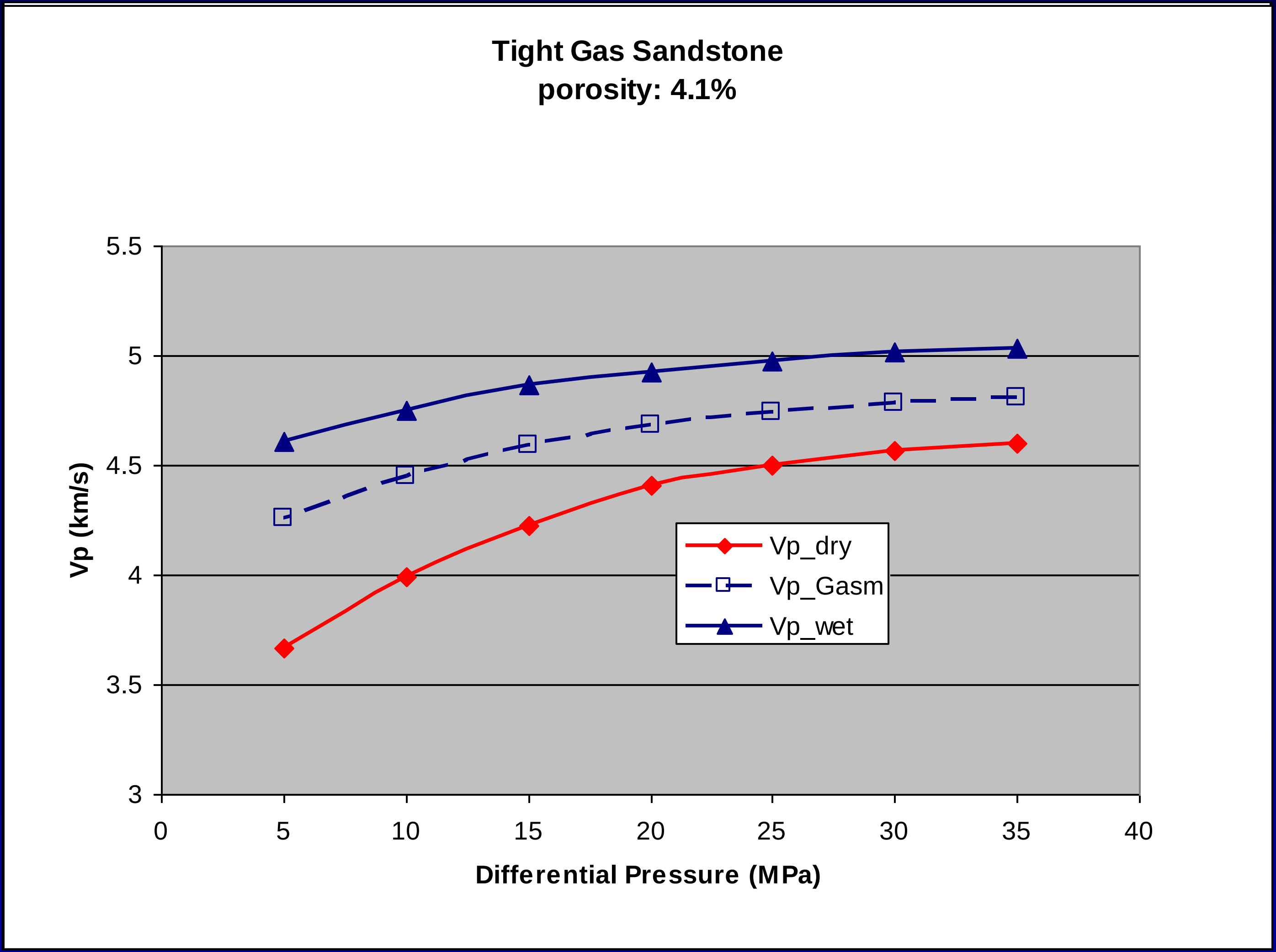
Fluid Substitution with Dynamic Fluid Modulus: Facing the Challenges in Heterogeneous Rocks

Qiuliang Yao, De-hua Han,
Fuyong Yan, Luanxiao Zhao

University of Houston

Apr. 22, 2013

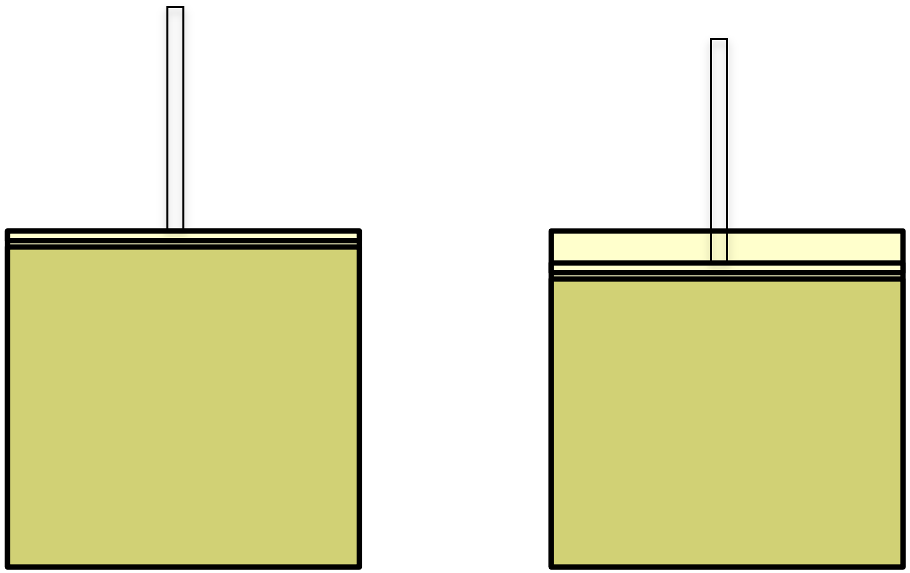
Observations: where does Gassmann break?



Outline

1. Fluid effect in closed system: Gassmann
2. Fluid effect in non- closed system: partial drainage and DFM
3. Wave induced internal flow and dispersion
4. Modeling Examples:
   - Mesoscopic heterogeneity
   - Microscopic heterogeneity (crack-pore system)
5. DFM from real measured data

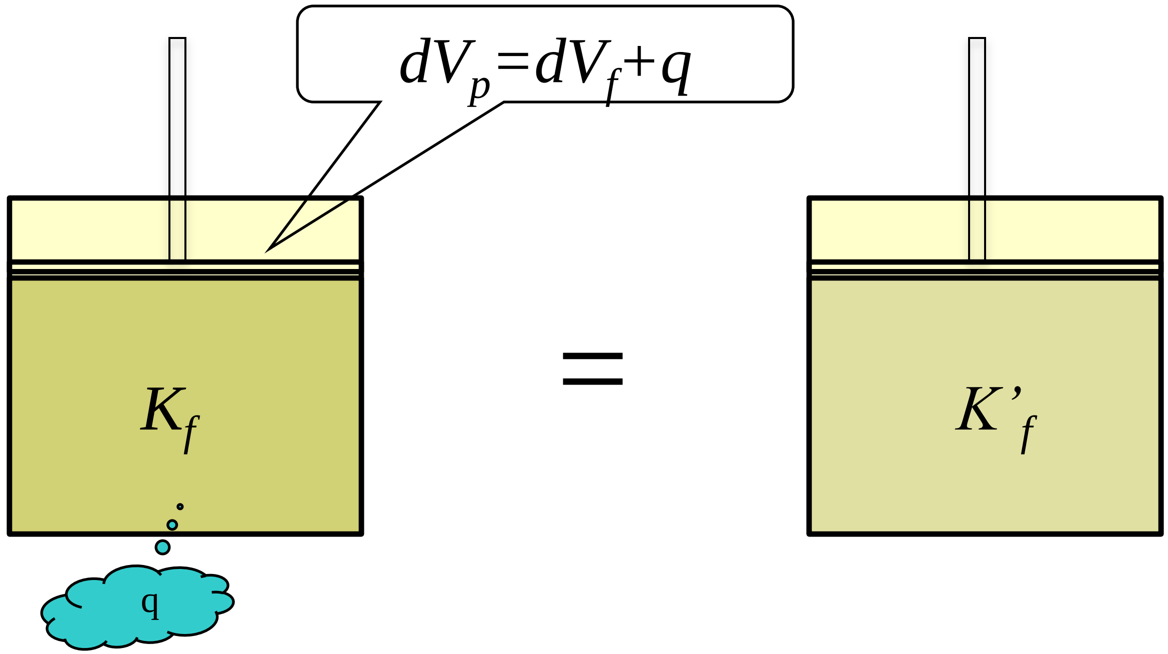
Fluid effect in closed system: Gassmann



$$-\frac{1}{K_f} = \frac{dV_f / V_f}{dP_f} = \frac{dV_p / V_p}{dP_p}$$

$$K_{sat} = K_{dry} + \frac{\alpha^2}{(\alpha - \phi)/K_0 + \phi / K_f}$$

Fluid effect in non- closed system: partial drainage and DFM

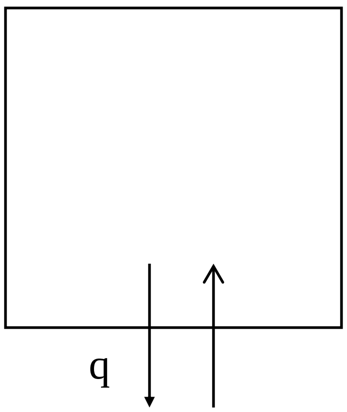


$$\frac{1}{K_f'} = -\frac{(dV_f + q)/V_p}{dP_p} = \frac{1}{K_f} - \frac{q/V_p}{dP_p}$$

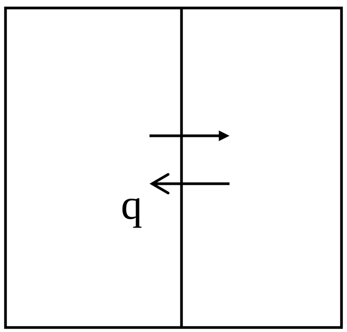
$$K_{sat} = K_{dry} + \frac{\alpha^2}{(\alpha - \phi)/K_0 + \phi/K_f'}$$

q: "+" for incoming flow, "-" for outgoing flow

What about closed system with internal flow?

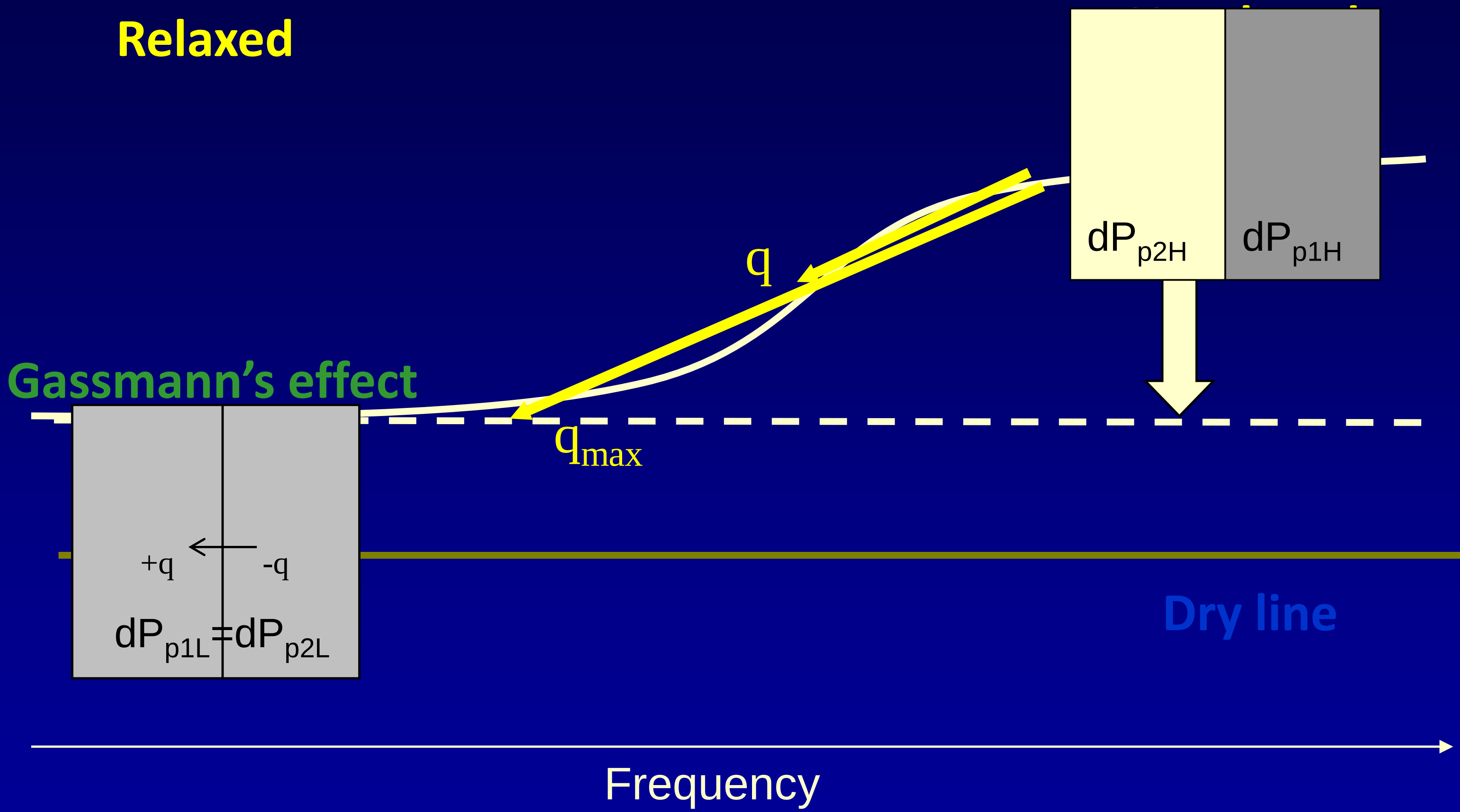


External flow

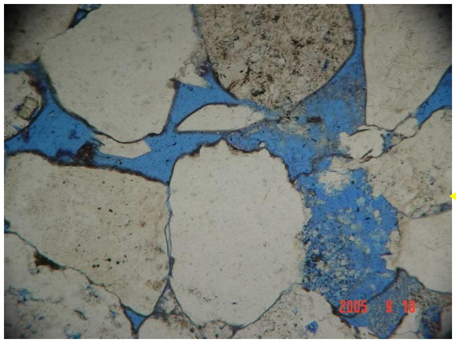


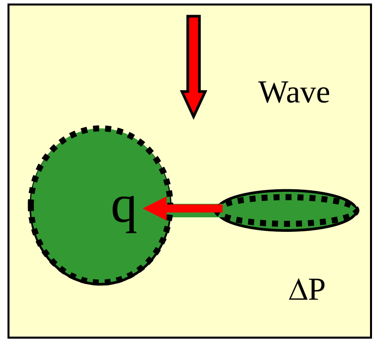
Internal flow

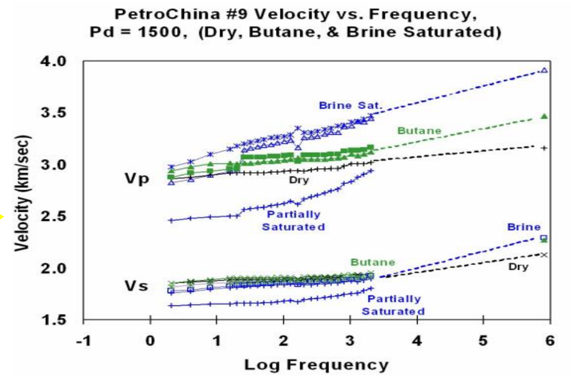
What's the role of fluid flow?



What's the role of fluid flow?







How much fluid moved?

$$q_{\max} = \frac{V_{p2}}{K_f}(dP_{p2H} - dP_{p1H})$$

How much more deformed due to relaxation?

$$\delta V_L - \delta V_H = -\beta_f V_{p2}(\delta P_{p1H} - \delta P_{p2H})$$

$$\delta V_L - \delta V_H = q_{\max}$$

How to calculate q=q(f) ?

* Need geometry info on heterogeneity
* Navier-Stokes equation with proper boundary condition
* Need proper approximation
* Mesoscale: general format with characteristic frequency ω_c

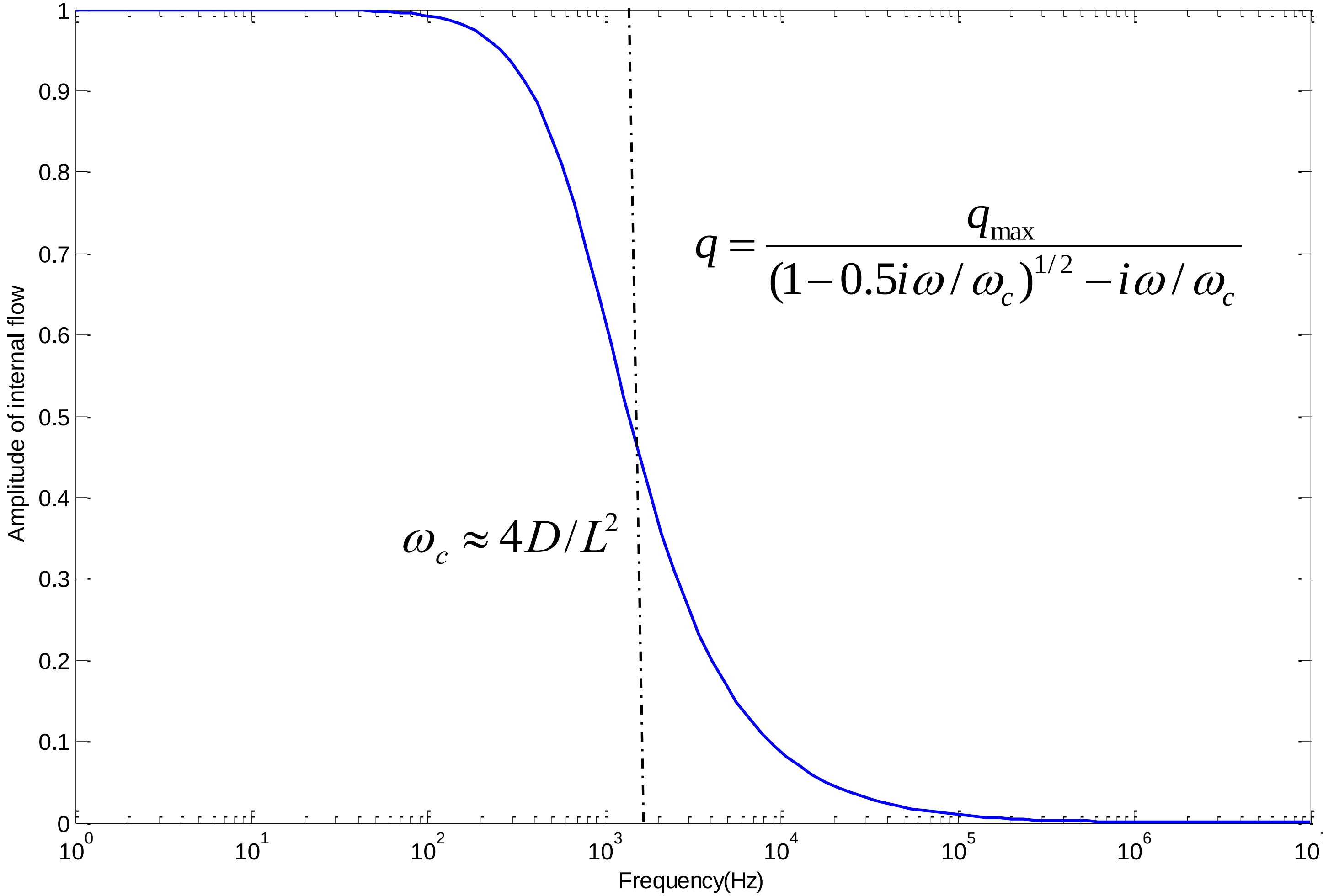
$$q = \frac{q_{\max}}{(1 - iP\omega/\omega_c)^{1/2} - i\omega/\omega_c}$$

* Microscale:

  Analytical solution

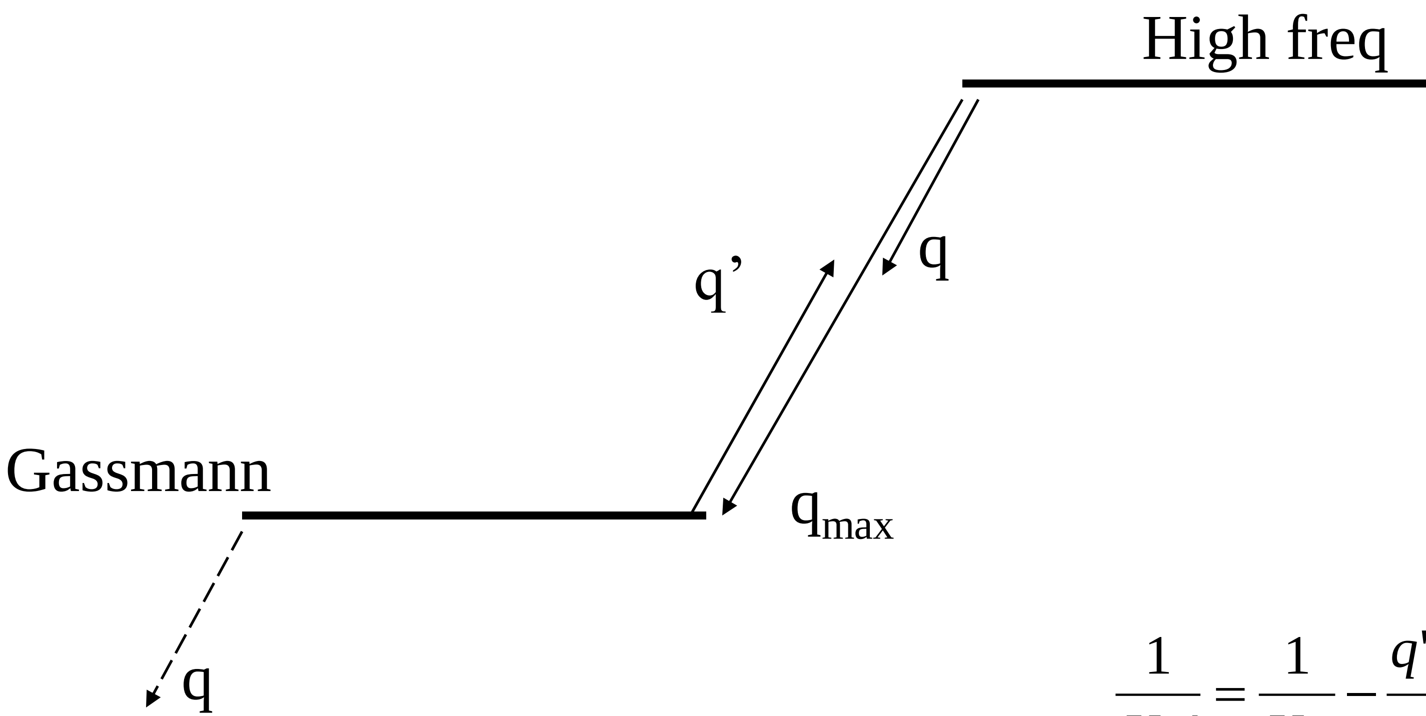
  Numerical solution

Frequency dependency of fluid flow: q=q(f)



Berryman, 2003

Where to start from: ∞ Hz or 0 Hz?

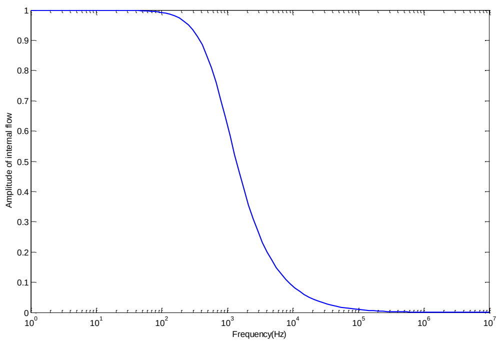


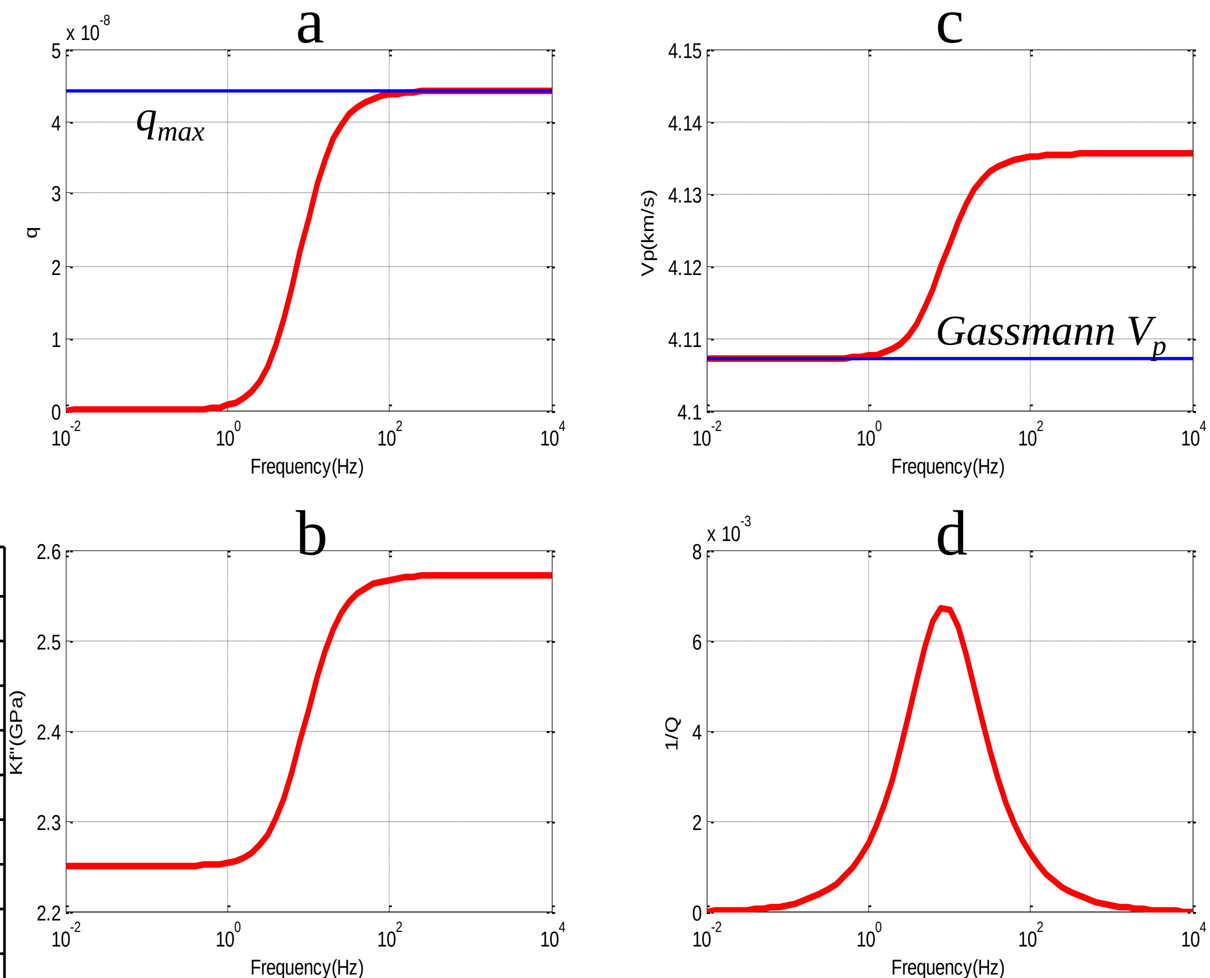
$$q' = -(q_{max} - q)$$

$$\frac{1}{K_f'} = \frac{1}{K_f} - \frac{q'/V_f}{dP_f}$$

$$K_{sat} = K_{dry} + \frac{\alpha^2}{(\alpha - \phi)/K_0 + \phi/K_f'}$$

q=q(f) in mesoscopic heterogeneity?



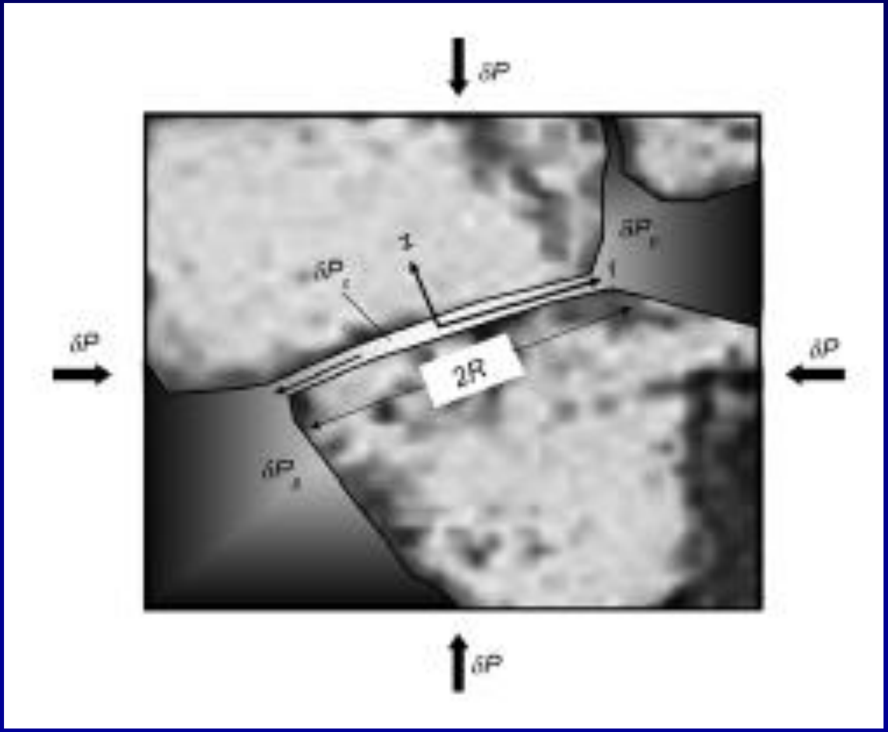


	Phase 1	Phase 2
Volume fraction	0.99	0.01
Grain bulk modulus K_0(GPa)	37	37
Dry bulk modulus K_{dry}(GPa)	18	2
Saturated shear modulus μ_{sat}(GPa)	15	15
Saturated density ρ (g/cc)	2.49	2.49
Porosity φ	0.1	0.1
Permeability κ (Darcy)	0.01	0.01
Fluid bilk modulus K_f (GPa)	2.25	
Fluid viscosity η (cP)	1	
Heterogeneity size L (cm)	30	

Heterogeneity size: 30cm

q=q(f) in microscopic heterogeneity?

$$\frac{q}{\delta P_f V_f} = \frac{8\pi\varepsilon(1-\nu)}{3\phi\mu} f(\zeta)\left[\frac{1/K_d - 1/K_s}{1/K_d - 1/K} - f(\zeta)\right] \Big/ \left\{1 + \frac{4(1-\nu)K_f}{3\mu\gamma}\left[1 - f(\zeta)\right]\right\}$$

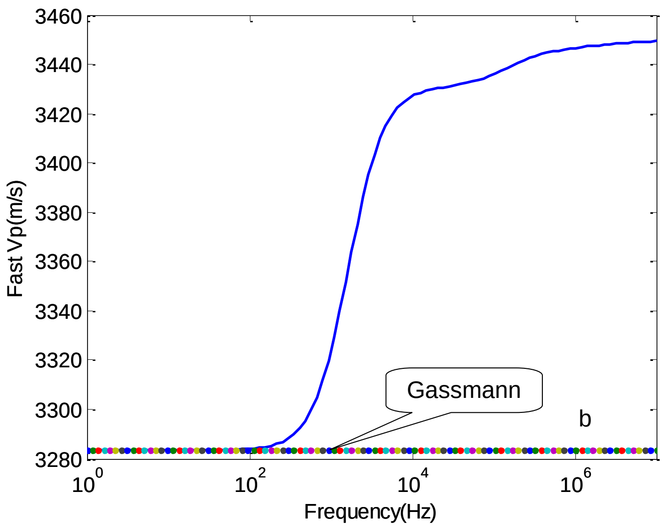


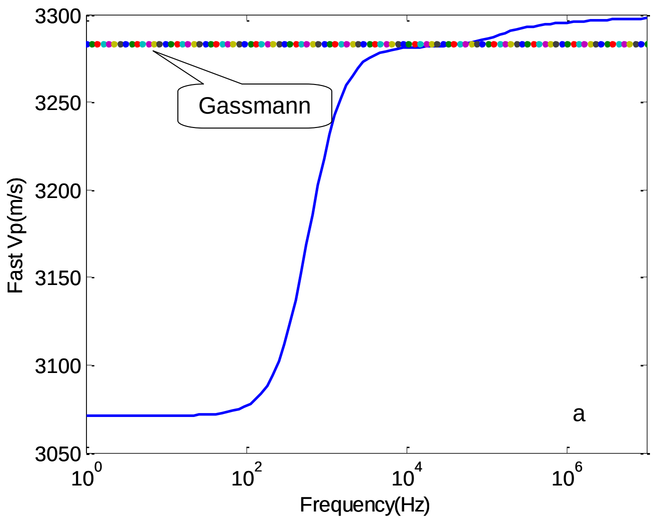
$$f(\zeta) = \frac{2J_1(\zeta)}{\zeta J_0(\zeta)}$$

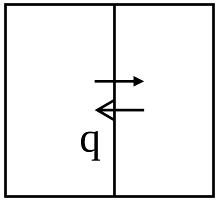
$$\zeta = \sqrt{3i\omega\eta / K_f} / \gamma$$

Tang 2011

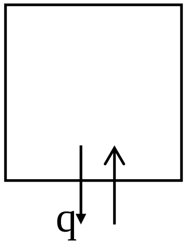
Squirt flow dispersion, by DFM



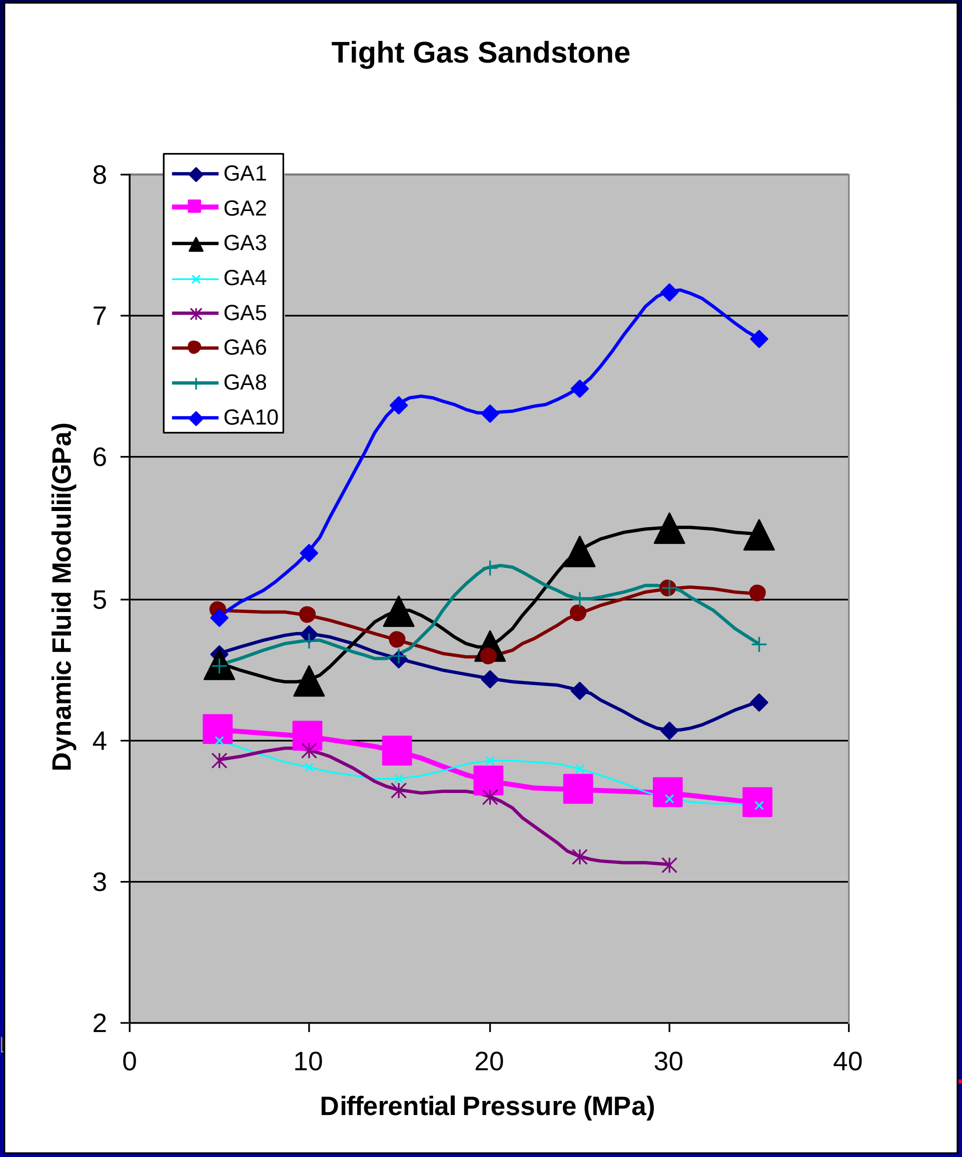


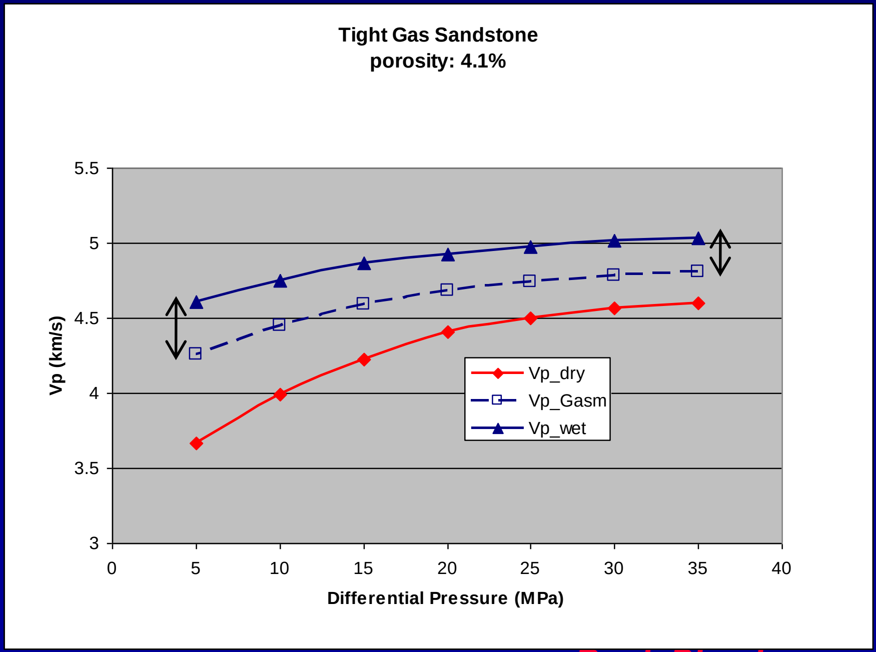


$q' = -(q_{max} - q)$



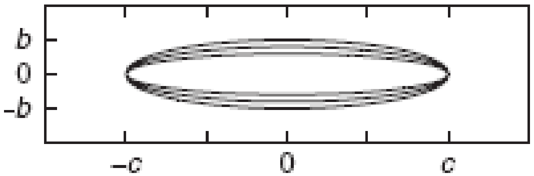
Pressure effect on heterogeneities

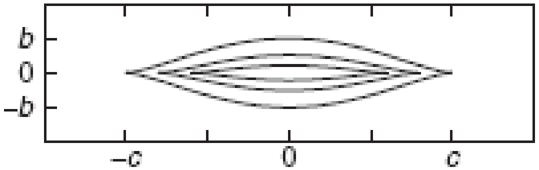




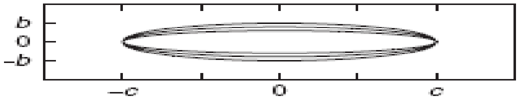
Rock Physics

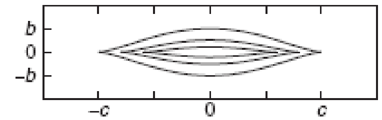
Elliptical vs. non-elliptical cracks

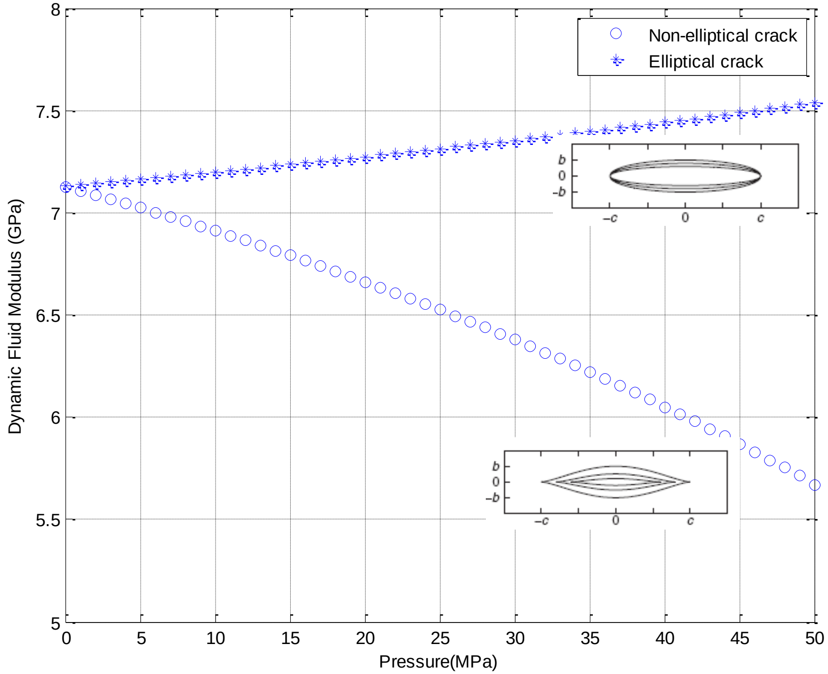




$$\varepsilon = \frac{3}{4\pi}\frac{\varphi_c}{\alpha}$$

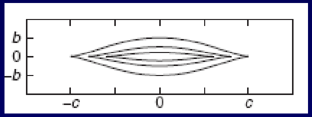


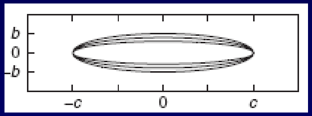


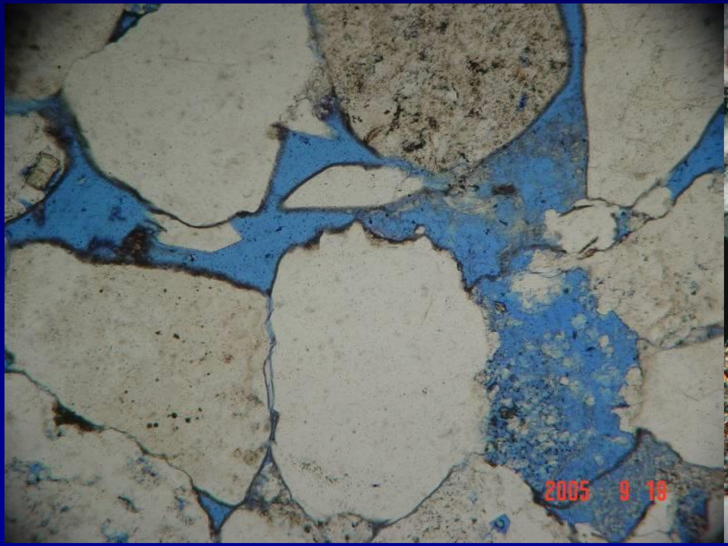


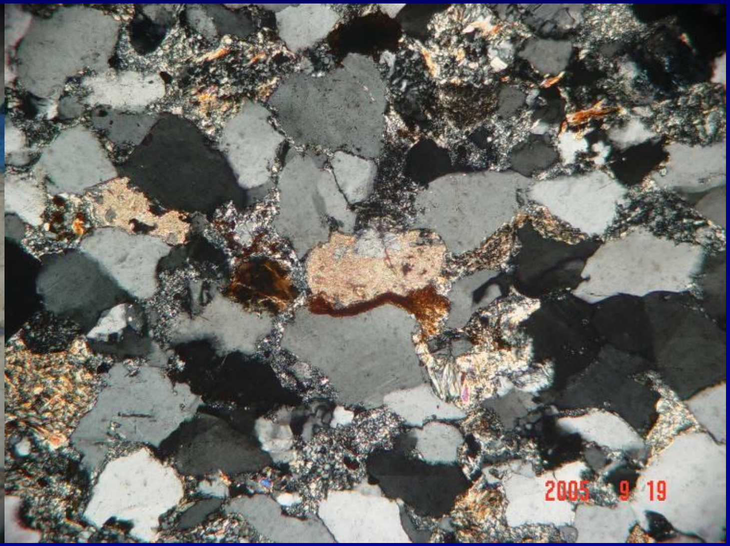
Elliptical vs. non-elliptical cracks

Tight Gas Sandstone









Sample GA2: ×100 ∥
Depth :2080.78

Sample GA3: ×100 ⊥
Depth: 2072.53m

Summaries

1. Using “dynamic fluid modulus”, Gassmann equation can be extended into heterogeneous rocks at non-zero frequency.
2. Explicitly link heterogeneities to dispersion and attenuation, by a fluid term.
3. More intuitive physical meaning.
4. Modeling: more powerful and flexible .
5. Inverting: new insight on rock microstructure

Thank You!