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WHY FRACKING WORKS AND WHY NOT WELL ENOUGH

ZDENĚK P. BAŽANT

COLLABORATORS: MARCO SALVIATO, YEWANG SU, VIET T. CHAU AND FERHUN C. CANER

SPONSORS: DoE, LANL AND NU-ISEN

UNIVERSITY OF CALIFORNIA SAN DIEGO, CE SEMINAR, FEB. 11, 2015

Motivation

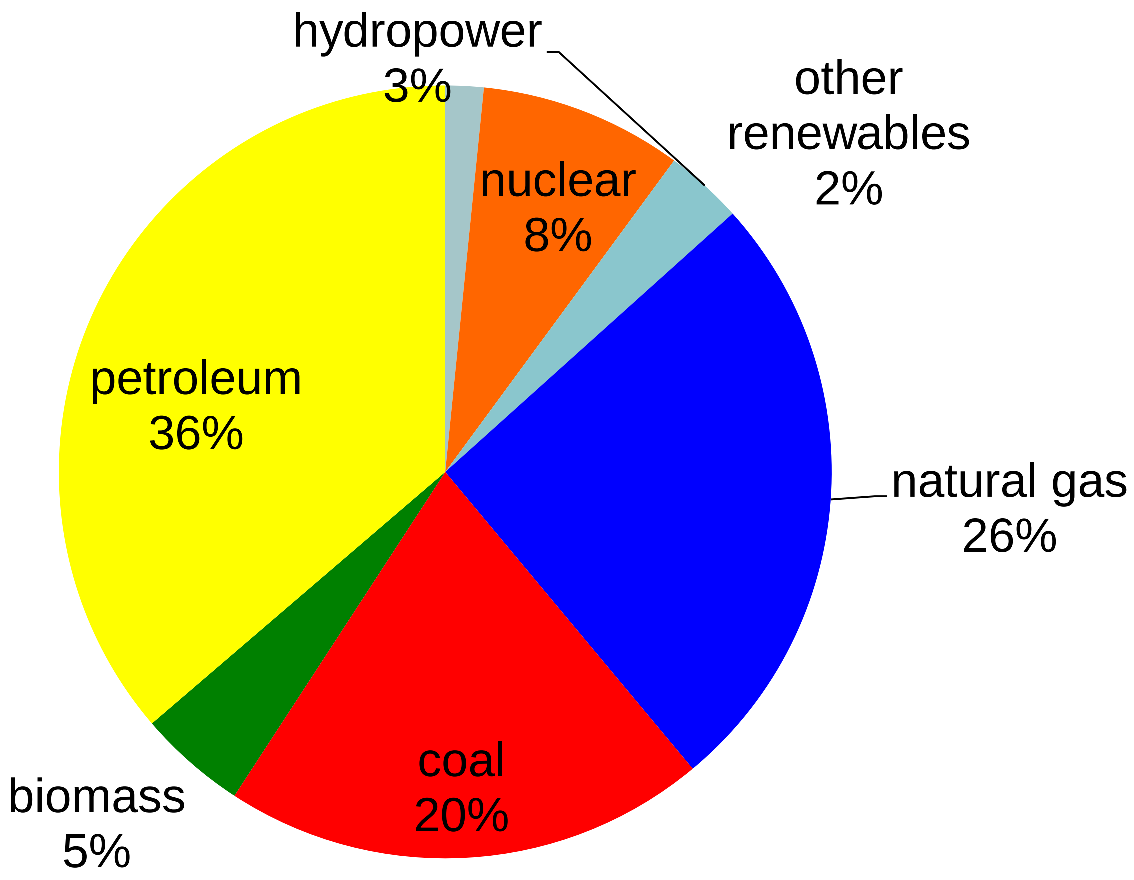
The advances in hydraulic fracturing technology have been astonishing. ***The impact on the national and world economies and geopolitical situation is amazing.***

Although many aspects of the technology are well understood, the ***fracture mechanics is <u>not.</u>***

Progress should increase the gas extraction percentage above current <u>5—15 %</u>. This would also reduce the environmental footprint.

Aperçu of Hydraulic Fracturing Technology (aka "Fracking")

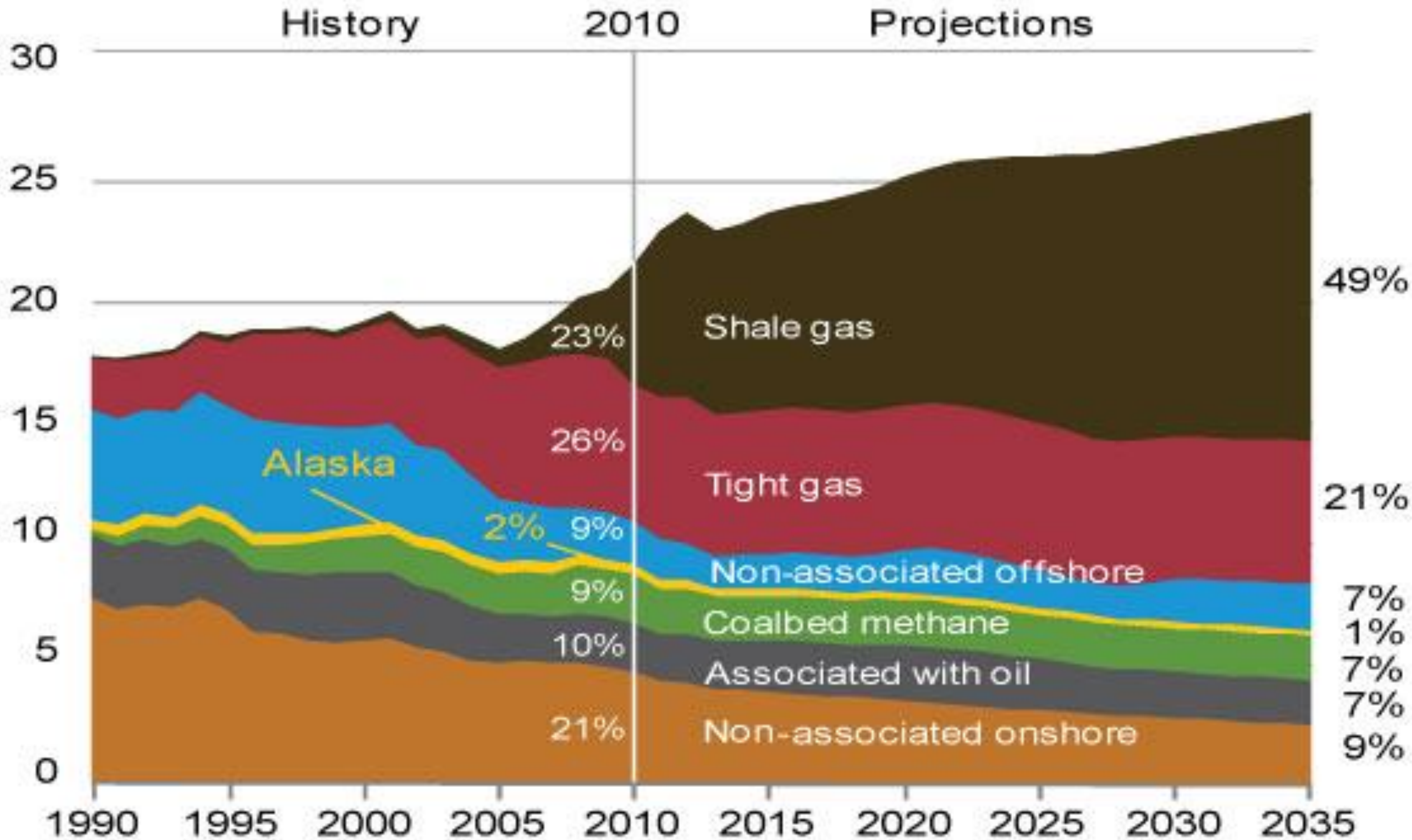
Where do we get our energy?



2012

U.S. Natural Gas Production, 1990-2035

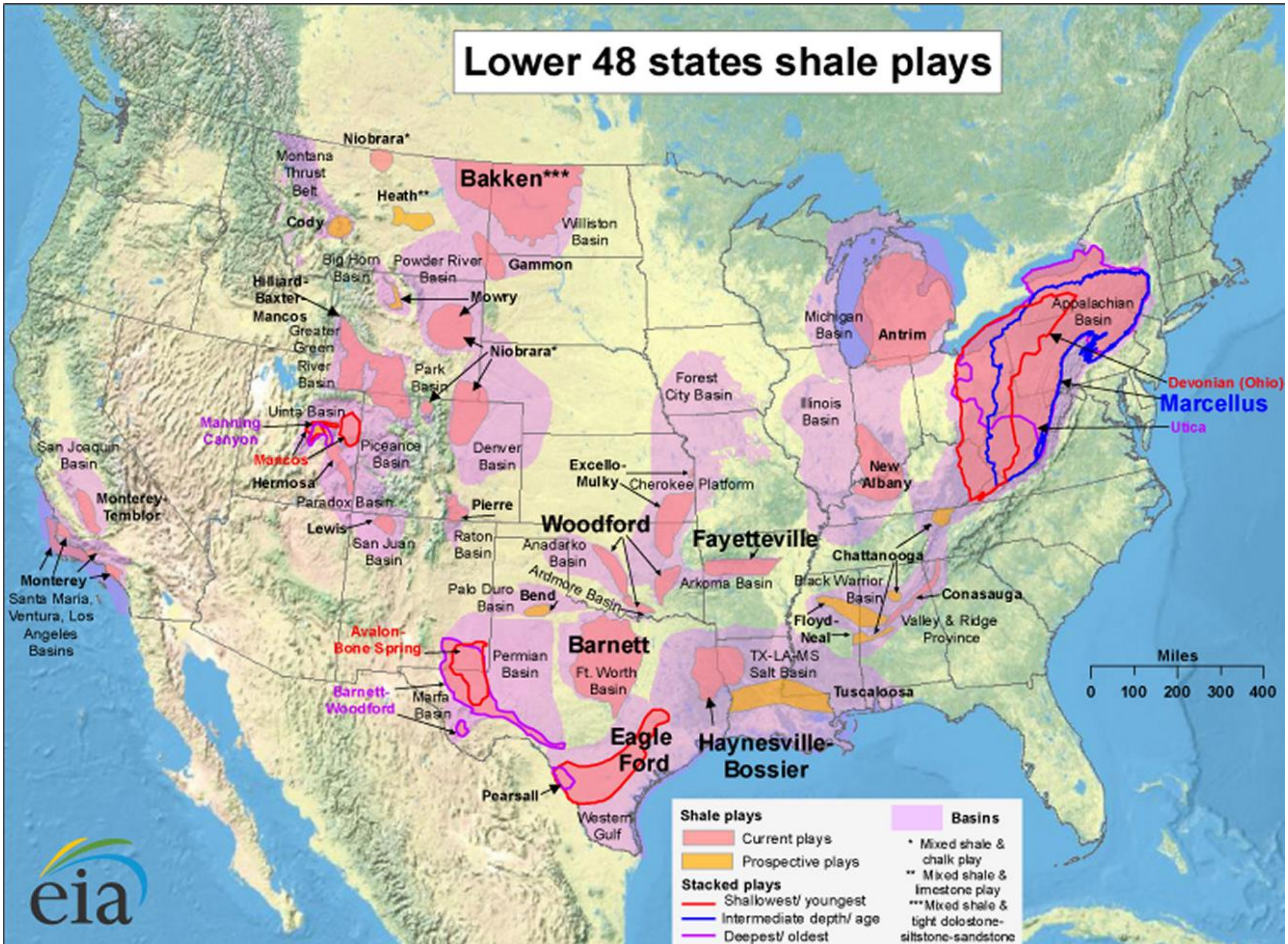
trillion cubic feet



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

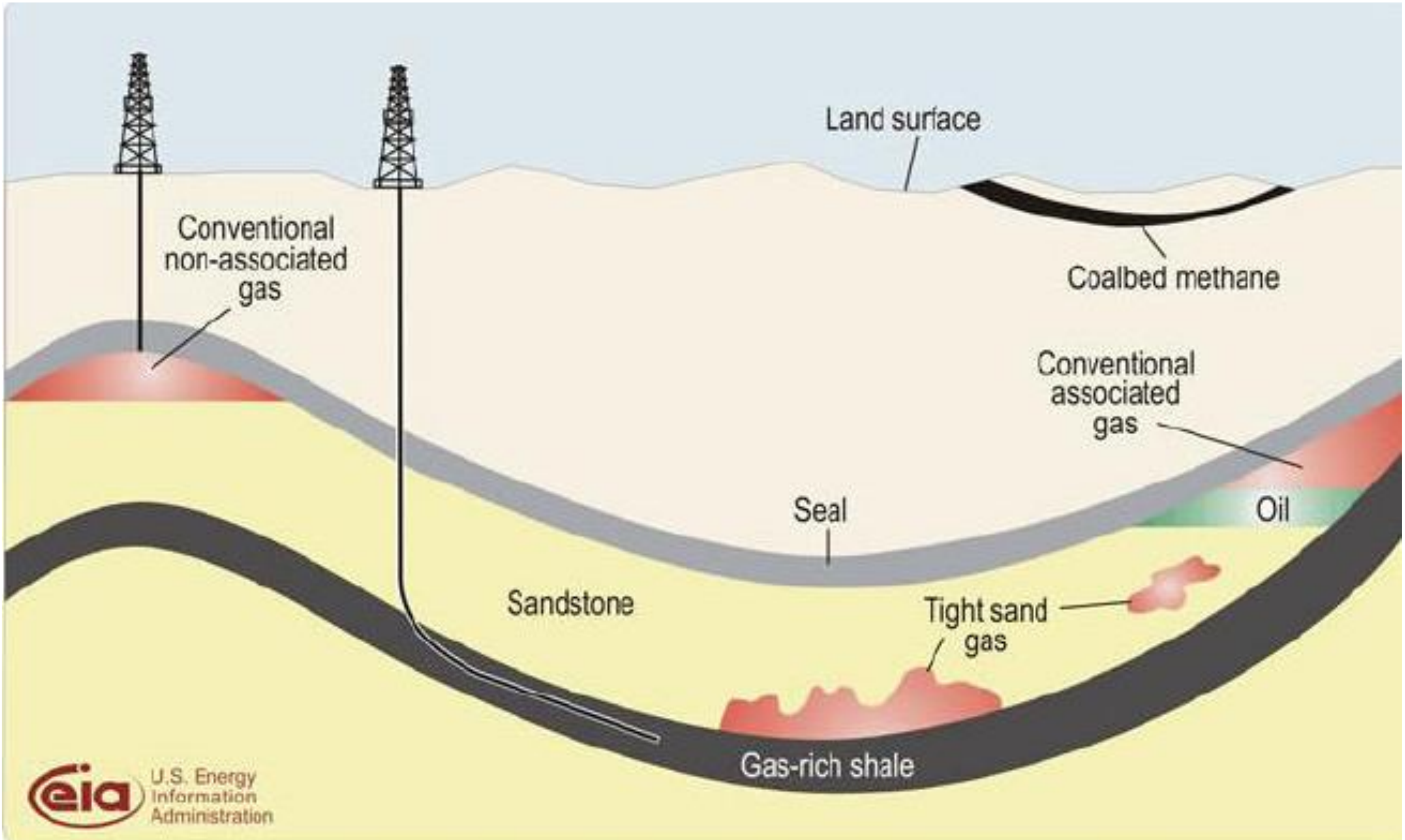


Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Provenance of Natural Gas

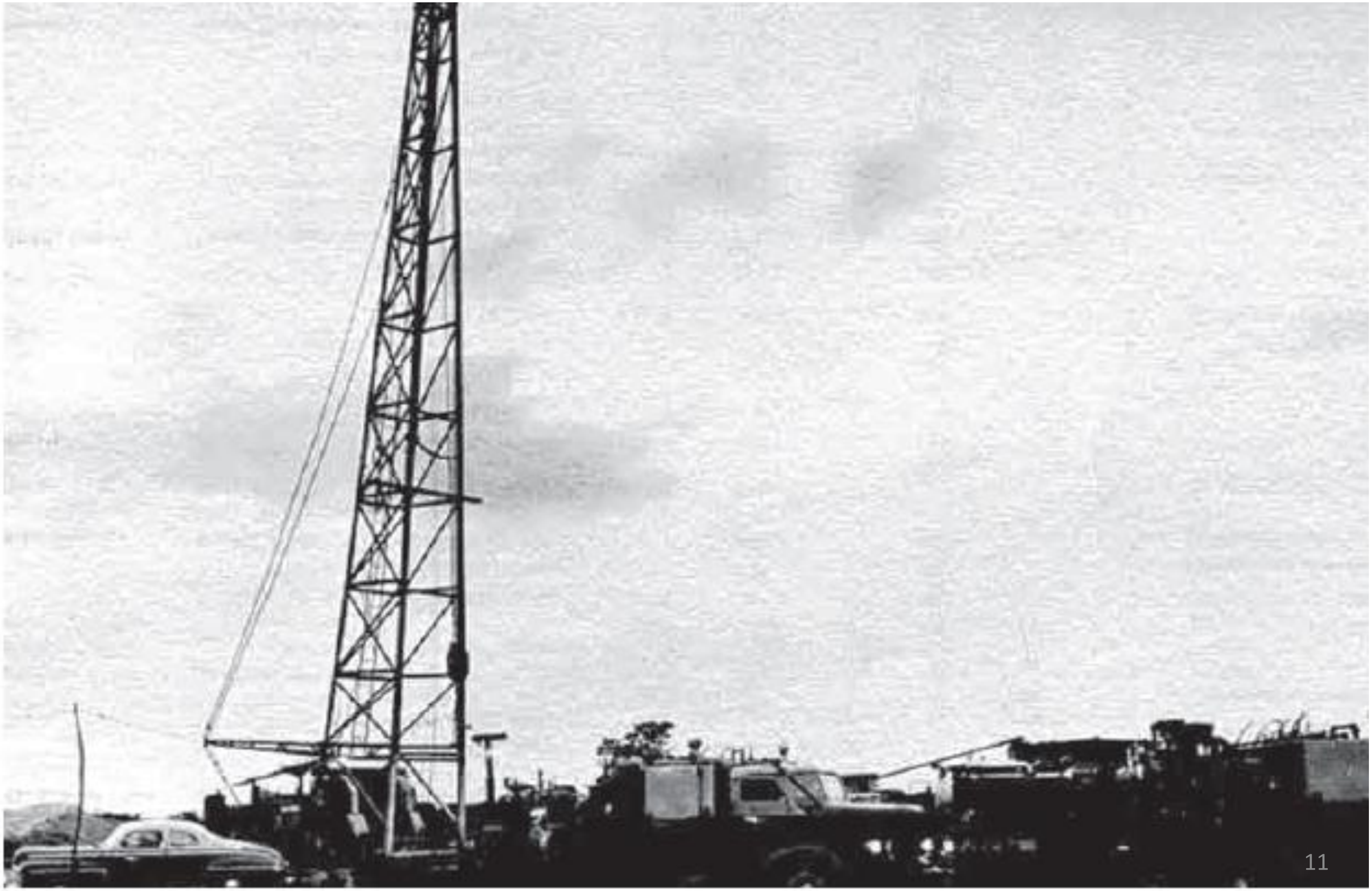
- Formed by organic matter (marine organisms, plants) trapped in sedimentary rocks
- "Conventional" natural gas is trapped in porous rock—sandstone domes
- "Unconventional" natural gas is trapped in micropores of tighter rocks and in **nanopores** of shale

Schematic of Natural Gas Resources



History: 1947, Hugoton, Texas: Hydraulic Fracturing with Sand Proppant

1949: Halliburton conducts fracking in Archer County, Texas

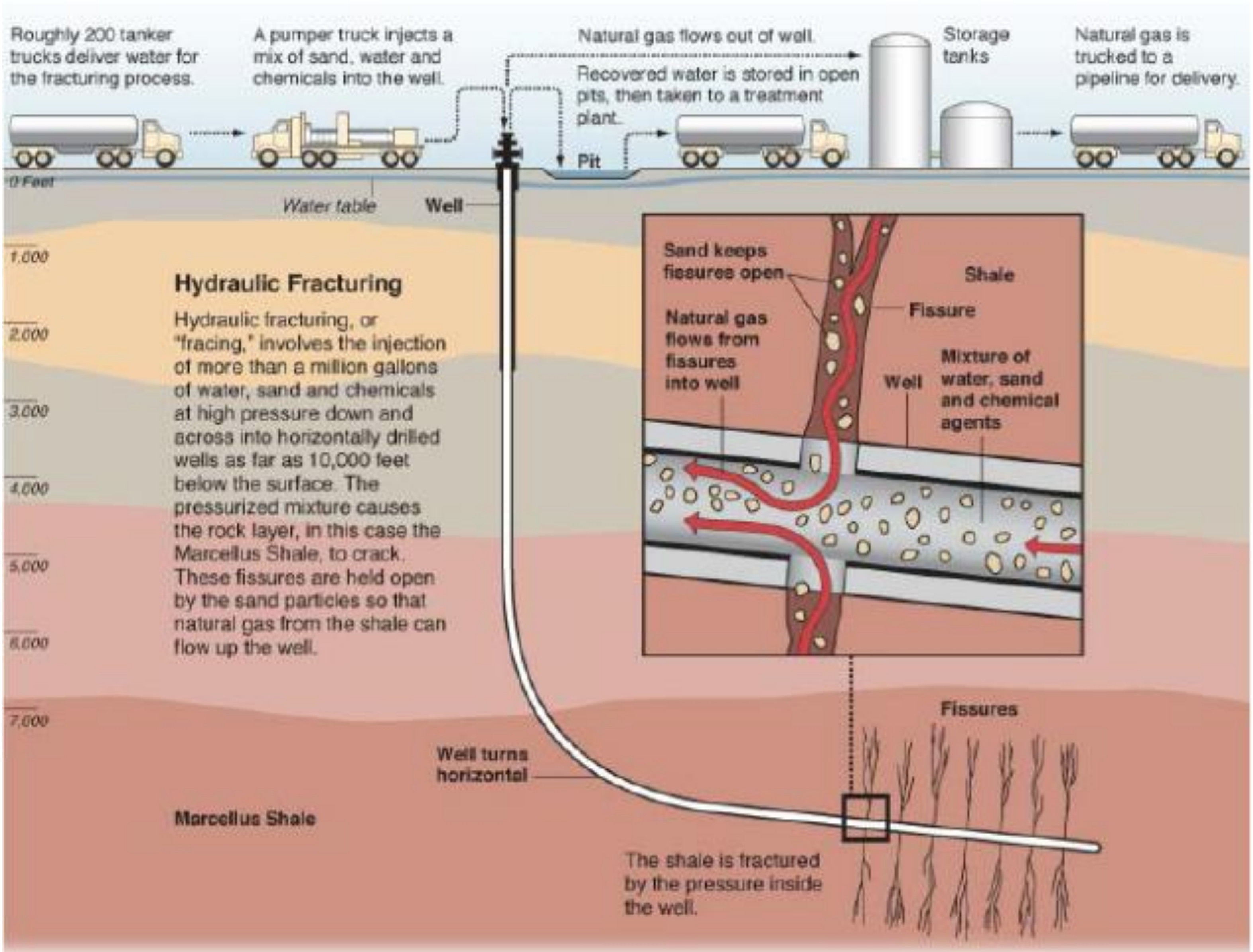


1955 Mass production of truck-mounted fracking pumps of 1475 HP, remotely controlled

Development and Features of Fracking

- Has been developed gradually **since 1947**, without government support (except recently, after success 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, < 1mm dia.). Only about 15% returns to the surface.
  - Extracting the gas, reinjecting contaminated water

Overall Scheme of Gas Extraction



Horizontal hydraulic hydrofracturing. Courtesy www.propublica.org/special/hydraulic-fracturing

Horizontal Drilling

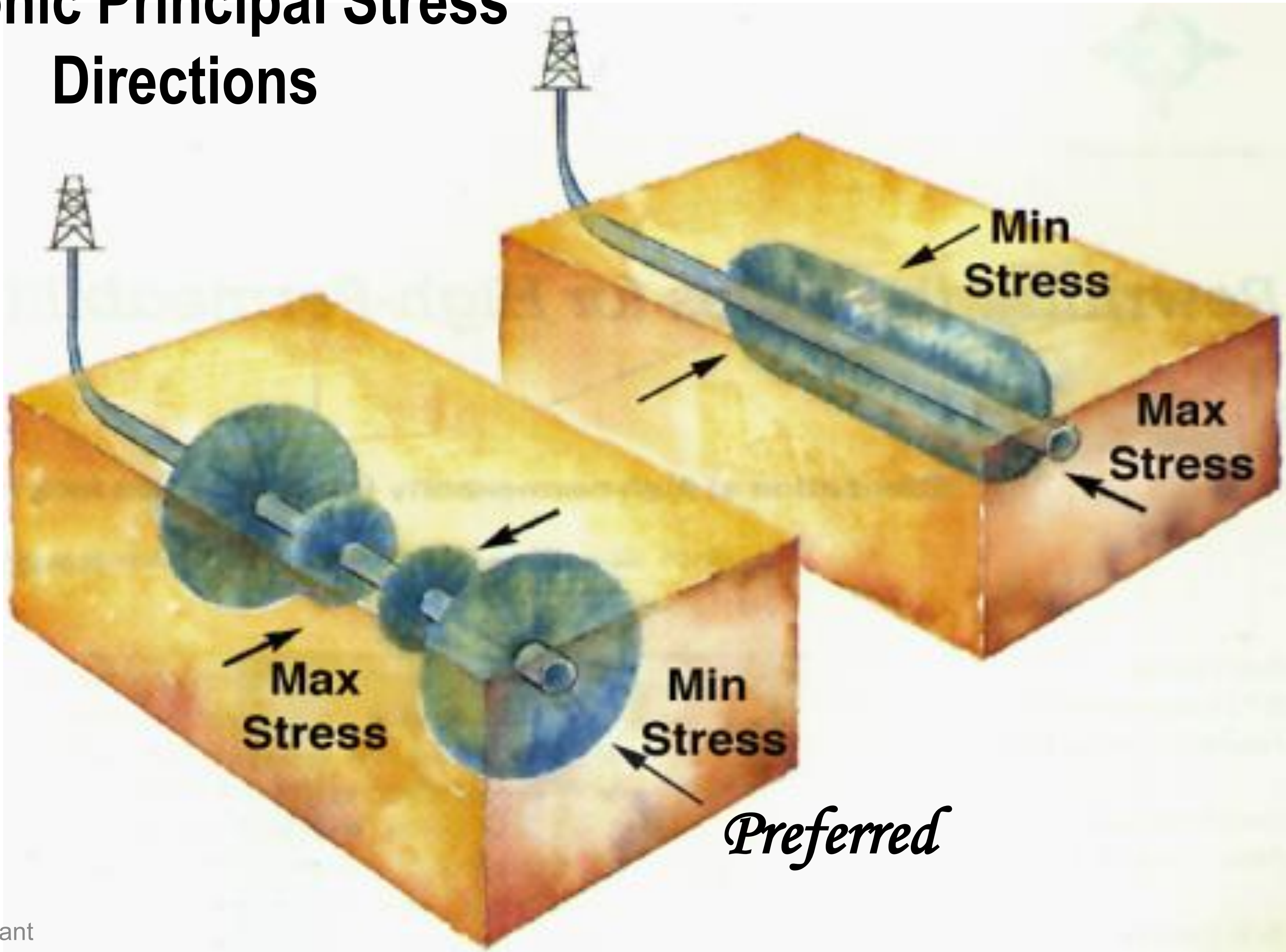
(Marcellus Shale)

- 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.).

Z.P. Bažant

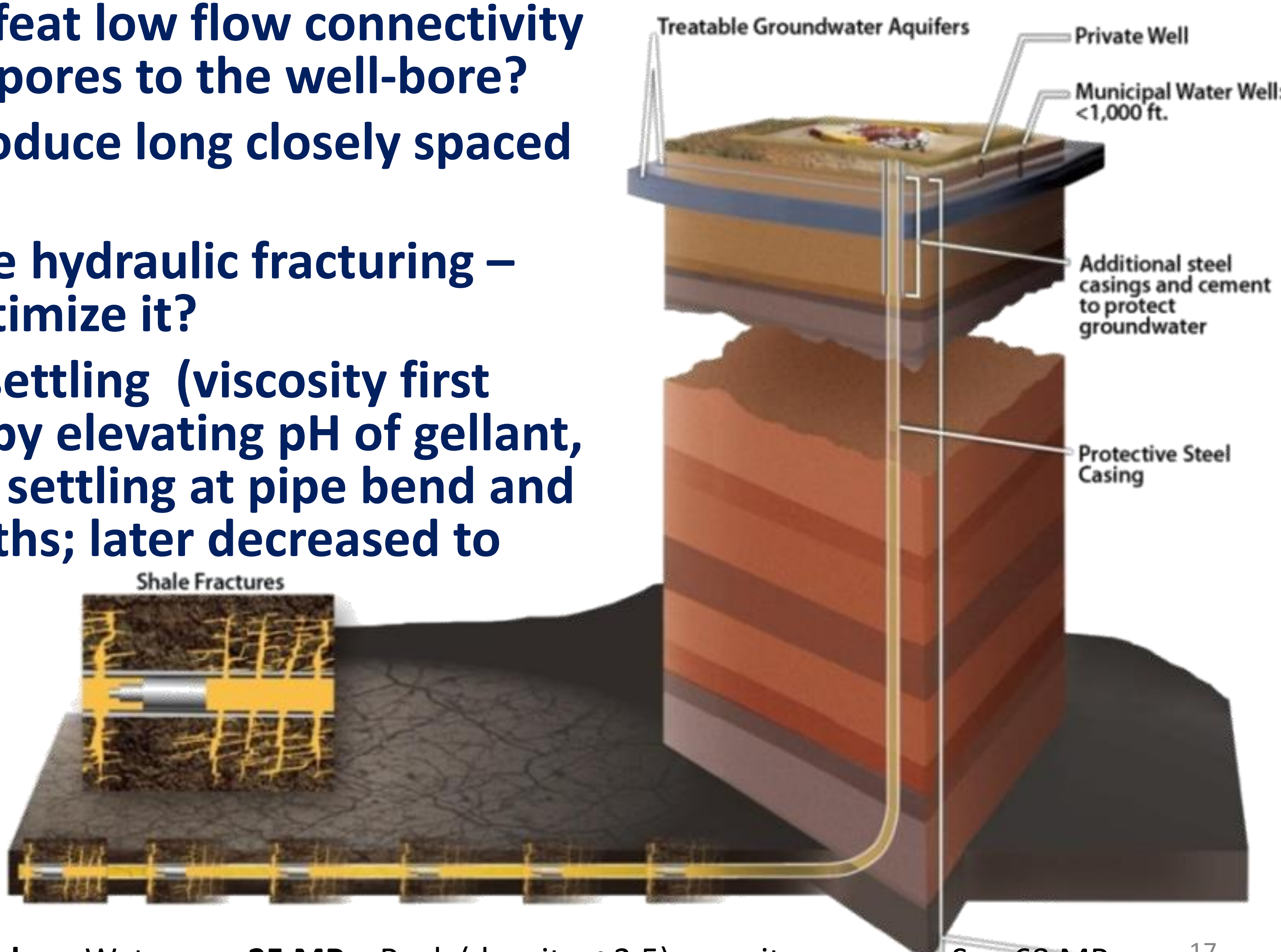
Source: Geology.com

Horizontal Well-Bore vs. Tectonic Principal Stress Directions



Drilling and Fracking Operations

- How to defeat low flow connectivity from nanopores to the well-bore?
- How to produce long closely spaced cracks?
- Multi-stage hydraulic fracturing – 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.



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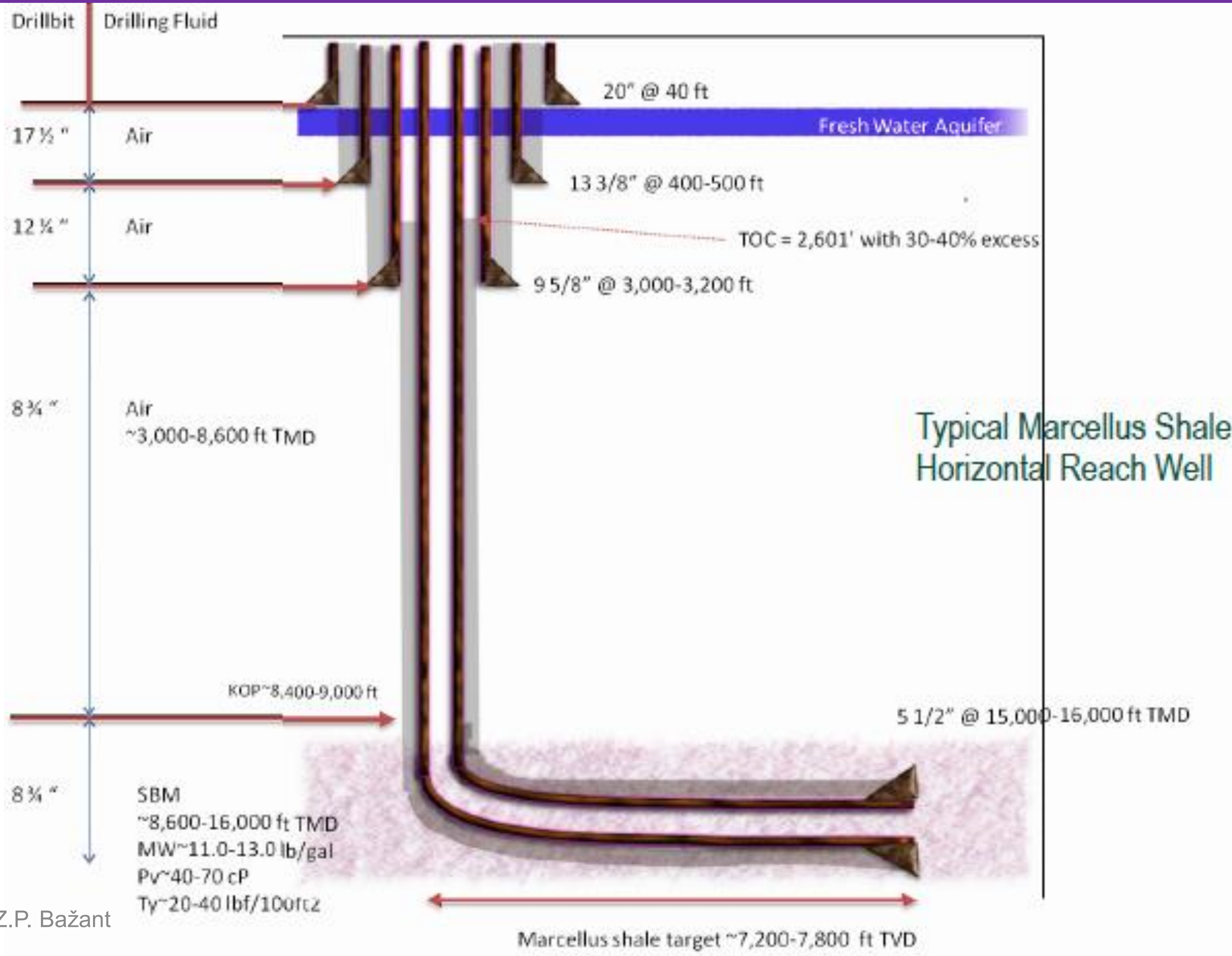
At depth **2.5 km**: Water p = **25 MPa**, Rock (density ~2.5) : gravity pressure $S_z \approx 68$ MPa, Tectonic pressures = 55 and 42 MPa, Pump: 25 MPa, Pump + water pressure = 25+25 MPa (more with drilling mud). Shale density = 2 to 2.7, typical 2.5. (cf. granite 2.75)

TYPICAL SHALE-GAS WELL DIAGRAM



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Undesirable Side Effects of 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.

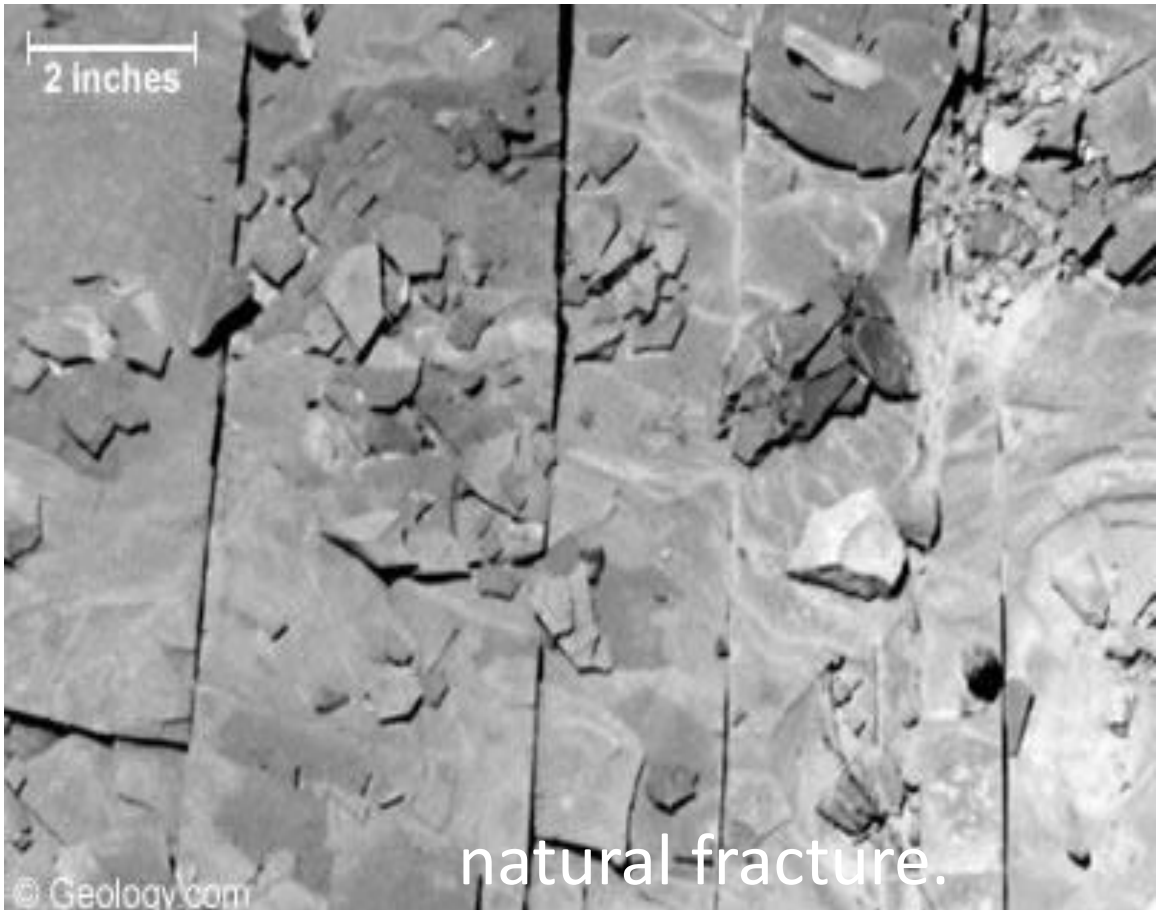
Typical Drill Pad and Extraction Site

Fracking Fluid

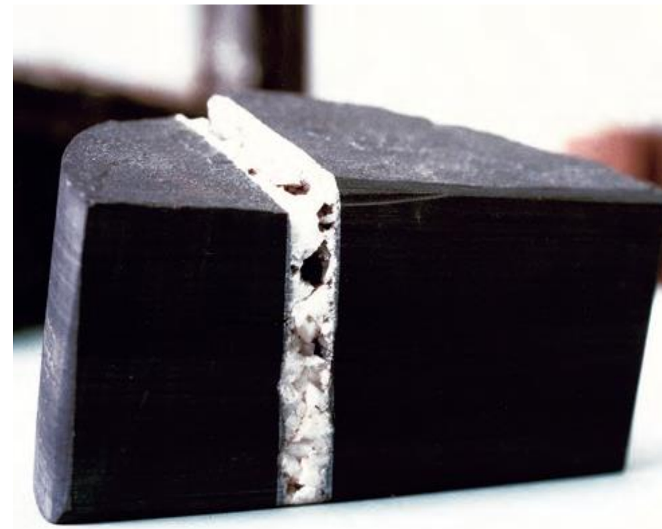
Often a small amount of **polymer** is added as a **friction reducer**.

Usually 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.

Vertical Joints in Devonian Shale (Marcellus)



Surface outcrop

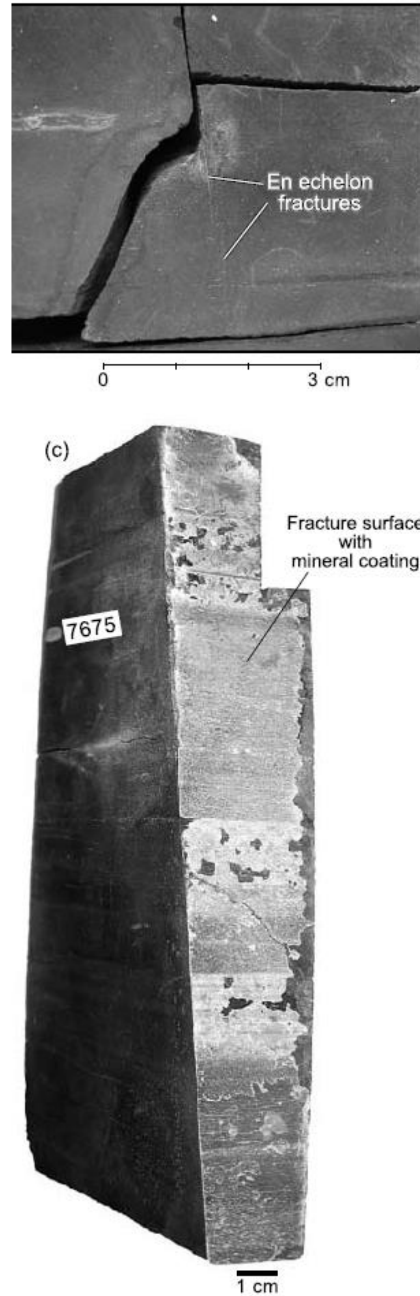


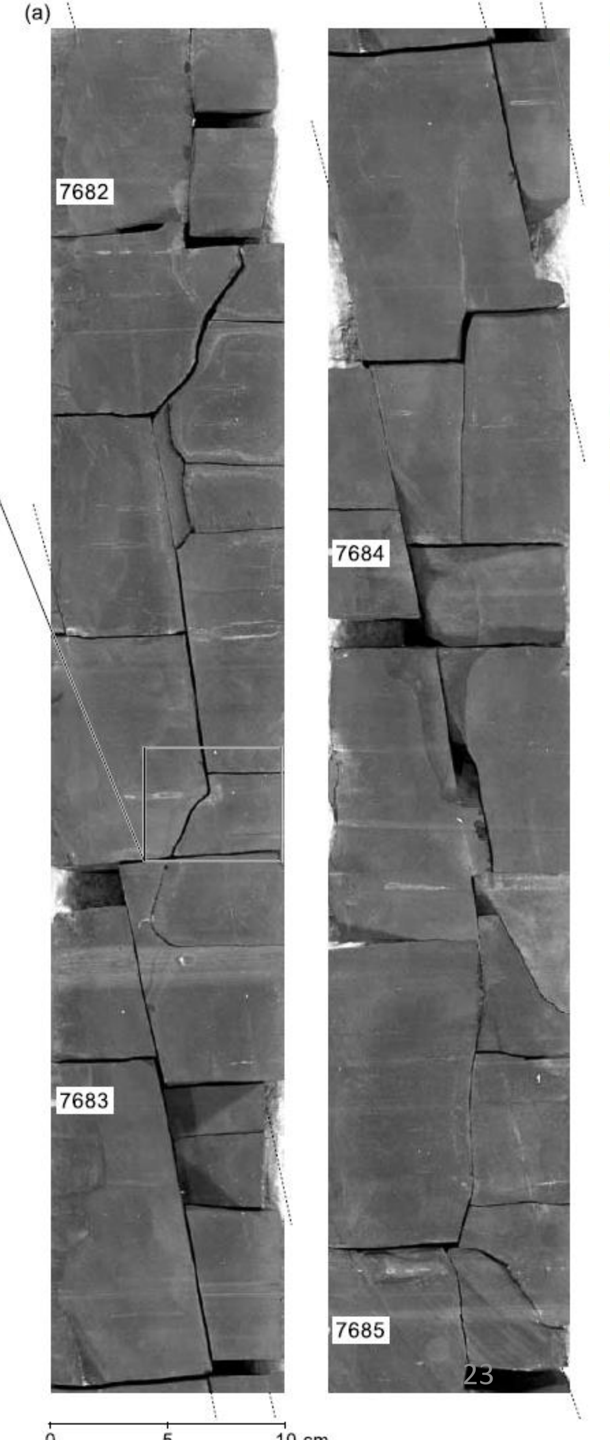
Drill core

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

Natural Fractures in Shale Cores, <u>Sealed with Calcite</u>

From depth 2640 m





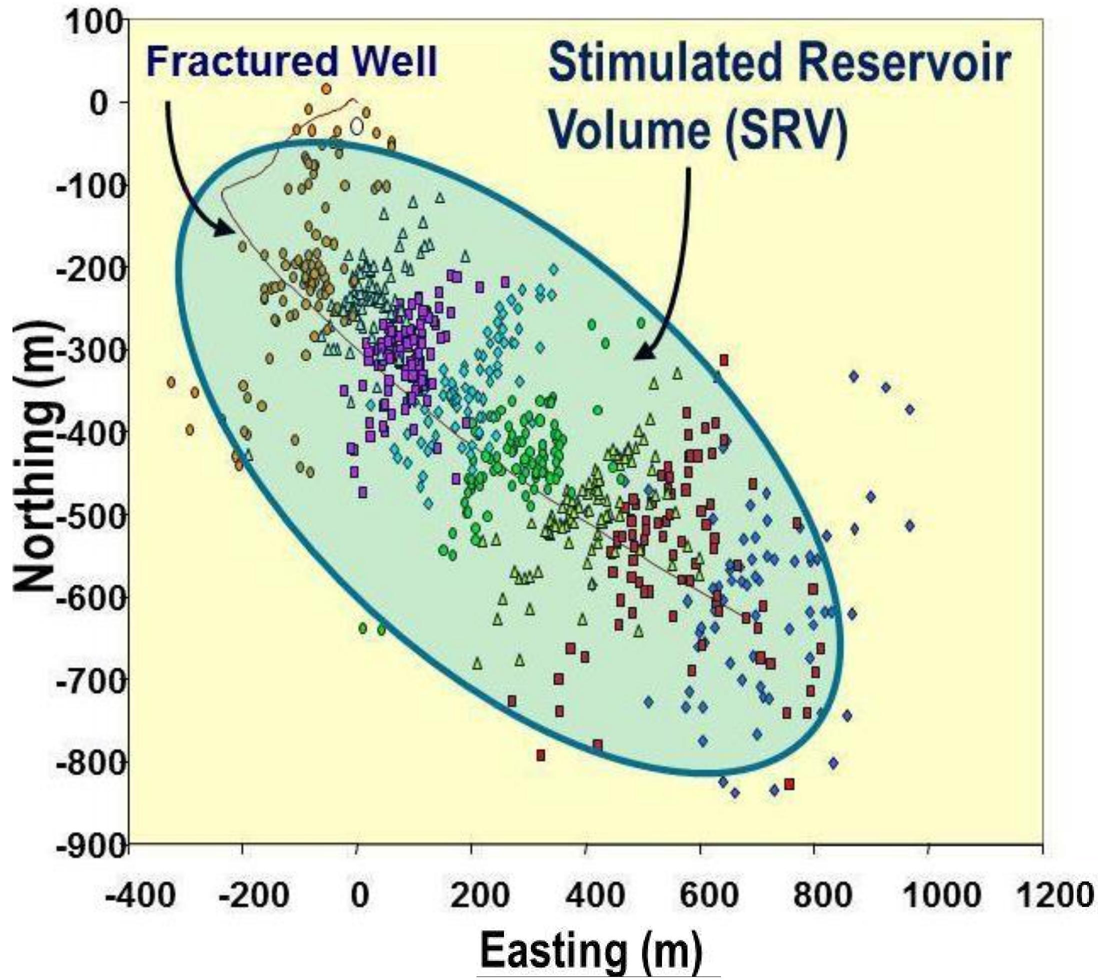
Gale et al. (2007), Am. Assoc. of Petroleum Engrs. Bulletin

Weak horizontal bedding planes, subjected to large overburden pressure

- they cause **material orthotropy**, much more pronounced in strength and fracture properties than in elasticity

Microseismic sources in Marcellus shale reveal extent of fracturing

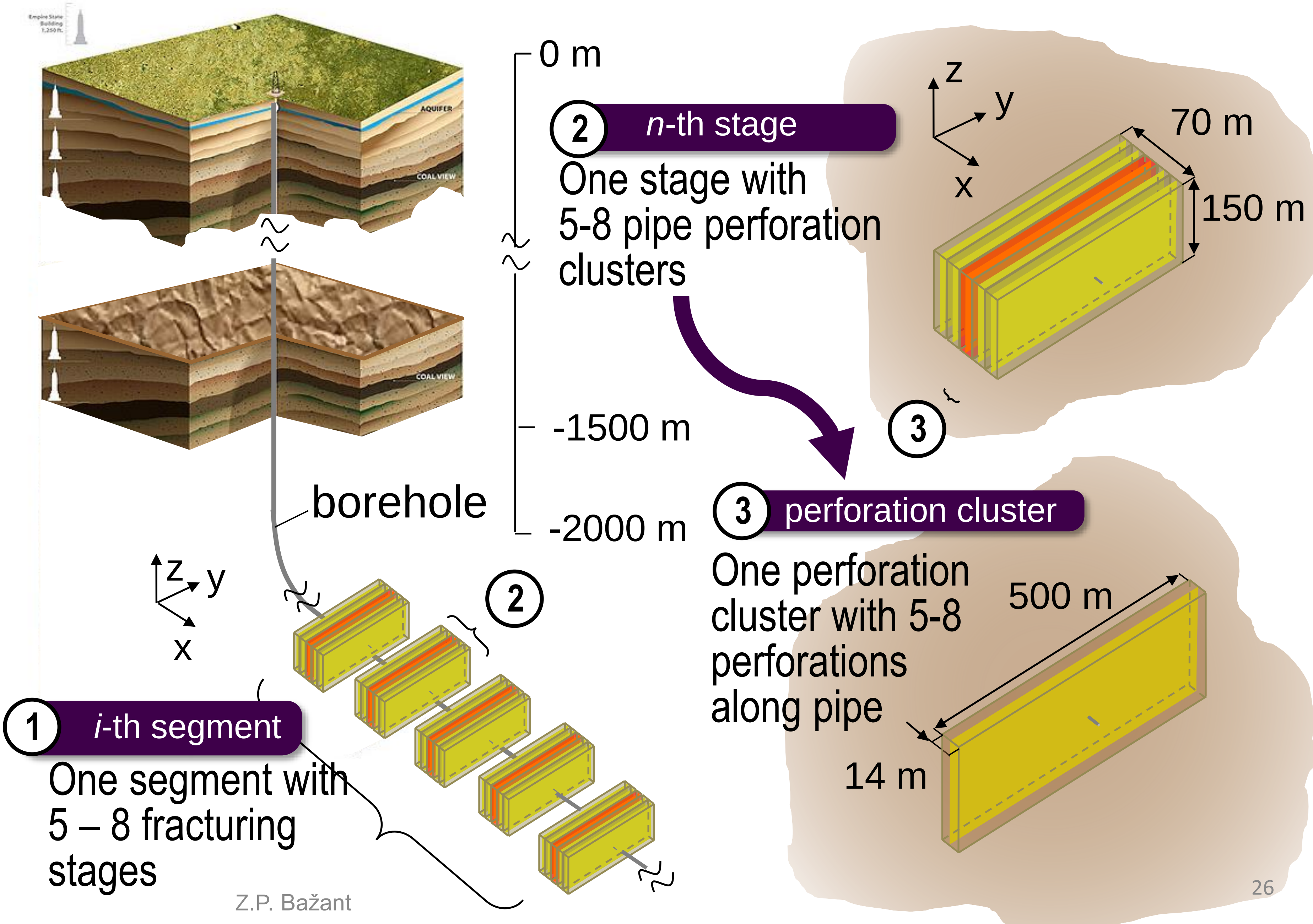
Plan view



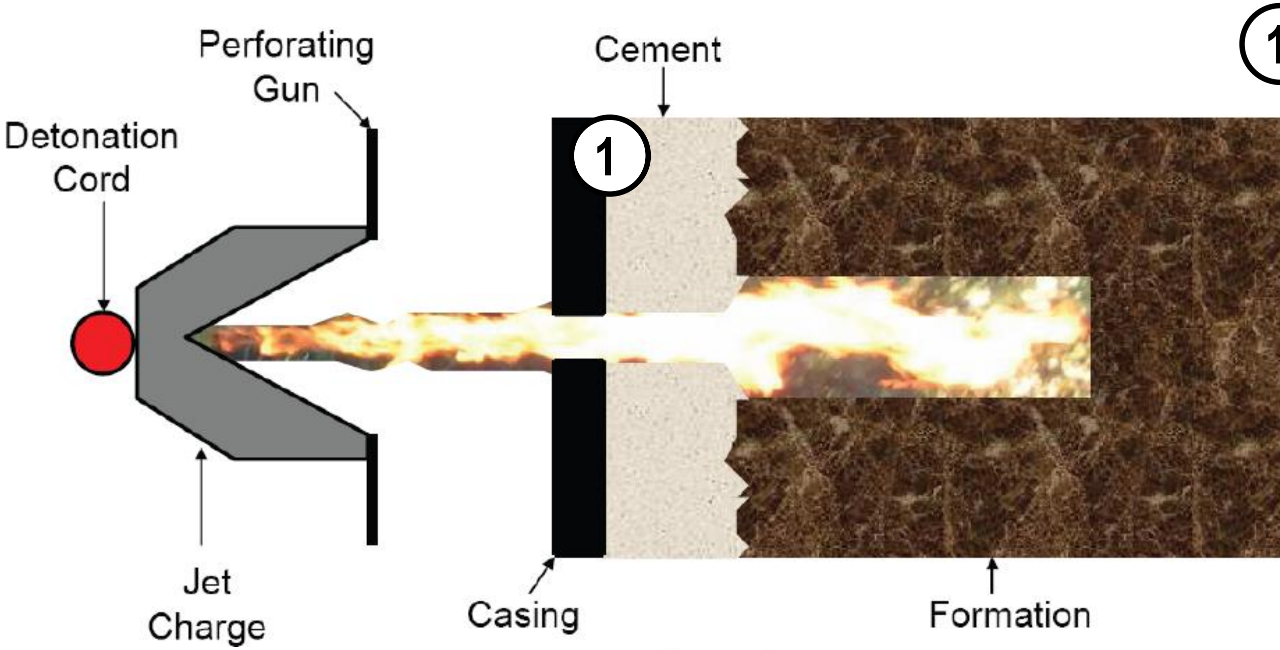
One **segment** with **12 stages** (each in a different color), each stage having **5 to 8 clusters,** each cluster having about **5 pipe perforations**

Source: Rimrock Energy, SPE 119896

Main Features of the Well

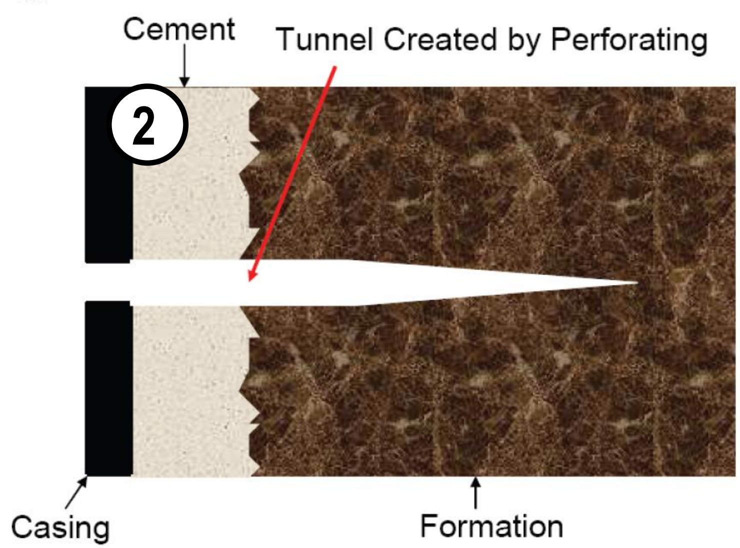


Perforation of High Strength Steel Pipe



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

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



(2)

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

Fracking works.
But why?
And why not well enough?

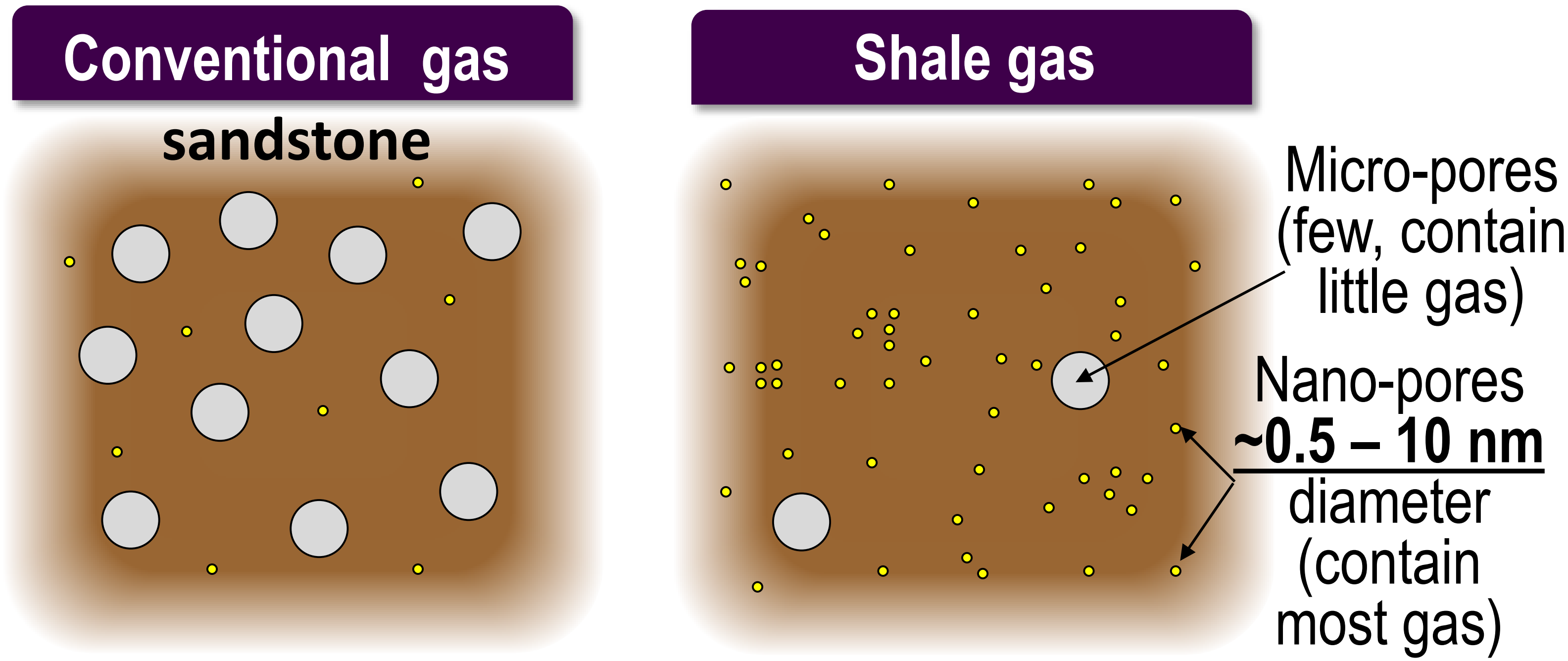
Usually, **only 5% to 15% of gas gets extracted**.
How to increase it?

1) Increase the fracked volume fraction
above 15%.

2) Achieve finer crack spacing.

What is the spacing of hydraulic cracks in shale?

Shale permeability is extremely low



PERMEABILITY, *b*, in mD (miliDarcy)

Sandstones:	$1 — 10^{2}$	(conventional gas)
Tight gas:	$10^{-3} — 10^{-1}$	
Concrete:	$10^{-4} — 10^{-3}$	
Shale:	$10^{-6} — 10^{-5}$	

The crack spacing can be deduced from:

1. **Known percentage of gas extracted from the shale stratum — 15 %.**
2. **Time to reach maximum gas flux on the drillpad.**
3. **Halftime of flux rate decay on the drillpad.**
4. **Known permeability of shale.**

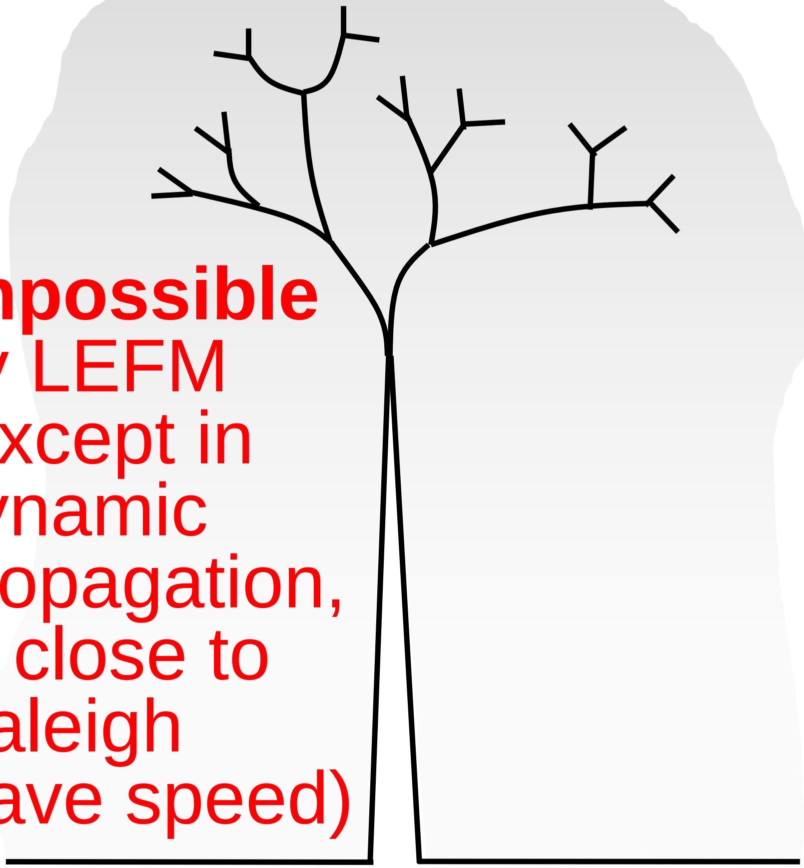
RESULT: <u>Crack spacing = 10 cm</u> (Fayetteville shale).

ZP Bažant, M Salviato et al (2014), "Why fracking works". ASME J of Applied Mechanics, October

Crack Topology

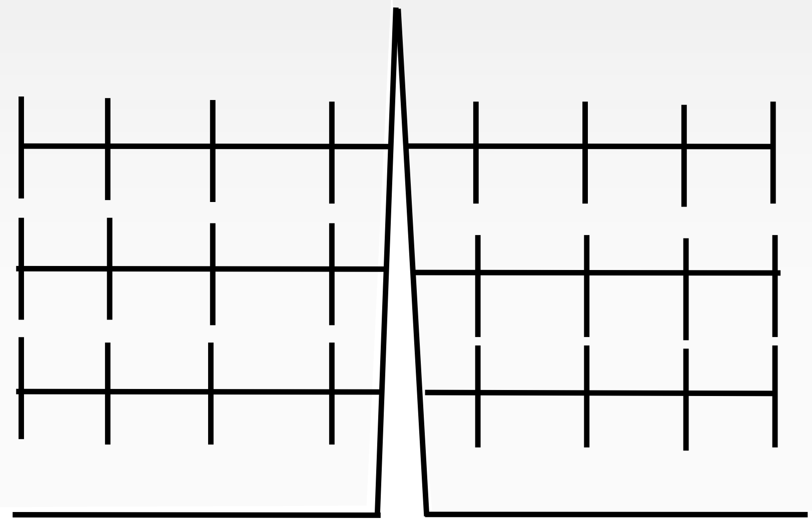
Ⓐ Branching at crack tips?

Impossible by LEFM (except in dynamic propagation, at close to Raleigh wave speed)



Ⓑ Nucleation from weak joints, faults, defects

Possible in statics (fracking takes many days)



IDEALIZED (PLANE VIEWS)

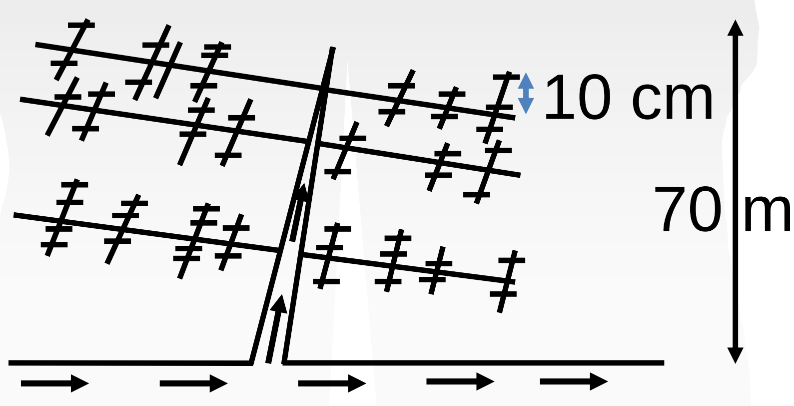
Gas Diffusion from Nanopores to Adjacent Cracks

Diffusion equation — nonlinear, compressible gas:

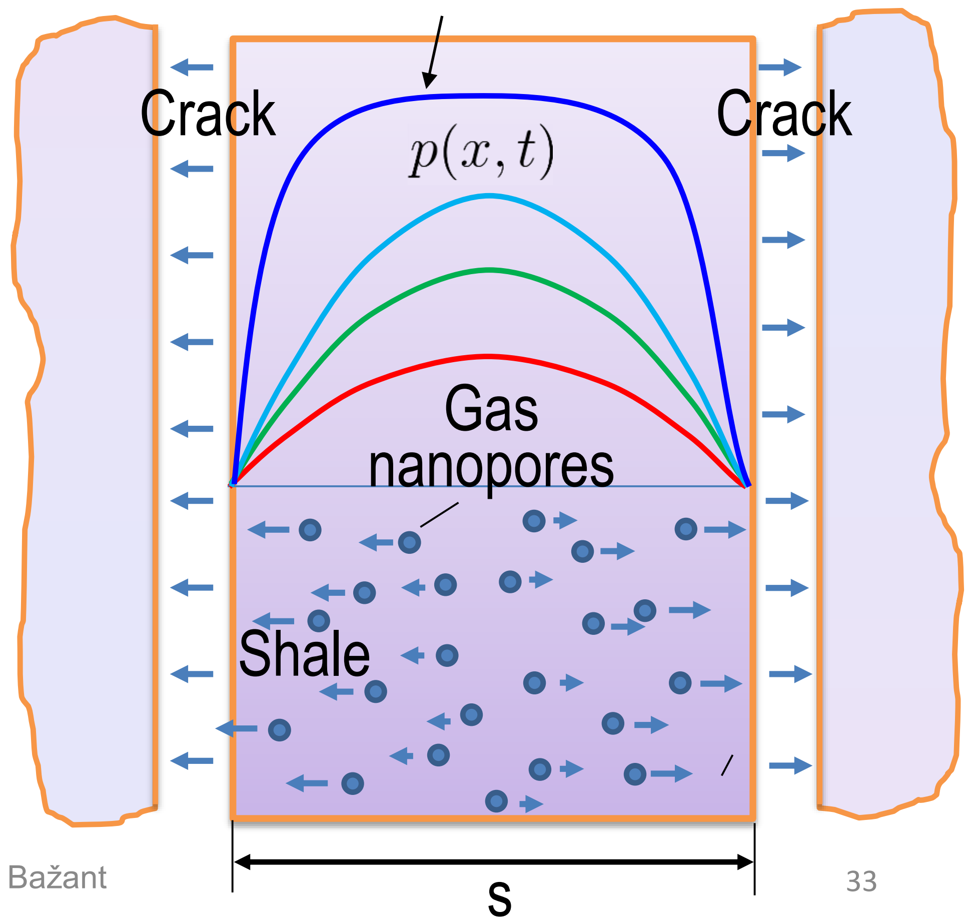
$$\frac{\phi}{k}\left(c_\phi + \underline{\frac{1}{p}}\right)\mu\,\frac{\partial p}{\partial t} = \frac{\partial^2 p}{\partial x^2} + \underline{\frac{1}{p}\left(\frac{\partial p}{\partial x}\right)^2}$$

Darcy gas flux: $$q = -\frac{k}{\mu}\frac{\partial p}{\partial x}$$

$1/p = c_g =$ gas compressibility
$c_\phi =$ shale compressibility
$\phi =$ shale porosity
$k =$ shale permeability
$\mu =$ gas viscosity



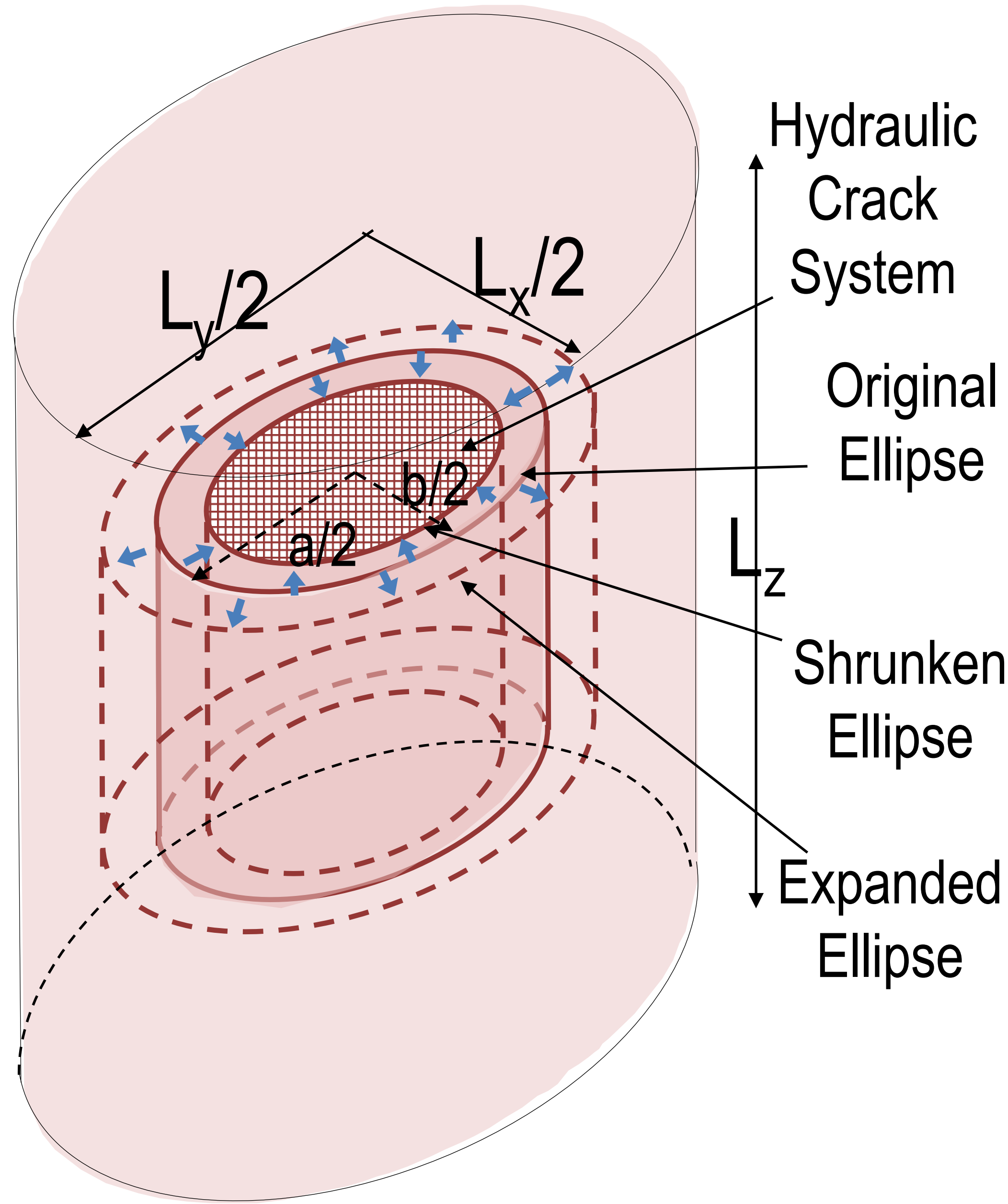
Profiles of gas pressure p at subsequent times



Volume of all cracks

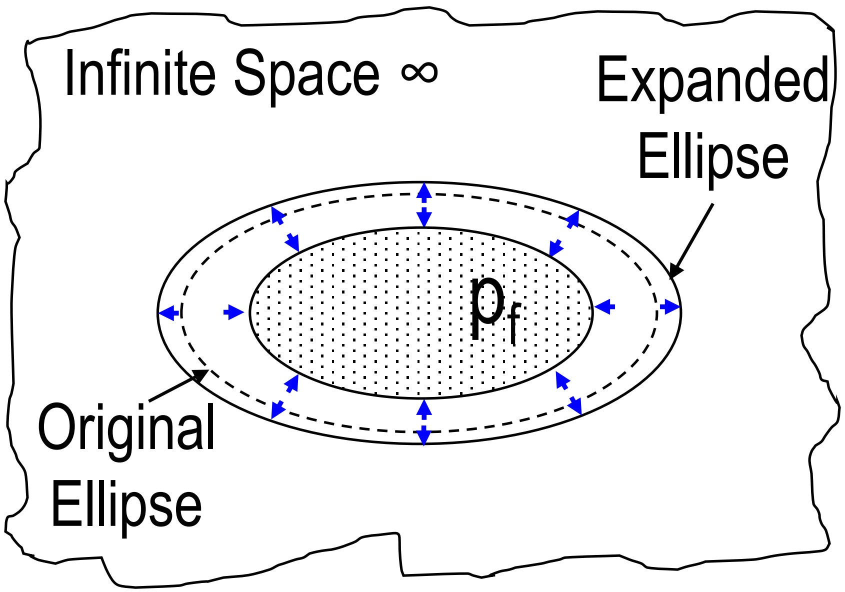
= expansion of fracking zone (approx. an elliptical cylinder) in infinite space

+ elastic contraction of shale between cracks



Calculation of Volume of All Hydr. Cracks in Fracking Stage

To find an analytical formula, consider the fracking stage to be an **elliptical cylinder** in plane strain, in infinite space



Elliptical coordinates:

$$z = c\cosh\zeta \qquad \zeta = \xi + i\eta$$

Complex potentials (Stevenson 1945):

$$\psi(z) = \frac{p_f c}{2}(\sinh\zeta - \cosh\zeta)$$

$$\chi(z) = -\frac{p_f c^2}{2}\zeta\cosh 2\xi_0$$

Displacement field:

$$u_x + iu_y = 1/2G[(3-\nu)/(1+\nu)\psi(z) - z\overline{\psi}(\overline{z}) - \overline{\chi}'(\overline{z})]$$

(e.g., Timoshenko -Goodier1970)

Calculation of Volume Expansion of Elliptic Cylinder

$$u_x = \frac{p_f c \sinh\xi \cos\eta}{2G(1+\nu)} \frac{\Pi(\xi,\eta) - (1-\nu)\coth\xi}{\cosh 2\xi - \cos 2\eta}$$

$$u_y = \frac{p_f c \cosh\xi \sin\eta}{2G(1+\nu)} \frac{\Pi(\xi,\eta) - (1-\nu)\tanh\xi}{\cosh 2\xi - \cos 2\eta}$$

$$\Pi(\xi,\eta) = (1-\nu)\cosh 2\xi + (1+\nu)\cosh 2\xi_0 - 2\cos 2\eta$$

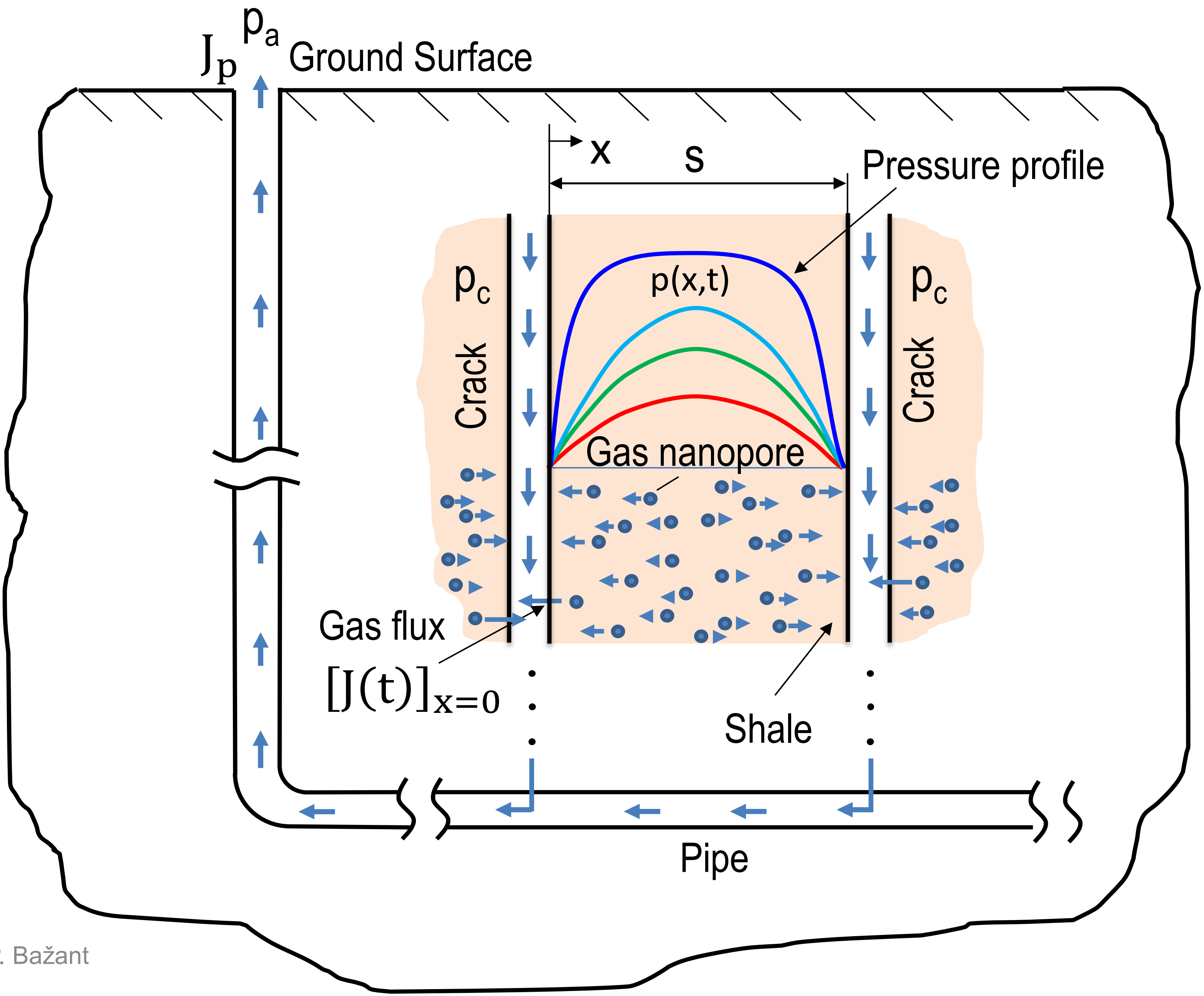
Curvilinear displacement components: $u_\xi + i u_\eta = e^{-i\alpha}(u_x + i u_y)$

$$u_\xi = \frac{u_x \sinh\xi \cos\eta + u_y \cosh\xi \sin\eta}{\sqrt{1/2(\cosh 2\xi - \cos 2\eta)}}$$

Expansion (exploiting symmetry of the problem):

$$\Delta V = 4 L_z \int_0^{\pi/2} u_\xi(\eta) c \cosh\xi_0 \mathrm{d}\eta$$

Transport of Gas from Shale to Surface



Gas Transport Model

Diffusion of Gas Through the Shale Toward the Hydraulic Cracks

Darcy's law:

$$v = -\frac{k}{\mu}\frac{\partial p}{\partial x}$$

Mass conservation:

$$\frac{\partial(\phi\rho)}{\partial t} + \frac{\partial(\rho v)}{\partial x} = 0$$

Shale Porosity, Gas Dynamic Viscosity

$$\frac{\phi\mu}{k}\left(C_s + \frac{1}{p}\right)\frac{\partial p}{\partial t} = \frac{1}{p}\frac{\partial}{\partial x}\left(p\frac{\partial p}{\partial x}\right)$$

Shale Compressibility

Transport of Gas from Crack System to Surface

Gas flux from shale surface into cracks: $J = -\frac{k}{\mu}\left[\frac{\partial p}{\partial x}\right]_{x=0}$

Hagen–Poiseuille law for gas flow in pipe:

$$J_p = -\frac{b_1}{\mu L}\left(\frac{p_c^2 - p_a^2}{p_a}\right)$$

Mass balance condition:

$$\frac{\mathrm{d}m_c}{\mathrm{d}t} = J_p - A_c J = \rho V_c C_g \frac{\mathrm{d}p_c}{\mathrm{d}t}$$

Gas Compressibility

shale permeability

$$\frac{\mathrm{d}p_c}{\mathrm{d}t} + \frac{p_c}{\tau}\frac{p_c^2 - p_a^2}{p_a^2} = \frac{A_1 k}{\mu} p_c \left[\frac{\partial p}{\partial x}\right]_{x=0}$$

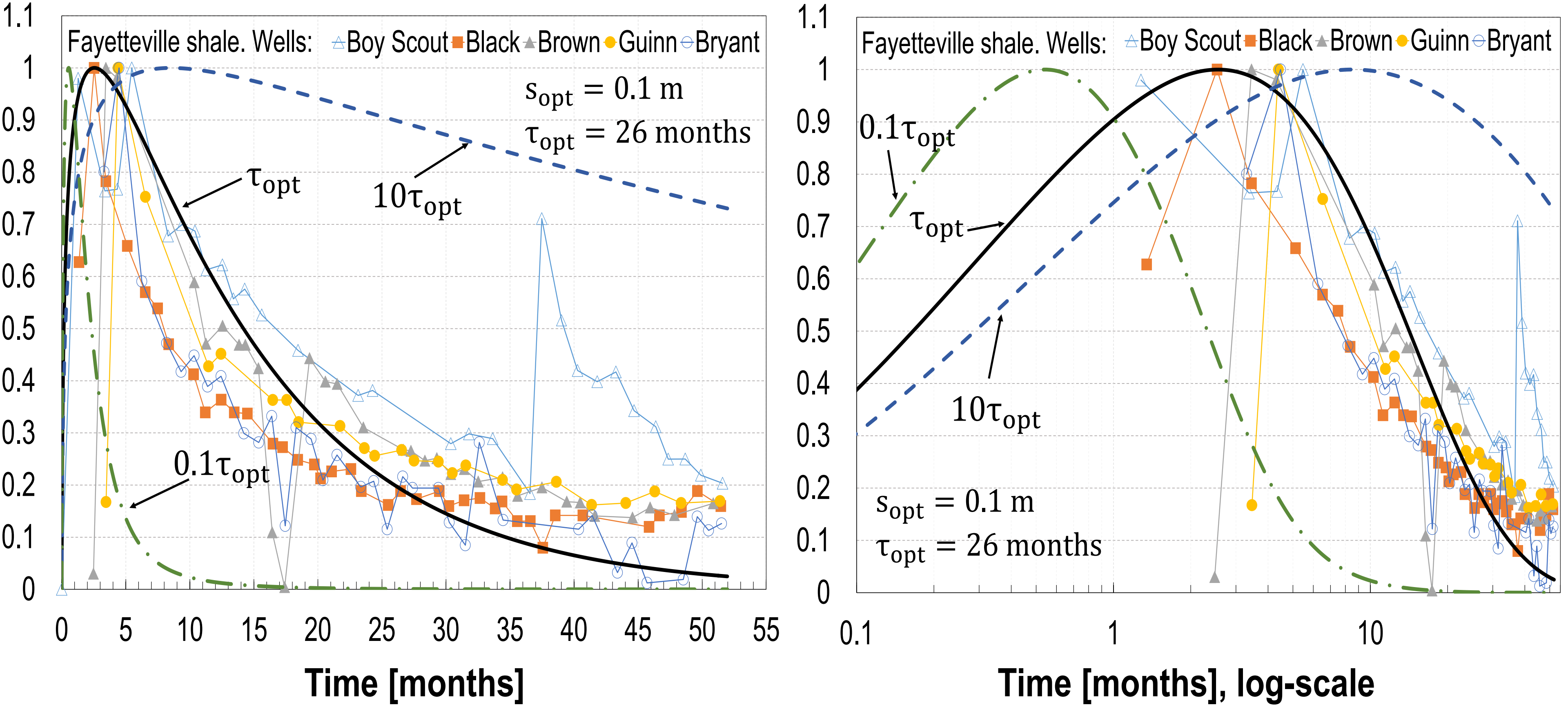
$\tau = LV_c\mu/b_1 p_a$ **= characteristic time**

$A_1 = A_c/V_c$

Total Crack Volume

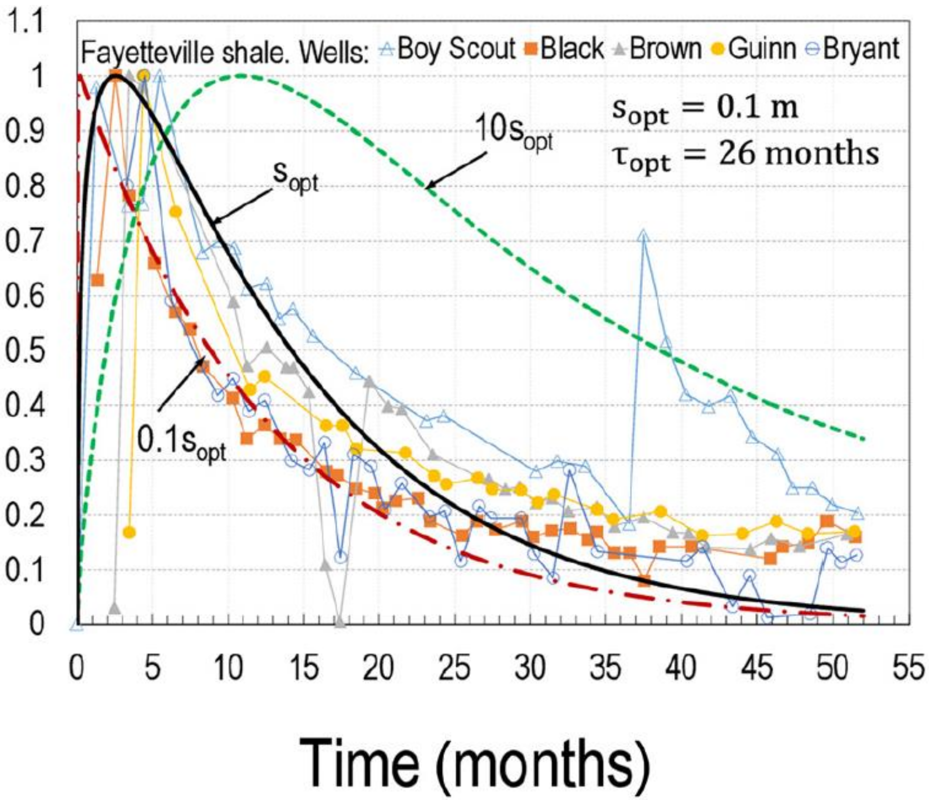
Surface Area of Cracks

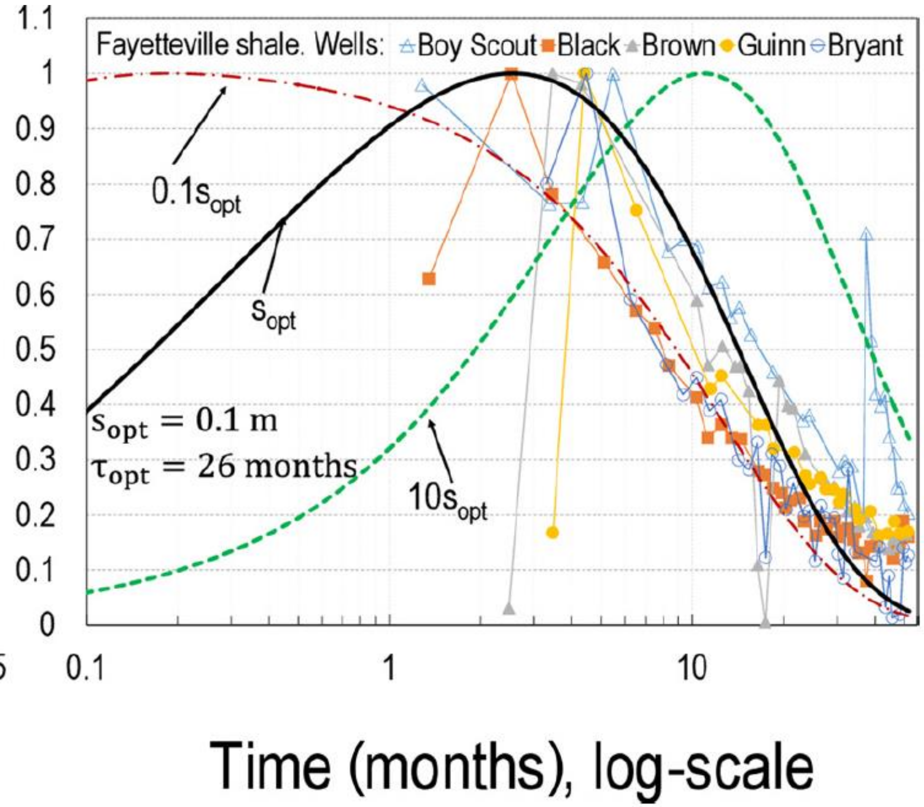
Effect of 10-fold change of characteristic time, τ_{opt}



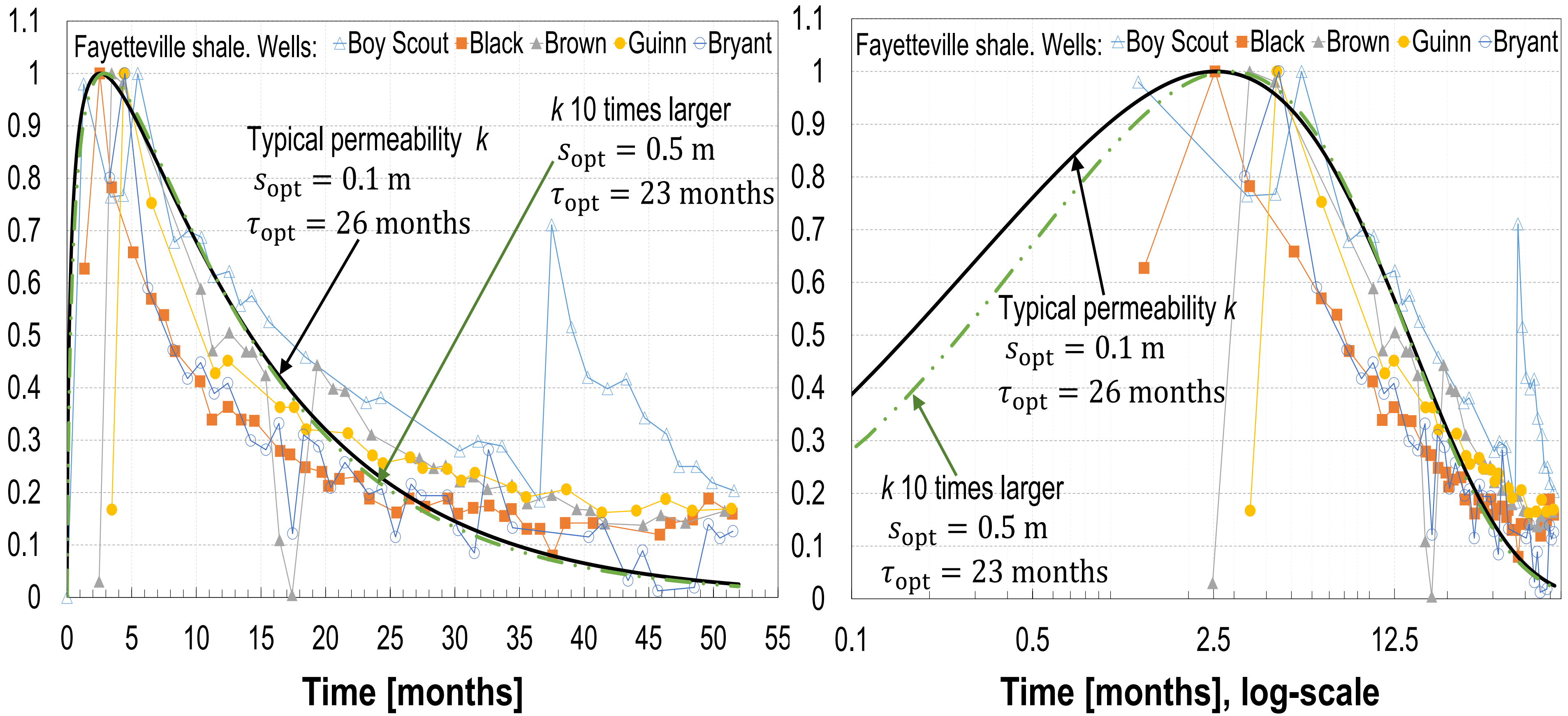
Time histories of gas flux observed on the surface

Effect of 10-fold change crack spacing, *s*





Effect of 10-fold change of permeability, *k*



— much weaker than the effects of crack spacing and of characteristic time

Conclusion from Diffusion Analysis

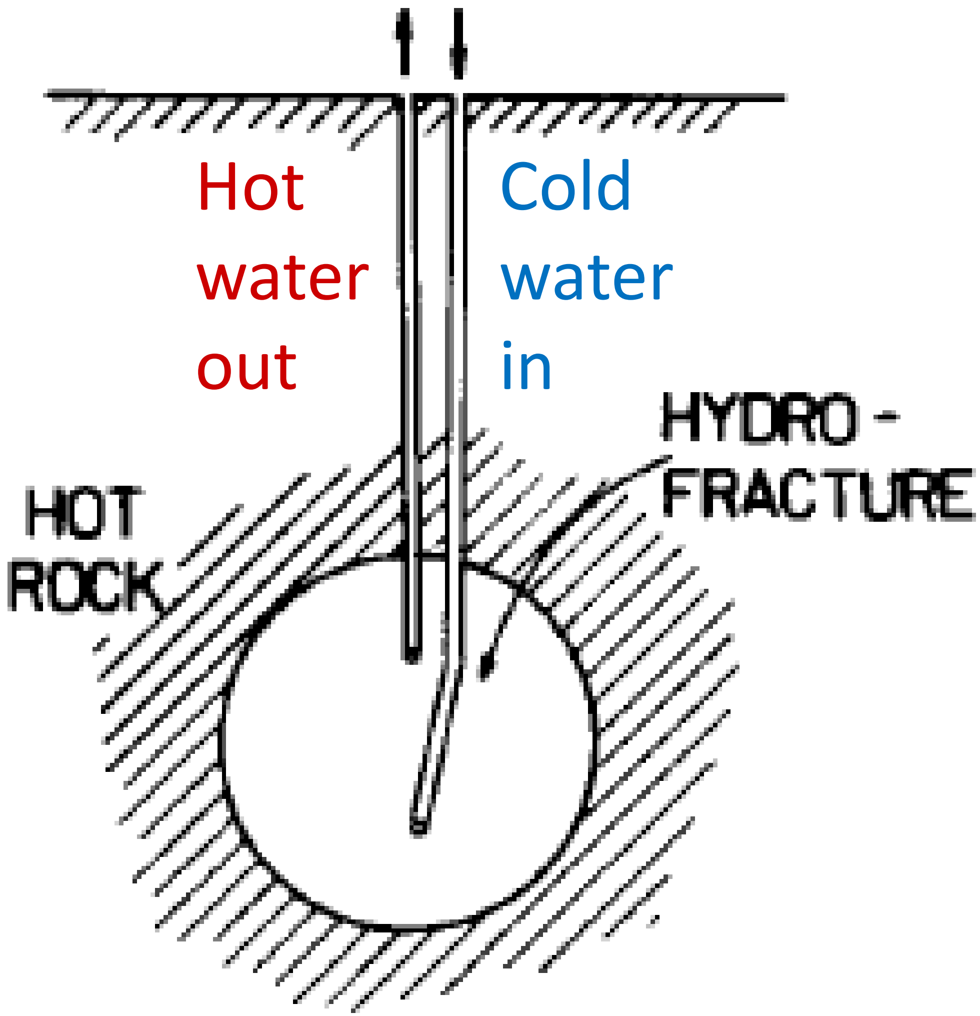
- If the gas flux peak occurs in about 2.5 months and 50% flux reduction in about 16 months, the spacing of hydraulic cracks and open joints in Fayetteville shale must be about 10 cm.

- For 1 m spacing (a 10-fold increase), the 50% flux reduction occurs in about 125 years.
- For a 3 m spacing, about 12,000 years.
- For a 10 m spacing, about 125,000 years.
- For a 1 cm spacing, about 4 days.

How to Achieve Small Enough Crack Spacing over a Large Zone?

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

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



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

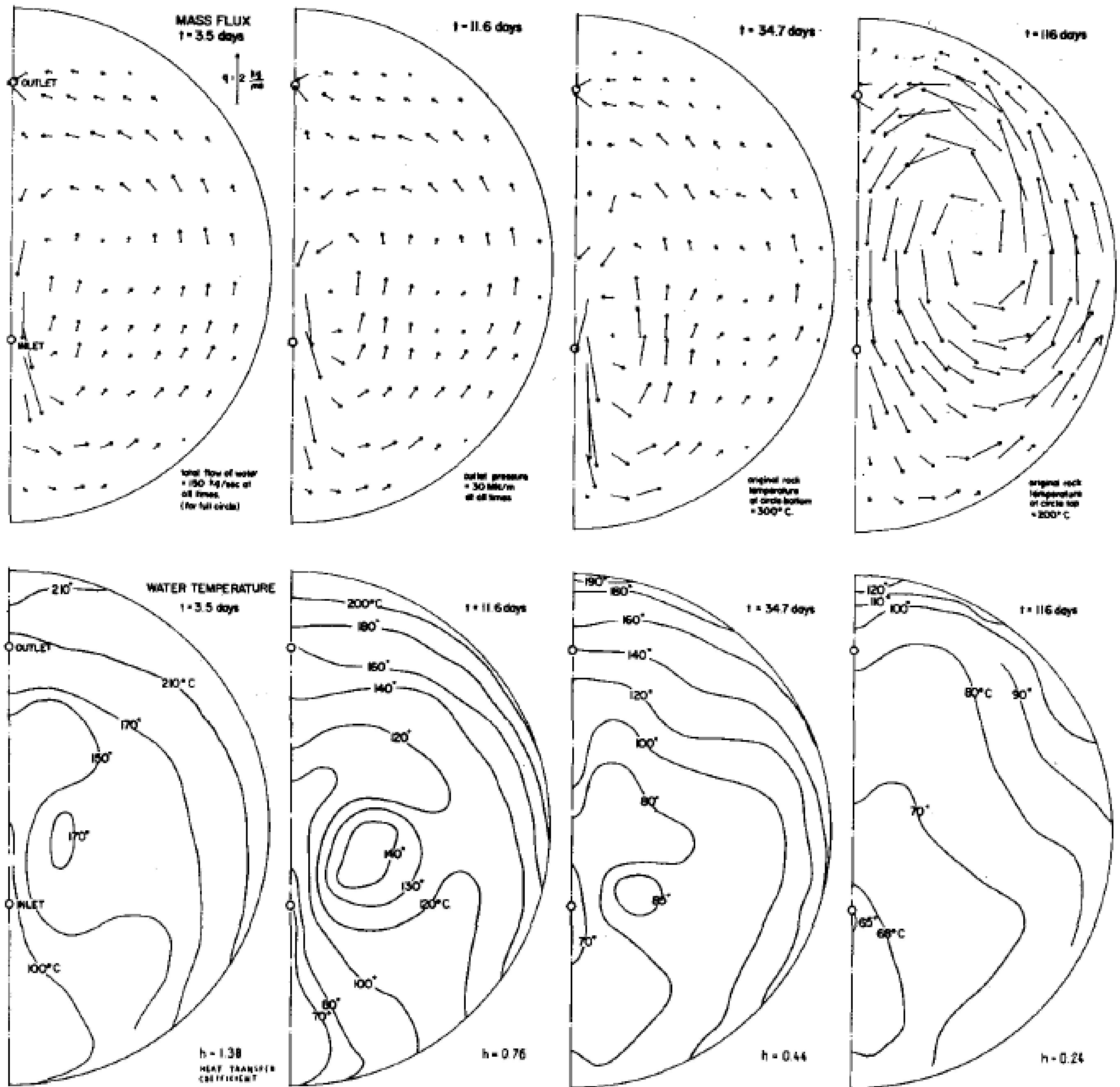
NU investigators:

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, ***<u>T = 300°C</u>.***

Water out: initially T_1 = 210°C. ***<u>After 116 days: 90°C.</u>***

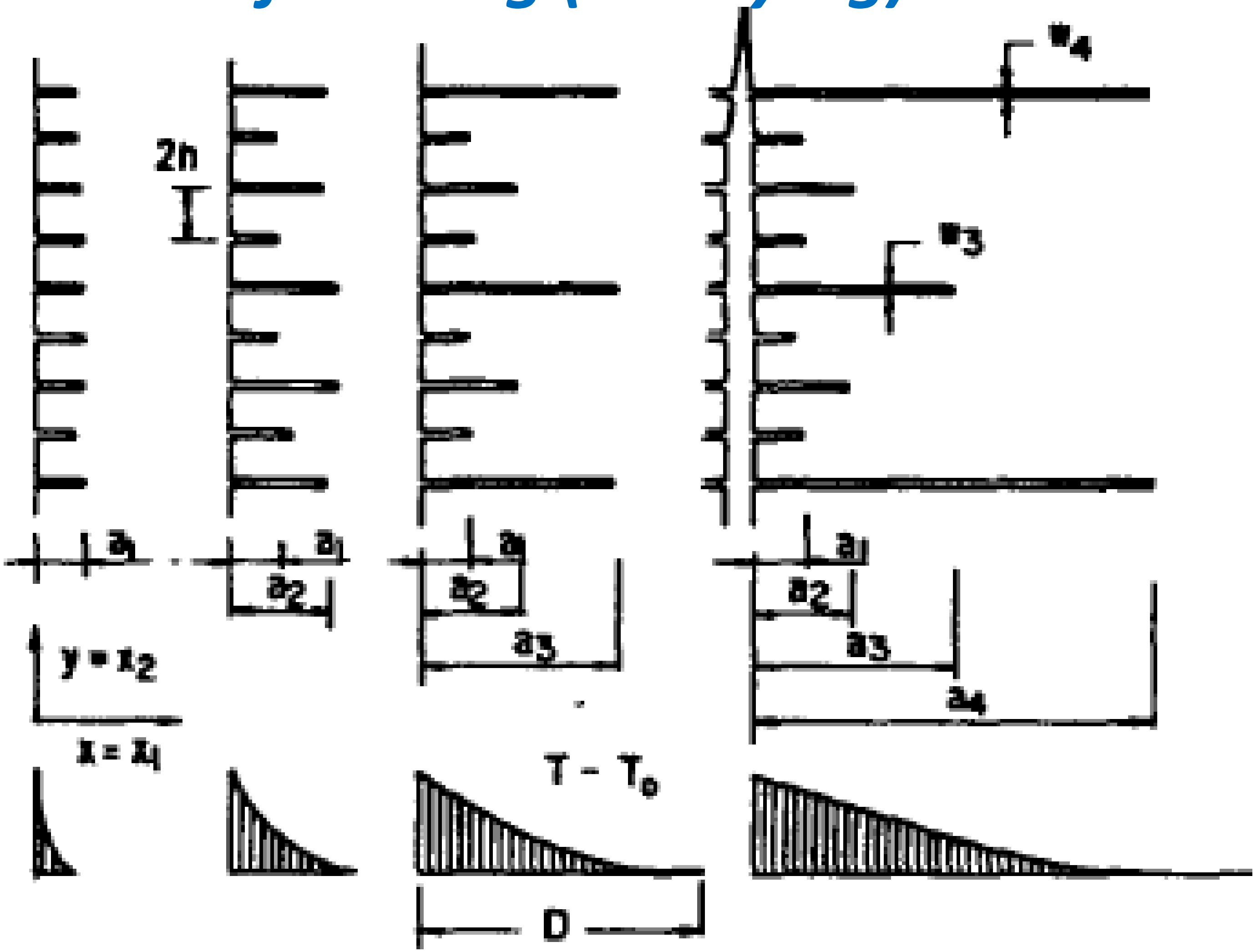


Bazant & H Ohtsubo: Int. J. of Numer. & Anal. Meth. In Engrg. 2, p. 317 (1978)

Localization Instability of Crack System

NU-LASL Hot Dry Rock Geothermal Energy Project, 1976

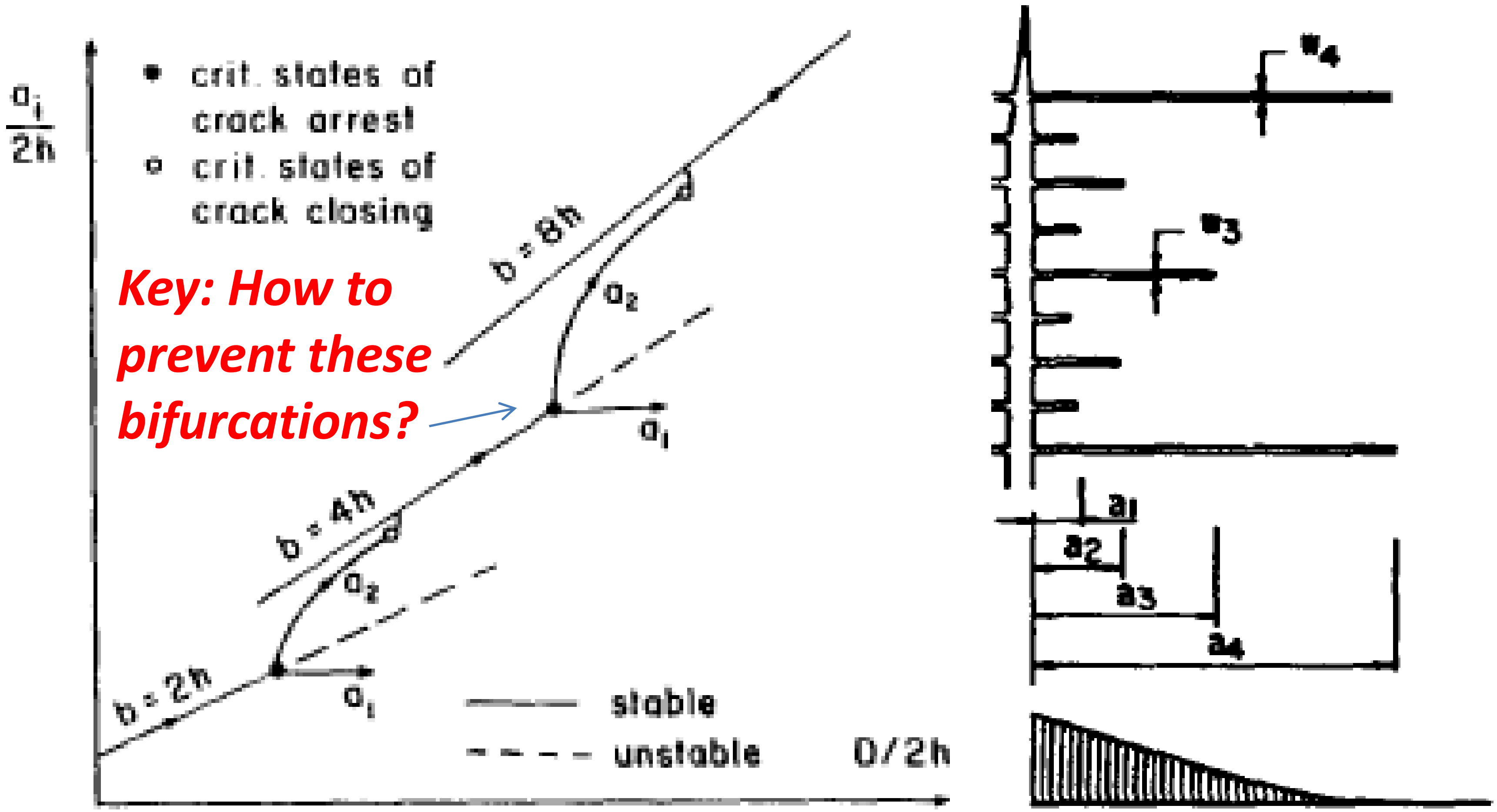
Evolution of Cooling (or Drying) Cracks



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

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

1976 NU-LASL Geothermal Energy Project

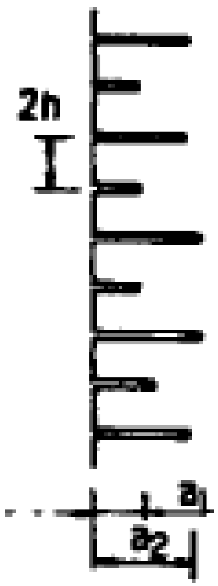


Key: How to prevent these bifurcations?

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

Stability of Crack System

Array of parallel cracks



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

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

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

Helmholtz Free Energy of Crack System:

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

$a_i =$ i-th crack length $\qquad \Gamma =$ fracture energy

$p =$ loading parameter: crack pressure or ΔT

$U =$ strain energy of the elastic body

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

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

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

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

Equilibrium condition: $\delta F > 0$

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

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

Stability conditions: $\Delta F > 0$ for all δa_i …positive definite matrix

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

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

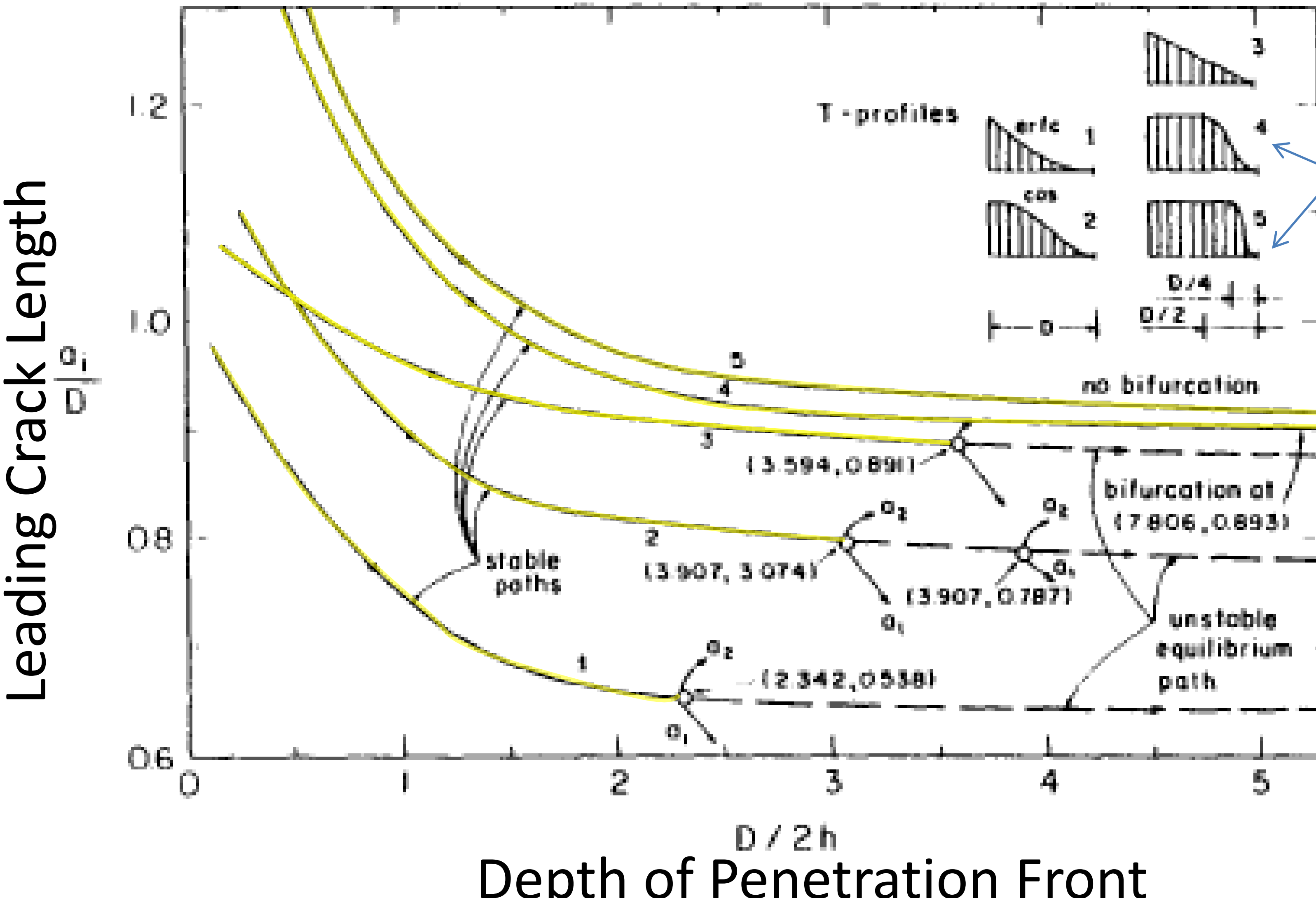
For 2 aternating crack lengths:

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

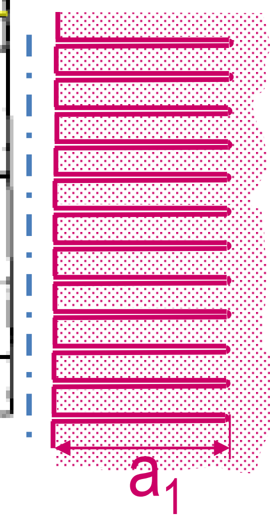
ZP Bazant, H Ohtsubo (1977), Mech. Res. Comm. 4 (5), 353-366; & IJF 15, 443-456 (1979)
S Nemat-Nasser, LM Keer, A Parihar(1978), IJSS.

Front Steepness: Key to Prevent Localization

1976 NU-LASL Geothermal Energy Project



For a steep front, cracks don't localize!



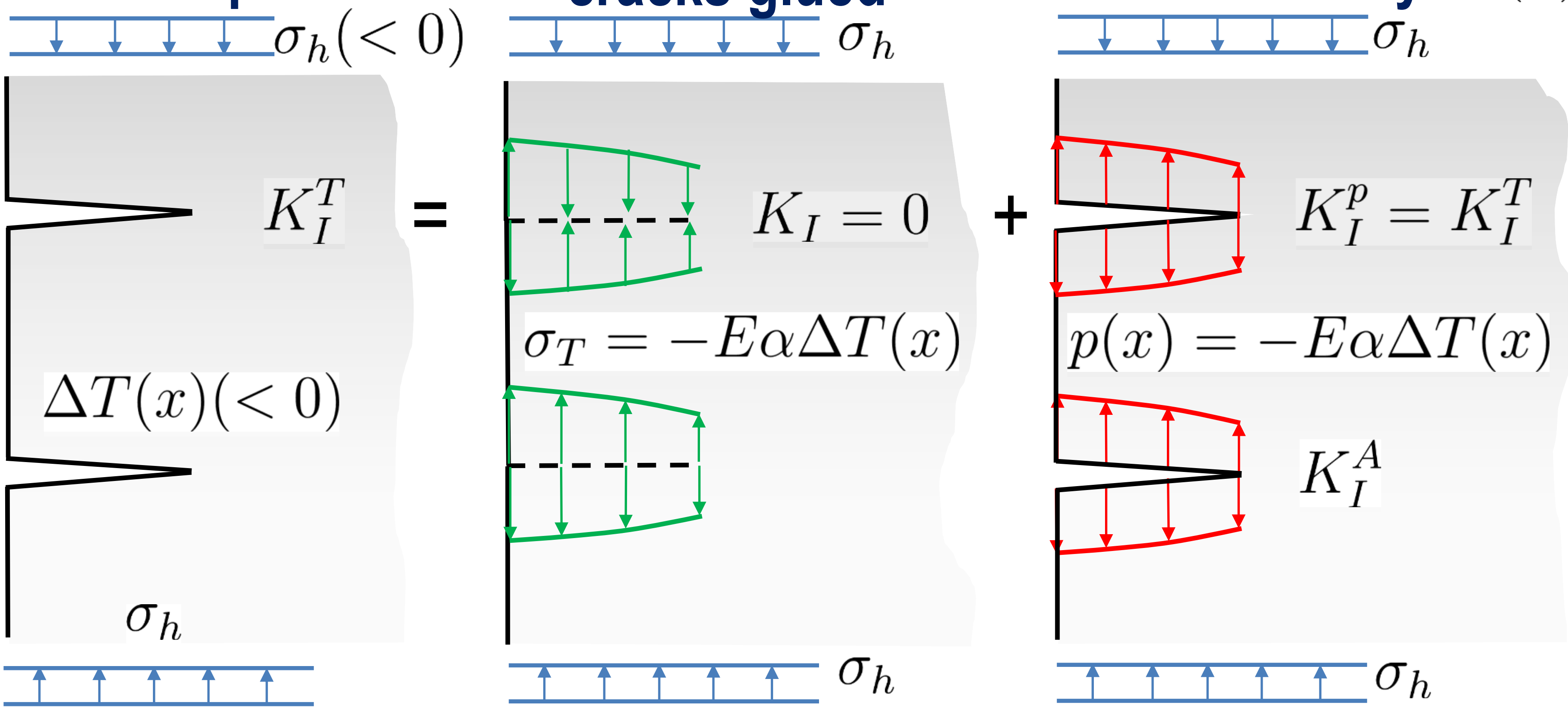
ZP Bazant, AB Wahab, J. Eng. Mech. ASCE 105, 873—889, 1979

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 the **pressure profile is nearly uniform over a long enough portion of the crack.**

Hydro-Thermal Analogy for Periodic LEFM Cracks

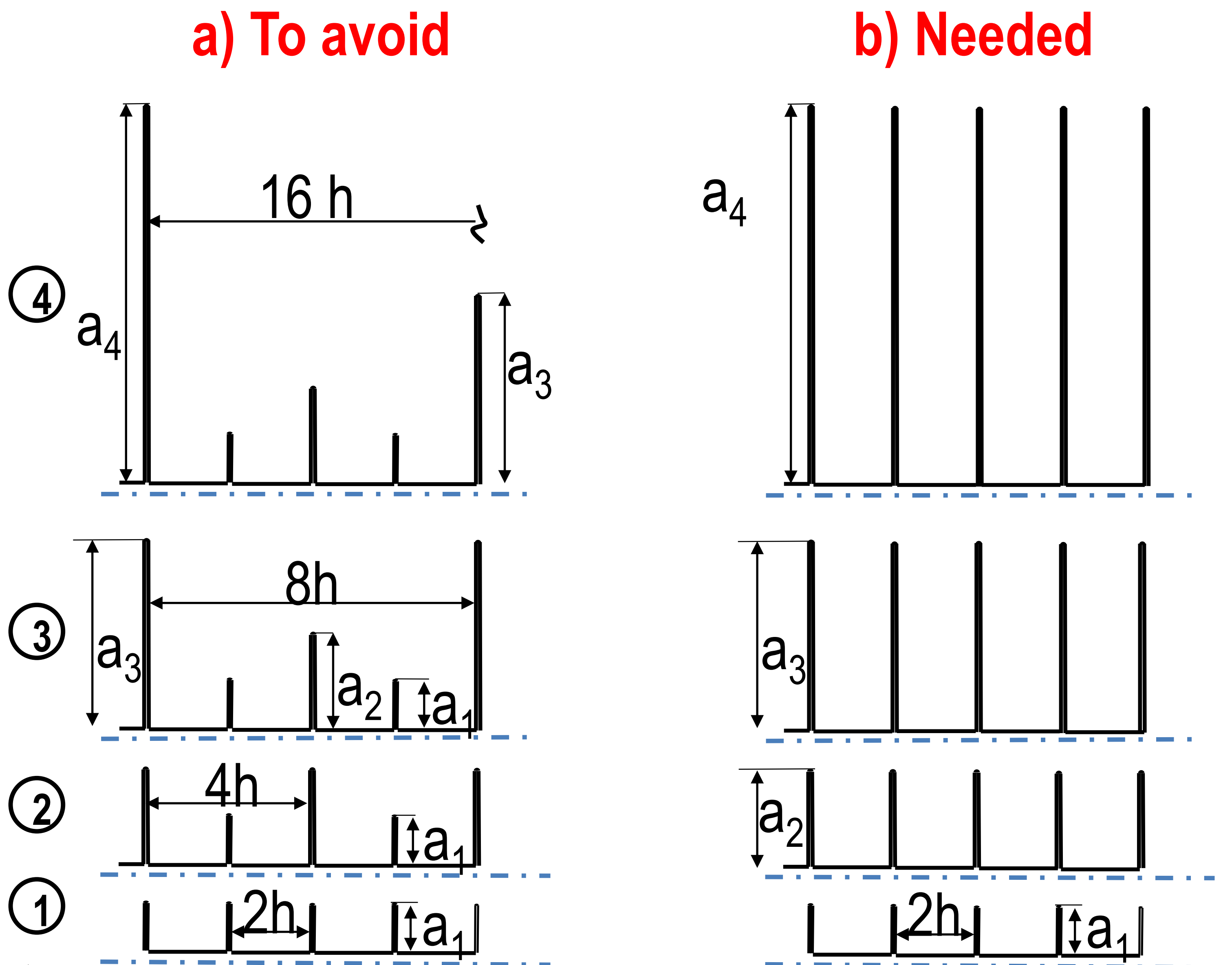
Cooled, cracks open = **I. Cooled, but cracks glued** + **II. Cracks unglued, faces loaded by $\sigma_T(x)$**



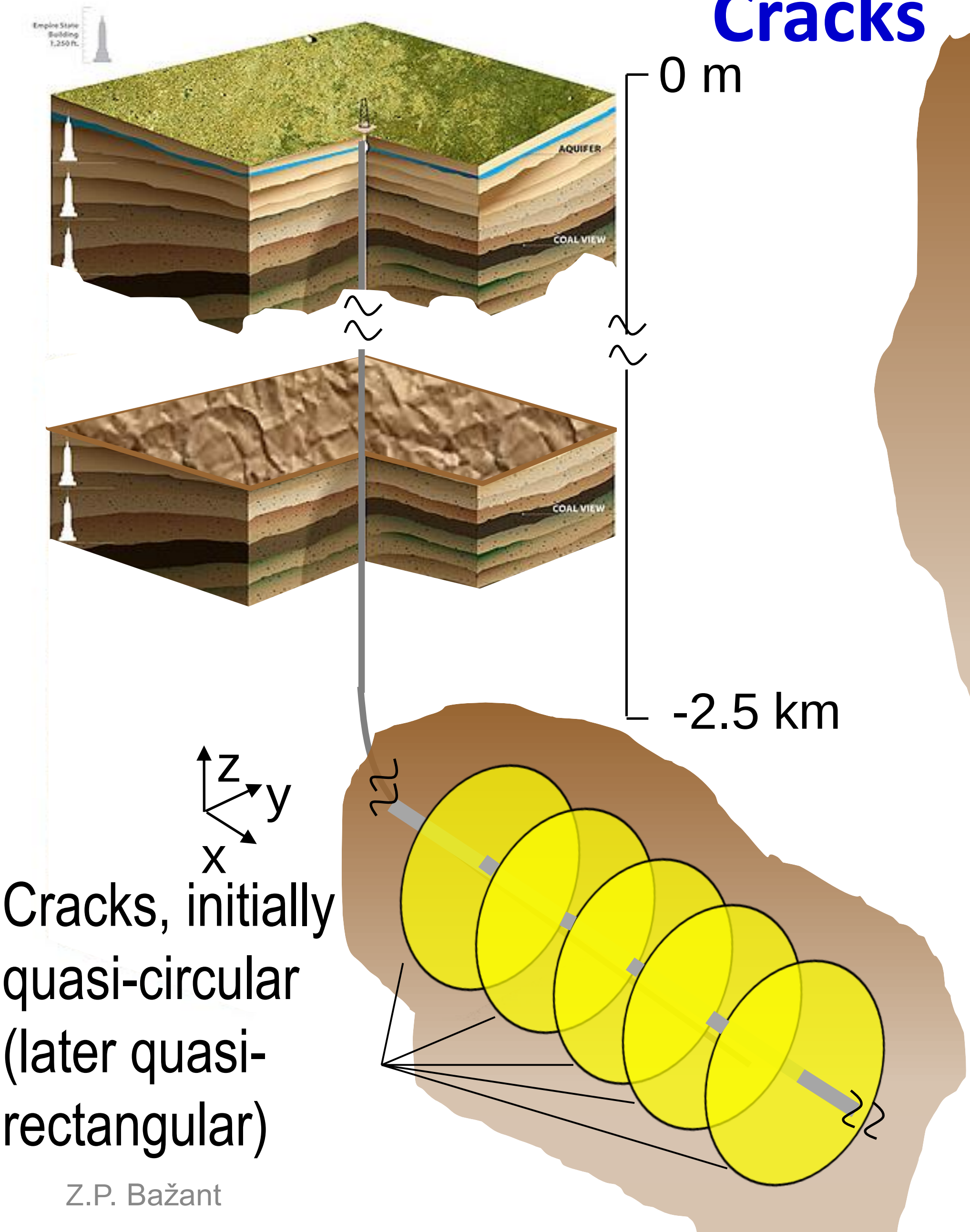
$$\sigma_T(x,y) + \sigma_h = [-E\alpha\Delta T(x) + \sigma_h] + [\sigma_p(x,y) + \sigma_h]$$

$$K_I^T = 0 + K_I^p$$

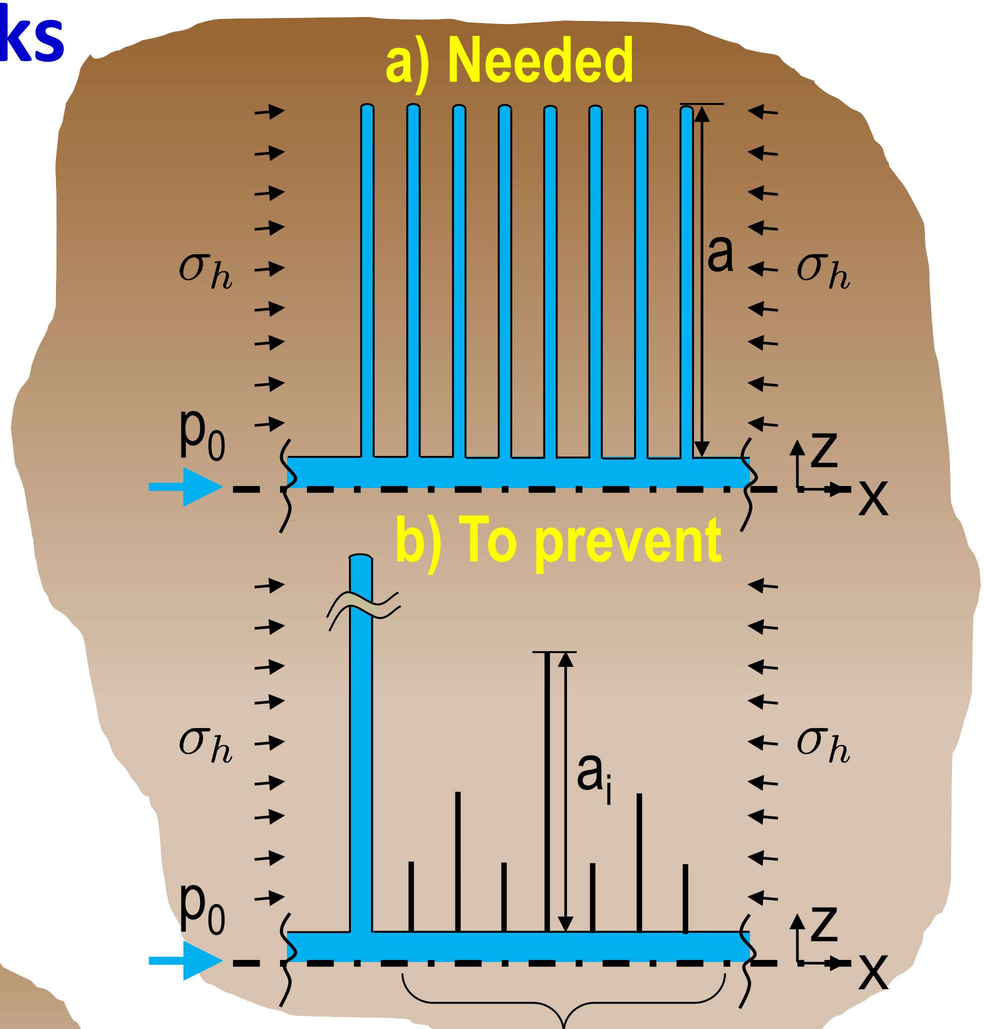
Circular Crack Localization



Localization Instability of Fluid-Pressurized Circular Cracks



Cracks, initially quasi-circular (later quasi-rectangular)



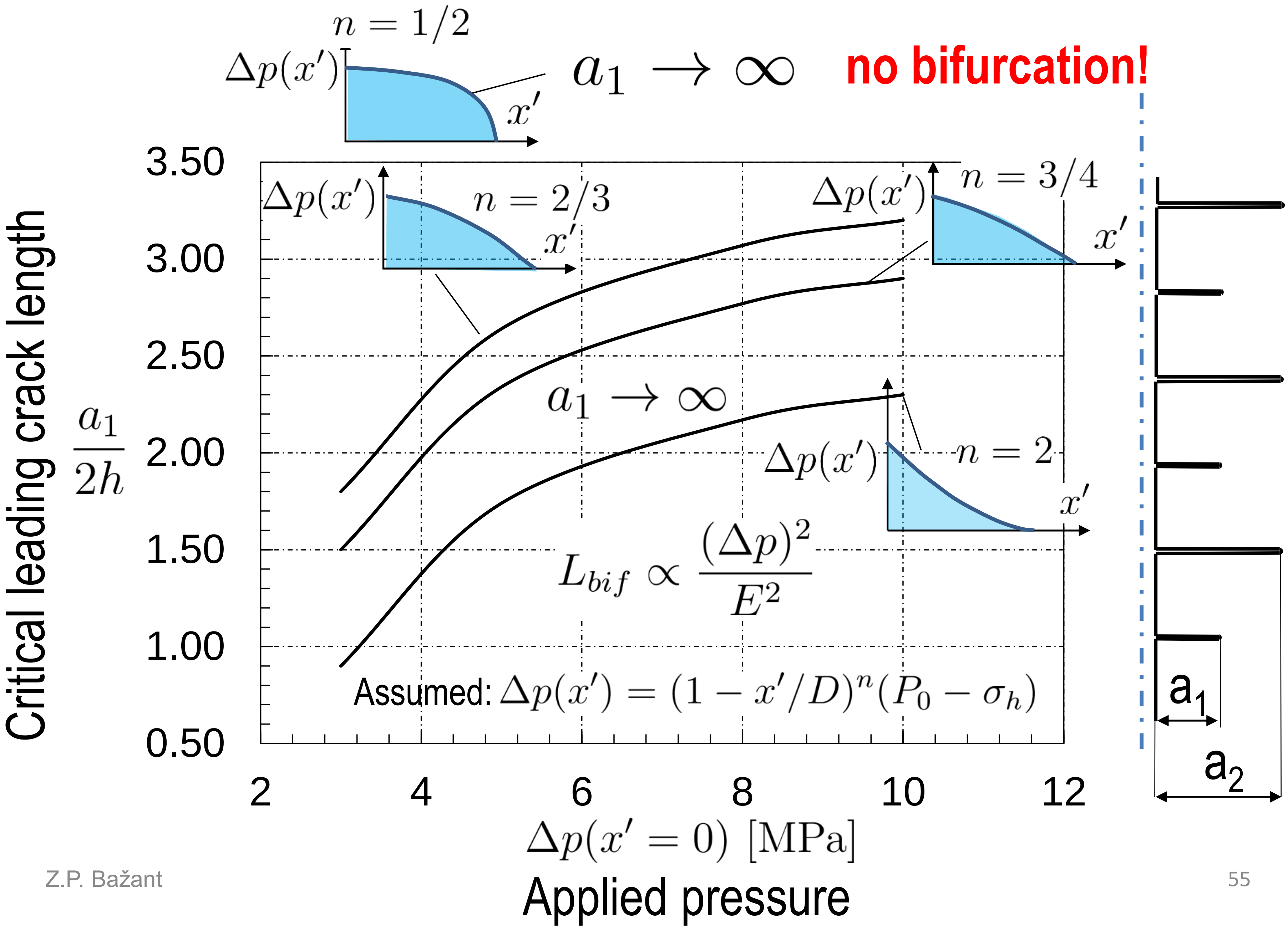
Cracks that have closed

p_0 = borehole pressure

σ_h = minimum horiz. stress

Z.P. Bažant

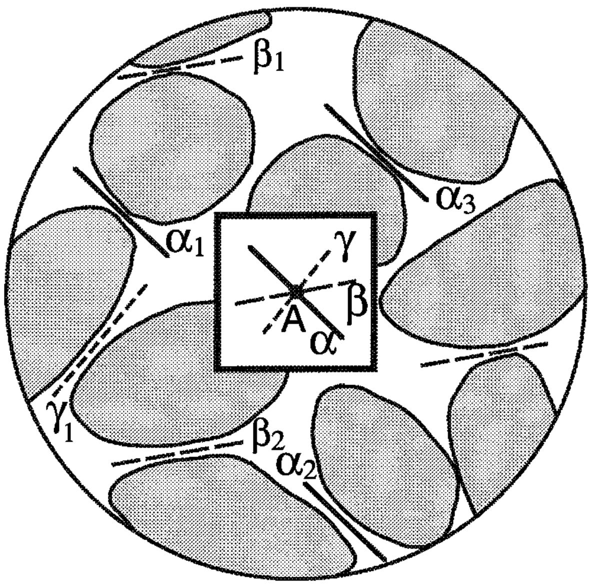
Effect of Front Steepness of Pressure Profile

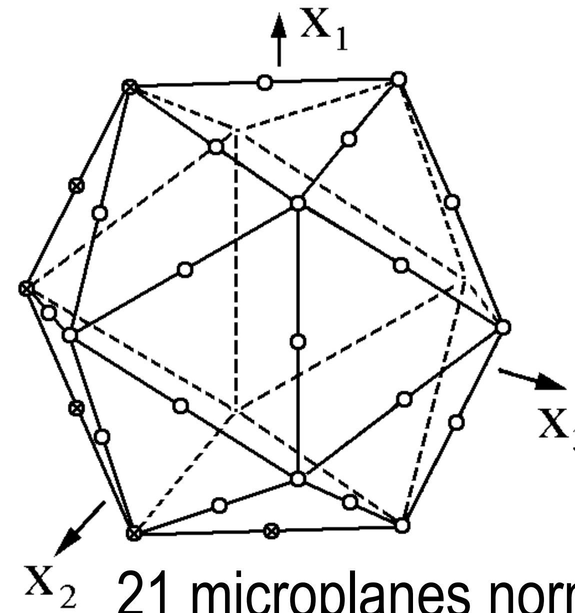


Summary of Four Omitted Slides on Ongoing Research in Bažant's Group

- Crack band model is used for a smeared continuum model of evolution of a fracking stage with millions of existing or potential cohesive cracks.
- The continuum model is dicretized by finite elements.
- Viscous pressurized compressible fluid flows through a 3D system of cracks in shale.
- Cracks interact with each other through the rock. with each other.
- Crack localization affects the flow of fluid.

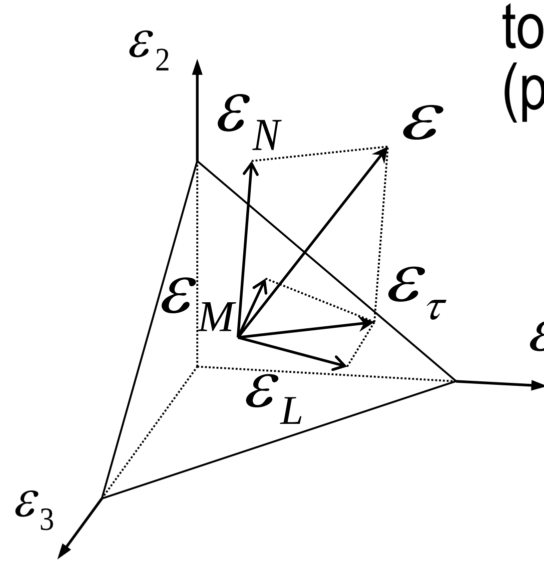
Microplane — a Semi-Multiscale Model





21 microplanes normal to circled directions (per hemisphere)

Subscale interactions among orientation are captured (lumped into a continuum point) but interactions at distance are not



Microplane strain components

General Algorithm in Microplane Model

Kinematic constraint

Macro-Strain
ε_{ij}

Micro-Strains
$\varepsilon_N, \varepsilon_V, \varepsilon_D, \varepsilon_L, \varepsilon_M$
on each plane

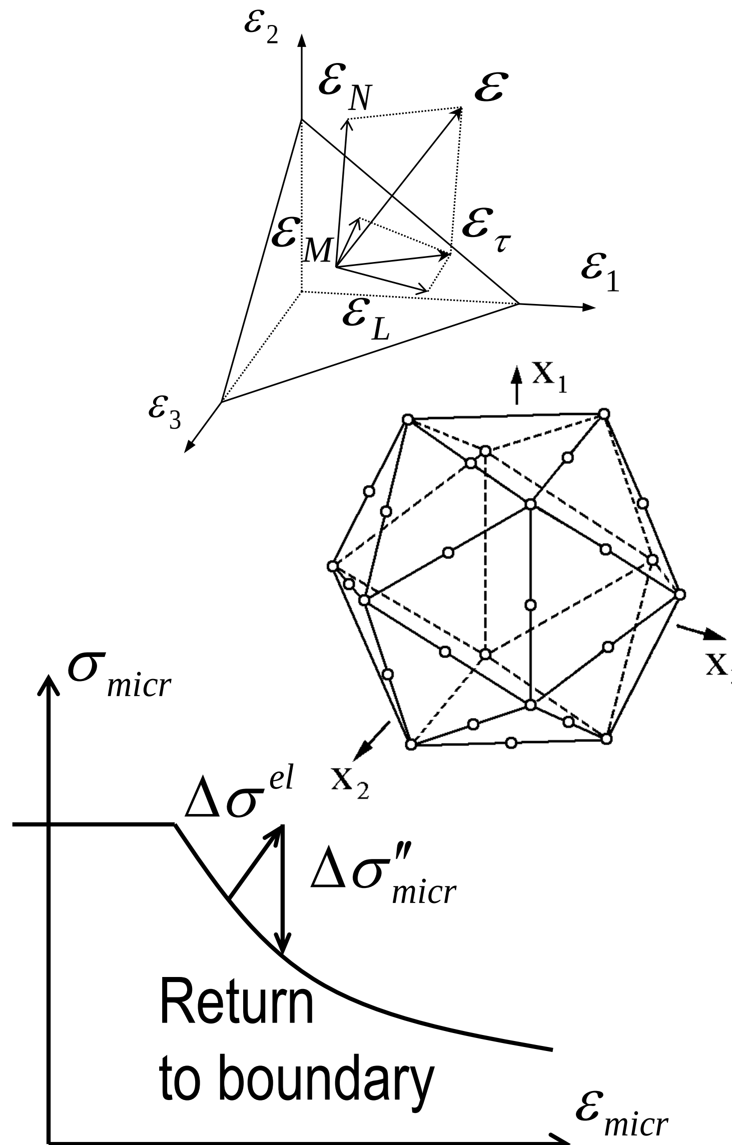
Classical tensorial models

Microplane constitutive relation

Macro-Stress
σ_{ij}

Micro-Stresses
$\sigma_N, \sigma_V, \sigma_D, \sigma_L, \sigma_M$
on each plane

Principle of virtual work



Microplane Model for Anisotropic Shale*

$$\Delta\sigma_e = K_e \Delta\epsilon$$

K_e =transversely isotropic elasticity tensor

$$\Delta\sigma_N^e = n^T \cdot \Delta\sigma_e \cdot n; \quad \Delta\sigma_\tau^e = n^T \cdot \Delta\sigma_e - \Delta\sigma_N^e\, n$$

$$\sigma_N = \max\left(\sigma_V^b + \sigma_D^b; \min\left(\sigma_N^b; \sigma_N^0 + \Delta\sigma_N^e\right)\right)$$

$$\sigma_\tau = \min\left(\sigma_\tau^b; \sigma_\tau^0 + \Delta\sigma_\tau^e\right); \;\; \sigma_L = \sigma_\tau \cos(\alpha); \;\; \sigma_M = \sigma_\tau \sin(\alpha)$$

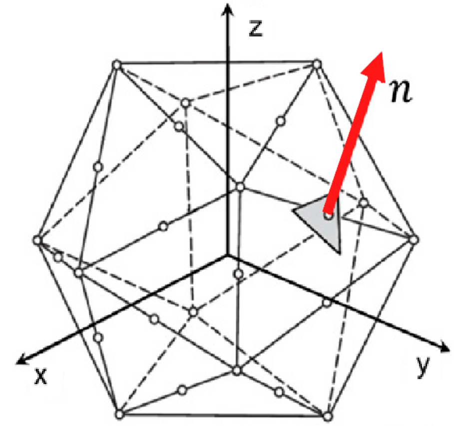
$$\sigma_V^b = \sqrt{\left(\frac{n_x}{\sigma_{Vx}^b}\right)^2 + \left(\frac{n_y}{\sigma_{Vt}^b}\right)^2 + \left(\frac{n_z}{\sigma_{Vt}^b}\right)^2}$$

$$\sigma_D^b = \sqrt{\left(\frac{n_x}{\sigma_{Dx}^b}\right)^2 + \left(\frac{n_y}{\sigma_{Dt}^b}\right)^2 + \left(\frac{n_z}{\sigma_{Dt}^b}\right)^2}$$

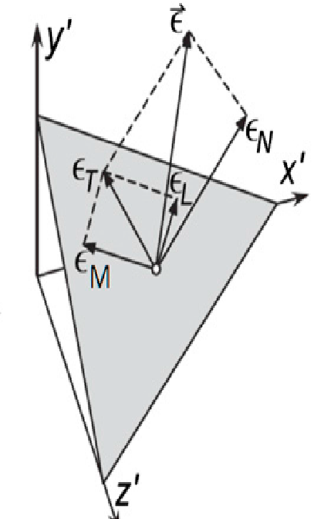
$$\sigma_N^b = \sqrt{\left(\frac{n_x}{\sigma_{Nx}^b}\right)^2 + \left(\frac{n_y}{\sigma_{Nt}^b}\right)^2 + \left(\frac{n_z}{\sigma_{Nt}^b}\right)^2}$$

x = direction normal to the bedding plane

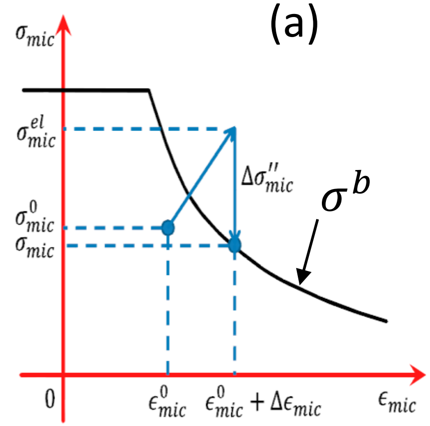
y, z, t = directions in the bedding plane



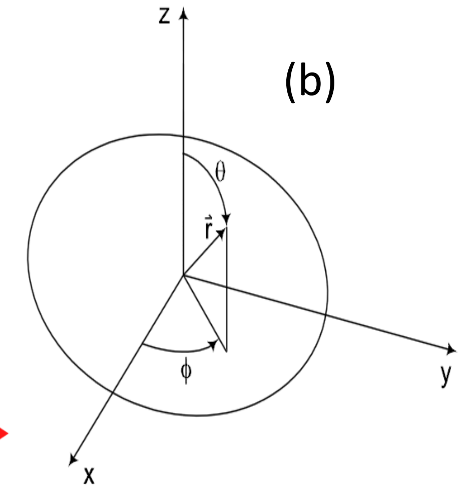
(a)



(b)



(c)

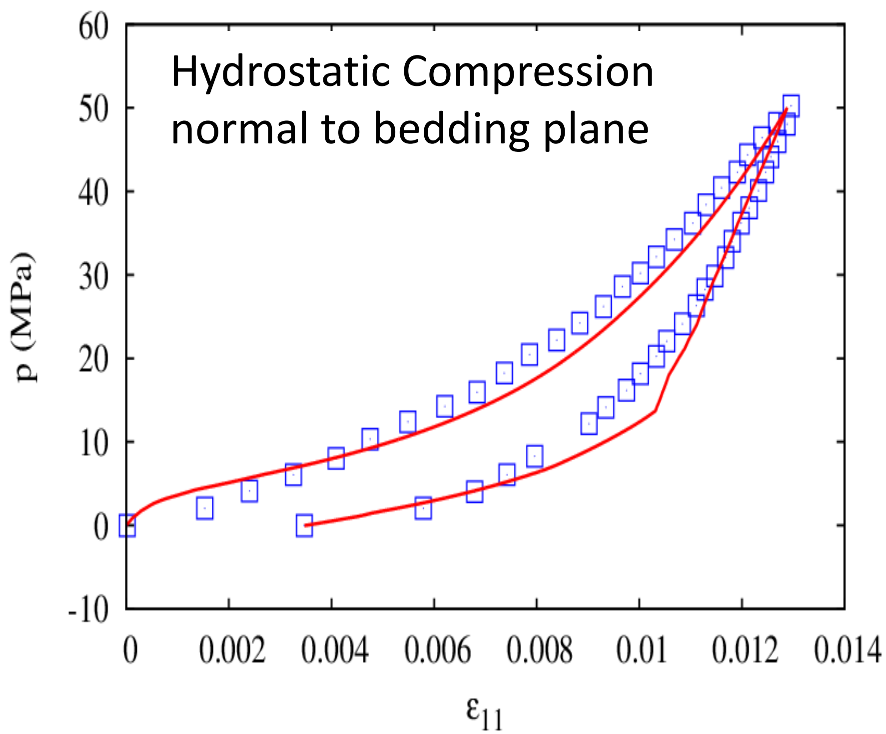


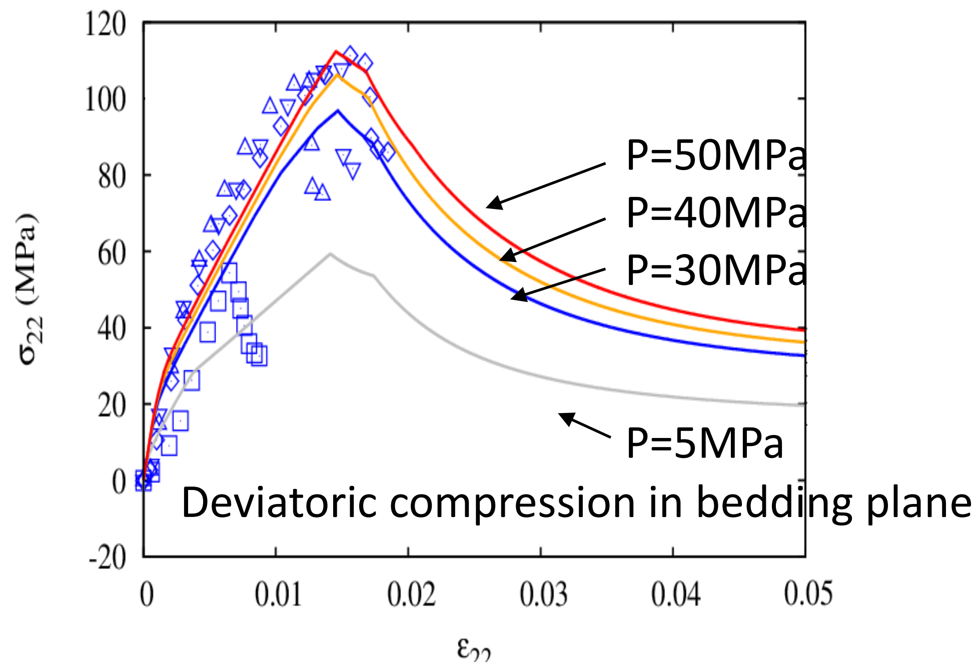
(d)

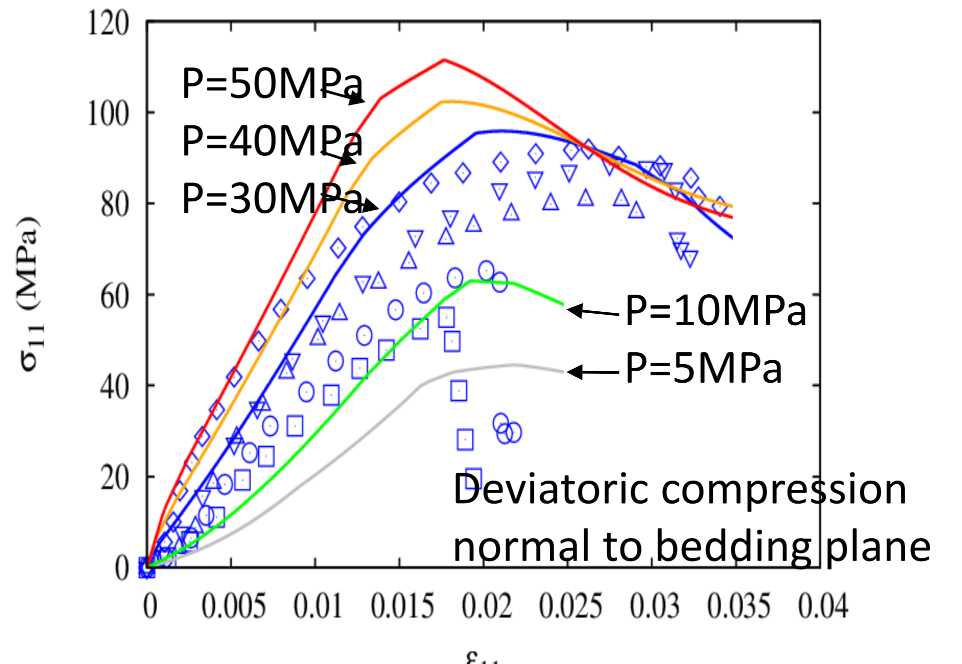
*By FC Caner, & ZP Bazant

$$\sigma_{ij} = \int_\Omega \left(\sigma_N n_i n_j + \sigma_M \frac{1}{2}\left(n_i m_j + n_j m_i\right) + \sigma_L \frac{1}{2}\left(n_i l_j + n_j l_i\right)\right) \mathrm{d}\Omega$$

Calibration of Microplane Model by Test Data







Test data: Niandou H, Shao JF, Henry JP and Fourmaintraux D (1997), “Laboratory investigation of the mechanical behavior of **Tournemire Shale**”, Int. J. Rock Mech. Min. Sci., 34(1):3-16.

SUMMARY: Why Fracking Works

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

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

1) Steep front of water pressure profile along the cracks, which can be achieved by appropriate pumping rate and history, proppant, viscosity control, acids, etc.;

2) Cracking localization instability requires some cracks to close — prevented if the closing is blocked by proppant.

Thanks for listening!
Questions?

Google “Bazant”, download freely:

1) Bažant, Z.P., Salviato, M., Chau, Viet T., Viswanathan, H. and Zubelewicz, A. (2014). "Why fracking works." ASME J. of Applied Mechanics} 81 (Oct.), 101010-1---101010-10.

Related works:

2) Bažant, ZP, FC Caner (Dec. 2013), **PNAS** 110 (48), 19291-19294;

3) Bažant, ZP, FC Caner (Feb. 2014), **JMPS** 139 (12), 714-1735.