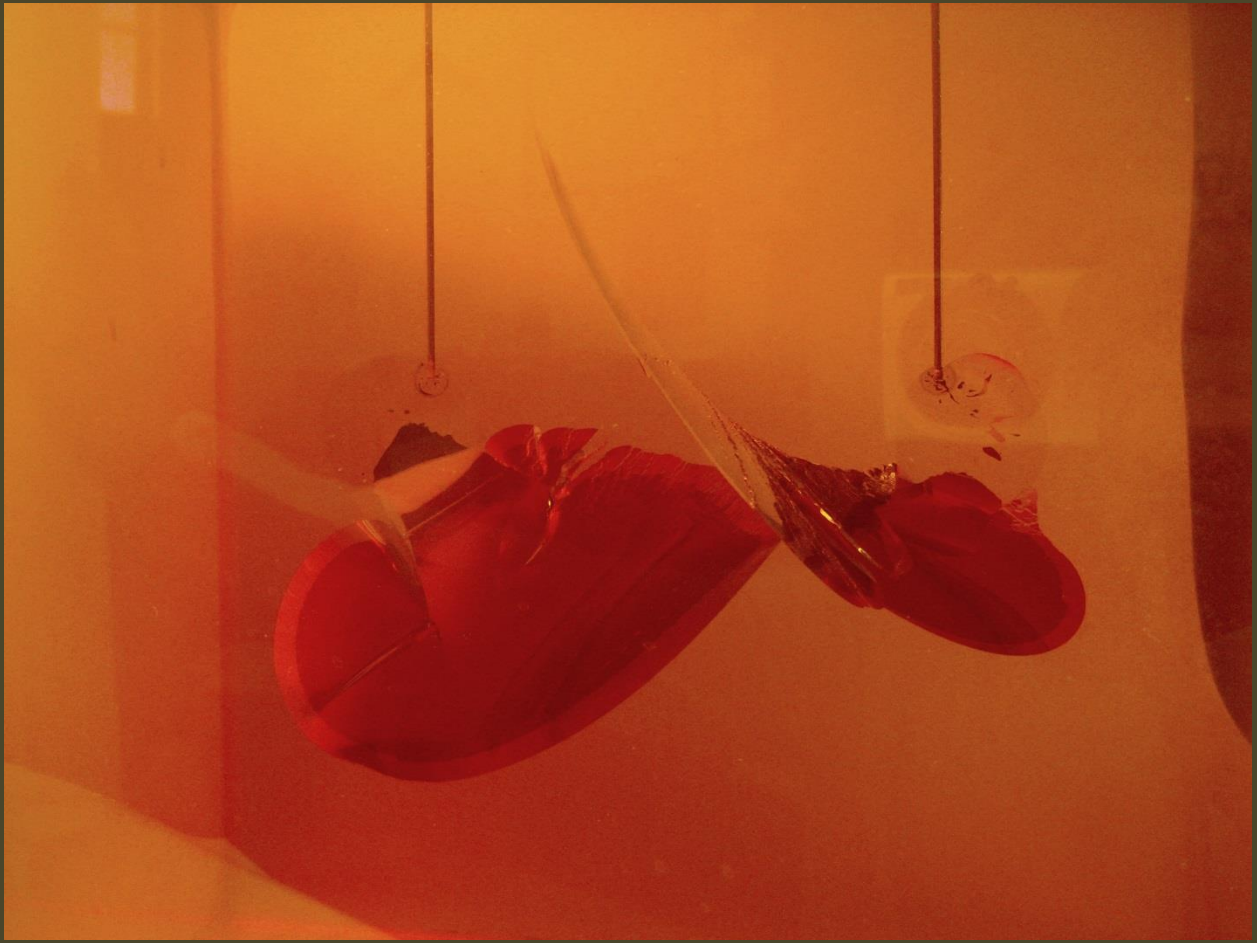
1970s NU-LASL Collaborative Project on Hot Dry Rock Geothermal Energy

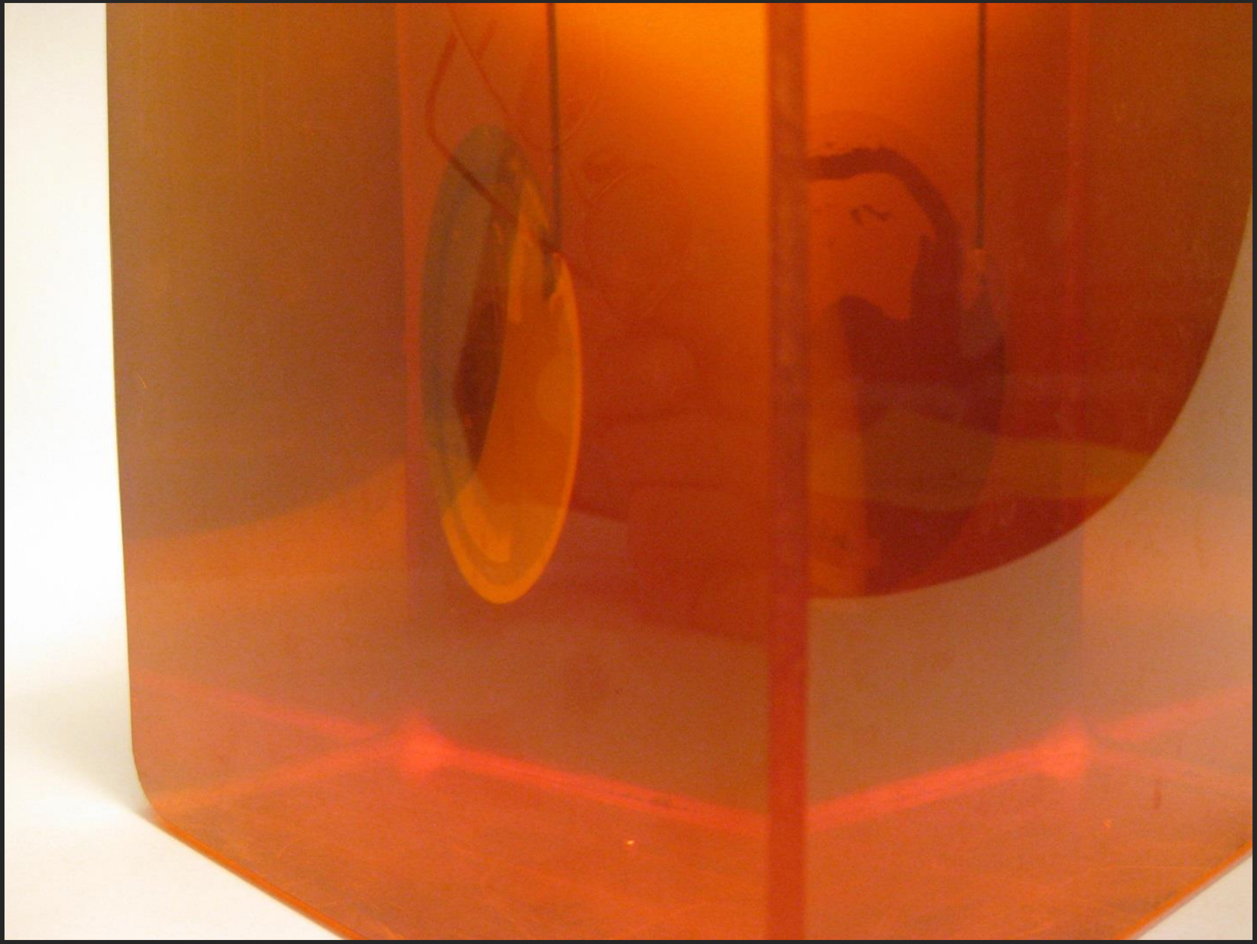
Negative result

but a valuable lesson

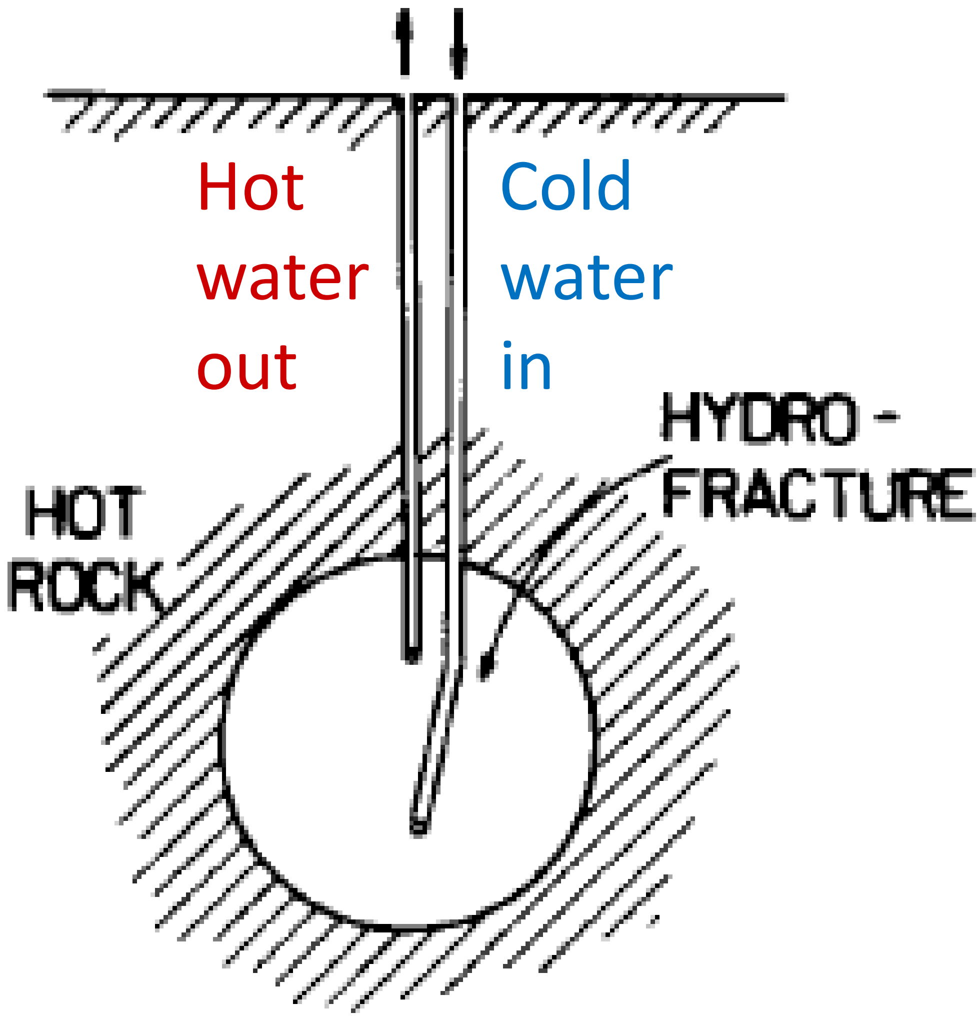
John Dundurs' 1976 Tests of Hydraulic Fracture in Epoxy Blocks







Concept of the Unsuccessful 1970s Hot Dry Rock Geothermal Energy Scheme[1]



LASL drilled a well in Valles Caldera, Jemez Mountains and created large fracture

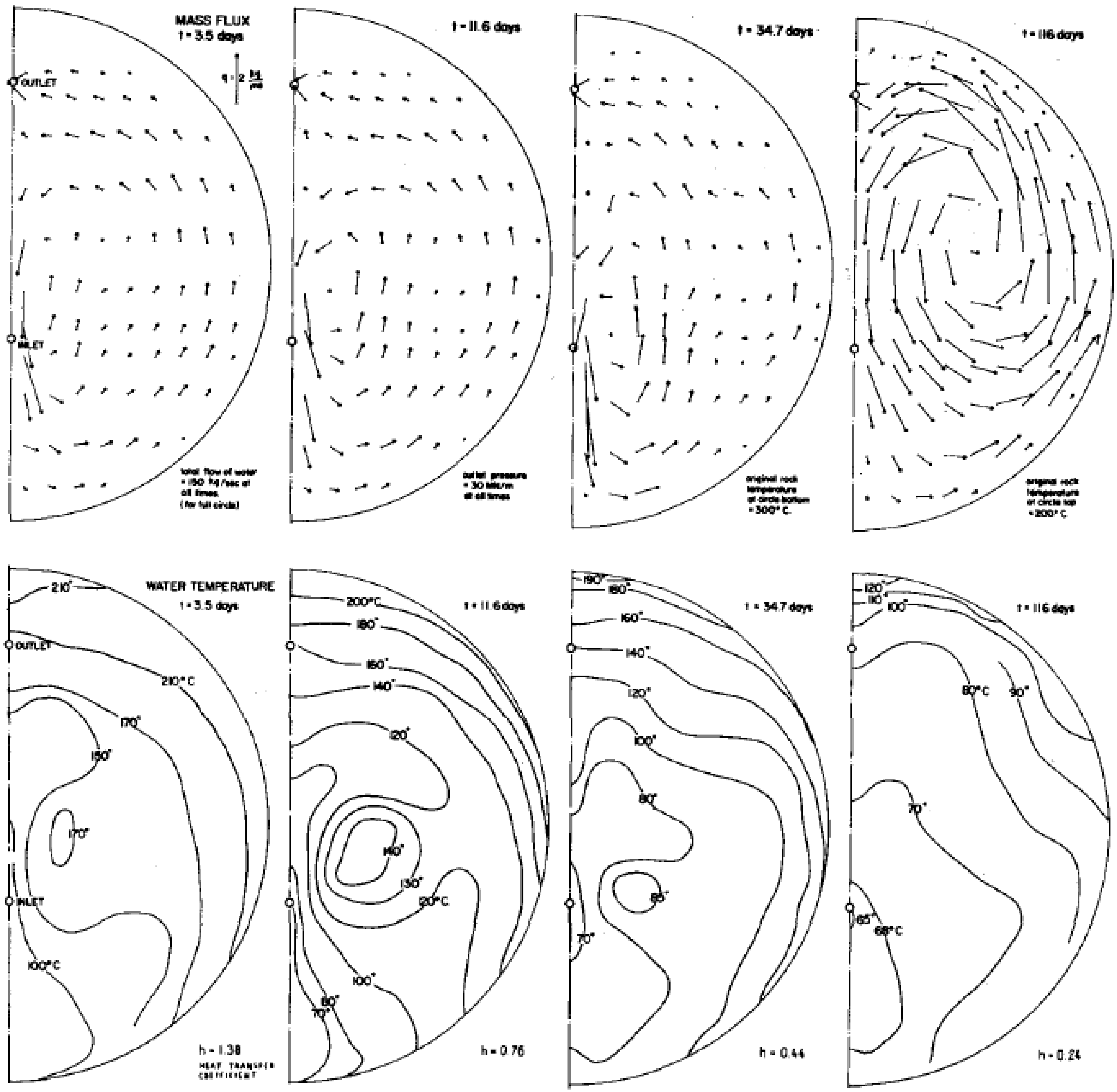
[1]NU-LASL Collaborative Project 1974-77.

NU investigators:
J Weertman, PI
JD Achenbach
ZP Bazant
J Dundurs
LM Keer
T Mura
S Nemat-Nasser

1970s NU-LASL Hot Dry Rock Geothermal Energy Project

Hydro-crack diameter 1 km. Granite, ***T = 300ºC*****.**

Water out: initially T_1 = 210ºC. ***After 116 days: 90ºC.***

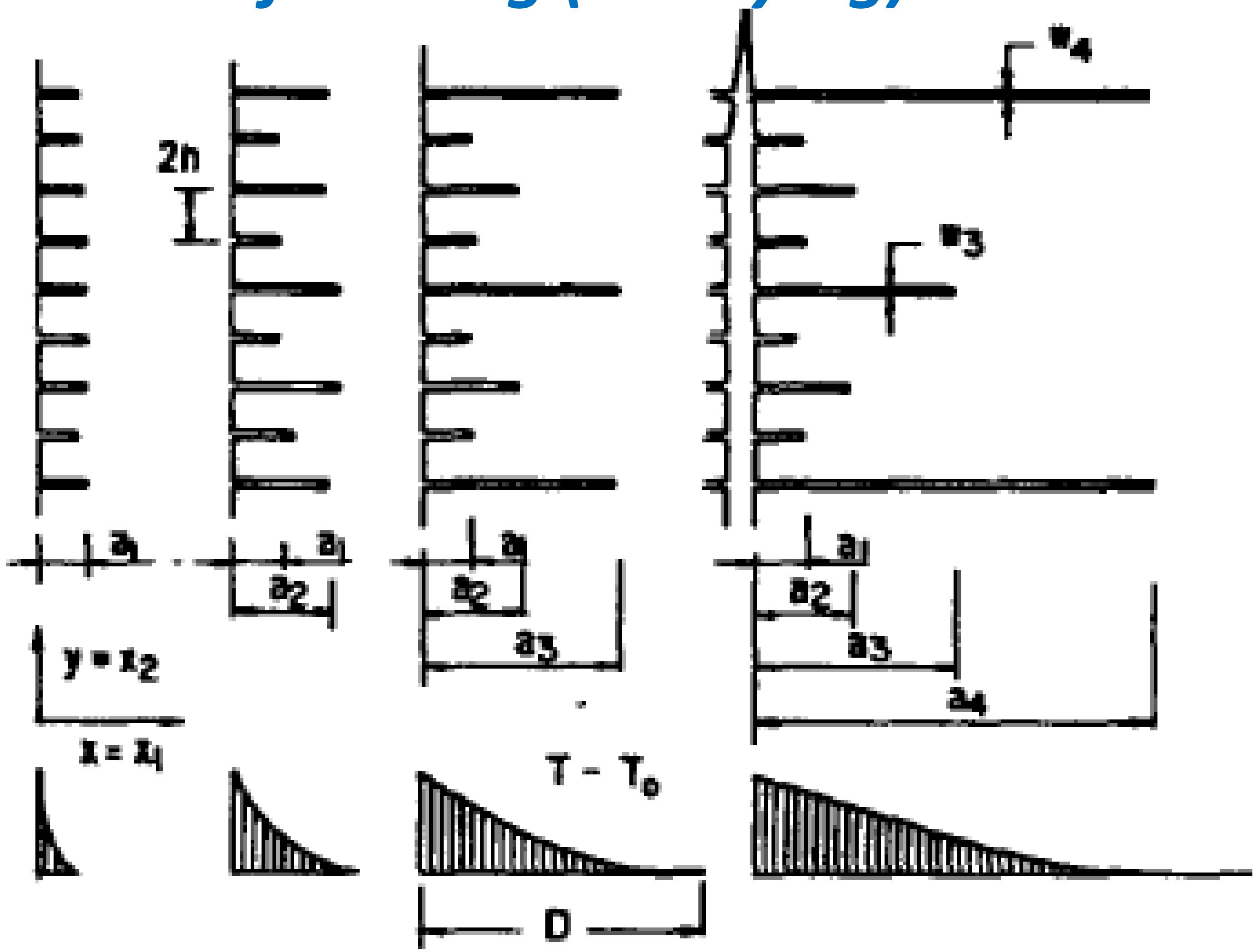


Bazant & H Ohtsubo: Int. J. of Numer. & Anal. Meth. In Engrg. 2, p. 317 (1978)

Localization Instability of Crack System

NU-LASL Hot Dry Rock Geothermal Energy Project

Evolution of Cooling (or Drying) Cracks



ZP Bazant, H Ohtsubo, Mech. Res. Comm. 4 (5), 353-366 (1977); and Int. J. of Fracture 15, 443—456 (1979)

Stability of Crack System

Helmholtz Free Energy of Crack System:

Array of parallel cracks

$$F = U(a_1, a_2, ..., a_N; p) + \sum_{i=1}^{N} \int \Gamma \, \mathrm{d}a_i$$

$a_i = \text{i-th crack length}$ $\quad \Gamma = \text{fracture energy}$

$p = \text{loading parameter: crack pressure or } \Delta T$

$U = \text{strain energy of the elastic body}$

Taylor's series expansion: $\Delta F = \delta F + \delta^2 F + ...$

For *m* growing cracks and *n*-*m* shortening ones:

$\delta a_i > 0 \quad i = 1, ...m$

$\delta a_i < 0 \quad i = m+1, ...n$

$\delta a_i = 0 \quad i = n+1, ...N$

$$\delta F = \sum_{i=1}^{m} \left(\frac{\partial U}{\partial a_i} + \Gamma \right) \delta a_i + \sum_{j=m+1}^{n} \left(\frac{\partial U}{\partial a_j} \right) \delta a_j$$

$$\delta^2 F = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\frac{\partial^2 U}{\partial a_i \partial a_j} \right) \delta a_i \delta a_j = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1} F_{ij} \delta a_i \delta a_j$$

Equilibrium condition: δF=0

$$\text{for } \delta a_i > 0: \quad -\frac{\partial U}{\partial a_i} = \Gamma \qquad \text{or } K_i = K_{Ic}$$

$$\text{for } \delta a_i < 0: \quad -\frac{\partial U}{\partial a_i} = 0 \qquad \text{or } K_i = 0$$

Stability conditions: ΔF>0

If $\delta F = 0$, stability will be ensured if:

$$2\delta^2 F = \sum_{i=1}^{n} \sum_{j=1} F_{ij} \delta a_i \delta a_j > 0 \text{ for any admissible } \delta a_i$$

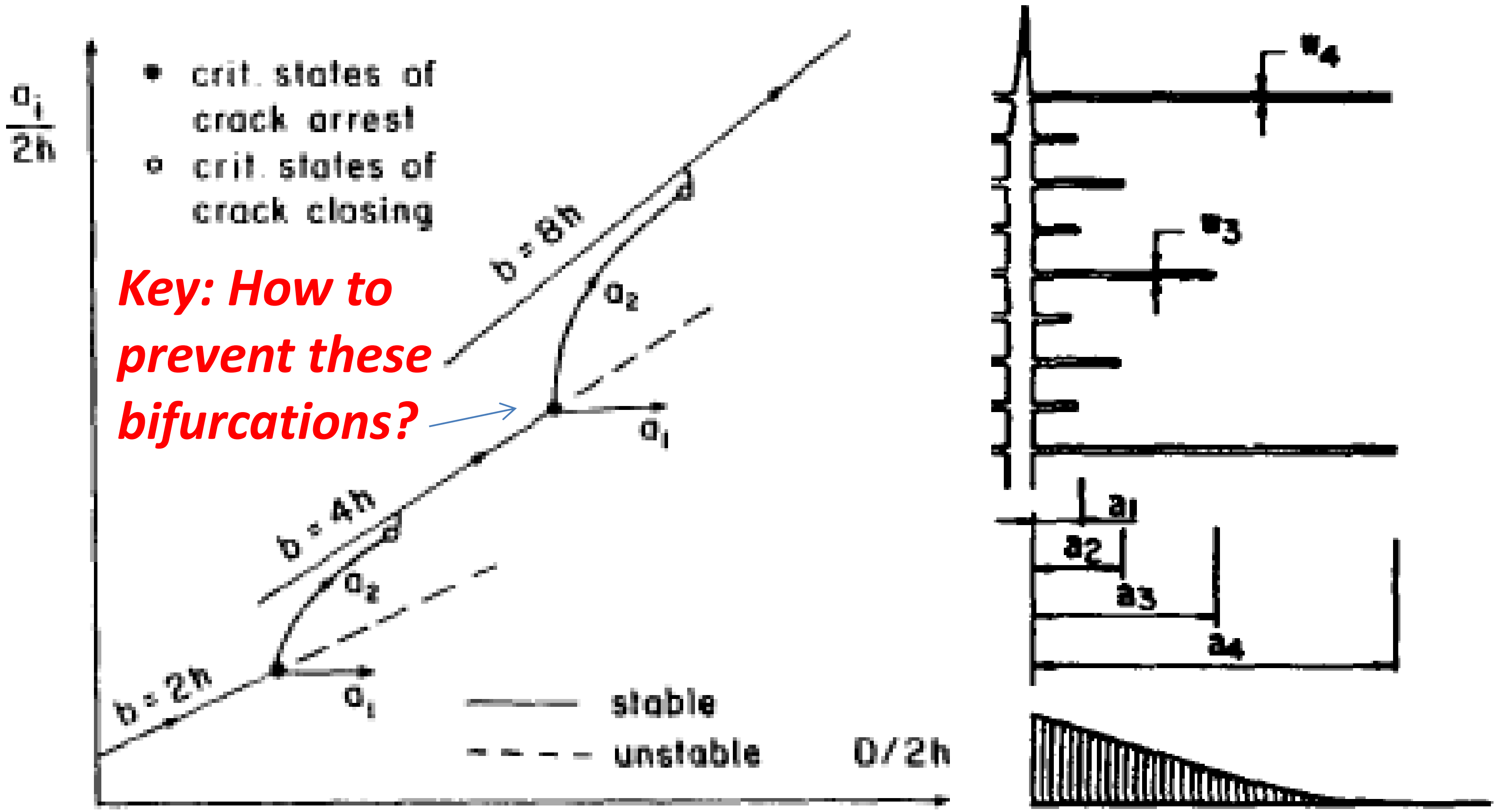
For 2 crack lengths:

$$F_{11} = F_{22} > 0 \text{ and } \begin{vmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{vmatrix} > 0$$

ZP Bazant, H Ohtsubo, Mech. Res. Comm. 4 (5), 353-366 (1977); & IJF 15, 443—456 (1979)

Max. Crack Depth vs. Penetration Front Depth in Localizing Parallel Crack System

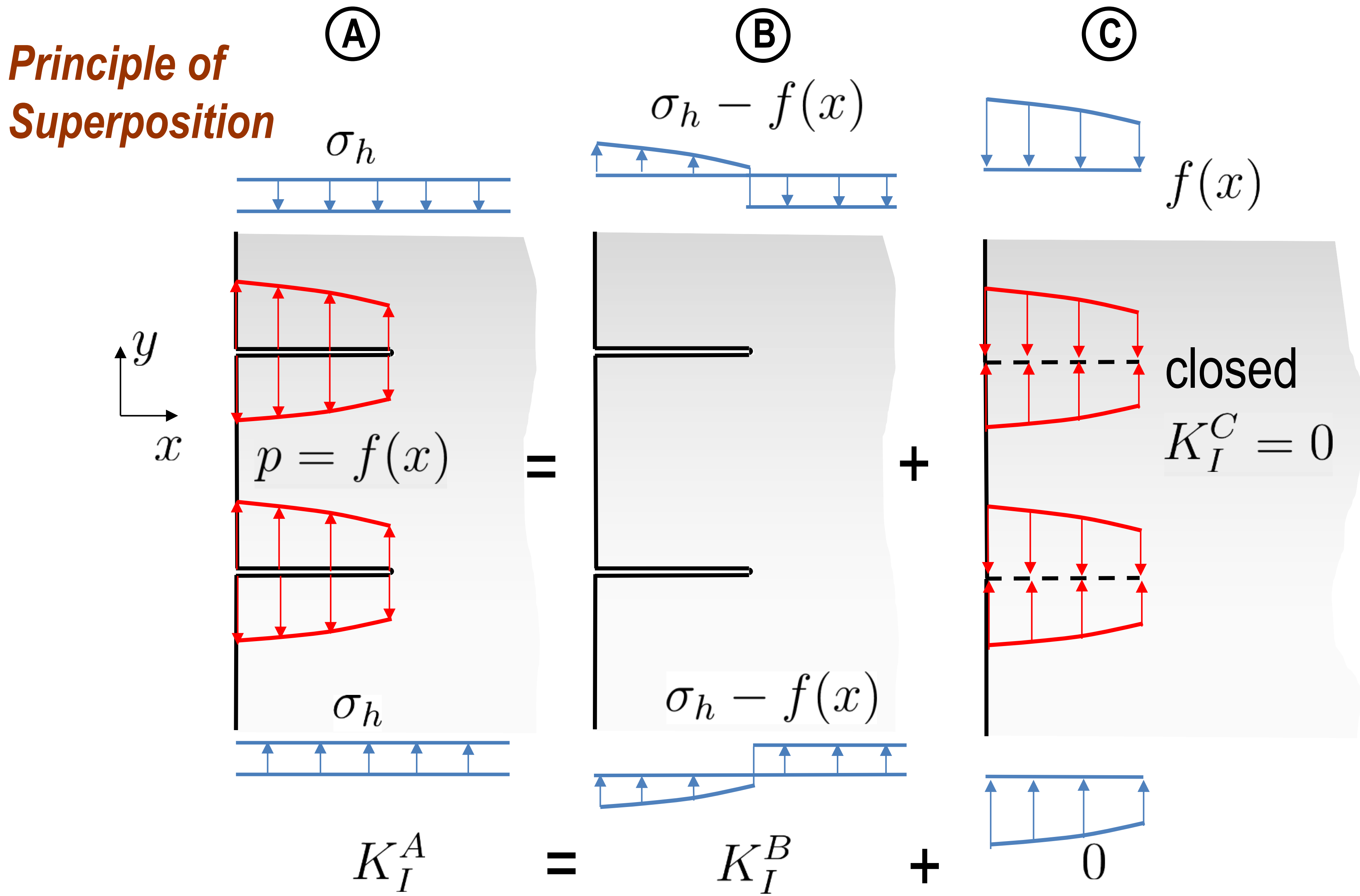
1976 NU-LASL Geothermal Energy Project



Key: How to prevent these bifurcations?

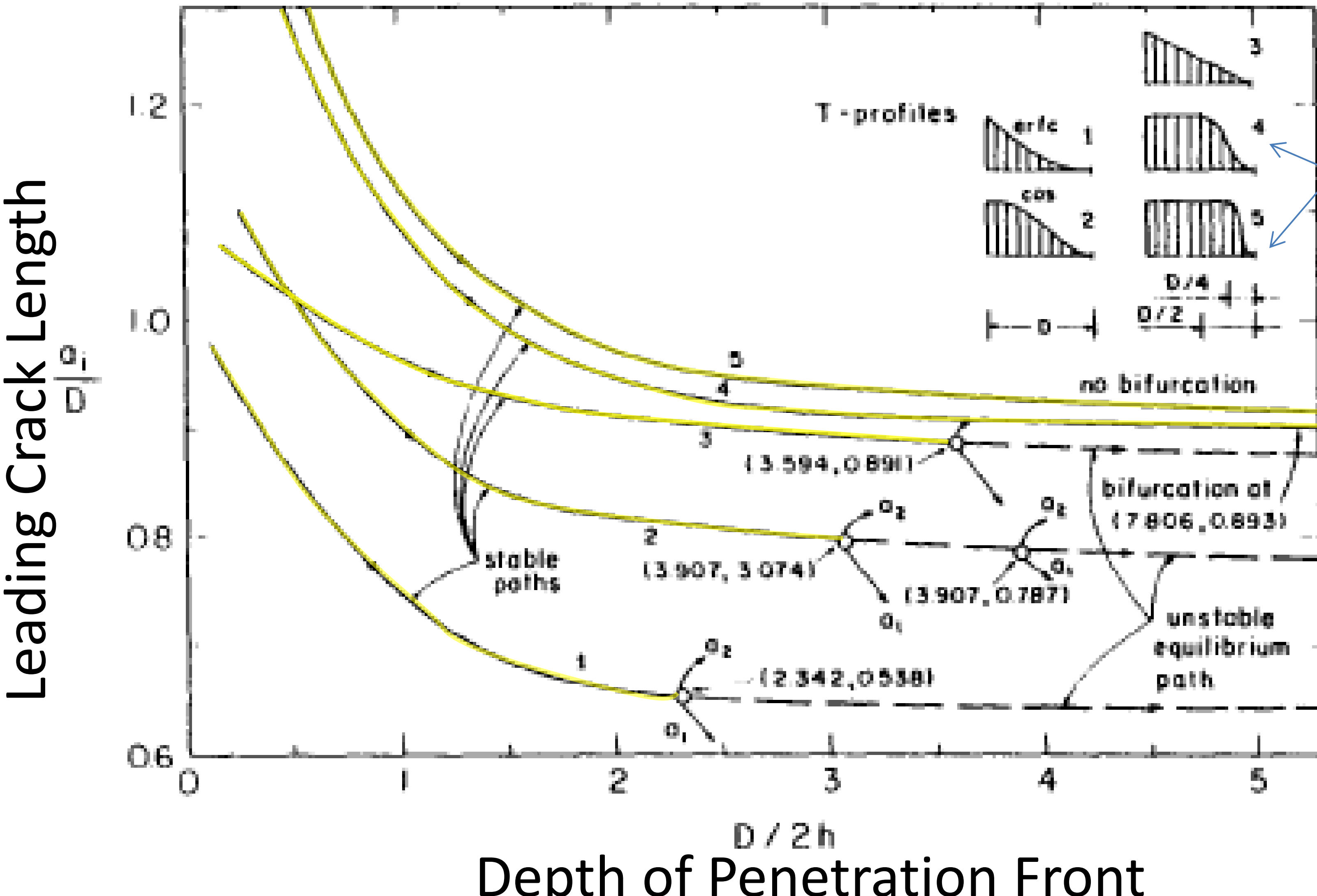
ZP Bazant, AB Wahab, J. Eng. Mech. ASCE 105, 873—889, 1979

Solutions for cooling or shrinkage cracks can be easily adapted to localization of hydraulic cracks

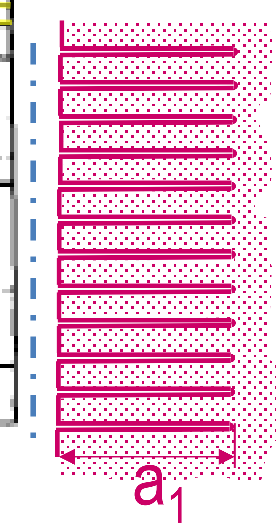


Front Steepness: Key to Prevent Localization

1976 NU-LASL Geothermal Energy Project



For a steep front, cracks don't localize!



ZP Bazant, AB Wahab, J. Eng. Mech. ASCE 105, 873—889, 1979

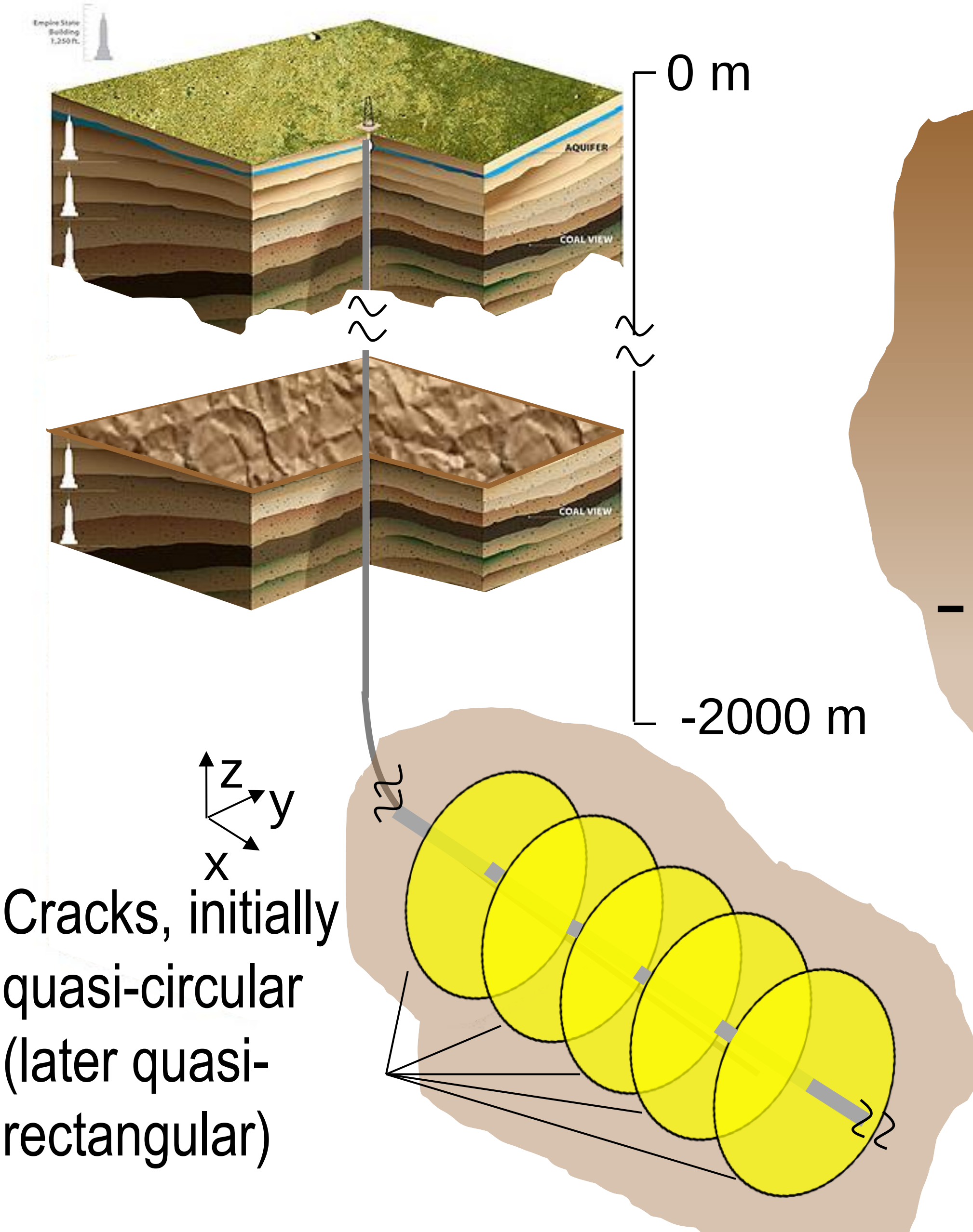
Lesson from the 1970s project

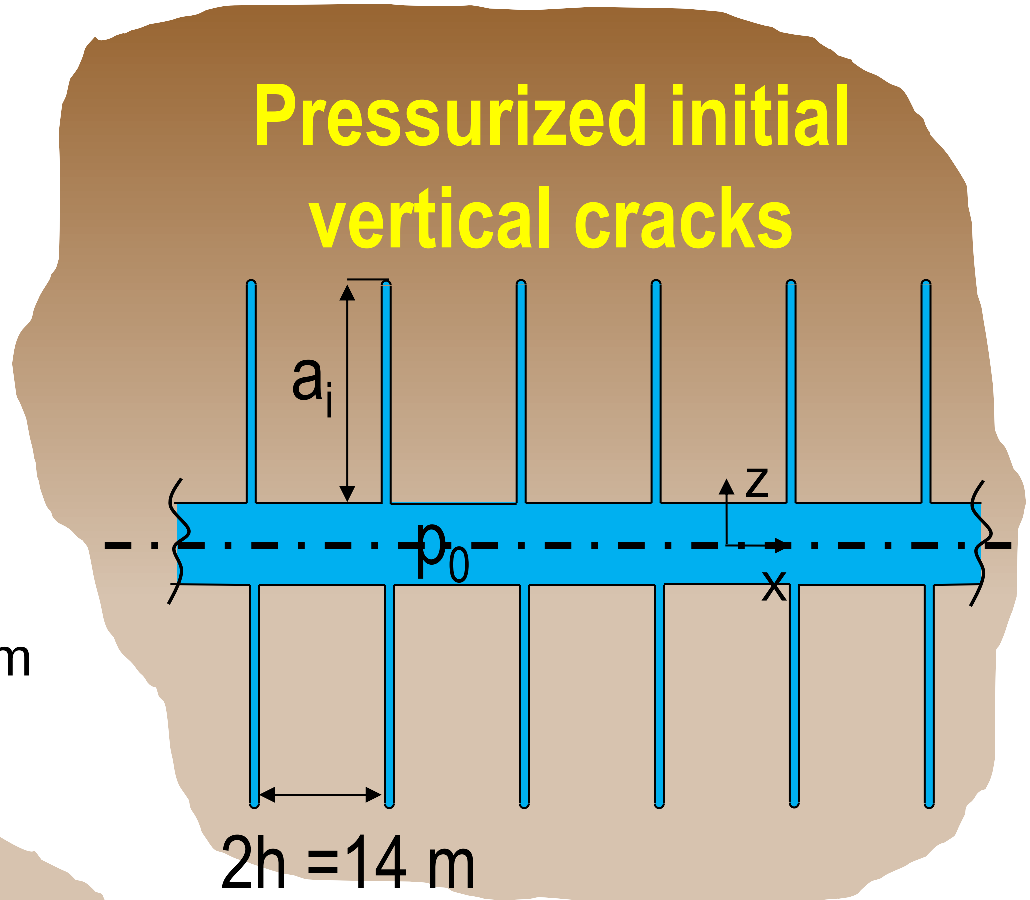
- Stability of crack system, is an essential part of hydraulic fracturing analysis (ignored so far)
- Localization can be prevented and a parallel crack system can be produced if and only if a **pressure profile <u>sufficiently steep</u> at the front can be created <u>during crack growth</u>.**

Why fracking works?

Suppression of localization instability of crack system

Stability Analysis of Pressurized Circular Cracks



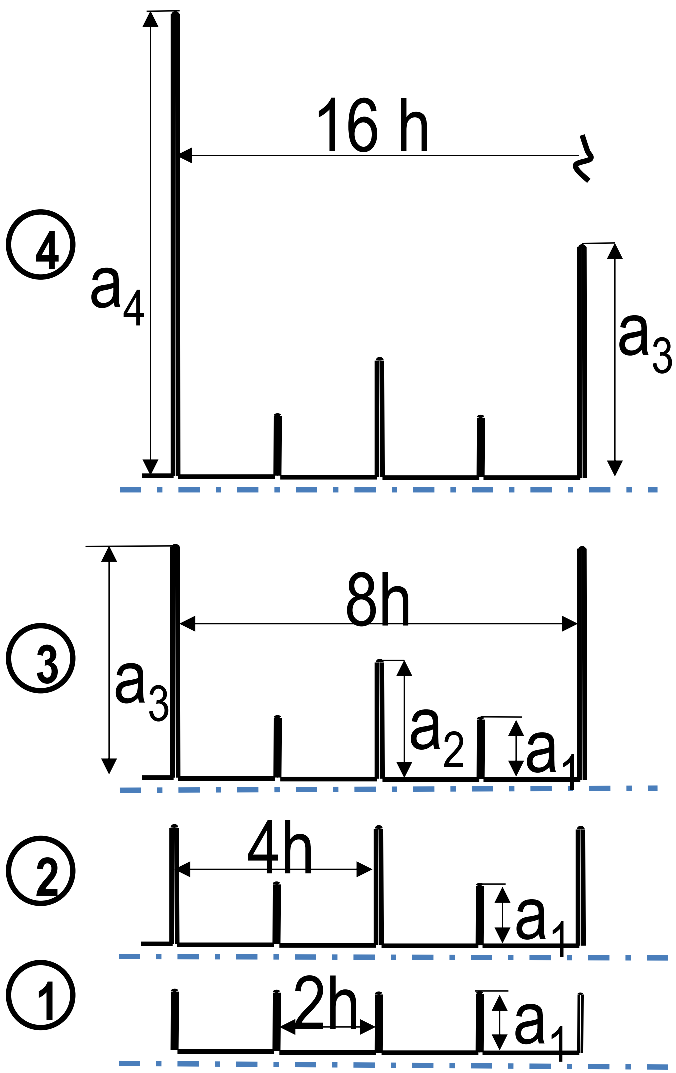


p_0 = borehole pressure

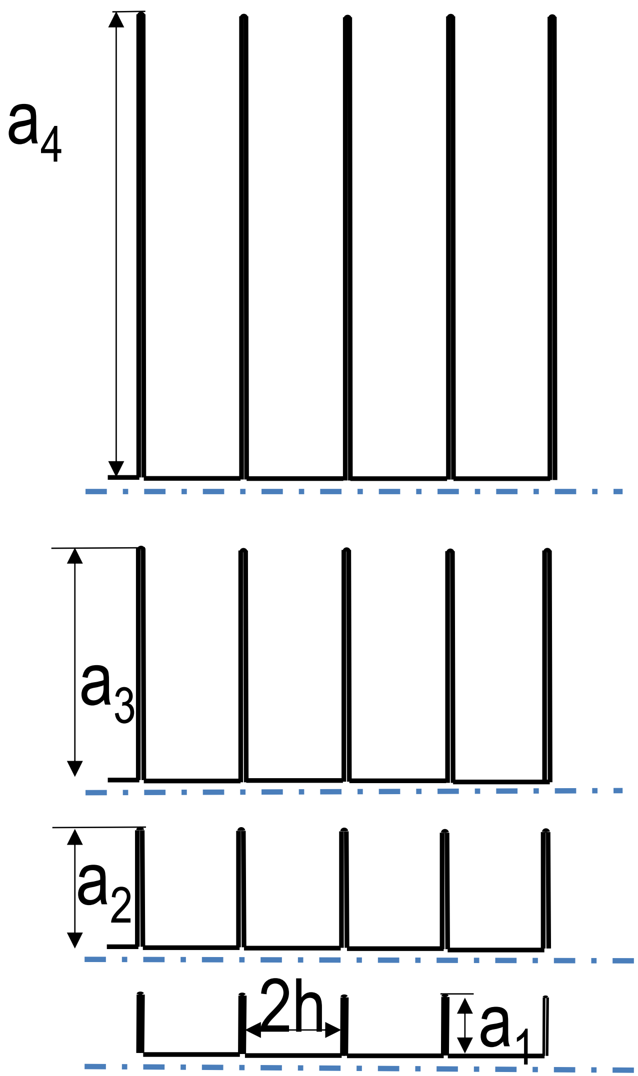
$\sigma_x = \sigma_h$ = minimum horiz. stress

Circular Crack Localization

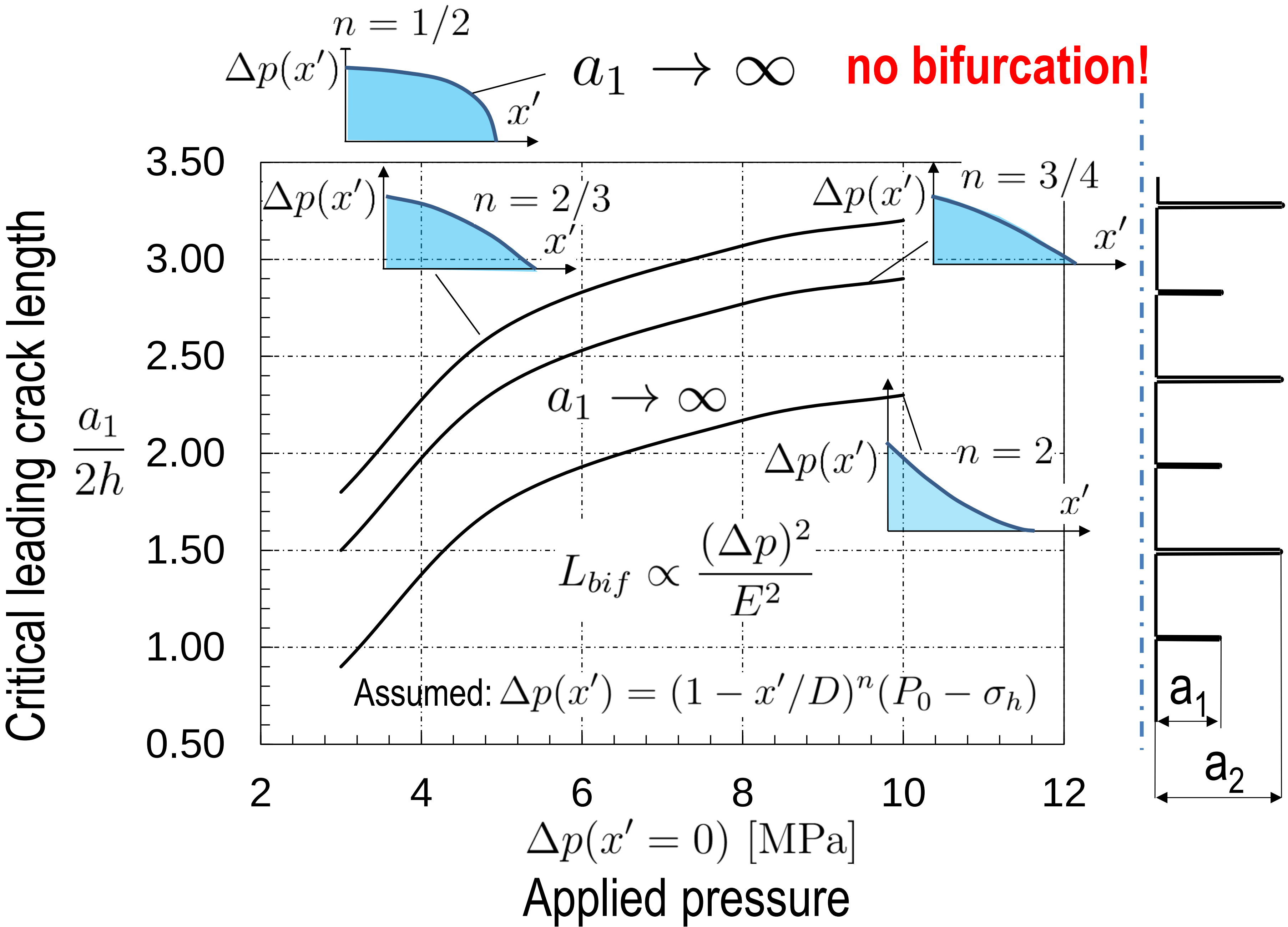
a) To avoid



b) Needed

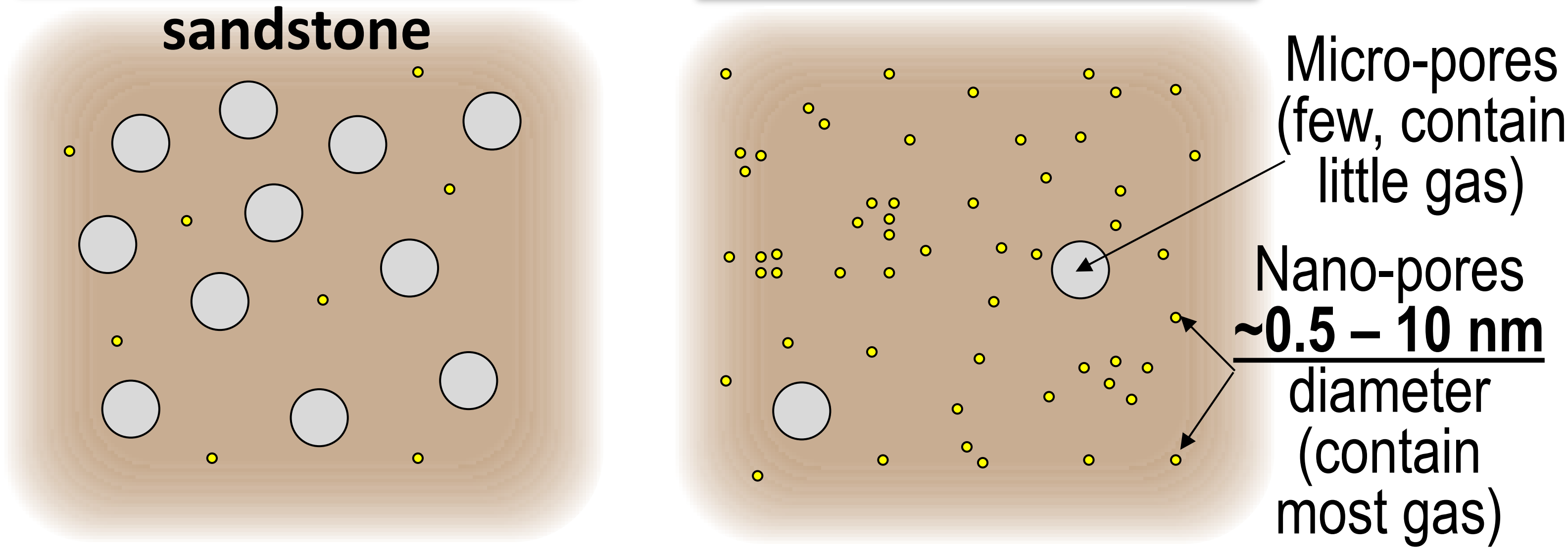


Effect of Front Steepness of Pressure Profile



Shale permeability is extremely low

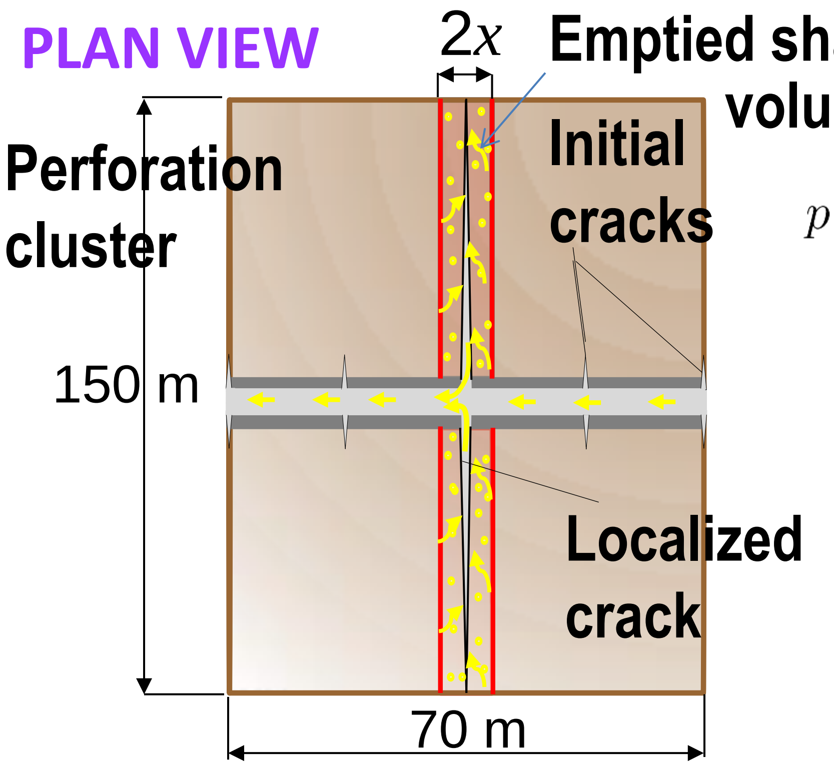
Conventional gas | **Shale gas**



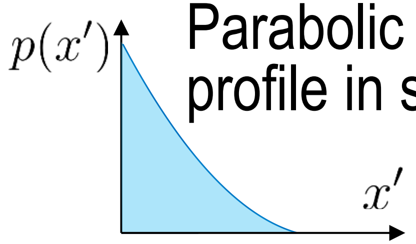
PERMEABILITY, *b*, in mD (miliDarcy)

Sandstones:	1—100	(conventional gas)
Tight gas:	0.001—0.1	
Concrete:	0.0001 —0.001	
Shale:	0.000001—0.00001	

How to explain known gas extraction percentage?



Known gas extraction: 15% of total



Parabolic gas pressure profile in shale layer

$x =$ penetration depth

$k =$ permeabilty

$\mu =$ dynamic viscosity

Darcy's law:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{k}{\mu}\frac{\mathrm{d}p}{\mathrm{d}x} \qquad x = \sqrt{\frac{2k}{\mu}pt}$$

dynamic viscosity, μ	Permeabilty, k	t	penetration depth, x	Extracted fraction
0.0135 cp (natural gas)	10^{-9} darcy	30 days	**0.03 m**	0.04%
	10^{-6} darcy	30 days	**0.98 m**	1.01%

So, crack system does not localize. Why?

Danger in Using Proppant

Congregation of proppant in the opened crack creates a steep pressure gradient.

If that happens at the crack tip, an event called in industry the “screen out”, hydraulic fracturing “locks up” and pressure rises dramatically, leading to shut-down.

To avoid it, water without propant is injected initially.

Why Fracking Works?

- The known 15% extraction percentage of gas content of shale implies formation of <u>nonlocalized</u> crack system.

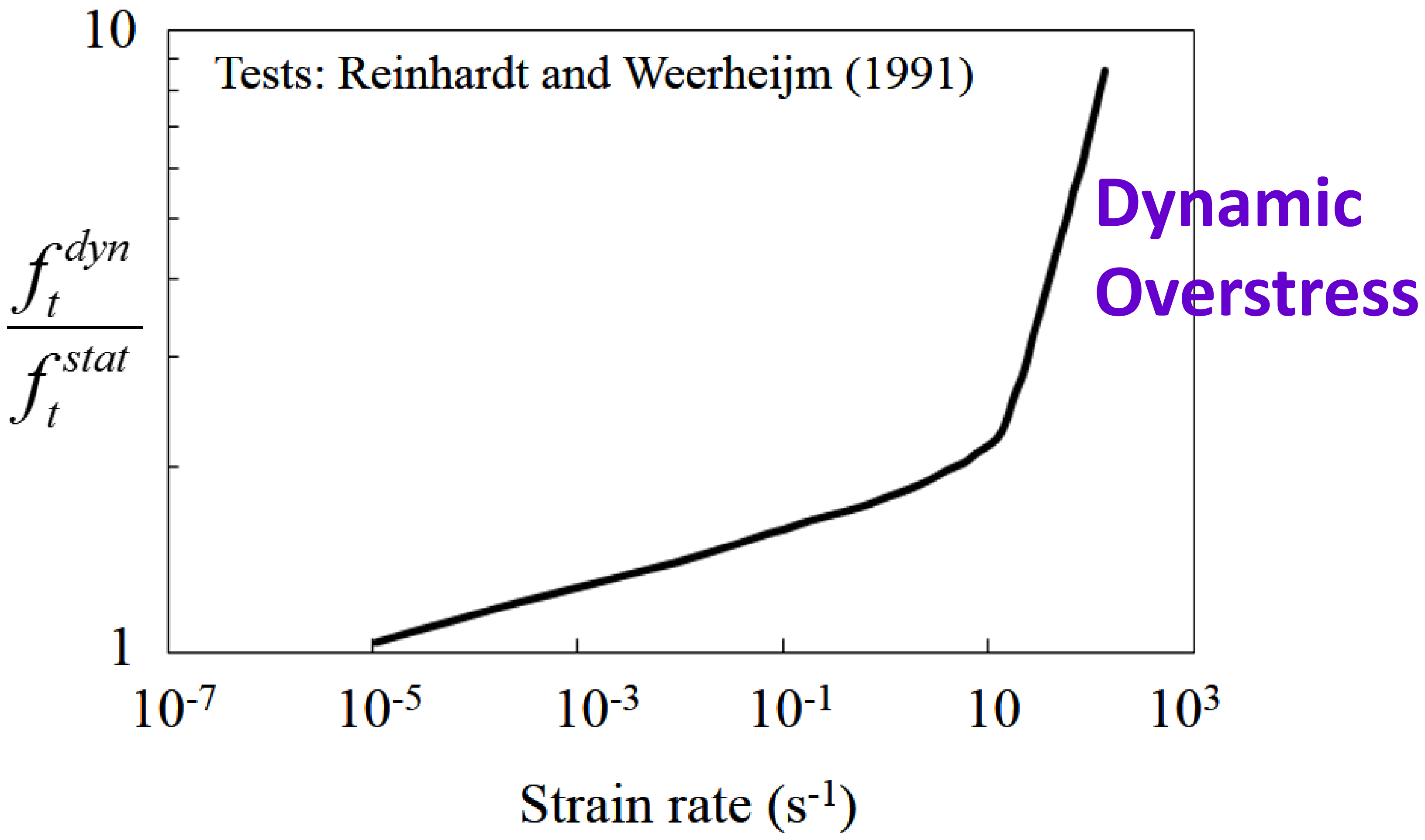
- **Preventing localization is crucial.** Two ways to achieve it:

1) <u>Steep front of water pressure profile</u> along the cracks, which can be achieved or promoted by appropriate pumping rate and history (e.g., multi-stage fracking);
2) Cracking localization instability requires some cracks to close. It can't happen if the closing is blocked by <u>proppant</u>.

Intriguing Possibility:

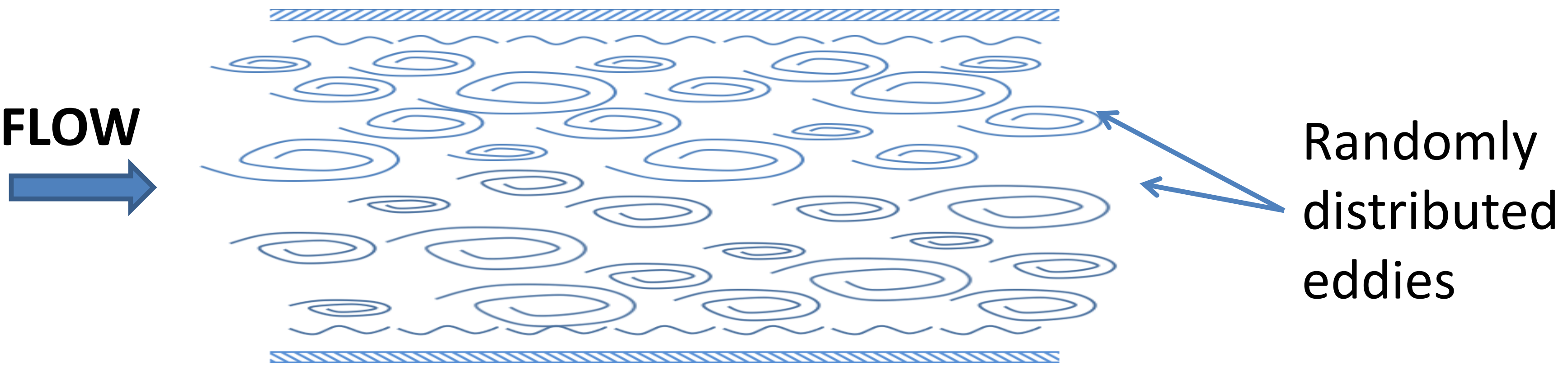
Shale Comminution by Shock Waves

Strength vs. Strain Rate Data

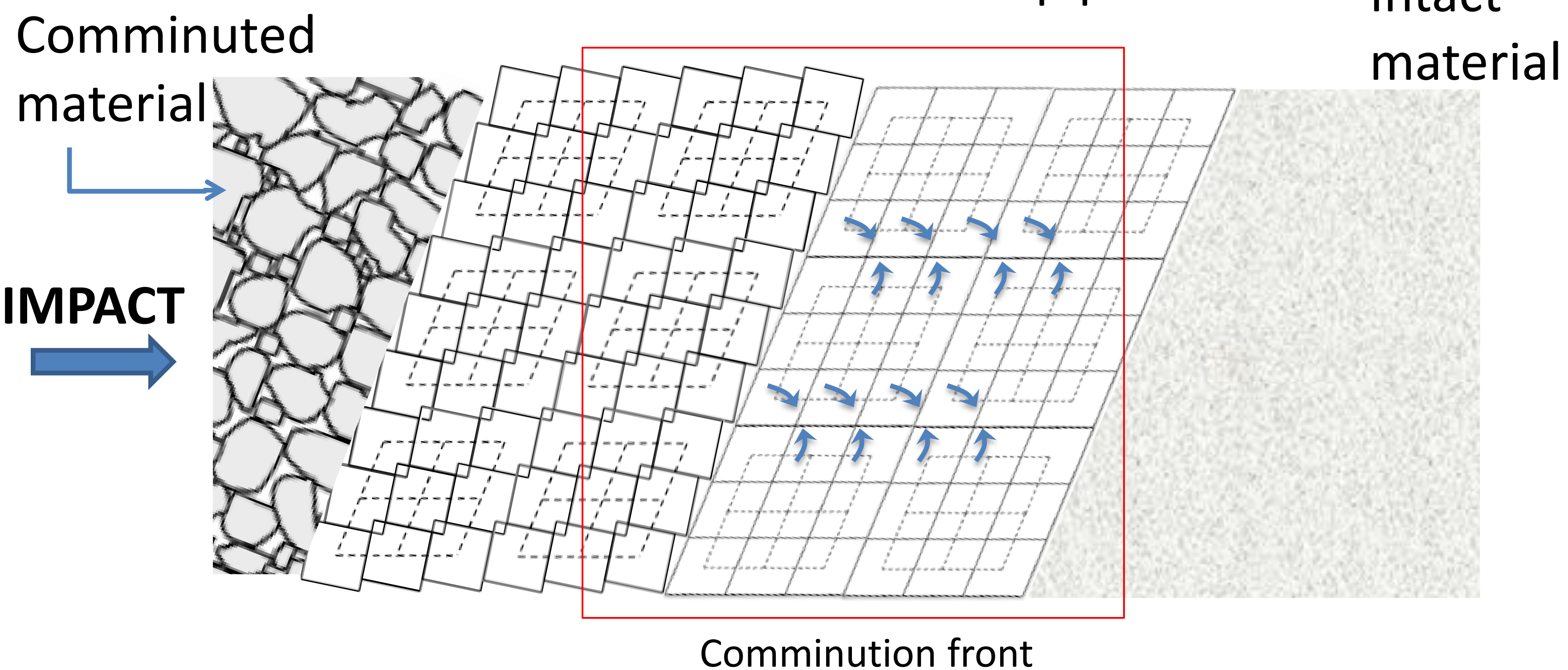


If compression dominates, quasistatic rate effects don't suffice

INSPIRATION: Analogy with Turbulence



Turbulent flow in a pipe

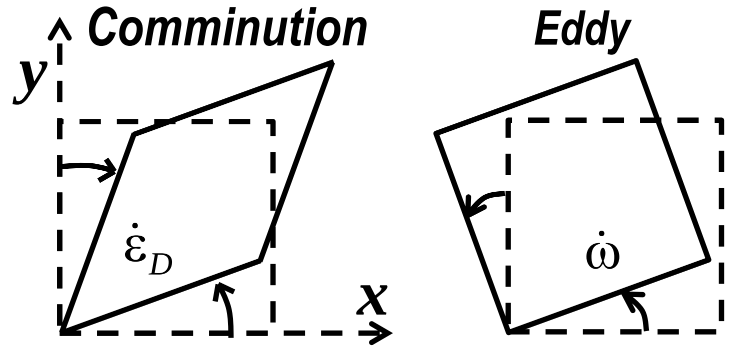


INSPIRATION: Analogy with Turbulence

In *both* comminution and turbulence:

- Maximization of overall dissipation by a micro-level energy dissipation mechanism — comminution or eddies.
- Micro-level kinetic energy of separating particles, or eddies, augments the kinetic energy of the macro-level straining or flow.
- Both increase macro-continuum viscosity.

$$\Delta\dot{u} = \dot{\epsilon}_D y, \quad \Delta\dot{v} = \dot{\epsilon}_D x$$
$$\Delta\dot{u} = -\dot{\omega} y, \quad \Delta\dot{v} = \dot{\omega} x$$

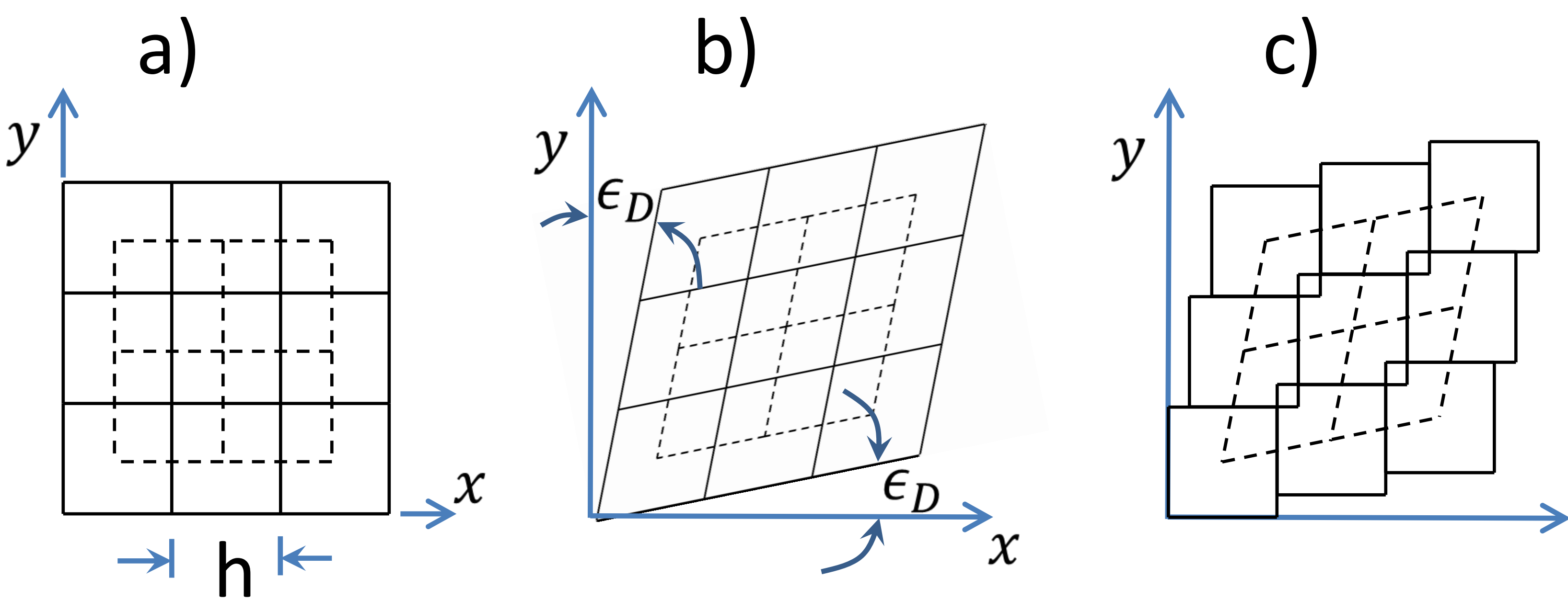


$$\mathcal{K}_{shear} = \int_A \frac{\rho}{2}|\boldsymbol{v}|^2 \mathrm{d}A = \int_A \frac{\rho}{2}[(\dot{\epsilon}_D y)^2 + (\dot{\epsilon}_D x)^2]\mathrm{d}A$$
$$\mathcal{K}_{eddy} = \int_A \frac{\rho}{2}|\boldsymbol{v}|^2 \mathrm{d}A = \int_A \frac{\rho}{2}[(\dot{\omega} y)^2 + (\dot{\omega} x)^2]\mathrm{d}A$$

When $\dot{\omega} = \dot{\epsilon}_D, \ \mathcal{K}_{shear} = \mathcal{K}_{eddy}$ even though the velocity vectors at corresponding points have different directions.

Comminution into Prismatic Square Particles

(velocities shown as infinitesimal displacements)



Corner overlaps are second-order small, thus ***negligible.***

KINETIC ENERGY RELEASE

Velocities: ***Before*** comminution:

$$\dot{u} = \dot{u}_0 - \dot{\omega} y + \dot{\epsilon}_D y, \quad \dot{v} = \dot{v}_0 + \dot{\omega} x + \dot{\epsilon}_D x$$

After: $\dot{u}^+ = \dot{u}_0 - \dot{\omega} y, \quad \dot{v}^+ = \dot{v}_0 + \dot{\omega} x$

Global kinetic energy density: $\bar{K} = \sum_i h^3 \frac{\rho}{2} (\dot{u}_0^2 + \dot{v}_0^2)_i$

Drop of kinetic energy of each cell:

$$-V_p \Delta \mathcal{K} = h \int_A \frac{\rho}{2} \left(\dot{u}^2 + \dot{v}^2 - (\dot{u}^+)^2 - (\dot{v}^+)^2 \right) \mathrm{d}A$$
$$= -c_k \rho h^2 \dot{\epsilon}_D^2$$

Note: Global $\dot{\omega}$ has no effect on $\mathcal{K}$!

Balance of Rates of Kinetic Energy and Surface Free Energy:

Total energy: $$\mathcal{F} = \Delta\mathcal{K} + S\Gamma$$

Critical state of comminution: $\mathcal{F} = 0$ or $-\Delta\mathcal{K} = S\Gamma$

(Alternative $\mathcal{F} = \min$ or $\frac{\partial\mathcal{F}}{\partial S} = 0$ or $\frac{\partial\Delta\mathcal{K}/\partial h}{\mathrm{d}S/\mathrm{d}h} = \Gamma$ is rejected)

This gives the **minimum particle size**: $$h = \left(\frac{C_a\Gamma}{\rho\dot{\epsilon}_D^2}\right)^{1/3}$$

Result:

$$-\Delta\mathcal{K} = (C_0\Gamma^2\rho)^{1/3}\ \dot{\epsilon}_D^{2/3}$$

Consider Strain Energy Density Release $\mathcal{U}$?

Shouldn't it be added, like in LEFM, i.e. $\mathcal{F} = \mathcal{U} + \Delta\mathcal{K} + S\Gamma$?

NO.

For strain rate 10^4/s: $\dfrac{\partial \mathcal{U} / \partial S}{\partial \Delta\mathcal{K} / \partial S} \approx 0.008$ **...insignificant**!

Hence, classical fracture mechanics does not apply.

Dimensionless number separating fracture driven by kinetic and strain energies

$$-\frac{\Delta \mathcal{K}}{\mathcal{U}} = B_a$$

$$B_a = \frac{G}{C_g \tau_0^2} \left(\Gamma^2 \rho \dot{\epsilon}_D^2 \right)^{1/3}$$

Comminution is:

kinetic energy driven if $B_a \gg 1$

in transition if $B_a \approx 1$

static or absent if $B_a \ll 1$

In FEM: Dissipate Local Kinetic Energy by Viscosity

Alt. I Consider $\Delta\mathcal{K}$ to be simply dissipated by **additional "viscous" deviatoric stresses:**

$$s^A_{ij} = \eta_D \, \dot{\epsilon}_{Dij}$$

This gives **fictitious deviatoric viscosity** depending on strain rate only:

$$\eta_D = (C_0 \Gamma^2 \rho)^{1/3} \; \dot{\epsilon}_D^{-1/3}$$

$$\sqrt{s^A_{ij} s^A_{ij}/2} \; \propto \; -\Delta\mathcal{K}$$ energy dissipation density

Potential Benefit of Shock Wave Comminution of Shale

- *Decrease the outflow of contaminated water – diminish environmental problems*

- *Increase the yield beyond the 15% of gas content of shale*

Main Points

- What makes fracking work?—Mitigation of crack localization instability.
- How to improve fracking? – Minimize crack localization (computer simulation should help).
- Achieve steep pressure profile front.
- Manipulate pressure profile front by proppant congestion and pumping history.
- Potentially: Shale comminution by shock waves.

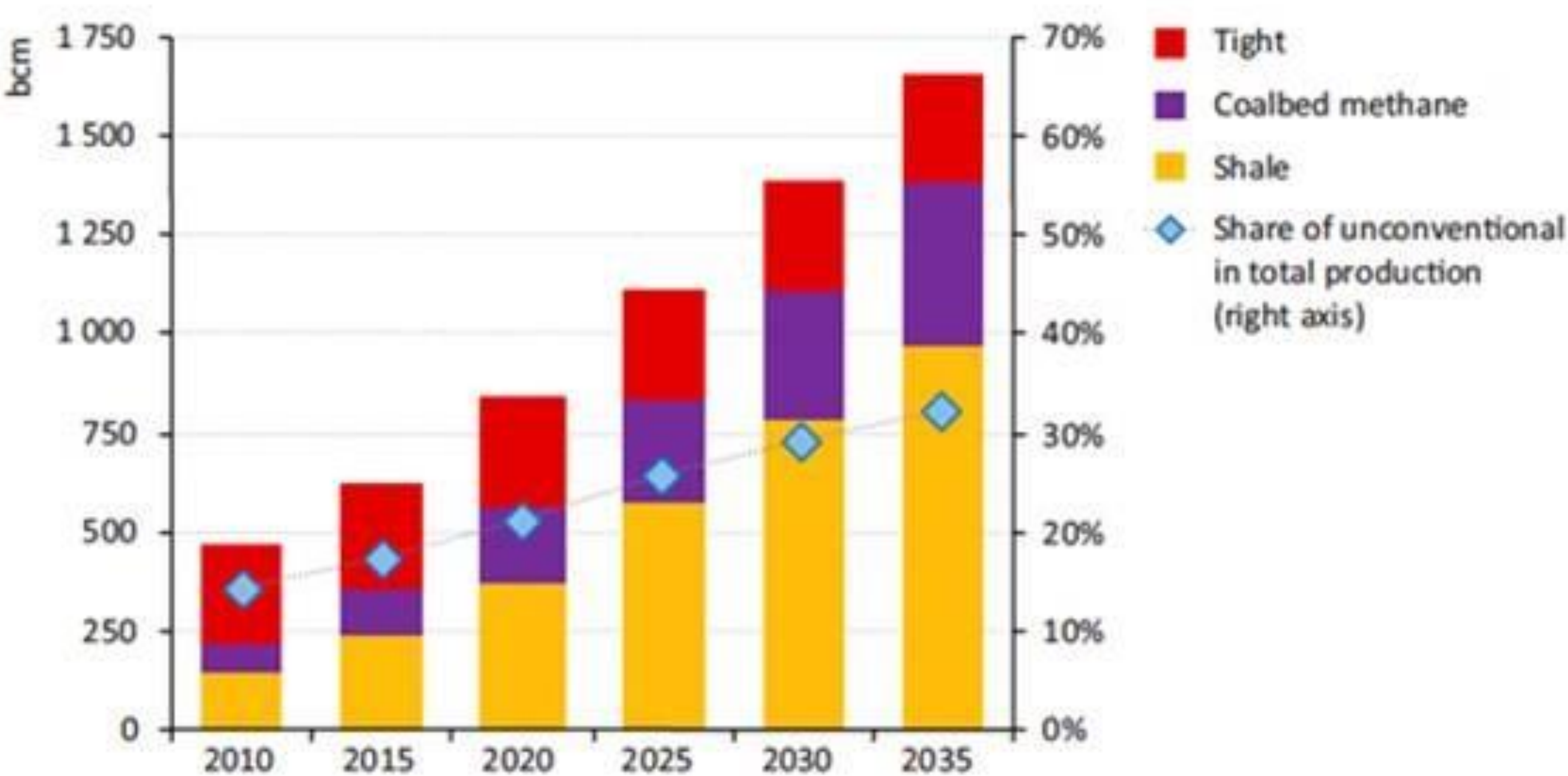
Thanks for Listening

Extras

I need at least one slide on shock-waves spreading from the borehole, from Su

Shales: *What's the Big Deal?*

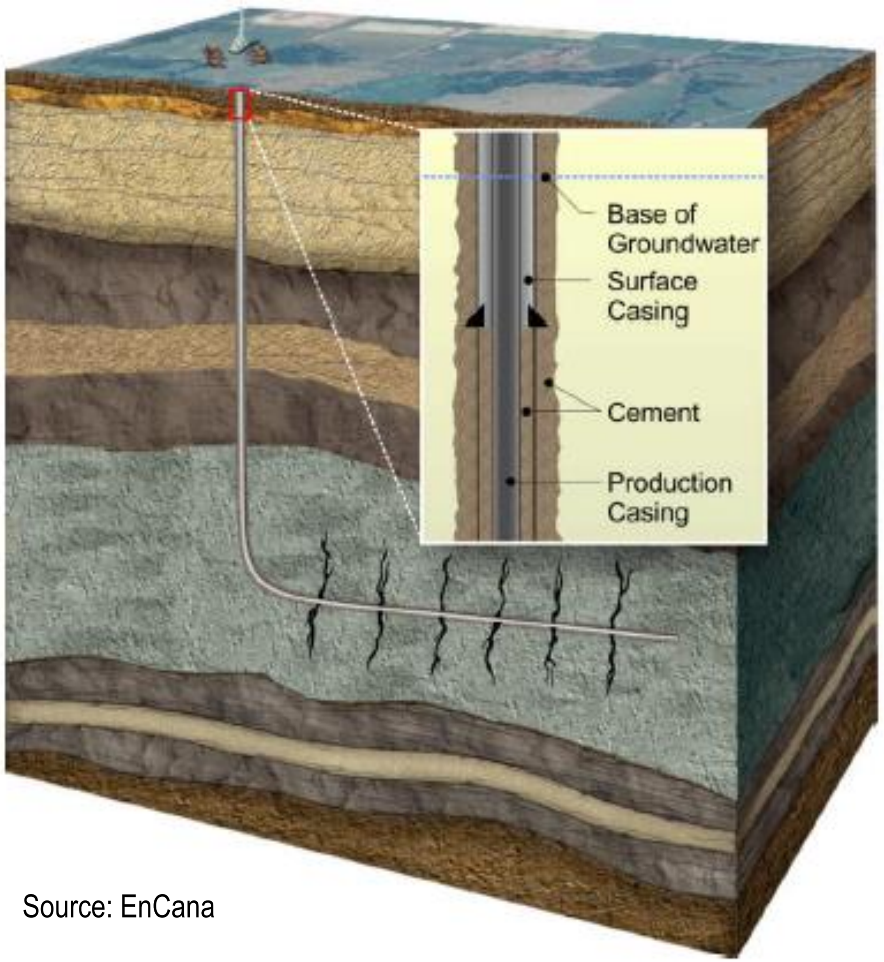
International Energy Agency Projections



Source: Source: International Energy Agency, *Golden Rules for a Golden Age of Gas: World Energy Outlook, Special Report on Unconventional Gas*, OECD/IEA, May 29, 2012

What Changed the Game?

Horizontal Well with Multi-Stage Fracturing



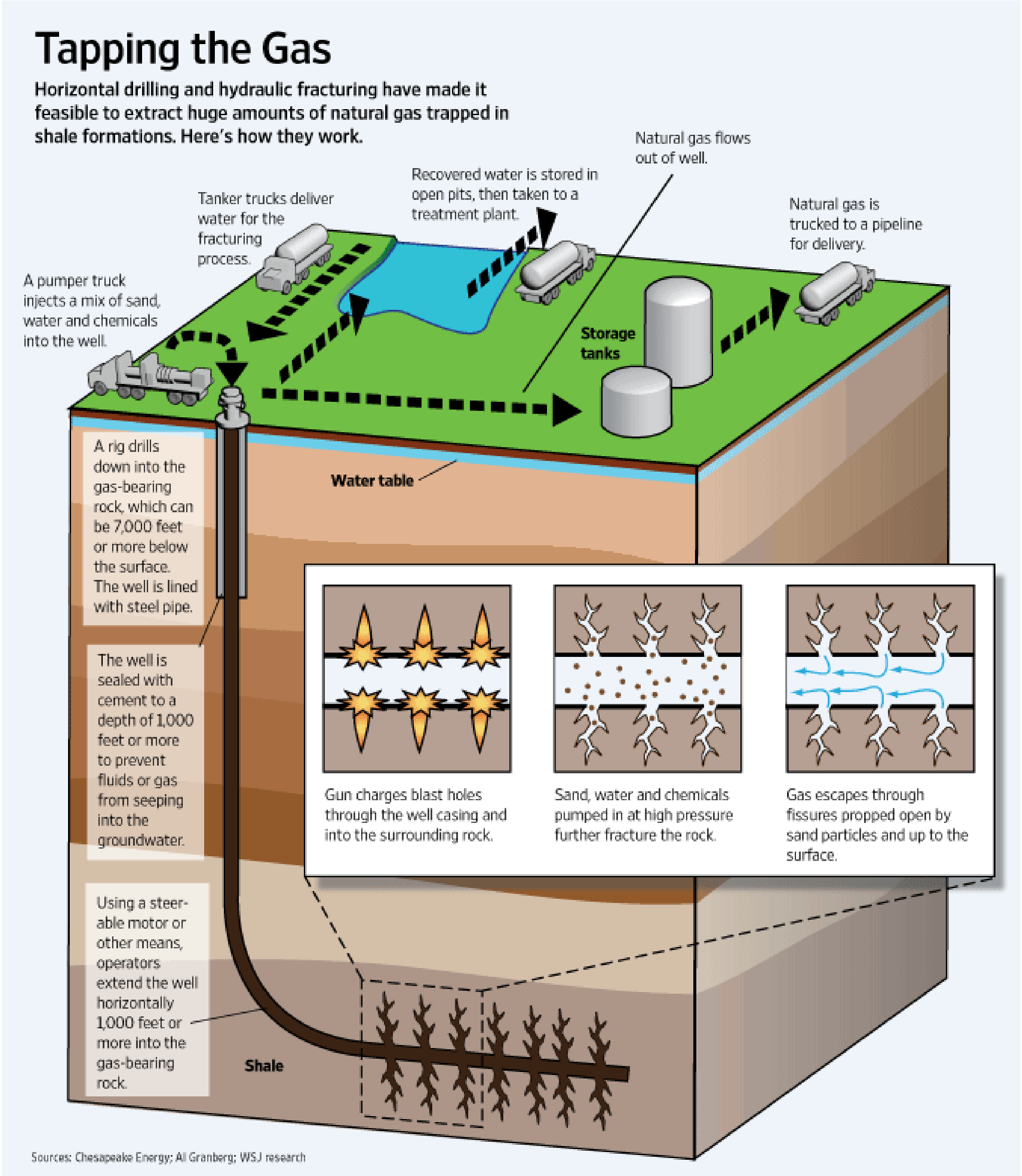
Source: EnCana

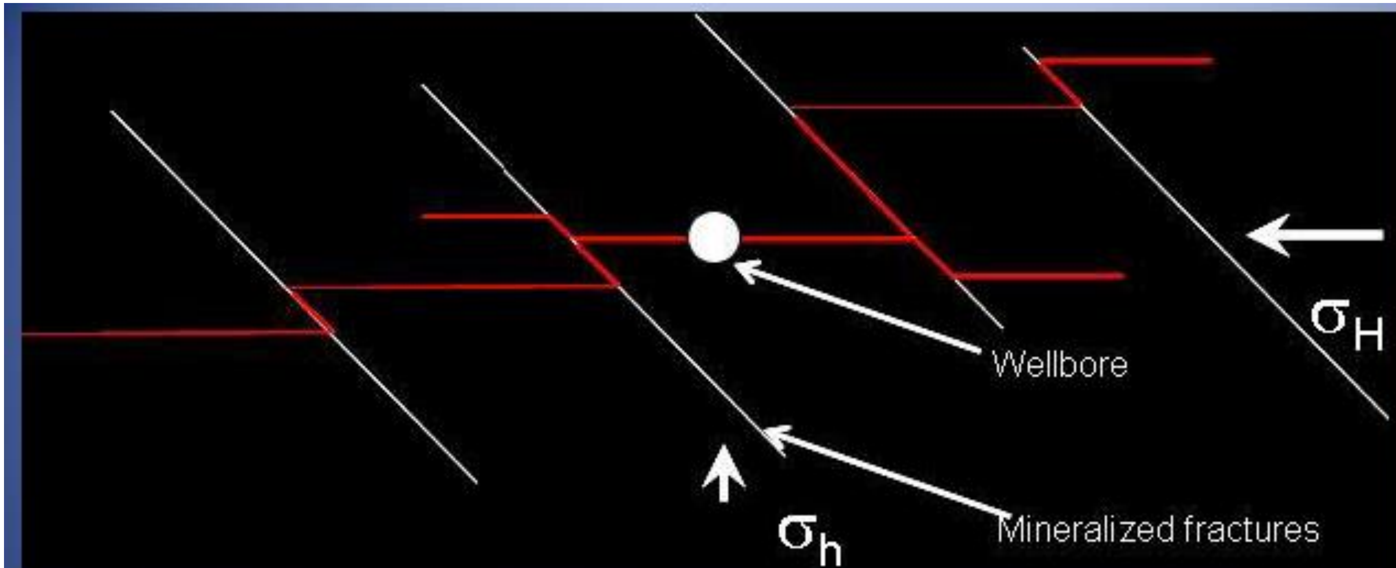
- Natural gas production from <u>shallow, fractured shale formations</u> not new
  - First shale well drilled in Fredonia, NY in 1821
  - First fractured well in 1947
  - 2.5 million fractures to date worldwide; > 1 million in U.S.
- What "changed the game" was the recognition that one could "create a permeable reservoir" and high rates of gas production by using intensively stimulated horizontal wells

BAD PROPORTIONS !

Distance between shale formation and ground water typically > 1 mile

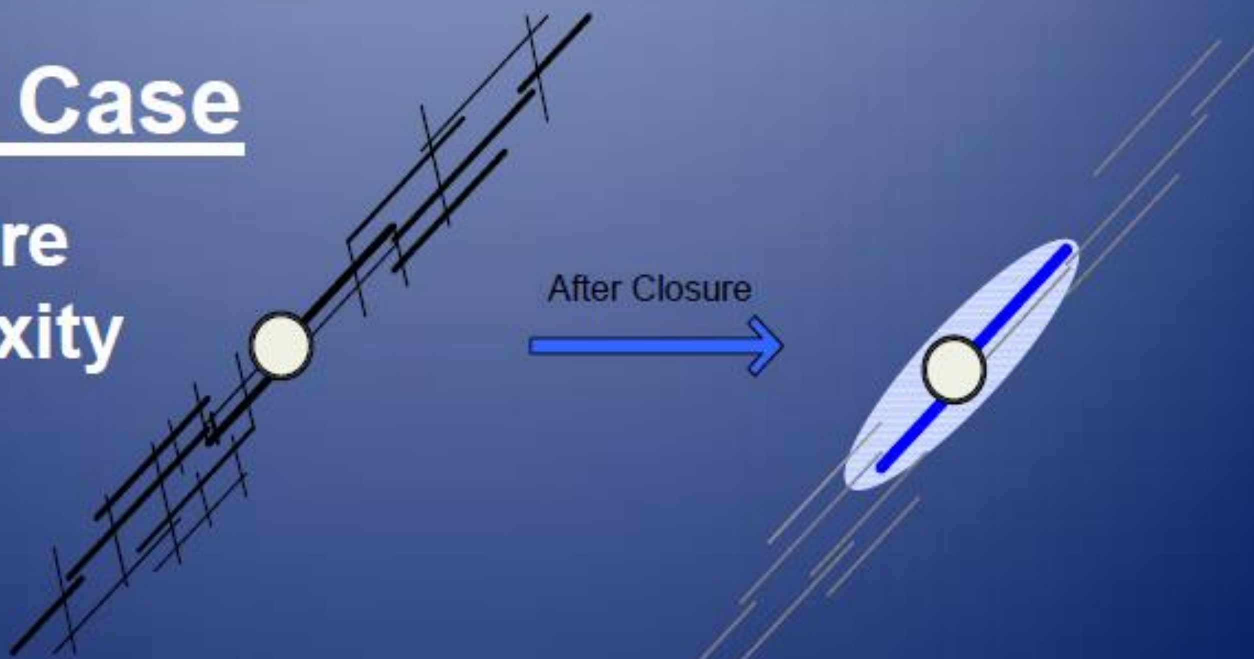
Vertical fractures rarely grow more than about 300 feet, and are usually much less





The Real Case

Fracture Complexity



Innovation Center

Auxiliary Steps for Hydraulic Fracturing

- Bring materials, mostly fresh water, onto the drilling pad . This is done via a **pipeline or tanker trucks.**
- Hold the water is held in **lined ponds or steel containers** for later fracking

Lined Fresh Water Supply Pit, Marcellus Shale Development in PA
Source: ALL Consulting, 2008

Source: AXPC

The Drilling Process: Hydraulic Fracturing

- While equipment and fluids for hydraulic fracturing are brought onsite, the well is drilled and pressure tests of pumping equipment are conducted.

- After tests are complete, an acid treatment is done in order to clean the well bore of drilling mud and dissolve certain rocks (like limestone)
  - – an acid treatment involves pumping concentrated hydrochloric acid into the well

- After acid treatment, a “slickwater pad,” of friction-reducing agents is pumped into the well.
  - – This allows the “proppant” and other fluids to flow more easily into fractures and helps to reduce pressure
  - – Typical friction-reducers are potassium chloride, petroleum distillates, or polyacrylamide

- Other additives are also added to control “fouling” from biological or chemical processes
  - – Biocides/slimicides are used for bacterial/slime growth that can reduce well conductivity
  - – Scale inhibitors, corrosion inhibitors, and oxygen scavengers are used for chemical fouling

Acid truck (below) *Source: Producers Service Corporation*

A fracturing fluid trailer *Source: Donnan.com*

Salviato Conclusions on May 25, 2013

- I am doing an extensive review to find more date on the fracture morphology and the dimensions of the well. Typically, the well is divided in segments. Each segment is divided into fracture stages of about 250 ft each composed of about 5-8 perforation clusters. Each cluster is usually composed of 5-6 perforations/fractures so that vertical cracks have a spacing of about 10 ft. Now, I found that according to microseismic analyses, the height of each crack can be about 250 ft while the width is about 800 ft for each side! (These data seem pretty common for Marcellus shale for example).
- Updating the previous analyses on the penetration depth with these new data, and assuming a permeability between 10^-9 and 10^-6, a 15% of gas recovered can be obtained only if there is no localization (i.e. all the 5 perforations in one perforation cluster develop as vertical cracks). With only one vertical crack only the 4% at maximum could be extracted in one month. About 15% could be extracted only after one year (assuming the highest permeability in the considered range).

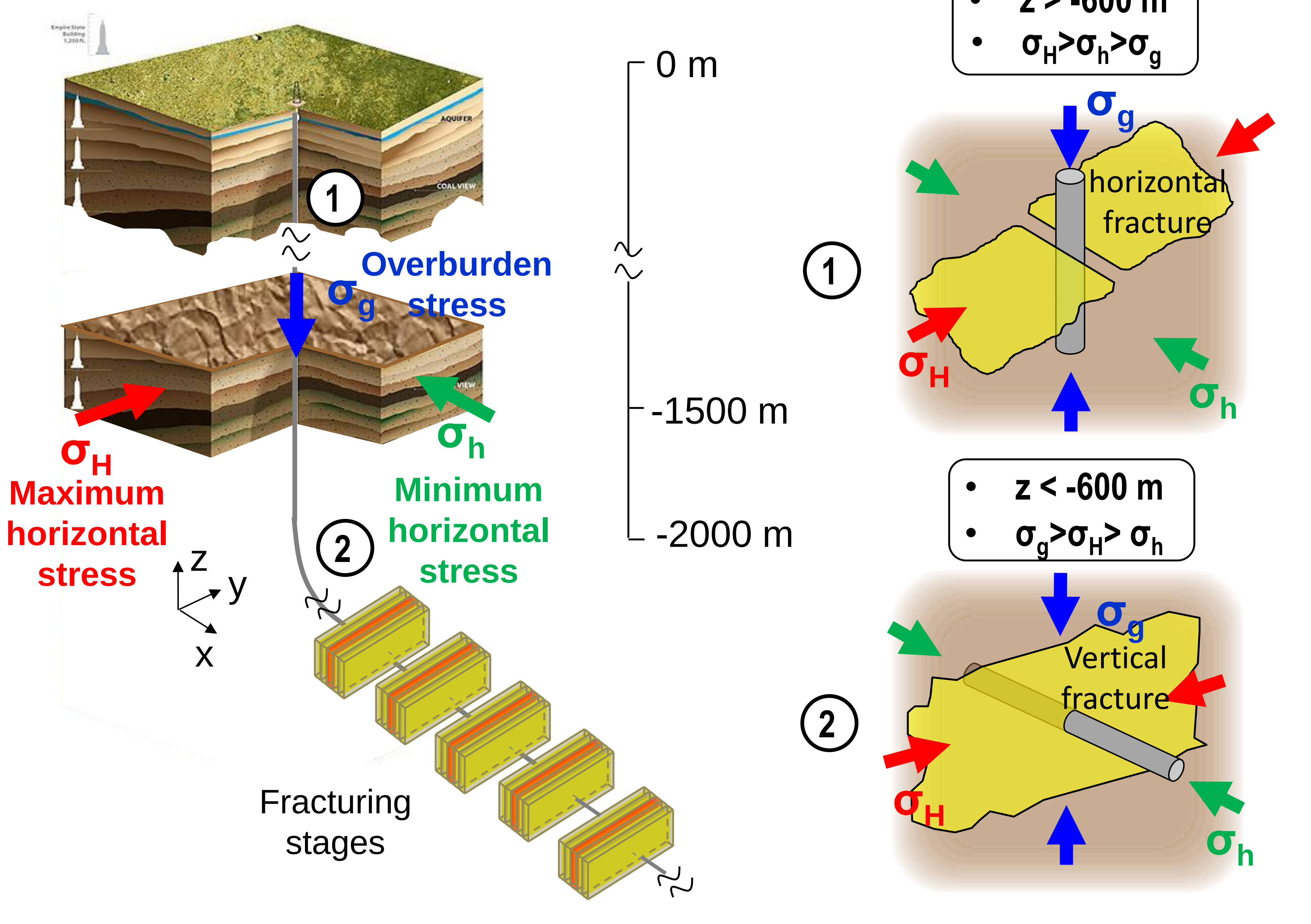
View of Operations on the Surface

A

a

SCHEMATIC OF SURFACE OPERATIONS

Hydraulic Fractures



Crack spacing < 1 cm ??? **is needed to allow gas escape**

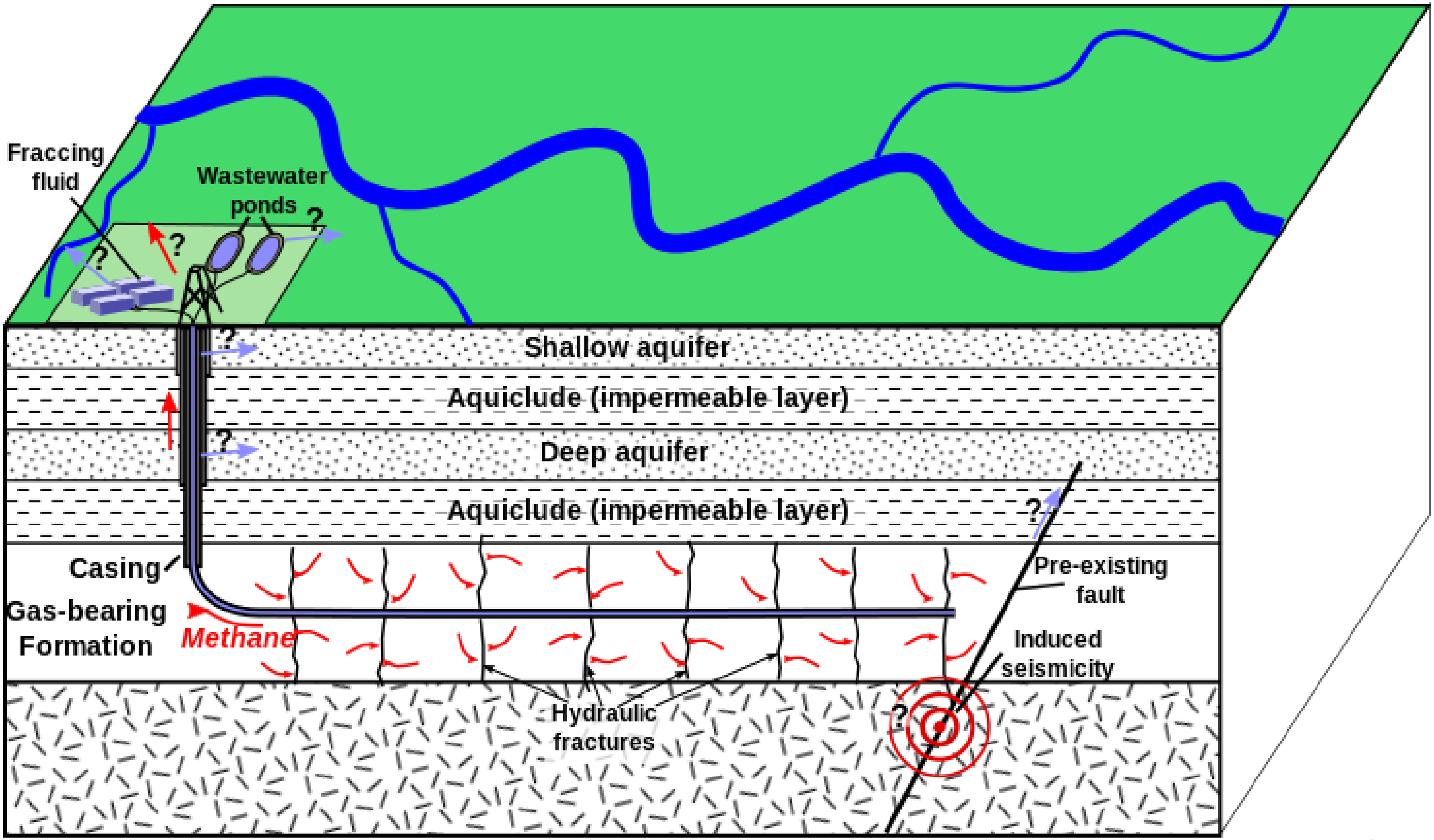
Since about 15% of gas does escape, how is it achieved?

INSERT FIGURES HERE AND/OR NEXT SLIDES
FROM MY 5/14, 5/16, 5/17

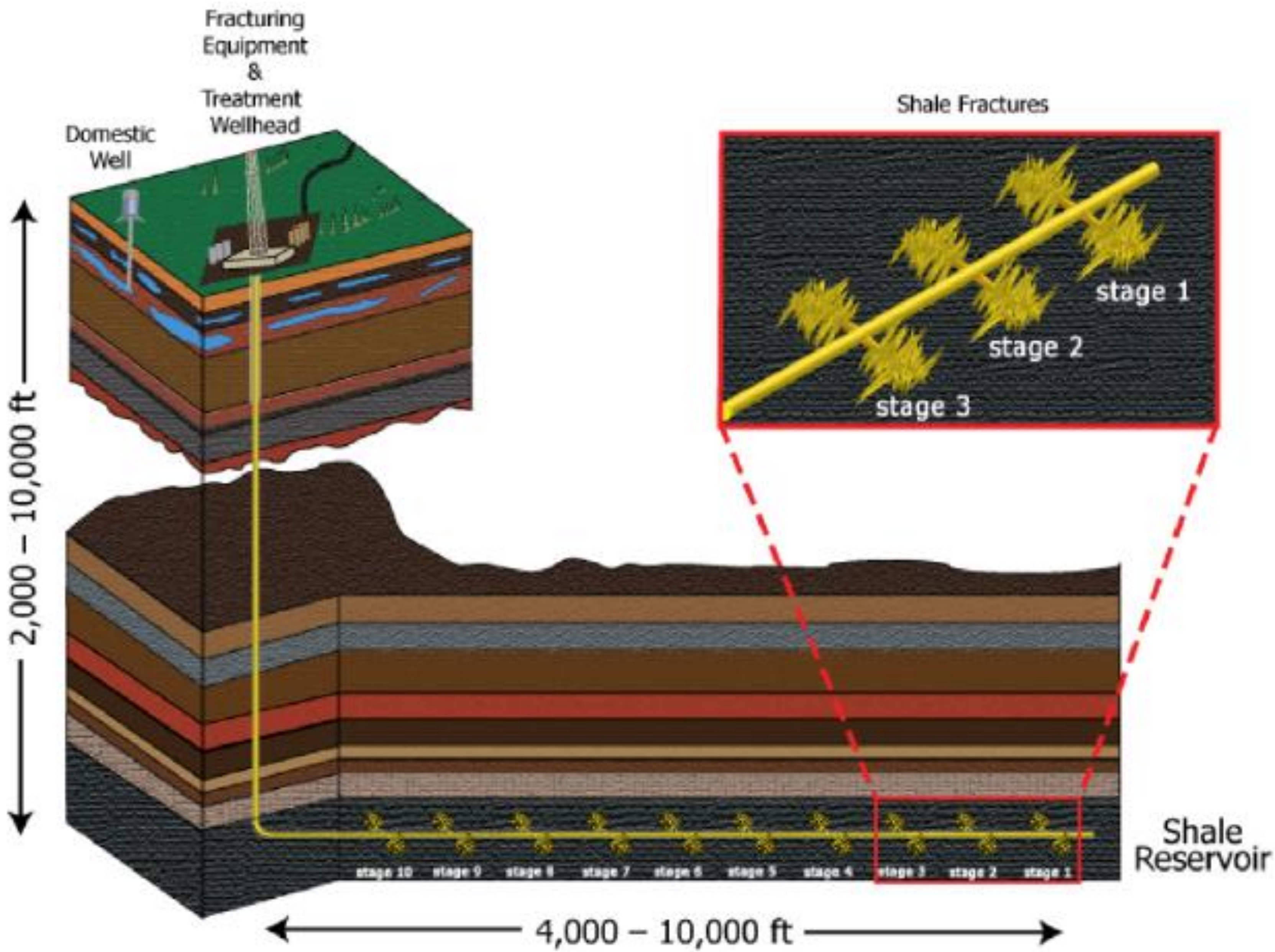
Simple calculation for a 20 m long segment of horizontal borehole, with circular vertical crack(s) of 20 m diameter:

- Alt I. One localized vertical crack only. Penetration depth ~ ?? cm from the crack faces. Indicates that only ?? % of shale volume (within a prism of size 20 m) gets emptied.
- Alt II. Vertical cracks in joints spaced by 0.5 m kept open by proppant. Here ?? % gets emptied.

Schematic of Hydraulic Fracturing ("fracking")



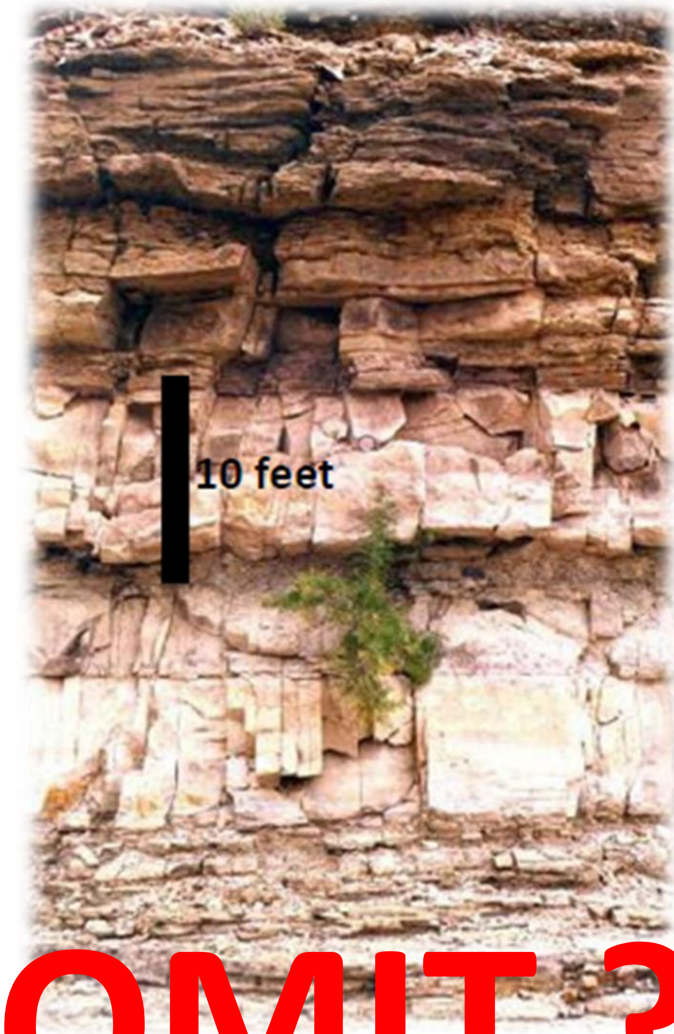
Schematic of Hydraulic Fracturing



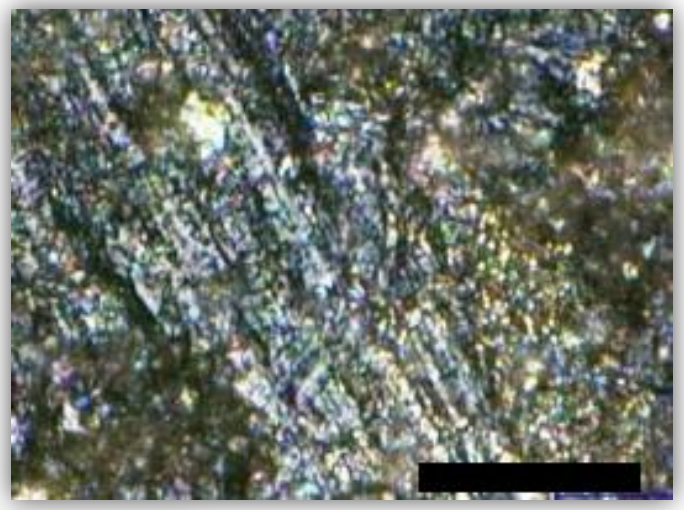
Pending issues for shales

- Anisotropy of the rock
- Multiscale material (cracks at all scales)

Bedding, Faultsc and Nanopores in Clay



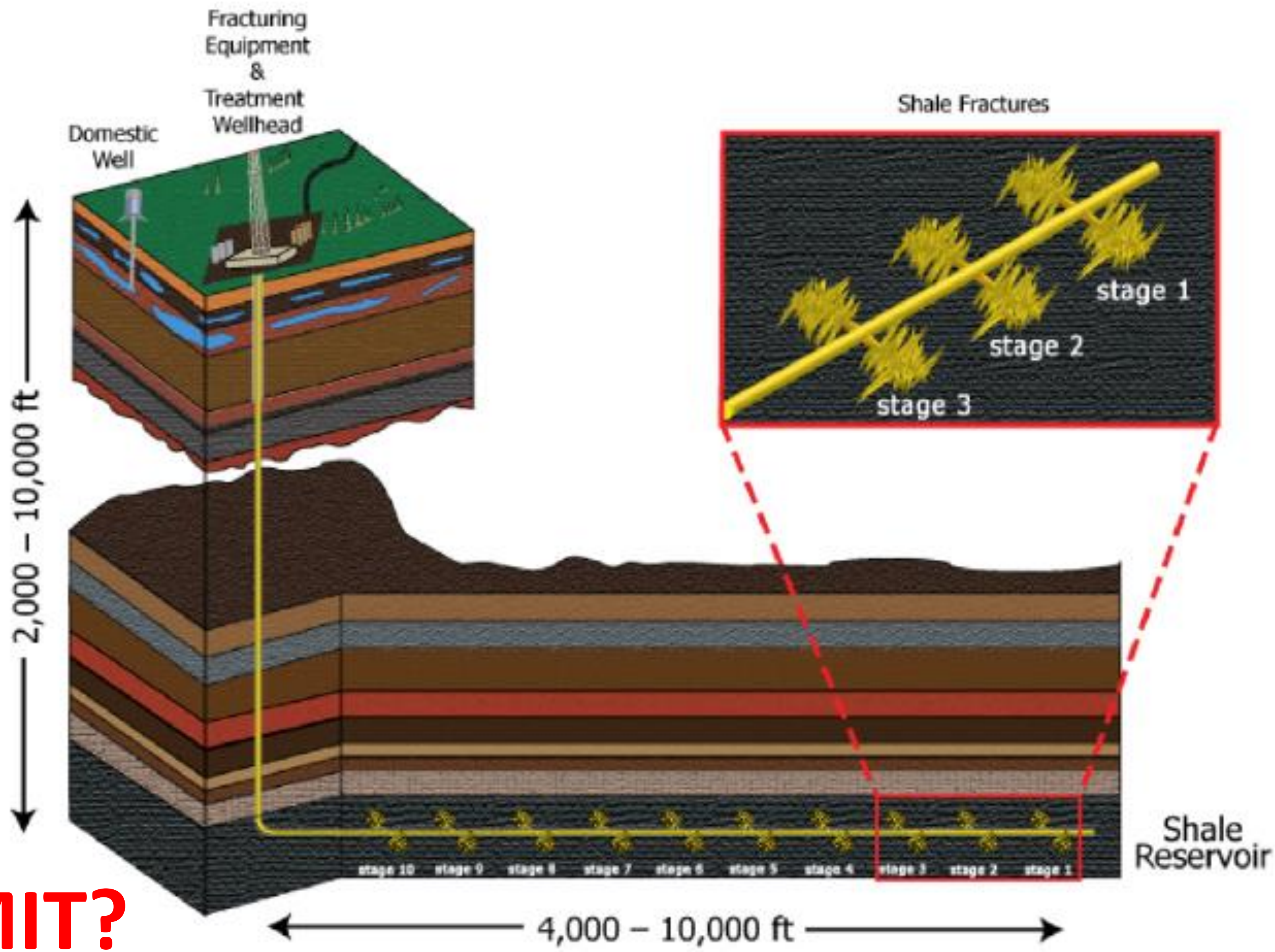
OMIT ?



10 micros

10 inches

Schematic of Hydraulic Fracturing



OMIT?

View of Operations on the Surface

(Marcellus Shale)

Typical Drill Pad and Extraction Site